Utilisation and Reliability of High Power Proton Accelerators

The use of high power particle accelerators in various areas of applied nuclear science is presented with special emphasis on accelerator driven reactor systems (ADS) for transmutation of nuclear waste. National programmes for the development of spallation neutron sources are presented and the performance and reliability of existing or planned accelerators for use in ADS are discussed. Effects, such as thermal shocks and material resistance, on the reactor part of an ADS from loss of accelerator beam are discussed more in greater detail.
OECD PROCEEDINGS

Proceedings of the Workshop on

Utilisation and Reliability of High Power Proton Accelerators

13-15 October 1998
Mito, Japan

NUCLEAR ENERGY AGENCY
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

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− to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
− to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
− to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter; Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996) and the Republic of Korea (12th December 1996). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of all OECD Member countries, except New Zealand and Poland. The Commission of the European Communities takes part in the work of the Agency.

The primary objective of the NEA is to promote co-operation among the governments of its participating countries in furthering the development of nuclear power as a safe, environmentally acceptable and economic energy source.

This is achieved by:

− encouraging harmonization of national regulatory policies and practices, with particular reference to the safety of nuclear installations, protection of man against ionising radiation and preservation of the environment, radioactive waste management, and nuclear third party liability and insurance;
− assessing the contribution of nuclear power to the overall energy supply by keeping under review the technical and economic aspects of nuclear power growth and forecasting demand and supply for the different phases of the nuclear fuel cycle;
− developing exchanges of scientific and technical information particularly through participation in common services;
− setting up international research and development programmes and joint undertakings.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has concluded a Co-operation Agreement, as well as with other international organisations in the nuclear field.
FOREWORD

The Nuclear Energy Agency (NEA) Nuclear Science Committee has a comprehensive work programme covering items of relevance both for present and for advanced nuclear applications. One specific area of interest is the different concepts proposed for the transmutation of nuclear waste. Among the concepts suggested is the possibility of using a hybrid nuclear system, that is a sub-critical reactor coupled with a high power particle accelerator. The performance of such a system depends to a large extent on the specifications and reliability of the particle accelerator.

Following a presentation by Professor N. Watanabe (Japan Atomic Energy Research Institute, JAERI) on the Utilisation and reliability of high power accelerators, the NEA Nuclear Science Committee decided to organise a workshop on the subject. The workshop was hosted by JAERI and was held in Mito, Japan on 13-15 October 1998.

These proceedings contain all papers presented at the workshop, including summaries of two working groups set up during the workshop. The working group’s respective topics were Accelerators and ADS and other sub-systems.

A follow-up meeting to this workshop will be held in Aix-en-Provence, France at the end of November 1999 and will be hosted by CEA Cadarache.
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EXECUTIVE SUMMARY

Scope of the workshop

R&D activities and construction plans related to high power proton accelerators (HPPAs) are being considered in various countries to promote basic and applied sciences, including accelerator driven nuclear energy system (ADS), using neutrons, protons and other secondary particles. Taking into account the fact that proton beams from existing HPPAs are not entirely stable (frequent beam trips), it is indispensable to understand the effects (e.g. thermal shocks) of such beam trips on different sub-systems, especially fission sub-systems. Additional R&D will be needed to accomplish highly reliable HPPAs and sub-systems resistant to thermal shocks.

The scope of the workshop comprises:

- the experiences and prospects of HPPA utilisation;
- reliability of existing HPPAs, especially focused on beam trips and power fluctuations;
- effects of resulting thermal shocks in fission sub-systems;
- required accelerator reliability in various applications;
- R&D of sub-systems resistant to thermal shocks;
- accelerator types suitable for ADS, interface technology between proton beam and sub-systems;
- control systems and safety concepts for ADS, as well as problems relevant to utilisation (multi-purpose vs. dedicated systems, etc.).

The purpose of the workshop is to exploit more efficient utilisation of HPPAs in various fields and to ensure the future possibility of accelerator-driven nuclear energy systems.

Major presentations

Applications of high power proton accelerators (HPPAs)

Five papers were presented on projects developing spallation neutron sources, and six papers were presented on the topic of accelerator driven systems.

The Spallation Neutron Source (SNS) project in the USA had been approved. The project aims at a 1 MW pulsed spallation neutron source for neutron scattering, with a view toward upgrading to 4 MW. The European Spallation Source (ESS) project with a 5 MW spallation neutron source has begun
an optional study of a superconducting proton linac, in addition to the projected non-superconducting one. There are currently two projects in Japan. It was reported that these two projects would merge:

- the JAERI Neutron Science Project for neutron science and for transmutation of long-lived nuclear wastes with 1.5 GeV, 5.3 mA superconducting linac;
- the JHF project promoted by the High Energy Accelerator Research Organisation (KKK), which includes two ring synchrotrons of 3 GeV, 200 mA and 50 GeV and four research facilities, i.e. for high energy nuclear physics, neutron scattering, muon science and RI beam nuclear physics.

The KOMAC project in Korea is a multipurpose accelerator complex. It aims at constructing a 1 GeV, 20 mA HPPA in conjunction with the ADS project of HYPER.

Many countries are currently developing ADS oriented projects. The Chinese project of a 150 MeV, 3 mA HPPA is moving toward injecting a beam to a 3.5 MWt LWR with a criticality of 0.94-0.98. Russian activities in ADS development include critical experiments with photo-neutrons from a Pb or Pb-Bi target. The Czech programme is for LLFP and TRU transmutation with a mixture of target/MA and Flibe cooled graphite/LLFP blankets driven by a 35 MeV deuteron external neutron source. In France, activities are co-ordinated by the GEDEON project for development in nuclear waste transmutation. Projects include spallation target experiments at SATURN and reactor experiments at MASURCA with a 14 MeV source, material research of structure and Pb, Pb-Bi target and 10 MeV, 100 mA accelerator developments. In Italy there is the TRASCO programme directed by the ENEA and the INFN, and the industrial programme conducted by Ansaldo Corp. The TRASCO programme is developing a 1 GeV, 30 mA accelerator, a sub-critical system comparable to the energy amplifier (EA) with nine sub-programs. The industrial programme focuses on a demonstration prototype of an 80 MWt system with a Pb-Bi target and sub-criticality of 0.95. In the USA, the ATW is concentrating on three areas of development: accelerators in APT (1 GeV, 140 mA), pyrochemical processes and a sub-critical burner (2 000 MWt/Pb-Bi).

<table>
<thead>
<tr>
<th>Project</th>
<th>Country</th>
<th>Specification</th>
<th>Utilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNS</td>
<td>USA</td>
<td>1 GeV, 1 mA, 1 MW (4 MW)</td>
<td>Neutron scattering</td>
</tr>
<tr>
<td>ESS</td>
<td>EU</td>
<td>1.333 GeV, 3.75 mA, 5 MW</td>
<td>Neutron scattering</td>
</tr>
<tr>
<td>JAERI-NSP</td>
<td>Japan</td>
<td>1.6 GeV, 5.33 mA, 8 MW</td>
<td>Neutron scattering, ADS</td>
</tr>
<tr>
<td>KEK-JHF</td>
<td>Japan</td>
<td>3 GeV, 200 mA; 50 GeV, 10 mA</td>
<td>Neutron scattering, muon, kaon</td>
</tr>
<tr>
<td>KOMAC</td>
<td>Korea</td>
<td>1 GeV, 20 mA</td>
<td>RI production, therapy, ADS</td>
</tr>
<tr>
<td>RCNPS</td>
<td>China</td>
<td>150 MeV, 3 mA</td>
<td>RI production, therapy, ADS</td>
</tr>
<tr>
<td>TRASCO</td>
<td>Italy</td>
<td>1 GeV, 30 mA</td>
<td>ADS</td>
</tr>
<tr>
<td>GEDEON</td>
<td>France</td>
<td>?</td>
<td>ADS</td>
</tr>
<tr>
<td>ATW</td>
<td>USA</td>
<td>1 GeV, 140 mA (APT)</td>
<td>ADS</td>
</tr>
<tr>
<td>?</td>
<td>Czech</td>
<td>35 MeV deuteron</td>
<td>ADS</td>
</tr>
</tbody>
</table>

Reliability of HPPAs

The reliability of accelerators has been investigated using a statistical code, based on operational data from LANSCE, ISIS, PSI and TJNAF facilities. The accelerator downtime predicted from the
mean time between failure (MTBF) and the mean time to repair (MTTR) agreed well with observations. The results of the analysis of beam trips and downtime at LANSCE during 1996 and 1997 showed that the most frequent trips (77%) depended on the H+ injector, but that downtimes in these cases were shorter than one minute. Another accelerator component with frequent trips is the RF system. At Moscow Meson (500 MeV, 20 mA peak current, 50 Hz and 90 ms duration), it was shown that the average beam current loss is less than 0.2% but is localised along the linac. The PSI cyclotron experience was that the major cause of beam trips is micro-sparks of the RF system. The shutdown time from the most common sparks is less than 200 ms, after which the beam is automatically restarted.

The concept of the SNQ project (1980s) of independent single cavities was adopted to isolate a fault in a cavity and to compensate by correctly surrounding working cavities. The multiplexing of accelerators and ADS systems largely increase the reliability. A method to improve the reliability of an accelerator based on experiences of IPNS and APS at ANL is to operate the accelerator well below the upper limit of its specification, i.e. with a suitable margin. From experiences of cavities, couplers and RF systems at LEP at CERN, it was shown that the life of 34 cyclotrons is expected to be more than 10 000 hours and that the reliability of superconducting electron linear accelerators is well established.

New accelerators

A H$_2^+$ cyclotron concept was proposed to reduce the space charge effect and to eliminate deflection with a stripping foil. A separated orbit cyclotron with superconducting magnets and cavities was also proposed with results from the test device TRITRON, in which three cascade rings can accelerate the beam up to 1 GeV. A fixed-field alternating gradient (FFAG) accelerator was proposed to improve the power efficiency of accelerators for ADS in the context of progress in cavity and magnet technologies.

Beam trips/fluctuations: Effects on ADS and the ADS resistance

From a preliminary analysis of a modest design concept of ADS, it was shown that the thermomechanical effects on the ADS components are the most important problem caused by a beam trip, whereas the effects on fuel pellets, fuel pins and beam window would be negligible. It was also shown from the results of temperature transient tests in a FBR structural design guide, that in repeated temperature variations between 250°C and 600°C, the test piece was damaged by thermal fatigue for short cycle periods and by creep fatigue for long cycle periods.

From the analysis of the components exposed to temperature variation during a beam trip, based on the EFR concept, it was pointed out that above core structure (ACS) and intermediate heat exchanger (IHX) were important components to analyse.

Interface technology

In the IFMIF analysis, the decay constant of Li temperature is a few minutes for the two kinds of trips caused by two deuteron beam injections with 40 MeV, 250 mA: two beams of 10 MW and one beam of 5 MW.
In transient thermal stress analysis of a window made of SS316 steel in a mercury target bombarded by pulsed protons at a beam power of 6 MW with 50 Hz, it was shown that an asymptotic temperature at the beam window was reached within a couple of seconds, although the temperature fluctuates at 50 Hz.

A temperature decay constant in the lead core and the cladding for a lead rod target is estimated to be 5-10 seconds for unscheduled beam trips or loss of coolant. Maximum stress was 90 MPa in the cladding through normal operation and beam trip transients.

In a lead-bismuth spallation target bombarded by a proton beam of 600 MeV, 6 mA, the thermal stress, decoupled by the fluid dynamic transient, showed a Mises stress (conserved quantity related to yield function) of 175 MPa and a fatigue damage induced by cyclic beam trips longer than 4-5 seconds. This leads to a prediction of the allowable number of interruptions to failure.

Discussions

Working Group on Accelerators

The items discussed were:

- origins of beam trips and fluctuations;
- possible improvements for HPPAs;
- achievable reliability in the future and necessary R&D;
- linear vs. ring accelerators as HPPA systems.

The major conclusions are as follows:

- Three types of beam trips were identified:
  
  (1) short (< 1 min.);
  
  (2) medium (1 min.-1 h);
  
  (3) long (>1 h).

  The most frequent trip is type (1). Most of (1) and (2) are caused by sparks in HV/RF systems. The downtime for z micro-spark is typically 100 ms, according to PSI data, and the recovery time is about 600 ms. The trip frequency depends on the machine.

- For possible improvements, to reduce sparks (and thus to reduce damage), it is advisable to carefully design the devices and controls, to build and maintain as clean a room as possible, and to maintain good conditioning. Micro-sparks are unavoidable. It is important to note that accelerators are normally tuned to obtain maximum and “possibly more” performance and this is the main cause of beam trips and faults.
To maintain reliability, over-design is necessary, i.e. the same concept applied to the HV/RF systems should also be applied to the other components. A reliable accelerator is possible, but the meaning of “reliability” should be universally established. The participants agreed that:

- mean time between failures (MTBF) can be reduced to about 100 furs;
- mean time to repair (MTTR) depends on spares and redundancy, i.e. cost.

It is important to rely as much as possible on proven accelerators and make a selection considering the specific application. For CW machines, a ideal cyclotron (1 GeV, 10 mA) was discussed and general opinions were collected. The “halo” aspect, being the most important technical issue, was emphasised. Compactness, modularity, flexibility, etc., were discussed, as well as achievable power.

**Working Group on ADS and Sub-Systems**

The following issues were discussed:

- definition and separation of problems:
  - system test facility (STF) vs. transmutation plant (TP);
  - driven facility (DF) vs. spallation target (ST);
  - nature of trips;
- issues not definitely resolved;
- issues not discussed that need to be considered.

The major conclusions are as follows:

- STF is defined as a demonstrator combining a sub-critical facility with an accelerator. Only one reliable accelerator will be utilised in this case. The facility should have maximised flexibility. TP is defined as the facility routinely carrying out actinide transmutation. Multiplexing of ADSs and HPPAs is conceivable; it is optimised for cost and reliability. In the discussions, separated coolant loops are assumed for DF and TP. DF consists of above core structure (ACS), intermediate heat exchanger (IHX), primary coolant piping (PCP), fuel core (FC), etc. TP has a beam window and a liquid or solid spallation target. Trips are separated into two time ranges:
  1. shorter than a system characteristic time t (40-60 sec or less);
  2. much longer than time t.

In the case of (1), self-recovery (automation) is considered and affects mainly ACS or PCP. In the case of (2), a special restart protocol is necessary.

- The effects of pulsed operation of the accelerator and possible restrictions on the pulse structure were not fully discussed. These questions are related to economy, the possibility of multiplexing and beam control.
The necessity of control rods in ADSs needs to be discussed, relating to the compensation for burn-up and to safety questions. The ability to control beam power and power surge should also be discussed. Specific questions such as partial loss of beam (LOB) for multiplexing, direct/indirect feedback of electricity to the system and construction philosophy were also neglected during the discussion.

Summary

The conclusions and recommendations from the workshop are summarised as follows:

- **Required accelerator reliability**
  Regulatory requirements are to be considered. They should be comparable to a “reactor” case. If unscheduled faults occur even once, much time will be lost. The accelerator should be extremely stable, especially at the beginning of commissioning. Power control must be studied.

- **Achievable accelerator reliability**
  Mean time between failures (MTBF) can be reduced to about 100 hours.

- **R&D needs in HPPA**
  MTBF for existing HPPAs are presently too short for ADS applications. The requirement from ADS is completely new for the accelerator community.

- **R&D needs in ADS**
  System analysis is required on a reference sub-critical system, in addition to precise safety analysis.

- **Linear vs. circular accelerators**
  This choice depends on current, power and energy. A linac is for several tens of mA and GeV, a linac or a cyclotron is for 10 mA and a cyclotron is for less than 10 mA. Beam shape and “halo” phenomena are also to be considered. At the same time, a good core with a stable \( k_{\text{eff}} \) is necessary.

- **Multiplexing vs. single accelerator**
  This should be considered with regard to cost, reliability and the number of components. The STF may be one accelerator, and TP is also an interesting possibility. The key question is economy in commercial operations, including repairing and maintenance.

- **Dedicated or multi-use facility**
  A multi-use facility such as JAERI-NSP and JHF aims toward performing multi-disciplinary or cross-disciplinary functions. Secondary particles such as neutrons and muons are the purpose of HPPA utilisation. Many dedicated facilities are not authorised, particularly in small countries. ADS, however, does not fall in this category. It is important to construct a dedicated facility so as to demonstrate this promising system to society.

- **Possible collaboration**
  International collaboration would facilitate a “melting pot” of ideas and would also help reduce R&D costs. A large amount of R&D could be shared. The OECD NEA framework is also useful.
Next workshop

Following a proposal from M. Salvatores it was agreed to organise a follow-up OECD NEA workshop in November 1999 at Aix-en-Provence, France. Proposed topics to be covered at the next workshop are:

- Requirements for accelerator reliability with special emphasis on safety, regulatory and technological requirements for commissioning, operation and restart-up, as well as power and burn-up power swing control.
- R&D in key components of HPPAs to improve the reliability.
- System analysis and impact of beam trips or beam fluctuations, especially on the window-target and the subcritical reactor fuel and component systems. A calculation benchmark for a system test facility is envisaged as well as discussions on further international collaboration.
SESSION I

Opening

Chairs: T. Mukaiyama and M. Salvatores
WELCOME ADDRESS

Shoujiro Matsuura
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On behalf of the Japan Atomic Energy Research Institute, and as General Chairman of the workshop, I cordially welcome all of you, especially those who come from abroad. First of all, I express my great thanks to the members of the Organising Committee and the Scientific Advisory Committee of the workshop.

This morning, I am a little bit excited, because I proposed this workshop two years ago and it was agreed upon when I was the Japanese delegate to the OECD/NEA Nuclear Science Committee, at its meeting of May 1996. After coming back to Japan, I consulted with Professor Watanabe on how to best proceed with this workshop. He did quite a bit of work on this subject, and he presented his idea for the next topic of the workshop at the seventh NSC meeting last year. His lecture was much appreciated, and approval to hold this workshop was obtained.

Let me discuss some of the activities of the OECD/NEA. Several years ago, the OECD/NEA implemented some restructuring of its activities and organisation. Before that time, there were several standing committees, e.g. Committee of Reactor Physics, Nuclear Data Bank, Library Code Committee and so on. During the restructuring, these groups were combined to form one standing committee, and the Nuclear Science Committee was thus established. In the past, the activities of the committees were geared toward the reactor field, but after the restructuring the activities of the Nuclear Science Committee began to cover other areas of the nuclear science field as well, including accelerator science and technology.

Recently, as you know, the utilisation of accelerators has greatly expanded. For example, as for the activities of JAERI in the Tokai Establishment, there is a powerful tandem accelerator with a superconducting heavy ion linac for nuclear physics, and in the Takasaki Establishment, there is an accelerator complex, TIARA, for biological and material researches. Another big facility in the Kansai area, is the SPring-8, Super Photon Ring with 8 GeV electrons; it is providing high intense photons. JAERI’s next big plan is to construct a high power proton linac for the creation of a spallation neutron source. JAERI would like to use it for many kinds of basic researches as well as the transmutation of minor actinides. This is one of JAERI’s most important programmes for the era to come.

These kinds of concepts have today expanded to many countries. As regards reliability or utilisation of very big accelerators in the past, they had only been used for basic research and there was not quite so much concern about reliability or unexpected shutdowns. Today and in the future,
however, stability is considered to be very important. For example, here before me I have two papers. One discusses the beam trip rate at LAMPF, a large and well-run facility. The paper shows that LAMPF has an unexpected trip rate of one hundred per week. The other paper here states the number of unexpected shutdowns in nuclear power stations around the world. Here a record in Japan shows the unscheduled shutdown rate is three times for one reactor in ten years. These are very typical examples of the stability and/or reliability of reactors and accelerators.

I would like to say that the reliability of high power accelerators should be very much improved for future versatile utilisation. This workshop is very good opportunity to exchange information, knowledge and wisdom between accelerator specialists and users. Such an information exchange also provides a very good chance to ameliorate the reliability and user convenience of the accelerators.

I think these kinds of workshop are an excellent forum for such an information exchange. I hope the workshop will be a great success, and I believe that it should be a big step toward the future development of high power proton accelerators.

I hope that you will fully enjoy this meeting.
OPENING ADDRESS

Claes Nordborg
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It is a great pleasure for me to welcome you to this workshop on behalf of the OECD Nuclear Energy Agency (NEA). I would first of all like to take this opportunity to thank our host, JAERI, for their superb preparation of this workshop and for having put together such an interesting programme for these three days of meetings.

Those of you who are familiar with the OECD Nuclear Energy Agency know that it is an international organisation set up to promote co-operation in the field of nuclear energy. It is based in Paris, France, and it covers most areas of peaceful nuclear energy production, from the more technical issues, such as nuclear safety, radioactive waste management, radioprotection and nuclear science, to the legal and economic aspects of nuclear power. The NEA also includes a section called the Data Bank that provides a direct and cost-free service of nuclear data and computer programs to scientists in Member countries. More detailed information about the NEA can be found on our internet web pages at the address http://www.nea.fr.

Among the different parts of the NEA, it is specifically the Nuclear Science and the Nuclear Development Committees that have demonstrated an interest in issues related to partitioning and transmutation. The proposal to hold the present workshop on reliability of high power accelerators was discussed and approved by the Nuclear Science Committee in June 1997. This committee comprises experts in reactor and fuel cycle physics, and has performed a number of international co-operative studies related to the back-end of the fuel cycle, including transmutation and plutonium recycling and disposition. A state-of-the-art report on different transmutation concepts was issued in 1994. This report was later followed by a benchmark exercise with the aim to compare the transmutation capability of a PWR, a fast reactor and an accelerator driven system. This benchmark is being finalised and the results should be published in the first half of 1999. In addition, the Data Bank has been very active in collecting and compiling neutron and charged particle induced intermediate energy data and in comparing the performance of computer programs used to calculate these data.

I am very much looking forward to the discussions during this meeting, having myself performed experiments on an accelerator a long time ago. However, the accelerators that we are going to discuss here are of quite another dimension than the one I used and it will be very interesting to hear the technological development and what can reasonable be achieved in the future. Another interesting point will be to hear the discussion between the accelerator and reactor physics communities, both present at this meeting. I believe that this meeting is one of the first occasions for these two communities to meet and to have a good possibility to exchange information.

I wish you all a very interesting and fruitful meeting.
UTILISATION AND RELIABILITY OF HIGH POWER ACCELERATORS

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Abstract

High power proton accelerators are being utilised in various fields of basic science and many projects for future accelerator-driven nuclear energy systems (ADS) have been proposed. In these applications the accelerator reliability, especially for beam trips and fluctuations, is essentially important, which may determine the future possibility of ADS. In the present paper we try to take a general view of these issues as an introduction to this workshop.
Introduction

R&D activities and construction plans related to high power proton accelerators (HPPAs) are being considered in various countries to promote basic and applied sciences, including accelerator-driven nuclear energy systems (ADS), using neutrons, protons and other secondary particles. For example, the SNS project in the US, the ESS project in Europe and both the Neutron Science and the JHF projects in Japan are for basic science (mainly for neutron scattering for condensed matter research). Also, many ADS projects which will be presented at the succeeding sessions are for the nuclear energy applications. Taking into account the fact that proton beams from existing HPPAs trip (suddenly stop) very frequently, it is indispensable to understand the effects (e.g. thermal shocks) of such beam trips on different sub-systems, especially a fission sub-system.

In order to ensure the future possibilities of these systems, we must solve the reliability issue of an HPPA for beam trips and power fluctuations, and develop an ADS which is resistant to beam trips and fluctuations.

The first step towards a more reliable HPPA is to study the operational experiences of the existing medium/high-power proton accelerators, paying special attention to the beam trip records. At the same time, we must know which parts of a fission sub-system (high-power sub-critical reactor) are most susceptible to possible thermal shocks caused by beam trips and fluctuations.

In addition to the beam-trip issue, to what level the beam-intensity fluctuation can be acceptable at a high-power fission device? This is another important question to be clarified.

The main purpose of the present workshop is to exploit more efficient utilisation of HPPAs in various fields and to call forth the attention of accelerator and reactor scientists to the importance of the beam trip and fluctuation issues. Finally we have to clarify a final goal of the accelerator reliability from both accelerators and reactor side.

Operational performance of existing HPPAs

Usually, the reliability of an accelerator is expressed as the ratio of the achieved beam time or the time-integrated beam intensity to the scheduled ones. The reliability in this definition is, of course, important from a user’s point of view. However, we are discussing here the accelerator reliability as concerns the beam trips and fluctuations, which becomes more important in the present application than the former reliability. For example in the case of IFMIF, a 14 MeV neutron source, a required reliability is determined from a required quality of the beam for irradiation experiments, in which a continuous beam without trips becomes very important in order to avoid the annealing effect of the radiation damage in test samples. While in the case of ADS, the reliability should, in the first priority, be determined from the safety consideration of a high-power sub-critical reactor, since sudden beam trips cause severe thermal shocks in the system.

Operational experiences with existing HPPAs will be presented in detail in Sessions III, focused on beam trips. An actual beam-trip rate with a beam stop time longer than one minute in the existing high-power accelerators is typically about 200 trips/week, as listed in Table 1 [1]. The trip rate is almost independent of accelerator type. Although the beam trip rate with a beam stop time shorter than one minute is much higher than those with a longer ones, such trips may not be as serious as those with a longer stop time, since the temperature change caused by such beam trips will relatively
be small. If we assume an annual operation time of about 40 weeks, the above trip rate becomes about 8000 trips/year, which shall be compared with actual numbers of unscheduled shut-down in existing power reactors (LWRs), which are in the range of 0.3-3.5 shut-down/year [2]. In order to seek a possible way for improving the beam reliability, it will be essentially important to accumulate database, calling to major accelerator facilities, on actual beam trips in more detail, including all information such as the operational condition, beam stop time, the origins of each trip, etc., although some data are already available [3].

At the same time, similar data for beam fluctuations are also important in addition to those on the beam trips. Since the power of a sub-critical reactor is proportional to the beam power, beam power fluctuations will cause material fatigue of the reactor components.

Even though there is no serious safety issue in the fission sub-system, frequent beam trips make it difficult to operate ADS at a rated power, since a finite time is necessary for the high-power sub-critical-reactor to reach at a rated power. In the worst case, never reach at the rated power (see Figure 1).

**R&D efforts and goal for future HPPA**

*What beam-trip rate is the maximum acceptable limit for a high-power sub-critical reactor?* This is one of the most important questions in the present workshop, since the R&D goal for a highly reliable HPPA is determined by this limit. For instance, if a beam-trip rate of the same level as the actual unscheduled reactor shut-down is required from a reactor safety point of view, a tremendous improvement, a factor of $10^5$-$10^8$ becomes indispensable, which seems to be very ambitious. On the other hand, if the maximum acceptable trip rate can be relaxed by about a factor of 10-100, the attainment of the goal seems to be more realistic, although it is still ambitious.

Similarly, the reliability for the beam fluctuations should also be considered and the maximum acceptable limit (in frequency, time rate of power change, etc.) must also be clarified.

A great deal of R&D efforts must be devoted towards a highly reliable accelerator. What R&D efforts are necessary for such a high reliability? This question is just another important purpose of the present workshop.

In order to realise a highly reliable HPPA, first of all, each accelerator component must be designed with an adequate allowance compared to a existing one mainly used for basic science [4]. Since arcing of RF high voltage at various components will be one of the major origins of the beam trips, the choice of a lower RF high voltage will improve the racking probability. However a lower RF field brings about a lower acceleration efficiency, resulting in a cost push, which must be estimated to judge the feasibility of ADS. The purity of materials used must be very high; for example, metal niobium in superconducting cavities [4]. The geometrical shape and structure of each component must be optimised to minimise the probability for racking [4]. A clean inner surface of each component, ultimately of the whole accelerator, is very important to reduce arcing. Recently it is being recognised that not only in the stage of component assemble, but also in the final process into a complete accelerator assembling, a highly dust free atmosphere is indispensable for achieving a higher reliability [4]. If an accelerator is composed of normal cavities and superconducting ones, as in the case of the projected accelerator at JAERI (a normal drift tube linac plus a superconducting high-beta
linac), the superconducting part absorbs gases from other part as a cryopump, eventually resulting in a higher arcing probability. There still exist many other origins for beam trips. Those origins must be overcome one by one, even though it takes many years.

What accelerator type is most suitable for future? ADS is another important issue to be discussed in this workshop. This topic will be discussed in the parallel Session VIa. Before it, new types of HPPA for future ADS applications will be proposed in Session IV.

The most important task in this workshop is to estimate and clarify an accelerator reliability which will ultimately be achieved after various R&D efforts mentioned above in the best guess base at the present knowledge. This topic will also be discussed in Session VIa.

If the expected reliability is still lower than a required value, a concept based on the parallel operation of several accelerators of the same type and the same power becomes necessary in order to mitigate the thermal shocks, since the probability for simultaneous beam trips will be very small. For instance, in the IFMIF project two identical deuteron linacs are under consideration. In the present application, the use of several (say 5-10) modest-power accelerators shall also be considered.

R&D efforts in the reactor side

On the other hand, what improvements can be considered in the reactor side? Before answering this question we must know what will happen in a high power sub-critical reactor with a sudden beam trip. As is well known, by a step function type source removal the neutron population in a sub critical reactor decreases very rapidly, faster than the case of a quick reactor shut-down by the insertion of control rods, and gradually approaches to a delayed neutron level. Temperatures at various reactor parts follow this power transient with different delay times depending on the part. For the transmutation of minor actinides, a liquid-metal-cooled fast-reactor-type core, as proposed at JAERI, is necessary, since a harder neutron spectrum is essential. If we assume a Monju-type sodium-cooled fast-reactor, temperature swings at various parts are larger and faster than the case of an LWR, due to a smaller heat capacity of the fast core and a larger coolant temperature difference between inlet and outlet. It is important to know, by careful thermal and structural analyses, which part is most susceptible to such thermal transients. For this topic see Session V.

However, even before such analyses, we can suppose that the reactor core seems to be less serious, due to a smaller diameter of the fuel pins and a thinner clad. On the other hand, external equipments such as a piping for primary sodium coolant, a heat exchanger, etc. will suffer much severe thermal shocks, due to a thicker piping wall (about 2 cm thick) and a larger temperature swing. The mechanical fatigue of those materials due to a large number of thermal cycling will determine the reactor life time. If the existing power reactors are designed such that the total number of unscheduled shut-down up to 300 is guaranteed over the reactor life (about 30 years), a beam trip rate of about 10 trips/year would be the maximum acceptable limit, if there is no drastic improvement in the reactor side.

In order to mitigate thermal shocks, what can be considered? Is a smaller inlet-outlet temperature deference by lowering the outlet temperature will acceptable? The requirement for the self sustained electricity will make it difficult. How is a quick control of the coolant flow to the beam trips? It also seems to be unrealistic from the reactor safety point of view. Is there any other good idea? If not, a drastic improvement in the accelerator reliability becomes indispensable.
What type of reactor is more acceptable, a solid core or a molten salt core? What relationship exists between the reactor lifetime and the frequency of beam trips together with the operational temperature? We need reasonable and realistic answers for these questions.

Another important issue concerns the sub-critical multiplication factor. We recognise that there exists a considerable variation in this factor between laboratories due to different safety considerations; for example, about 15 at JAERI, while almost 100 at BNL. As already mentioned, if a higher accelerator reliability can be obtained only by tailoring the acceleration efficiency, we have to accept a lower beam power under an equal cost condition. In such a case a higher multiplication factor becomes indispensable to keep a required reactor power. What multiplication factor is the maximum acceptable limit? Concerning this limit, intensive discussions are expected. If the original design value of the multiplication factor is relatively low, there may exist a possibility for adopting a higher value, while if a higher value has already been assumed, a further increase seems to be difficult.

Thus, another most important task of this workshop is to estimate and clarify a required accelerator reliability for ADS after future improvements for the beam trip resistance, again in the best guess base at the present knowledge.

Interface technology and material testing

An accelerator beam window and a neutron generating target are important components for an ADS as well as for spallation neutron sources. How to increase and how to estimate the lifetime of these components is another important issue. Some useful data are being accumulated at various spallation neutron facilities. Those experience taught us that the actual lifetime of depleted and enriched uranium targets are much shorter than we expected, even at a lower maximum temperature (below 500 K) with a fairly low total number of protons (less than 1000 mA-hrs) but under the condition of a higher beam trip rate (about tens of thousands trips over the target life time). In the case of uranium targets, with zircaloy clad by diffusion bonding (HIP), a typical life time was in the range of one month to one year at ISIS in the Rutherford Appleton Laboratory (800 MeV, 0.2 mA in time average current, 160 kW in beam power). Although, up to now, no clear relationship between the target life time and the operational condition (temperature, total number of protons and beam trips) has been found, a higher peak temperature seems to shorten the life time. How is the life time of a non-actinide target? The result of destructive test of the ISIS first Ta target is being awaited with great interest. In a proposed ADS the maximum beam density will not exceed a typical value at a 5 MW class intense spallation source, about 0.1-0.05 mA/cm², because of a larger target and beam sizes in ADS. Therefore, the target and beam window problems are common in the neutron source and ADS communities. Collaborative research between two the communities is highly desirable.

The next important issue is material testing by proton beam irradiation. For the design of an ADS, sufficient information concerning the irradiation effects on materials for a target and a beam window is indispensable, especially by intense protons. However, up to now, available data are extremely insufficient, although some programmes for such irradiation experiments are in progress or at the planning stage. Since such experiments are very time consuming (for irradiation, cooling and characterisation), every existing or planned facility with a medium/high-intensity proton accelerator is highly requested to share such efforts. It should also be noted that neutron scattering techniques are very useful for characterising materials after irradiation in atomic scale. Such measurements are under
planning using a neutron scattering facility at PSI on those samples irradiated at its own neutron
target. We at JAERI are also thinking to construct a special neutron scattering instrument dedicated to
highly radioactive irradiated samples, for future nuclear systems using intense protons.

**Recognition as a completely new system**

ADS is not a simple combination of an accelerator and a fission device but a completely new
system. Based on this fact a new fundamental concept for safety, instrumentation/control, operation,
etc., must be established before a real system is constructed.

For example, how can stabilise the power level of the fission device against beam power
fluctuations? No reactivity (sub-critical multiplication factor) control will be acceptable. If the beam
intensity has a sufficient allowance and a required beam power is lower than the minimum level of
the fluctuating beam, the reactor power could be stabilised at an additional cost by controlling the
beam intensity at a fixed level.

It has often been said that the proton beam can be turned off immediately when it is requested.
However, we must defend against such an argument by a safety reviewer that the beam may not stop
for a certain time. In ADS the beam size will usually be defocused in an appropriate size at the target
position. If the beam is suddenly focused, for example, by a power failure in the defocusing magnet,
the target might be immediately destroyed by one pulse (assuming pulsed beam).

Is it necessary to monitor the reactivity (sub-criticality) continuously? It may be necessary in the
case of a system employing a higher multiplication factor. How one can do it?

Apart from the beam trip and fluctuation issue, how one can separate the target from the core
(blanket)? If there is no distinct boundary between target and core, how one can guarantee the
integrity of the reactor vessel having a thin beam window? These problems do not exist for an
accelerator nor for a fission device alone. We think that there are many items to be considered and
clarified.

**Utilisation of high-power accelerator**

The first question is whether a common use of one HPPA between different fields (for example,
nuclear energy and basic science) is feasible and useful? At JAERI a high-power proton linac, about
8 MW in total power, is projected aiming at a multi-purpose use, not only in two major applications
(nuclear transmutation of minor actinides and an intense pulsed neutron source for condensed matter
research) but also in various fields of research such as proton and neutron irradiation, neutron nuclear
physics, nuclear data, low energy nuclear physics using RI beams, RI production, etc. In both the ESS
and SNS projects, however, the accelerators are dedicated for an intense pulsed spallation neutron
source. Although a dedicated use is clearly better in performance than a multi-purpose use, provided
that a sufficient amount of budget is available, the point we want to discuss here is to what extent
such a common use is feasible and useful. We from JAERI have already recognised that the
specifications for a main accelerator, a P/H linac, requested by different fields are fairly spread: the
nuclear transmutation and the material irradiation groups requested a CW beam, while the pulsed
neutron group for condensed matter research requested the possible highest current (or power) of H
beam with a pulse duration less than 1 ms in order to ensure a charge exchange injection of H beam
into a compressor ring. The neutron nuclear physics and the nuclear data groups requested the shortest proton pulses (micro bunch). Even between two major groups the requirements are quite different. We had to find a good compromise between different groups.

The next issue we would propose is concerning a common use of a HPPA with a 14 MeV neutron source based on the muon catalysed fusion. Is a hybrid use of one proton beam between a pulsed neutron source or a nuclear transmutation facility and a muon source is feasible? Such an utilisation has already been adopted at ISIS between the neutron source and the muon facility in the fields of basic science, including muon catalysed fusion, and has proven to be useful. The question here is whether a common use with a 14 MeV neutron source (for material testing) based on muon catalysed fusion is useful?

It would be interesting for future applications of HPPAs, if we have an opportunity to discuss some of these topics to some extent at the parallel Session VIa or during Session VIII (panel discussion).

Summary

A highly reliable HPPA, especially for beam trips and fluctuations, is indispensable for a future ADS. However, there exists an extremely large difference between the actual reliability in the existing HPAs and the required one, which shall be determined from the reactor side. The main purpose of this workshop is to find a reasonable goal for the accelerator reliability, which is achievable in future by R&D efforts in the accelerator side and acceptable in ADS side. Although it may be difficult to reach at a final goal only with this workshop, it will be worthwhile, as a first step, to recognise the problems commonly and more clearly by both accelerator and reactor scientists. However, the necessary steps for reaching at the final goal must also be discussed at this meeting.

Based on the fact that extensive R&D efforts are necessary to ensure the future possibility of ADS, more active international collaborations will be indispensable.

REFERENCES

[3] For example, C.M. Piaszczyk, Accelerator Reliability, Availability and Maintainability, MARCON 97.
Table 1. Beam trip rate at LAMPF

<table>
<thead>
<tr>
<th>Beam stop time (min.)</th>
<th>No. of trips/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1</td>
<td>8 *</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>7</td>
</tr>
<tr>
<td>&gt; 2</td>
<td>5</td>
</tr>
<tr>
<td>&gt; 3</td>
<td>4</td>
</tr>
<tr>
<td>&gt; 4</td>
<td>3</td>
</tr>
<tr>
<td>&gt; 5</td>
<td>3</td>
</tr>
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<td>&gt; 6</td>
<td>3</td>
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<tr>
<td>&gt; 7</td>
<td>2</td>
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<tr>
<td>&gt; 8</td>
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<td>&gt; 9</td>
<td>2</td>
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<td>&gt; 10</td>
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<td>&gt; 30</td>
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<tr>
<td>&gt; 60</td>
<td>1</td>
</tr>
<tr>
<td>&gt; 120</td>
<td>0</td>
</tr>
</tbody>
</table>

* This is not accurate.

Table 2. Number of unscheduled reactor shut-downs in world’s nuclear power stations

<table>
<thead>
<tr>
<th>Country</th>
<th>No. of stations</th>
<th>No. of shut-downs</th>
<th>Shut-down rate/reactor/yr.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scheduled</td>
<td>Unscheduled</td>
<td>Total</td>
</tr>
<tr>
<td>Japan</td>
<td>40</td>
<td>32</td>
<td>12</td>
</tr>
<tr>
<td>USA</td>
<td>107</td>
<td>196</td>
<td>386</td>
</tr>
<tr>
<td>France</td>
<td>55</td>
<td>56</td>
<td>191</td>
</tr>
<tr>
<td>Germany</td>
<td>20</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>Sweden</td>
<td>12</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Canada</td>
<td>18</td>
<td>8</td>
<td>45</td>
</tr>
<tr>
<td>Belgium</td>
<td>7</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Finland</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Spain</td>
<td>9</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Switzerland</td>
<td>5</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Korea</td>
<td>9</td>
<td>9</td>
<td>13</td>
</tr>
<tr>
<td>Russia</td>
<td>27</td>
<td>35</td>
<td>56</td>
</tr>
<tr>
<td>Ukraine</td>
<td>14</td>
<td>13</td>
<td>34</td>
</tr>
</tbody>
</table>

Figure 1. ADS power level for various beam-trip rates

Case A: Acceptable

Rated power

Occurrence of beam trip

Case B: Not acceptable

Rated power

Occurrence of beam trip

Case C: Never reach to the rated power

Rated power

Occurrence of beam trip

Operation time
HIGH-POWER PROTON ACCELERATORS

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Abstract

Important issues for realising the high-power proton accelerators are discussed on the basis of eliminating the beam loss which will limit the beam power. In particular, recent progress is reviewed from the view point of how to overcome this problem.
Introduction

High-intensity (typically higher than 0.1 mA), high-energy (higher than 1 GeV, but lower than 100 GeV) proton beams are required in various fields of science and industry, including pulsed spallation neutron experiments (materials science, life science), muon spin rotation/resonance/relaxation experiments, nuclear physics experiments and nuclear waste transmutation.

Table 1. Examples of existing and planned high-intensity, high-energy proton accelerators. The first three columns show the operational machines, while all the others are planned. The MMF linac is partly operational.

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>ISIS</th>
<th>LANSCE</th>
<th>AGS</th>
<th>MMF</th>
<th>ESS</th>
<th>SNS</th>
<th>K/J-3</th>
<th>K/J-50</th>
<th>JK/J-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection energy (GeV)</td>
<td>0.07</td>
<td>0.8</td>
<td>1.5</td>
<td>0.6</td>
<td>1.33</td>
<td>1</td>
<td>0.2</td>
<td>3</td>
<td>0.4-1</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>50</td>
<td>20</td>
<td>0.56</td>
<td>100</td>
<td>50</td>
<td>60</td>
<td>25</td>
<td>0.3</td>
<td>25-50</td>
</tr>
<tr>
<td>Average current (mA)</td>
<td>200</td>
<td>70</td>
<td>5</td>
<td>500</td>
<td>3800</td>
<td>1000</td>
<td>200</td>
<td>10</td>
<td>6000-1000</td>
</tr>
<tr>
<td>Total power (MW)</td>
<td>0.16</td>
<td>0.056</td>
<td>0.12</td>
<td>0.3</td>
<td>5</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>6</td>
</tr>
</tbody>
</table>

ISIS: Rutherford Appleton Laboratory, United Kingdom
LANSCE: Los Alamos Neutron Science Centre, USA
AGS: Alternating Gradient Synchrotron, Brookhaven National Laboratory, USA
MMF: Moscow Meson Factory, Institute for Nuclear Research, Russia
ESS: European Spallation Source
SNS: Spallation Neutron Source, Oak Ridge, USA
K/J: KEK/JAERI Joint Hadron Facility Project
K/J-3: 3 GeV Ring / Phase I
K/J-50: 50 GeV Ring / Phase I
K/J-up: Upgrade plan to be optimised/Phase II

We have various possible accelerator schemes for these purposes. The advantages and disadvantages of the parameter choices will be summarised. Here, we should note the following points:

1. The beam current to be accelerated is actually limited by the amount of beam loss, which is critically dependent upon the amount of beam halo, both longitudinal and transverse.

2. The optimum design is also dependent upon the future performances of the key components, such as high-intensity, low-emittance ion sources. Thus, we should concentrate our efforts on the development of these components and innovative invention in order to realise these machines. Some examples of the efforts being made in this direction are presented.

Time structure of a beam

The optimum design of an accelerator is dependent upon its detailed specifications such as intensity, energy, time structure and emittance. In particular, time structure is an important parameter. For example, a few 10 ns beam is used for muon spin rotation/resonance/relaxation experiments mainly in order to study materials science, a few 100 ns beam is used for spallation neutron experiments with a high-energy resolution based upon the time-of-flight method, and CW or nearly
CW beam is used for nuclear waste transmutation/incineration, nuclear-physics experiments. A relatively low emittance (typically an un-normalised 90% emittance of around $2 \pi$ mm-mrad) is necessary for the nuclear-physics experiments.

For the pulsed beams in the above the following matters should be noted. In contrast to electron guns a peak current of a few 10 A cannot be obtained directly from an ion source, the maximum peak beam current of which is on the order of 100 mA. A typical schematic accelerator complex thus comprises an injector linac and a synchrotron/storage ring with a revolution time of a few 100 ns.

The highest possible beam current will be filled up in the ring, and will then be fast-extracted. The ring is used as a compressor with a pulse length equivalent to its revolution time in this case. Additional bunch compression with a bunch rotation is possible down to a few 10 ns in a storage ring by applying a high voltage.

For the CW or nearly CW beam, the following matters are noted. If what one needs is only a high average current, for example a few 100 mA, a unique solution would be a CW proton linac. However, if the necessary average current is much lower than the possible peak beam current in a linac, the CW proton linac scheme is extremely expensive. The best choice is again the accelerator complex comprising a linac and a ring, where the ring is used as a stretcher. The beam is slowly extracted from the ring in this case. If the necessary energy exceeds around several GeV, one more ring should be built as in the case of JHF.

**Beam loss**

The beam current to be accelerated is really limited by the amount of beam loss. Beam loss in the high-energy region not only gives rise to a radiation-shielding problem, but also to the radioactivity of the machine itself. The radioactivity should be reduced to a certain level which would allow hands-on maintenance (at worst around 5 nA/m/GeV, preferably much less). Accidentally, this level of the radiation can be shielded by a reasonable amount of concrete down to an environmentally allowable level.

At present it is believed that the behaviour of the beam core can be well controlled during the injection, acceleration, and extraction processes. Also, we perhaps understand some mechanism concerning the growth of RMS emittance during the acceleration in linacs. However, beam loss at a level of $10^{-7}$/m/GeV arises from the beam halo, the generation mechanism of which has not yet been fully understood. The difficulty to reliably estimate the beam loss gives rise to controversy for determining the optimum design. For this reason, considerable efforts have been devoted to a theoretical study of the beam-halo generation mechanism. For example, it was shown that the halo is formed from particles interacting with the core oscillation or breathing. Recently, Kluas Bongardt commented in LINAC98 that, “parametric resonances can occur between single particle tunes and the frequency of the oscillating mismatched beam core”.

Many computer-simulation results have shown that a beam with a hard core eventually results in a soft beam during the course of acceleration in a proton linac. Since a halo comprising a fraction of $10^{4}$ of the total beam current grows far beyond the Gaussian tail, these kinds of halos cannot be recognised by watching only the RMS emittance growth. It is quite common that non-linear phenomena are strongly influenced by the error field, such as a deviation from the ideal focusing or accelerating system in the present case.
It has been theoretically known that emittance growth arises due to the following mechanisms: the charge redistribution from the given one to a uniform one, the energy transfer among the longitudinal and transverse oscillations, RMS mismatching and structure resonances. The latter two mechanisms imply the effect of a deviation from the ideal focusing and/or accelerating systems within the framework of non-linear space charge dynamics, which is perhaps common in both halo formation and RMS emittance growth.

**Rapid-cycling synchrotron (RCS) versus storage ring**

The yield of the spallation neutrons is approximately proportional to the beam power, if the beam energy exceeds several hundred MeV. Then, there are two ways of obtaining MW proton beams with a µs pulse duration: combining a full-energy linac and a storage ring, or combining a low-energy linac and a rapid-cycling synchrotron (RCS). The former option is advantageous regarding: 1) the space charge limit in a ring; and 2) a relatively short stay of the beam in the ring. The RCS option requires: 3) a larger number of powerful RF cavities in order to rapidly accelerate the beam; and 4) ceramic vacuum chambers with RF shields to eliminate any eddy current which would otherwise be induced by rapidly changing magnetic fields.

The latter option is advantageous regarding: 1) the lower beam current, if the energy of the ring is higher; 2) the higher beam loss is allowed during the injection process. For example, beam loss of approximately an order of magnitude higher will be allowed in 200 MeV injection than in 1 GeV injection. One may partly attribute the success of ISIS to its low injection energy (70 MeV) to RCS. Since the beam-loss mechanism in a ring is another – or more difficult – problem to understand, the question of which option is more advantageous has not yet been settled.

One innovation overcoming one of disadvantages of RCS came from a new type of accelerating cavities loaded with magnet alloys by Yoshi Mori, *et al.* (KEK). This new cavity system will replace all the cavities in a proton synchrotron in future. Another innovation may be the realisation of a negative, or extremely small momentum compaction factor, by which no transition need be crossed during acceleration. The beam loss otherwise arising from the transition crossing will be drastically eliminated. This kind of lattice has been extensively and carefully tested in Super ACO, showing the validity of the theory.

If beam-halo formation is unavoidable in a linac, and if high-energy injection is necessary regarding the space-charge limit, a series of halo collimators should be installed, particularly in longitudinal phase space, in order to eliminate the halo, which would otherwise result in a beam loss during injection. The longitudinal collimators must be located in the high-dispersion, (hopefully) low-β region. In any case, the beam loss should be localised by the halo collimators.

**Ion source**

If one has to inject the beam into the ring for an order of several hundred µs or turns, it should comprise negative hydrogen ions. In contrast to positive ions negative ones can be injected with the same condition as that of circulating positive ions (until the time is limited by other effects, such as the space-charge limit and/or beam instabilities and/or Coulomb scattering in a charge-exchange foil). At present we are about to realise the ion source which meets all the requirements simultaneously for MW machines: a peak current of several 10 mA, an emittance of 1 π mm-mrad (90%,), a pulse length of several 100 µs and a repetition of several 10 Hz.
It is very difficult to predict what will be the current limit of a single negative hydrogen ion source in the future. This is another reason for controversy regarding choosing parameters. At first, the volume-production type of ion sources was considered to be advantageous regarding not only high brightness, but also the elimination of Cs vapours. There are some indications that the Cs vapours reduce the discharge limit, possibly being harmful to the high-field operation of the following RFQ. Since it has been indicated that the introduction of a very small amount of Cs vapour drastically (approximately by a factor three) improves the beam current, even in the volume-production type, it is important to empirically test the effect of this small amount of Cs on the discharge limit in the RFQ. It seems to be quite possible that a small amount of Cs vapour is practically harmless.

Some development is noted concerning the driving of the ion sources. The RF drive is replacing the filament drive which has a finite lifetime.

**Frequency issue**

The frequency is another important parameter which needs to be determined. Conventional proton linacs have been using around 200 MHz for the drift-tube linac (DTL). Most of the recently proposed designs have suggested the use of a higher frequency (300 MHz to 400 MHz) for the following reasons:

1. If one doubles the frequency, it is possible to halve the number of particles per bunch. In addition, the focusing period becomes more frequent both longitudinally and transversely. As a result the space-charge effect would be approximately halved.
2. The best advantage of the higher-frequency scheme is the use of klystrons, which are the most powerful and stable RF power sources, and having mature engineering techniques.
3. The discharge limit is increased approximately in proportion to a square root of the frequency. Thus, the higher the frequency, the more stable the operation.
4. The shunt impedance is also proportional to a square root of the frequency.
5. The sizes of components is inversely proportional to the frequency. Easy handling and more inexpensive.

It is difficult to increase the frequency of the low-energy front DTL further, if one wishes to contain quadrupole electromagnets in drift tubes in order to keep the flexibility for the future upgrade of the peak beam current. This is the reason why we choose 324 MHz DTL to accelerate the beam from 3 MeV for the JHF.

**Radio-frequency quadrupole (RFQ) linac**

An RFQ linac is an ideal device, in which both longitudinal and transverse focusings are incorporated together with the ideal adiabatic bunching. Therefore, it is preferable to use the RFQ up to the highest-possible energy. However, the field of a conventional four-vane RFQ is difficult to stabilise if the RFQ is elongated over four wavelengths in order to accelerate the beam up to typically 3 MeV. The \( \pi \)-mode stabilising loop (PISL) invented by A. Ueno (KEK) is easy to water-cool while
keeping similar beam stabilising characteristics to that of the vane coupling ring (VCR). The PISL will be used for both the SNS and JHF. Together with a recent further development for elongating the RFQ, it has been proposed to use an RFQ of up to 8 MeV.

The transition energy from an RFQ to a DTL should be carefully chosen by taking into account the detailed design of the medium-energy transport (MEBT) for matching the beam both longitudinally and transversely. In addition we should find the optimum space for installing the chopper. In the ESS design the 5 MeV RFQ is separated into two parts, between which the chopper is located at 2 MeV. The beams of the two RFQs are funnelled together into the DTL by choosing the frequency of the two RFQs as one half of that of the DTL. In this case one should find some means to minimise the emittance growth and halo formation during the funnelling process.

### Accelerating structure

**Medium energy: Drift-tube linac (DTL)**

In a conventional DTL, the focusing magnets are contained inside the drift tubes. In contrast to this, for a separated DTL (SDTL) first proposed by T. Kato (KEK) for a proton linac, the focusing magnets are located outside the drift tubes. The following advantages and disadvantages for the SDTL are noted:

1. The shunt impedance of the SDTL can be optimised even further, since the drift tubes become free from the constraint of containing the quadrupole magnets.

2. The drift tubes become significantly easier to fabricate by removing the magnets, resulting in a drastic reduction in the cost of the DTL.

3. The focusing quality of the SDTL is inferior to that of the conventional DTL (the focusing period of the SDTL is longer than that of the DTL). If one wishes to have a better quality in order to overcome various space-charge effects, one should choose a higher transition energy from DTL to SDTL (50 MeV for the JHF).

There may be several versions of SDTL: a single SDTL to be used for JHF, a bridge-coupled DTL and a coupled-cavity DTL to be used for APT and to be used at higher energy for SNS. Pros and cons of these versions should be discussed in more detail, but are omitted here.

**High β structure**

The transverse electric kick existing in the side-coupled structure (SCC) gives rise to a slight amount of continuous transverse oscillation of the beam core, possibly resulting in halo formation. If this is really significant, the annular-ring coupled structure (ACS) first realised by KEK is the one which has the balanced characteristics of both the shunt impedance and the field symmetry.

**Transition energy**

The frequency jump at lower energy is preferable from a power-saving point of view. In addition, the beam loss arising from the frequency jump at a lower energy can be managed more easily than
that at a higher energy. The ratio of the acceptance to the emittance is higher in the case of a high-energy frequency jump due to adiabatic damping, favouring the high-energy option from the beam-loss viewpoint. It should also be noted that a low-energy, high-frequency structure is difficult to fabricate, particularly to equip it with water-cooling channels for a high-duty machine.

**Superconducting cavity (SCC) versus normal conducting cavity (NCC)**

It appears to be energy-saving to use a superconducting cavity (SCC) structure. This is true only if the beam pulse is longer than a few ms, since the filling time of the typical superconducting structure is of several 100 µs under practically “reasonable” beam loading. In a long beam-pulse machine the SCC approach implies the following additional advantages over the normal conducting cavity (NCC) scheme (sometimes referred to as room-temperature cavity):

1. It is possible to use a low peak current in order to ease the space-charge problem by increasing the beam pulse length.

2. We can use large bore radii, which are impractical in an NCC scheme due to the increase in power dissipation. This is advantageous regarding a reduction in the beam loss. (This is only true if the present theories concerning the halo formation correctly predict the behaviour of the halo, which is characterised by a saturation in the halo-envelope development. Otherwise, the large bore radii may give rise to a delay in beam loss to the high-energy region, resulting in more radioactivity.)

3. We can use a higher field gradient, typically 5 MV/m and hopefully 10 MV/m, than that of the NCC (typically around 1 MV/m for CW). The former is determined by the power capability through input couplers or by the refrigerator power consumption, while the latter is usually determined by optimising both the capital and operational costs. Since the RF power becomes expensive both capital and operationally as the pulse is elongated, the total shunt impedance must be increased by elongating the NCCs, that is, by decreasing the field gradient.

4. The stored energy in the SCC system is extremely higher, being immune against any variation of the beam loading, as in the case of beam chopping.

Disadvantages of the SCC may be summarised as follows:

1. The amplitude-phase control is more difficult than the NCC scheme, since the beam loading is extremely heavier than the power dissipation. It is noted that the tolerance of the amplitude-phase control in proton accelerators (typically 1% and 1°, respectively) is much more severe than in electron accelerators.

2. It will also be necessary to carefully investigate the radiation-damage effect on the superconductivity, although preliminary studies showed that the SCC is sufficiently radiation-hard.

If one wishes to inject the beam into a ring, there is a limit in the number of turns by which higher-order resonances can be excited. The number can be significantly reduced by the tune spread due to the space-charge effect, being the same order of magnitude as that of the typical filling time, as mentioned above. In addition, the beam instability and the Coulomb scattering by the charge-stripping foil effect limit the number of possible turns for injection.
A careful study is still necessary in order to settle the problem of whether the SCC scheme is really advantageous if the injection to a ring is required.

Conclusion

After LANSCE and ISIS were built, extensive studies were performed in order to improve the design of high-intensity, high-energy proton accelerators. The experience obtained by operating these accelerators has been playing an important role in the studies. However, since no such machine has been built afterwards, we have had only a few chances to test the new theories. This is the main reason why we have so many controversial issues. It is really necessary to build and to operate a new machine with an improved design and with newly invented devices such as PISL, SDTL, Chopper, ACS (or SCC), magnetic alloy cavities, and so forth in order to further improve the design.

Also, many more innovations are necessary to reach several MW machines.
Abstract

Structural biology is one of the most important fields in the life sciences which will interest human beings in the twenty-first century. Hydrogen atoms and water molecules around proteins and DNA play a very important role in many physiological functions. Neutrons can provide not only the position of hydrogen atoms in biological macromolecules but also information about the dynamic molecular motion of hydrogen atoms and water molecules. Next generation neutron source scheduled in JAERI (performance of which is 100 times better than that of JRR-3) opens the twenty-first century in life science. A few prospective examples will be demonstrated.
Introduction

It is said that the universe began with the so-called “Big Bang” about 15 billion years ago, and the first living cell was born about 3.5 billion years ago. As a consequence of evolutionary processes, a tremendous number of diverse living cells from different organisms exist on the earth. Human beings, for example, are constructed from many living cells with a total number of proteins of about 100,000. In the latter half of the twentieth century, X-ray single crystal structure analysis has been used to determine the three-dimensional structures of biological macromolecules such as proteins and DNA, to bring many of the mysteries of life sciences to light. This structural information contributes to the understanding of the physiological function of proteins and DNA. This field is called structural biology.

Structural biology is one of the most important fields in the life sciences that will interest human beings in the twenty-first century. There is already clear evidence that hydrogen atoms and water molecules around proteins and DNA play a very important role in many physiological functions. However, since it is very hard for X-rays to determine the positions of hydrogen atoms in protein molecules, detailed discussion of protonation and hydration can be only speculative in many cases.

On the other hand, neutrons can provide not only the positions of hydrogen atoms in biological macromolecules but also information on the dynamic molecular motions of hydrogen atoms and water molecules. Since physiological functions accompany microscopic motion of atoms at active sites, neutron inelastic scattering is expected to provide experimental clues to clarify physiological functions on a microscopic scale. In principle, these contributions have been well identified, but there are only a few examples experimentally determined at present simply because it takes enormous long times, such as several 10 days, to collect data necessary to obtain the final results because of the lack of neutron intensity.

In the last section we show how the next generation neutron sources, the performance of which is expected to be 100 times better than that of the existing reactor JRR-3M, will be expected to provide a breakthrough in the life sciences of the twenty-first century by taking several examples.

Neutron scattering for structural biology

A neutron has the following distinctive features of value to investigations in structural biology:

1) a neutron can identify hydrogen in a protein;

2) a neutron can distinguish deuterium from hydrogen;

3) a neutron can observe dynamics of atoms and molecules;

4) a neutron does not cause radiation damage to a protein.

In order to apply these features to structural biology, single crystal neutron diffractometry (SCND), small angle neutron scattering (SANS) and inelastic neutron scattering (INS) experiments are carried out.

Figure 1 shows the correlation between neutron experiments and areas of structural biology investigated.
Structure of biological macromolecular complexes

A protein located in the cell membrane receives extra-cellular information that becomes a trigger for the following processes. Information contained in the cellular DNA is transferred to RNA by DNA-binding protein, and RNA then transfers this information to the protein synthesis factory, ribosomes, where proteins are synthesised according to the information contained in the cellular DNA. During this process, a number of protein complexes are formed. Such complexes include the membrane protein which is a complex of protein and lipid, the DNA-binding protein which is a complex of DNA and protein, and the ribosome which is a complex of various types of protein and RNA.

SANS experiments are very effective at determining the structure of biological macromolecular complexes using the contrast variation method. Although the spatial resolution determined by the SANS technique is only about 10Å, this technique will contribute to structural studies in the following topics:

a) complexes that will not crystallise;

b) complexes whose solution structure is different from that in the crystal.

Hydrogen and hydrates of biological macromolecules

It is readily understood that hydrogen atoms and hydration water molecules play an important role in most physiological functions (e.g. hydrolysis, dehydrogenation, oxidation-reduction, phosphorylation, dephosphorylation and so on) since half the constituents of biological macromolecules are hydrogen atoms and life cannot exist without water. Furthermore, hydrogen atoms and hydration water molecules play an important role in the folding and stabilisation of a protein in a globular conformation. There are hydrophilic and hydrophobic amino acids that form the protein. The hydrophilic amino acid side chains tend to be located on the outside of the protein where they can interact with water, whilst the hydrophobic ones are usually buried in the interior to form a hydrophobic core that is hidden from water. However, since there are few reports that define the accurate position of hydrogen atoms of a protein and its hydration water molecules, a quantitative discussion of the folding and protein stability is not always possible currently.

The X-ray diffraction of single crystals has supplied knowledge on the atomic structures of proteins, viruses, t-RNA and DNA. Since the structure-function relationship of a protein is dominated by the behaviour of hydrogen atoms, it is important to know their positions. However, it is difficult for X-ray crystallography to provide structural information of hydrogen atoms. On the other hand, neutron diffraction provides an experimental method of directly locating hydrogen atoms. To date, there are relatively few examples of neutron crystallography in biology since it takes considerable time to collect a sufficient number of Bragg reflections.

A large area detector system can be constructed using an imaging plate (IP), a technique now routinely used in X-ray protein crystallography. An X-ray IP can be converted into a neutron detector if a neutron converter, such as $^{10}$B, $^6$Li or Gd, is combined with the IP. We have successfully developed a neutron IP (NIP), by mixing the neutron converter, $^6$Li or Gd with a photostimulated luminescence (PSL) material on a flexible plastic support [1].
Neutron quasi-Laue diffraction data (2Å resolution) from tetragonal hen egg-white lysozyme were collected in ten days with a NIP [2]. Figure 2 shows one set of raw data that was displayed on the cover of the journal, Nature Structural Biology. Figure 3 shows the three-dimensional arrangement of the lysozyme molecule with the 157 bound water molecules and 696 hydrogen and 264 deuterium atoms determined in that study [2].

Dynamics of biological macromolecules

It is expected that most physiological functions correlate strongly with the dynamics of biological macromolecules. Figure 4 shows the temperature dependence of isotropically-averaged mean-square displacements of atoms of myoglobin from neutron experiments [3]. For temperatures below 200 K, the mean-square displacement increases linearly with temperature, in accord with harmonic models for internal dynamics. Above 200 K there is a transition above which the mean-square displacement increases more rapidly with temperature. This non-linear behaviour implies an anharmonicity in the potential-energy surface. It should be noted that most physiological functions (such as the processes mentioned earlier: hydrolysis, dehydrogenation, etc.) occur most efficiently at temperatures above 200 K, and not many of them take place below 200 K.

This predicts that protein dynamics are strongly correlated with physiological functions and INS experiments from proteins can be expected to produce useful results.

Dynamics of biological macromolecules are theoretically treated by normal mode analysis or molecular dynamics that can provide the dynamic structure factor observed by INS experiments. The vibrational frequency distribution from the molecular dynamics of BPTI (bovine pancreatic trypsin inhibitor) in solution has been measured [4] and compared with the neutron-derived frequency distribution (coming from incoherent scattering) from the BPTI in solution experiment [5].

Figure 5 shows time-of-flight spectra from BPTI and HEWL [6]. Although the molecular structures as well as physiological functions of the two proteins are different, no big differences are evident except at a large energy transfer region, which is not so relevant for protein dynamics. Why? Is INS useless for studying protein dynamics? In the INS spectra of proteins, the incoherent scattering coming from the nuclear spins of hydrogen atoms in the sample is dominant. Generally speaking, INS observes the quantity $\langle \mathbf{R}_i(0)\mathbf{R}_j(t)\rangle$, where $\mathbf{R}_i(0)$ and $\mathbf{R}_j(t)$ are the position vectors of the i-th atom at $t = 0$ and the j-th atom at $t = t$, respectively. When the i-th and j-th atoms are different from each other, it is coherent, and when they are the same, it is incoherent. Coherent or incoherent scattering provides the dynamical amplitude between different atoms or of an atom itself, respectively. Big differences among proteins might not appear in the dynamical amplitudes of the atoms themselves. If so, coherent scattering must be separated from incoherent scattering by measuring neutron spin flip and non-spin flip processes.

The next generation neutron sources and the future of neutron structural biology

At present, because of the low level of current neutron fluxes, it takes a prohibitively long amount of time to collect a full diffraction data set, and/or it is necessary to prepare a large specimen. An improvement in neutron flux would be beneficial not only to ease the above limitations but also to enable new experiments to be carried out.
Figure 6 shows the type of proteins that can be measured by neutron single crystal diffractometry in accordance with increments in incident neutron flux. Note that in a diffraction experiment the neutron diffraction intensity is proportional to the crystal volume, and to the inverse square of the cell volume. Line (a) indicates that a protein sample with crystal and cell volume above line (a) can be measured using a diffractometer equipped with a normal position sensitive detector installed on a 20-60 MW reactor. If a NIP (neutron imaging plate) is installed on the diffractometer, a sample with crystal and cell volume above line (b) can be measured since a NIP enables a 10-fold increase in data collection efficiency. If the next generation neutron sources project (for example, a several-megawatt spallation neutron source) is realised, a protein sample above line (c) can be measured. The cell volume of most of the important protein crystals studied today is less than $10^6 \, \AA^3$ (thick vertical dotted line) and the crystal volume that X-ray crystallography requires is larger than 0.003 mm$^3$ (thick horizontal dotted line). Figure 8 thus shows that the neutron source resulting from the next generation neutron sources project will cover most of the important proteins to be investigated.

REFERENCES


Figure 1. The correlation between neutron experiments and areas of structural biology investigated

Figure 2. Raw data recorded on the NIP
Figure 3. The three-dimensional arrangement of the lysozyme molecule with the 157 bound water molecules and 696 hydrogen and 264 deuterium atoms determined in the study.

Figure 4. Temperature dependence of the isotropically averaged mean-square displacements of myoglobin from neutron experiments.
Figure 5. Time-of-flight spectra from BPTI and HEWL
Figure 6. The types of protein that can be measured in a neutron single crystal diffractometry experiment in accordance with increments in incident neutron flux.
SESSION II

Application of HPPAs – Part I

Chairs: M. Nakagawa and M. Napolitano
STATUS REPORT ON THE SPALLATION NEUTRON SOURCE

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Abstract

The purpose of the Spallation Neutron Source Project (SNS) is to generate low-energy neutrons (ambient [-200 meV] and cold [-50 meV]) which can be used by up to 18 neutron beam lines to study the structure and functionality of materials. The neutrons are generated by the spallation process initiated by the interactions of 1 GeV protons with a Hg target. These neutrons are reflected by a Pb reflector and are moderated by two water (ambient) and two super critical hydrogen (cryogenic) moderators. The pulse structure for the 1 MW proton beam is 60 Hertz and < 0.7 µs/pulse. The facility must be upgradable to higher power levels (2 and 4 MW) with minimal operational interruptions. Although not included in the current funding or baseline, a second target station and associated support structure which will be designed to utilise cold neutrons is also considered to be an upgrade that must be incorporated with minimal impact on operations.
Introduction

Following three plus years of effort by five National Laboratories and the neutron science community, the SNS project has obtained line item status as of October 1998 (FY99). In FY96 the US Department of Energy Office of Energy Research (DOE ER) provided $8M to initiate the R&D and conceptual design of the accelerator-based spallation neutron source. This was followed by $8M in FY97 to continue the R&D and to finish the Conceptual Design Report (CDR). A DOE ER review in June 1997 responded positively and recommended certain changes to the CDR design. In FY98 funding of $24M was provided to continue the R&D and to prepare for line item status. In June 1998, another DOE ER review was held to examine the project’s response to the previous year recommendations and to scrutinise the project management’s approach to this construction project. With the first year work packages completed and approved, detail design started in October 1998. The total cost of the project (TPC) will be $1.333B.

The State of Tennessee in collaboration with the University of Tennessee has provided $8M for the construction of a Joint Institute for Neutron Sciences (JINS). This facility will provide scientific focus and a gateway for the expected 1000-2000 users per year from universities, laboratories and the private sector for the SNS and High Flux Isotope Reactor (HFIR) facilities. The facility will provide teleconferencing, conference and meeting rooms, offices, laboratory space, education and training facilities, and housing rooms.

The SNS collaboration

Figure 1 gives a schematic representation of the SNS. It also highlights the fact that the SNS will be designed and constructed by a collaboration of five DOE National Laboratories. The design selected for the SNS is an H ion source, a 1 GeV conventional linac, accumulator ring and a mercury target system with water and supercritical hydrogen moderators that provide pulsed neutrons to 18 beam lines.

When Oak Ridge National Laboratory (ORNL) was asked by DOE ER to assume responsibility for the design of the SNS, a full collaboration was established that focused the considerable expertise of the DOE ER National Laboratory system. Not only were those laboratories with recognised expertise in accelerator/target/instrument technologies chosen, but also laboratories were sought that also were experienced in the operation and/or design of major neutron facilities. This added dimension enhanced our connection with the neutron science community, who is our ultimate customer, and provided an understanding of the essential elements of a successful neutron facility.

The Lawrence Berkeley National Laboratory is responsible for the front-end systems of the SNS (H ion source, RFQ and initial beam chopping). Los Alamos National Laboratory (LANL) is responsible for the conventional linac accelerator system, which accelerates the H ions to 1 GeV energy through use of a drift tube linac (DTL), coupled cavity DTL (CCDTL) and a coupled cavity linac (CCL). LANL also directs the integrated controls systems effort for the SNS. Brookhaven National Laboratory is responsible for the accumulator ring and the associated beam transport systems. Argonne National Laboratory is primarily responsible for instrument development. ORNL is responsible for developing the mercury target, conventional facilities and overall project co-ordination and management. ORNL is also responsible for final operations of the SNS for the DOE ER and scientific community, and for establishing the staff and expertise for operating and upgrading the SNS in the future.
Reference design

In many areas of physics, materials and nuclear engineering, it is extremely valuable to have a very intense source of neutrons so that the structure and functionality of materials can be studied. The SNS is the approved project that will satisfy this requirement and the reference design is shown in Figure 2 and Table 1. This facility will consist basically of three parts: 1) a high-energy (~1 GeV) and high-powered (~1 MW) proton accelerator (60 Hertz, < 0.7 µs/pulse, 17 kJ/pulse); 2) a target/moderator/reflector assembly (TMRA) which converts part of the proton beam power to low-energy (< 2 eV) neutrons through spallation and moderation, and delivers them to the third part, the neutron scattering instruments.

The 17 kJ/pulse is achieved by injecting ~1 ms pulses of H\textsuperscript{+} from the linac at 1 GeV, through a stripper foil, into the accumulator ring as H\textsuperscript{+}. The ring accumulates about 1200 linac mini-pulses contained in the ~1 ms marco-pulse and compresses them into ~0.7 µs pulses, which are delivered to the mercury target at a frequency of 60 Hz.

The SNS is designed to be upgradeable to significantly higher powers in the future. An initial upgrade to 2 MW requires only minor system improvements, but the ring and shielding are already capable of accommodating the increased powers. The design of the accelerator systems was made to be robust and flexible so that a variety of higher-power upgrades would be possible. This facilitates future upgrades that will be selected based on current technologies and neutron community needs at the time.

R&D programme

The R&D programme for the SNS is focused on concerns in each of the sub-projects. Part of the R&D in the accelerator area deals with high current, small duty factor ion gun development; small duty factor development of the RFQ; mass production of CCL modules; halo formation leading to beam losses; space charge issues in the ring; and the development of high-temperature, high-efficiency, low-mass stripper foils. In the target area, R&D encompasses thermal shock production in the Hg/target container; thermal hydraulics; neutron production from Hg; material radiation damage and compatibility; remote handling issues; and the development of super critical hydrogen loops for cryogenic moderators.

Many of these R&D topics are being addressed through international collaborations with England, Germany, Switzerland, Japan, Latvia and Russia to name some of the involved countries.

Progress on SNS

The project has started site specific Title I design and construction activities. Project management systems, plans and schedules, technical baselines and detailed work plans with milestones that are in place for FY99, have been approved by the DOE. The project management is currently working toward the re-baseline review that will occur at the end of January 1999. Included in this review will be our baseline changes that have resulted from value engineering studies and Title I and R&D efforts. The project is off to a good start with completion expected toward the end of 2005.
Acknowledgements

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Table 1. Design parameters

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<td>Number of injected turns</td>
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<td></td>
</tr>
<tr>
<td>Ring filling time (ms)</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>Protons per pulse on target</td>
<td>$1.04 \times 10^{14}$</td>
<td>$2.08 \times 10^{14}$</td>
</tr>
<tr>
<td>Protons per second on target</td>
<td>$6.3 \times 10^{15}$</td>
<td>$1.25 \times 10^{16}$</td>
</tr>
<tr>
<td>Time average beam current on target (mA)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Target</td>
<td>Hg</td>
<td></td>
</tr>
<tr>
<td>Beam power on target (MW)</td>
<td>1.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Figure 1. The Spallation Neutron Source Project is a collaborative effort.

Figure 2. The Spallation Neutron Source reference design. For the upgrade, a second target station and ring will be added above the linac in a symmetrical fashion.
THE EUROPEAN SPALLATION NEUTRON SOURCE PROJECT (ESS)

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Abstract

The ESS project aims at constructing a 5 MW, 50 Hz short pulse spallation neutron source, which is about a factor 30 more powerful than what is presently state of the art. This requires new routes to be explored both in accelerator technology as well as in target design. Being conceived as a multi-user facility for a large and diverse community, the facility must have high availability and high reliability. Although a project study conducted over a three-year period with the participation of 12 institutions from five European countries has not surfaced any real feasibility issues, substantial R&D work is still required to be able to carry out the detailed design work which is scheduled to be completed in the year 2003. While on the accelerator side all proposed systems are based on existing experience, although with sometimes significant advancements of the technology, a completely novel target concept, based on the use of flowing mercury as target material has been adopted to cope with the high heat load and, at the same time, optimise neutronic performance. This means exploring a variety of questions that had not been an issue in existing spallation neutron sources. Extensive prototyping is planned on the accelerator side as well as on the target part. This paper gives a brief description of the technical concept of the neutron source and outlines the R&D work in progress.
Introduction

Europe has a large and diverse community of scientists using neutrons in their research activities. The intensity of usage ranges all the way from professionals to very occasional users that resort to neutrons only as a complementary tool to round off their results obtained by other methods [1]. This research covers fields from condensed matter physics via materials science, earth science, etc., all the way to life sciences and environmental research. This intense use of neutrons has become possible by a policy of devising first rank neutron sources on the one hand and by opening the existing facilities to outside users, providing expert support where needed, on the other. In this tradition Europe has held a leading role by operating the world’s highest performing beam reactor, the RHF at ILL, Grenoble, as an international facility, as well as a substantial number of national facilities, such as the leading pulsed neutron source ISIS in the UK and medium flux research reactors in various countries. The latest member in this community is the world’s most powerful, albeit continuous spallation neutron source, SINQ in Switzerland. A new high performance reactor is under construction in München, Germany. While a first attempt to broaden this scope by constructing a 5.5 MW spallation neutron source, the SNQ, in Germany [2,3,4] failed in the mid-80s, a high level panel called by the Commission of the European Community in 1990 recommended that Europe should aim at having both a steady state source based on the best reactor technology available and a pulsed source in the realm of the SNQ proposal but taking credit of the experience that had, in the mean time, accrued at ISIS. This latter recommendation was taken up by a group of interested institutions and, with partial funding by the European Union in the frame of its programme for Training and Mobility of Young Researchers, a study was carried out, aiming at designing a 5 MW short pulsed neutron source called ESS. While the aim clearly is to provide a next generation facility for research with neutrons, it is obvious that technologically such a facility has a high degree of relevance also for the driving accelerator and the target system of an ADS. In contrast to all present spallation neutron sources, which were conceived and constructed around previously built accelerators or used existing components of such machines, the next generation spallation neutron source would be purpose designed from scratch. This implies that the quest for high availability and performance shall not be compromised by having to use existing equipment and that the technologies required to meet the users’ needs shall be developed. Thus, when the technical study report [5] was published in 1996, it also identified a comprehensive research and development programme that should be carried out over the next several years in order to substantiate the proposed design and generate a database that would allow to answer some of the questions that had to be left open. This work is currently in progress.

The general concept and reference layout of ESS

ESS is conceived as a short pulse neutron source in order to be able to take advantage of the superior neutron utilisation and resolution of time of flight techniques in a fairly large class of experiments. The goals for the beam power and pulse characteristics for the accelerator were set at about 5 MW and 1 µs duration with 50 Hz repetition rate respectively. The choice of these parameters was a result of a compromise between what was considered on the edge of feasibility on the one hand and the desire to be able to match a high flux reactor in terms of average flux (of the order of \(5 \times 10^{14} \text{n/cm}^2\text{sec}\)) while maintaining the option to use epithermal neutrons on the other. From previous studies it was known that, with well coupled moderators, one should be able to generate a time average thermal neutron flux around \(10^8 \text{n/cm}^2\text{sec} \) per MW of beam power, a number which may be slightly compromised by engineering constraints at higher power levels. On the other hand, for a good hydrogenous moderator the product of the neutron velocity \(v\) and standard deviation of the
slowing-down time to that velocity, \( \tau_v \), is of the order of 2 cm. This means, that the 1 \( \mu \)s long proton pulse would start to make a significant contribution to the pulse width for neutron velocities above some 20 000 m/s or 2 eV, an energy practically inaccessible on reactors for experimental work. Of course, this pulse width would practically not contribute to the pulse width at thermal neutron energies (2 200 m/s) and below.

From several accelerator options examined to achieve the desired parameters, the final choice was a full energy 1.334 GeV linac with two compressor rings. Two compressor rings are considered necessary because only about \( 2 \times 10^{14} \) protons can be stored in a ring before the beam becomes unstable due to space charge effects, whereas the ESS time average current of 3.75 mA corresponds to nearly \( 5 \times 10^{15} \) protons per pulse at 50 Hz. Since injection into the rings will, according to the present concept, be by charge exchange of \( H^- \) ions in a stripper foil, a certain fraction of \( H^+ \) atoms in excited states will be generated, which may subsequently be ionised by the magnetic field of the first bending magnet and lead to activation in the injection region, which would be difficult to control. In order to mitigate this problem, the energy was chosen as 1.334 GeV, where the generation of excited \( H^+ \) states is minimum.

The overall layout of the ESS facility is shown in Figure 1. The total length of the linac is more than 700 m, followed by 75 m of drift section and a \( 180^\circ \) achromatic bend to shape the phase space volume occupied by the beam in a way that is suitable for multiturn injection into the rings. Several beam catchers are located along the high energy beam line for use in the beam development process or to catch, in a controlled way, particles that cannot be transported further. It is anticipated that about 0.5% of the beam, i.e. nearly 20 \( \mu \)A will not be captured in the injection process into the ring. Those particles will be collected and transported to a beam bump or will be available for other uses such as pion production or a radioactive beam ion source. No firm decision has, so far, been made on their use.

**Figure 1. Schematic layout of the ESS facility**

![Figure 1. Schematic layout of the ESS facility](image)
The two compressor rings will be located on top of one another and will be filled from the linac sequentially with 1000 turns each. In order to fill the rings in such a way that about two-fifths of the circumference is kept free of particles, as required to be able to excite the extraction kicker without spilling beam, a pulse structure as shown in Figure 2 must be accelerated in the linac. The 100 µs long gap after the first 1000 micropulses (600 µs) serves to switch the beam from one ring to the other. As soon as the second ring is full, both rings are emptied in sequence with a time separation of 200 ns between the two pulses, each of which is 400 ns long. This separation, again, is required in order to merge the two pulses into a common transport line by a fast kicker magnet. The result is a double pulse with a total length of 1 µs and a gap of 200 ns between the subpulses.

Figure 2. Pulse structure accelerated in the ESS linac

Making optimum use of the neutrons over a wide spectral range requires at least two target stations operating at different repetition rates in order to have a longer and a shorter frame between pulses, which the neutrons can fill, depending on the velocity range to be used. Slow (long wavelength) neutrons take a longer time to travel through the target shield all the way to the detector than faster ones. Therefore two target stations have been foreseen which share the 50 Hz pulses on an unequal basis. This pulse distribution will be accomplished by a “slow” kicker which can be operated on demand and which must rise and reset between two pulses only, i.e. within 9 ms, but will, in practice, be much faster than this. As a rule, the low repetition rate target station (LRRT) will receive one out of five pulses, making it a 10 Hz target at an average power of 1 MW. The remaining four pulses will go to the high repetition rate target (HRRT) which operates at 4 MW and 20 ms pulse separation with a missing pulse every 100 ms. Clearly, this target will be designed to accept the full beam of 5 MW. For practical reasons it was decided to have two targets of identical design and most likely the savings in fitting the LRRT with a lower heat removal capacity is so small that either one will be able to operate at 5 MW. This facilitates many things, not the least one being the stock of spare parts.

The beam transport line and its shielding to the HRRT will be designed such that retrofitting of a pion/muon production target is not excluded, although no further provisions for this have been made in the reference layout. A summary of the main parameters of the ESS facility is given in Table 1.

The ESS accelerator system

Major design criteria for the ESS accelerator system have been a high availability in terms of service hours per year and the minimisation of beam losses, which is a prerequisite for hands-on maintenance, i.e. easy and rapid access to as many components as possible. Although not mutually exclusive, the combination of these two requirements has severe consequences in many respects.
### Table 1. Main parameters of the ESS facility

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Short pulse spallation neutron source</td>
</tr>
<tr>
<td><strong>Main purpose</strong></td>
<td>Neutron scattering in condensed matter research</td>
</tr>
<tr>
<td><strong>General concept</strong></td>
<td>Full energy linac with accumulator rings</td>
</tr>
<tr>
<td><strong>Accelerator</strong></td>
<td>Side coupled cavity room temperature linac</td>
</tr>
<tr>
<td><strong>Proton energy</strong></td>
<td>1.334 GeV</td>
</tr>
<tr>
<td><strong>Total beam power</strong></td>
<td>5 MW</td>
</tr>
<tr>
<td><strong>Pulse repetition rate</strong></td>
<td>50 Hz</td>
</tr>
<tr>
<td><strong>Mean radius of rings</strong></td>
<td>26 m</td>
</tr>
<tr>
<td><strong>Number of circulating protons per ring</strong></td>
<td>$2.34 \times 10^{14}$</td>
</tr>
<tr>
<td><strong>Revolution frequency in rings</strong></td>
<td>1.6714 MHz</td>
</tr>
<tr>
<td><strong>Bunch length at extraction</strong></td>
<td>0.4 $\mu$s</td>
</tr>
<tr>
<td><strong>Final pulse length</strong></td>
<td>1 $\mu$s (2 subpulses 0.4 $\mu$s long, 0.2 $\mu$s apart)</td>
</tr>
<tr>
<td><strong>Energy content of 1 pulse</strong></td>
<td>100 kJ</td>
</tr>
<tr>
<td><strong>Target concept</strong></td>
<td>Flowing liquid metal; horizontal beam injection</td>
</tr>
<tr>
<td><strong>Target material</strong></td>
<td>Mercury</td>
</tr>
<tr>
<td><strong>Moderators</strong></td>
<td>Ambient temperature H$_2$O and supercritical H$_2$</td>
</tr>
<tr>
<td><strong>Reflector</strong></td>
<td>D$_2$O cooled lead</td>
</tr>
<tr>
<td><strong>Peak thermal neutron flux in pulse</strong></td>
<td>$7 \times 10^{17}$ n/cm$^2$s</td>
</tr>
<tr>
<td><strong>Pulse distribution between two target stations</strong></td>
<td>40 pps (50 Hz) and 10 pps (10 Hz)</td>
</tr>
</tbody>
</table>

**The ESS linac**

With the repetition rate of 50 s$^{-1}$ and a macropulse length of 1.3 ms the macro duty cycle of the linac is 6.5%. (On top of this, there is a duty cycle or fill factor of 70% in each macropulse, cf. Figure 2, during which the rf in the accelerator will not be switched off.) Since the average power of 5 MW at the chosen particle energy of 1.334 GeV corresponds to an average current of 3.75 mA, the necessary pulse structure requires a pulse current of 107 mA in the linac. This is much more than what has ever been achieved in a linac of comparable duty factor.

Since, so far, no H$^-$ ion sources exist that are routinely capable of delivering the necessary current, two sources have been foreseen to operate in parallel. In order to avoid as much as possible emittance growth in both longitudinal and transverse phase space, which would generate a beam halo, i.e. a major source of particle losses, the whole front end of the linac up to 5 MeV is duplicate (see Figure 3). Both lines consist of two 175 MHz RFQs and a fast chopper operating synchronously with the beam revolution in the compressor rings. The two pulse trains, which are shifted in phase by 180°, are combined at 5 MeV in a funnel section ("inverse bunch kicker") that merges them to a 350 MHz pulse train. This is the rf-frequency of the following drift tube linac (DTL), where the beam is accelerated to 70 MeV.
Following the example of the LANSCE linac, a side coupled cavity structure (SCCL) operating at 700 MHz was chosen for the high energy part. A combined optimisation of capital and operating cost for a period of ten years yielded an rf field gradient of 2.8 MV/m. Since this is a fixed-β structure (β being the ratio of the local particle velocity to the velocity of light), the length of the cells increases as the particle velocity increases and the number of cells per cavity decreases from 16 at the beginning to 10 at the end of the HELA (see Figure 4). The resulting length is about 660 m. Although, in principle, each cell in a fixed-β structure should be slightly different in length from its neighbours, all 10-16 cavities in each cell will be identical, which means that a slight deviation from the optimum rf-phase angle will have to be accepted in most of the accelerating gaps. The CCL will be equipped with klystrons of 2 MW peak power, each feeding two cavities. An overview of the main parameters of the ESS-HELA is given in Table 2.

**Beam transport and pulse compression**

Although pulse compression is crucial for the performance of ESS as a short pulse neutron source and involves a number of interesting and demanding technological issues, we will treat it relatively briefly here, because, apart from the technology for pulse splitting and recombination, it is of a lesser direct interest in the context of the present workshop topic. The 75 m long drift space following the linac is for momentum ramping, debunching, bunch rotation and horizontal betatron collimation, while the 180° bend provides for momentum and vertical betatron collimation. The rather large mean radius of 42.5 m was chosen to avoid magnetic field stripping of the H- beam in the bending magnets. After the bend, the two beams for the upper and lower ring are separated vertically by 2 m and are focused to the spot size desired at the injection stripping foil.

The main losses within the rings are due to multiple beam traversals of the stripping foil during and after injection, whose number must therefore be kept at a minimum by a scheme for careful “painting” of the phase space in the rings, which also keeps heating at tolerable levels (ca 2 000°C) in the 350 mg/cm² graphite foil with two unsupported edges. With 1 000 turns accumulated in each ring, the peak circulating current is 104 A. Rf systems are integrated into the ring lattice in order to maintain the extraction gap, thereby also minimising beam losses in the ring.

- **Note:** After the end of the study, a new injection scheme based on an intense laser beam and undulators in the injection line has been proposed in Japan. If this scheme turns out to be feasible, it would allow to work without any material in the stripping process and thus avoid many of the problems associated with the stripper foil. Implementation of this scheme might also affect the overall ring design and even the linac to some extent. These problems are currently under study by the ESS R&D team.
Figure 4. The first and last side coupled cavities of the ESS-CCL

Table 2. Main parameters of the ESS linac

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse repetition rate (Hz)</td>
<td>50</td>
</tr>
<tr>
<td>Duty cycle (%)</td>
<td>6.5</td>
</tr>
<tr>
<td>Beam pulse duration (ms)</td>
<td>$2 \times 0.6 + 0.1$ gap</td>
</tr>
<tr>
<td>Linac average beam power (MW)</td>
<td>5.1</td>
</tr>
<tr>
<td>Average output current (mA)</td>
<td>3.84</td>
</tr>
<tr>
<td>Accelerator sequence</td>
<td></td>
</tr>
<tr>
<td>RFQ 1</td>
<td></td>
</tr>
<tr>
<td>RFQ 2</td>
<td></td>
</tr>
<tr>
<td>DTL</td>
<td></td>
</tr>
<tr>
<td>SCCL</td>
<td></td>
</tr>
<tr>
<td>Input energy (MeV)</td>
<td>0.05</td>
</tr>
<tr>
<td>Output energy (MeV)</td>
<td>2.0</td>
</tr>
<tr>
<td>Length (m)</td>
<td>2.95</td>
</tr>
<tr>
<td>Rf-frequency (MHz)</td>
<td>175</td>
</tr>
<tr>
<td>Peak power in cavities (MW)</td>
<td>0.36</td>
</tr>
<tr>
<td>Peak power in beam (MW)</td>
<td>0.132</td>
</tr>
<tr>
<td>Number of tanks (cavities)</td>
<td>1</td>
</tr>
<tr>
<td>Number of cells</td>
<td></td>
</tr>
<tr>
<td>Number of klystrons</td>
<td>1</td>
</tr>
<tr>
<td>Average accelerating gradient (MV/m)</td>
<td>0.6</td>
</tr>
<tr>
<td>Average current in micropulse (mA)</td>
<td>59.5</td>
</tr>
</tbody>
</table>

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65
With $\beta = 0.91$ at 1.334 GeV, the 600 ns, revolution period requires a ring radius of 26 m. An important feature of the accumulator ring lattice is the need for relatively long straight sections. Separate regions of high dispersion are required for the $H^-$ injection and momentum collimation, while separate regions of zero dispersion are needed for betatron collimation, fast extraction and the rf systems. Three lattice superperiods, each containing both an achromat and a long straight section were found to be appropriate. The layout of the 1.334 GeV accumulator lattice with threefold symmetry is shown in Figure 5.

**Figure 5. Schematic perspective of the 1.334 GeV accumulator rings**

Beam extraction from the rings is in the horizontal plane from a dispersion free region with fast kicker magnets placed upstream of a quadrupole triplet and a septum extraction magnet one cell downstream. In order to achieve the desired double pulse with a 200 ns gap after extraction, the rf systems of the two rings must be properly synchronised, with the beam from the upper ring extracted with a delay of one revolution, i.e. 600 ns.

A larger ring (e.g. with four periods) would, of course, also allow to meet the 1 $\mu$s specification for the pulse duration and provide for a longer extraction gap. While this would also affect the linac mode of operation, it might be desirable if the novel injection scheme mentioned above would be realised.

From the rings the beam, which now has a rather large emittance, is transported to the two target stations up to more than 200 m away. In order to achieve a high transmission for minimum activation of the vacuum chambers and other equipment, the acceptance of the beam lines is chosen to be equal to that of the rings, i.e. $480\pi$ $\mu$rad m. In a switchyard the beam can be directed to either one of the target stations or to a beam dump.

**The ESS target systems**

**Target geometry and target material**

Horizontal beam injection into the targets was chosen for reasons of practicality. Based on results obtained in the SNQ study [6], a slab target geometry was foreseen for ESS from the very beginning, because it allows the best combination of a tight target-moderator coupling and a large
proton beam cross-section which is desirable to keep radiation damage and heat load in the target window low. The cross-section of the beam at the target window was selected as elliptical with half axes of 10 and 3 cm in the horizontal and vertical directions. The moderators are located above and below the target.

After examining several options, including solid state target materials in both rotating and stationary configurations [7] the ESS study group decided in favour of a proposal for a liquid metal target with mercury as the reference target material [8,9] for both stations.

Important arguments in favour of a liquid metal target are the absence of radiation damage in a liquid and the fact that the target is its own primary cooling loop. This not only avoids dilution of the macroscopic target density by cooling water (which reduces the luminosity of the primary neutron source the more, the more power needs to be removed), it also makes cooling much more effective, because it is by convection only rather than by conduction in the target material and subsequent convection in the coolant. A further important advantage is the absence of water in the target volume for two reasons:

a) It avoids radiolysis and production of radioactive species, in particular $^7$Be and several short lived positron emitters in the cooling water. While the positron emitters (such as $^{11}$C and $^{13}$N) generate a high level of 511 keV radiation everywhere in the loops but decay rather rapidly, $^7$Be, which is a $\gamma$-emitter with a half-life of 53 days, tends to plate out quantitatively on the walls of the pipework and the components, in particular heat exchangers, making access to the plant room for maintenance and repair work difficult even when the water has been drained from the loops [10].

b) Water in the target volume, even D₂O, has a moderating effect on the neutrons. This increases the probability of capture in the solid target materials, in particular Ta, which has a large resonance integral. This reduces the effective source brightness and leads to a high level of radioactivity in the target and increased afterheat production, making a second cooling loop necessary for targets at the power level in question.

Mercury is an attractive target material for pulsed spallation neutron sources because, not only is it liquid at room temperature and thus does not require auxiliary heating for the loop, it also has the highest density of all candidate materials (25% more than the PbBi-eutectic) and thus generates the brightest primary neutron source. Neutronic calculations showed [11] that the leakage from a mercury target has a higher peak value as well as a larger axial extension than the next best option, a water cooled W-plate target. This is a clear advantage, especially if more than one moderator needs to be placed on either side of the target. The fact that mercury has a high thermal neutron absorption cross-section (390 barn) is not a disadvantage for pulsed spallation neutron sources, because in most cases the moderators are surrounded by absorbing material anyway in order to keep the trailing edges of the pulses short by preventing slow neutrons from being scattered back into the target. These “decouplers” are not easy to cool at high power levels, especially on the side facing the target, where it is not required in the case of mercury. For “coupled” moderators, i.e. without such a layer of absorber, the effect of having it on one face out of four or five is not very serious.

The boiling point of mercury, although much lower than for other liquid metals (350°C at 1 bar and about 400°C at the likely operating pressure of 3 bar) is still much further away from the actual operating temperature of the loop than the boiling point of water is from the surface temperature of a target plate in case of a solid target.
Accounting also for the fact that mercury itself has virtually no long-lived radioactive isotope (except for $^{208}\text{Hg}$ (367 y), which is a very rare spallation product) and is very easy to purify from other elements as well as to transform into a solid compound (stable amalgam) for final disposal, it makes the material of choice for pulsed spallation neutron sources, a fact that has, in the mean time, also been acknowledged by other projects similar to ESS [12,13]. The inventory of mercury in the target loop will be a few tons, meaning that it will not be used up during the life time of the facility. Calculations of the spallation product yield [14] over a ten-year service period at 5 000 hours per year also showed that virtually all elements produced are in quantities well below their solubility limits in mercury [15] (Figure 6).

![Figure 6. Production and solubility of spallation products in the ESS mercury target. HETC calculation with fission for 1.334 GeV protons, 5 MW on target for 5 000 h/y during 10 years. Diamonds show limits of solubility.](image)

The mercury loop

All mercury will be contained in a closed loop mounted on a trolley that can be moved into a hot cell area for service and replacement of the target shell (Figure 7). A shielded storage tank is part of the mobile unit to allow draining of all mercury into a safe place before manoeuvring or manipulating on the system. Due to the low specific afterheat in the mercury and the large surface of this tank probably no active cooling of the storage tank is required. An important design feature is the separately cooled shroud enclosing the mercury target vessel and providing an interspace with a connecting pipe to the storage tank that would return all spills to that tank in case of leakage from the target container. The tapered shape of the target vessel was chosen for several reasons: the sloping bottom wall facilitates draining of the vessel, whereas the rising top enables gas bubbles to escape from the volume more easily. Furthermore, the increasing cross-section accounts for the volume expansion of the mercury as it is heated by the beam on its way out, as well as for the spreading of the beam as it penetrates into the target.

Based on CFD results [16], the forward flow into the target vessel was split in three streams, one entering along the bottom and two along the side walls (Figure 8) In this way adequate cooling of the window in cross flow can be ensured, while the recirculation behind the inlet baffles is small enough to avoid significant temperature rise in these regions. Figure 9 shows calculated iso-temperature lines
Figure 7. Schematic mercury target system

Figure 8. Planned flow configuration in the ESS mercury target

1. beam window
2. target shell
3. lower baffle plate with He gas injection
4. side baffle plate
5. return hull beam window
6. return hull shell with cooling
7. target flange connector
8. return hull skirt
9. return hull coolant
10. gas injection system
11. gas supply
12. Hg-He mixture outlet

Figure 9. Calculated iso-temperature lines for the ESS Mercury target (°C above inlet) in the planes containing the temperature maximum; top: horizontal plane, bottom: vertical plane
in the horizontal and vertical planes of the target containing the temperature maximum. It is obvious that the temperature peak that exists at the end of the proton range is well away from the walls and at a level of about 140 K above the inlet temperature. So there exists ample freedom to choose the inlet temperature in a way as required under the aspects of heat removal and thermal operating regime of the beam window in view of possible embrittlement effects under irradiation. For the time being, the martensitic steel DIN 1.4926 with 9% Cr and 1% Mo, which is free of nickel and has better thermal conductivity than austenitic steels, has been chosen as reference material for the container. However, no final decision on this question has been arrived at because of an insufficient database on the behaviour of the candidate structure materials under the specific load characteristics of a spallation spectrum. Pertinent research is, however, under way [17,18] and is producing first results. While a first concept for the mercury loop has been drawn up to establish its feasibility, details as to what components will actually be used (EM vs. mechanical pump, mercury-water heat exchanger vs. heat pipe system, etc.) need yet to be worked out and will also depend on the temperature level at which the loop will be operating.

**The moderator-reflector system and neutronic performance**

As indicated in Figure 7, two moderators each are foreseen to be placed above and below the target. They are surrounded by a relatively large reflector, for which heavy water cooled lead has been chosen, because it gives only a small contribution to the long time tails of the neutron pulses from the moderators. While a detailed layout of the moderators in compliance with the users’ wishes has yet to be produced, first performance calculations for a coupled light water moderator yielded the result shown in Figure 10. While the peak thermal flux reaches the unparalleled value of \(2 \times 10^{17} \text{n/cm}^2\text{sec}\), the time average flux was found to be \(2.5 \times 10^{14} \text{n/cm}^2\text{sec}\), which falls slightly short of the goal mentioned in the introduction. This is partly due to the use of a lead reflector, which produces less neutrons in the tails of the pulses than a Beryllium reflector, and hence a lower time average flux. Also shown in the insert is the pulse shape anticipated for a decoupled and poisoned ambient temperature water moderator. It can be seen that not only is the long time tail significantly reduced, but also the peak flux is only of the order of 60% of the coupled case.

A full account of the nuclear and neutronic assessments, which led to the particular layout of the target-moderator-reflector assembly can be found in Ref. [19].

**Figure 10:** Expected thermal neutron pulse structure for ESS with a coupled water moderator. The dashed line in the insert shows an estimate for a decoupled and poisoned water moderator.
Ongoing research and development work

Although the ESS study did not surface any problems that would put the feasibility of the project in question, it clearly showed that a significant amount of R&D work must still be done in order to optimise various subsystems and to be able to assess in detail the overall availability and life expectancy of various components.

On the accelerator side, important development areas are:

- The H- ion source. Until recently, no negative hydrogen ion sources that would have met ESS requirements, even for the case with funnelling, were available. Yet recently the development work going on at the University of Frankfurt for the ESS project seems to have achieved a breakthrough with a 140 mA H– beam extracted over a time almost long enough time for ESS needs [20]. The source still needs further refinement, though.

- Low energy beam transport between the ion source and the RFQ. This is a critical region due to the low particle velocity and must be prototyped.

- The funnelling section. While not being conceptually new, such a system has never been realised to full working conditions. This will have to be done in order to prove its reliability and robustness.

- Particle tracking. The extreme requirements with respect to loss-free beam transport all along the linac and beam lines at the high current required makes it necessary to study in detail all possible loss mechanisms by beam dynamics calculation, taking into account not only the standard deviation of the beam envelope, but, as far as possible, all particles and to optimise beam optics all along.

- Stripping foil development. Although ways must be foreseen for automated exchange of stripping foils in the accumulator rings, it is necessary to achieve a life time of the foils with which at least the production and preparation of new foils can keep up. It is hard to conceive that operation could continue while the foils are exchanged. So, in order to not hamper the availability of the facility too much, significantly less than an hour per day should be lost on average by what will have to become a routine operation.

- Furthermore, studies on the option of a superconducting version for the linac have been initiated in view of the fact that this technology is maturing rapidly and that substantial savings in operating cost are being prognosed. In this context questions relating to pulsed operation with the time structure required for ESS are of particular importance.

These points and more work related to details of the design of numerous components in the highly complex accelerator system have been taken up in the current R&D phase of the ESS project.

While most of the concepts on the accelerator side are based on or build on existing experience, this is not so for the liquid mercury target. No flowing heavy liquid metal target has ever been realised on any spallation neutron source, let alone at the kinds of load levels one is looking at in the ESS project. And yet, there is a growing number of (courageous ?) proposals to use liquid metal targets in all kinds of very ambitious projects. It is, therefore, of extreme importance to explore in detail all the effects that might limit the life time or jeopardise the safety of operation of such a system. The most important ones of the problems currently under study by the ESS team and the international collaborations hey are involved in are:
Radiation effects in candidate materials for the target container. The database for the effects of a spallation spectrum on the properties of materials was, until recently, almost non-existent. It is only in the context of the recent research towards high power spallation sources that serious efforts to obtain such data have been started. An overview over the topic can be found in Ref. [21] and some recent results as well as ongoing efforts are reported in Ref. [18]. One important activity in this context is the incorporation of a large number of test specimens in the operating SINQ target [17], because this is a unique opportunity to perform irradiations under the most realistic spectral and thermal conditions, even including the effects of frequent beam trips. Unfortunately, with the current density at SINQ being only 1/4 of what will prevail at ESS, it will take a long time to obtain fully relevant data, especially since post irradiation examinations are also very time consuming.

The question of flow distribution and heat transfer from the solid to the liquid metal especially in the possible presence of gas in the liquid is of prime importance for the operating temperature of the window and many effects depending on this temperature. The presence of gas may be deliberate (see below) or may be just a consequence of the operating conditions, namely production in the spallation process, pick-up from the cover gas or a necessity to maintain the required quality of the coolant. All of these issues are not yet sufficiently clear and therefore knowledge of their possible effects is important. In order to generate relevant data, a series of experiments have been started, the most important and realistic ones being carried out at the large mercury loop of the University of Latvia in Riga. The data obtained from these experiments will be used to validate the codes employed in the theoretical studies for both ESS and SINQ liquid metal targets.

Liquid metal corrosion and liquid metal embrittlement. Both of these effects have been observed under various conditions. Unfortunately, while it seems desirable to have a low and weakly temperature dependent solubility of the solid component in the liquid one in order to avoid liquid metal corrosion, this seems to be the condition which favours liquid metal embrittlement. However, virtually nothing is known about possible effects of irradiation and especially of simultaneous irradiation and stress on these effects. These are difficult experiments to carry out, since access to an appropriate beam facility and construction of suitable equipment is required. A proposal has been worked out to establish such a facility at the Moscow Meson Factory in Troitsk [22], but funding for this work is still being sought.

Effects of pulsed power input in the liquid metal. It has been realised from the very beginning when the liquid metal target was proposed for ESS that the deposition of 60 kJ of energy in a volume of little over a litre would give rise to pressure waves in the liquid metal which might cause substantial mechanical stress when hitting the container [23,24]. In order to cope with this problem, it has been suggested to try and render the liquid more compressible by maintaining a certain amount of gas bubbles in the volume. Calculations have shown that 3 vol.% of helium bubbles might lower the resulting stresses by about two orders of magnitudes if dynamic effects don’t preclude the compression of the bubbles. This needs to be examined in more detail on both theoretical and experimental grounds, especially since the question of void formation (cavitation) may play an important role in this context. Measurements to verify the theoretical predictions are in progress at the AGS in Brookhaven in the frame of the international ASTE collaboration [25]. Preliminary results seem to confirm theoretical predictions with respect to the amplitudes of the strain waves [26]. Simultaneously, efforts are under ways to inject and diagnose gas bubbles of controlled size into mercury.
Questions of liquid metal quality control, mercury loop technology and remote handling of loop components. While the above problems are of a more fundamental nature, there is also practically no experience in operating and maintaining a liquid metal loop under the conditions required for ESS. It is, therefore, indispensable to build a prototype loop and its ancillary equipment to gain experience in its operation and maintenance, select the most suitable components and to demonstrate that safe and spill-free replacement of the target container will be possible under remote control conditions as well as that methods are at hand, which allow to control the consequences of the need to open a loop which is contaminated with radioactive mercury.

Furthermore, there is also a strong incentive to try and develop more efficient cryogenic moderators than are presently available for use at high power neutron sources (liquid or supercritical hydrogen). It is very intriguing that solid methane yields about 2.5 times more cold neutrons and generates even a much better pulse shape. A development programme has been started in an international collaboration (ACoM [27]), which aims at developing a system that would allow to overcome the problems associated with the use of methane in high radiation fields (radiolytic decomposition, sudden stored energy release and formation of tar-like polymers) and to recover at least a significant fraction, if not all, of the potential advantage of its use.

In order to improve the predictive capabilities in terms of neutronic performance as well as to verify experimentally the moderator-reflector concepts proposed, construction of a full scale mock-up of the ESS target-moderator-reflector unit is planned at the 2.5 GeV proton synchrotron COSY in Jülich [28]. The experiment, named JESSICA, is supported by a large international community of interested scientists and would allow a full verification of the predicted performance of ESS in terms of neutronic output. There is not enough power, however, to carry out also experiments on the thermal shock problem. These will continue at Brookhaven.

While this is not a comprehensive list of all development activities in the ESS R&D phase, it shows clearly that there is still a large amount of work to be done in order to be able to come up with a detailed technical design. It is for this reason, that an R&D phase has been scheduled that lasts until the year 2003 and in which a large number of laboratories and institutions throughout Europe take an active part.

Conclusions

Although the study carried out for the 5 MW short pulse spallation neutron source ESS clearly showed that there is no reason to believe that such a facility could not be built with present day technology, this does not mean that it could be built without further development work. Most of this work is of the nature that confirms in practice results obtained on paper or optimises concepts in detail. However, some of it is also relevant in estimating the anticipated service life of components and in achieving the high degree of reliability a facility serving a large and diverse user community must have. The R&D phase of the ESS project will, therefore, be characterised by intense and demanding work. However, there is every reason to believe that, if properly funded, it will produce the necessary information that would justify to start construction in the year 2004, after a timely decision has been made. It is a fortunate situation that the SNS project now obtaining funding in the US uses practically the same concepts and that ESS and SNS teams will be able to share information
in the future, as they have in the past. Apart from the extra features required to go from 1 to 5 MW, SNS can almost be regarded as a demonstration facility for ESS. The route up to 4-5 MW on SNS, which is in the planning stage, could then be a joint venture between the two facilities.

However, apart from providing the scientific community with a top notch research facility, ESS can also be considered as an important step towards the development of future ADS. It incorporates in its design many of the features also found in the accelerator and target concepts of ADS, as far as they exist. The fact that ESS will use mercury whereas most ADS look at PbBi is not a serious issue, because in many respects all heavy liquid metals are very similar. (Besides, in the SINQ target improvement programme, a liquid PbBi-eutectic target is foreseen whose development will be going on in parallel to the ESS R&D phase.) The fact that ESS is a pulsed facility does not mean that it would be of lesser interest for ADS. On the contrary, as is argued in a different paper presented at this workshop [29], it might even be desirable to have pulsed accelerator as driver for an ADS or a group of them. In this case beam routing capabilities will be important, which is exactly what will be demonstrated in the ESS project with one accelerator system serving two target stations. It would, therefore, be clearly desirable that more intense collaboration take place between the two interest groups.

Acknowledgement

This paper is largely based on the results of the ESS study group, whose members cannot be listed here individually. More technical information is contained in the ESS study report, Vol. III, which was produced with partial funding from the European Community under contract No. DRBCHRXT 940503 and the Swiss Bundesamt für Bildung und Wissenschaft (BBW) under contract No. 94.0134, as well as significant contributions from the participating institutions out of their own funds. These institutions are: Paul Scherrer Institut (CH), Forschungszentrum Jülich (DE), Hahn-Meitner Institut Berlin (DE) Universität Wuppertal (DE) Universität Frankfurt (DE), University of Aarhus (DK), Risø National Laboratory (DK), University of Naples (I), Technical University of Eindhoven (NL), The Svedberg Laboratory (S), Rutherford-Appleton Laboratory (UK), University of Birmingham (UK).

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Abstract

JAERI has launched the Neutron Science Project, which aims at bringing scientific and technological innovation for the 21st century in the fields of basic science and nuclear technology using a high intensity proton accelerator. The project is preparing the design for a high intensity pulsed and CW spallation neutron sources for such basic science as neutron structural biology, material science and for accelerator-driven transmutation of long-lived radionuclides, which are associated with nuclear power generation. The major facilities to be constructed under the project are:

- a superconducting proton linac with proton energy of 1.5 Gev and maximum beam power of 8 MW;
- a spallation target station with input beam power of 5 MW allowing high intensity pulsed neutron beams for neutron scattering;
- a research facility complex for accelerator-driven transmutation experiments, neutron physics, material irradiation, isotopes production, spallation produced RI beam experiments for exotic nuclei investigation.

JAERI has also been carrying out R&D for partitioning and transmutation with the intention of solving the problem of the back end of the nuclear fuel cycle under the auspices of the OMEGA Programme. The accelerator-driven transmutation study is also covered in this programme.
Introduction

The neutron is the ideal probe to study basic microscopic structure and dynamics of materials. Neutron scattering has achieved some notable successes in recent years, such as unravelling the crystal structures of high-temperature superconductors, and is now exciting a lot of interest among biologists for probing large organic molecules. A limiting factor for neutron scattering research is the intensity of the neutron beams. High intensity of neutron beams allows researchers to carry out experiments that would otherwise be impossible. In Europe, the European Spallation Source (ESS) with 5 MW proton beam power is under design, and in the USA the Spallation Neutron Source (SNS) is in the construction phase by ORNL, with 1 MW planned for the first stage, and an eventual upgrade to 4 MW. In Japan, the High Energy Accelerator Research Organisation (KEK) is designing a spallation neutron source with 0.6 MW proton beam power as a part of its Japan Hadron Facility project (JHF). These spallation neutron sources are dedicated to basic science.

Since the middle of the 1970s, JAERI has been carrying out R&D for the partitioning and transmutation of long-lived radionuclides which are produced in nuclear power generation. In 1988, the Atomic Energy Commission set up the long term partitioning and transmutation R&D programme “OMEGA”, which is the acronym of Options Making Extra Gain from Actinide and Fission Products. The activities of JAERI under the OMEGA programme cover a very wide field of nuclear technology such as advanced chemical separation, transmutation technology including dedicated fast neutron reactors and accelerator-driven system for transmutation, nitride fuel manufacturing and pyrochemical reprocessing, nuclear and fuel property database including measurements and evaluation and development of a high intensity proton accelerator for accelerator-driven transmutation.

In the course of designing of a proton accelerator, it was recognised that the neutron scattering community desires to have very high neutron source strength, two orders of magnitude stronger than those existing. Also, JAERI has been one of the major neutron suppliers for the basic science community in Japan with its research reactor JRR-3M, and has been asked to continue to be a supplier in the future.

Under these circumstances, JAERI started the Neutron Science Project. The objective of the project is to construct a high intensity proton accelerator with proton energy of 1.5 GeV, proton beam power of 6-8 MW, and a research facility complex. The R&D on accelerator-driven transmutation is performed under both the Neutron Science Project and the OMEGA programme.

Facilities for basic research

The proton linac is designed to deliver 8 MW beam power and at the first stage is constructed at a power of 1.5 MW (1.5 GeV, 1 mA), and then gradually is increased to 8 MW as experience of high power accelerator operation is accumulated. At the first stage, the accelerator will be operated with the pulsed mode and at the final stage, both with pulsed and CW mode.

Basic science in the Neutron Science Project covers the fields of structural biology for investigating the structure and dynamics of biological molecules such as protein, advanced material science (e.g. under extreme conditions), high-energy neutron science (e.g. spallation phenomena), nuclear cross-section measurements for transmutation study, heavy-ion science for creating unstable heavy nuclei through spallation and synthesis of super heavy extremely-neutron-rich nuclei.
Research facilities considered are classified into three groups on the basis of difference of pulse time durations, namely, a short pulse facility, a very short pulse facility, and a long pulse or continuous beam facility. Also, a direct use of proton beam of 100-200 MeV is considered for medical RI production. The concept of the facility complex is shown in Figure 1.

**Figure 1. Concept of neutron science facility complex**

A neutron scattering facility requires a short pulse of which the duration is shorter than 1 µsec. Two storage rings act to compress the duration of the output pulse of 2-3.7 ms from a superconducting linac to be shorter than 1 µs.

A very short pulse around a duration of 1 ns is required for such experiments with high time resolution as high energy neutron physics by neutron time-of-flight (TOF) spectrometers, muon spin resonance (µ SR) probe for material science. A very short pulse beam is also required for low current duty in such low power experiments as spallation RI beam science. Various radioisotopes are produced by bombarding a target with 1.5 GeV protons through the spallation process. In this facility, the produced radioisotopes are separated with an isotope separator on-line (ISOL), and then accelerated by the existing tandem Van de Graaff accelerator at the Tokai site. Extremely-neutron-rich nuclei are produced which change easily into many exotic nuclei, heavy and super-heavy nuclei. The material irradiation facility utilises a long pulse beam or a continuous beam directly from the linac. The irradiation facility has a slender metal target to obtain a high neutron flux of $2 \times 10^{14} \text{n/cm}^2/\text{s}$ around the target by 1 MW.

In order to utilise the accelerator efficiently, it is preferable to carry out different kinds of experiments in parallel. For the compression ring, negative hydrogen beam is suitable but is not adequate for the experiments, which require a small bending radius of proton beam line arrangement.
because of Lorenz charge stripping. In the latter case, a positive hydrogen beam is better. In our accelerator, both positive and negative hydrogen ions are accelerated alternatively in successive bunches and these are separated by a static bending magnet. A negative hydrogen beam is introduced into the compression ring for neutron scattering and positive hydrogen beam to other facilities. Very short pulses can be switched out of the positive beam trains by a kicker magnet.

**R&D on accelerator-driven transmutation**

*Conceptual design study of transmutation system*

Under the OMEGA programme, JAERI is carrying out studies on transmutation systems [1,2]. The studies are aiming at developing technologies of a dedicated system for transmutation of minor actinides and long-lived fission products recovered from high-level radioactive waste. The dedicated transmutation system is designed to induce efficient fission of minor actinides (MA) under a very hard neutron energy spectrum and high neutron flux. A concept of an accelerator-driven system has been proposed as a dedicated transmutation system to be introduced in the second stratum (partitioning and transmutation fuel cycle) of the double strata fuel cycle concept [3].

In the conceptual design study of accelerator-driven transmutation system, two types of system concepts are being investigated. One is the solid system consisting of tungsten target and nitride fuel subcritical core cooled by liquid sodium. Another option is the system with flowing chloride fuel.

**Solid system concept**

The design of the solid target/core system is based on a liquid metal cooled fast breeder advanced molten-salt reactor. The proton beam is injected through a beam window into the solid tungsten target at the centre of the target/core. Surrounding the target is the subcritical core loaded with actinide nitride fuel. The target consists of multiple layers of tungsten disk with through holes for coolant passage. The target is designed to maximise the neutron yield and to flatten the axial power distribution. The target and fuel subassemblies are cooled by forced upward flow of primary sodium. The whole target/core including reflectors is contained within a steel vessel as shown in Figure 2. Impinging coolant flow from the target exit cools the beam window.

Nitride fuel has the advantages of a high thermal conductivity and a high melting point. With a 1.5 GeV, 40 mA incident proton beam, the target/core having an effective neutron multiplication factor of around 0.93 produces 820 MW thermal power. The net MA transmutation rate is approximately 10%/y, at a plant load factor of 80%. Heat transport and power conversion systems in the plant design are similar to those for an LMFBR plant. Electricity of 270 MW is generated through a conventional steam turbine. One-third of electric power is supplied to its own accelerator operation.

**Molten-salt system concept**

A conceptual design study is being performed on a molten-salt target/core system as an advanced option for an accelerator-based transmutation system. Chloride salt with a composition of $64\text{NaCl} \cdot 5\text{PuCl}_3 \cdot 31\text{MACl}_3$ is chosen as the fuel for its sufficiently high actinide solubility.
The molten-salt fuel also serves as target material and as a coolant. This eliminates the physical and functional separation of target and core, and thus significantly simplifies the target/core configuration. One of the attractive features of the molten-salt fuel is the possibility of continuous fuel feed and on-line processing of reaction product removal. An internal reflector surrounds the target/core region. Intermediate heat exchangers and salt pumps are installed in the annular region around the internal reflector to reduce radiation damages.

Comparison of major system performance parameters [4] of the accelerator-driven transmutation system design is shown in Table 1.

**Table 1. Comparison of 820 MW nitride fuel ADS**

(Proton beam 1.5 GeV, 45 mA, ~30 spallation neutrons/proton)

<table>
<thead>
<tr>
<th>@type of ADS</th>
<th>MA burner</th>
<th>MA burner</th>
<th>MA, FP burner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant</td>
<td>Na cooled</td>
<td>Pb-Bi cooled</td>
<td>Pb-Bi cooled</td>
</tr>
<tr>
<td>Target material</td>
<td>Solid tungsten</td>
<td>Liquid lead-bismuth alloy</td>
<td></td>
</tr>
<tr>
<td>Material inventory (MA/FP)</td>
<td>1950 kg/–</td>
<td>2500 kg/–</td>
<td>2500 kg/1000 kg</td>
</tr>
<tr>
<td>$k_{\text{eff}}$ (initial/max./min.)</td>
<td>0.93/0.94/0.90</td>
<td>0.95/0.95/0.94</td>
<td>0.93/0.93/0.92</td>
</tr>
<tr>
<td>Coolant void reactivity % $\delta k/k$</td>
<td>+4.5</td>
<td>-4.8</td>
<td>-7.1</td>
</tr>
<tr>
<td>Transmutation ratio (MA/FP)</td>
<td>250 kg/y/–</td>
<td>250 kg/y / 40 kg/y</td>
<td></td>
</tr>
<tr>
<td>Power density (max./av.) MW/m$^3$</td>
<td>550/380</td>
<td>310/180</td>
<td>340/180</td>
</tr>
<tr>
<td>Coolant velocity (max.)</td>
<td>8 m/s</td>
<td>2 m/s</td>
<td></td>
</tr>
<tr>
<td>Coolant temp. (inlet/outlet)</td>
<td>330/430°C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Spallation integral experiments** [5]

In the design study of accelerator-based transmutation system, a nucleon-meson transport code, NMTC/JAERI, is used to simulate high-energy nuclear reactions and particle transport. To estimate and validate the accuracy of the code system, a spallation integral experiment is in progress using a large-scale lead assembly. The lead assembly with lead or tungsten target is bombarded with 500 MeV protons at KEK. Reaction rates in a lead assembly were measured. In general, calculations with the codes NMTC/JAERI and MCNP 4.2 were agreed fairly well with experiments.

**Development of high intensity proton linac** [6,7]

The Neutron Science Project of JAERI comprises very wide fields of basic science, which utilises the neutron as the probe to investigate materials of their structure and dynamics, and of nuclear technology. Various beam modes are required to fulfil the experimental requirements of these wide fields, namely, very short pulse for neutron physics, short pulse for neutron scattering, and continuous wave (CW) or long pulse mode for transmutation experiments and material irradiation.

A preliminary specification for the proton linac is given in Table 2.

**Table 2. A preliminary specification of the superconducting linac**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total beam power at targets:</td>
<td>8 MW</td>
</tr>
<tr>
<td>Proton energy:</td>
<td>1.5 GeV</td>
</tr>
<tr>
<td>Accelerated particle:</td>
<td>Negative and positive hydrogen ion</td>
</tr>
<tr>
<td>Average current:</td>
<td>5.33 mA</td>
</tr>
<tr>
<td>Peak current:</td>
<td>30 mA</td>
</tr>
<tr>
<td>Linac type:</td>
<td></td>
</tr>
<tr>
<td>Low energy part:</td>
<td>Normal conducting linac (200 MHz)</td>
</tr>
<tr>
<td>High energy part:</td>
<td>Superconducting linac (600 MHz)</td>
</tr>
<tr>
<td>Beam mode:</td>
<td></td>
</tr>
<tr>
<td>First stage:</td>
<td>Pulse mode operation</td>
</tr>
<tr>
<td>Second stage:</td>
<td>CW and pulse mode operation selectable</td>
</tr>
<tr>
<td>Repetition rate:</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Intermediate pulse width:</td>
<td>400 ns (interval 270 ns)</td>
</tr>
<tr>
<td>Chopping factor:</td>
<td>60%</td>
</tr>
</tbody>
</table>

The total beam power at targets of 8 MW with pulse mode operation is the total of 5 MW for neutron scattering targets, 2 MW for transmutation experiments and 1 MW for other experiments. Several MW CW mode operations are required for the thermo-hydraulic and material tests of a spallation target of a transmutation system. The proton energy of 1.5 GeV was chosen considering the peak current limit of the linac and the pulse width limit of the storage ring.

The layout of the superconductive linac under development at JAERI is shown in Figure 3. The superconducting cavity acceleration was chosen for high energy portion (higher than 100 MeV). The motivation for choosing a superconducting option is: 1) adequacy for large current acceleration with smaller beam hollow; 2) the cost reduction owing to the reduction of length of the linac which leads to the reduced investment costs and savings in operating costs; and 3) because of the technology of the bright future.
The major R&D efforts are presently: 1) the beam dynamic calculation including the high $\beta$ linac; 2) the development of the negative ion source and the fabrication of high power test models for a CW-radio frequency a quadrupole linac (RFQ) and a CW-drift tube linac (DTL); 3) the development of superconducting cavity; 4) the development of high intensity proton beam storage ring; and 5) the optimisation of the system design. In the course of the superconducting cavity development, the vertical cavity test for $\beta = 0.5$ (145 MeV) was successfully conducted toward the end of this June with a maximum field strength of 20 MV/m at 4K and 44 MV/m at 2K.

**Spallation target development** [8,9,10,11]

The target system is one of the major facilities and it requires extensive development efforts. It suffers from severe irradiation of high energy protons and neutrons and thermal shocks.

Two types of target systems are used corresponding to beam power and development stage. A solid system is used at low power and at the initial stage, and a liquid metal system is used for the high power stage. A concept of liquid target and moderator system is shown in Figure 4.

**Solid-metal target**

A compact target of solid metal plates will be used for 1.5 MW proton-beam power. The target plates are exposed to high heat flux up to 12 MW/m$^2$. Thus it is necessary to develop a method of heat transfer augmentation against the high heat flux, especially for coping with anticipated transient phenomena. A test of rib-roughened target surface is planned for augmenting method of heat transfer.
Figure 4. Concept of spallation target system

Liquid-metal target

Mercury is selected as the high power target material, because it has several advantages compared to solid targets. These are: 1) no radiation damage; 2) work with room temperature in liquid metals; and 3) no need for cooling water which act as a neutron absorber and a tritium generator under the spallation source environment. A laboratory-scale mercury-loop of mercury flow rate of 15 l/min. was constructed to obtain the data on controllability of the electric-magnetic pump, the stability of electric-magnetic flowmeter, the coolability of thermal exchanger and so on.

Pressure and stress behaviors of liquid mercury and its container are very crucial to design the target structure. In order to obtain such experimental data, high energy proton injection experiments have been performed using the AGS accelerator complex at Brookhaven National Laboratory in the context of an international collaborative work among the JAERI, ESS, SNS and BNL teams.

Target neutronics design

A series of neutronics analyses are performed for solid and liquid metal target with reflector and moderator systems to optimise the configuration to obtain the maximum neutronics performance. At the same time nuclear heating distribution is evaluated to feedback to design of cryogenic system for moderators. The optimisation study of moderator arrangement is also feedback to optimisation of neutron beam tube arrangement.

Schedule [12,13]

The R&D efforts will continue for another 3-4 years. The proposal of the facility construction will be submitted in 2-3 years. The first stage construction will be completed by 2005 with the beam power on target of 1.5 MW and some of the research facilities. For upgrading the beam power up to 8 MW and constructing the transmutation test facility, it will take another 3-4 years.
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JAPAN HADRON FACILITY (JHF) PROJECT

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Abstract

The Japan Hadron Facility (JHF) is the next accelerator project proposed at KEK to promote exciting sciences by utilising high-intensity proton beams. The project is characterised by three unique features:

1. hadronic beams of the world’s highest intensity;
2. a variety of beams from one accelerator complex;
3. frontier sciences to cover a broad research area including nuclear physics, particle physics, material sciences and life sciences by utilising a common accelerator complex.

The project is supported widely by the science community in Japan as well as by the world community. Clearly, the facility must be open to all users in the world, but a special emphasis will also be placed upon promoting sciences in Asia.

Around the time when the present workshop was held, strenuous negotiations were extended between KEK’s funding agency (Monbu-sho) and JAERI’s funding agency (Science and Technology Agency, STA) to try and combine the JHF project and JAERI’s high-flux neutron beam project. Although I did not describe this point very much at the workshop, I would like to add the summary view on this point. At the end of August a new idea was proposed at Monbu-sho for the JHF project. This idea was to pick up the JHF project as a first example of the joint proposal between Monbu-sho and STA, since these two agencies will eventually merge in 2001. Also, by utilising the opportunity of a large JFY98 supplemental budget from the government, Monbu-sho hoped to officially start this JHF project.

Although strenuous negotiations were extended between Monbu-sho and STA, between KEK and JAERI, etc., in September and October the final conclusion reached was that:

- it was too early to provide a full approval of JHF by using the 1998 supplemental budget;
- the effort must be continued in the future by aiming toward the creation of a fruitful solution of the joint proposal.

In fact, the two-month effort created important results. The first point is that KEK and JAERI reached a full agreement to create one unified proposal by including JHF and JAERI’s high-flux neutron beam
project. KEK and JAERI also agreed to propose the entire JHF plus a test experimental area for transmutation as a first stage of this joint proposal, while in the second stage both shall try to explore a solution of much higher flux accelerator.

We are presently forming a new collaboration team in order to promote this new joint project. Also, we are trying to create a new proposal document which describes the joint plan. The present hope is to start the joint project from JFY2000 and to have beams in 2005.

I personally feel that the JHF project becomes even stronger than before by having the support of both Monbu-sho and the Science and Technology Agency (STA). It is likely that the JHF accelerator complex including the 50 GeV PS shall be constructed at the site of Japan Atomic Energy Research Institute (JAERI) as a co-operative project between KEK and JAERI.
THE KOMAC PROJECT

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H.E. Ahn, Y.S. Cho, J.M. Han, T.Y. Song, and J.H. Lee
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Abstract

Korea Atomic Energy Research Institute (KAERI) launched the KOMAC (Korea Multi-Purpose Accelerator Complex) project to develop and build a high current H+/H− linear accelerator capable of delivering a 1 GeV CW proton beam with an intensity of 20 mA. The KOMAC is to be utilised for emerging nuclear research including the studies on nuclear transmutation and energy production, basic neutron and muon sciences, industrial uses and medical applications. The H− beam of 100 and 260 MeV will be extracted partially at two different stages of the accelerator for low current applications and the 1 GeV proton beam will be used for transmutation purpose. The superconducting structure is considered to be a major option for development in effort to reduce CW operation costs and machine size. The project is scheduled to develop an injector, RFQ, and CCDTL to 20 MeV in the first phase from 1997 to 2002. In the second stage – from 2002 to 2007 – the machine is expected to be completed.
Introduction

Korea Atomic Energy Research Institute (KAERI) has played a major role for the peaceful use of nuclear energy since its foundation (1959) in Korea. The declining and stagnant use of nuclear energy is pushing KAERI to reshape its role. Many efforts are devoted to diversifying and expanding the research field of KAERI. As one of such efforts, KAERI has been performing the project named KOMAC (Korea Multi-Purpose Accelerator Complex) [1-5] within the framework of a national mid- and long-term nuclear research plan.

The final objective of KOMAC is to build a 20 MW (1 GeV and 20 mA) CW (100% duty factor) proton linear accelerator. The key element of the KOMAC design is to accelerate both H\(^+\) and H\(^-\) to 1 GeV while partially extracting H\(^-\) at 100 and 260 MeV. The major H\(^+\) beam (18 mA and 1 GeV) will be used for nuclear waste transmutation, energy production and medium energy physics experiments with high intensity while utilising the minor H\(^-\) beam (2 mA) for basic science research and medical therapy. Specifically, the 1 GeV H\(^-\) beam will be used for the production of π and μ beams. The 100 MeV beam will be used for fast neutron generation, proton-therapy of eye melanomas (60-70 MeV), solar proton studies and nuclear data. We will utilise the 260 MeV beam for deep-sited tumour therapy. We are planning to extract the partial (0-100%) beam by employing either a magnetic stripper or a laser. The KOMAC is scheduled to develop an injector, RFQ, and CCDTL to 20 MeV in the first phase from 1997 to 2002. In the second stage from 2002 to 2007, the machine will be completed.

In parallel with the KOMAC project, KAERI initiated the HYPER (Hybrid Power Extraction Reactor) programme that may open new horizons for nuclear industry in Korea. Currently the spent nuclear fuels are becoming a bottle neck for the peaceful use of nuclear energy. The HYPER project is expected to provide a breakthrough to the current stagnant situation that the nuclear industry is faced with. The HYPER programme is also being performed within the framework of the national mid- and long-term nuclear research plan. KAERI is aiming to develop the elemental technologies for the subcritical transmutation system by the year 2002 and build a small bench scale test facility (~5 MWth) by the year 2007.

The proposed KOMAC-linac configuration is shown in Figure 1. The low-energy part is a normal conducting (NC) linac which consists of an injector, RFQ and CCDTL to achieve CW operation while the high-energy portion is a superconducting linac (SCL) employing niobium cavities. In the first stage (1997-2002), the NC linac up to 20 MeV CCDTL will be completed. The completion of KOMAC including the target is expected in 2007.

Figure 1. KOMAC configuration

![KOMAC configuration diagram](image-url)
Since KOMAC is adopting both H⁺ and H⁻ beams, the alignment is a crucial issue as the two beams deflect toward two different directions with a steering magnet. We are considering an independent alignment of both beams at several different places: injector region (50 keV), phase matching section (3 MeV), and beam-extraction regions (100 and/or 260 MeV).

**KOMAC injector**

A duoplasmatron H⁺ ion source has been built at KAERI. It has a peak current of 30 mA with a normalised 90% emittance of 0.5 mm-mrad. Korea Advanced Institute of Science and Technology (KAIST) is responsible for designing the H⁺ ion source. KAERI is responsible for an injector delivering both H⁺ and H⁻ beams to 50 keV. As options to achieve a long life for a proton ion source and to produce efficiently negative ions, high-density plasma sources using RF powers are developed for the KOMAC (H⁺/H⁻) ion source. Noting that helicon wave can propagate in a low-frequency, low-field, and high-density regime, the helicon plasma source may be a good candidate as an ion source for CW high-current, low-emittance accelerators.

**Ion source**

As an H⁺ ion source, duoplasmatron was modified to extracting high current and bright beam. Beam extraction geometry is simulated and confirmed by using the IGUN code. The simulated beam profiles with this extraction geometry shown in Figure 2 provide beam currents of 50 mA at an extraction voltage of 50 kV. The injector system is shown in Figure 3. The injector system is composed of an accelerating high voltage power supply, ion source power supplies in a high voltage deck, hydrogen gas feeding system and vacuum system. The axial magnetic field from solenoid coils in the source is measured up to 4 kG. The base pressure of vacuum chamber is less than 10⁻⁶ torr, but the operation pressure is less than 5 × 10⁻⁶ torr. It has a low normalised emittance of 0.5 π mm mrad from 90% beam current and proton fraction of over 50%. The filament lifetime has been achieved over 40 hrs.

**Figure 2. Simulated beam profile**
The Radio Frequency Quadrupole (RFQ) linac is a CW linac which will produce a 20 mA beam of $\text{H}^+ / \text{H}^-$ with energy of 3 MeV. The main focuses of this physics and engineering design in the KOMAC RFQ are as follows:

- to obtain the focusing required to match the $\text{H}^+ / \text{H}^-$ beam to the RFQ;
- to maintain a constant capacitance per unit length along the axis of the RFQ;
- to minimise the power dissipated on the cavity walls and the end region of the vanes;
- to stabilise the longitudinal mode in the structure.

**Physics design**

The KOMAC system requires 20 mA of $\text{H}^+ / \text{H}^-$ beams from the 350 MHz RFQ. The proper energy needs for injection into the coupled cavity drift tube linac (CCDTL). The maximum vane voltage is given by the peak electric field that could cause sparking. In this design, the peak electric field was limited to 1.8 times the Kilpatrick criterion.

To obtain the focusing required to match the beam from LEBT to the RFQ requires a weaker focusing and a larger aperture at the entrance of the RFQ. However, the transmission rate of the beam decreases with the inverse of the aperture at the entrance of the RFQ. In order to design a radial matching section with a weak focusing and large aperture, we used CURLI and RFQUICK. The aperture in the KOMAC RFQ is smoothly reduced as it moves from the entrance to $z = 26.8$ cm where the focusing strength is peak.

Another important factor in the RFQ design is to maintain a constant capacitance per unit length along the axis of the RFQ. In order to maintain a constant capacitance, the average radius from the vane tip to the axis of the RFQ is changed. A change in the average radius would result in a change in the capacitance and in the local resonant frequency of the wave-guide by a severe tilt in the fields. To maintain a constant capacitance per unit length, we fix the ratio of the vane tip transverse radius of...
curvature, \( \rho \), to the average radius, \( r \). For the KOMAC RFQ, the value of \( \rho/r \) is kept constant at 0.792. The resonant frequency is kept constant by varying the cavity cross-section by adjusting the width of the vane base while \( r \) changes. Because the power dissipated in the cavity walls will not be longitudinally uniform, this also minimises the structure power. We used PARMTEQM to match the beam into the CCDTL. The percentage transmission is 95.4%.

**Engineering design**

The length of the KOMAC RFQ is 3.24 m long and consists of two resonantly coupled 1.62 m sections. The length is determined by the final energy which is 3.0 MeV. The resonant coupling provides the longitudinal field stabilisation and a stop band in the dipole mode, which has improved the transverse stability by eliminating dipole modes. In order to tune the resonant frequency of the end regions of the RFQ, we have used the three-dimensional MAFIA code. There is the rectangular undercut of the vanes. However, the exact shape of the undercut will be determined empirically by the cold model which is being fabricated into the aluminium alloy. The cavity cross-section is four triangular shapes with the axial variation in the width of the vane base as shown in Figure 4. The vane-cavity will be joined longitudinally by a brazing. Thus the RFQ is a completed monolithic structure and the vanes are permanently aligned. This structure serves to mitigate the cost and to simplify the mechanical support system.

**Figure 4. Temperature distribution of the cavity at the high energy end of the KOMAC RFQ**

A serious problem in the design of the KOMAC RFQ with CW operation results from the RF thermal loads on the cavity walls. The average structure power by RF thermal loads is 0.35 MW and the peak surface heat flux on the cavity wall is 0.13 MW/m\(^2\) at the high energy end. In order to remove these heat, we consider 24 longitudinal coolant passages in each of the sections, as shown in Figure 4. Figure 6 also shows a temperature distribution of the cavity at the high energy end. The material is oxygen-free copper. The thermal load was given by the SUPERFISH analysis. The heat transfer coefficients is between 11 kW/m\(^2\)-C to 15 kW/m\(^2\)-C. Because of the flow erosion of the coolant passages, we consider the maximum allowable bulk velocity of the coolant as 4.5 m/sec. From the thermal-structural analysis of ANSYS, the peak temperature on the cavity wall is 50°C, the displacement is about 18 \( \mu m \) and the intensity stress is 30 MPa.
Present status

A cold-model of the RFQ is being machined at the Samsung Heavy Industries Co., Ltd and the Dae-Wung Engineering Co. We are going to test a brazing of one section in this year.

KOMAC coupled-cavity, drift-tube linac (CCDTL) and super-conducting linac (SL)

KAERI is responsible for developing CCDTL, which combines the features of conventional DTL and CCL. The CCDTL will accelerate 3 MeV H+/H to 100 MeV. The benefit of CCDTL is a reduction in the cost of DTL since the quadrupole magnets are located outside the accelerating cavities. It is also easy to fabricate and install it on the structure without breaking vacuum. The length of the CCDTL accelerating beam of 3 MeV to 20 MeV is 29.8 m with the total power of 1.49 MW. However, we consume 12 m of length for an energy gain of 5 MeV, so we are doing a trade-off study by replacing the first part of CCDTL with a longer RFQ. In the first phase (1997-2001) of developing KOMAC, the first part of CCDTL will be fabricated to deliver the beams to 20 MeV. In the second stage, 94.2 m CCDTL will accelerate the beam to 100 MeV. The design of the CCDTL is shown in Figure 5. The test model will be fabricated in this year.

Figure 5. KOMAC CCDTL

Seoul National University (SNU) is responsible for the superconducting linac. Compared with the normal conducting (NC) cavity, a superconducting (SC) cavity reduces the required RF power as well as operating and capital costs. It also allows a much larger aperture with the same gradient to reduce the beam loss. We have three designs of SC cryo-modules. From 100 MeV to 140 MeV, the cavities are optimised at $\beta = 0.45$, and from 140 MeV to 260 MeV, at $\beta = 0.53$, and in the section above 260 MeV, at $\beta = 0.71$. The cryostats contain four 4-to-6-cells 700 MHz niobium cavities. The transverse focusing is done by doublet quadrupoles located outside the cryostat. The design of the SCL is shown in Figure 6.

Figure 6. KOMAC superconducting linac
Beam extraction

Beam extraction is important in the KOMAC project where the H⁻ beam is partially extracted at 100 and 260 MeV while the H⁺ beam is accelerated up to 1 GeV. The beam sharing is the most important issue regarding the extractor design since the current of the beam being extracted should be regulated depending on the user’s need. We have studied two options for the extractor design: one for utilising a laser and another for a stripper magnet.

Laser extractor

One advantage in utilising a laser as a beam extractor is to produce a pulsed beam. It is technically possible to select a single bunch of H⁻ with a laser. Figure 7 shows a beam extractor design with a laser.

Figure 7. Beam extractor employing a laser

It consists of six dipoles (BM01 to BM06) and 12 quadrupoles (QM01 to QM12). The dipole bends the H⁻ beam by 20° with 1 T magnetic field. The effective length is 52 cm. The laser is located between QM01 and QM02. In order to select a bunch, the pulse length should be about 0.2 nsec since the bunch size is about 2 cm for the 100 MeV H⁻ beam. The repetition rate can be regulated depending upon the time structure of the required extracted beam. If we desire to extract the whole H⁺ beam, then the rate should be 350 MHz. The photodetached H⁻ beam (i.e. H⁺) goes through BM02 without being bended while the undetached H⁻ beam travels toward BM03 after being bended by 20°. TRACE3D run of the design shows that the beam profile after the extractor matches well with the one before the extractor.

Magnet extractor

A beam extractor design employing a magnetic stripper has been studied extensively. We finally come up with a simple design, which replaces BM02 from Figure 8 with a stripper magnet. Since all five dipoles are fixed (i.e. 20° bending), we only have to be concerned with the stripper magnet. Of course the laser is out in this design. The stripper magnet is required not only to extract H⁺ but also to deliver unextracted H⁻ to BM03. This means that \[ \int B \, dl \] of the stripper should be constant. Figure 8 shows the stripper magnet design. It consists of both superconducting coils and normal conducting...
coils. When H\(^-\) goes through this stripper, it encounters the strong field generated by the superconducting coils and it looses an electron and becomes H\(^0\). The FWHM of the field should be as narrow as possible to minimise the emittance growth. The survived H\(^-\) after the strong field still need to be bended up to 20° and an additional bending is given by the field from the normal-conducting coils. Figure 9 shows the field generated by the stripper magnet.

**Figure 8. Stripper magnet design**

![Stripper magnet design](image)

**Figure 9. Field generated from the stripper magnet**

![Field generated from the stripper magnet](image)

The high field from the superconducting coils set the intensity of the extracted beam while the low field from the normal conducting coils ensures the constant value of \(\int B \, dl\). In practice, this can easily be achieved by monitoring the beam at the region before BM03 to make sure the beam bended exactly by 20°. We have two knobs to vary: one for extracted beam intensity and another for 20° bending.

**Applications of KOMAC Accelerator**

**HYPER System**

Korea Atomic Energy Research Institute (KAERI) initiated an accelerator driven subcritical reactor development programme, named HYPER (HYbrid Power Extraction Reactor) to solve the spent fuel problem within the framework of the national long-term nuclear research plan as the major
application of the KOMAC accelerator. The sub-criticality of HYPER is expected to provide many attractive features that can not be obtained in a critical reactor: (1) the safety of the system is enhanced considerably by removing the possibility of reactivity accident and simplifying the power control mechanism; (2) the flexibility of the fuel (or targets to be incinerated) enables the system to have high transmutation capability and to be proliferation resistant; (3) the surplus neutrons by the spallation increase the self-clean power of the system. Figure 10 shows the basic concept of the HYPER reactor vessel. The HYPER project will be completed by the year 2006. The design concept of the transmutation system and some basic key technologies are to be developed in Phase I (1997-2001). A small bench scale test facility (~5 MWth) is to be designed and built in Phase II (2002-2006).

Figure 10. Hyper reactor vessel concept

![Hyper reactor vessel concept](image)

HYPER core is aiming at the incineration of TRU and some fission products (Tc, I) from LWR. In order to minimise the fluctuation of reactivity, on-line refuelling concepts are employed. It is utilising fast neutrons for the effective TRU incineration.

The core in Figure 11 is designed to produce 1 000 MWth with $k_{ef}$ of 0.97, 16 mA of 1 GeV proton beam. The active core height is 1.2 m and the effective core diameter is 3.8 m. Each fuel channel contains four unit assemblies of which the length is 30.0 cm. The reflector assemblies filled with liquid Pb-Bi are located at the core perimeter. HT9 shield assemblies are located at the outermost core perimeter to prevent excessive irradiation damage to reactor structures and components surrounding the core. Four fission product burning assemblies are provided to transmute $^{99}$Tc and $^{129}$I. In order to achieve the effective neutron spectrum to transmute these fission products, the assemblies are surrounded by the graphite moderator wall. HYPER burns (or transmutes) about 380 kg of TRU per year. This means more than 1 kg of TRU should be fed into the system a day. With 18%at designed burn-up, 1–2 (1.45) fuel assemblies are loaded per day. The support ratio of HYPER for LWR units producing the same power is to be 5–6. The core-averaged neutron flux is about $6 \times 10^{15}$ neutrons/sec-cm$^2$.

HYPER is considering the metal fuel combined with pyrochemical process which is generally believed to be one of the most proliferation resistant fuel types. The chemical composition of the fuel for the HYPER system is designed to meet the requirement of system subcriticality. The Pb-Bi coolant will be used as a spallation target. The beam window is located 0.35 m below the top of the active core. The cross-section of the beam tube is 30 cm $\times$ 30 cm square and the window has a cylindrically curved profile.
Other applications

The minor H⁻ beam (2 mA) will be utilised for basic science research and medical therapy as shown in Figure 12. The 1 GeV H⁺ beam will be used for the production of π and μ beams which will be a tool of material science and fusion. The spallation neutron source will be the other application of the 1 GeV beam. It will provide the neutron for biological science and industrial purposes. For the medical therapy of tumours, a 260 MeV beam will be used. A 100 MeV beam will be used for fast neutron generation, proton-therapy of eye melanomas (60-70 MeV), solar proton studies and nuclear data.
Summary

The design goal of the KOMAC is to accelerate both \( \text{H}^+ \) and \( \text{H}^- \) to 1 GeV while partially extracting \( \text{H}^- \) at the intermediate stages of 100 and 260 MeV and study has focused on realisation of continuously sharing and extracting the beam with low beam current applications and high current application at the end of accelerator for multipurpose uses. Also much effort is being made toward the realisation of the CW mode operation. The design works have been carried out through collaborations with national institutes and universities in Korea.

The HYPER (HYbrid Power Extraction Reactor) to solve the spent fuel problem has been studied as the major application of the KOMAC proton beam at KAERI. Other applications of the KOMAC for basic science, industries and medical therapy have been considered.

The project is scheduled to develop the first 20 MeV normal conducting accelerator of the KOMAC in the first phase from 1997 to 2002. In the second stage to 2007 the KOMAC will be completed and dedicated to the experiments for the low beam current applications.

REFERENCES


Application of HPPAs – Part II

Chairs: I.P. Matveyenko and M. Nagamiya
PROPOSAL FOR A VERIFICATION FACILITY OF ADS IN CHINA*

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China Institute of Atomic Energy

Abstract

The concept, general layout and some specifications of a proposed verification facility of the accelerator driven radioactive clean nuclear power system (AD-RCNPS) in China are described. It is composed of a 150 MeV/3 mA low energy accelerator, a swimming pool reactor and some basic research facilities. The 150 MeV accelerator consists of an ECR proton source, LEBT, RFQ, CCDTL and SCC. As the sub-critical reactor, the swimming pool reactor is an existing research reactor at the China Institute of Atomic Energy, whose maximum output power is 3.5 MW. The effect of the instability of proton beam and possibility of simulation tests on the verification facility have been analysed.

* This study is completely in collaboration with the accelerator of IHEP and Peking University.
Introduction

In recent years, there has been a growing interest in the R&D of high power proton accelerator (HPPA) driven systems (ADS) for the application of energy resources, nuclear fuel breeding and high level radioactive waste transmutation [1]. In almost all known ADS projects, the high power proton accelerator, in general, is required as an ADS driver, delivering an average beam of 30 mA to 100 mA at 1 GeV energy and operating at CW mode [2]. In accelerator development, the proton linear accelerator has been selected to meet the requirement of such a high beam power.

In China, the rapid increase of the national economy asks for a rapid increase of the energy supply. It is a more and more important issue at present to develop energy resources science, especially nuclear fission energy. At the advocacy of some nuclear scientists, a conceptual study on the accelerator driven radioactive clean nuclear power system (AD-RCNPS) has begun in China. A group of scientists in the field of nuclear physics, reactor physics and technology, accelerator physics and nuclear chemistry from the China Institute of Atomic Energy (CIAE), Institute of High Energy Physics (IHEP) and Peking University was formed in the middle of 1995.

As the first phase of a long-term plan, a proposal for a verification facility was made [3]. The facility consists of a 150 MeV/3 mA low energy accelerator and a sub-critical light water swimming pool reactor, which is a modified core structure of an existing research reactor at the China Institute of Atomic Energy. The verification facility will also include some facilities to be built for neutron nuclear reaction measurement, material testing, target assembly testing and manufacturing of superconducting cavity and high power klystron laboratory.

This facility will play a role in testing and verifying the most basic concepts of the physics and technology for ADS. It should give us a better understanding of the critical points for the HPPA at different operation modes, for example, the low duty factor or the high duty factor and even the CW operation possibility. It should also give us a better understanding of some problems for the target and for the sub-critical reactor. This verification facility will be also used for some basic research topics, such as material science, neutron physics and nuclear transmutation study.

The accelerator should operate at two different operation modes; it will be not only at a long pulse mode (1 ms) to drive a sub-critical reactor system, but also at a short pulse mode (1 ns) to realise the time-of-flight (TOF) experiments for neutron physics. The conceptual layout of the verification facility [3] is shown in Figure 1.

The front end of the accelerator part

The accelerator portion is composed of an ECR ion source, a low energy beam transportation (LEBT) section, a low energy radio-frequency quadrupole accelerator (RFQ), a normal conducting cavity coupled drift tube (CCDTL) linac and a super conducting cavity linac (SCC). The primary specifications of this accelerator are listed in Table 1.

In order to meet the requirements mentioned above, a proton electron cyclotron resonance (ECR) ion source is selected for the source of our verification facility system. This kind of ion source has some attracting advantages [4], for example, better reliability; high ionisation efficiency; low emittance and high intensity; low gas load on the vacuum system. The structure of the ECR source is similar to the one at Chalk River Laboratory in 1993 [5], which is shown in Figure 2.
Figure 1. Conceptual layout of verification facility for ADS

Table 1. Primary specifications of the accelerator

<table>
<thead>
<tr>
<th>Accelerated particle</th>
<th>Proton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle energy</td>
<td>150 MeV</td>
</tr>
<tr>
<td>Average current</td>
<td>3 mA</td>
</tr>
<tr>
<td>Accelerating frequency</td>
<td>350 MHz</td>
</tr>
<tr>
<td>Pulse structure</td>
<td></td>
</tr>
<tr>
<td>• Long pulse mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pulse duration: 1 ms</td>
</tr>
<tr>
<td></td>
<td>Duty factor: 5%</td>
</tr>
<tr>
<td></td>
<td>Micro pulse: Repetition rate 350 MHz</td>
</tr>
<tr>
<td></td>
<td>Average current: 3 mA</td>
</tr>
<tr>
<td>• Short pulse mode</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Macro pulse: Repetition rate 50 Hz</td>
</tr>
<tr>
<td></td>
<td>Pulse duration: 1 ms</td>
</tr>
<tr>
<td></td>
<td>Micro pulse: Repetition rate 1.75 MHz</td>
</tr>
<tr>
<td></td>
<td>Repetition period: 571 ns</td>
</tr>
<tr>
<td></td>
<td>Pulse duration: 1 ns</td>
</tr>
<tr>
<td></td>
<td>Pulse intensity: 4 × 10^7 ppp</td>
</tr>
<tr>
<td></td>
<td>Average current: 15 μA</td>
</tr>
</tbody>
</table>
The 2.45 GHz microwave power is adopted, 1 kW microwave power is coupled to the plasma chamber by a rectangular-to-ridged wave-guide through a microwave window. The plasma chamber is a cylinder 100 mm long and 100 mm in diameter. An accelerating and decelerating three electrodes extraction structure is adopted. A normalised rms emittance as low as 0.2 \( \pi \) mm mrad is required. The discharging chamber is designed to withstand up to 75 kV potential voltage. At CIAE and Peking University, the DC proton beam current can be produced up to 45 mA with a slit extraction structure. A new source is under construction now at the CIAE.

The low energy beam transport (LEBT) is used to match the beam transport between the ion source and the RFQ accelerator. The LEBT should consider two operating modes. The long (1 ms) and short (1 ns duration pulse, 1.75 MHz modulating) pulse operating modes should be incorporated in one optical arrangement. In the long pulse mode, the pulse duration of 1 ms is a result of modulation of microwave support of ion source with 50 Hz repetition rate. It gives us a duty factor of 5%. At the peak current of 60 mA, the average current can reach 3 mA. In order to space-charge neutralise by the electron ionisation, two solenoid magnets are used to match lenses in LEBT. The beam optics layout of LEBT section is illustrated in Figure 3.

**Figure 3. Beam optics of LEBT section**
The proton beam from the ion source is focused by two solenoid magnet lenses. A beam diagnostic box is put in between. The solenoid magnet used in the LEBT is 200 mm in length and 80 mm in diameter, and the maximum magnetic field strength at beam axis is about 0.7 Tesla.

In order to realise the short pulse mode, a pair of chopper plates at a repetition rate of 1.75 MHz and a bunched gap at a repetition rate of 7 MHz have to be inserted between two solenoids. The time period of pulse structure is 571 ns and the pulse width is around ~1 ns at the entrance of RFQ. The total length of the LEBT section is around 2.1 meters.

The RFQ accelerator and CCDTL linac

The rationalisation of the parameters for the verification facility of 150 MeV is dependent on the estimation and empirical fitting; the neutron yield is estimated to be roughly one to one proton at 150 MeV [6]. We can take this value as the threshold of the spallation reaction. The proton range in lead is roughly 3.5 cm at 150 MeV, which allows the possibility of attaining the target heat-extraction and meeting its hydraulic properties.

The maximum output power of the original swimming pool reactor is 3.5 MW. The reason why we take the maximum beam current up to 3 mA, then, is because of the requirement of running the sub-critical reactor with the k value varying from 0.90 to 0.97. The proposed accelerator facility contains nearly all of the accelerating structures, such as ECR source, RFQ and CCDTL, which are essential components for the construction of a full-scale accelerator.

The RFQ is a four-vane type and designed to accelerate 60 mA peak current of proton beam with an energy of 75 kV. The structure of this proposed RFQ is similar to the one of Los Alamos Laboratory (APT). At Los Alamos, the CW APTF RFQ is described in detail in Ref. [7]. In our verification facility, the RFQ machine is composed of four segments joined together with three coupling plates which separate the segments and reduce the magnetic coupling. The RFQ linac overall is 8 meters in length. Each segment is 2 meters long. The dipole stabilisers will be designed to be mounted on the coupling plates and on the end plate as well. The structure of the coupling plates and the dipole stabilisers is shown in Figure 4 [8]. The specifications of the proposed RFQ are listed as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Four-vane type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injecting energy</td>
<td>75 keV</td>
</tr>
<tr>
<td>Output energy</td>
<td>7 MeV</td>
</tr>
<tr>
<td>Peak current</td>
<td>60 mA</td>
</tr>
<tr>
<td>Duty factor</td>
<td>5%</td>
</tr>
<tr>
<td>Output average current</td>
<td>3 mA</td>
</tr>
<tr>
<td>Normalised rms emittance</td>
<td>0.2 π-mm-mrad</td>
</tr>
<tr>
<td>Work frequency</td>
<td>350 MHz</td>
</tr>
<tr>
<td>Cavity length</td>
<td>8 m</td>
</tr>
<tr>
<td>Average accelerating gradient</td>
<td>1.4 MV/m</td>
</tr>
<tr>
<td>Cavity average power losses</td>
<td>7.2 kW</td>
</tr>
<tr>
<td>Peak RF power consumption</td>
<td>1.6 MW</td>
</tr>
<tr>
<td>Average RF consumption</td>
<td>96 Kw</td>
</tr>
</tbody>
</table>
At Peking University, an integral splitting RFQ has been built and beam test has been conducted, especially for the purpose of ion implantation with adjustable output energy [9,10]. At the Institute of High Energy Physics, a four-rod type RFQ is under conduction as the injector of the existing proton linac of 35 MeV [11,12]. The new model of proposed RFQ machine will be built based on these experiences.

The Coupling Cavity Drift Tube Linac (CCDTL) [13] system will subsequently be the RFQ and MEBT bringing the beam energy from 7 MeV to 100 MeV. And then a Super Conducting Cavity Linac (SCC) is proposed to accelerate the beam up to 150 MeV. The work frequency of the CCDTL and the SCC is 700 MHz. The specifications of the proposed CCDTL are listed as follows:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injecting energy</td>
<td>7 MeV</td>
</tr>
<tr>
<td>Output energy</td>
<td>100 MeV</td>
</tr>
<tr>
<td>Peak current</td>
<td>50 mA</td>
</tr>
<tr>
<td>Length</td>
<td>100 meter</td>
</tr>
<tr>
<td>Bore radius</td>
<td>1-1.7 cm</td>
</tr>
<tr>
<td>Structure accelerating grad.</td>
<td>1-1.8 MV/m</td>
</tr>
<tr>
<td>Synchro phase</td>
<td>-30°</td>
</tr>
<tr>
<td>Cavity power losses</td>
<td>5.0 MW</td>
</tr>
<tr>
<td>Beam power</td>
<td>2.8 MW</td>
</tr>
</tbody>
</table>

The construction of the verification facility is expected to be in two phases until 2007. In Phase I, the technical development will be carried out individually, while in Phase II the integral project will be undertaken. In the first five years, the front end of the verification facility should be completed, including ECR ion source, LEBT and a 2.5 MeV RFQ. At the same time, it is expected to develop the CCDTL model tests, to build a superconducting accelerator cavity laboratory and a high power CW klystron laboratory.

On the base of this verification facility, we expect that a full-scale demonstration experimental facility may be realised in the mid-2010s.
The core structure of modified swimming pool sub-critical reactor

The modified core structure of the swimming pool reactor is shown in Figure 5. The fuel elements and assembly will be the same as in the original, while 3 × 4 assemblies of the fuel in the central of the core is substituted by beam pipe and target with some space for different materials, in order to meet the purpose to verify various conceptions of blanket structure, including the fast thermal coupling, transmutation and so on. The k-value is 1.035 when all cells are filled by the fuel assembly besides the central part is filled by lead moderator. This give us a quite large range to vary the k-value by changing the fuel assemblies used and/or the fuel management in meeting the requirement of k-value from 0.90 to 0.97.

Figure 5. Core lattice structure of verification facility blanket

Some specifications of the core structure are listed as follows:

<table>
<thead>
<tr>
<th>Target and moderator</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of core</td>
<td>500 mm</td>
</tr>
<tr>
<td>Fuel</td>
<td>U²³⁵ (10%)</td>
</tr>
<tr>
<td>K</td>
<td>1.035</td>
</tr>
<tr>
<td>Anticipated $k_{\text{eff}}$</td>
<td>0.94-0.98, power ≤ 3 MW</td>
</tr>
</tbody>
</table>

Accelerator reliability required by sub-critical reactor in ADS and simulation study of reactor’s resistance to thermal shock

In this section a conceptual analysis about the effect of the instability of proton beam and beam trip, and the possibility of a simulation test on the verification facility is presented. In a sub-critical reactor of ADS operating at high power level, the thermal power density due to fission is about the same magnitude as that in reactor core of similar nuclear power plant, thus the design criteria relevant to reactor safety are similar to those for the existing reactor core. As the power level of a sub-critical
reactor core in ADS is sustained by the neutron source generated from bombarding the spallation target by high current protons, both the instability of proton beam and beam trip in any form will influence the power level of the sub-critical reactor.

The reliability of the high power proton accelerator (HPPA) in ADS comprises beam stability and beam trip. In conjunction with the sub-critical reactor, the beam trip refers to proton beam interruption in HPPA or its loss from beam tube due to various causes. Such beam trip will result in a fission power of the sub-critical reactor to drop and force the reactor shut-down.

In power reactor design, various measures are taken to avoid thermal stress concentration due to repeated thermal shock, which will bring about fissure occurrence and result in harmful effects on nuclear safety. First, for large scale thermal neutron tractor, restraining xenon oscillation induced by neutron flux oscillation in space and time domains is taken into consideration. Second, emergency shutdown of power reactor will undoubtedly bring about intense thermal shock to the system’s corresponding parts, thus in the operation phase, unplanned reactor shutdown is strictly prevented and the time of emergency shutdowns is limited. Besides economic considerations, the purpose is the reduction of thermal shocks so as to guarantee the good condition and reliability of the equipment.

In ADS, the spallation target, located in a certain reactor zone, is equivalent to a localised neutron source, which instability will produce a disturbance to the neutron flux density nearby. The disturbance and its probably induced xenon oscillation result in fission power fluctuation. On the other hand, the proton beam trip causes emergency shutdown whose speed depends on the reactor’s sub-criticality and swiftness of the scram mechanism. For ordinary nuclear power plants, by mechanic and electronic means and relying on gravity drop to insert the control rods, the action time of the order of a second. For ADS during operation with existing sub-criticality, the action time is of the order of a millisecond for the fission power cut-off by interrupting the proton beam. Thus in regard to the same sub-criticality, the shutdown speed of ADS is faster. It is to our advantage to prevent unexpected power increases when an accident occurs [14], but is, however, unfavourable from the view point of reducing thermal shock, as the faster the shutdown speed and the greater the number of shutdowns, the greater the thermal shock to the equipment and more concentrated the thermal stress. Therefore, in order to reduce thermal shock, as well as improving the reliability of HPPA and lowering the unexpected beam trip probability, it is not good if the sub-criticality of the sub-critical reactor in ADS is too low.

On verification facility problems relevant to the accelerator reliability will also be explored. We know that a reactor, as a power system, in linear condition, has the properties of an inertia system. Its response characteristic to external disturbance can be described by proper time constant. Hence, by creating artificial beam disturbance on the verification facility, combining theory with experiment, the study on dynamic behaviour of sub-critical reactor, determining the time constant will be helpful to the understanding of problems concerned.

In ADS, HPPA beam disturbance brings about the disturbance of super-high energy neutron source, with average neutron energy at 10 MeV or so. But average neutron energy in sub-critical fission reactors is very low. For fast breeding systems it is less than 1 keV, for thermal neutron systems below 1 ev. Therefore the disturbance magnitude and average energy of the spallation neutron source strength will have complicated problems in space-dependent neutron dynamics.

In fission reactors, the thermal power disturbance produced with the disturbance of neutron flux density is the direct cause of the formation of thermal shocks. Hence, to study the sub-critical reactor’s resistance to thermal shock, it is possible and practical to begin with space-dependent
neutron dynamics of HPPA beam instability acting on sub-critical reactors. As neutron dynamics and thermodynamics work together in the reactor, two kinds of time constant are needed to describe high power sub-critical reactor, one being neutron dynamic, the other thermodynamic.

As reactor thermodynamics time constant is related to thermal transfer process, it is much larger than that of neutron dynamics. This means, as viewed from coupling of neutron-thermodynamics. If the sub-critical reactor is not sensitive to the neutron disturbance of this transition frequency, it then must not be sensitive to various thermodynamic disturbances. Hence, using verification facility to simulate proton beam disturbance and find ways of preventing beam loss; through studying time-space behaviour of neutron flux density in sub-critical reactor to study the reliability requirement of HPPA; and developing early research on thermal shock resistance of sub-critical reactor, all these are feasible.

REFERENCES


A PROGRAMME OF NEUTRON EXPERIMENTS IN IPPE ON THE ADS PROBLEM

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Abstract

Experimental investigations on the problem of ADS systems are carried out in the following areas:

- ADS models study (both bound fast-thermal and one-zone models);
- creation of experimental benchmarks based on Pb (or Pb-Bi) coolant;
- integral experiments on the problem of minor actinides;
- creation of experimental benchmarks for Th neutron data testing.
ADS models study

A general concept of ADS with two blanket regions – inner fast spectrum blanket (F-blanket) and outer thermal blanket (T-blanket) has been developed in Russia. The ADS takes advantage of the exceptional properties of liquid lead-bismuth, both as nuclear coolant and as a spallation neutron source. Liquid Pb-Bi with natural convection pumping is used as target material and coolant in F-blanket. The sub-critical inner F-blanket operates in the fast neutron spectrum region that ensures optimal destruction efficiency for the actinides. The outer T-blanket is a vessel with heavy water moderator and CANDU-type pressure tubes. Fuel pins are made of mixed commercial Pu or weapons-grade (WG) Pu + actinides and Th oxides clad in stainless steel for the F-blanket and zirconium alloy for the T-blanket. Thermal power output is 300-600 MW and 200 MW provided by $^{99}$Tc dissolved in heavy water moderator and continuously extracted from the system at a proper rate.

A system with two sections – fast and thermal parts of a blanket separated by an absorbing layer – can be simulated as follows:

a) The fast part of the blanket is a combination of Pu with a high content of $^{239}$Pu (WG), metallic or nitride, with Pb (or Pb-Bi) coolant. This multiplying sub-system can be irradiated by electron pulses from microtron (in real systems the target is irradiated by ≅1 GeV proton beam).

b) The thermal part of the blanket can be loaded by uranium and thorium. Polythene and graphite can be used as moderator for systems with intermediate and thermal spectrum. This approach was used for critical assemblies BFS-57, BFS-59 having lattices as the models of light water reactors with U and Pu fuel.

c) The thermal part of the blanket is separated from the fast part by a neutron absorbing layer made of stainless steel, carbide of boron, Eu, etc., and by an inner reflector. The neutron absorbing layer suppresses the back current from the thermal to the fast part of the blanket. The inner reflector provides moderation of neutrons to thermal energies, making the absorbing layer more effective in suppressing the backward current of neutrons.

At the first stage the following investigations seem to be justified:

a) investigation of steady state parameters as well as the kinetics of (one-directionally) coupled systems (including neutron-physical parameters of separate sub-systems studied in critical experiments);

b) investigation of neutron spectrum parameters in fast and thermal regions by the measurements of spectrum indices with fission chambers having different layers and foils;

c) the measurements of power distributions and other reaction rate distributions in both parts of the blanket;

d) investigation of the system response to the local perturbation of physical properties;

e) reactivity effects of fuel, coolant, moderator, structural and neutron absorbing materials;

f) utilisation of the facility for the investigation of burning of WG materials and long-lived radionuclides from spent fuels.

The first stage of the investigation has already been completed (metal fuel, sodium coolant).
Experimental benchmarks with Pb coolant

The experimental studies of neutron parameters on the models of lead-cooled fast reactor with plutonium nitride fuel have been carried out.

Three core configurations and radial reflector have been assembled:

a) BFS-61 – a core of 85 cm height and 90 cm diameter has been surrounded with reflector containing lead, stainless steel and depleted uranium dioxide;

b) BFS-61-1 – A core similar to that of BFS-61, in which stainless steel has been substituted with the uranium dioxide in the radial reflector;

c) BFS-61-2 – a core of 100 cm diameter; its radial blanket of 45 cm thickness consisted of depleted uranium dioxide.

The scope of the experiments involved:

- spectral indices in the centre of core measured using different types of fission chambers and activation foils;
- central reactivity worths of reactor materials samples;
- multiplication and conversion factors;
- effective fraction of delayed neutrons;
- efficiency of control rod simulators;
- Doppler effect factors for uranium and plutonium samples;
- lead voiding reactivity worth;
- hydrogen reactivity worth;
- fuel melting reactivity worth.

A calculational analysis of the experimental results has been carried out using ABBN-78 and ABBN-90 nuclear data libraries. Inelastic scattering cross-section of lead has been corrected as a result which has resulted in ~2% $K_{eff}$ shifting.

At the current time an experimental programme is being prepared for studying essentially larger cores (up to 2.5 m diameter) cooled with Pb, Pb-Bi.

Integral experiments on minor actinides problem

These experiments involve some types of measurements:

- fission cross-section ratios (to some reference element: $^{235}$U or $^{239}$Pu) for systems with different spectra;
• core reactivity perturbations by minor actinide samples (including Doppler effect for $^{237}$Np sample);

• influence on the main core parameters of $^{237}$Np incorporation in the core fuel;

• minor actinide samples irradiation in power reactors.

**Experimental benchmarks for thorium neutron data testing**

Six cores on the base of Th, $^{235}$U and different amounts of polythene have been simulated (from fast to thermal spectrum). Multiplication factors for infinite media, central reactivity worths and spectral indices have been measured.

A thorium reflector has been studied.

Irradiation of samples in the BN-350 reactor has been fulfilled.
Abstract

The problem of spent nuclear fuel from the so far operated PWRs has become a crucial issue in the Czech Republic not only for the nuclear power but also for the country’s future development at all. The first attempts to solve this problem by a final deposit of spent fuel into a suitable geological formation have been shown not to be fully acceptable not only for the public but also for the nuclear scientific and professional community. Therefore, the revival of nuclear transmutation technology application for nuclear incineration of nuclear waste and spent fuel in particular was welcomed with a high level of enthusiasm among them. The efforts of world-wide famous nuclear institutions and laboratories and major national transmutation projects such as LANL, CERN, JAERI and others were studied and have become stimulating examples for a national project of transmutation technology adoption in the national nuclear power programme.

After preliminary studies during 1994 and 1995 (including a study visit to LANL) and close contacts with other laboratories and centres, the more realistic national project started to be developed in 1996. The four major nuclear research institutions of the country (Nuclear Physics Institute of Czech Academy of Sciences, Nuclear Research Institute Řez plc, R&D Basis of the SKODA Nuclear Machinery Ltd, and Faculty of Nuclear Sciences and Engineering of the Czech Technical University) formed a consortium focused on an adoption of the world-wide experience and a development of a national project of a transmutation technology (experimental transmuter LA-0) or an efficient participation in the international effort in that field. Because the LA-0 transmuter concept of subcritical reactor with liquid fuel based on molten fluorides driven by an external neutron source has been adopted, the R&D effort has been focused on those three regions. The first is devoted to the problem of a suitable neutron source, the second to a pre-conceptual design of a blanket being convenient for burning of actinides contained in spent fuel from PWRs and simultaneously for nuclear incineration of long-lived fission products as well as other radionuclides from radioactive waste produced during the operation of NPP with PWRs. The third region is devoted to the utilisation of the experience from a specific field of dry (fluorine) reprocessing of spent fuel and a preparation of liquid fuel in the form of molten fluorides for the transmuter LA-0.
Neutron production in relativistic proton and ion induced reactions

Introduction

In the originally proposed system, the high parameter accelerator bombards a suitable target with high energy protons to produce a very intense neutron source by the spallation reactions. The neutrons can consequently be multiplied in a subcritical reactor which surrounds the spallation target and in which long-lived nuclear waste could be transmuted into stable or short-lived isotopes. Therefore good knowledge of the spallation process is essential for designing and optimising the target-blanket assembly. Since all possible configurations cannot be experimentally tested, reliable codes accounting for the various aspects of the spallation have to be used.

Although the spallation mechanism has been known for many years, the actual understanding of the process is not sufficient when one has to face the design of realistic target-blanket systems. Recent comparisons [1,2] of simulation codes have shown that many improvements are still needed and that there is a lack of experimental data to perform a good validation. Measurements of elementary exclusive production cross-sections through the whole energy range from 100 MeV up to 10 GeV are necessary to improve basic nuclear models used in simulation codes [3,4]. The wide energy range is needed to satisfactorily describe the interaction of secondaries produced during primary interaction of protons with the nucleus with other target nuclei. In particular, it is very important to obtain detailed sets of data about the energy spectra and angular distributions of the produced particles (neutrons, protons, light nuclei, meson, etc.), which are necessary for the optimisation of the target geometry. They are also essential for estimating radiation damage in target and structural material [5].

Qualification

The main problem with the concept of nuclear power adopted up to now is the accumulation of relativistic heavy ion (RHI). A group addressing this question was founded by the Nuclear Physics Institute in 1990. The RHI group became a part of the international collaboration (GANIL, Giessen, GSI, KVI, NPI, Valencia) concentrated around the Two Arm Photon Spectrometer (TAPS) project, a European nomad detector. We have participated in the TAPS experimental programme, i.e. in studies of bremsstrahlung photons, pion and eta mesons production in the reactions induced by heavy ions with $E \sim 1-2$ AGeV at GSI Darmstadt (1991,1994-5). We also studied energy spectra of neutrons [22], in 1 AGeV Bi + Pb collisions. Results of the study of neutron and charged particle detection in a BaF$_2$ scintillator were recently published [18]. Neutron emission from reaction induced by 200 MeV proton beam with various thin targets was studied recently by us in TAPS experiments performed at KVI Groningen in 1996-1997.

We studied neutron transport through tungsten target using neutron source at NPI Řž. This work tested the possibility of using neutron source based on the isochronous cyclotron and d + Be reaction for transmutation studies [24]. Monte Carlo programmes for the LAHET and the other INC model calculations are currently carried out at NPI Řž.

Experiments at KVI

The data concerning neutron yields in a 196 MeV proton induced reaction at thin Ni and W targets are displayed in Figure 1. The results of corresponding model calculations (LAHET code) are shown by open symbols. The agreement between gross features of data and results of the LAHET
code is satisfactory. A detailed comparison of absolute values and energy spectra remains to be done. The experimental values were extracted from experiments performed at KVI in 1997 using the TAPS spectrometer. The TAPS spectrometer was built-up and it is used by international collaboration mentioned above. It consists of six square blocks of 64 mm, length 250 mm) in front of which is placed thin plastic veto detector. Details can be found in Refs. [14,15]. The geometrical configuration of the blocks depends on the experimental necessity. The main physical task of TAPS measurements is hard photon and neutral meson studies. However, the BaF$_2$ scintillator is also an efficient detector for neutrons in the range of energy from MeV up to GeV, see Refs. [16-18]. The examples of neutron efficiency of TAPS spectrometer are shown in Figure 2. [18,19].

**Studies carried out at NPI**

Transport of fast neutrons through a tungsten target was studied using neutron source at NPI Říž. This work tested the possibility of using a neutron source based on the isochronous cyclotron and $d+Be$ reaction for transmutation studies [24]. The mean energy of neutrons is about 6 MeV, and the neutron dose was $6.10^{13}/cm^2$ in front of the target. The target was a cylindrical form of 1 cm radius and a total length of 8 cm. It was divided into 14 small cylinders (see Table 1).

**Table 1. Composition of tungsten target**

<table>
<thead>
<tr>
<th>Piece</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width (mm)</td>
<td>1.75</td>
<td>2.10</td>
<td>2.30</td>
<td>2.10</td>
<td>2.05</td>
<td>2.00</td>
<td>2.00</td>
<td>2.05</td>
<td>2.20</td>
<td>2.10</td>
<td>2.15</td>
<td>19.8</td>
<td>35.3</td>
<td></td>
</tr>
<tr>
<td>Weight (g)</td>
<td>10.9</td>
<td>12.9</td>
<td>14.1</td>
<td>12.9</td>
<td>13.0</td>
<td>12.5</td>
<td>12.3</td>
<td>12.2</td>
<td>12.4</td>
<td>13.1</td>
<td>12.9</td>
<td>13.1</td>
<td>119</td>
<td>211</td>
</tr>
</tbody>
</table>

Between its part were placed thin foils of aluminium, molybdenum and gold. The intensity of the neutron field was deduced using activation induced in foils. The reaction with different thresholds in neutron energy were used (see Table 2).

**Table 2. Radioactive isotopes produced in foils and corresponding absorption coefficients of neutrons in tungsten derived from data**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Lifetime [hours]</th>
<th>Energy gamma [keV]</th>
<th>Absorption coefficient $\mu$ [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}$Al(n,$\alpha$)$^{24}$Na</td>
<td>14.959</td>
<td>1368.633</td>
<td>0.190(4)</td>
</tr>
<tr>
<td>$^{27}$Al(n,p)$^{27}$Mg</td>
<td>0.157633</td>
<td>843.75, 1014.4</td>
<td>0.210(9)</td>
</tr>
<tr>
<td>$^{197}$Au(n,$\gamma$)$^{198}$Au</td>
<td>64.68408</td>
<td>411.8, 675.88</td>
<td>–</td>
</tr>
<tr>
<td>$^{197}$Au(n,2n)$^{196}$Au</td>
<td>148.392</td>
<td>333.0, 355.72, 426.0</td>
<td>0.190(5)</td>
</tr>
<tr>
<td>$^{197}$Au(n,2n)$^{196m}$Au</td>
<td>9.7</td>
<td>147.73, 168.33, 188.23, 285.45</td>
<td>0.21(1)</td>
</tr>
<tr>
<td>$^{97}$Mo(n,p)$^{97}$Nb</td>
<td>1.20166</td>
<td>657.72</td>
<td>–</td>
</tr>
<tr>
<td>$^{98}$Mo(n,p)$^{98}$Nb</td>
<td>23.35</td>
<td>777.65</td>
<td>–</td>
</tr>
</tbody>
</table>

The simulations were carried out using MCNP code. The number of fast neutrons decreases along the target due to their absorption in accordance with simulations. Straightforward simulation of slow neutron absorption however fails to describe the data. Only a careful description of actual experimental geometry taking into account various shields located nearby and the shape of the neutron collimator placed in front of the neutron source allowed to describe the data.
Outlook

We propose to further study neutron production in proton induced reactions and also in high energy collisions of heavier nuclei using experimental data obtained recently by the Two Arm Photon Spectrometer (TAPS). The energy spectra for different angles and angular distribution of produced neutrons will be extracted. The results will be compared with predictions of different models used to describe spallation reaction or heavy ion collisions.

The huge number of neutrons was detected during different experiments performed at GSI Darmstadt (Germany), KVI Groningen (The Netherlands) and GANIL Caen (France). The main part of these experiments was devoted to studies of relativistic heavy nuclei collisions. However during the latest experiments at KVI Groningen the proton induced reactions were also studied and some experiments were devoted especially to studies of the neutron production at spallation reactions [19] (see Table 3).

<table>
<thead>
<tr>
<th>Beam</th>
<th>Target</th>
<th>Energy [MeV/u]</th>
<th>Polar angles [deg.]</th>
<th>Institute</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>Au</td>
<td>190</td>
<td>60-180</td>
<td>KVI Groningen</td>
</tr>
<tr>
<td>p</td>
<td>W</td>
<td>190</td>
<td>60-180</td>
<td>KVI Groningen</td>
</tr>
<tr>
<td>p</td>
<td>Ni</td>
<td>190</td>
<td>60-180</td>
<td>KVI Groningen</td>
</tr>
<tr>
<td>p</td>
<td>Ca</td>
<td>190</td>
<td>60-180</td>
<td>KVI Groningen</td>
</tr>
<tr>
<td>p</td>
<td>C</td>
<td>190</td>
<td>60-180</td>
<td>KVI Groningen</td>
</tr>
<tr>
<td>Au</td>
<td>Au</td>
<td>800, 1000</td>
<td>45-59</td>
<td>GSI Darmstadt</td>
</tr>
<tr>
<td>Bi</td>
<td>Pb</td>
<td>1000</td>
<td>23,40,60,90</td>
<td>GSI Darmstadt</td>
</tr>
<tr>
<td>Ni</td>
<td>Ni</td>
<td>2000</td>
<td>33-47</td>
<td>GSI Darmstadt</td>
</tr>
<tr>
<td>Ca</td>
<td>Ca</td>
<td>180, 1000, 2000</td>
<td>33-47</td>
<td>GSI Darmstadt</td>
</tr>
<tr>
<td>C</td>
<td>C</td>
<td>2000</td>
<td>33-47</td>
<td>GSI Darmstadt</td>
</tr>
</tbody>
</table>

We propose

• to extract energy spectra of neutrons and their azimuthal distribution from the data obtained during TAPS experiments;

• to make simulation of obtained results using different models;

• to compare model simulation and experimental data.

The proposed study is partly a continuation of our previous investigations supported by the Granting Agency of Academy of Science in the 1991-1993 period under contract No 14808 and by the Granting Agency of Czech Republic in the 1993-1995 period under contract No 202/93/1144 and studies “Transmutation-research of neutron source” made for the Ministry of Industry and Trade during 1996 and 1997.
Neutron sources for transmuters based on low parameter accelerators

In various concepts of the accelerator driven transmutation technologies (ADTT) the distinct effort is devoted to an employment of external neutron source other than spallation reactions initiated on (mostly future proposed) high-energy proton linacs (>1 GeV, 100 mA, 10^{19} n/s). The obvious reason is that the lengths (1 km) and expected cost (above 1 B US) of these facilities, which are an inherent and insuperable weak point of high-energy proton linacs [25], could make unreliable the wide application of the ADTT. In the “subcritical enhanced safety molten/salt reactor concept”, the effective way of reducing the external neutron source power (below 3.5 \times 10^{16} n/s) is accomplished by the cascade neutron multiplication in the system of coupled reactors with suppressed feedback between them. For such a “burner” reactor scheme the possibility of replacing proton linac with 100 MeV electron linac (of substantially lower length and cost than proton linac) has been argued [25]. In a similar scheme, an employment of the isochronous AVF cyclotron-based neutron source was also considered [26].

Although external beams in the mA range (10^{14} n/s) have already been demonstrated for conventional AVF cyclotrons, the cryogenic technology for compact cyclotrons and also a wide class of commercially available, low-cost (below 3 M US) cyclotrons of a type CYCLONE seem to be well methodical and technical basis for further beam-intensity improvements. Nevertheless, for a significant increase of beam intensity and neutron source strength the drift tube of Alvarez linear accelerators with the RFQ (radio-frequency quadruple) injector are more promising. The most developed proposal for 3 \times 10^{16} n/s source strength projected originally for fusion material irradiation tests (FMIT) is based on 35 MeV, 100 mA deuteron linac [27]. A fast flowing lithium jet is considered to be the best target material [28] for megawatt powers of proton and deuteron beams with medium energy. The medium energy (E < 100 MeV) proton and deuteron induced reactions on thick Li target produce a forward-directed fast-neutron fields (the fluency-averaged energy E_n of about 15 MeV is to be compared with E_n \approx 3 MeV which corresponds to the spectral yield from a spallation reaction). Therefore, it seems appropriate to perform any computational and experimental study of target-blanket systems employing primary neutron sources, which in general have energy spectra with suppressed contribution of low energy neutrons.

In the NPI Řž, the d(18 MeV) + Be neutron generator, originally developed for military directed research, is now being upgraded with the main task being to take advantage of H^- and D^- negative ions recently implemented on the NPI isochronous cyclotron U-120M. Conversion of the cyclotron into H^-, D^- machine enabled to utilise a high efficient extraction by means of the stripping, which resulted in substantially increased extracted beam currents of positive p^+ and d^+ ions. Nowadays, up to 20 \mu A currents of the 15-30 MeV protons are routinely extracted from various types of targets for radionuclides production. The purpose of employing these beams for fast neutron production is to perform a broad range of experiments closely related to the activation analysis and ADTT programme as well.

For ADTT empirical research in NPI, an experimental study of the spectral and yield characteristics of various neutron produced reactions between light nuclei is now under way, the main tasks of which are as follows: a) to verify yield calculations from cross-section data; b) to determine an empirical shape of spectral yield of neutrons from deuteron break-up processes so as it can not be predicted reliably from simple phase-space calculations; and c) to determine the contribution of the target-v station arrangement to the background part of produced neutron fields. Knowledge of these characteristics is needed to evaluate the target and beam options for the best simulation of ADTT.
external neutron source mentioned above. The results of the first experiments are illustrated in Figures 3 and 4. The net spectral yields of neutrons from p + D and d + D reactions are shown there. They were determined from measured data for thick deuterium target irradiated by 15.8 MeV protons and 14 MeV deuterons respectively. Measurements were performed using an open geometry and shadow-bar method. Neutron spectra were measured with stilben spectrometer, equipped with the two-dimensional \( (n,\gamma) \) discrimination technique. The integrated yield for both reactions was found to be in a good agreement with calculations based on an updated cross-section database (EXFOR). The preliminary calculations show that for the present neutron facility the neutron source strength up to \( 6 \times 10^{12} \) n/s.sr and fluency-averaged neutron energy \( E_n = 15 \) MeV could be achieved from a thick deuterium target irradiated by 30 MeV protons.

**Conclusions**

The last few years have been devoted to an idea of nuclear waste (accumulated during the previous era of nuclear power as well as military applications of nuclear energy) incineration in a subcritical reactor driven by an external neutron source. Up to now, the majority of published projects trying to solve this problem supposed that a high power accelerator inducing extremely strong neutron source by spallation reactions would be used for that purpose. Even this workshop was proposed to summarise the latest status in utilisation and reliability of high power proton accelerators. We may conclude by summarising the experience from our national project of a transmuter being developed for PWRs spent fuel incineration that, the longer the problem has been studied, the more we are focusing our attention towards a low power subcritical transmuter which might be kept in a steady state by a set of low level external neutron sources initiated by small accelerators with the energy of particles up to 50 MeV and utilising some of the convenient reactions giving an optimal yield. The optimisation criterion will be the compromise between the level of yield and losses which will occur during the necessary moderation of source neutrons depending on their spectra and energy dependence of the individual waste radionuclides cross-sections.

**REFERENCES**


Figure 1. The neutron production on the W and Ni targets. The angular distributions for the low and high energy component are shown at left and right side, respectively. The preliminary experimental data (closed symbols) are approximated by LAHET based calculation (open symbols) [19]

Figure 2. The neutron efficiencies of the TAPS detectors for electron-equivalent amplitude threshold $L_{\text{thr}} = 4 \text{ MeV}_{\text{ee}}$ (full line) and $10 \text{ MeV}_{\text{ee}}$ (dashed line)
Figure 3. The energy spectrum of neutrons from \( p (14.5 \text{ MeV}) + D (14.5 - 9.5 \text{ MeV thick target}) \) reaction. The data of \( p (14.8 \text{ MeV}) + \text{Be (thick target)} \) are taken from the work of Lone, \textit{et al.} [\textit{Nucl. Instr., and Meth.}, 143 (1977), 331].

Figure 4. The energy spectrum of neutrons from \( d (11.4 \text{ MeV}) + D \) (thick target) reaction. The data of \( d (11.5 \text{ MeV}) + \text{Be (thick target)} \) are taken from the work of Brede, \textit{et al.} [\textit{Nucl. Instr. and Meth.}, A274 (1989), 332].
ADS IN THE FRAME OF WASTE MANAGEMENT ACTIVITIES IN FRANCE

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Abstract

The potential role of ADS for waste management is the major motivation in France to perform theoretical and experimental studies in that field, and even to envisage the possibility to build a demonstrator in the near future (2010-2012), possibly in the frame of a European initiative.

The CEA, CNRS, EDF and FRAMATOME are presently co-operating within a research network called GEDEON.

As an illustration of the issues under discussion a few examples will be given, related to physics characteristics of the subcritical core which can have impact on the required accelerator performances, and on the safety assessment of the overall system.
Introduction

The development of nuclear energy as a sustainable option in the next century is related to the establishment of a sound strategy both in terms of optimal resource utilisation and in terms of reliable waste management. In fact, economy and public acceptance will play a major role and far-reaching decisions in these fields are expected in the next decades.

No unique strategy has emerged up to now. On the contrary, some of the basic arguments developed in the seventies (such as the early need of breeder fast reactors) have been questioned.

Moreover, the management of plutonium has become a very controversial issue, even in the case of irradiated fuel reprocessing.

Finally, partitioning and transmutation techniques are actively studied in the frame of waste management strategies, mostly to provide a complementary option to geological storage.

Partitioning and transmutation techniques are applied both to minor actinides (americium, curium, neptunium, etc.) and to long-lived fission products (iodine-129, caesium-135, technetium-99, etc.).

In fact, the criteria to judge the effectiveness of the partitioning/transmutation techniques and their impact on the performance of a deep geological storage are themselves the subject of controversy, since both the potential radiotoxicity source and the residual risk associated with the return of radioactive materials to the biosphere are quoted. In the first case (potential radiotoxicity), the actinides are the major contributors, whereas in the second case (residual risk), some long-lived fission product isotopes are the major contributors.

The combined management of plutonium, minor actinides and long-lived fission products represents a formidable task for any system. Besides fission reactors, the task of their management can in principle be accomplished by other systems providing neutrons in large quantities, like accelerator driven systems (ADS).

Accelerator driven systems as a technical option for the transmutation of MA and LLFP

It is well established that a relevant surplus of neutrons should be available to allow the effective transmutation of MA and LLFP, separately or jointly.

The surplus of neutrons can be obtained in different ways:

- **By the use of fast critical reactors, used in a “burner” mode, with the hardest possible spectrum.** The eventual high flux of fast neutrons leaking out of the core can be used to transmute fission products by different techniques: the “leakage with slowing down (LSD)” concept or the “Adiabatic Resonance Crossing” proposed by C. Rubbia. However, in some specific cases, a critical core heavily loaded with minor actinides (up to 100%) can present unfavourable safety features (i.e. very low delayed neutron fraction \( \beta_{\text{eff}} \), positive coolant void reactivity effect and low Doppler effect).

- **By the use of extra enrichment (e.g. in \(^{235}\text{U}\)) in thermal (e.g. PWR) reactors.** This technique has evidently an economic burden and some potential consequences on reactivity coefficients and fuel cycle (e.g. high production of Cm).
• By the use of externally-supplied neutrons. This is the case of an accelerator driven system. The subcriticality of the core can also help in the cases when the safety features of the corresponding critical core are not satisfactory (low $\beta_{eff}$, positive void reactivity effects, etc.).

• By avoiding the use of neutrons for non-relevant purposes. This is an indirect way of providing neutrons; isotopic separation in the case of LLFP can be seen as such a technical option.

Role for ADS in nuclear power scenarios

Pu burning and MA transmutation

For this scenario, in general, the neutron availability due to the presence of fast reactors in the nuclear power park, or due to the use of enriched $^{235}$U as support of MOX fuel, allows to propose two options based only on critical fission reactors.

In fact, in this case (Pu burning and MA transmutation) the use of accelerator driven systems is not strictly justified on the basis of neutron availability or safety related considerations, but rather to envisage a “double strata” type of strategy, namely to transmute MA in a separate stratum of the fuel cycle. Previous studies [1] indicate that such an option gives rise to the following nuclear power park structure:

- PWR (UOX) + PWR (MOX): 76%  
  CAPRA Fast Reactor (MOX): 18%  
  ADS (MA): 6%

In this case, an extra availability of neutrons can allow the transmutation of selected LLFP.

Pu burning, MA and $^{99}$Tc, $^{129}$I, $^{135}$Cs transmutation

In this type of scenario, isotopic separation is deployed to reduce the neutron requirement for LLFP transmutation.

The use of ADS will give rise to the following structure of the power reactor park:

- PWR (UOX) + PWR (MOX): 76%  
  CAPRA (MOX): 18%  
  ADS (MA + LLFP): 6%

The neutron availability provided by a rather subcritical ADS ($K_{eff} \sim 0.95$), will be sufficient to transmute the three major isotopes among LLFP. The burden in terms of energy spent to feed the accelerators stays moderate (fraction of energy produced is approximately equal to 15% for each ADS). As for the previous case, this option has the advantage of keeping separate the functions of “energy producer” reactors (stratum 1) and “MA and LLFP transmuters” (stratum 2).

In turn, such “MA and LLFP” transmuters can hardly be envisaged as critical reactors (for safety and inventory reasons).

Pu burning, MA and LLFP transmutation without isotopic separation

In this type of scenario, any technical option based only on evolutionary critical fission reactors become very complex or not realistic.
In that case, the use of ADS can provide an option for the nuclear power park structure, namely:

- PWR (UOX) + PWR (MOX): 70%  CAPRA (MOX): 20%
- ADS (MA + LLFP): 10%

A simpler option can be the following one (under the condition that the reactivity evolution with time would not require strong variations of the proton beam current):

- PWR (UOX): 78%  ADS (Pu, MA, LLFP): 22%

**ADS programmes in France**

Having recognised the potential role of ADS for waste management, activities in the field of ADS have been underway in France for several years. In the present paper we will focus on the national research network GEDEON.

Proposed by the EDF in 1995, GEDEON is a meeting point for CEA and CNRS researchers in the area of ADS and thorium studies. Recently it has been extended to FRAMATOME. It works as a network for basic research with no strong financial commitments, but with about 100 scientists involved. Research programmes are discussed and, for some, carried out in common. Examples are:

- SATURNE programmes (ended in 1997) for spallation physics investigations;
- subcritical experiments at MASURCA at CEA Cadarache for neutronics studies.

The main motivation of GEDEON comes from the respective missions or roles of the different organisms. In fact, CEA is in charge of R&D in nuclear waste incineration, up to now carried out mostly in the frame of critical reactors. CNRS is traditionally not involved in such studies, but shares with CEA an expertise in nuclear and accelerator physics. The EDF has a medium term policy with respect to spent fuels management and has an open scientific watching activity as far as new options for the back-end of the fuel cycle. Finally FRAMATOME proposes to use its know-how in the framework of new reactor development (e.g. HTR), or in case a hybrid demonstrator would be decided upon.

The following areas are explored in the frame of GEDEON:

- Spallation target physics:
  - neutron production from heavy targets;
  - residues measurement (heat, radiotoxicity, corrosion);
  - theoretical efforts to qualify intra- and inter-nuclear cascade codes.

- Nuclear data acquisition:
  - cross-sections, differential or integral, in the field of minor actinides, long-lived fission products, etc.;
  - extending neutron libraries from 20 to 200 MeV, in particular for target materials.
• New material studies:
  − window: radiation damage in n and p fields, in order to provide recommendations for materials to be used (e.g. martensitic steels);
  − Pb, Pb/Bi: corrosion, embrittlement, irradiation effects.

A wide common CEA/CNRS programme is being established at present.

• Subcritical neutronics studies with the MASCURA reactor at Cadarache. This is a major programme, which allows to validate data and methods used for subcritical core assessment.

• Scenarios studies and system studies (demo experiment, targets design, etc.).

• IPHI project between the CEA and the CNRS to develop a 10 MeV, 100 mA accelerator module, which will be described at this workshop.

Finally, it should be emphasised that several international collaborations are underway, both with European and non-European countries.

As far as a possible demonstrator experiment, the CEA and the CNRS represent France in a trilateral (Italy, Spain, France) initiative to define a common project, to be proposed later to the wider European Community.

Issues related to subcriticality and accelerator performances

As an example of typical fundamental issues under investigation, we will focus on some safety aspects of ADS. They are of major relevance, since ADS should in principle provide a favourable case with respect to critical reactors, at least in terms of prevention of reactivity accidents.

However, there are characteristics of the subcritical core which can have an impact on the requirements for accelerator performances, and, consequently on new safety features of ADS.

We have chosen a few cases, without any pretension of establishing an exhaustive list.

Nuclear data uncertainties

It has been often pointed out that nuclear data uncertainties can have an impact on proton current requirements, with potential safety implications.

In fact, in the safety approach, uncertainties have to be associated to nominal values of reactivity, to define control needs at beginning and end of cycle (e.g. control rod worth in critical reactors or proton beam current intensity in a subcritical ADS).

Uncertainties can indeed play a relevant role. In fact in a fast spectrum ADS dedicated to burn MA (Np, Am, Cm), with the following fuel:
Sixty-two per cent of fissions come from Pu and 38% from MA. However, uncertainties on the MA fission contribution to the neutron balance can be very significant. In fact, in that system, ±20% uncertainty on the fission cross-section $\sigma_f$ of each MA isotope has the following effect on the beginning-of-cycle $k_{eff}$:

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$\Delta k/k$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{241}$Am</td>
<td>~ 1.2</td>
</tr>
<tr>
<td>$^{237}$Am</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{244}$Cm</td>
<td>0.6</td>
</tr>
<tr>
<td>$^{238}$Cm</td>
<td>0.4</td>
</tr>
<tr>
<td>$^{239}$Np</td>
<td>1.2</td>
</tr>
</tbody>
</table>

End-of-cycle effects can be larger, since MA contribution to fissions can be larger.

This can imply a ±50% uncertainty on the accelerator current needed intensity, even without having taken into account the effects due to the Pu isotope cross-section uncertainties.

**The subcritical reactivity control and the possible role of pulsed experiments**

Reactivity control in a subcritical core cannot be achieved with standard methods (i.e. derived from critical reactors). In order to explore the potential of alternative experimental methods, an experiment has recently been performed at the MASURCA reactor at Cadarache in the frame of the MUSE-3 experimental programme.

In a subcritical configuration, driven by an external 14 MeV neutron source, the pulsed mode of operation can allow the determination of the subcriticality. In fact, the relation between the exponential behaviour of the counting rate in time and the reactivity offers a potential and clean method to evaluate the reactivity, in particular if a good “quality” of the neutron pulse is obtained. This will be the case in particular in the MUSE-4 configuration in 1999, when a deuteron accelerator realised by CNRS (ISN-Grenoble) will be installed at the CEA MASURCA facility. Pulses of ~ 1 µs will be used to produce neutrons both with (D,T) and (D,D) reactions.

**Delayed neutrons in a subcritical ADS and the “coupled ADS” concept**

As far as the source of energy supply to the accelerator, two conceptual schemes can be envisaged, as shown in Figure 1.

The “coupled” and “independent” ADS concepts can be compared to the critical reactor case, to find out relevant differences of behaviour in the case of prompt or slow transients.

In a very general sense, a comparative table can be established, as shown in Table 1.
Figure 1

Table 1

<table>
<thead>
<tr>
<th>Critical reactors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of delayed neutrons</td>
</tr>
<tr>
<td>Prompt power jump $W/W_0$ (insertion of $\Delta \rho_{\text{TOP}}$)</td>
</tr>
<tr>
<td>Transient slow rates</td>
</tr>
<tr>
<td>Asymptotic power after LOHS-WS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ADS – Independent feed of the accelerator (ADS-I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of all “delayed” neutrons</td>
</tr>
<tr>
<td>Prompt power jump $W/W_0$</td>
</tr>
<tr>
<td>Transient slow rates</td>
</tr>
<tr>
<td>Asymptotic power after LOHS-WS</td>
</tr>
</tbody>
</table>


$\lambda; \ell; \omega$: Decay constant for delayed neutrons; neutron lifetime; inverse of reactor period.
Table 1 (cont.)

<table>
<thead>
<tr>
<th>ADS – Coupled feed of the accelerator (ADS-C)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fraction of all “delayed” neutrons</td>
<td>$\beta_{\text{eff}} + \rho_0$</td>
</tr>
<tr>
<td>Prompt power jump</td>
<td>$\frac{W}{W_0} = 1 + \frac{\Delta P_{\text{TOP}}}{\beta_{\text{eff}} - \rho_0}$</td>
</tr>
<tr>
<td>Transient slow rates</td>
<td>$\omega = \frac{\Delta P_{\text{TOP}}}{\ell_{SD} + \ell + \frac{\beta_{\text{eff}}}{\lambda}}$ (as low as required)</td>
</tr>
<tr>
<td>Asymptotic power after LOHS-WS</td>
<td>$\Rightarrow 0$ (because of the source/power coupling)</td>
</tr>
</tbody>
</table>

\(\lambda, \ell\): Decay constant for delayed neutrons; neutron lifetime; inverse of reactor period.

The main point of this table is to stress the favourable behaviour of an ADS in case of a prompt jump, but also of the potential interest of the “coupled” ADS concept for slow transients. Of course, one should investigate in practice how this concept could be implemented.

**Space effects and power shape tiltiness in an ADS**

The neutronic decoupling due to the presence of a large inert zone at the centre of the subcritical reactor (i.e. the spallation target zone), can induce significantly larger spatial effects with respect to the corresponding “homogeneous” core.

This phenomenon was observed in large fast neutron cores with a fertile region at the core centre. Theoretical studies allow to relate the spatial power shape tiltiness due to a perturbation, to the system eigenvalue separation (see Figure 2). This phenomenon has been confirmed experimentally, and measurements have been performed at ANL and in Japan of the separation of the first two eigenvalues.

New experiments of this type are foreseen in the MASURCA reactor in the frame of the MUSE programme, in particular in configurations large enough to stress the potential spatial effects of a subcritical core, in presence of a central region simulating the spallation target and associated buffer zone, of variable geometry and composition.

**Conclusions**

A role for ADS systems can be found when looking for innovative options for the back-end of the fuel cycle and waste management.

In France, the GEDEON initiative has been a meeting point for scientists of different organisms, in particular to launch common programmes.

From a scientific point of view, ADS is an innovative option which requires a physical understanding of the coupling of its main components.
It is important to realise that the physics of the subcritical system has to be carefully reviewed, in order to make a convincing safety case.

A few examples have been given in the present paper to show that some physics features can have an impact on the performances required of the accelerator, and that experiments on subcritical cores (like the ones of the MUSE programme at MASURCA), can help to improve the knowledge and allow to make more justified requirements to the accelerator developers.

**Figure 2. Distortion of power distribution due to an “asymmetrical” reactivity insertion, as a function of the eigenvalue separation, SVP**

\[ P_R = \text{average power level in the “right” part of the core} \]

\[ P_L = \text{average power level in the “left” part of the core} \]

\[ SVP = \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \]

- Introduction of -200 pcm of reactivity in the external core
- Introduction of -200 pcm of reactivity in the internal core
- Introduction of \( \rho \) in the outer core
- Introduction of \( \rho \) in the inner core
REFERENCES

RESEARCH AND INDUSTRIAL PROGRAMMES ON ADS IN ITALY

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Abstract
A growing interest in accelerator driven systems led to the establishment, in Italy, of a basic R&D programme, TRASCO, aiming at the study of physics and development of technologies needed to design an ADS for nuclear waste transmutation, and an industrial programme, whose short term goal is to issue a reference configuration description of a low power prototype of such an ADS. The objectives and the status of both TRASCO and the industrial programme are briefly described.

* On behalf of Ansaldo-ENEA-INFN Collaboration.
Introduction

Starting from 1996, a growing interest in the concept of accelerator driven systems has taken place in Italy and has given origin to several studies, a basic R&D programme (TRASCO) and an industrial programme, in which are involved major Italian research institutions and industries. This interest, also shown at governmental level, is confirmed by the 17 billion lire assigned to the two-year programme TRASCO, about half of which have been given by the Ministry of University, Scientific and Technological Research (MURST).

TRASCO started in 1998 under the leadership of the INFN (National Institute for Nuclear Physics) for the accelerator and of the ENEA (National Agency for New Technologies, Energy and Environment) for the sub-critical system. This programme is considered of particular relevance for the creation of a well mixed group of competencies and it will provide results of relevant importance in support of any related industrial programme.

In parallel to the basic activities above, Ansaldo, a major Italian firm, proposed and started the aforementioned industrial programme, with the collaboration of CRS4, the ENEA and the INFN. This programme foresees two main steps:

1. On-going short term activities in the Italian context to issue a reference configuration description of the ADS demonstration prototype; this reference configuration will be submitted to the European partners as a contribution to the upcoming discussion to converge upon the prototype objectives and upon a configuration on which the detailed engineering design will be based; the main supporting R&D needs will also be assessed.

2. Medium term activities in a European context with the aim to perform the detailed engineering design, the realisation phase and the commissioning of the demonstration prototype along with all the supporting parallel R&D deemed necessary.

In the present paper the objectives and status of the TRASCO programme are first described. Then, the attention will be focused on the ongoing short term activities of the industrial programme, which aim at the preparation of the proposed reference configuration, leaving the deal to define the details of the subsequent medium term activities to the expected common programme in the European context.

The TRASCO programme

The programme aims to study the physics and to develop the technologies needed to design an accelerator driven system (ADS) for nuclear waste transmutation and was prepared with close reference to Carlo Rubbia’s energy amplifier (EA) proposal [1].

It consists of two main parts, regarding, respectively, the accelerator and the sub-critical system. Although the ENEA and the INFN are jointly responsible for the whole programme, the INFN essentially manages the first part and the ENEA the second part.

The project concerns all the main subsystems of an ADS (accelerator, window/target, sub-critical reactor). However, due to the limited available financial resources, efforts are concentrated on some significant and qualified activities, in view of the goal of participation in an international project for the construction of an ADS prototype, like the energy amplifier for waste transmutation.
The main objectives of the research programme can be summarised as follows:

- conceptual design of a 1 GeV, 30 mA proton linac;
- design and construction of the proton source and of the first section of the RFQ, as well as of some prototypical cavities concerning the superconductive linac;
- development of methods and criteria for neutronics, thermal-hydraulics and plant design for an EA-like sub-critical system, as well as some specific aspects related to the safety analysis of this type of nuclear installation;
- materials technologies and development of components to be used in a plant in which lead or lead-bismuth acts both as a primary target and as a coolant;
- experiments to validate and verify proposed technologies for materials compatibility with lead and lead-bismuth alloys.

The foreseen activities will last two years. Besides the ENEA and the INFN, some qualified Italian firms and other Italian public research institutions are also participating in the project (specifically, universities and the National Institute for Physics of Matter – INFM).

The following nine research sub-programmes have been foreseen; each of them is being carried out by a corresponding research group, involving the research institutes and firms listed in brackets:

- proton source (INFN, SISTEC, HITEC);
- low and medium energy accelerator section (INFN, CINEL);
- high energy accelerator section (INFN, CISE, SAES-Getters, ZANON);
- neutron production for material characterisation (INFN, INFM);
- general safety criteria and classification (ENEA, ANSALDO);
- neutronics and transmutation efficiency (ENEA, CIRTEN, CRS4, University of Bologna);
- thermal-hydraulic analysis (ENEA, CIRTEN, CRS4, ANSALDO);
- beam window technology (ENEA, CIRTEN, ANSALDO, INFM);
- materials technology and compatibility with lead and/or lead-bismuth alloy (ENEA, CIRTEN, CRS4, FN, ANSALDO).

A short description of each sub-programme is given below.

**Proton source**

Prototypical proton sources of several tens of mA already exist (e.g. at Chalk River National Laboratory, at LANL and at CEA Saclay), but R&D is still necessary for ensuring the availability and reliability required by an ADS.
The objectives of this sub-programme are the feasibility study, design, construction (to be completed in the frame of other INFN programmes) and test of a 2.45 GHz microwaves source which can produce a 50 mA, 75 keV proton beam. Taking into account the state-of-the-art of such devices, R&D is required for achieving the required current and voltage stability, as well as a satisfactory controlled low emittance.

The conceptual design addresses all the parts of the source and includes the matching of it with RFQ, which constitutes the first part of the linac.

Before the source construction, some theoretical and experimental benchmarking of the calculations versus the performances of existing high intensity proton sources will be carried out.

Final design, construction and testing of a prototypical proton source will follow the preliminary activities mentioned above. Finally, an extended optimisation of the main components of the source is foreseen for achieving the best compromise between different parameters (impedance, energy resolution, proton fraction, electronic density, emittance, etc.).

**Low and medium energy accelerator section**

The final goal of this research sub-programme is the complete conceptual design of a 100 MeV, 30 mA proton linac, to be used as an injector for the CW superconductive linac at 352 MHz, described in the next section, and the design and construction of prototypes of some critical components.

Three different options are being analysed and compared:

- normal conductive, continuos wave RFQ (up to 5 MeV) and DTL at 352 MHz;
- normal-conductive RFQ followed by two-gap, $\lambda/4$ or $\lambda/2$, superconductive cavities at 176 MHz or 352 MHz;
- normal conductive RFQ followed by superconductive cavities at 352 MHz.

This sub-programme includes the construction of a full-scale aluminium mock-up of the RFQ for RF tests at low power and, after the engineering validation phase, the construction of a full-scale section of the RFQ, in which low and high power tests will be performed.

As far as the development of a superconductive cavity for the medium energy section is concerned, two prototypes are foreseen:

- a steel cavity at room temperature for developing constructive technologies (such as sputtering, or welding of pre-shaped niobium plates) as well as for performing electrodynamics studies;
- a niobium cavity, for low and high power tests.

**High energy accelerator section**

The high energy section accelerates the proton beam from 100 MeV to 1 GeV, thus representing the biggest and most expensive component of the accelerator.
Its design is based on superconductive LEP-like accelerating structures at 352 MHz. Three different families of $\beta$-graded multi-cell cavities are foreseen, corresponding to matched $\beta$ of about 0.5, 0.65 and 0.85 respectively.

The present research sub-programme concerns the conceptual design and the beam dynamic analysis of the whole superconductive linac, as well as the development and construction of prototypical superconductive cavities.

The first part of the sub-programme, while defining the general layout of the accelerator, will be particularly focused on the detailed study of the:

- electromagnetic design of the accelerating structures;
- thermal and mechanical performances of the same structures;
- halo problems, with the goal of minimising the particle losses.

The design, construction and test of typical SC cavities, as well as the development of the cryostat design will be the objective of the second part of the activity. In particular, it is planned to develop a single cell Nb cavity at the lowest $\beta$, a complete five-cell copper structure for mechanical and RF warm tests and a complete five-cell copper, Nb-sputtered, cavity at the highest $\beta$.

The “halo” problem will be carefully investigated for the whole linac, with the aim of keeping the beam losses below 1 nA/m in order to limit the neutron and proton activation of the device and to reduce dose rates of personnel during maintenance.

**Neutron production for material characterisation**

The proton beam of an ADS is particularly suitable for testing high intense neutron sources which are currently of great interest to the international scientific community (e.g. the European Spallation Source). This research sub-programme aims to optimise the accelerator design to allow for an efficient “spill-out” of the primary beam for producing a high intensity neutron flux for fundamental studies.

**General safety criteria and classification**

The ADS is a very innovative concept, with higher intrinsic safety than existing or advanced nuclear reactors. However, the identification of general safety requirements and the selection of design regulations will allow to address the subsequent final design.

In this framework four activities are being pursued:

1. identification of general safety issues and requirements;
2. selection of applicable codes and standards;
3. safety classification;
4. definition of mechanical design criteria.
Neutronics

Many specific aspects of its core make the neutronics of an ADS different from that, for instance, of a critical sodium-cooled fast reactor. In particular one has to consider its geometrical complexity, the use of lead or lead-bismuth as a coolant, the neutron energy spectrum, the physics of spallation as well as the presence of high order harmonics characterising the flux spatial distribution. Such features require developments both in nuclear data evaluations and in codes for static and kinetic reactor analysis. In particular, nuclear data models for such nuclides such as Th, Pb, etc. have to be investigated in an energy range usually not considered in nuclear reactors, and new evaluations are required.

Concerning reactor analysis, it has been claimed that for the lead-cooled ADS concept a continuous energy description is necessary in the whole energy range. This is motivated by the large mismatching of the neutron spectrum between the target zone and the sub-critical system (due to the relatively small neutron energy loss per elastic collision) and by the need for a correct evaluation of the coolant void effects. These considerations, along with the geometrical complexity, suggest the use of Monte Carlo codes. On the other hand, faster and suitably simplified deterministic codes (based on homogenisation and energy grouping), after appropriate validation, can play a relevant role for extensive system analyses. Thus, uncertainties coming from standard deterministic multi-group methods will be assessed via an extended comparisons with reference Monte Carlo codes, developed at CERN in the frame of the EA project. In addition, a new deterministic neutron kinetic model (in full transport theory) will be developed and compared, where possible, with Monte Carlo performances. Such a model will specifically address some reference transients in an ADS.

Last, but not least, the overall efficiency of an ADS as an actinide and fission product burner, as well as other aspects of its fuel cycle, will be analysed by using recent developments of Monte Carlo codes coupled with deterministic depletion codes.

Thermal-hydraulic analysis

The proposed ADS concepts present some peculiar aspects which require the development of new thermal-hydraulic models, as well as a deep investigation of some fundamental phenomena, at present far from a complete comprehension. In particular, the use of lead or lead-bismuth alloy as a beam target and nuclear coolant, as well as heat removal based on natural convection have to be carefully studied. Therefore, the use and development of advanced, 3-D CFD (Computational Fluid Dynamics) codes is necessary, in particular for analysing the boundary layer stability and its interaction with the hot rising flow, the fluid flow in the sub-channels, and the formation and stability of fully developed turbulent flow. In addition, transients at start-up and shut-down in a natural convection regime will be investigated.

The above fundamental studies will provide data for establishing correlations to be implemented, after appropriate validation, in any ADS oriented thermal-hydraulic design code.

Plant design requires the development of a thermal-hydraulic system code which can simulate the various reactor transients. Such a code must include the following modules, some of which have to be developed or validated to include specific features of a lead-cooled ADS:

- neutron source model;
- target and core thermal-hydraulic model (including simplified neutron kinetic model);
primary loop model;

secondary loop model;

residual heat removal model.

In addition, for the sake of a “best estimate” analysis and for validating the neutronic and thermal-hydraulic design of lead cooled system, a few specific, high accuracy modules will be written and benchmarked, to make them suitable for use in the international context.

**Technology of the beam window**

Being subjected to heavy operational conditions, concerning irradiation and corrosion, the beam window is universally considered as a “key” component of a sub-critical system. Advanced materials and technologies have, thus, to be foreseen and developed for this component. Unfortunately, there is a general lack of data on the mechanical properties of these new materials under the synergetic conditions of high neutron and proton fluence and of the interaction with lead or lead-bismuth.

This sub-programme aims to analyse the effects of high fluence proton irradiation in order to obtain reliable data on the mechanical properties of candidate materials vs. the irradiation dose. Furthermore, new technologies will be investigated for demonstrating the feasibility of windows of actual size.

As far as the theoretical studies are concerned, a finite element model will be developed for mechanical tests interpretation. Calculations performed with such a code will be compared with TEM analyses.

**Material technology and compatibility with lead and/or lead-bismuth alloy**

The present sub-programme foresees experimental investigations aiming at increasing know-how on the performance of candidate window materials and of system components in contact with lead at high temperature and velocity. These experimental investigations are done by a plant able to operate either with lead or lead-bismuth. The loop is shaped like a “figure 8”, thus allowing the presence of a hot and a cold leg for corrosion product deposition analyses. There are three independent test sections for housing different material tests at the same time.

The experimental programme includes:

- erosion/corrosion and tenso-corrosion tests at high lead temperature (about 600°C) and flow rate (about 4 m³/h) on candidate materials for the beam window;

- mechanical tests on the same materials after extended interaction with flowing lead in relevant thermal-hydraulic conditions (endurance tests);

- erosion/corrosion and mechanical properties degradation studies on structural materials (e.g. martensitic steel);
• deposition and distribution of corrosion products between the cold and hot leg of the loop;
• development of prevention and protection methods against corrosion, based on superficial coatings and/or inhibitors.

A parametric analysis will be carried out by performing tests for different values of the relevant parameters (temperature, temperature gradient, cooling speed, impurity composition and concentration).

Status of TRASCO

Although the programme officially started this past summer, some activities have already been performed both on the accelerator and the sub-critical system.

A reference conceptual design of the medium energy section, which includes an RFQ and a DTL (352 MHz), has been determined for some time; 30 mA or more can be accelerated. A more detailed design work of the RFQ started several months ago, and a 3 m long aluminium model of the RFQ has been built for RF field stabilisation tests.

Preliminary studies of an Independently Phased Superconducting Cavity Linac (ISCL) to be used instead of the traditional DTL have been also done. The ISCL is an accelerator similar to those used for low energy heavy ion in several nuclear physics laboratory, like the Italian LNL. In the present case it has to be adapted to a much higher beam intensity and to a wider velocity range of the accelerated particles. Various approaches have been checked, like single and double gap cavities, 176 and 352 MHz. The most promising design [2] of a 352 MHz ISCL, able to accelerate a 30 mA proton beam from 5 MeV up to 100 MeV, is based on the so-called “re-entrant cavities”, that are modified pillbox cylindrically symmetrical and, therefore theoretically dipole free. Many points of this design work are very preliminary but can be used for cavity R&D.

A conceptual design [3] of the 352 MHz superconducting linac, able to bring protons (30 mA) from 100 MeV up to 1700 MeV, has already been worked out and is mostly based on the LEP200 technology. The design foresees three different sections with transition energies at 190 and 430 MeV, using cavities with a synchronous beta of 0.5, 0.65 and 0.85. A doublet array structure, with cavities placed in the long drift space between the quadrupoles will provide the necessary transverse focusing. The three sections will employ 2, 3 and 4 five-cell cavities per focusing period, respectively. A first design of the cavities has been done and the electromagnetic and structural behaviours have been carefully investigated. Prototypes of cavities are being built. Part of the construction work and the tests of prototypes will be done at CERN, under a collaboration agreement between CERN and INFN.

Some work has also been done on the part of TRASCO relative to the target and the sub-critical system. Studies on the target physics are in progress, namely: characterisation of the neutron source, evaluation of residual nuclides, evaluation of activation and damage of structural materials. As concerns neutronics, an H-3-D neutron kinetic transport code is under development, while a 2-D diffusion model has already been implemented. A collaboration with CERN is also going on for MC code development.

On the side of material technology, some preliminary tests were done, aiming at studying the basic behaviour of materials suitable for the ADS. In particular, a set of static tests [4] in stagnant molten lead at 793°K was carried out in order to investigate the basic mechanisms and the
thermodynamic aspects of the corrosion process. Three materials were tested: 1) mod. F82H martensitic steel; 2) tungsten; 3) mod. F82H martensitic steel hot dip aluminised. The final design of the experimental loop for corrosion/erosion tests in flowing molten Pb or Pb-Bi has been done and construction is starting.

Some work on general safety criteria and on safety classification was done in the frame of the industrial programme and can be borrowed from it.

The industrial programme

Background and considerations

The design and construction of a (low power) demonstration prototype is the key (and only) choice to assess the feasibility and operability of an accelerator driven system for nuclear waste transmutation and, specifically, to demonstrate in subsequent steps:

- the accelerator and sub-critical system coupling;
- innovative fuels qualification and operation;
- plutonium, minor actinides and long-lived fission products transmutation efficiency.

The design, realisation and commissioning of such a demonstration prototype might be developed in a regional context, namely in an European context, also making reference, where needed, to similar ongoing projects in other regions, namely the USA and the Far East.

In Europe a strong industrial interest exists for ADS technology in general and for the realisation of a prototype in particular. Such interest has been witnessed in the common signature by Ansaldo, FRAMATOME, NNC and Siemens of the document “An European Nuclear Industry Interest for the Accelerator Driven Systems Technology to assess an European Reference System Configuration”, which has been transmitted to the European Union.

The Fifth European Community R&D Programme, starting in 1999, is a possible source of funding for ADS specific R&D activities within the specific programme “Nuclear Fission Safety”.

It is highly advisable that, starting from studies developed in recent years, the different technical options and alternatives converge, at least on a European basis, in the definition of an agreed upon reference configuration to be taken as the basis for engineering design, construction and commissioning of the demonstration prototype, on a medium term time scale (10-12 years).

For all these reasons, the Italian ENEA, INFN, CRS4 and Ansaldo have set up a team since early 1998, led by Ansaldo, that is studying the design issues bound to the construction of a low power (∼100 MWt) demonstration prototype of an ADS for nuclear waste transmutation (see Table 1). The aim of this activity, which has to be concluded in a short term (<1 year), is twofold: first, to assess the main supporting R&D needs; second, to issue a reference configuration description to be submitted to the European partners as contribution to the upcoming discussion to converge, as said before, on a prototype configuration and objectives, on which the detailed engineering design will be based.
Table 1. Respective functions of the organisations participating in the co-operative study

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ansaldo Nuclear Division</td>
<td>Provides the overall programme co-ordination. Also, technical co-ordinator of the sub-critical system design activities and involved in all the main working tasks in order to assure integration and consistency.</td>
</tr>
<tr>
<td>ENEA</td>
<td>Technical co-ordinator of core and fuel design activities and provides support to sub-critical system design.</td>
</tr>
<tr>
<td>INFN</td>
<td>Technical co-ordinator of accelerator configuration and provides interface data at core/sub-critical system boundary.</td>
</tr>
<tr>
<td>Centro di Ricerca, Sviluppo e Studi Superiori (CRS4), Sardegna</td>
<td>Provides support to core/fuel and subcritical system design activities.</td>
</tr>
<tr>
<td>Ansaldo Energie (Magnets Unit)</td>
<td>Provides support to accelerator configuration.</td>
</tr>
</tbody>
</table>

Starting from the conceptual configurations presently available in literature and, more specifically, from the Energy Amplifier Project [1], the purpose of this work is to define/confirm the main technical features applicable to an ADS demonstration prototype. In particular, the main technical issues that are investigated are:

- plant safety and functional requirements;
- accelerator configuration (including proton beam transport tube to the sub-critical reactor);
- target/window configuration;
- fuel element type, composition and thermal-hydraulic evaluation;
- core and supporting structures configuration;
- core reference cycle;
- primary coolant fluid and circulation;
- structural materials;
- plant thermal cycle and heat removal system (normal and emergency) configuration;
- fuel handling system and storage configuration;
- containment system configuration;
- main components preliminary design;
- primary system auxiliaries configuration;
- instrumentation and control architecture;
- plant building preliminary layout (plot plan and general arrangements);
- civil structures preliminary design.
Status of the industrial programme

The results obtained so far, though preliminary and not exhaustive, allow to outline a consistent demonstration prototype configuration, of which the main key technical features, with corresponding reference solutions, are concisely reported in Table 2.

Table 1. Main characteristics of the demonstration prototype design

<table>
<thead>
<tr>
<th>Power</th>
<th>80 MWth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator</td>
<td>Three-stage cyclotron based on PSI configuration.</td>
</tr>
<tr>
<td>Target</td>
<td>Pb-Bi eutectic preferably separated from primary coolant.</td>
</tr>
<tr>
<td>Window</td>
<td>a) Window cooled by primary coolant or by separate coolant.</td>
</tr>
<tr>
<td></td>
<td>b) Windowless target (separated, continuously renewed free-level target in forced circulation and cooled by primary coolant).</td>
</tr>
<tr>
<td>Core</td>
<td>$K_{\text{eff}} \approx 0.95$</td>
</tr>
<tr>
<td>Fuel</td>
<td>U and Pu MOX. Same geometry of the pellets and comparable isotopic composition of the fuel at the higher enrichment of the second SPX core.</td>
</tr>
<tr>
<td>Primary coolant</td>
<td>Pb-Bi (300°C at core inlet, 400°C at core outlet).</td>
</tr>
<tr>
<td>Primary coolant circulation</td>
<td>Circulation enhanced by gas injection in a natural-circulation reactor configuration.</td>
</tr>
<tr>
<td>Secondary coolant</td>
<td>Low vapour pressure organic diathermic fluid (280-320°C).</td>
</tr>
<tr>
<td>Normal power removal</td>
<td>Air coolers (system designed to use six air coolers available at the ENEA).</td>
</tr>
<tr>
<td>In-vessel fuel handling</td>
<td>Two rotating plugs, one fixed arm and one direct lifting machine.</td>
</tr>
<tr>
<td>Safety-related decay heat removal</td>
<td>Reactor vessel air cooling system (RVACS).</td>
</tr>
<tr>
<td>Earthquake protection</td>
<td>Reactor vessel and safety vessel on horizontal anti-seismic supports.</td>
</tr>
<tr>
<td>Reactor roof</td>
<td>Metallic plate.</td>
</tr>
<tr>
<td>Main vessel and safety vessel</td>
<td>Hung, 316L steel.</td>
</tr>
<tr>
<td>Hot shut down temperature</td>
<td>280°C</td>
</tr>
<tr>
<td>Cold shut down temperature</td>
<td>200°C</td>
</tr>
<tr>
<td>Fuel assembly monitoring</td>
<td>Thermocouples and failed fuel pins detection system.</td>
</tr>
<tr>
<td>Pb-Bi purification</td>
<td>Internal.</td>
</tr>
</tbody>
</table>

The choice of the power (80 MWt) is motivated by the fact that 80-100 MWt is the minimum consistent with a representative core characterised by annular configuration. Moreover, the accelerator needed to operate the subcritical reactor with a $K_{\text{eff}} \approx 0.95$ requires a beam power upscaling factor of 2-4 with reference to existing ones and, at last, the decay heat can be removed by the reactor vessel air cooling system (RVACS), with negligible creep damage, according to RCC-MR.

Though the process of selection of the accelerator type for the demonstration prototype is continuing at present, the basic scheme assumed is a reasonable extrapolation of the operating PSI facility and is based on a three-stage system capable of supplying a proton beam of a few mA (up to
5-6 mA) at 590 MeV. The first stage, made of the proton source and a small cyclotron, supplies the low energy pre-injection beam (5-6 MeV). The following accelerator stages are provided by two separated-sectors cyclotrons. The intermediate-stage cyclotron provides a low-medium acceleration with extraction at 100 MeV. The final stage cyclotron (the so-called “ring cyclotron”) boosts the proton beam to the final energy of 590 MeV. The booster is an eight-sector magnet cyclotron with six RF cavities operating at 50 MHz, 1 MV.

The target consists of a molten Pb-Bi eutectic, separated from the primary coolant. Pb-Bi has good spallation efficiency and neutronics properties and low melting temperature. Two options have been envisaged for the target, with and without window. In the option with window, this is cooled either by the primary coolant – which is the same Pb-Bi eutectic of the target – or by a separated coolant (back-cooled by the primary coolant or by an auxiliary cooling loop). In target configurations with separated coolant, the eutectic circulates driven by a stream of cover gas, according to the same gas lifting principle [5] adopted for circulating the reactor coolant. The eutectic target volume is a few litres, but the spallation reactions power to be removed amounts to 3 MW, because of the high power density of about 0.5 kW/cc.

Coming now to the sub-critical reactor, the basic fuel assembly is similar to that of SPX and, also, the fuel pellets have the same geometry and comparable composition (about 20% of Pu) of the higher enrichment of the SPX core. The core multiplication factor is about 0.966 at the beginning of life. At the core rated power of 80 MWt, the average fuel power density is 22 W/g-MOX (227 W/cc-MOX), with maximum radial peaking of 1.32 and axial of 1.13. The core is surrounded by an outer region of four rows of dummy assemblies, which are empty duct structures. This offers a continuous fast-to-thermal neutron flux region, usable for burning tests of MA and LLFF SAs.

Molten Pb-Bi eutectic has been chosen as primary coolant. From the neutronics point of view it behaves like pure lead – which was the first candidate for the energy amplifier – but it allows a lower operating temperature (300°C at the core inlet and 400°C at the core outlet) of the reactor and there is the important experience on its use made by the Russians with the reactors for submarine propulsion.

The reactor has been designed in the pool-type configuration because of the possibility to contain within the main vessel all the primary coolant with the highly active polonium, originated by bismuth, and of the large experience acquired with the design and operation of sodium cooled pool-type reactors. In the EA concept proposed by CERN, the lead coolant operates in natural circulation, driven by the density difference between the riser and the down-comer of the primary circuit. For the demonstration prototype the lead-bismuth circulation is enhanced [5] by a flow of 80 Nl/s cover gas, injected into the bottom part of a circular array of identical pipes (0.2 m ID), which make up the riser.

The secondary circuit is a closed loop circuit that in normal operation dissipates the generated heat from the reactor to the atmosphere. It is made up of four intermediate heat exchangers (IHX), arranged in parallel, and of six air-fin heat exchangers (AHX, re-usable from the ENEA-PEC reactor), arranged in series, two circulation pumps in parallel and of the interconnecting piping. The secondary coolant is a low vapour pressure diathermic fluid that is fully compatible with the thermal cycle (280-320°C) and ensures, in case of leak, no fast chemical reaction with lead-bismuth or air.
REFERENCES


DISPOSITION OF NUCLEAR WASTE USING
SUBCRITICAL ACCELERATOR DRIVEN SYSTEMS

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Mark Williamson, Michael Houts, George Lawrence
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Abstract

Los Alamos has led the development of accelerator driven transmutation of waste (ATW), to provide a fundamental technological solution to the nuclear waste problem. While ATW will not eliminate the need for a high-level waste repository, it offers a new technology option for altering the nature of nuclear waste and enhancing the capability of a repository. The basic concept of ATW focuses on reducing the time horizon for the radiological risk from hundreds of thousands of years to a few hundred years and on reducing the thermal loading. Furthermore, ATW will greatly reduce the amount of waste that has to be disposed of in a high-level waste repository. The goal of the ATW nuclear subsystem is to produce a three orders of magnitude reduction in the long-term radiotoxicity of the waste sent to a repository, including losses through processing. If the goal is met, the radiotoxicity of ATW-treated waste after 300 years would be less than that of untreated waste after 100,000 years.

Through the use of high neutron fluxes produced in accelerator driven subcritical systems, these objectives can be achieved. While critical fission reactors can produce high neutron fluxes to destroy actinides and the selected fission products, the effectiveness of the destruction is severely limited by the criticality requirement. Furthermore, to achieve safe reactor operations, a substantial amount of excess reactivity would have to be supplied initially and compensated for by control poisons. To overcome these intrinsic limitations, we searched for solutions in subcritical systems freed from criticality requirement by taking advantage of the recent breakthroughs in accelerator technology and the release of liquid lead/bismuth nuclear coolant technology from Russia. The effort led to the selection of an accelerator driven subcritical system that results in near complete destruction of the actinides and fission products of concern, as well as permitting easy operational control through the external control of the neutron source rather than the internal control rods.
Introduction

Spent reactor fuel from commercial power plants contains significant quantities of plutonium, other fissionable actinides and fission products, all of which create challenges for permanent disposal because of the very long half-lives of some isotopes and because of the potential for diversion. If the level of global nuclear power generation for the near future continues as it exists today, then in the year 2015 more than 250,000 tonnes of spent fuel worldwide will have to be stored, containing over 2,000 tonnes of plutonium. Well over 70,000 tonnes of this spent fuel will be in the US, containing more than 500 tonnes of plutonium (600 tonnes of transuranic actinides).

While there is agreement on using geologic repositories for the ultimate disposal of high-level nuclear waste, different strategies for dealing with spent nuclear fuel are being followed by various countries, reflecting their views on nuclear power, reprocessing and non-proliferation. Current US policy is to store un-reprocessed spent fuel in a geologic repository. Other countries are opting for treatment of spent fuel, including partial utilisation of the fissile materials contained in the spent fuel prior to geologic storage.

Key issues for the current US repository concept fall into two categories: 1) a long-term radiological risk with the peak risk projected tens of thousands of years after repository closing; and 2) a short-term thermal loading (decay heat) that limits the capacity of the repository. While not identified as an issue, it is clear that the repository, designed for 70,000 tonnes of commercial spent fuel and other government-generated high-level waste (mostly from defence-related activities), will be fully occupied by the spent fuel produced through the year 2015. If the nuclear energy remains to be a viable option for electricity generation in the future, ultimately there will be a need for a second high-level waste repository.

Studies have shown [1,2] that the repository long-term radiological risk is from the long-lived transuranics and the fission products $^{99}\text{Tc}$ and $^{129}\text{I}$, whereas thermal loading concerns arise mainly from the short-lived fission products $^{99}\text{Sr}$ and $^{137}\text{Cs}$.

In relation to the disposition of nuclear waste, ATW is expected to accomplish the following:

1) **Destroy over 99.9% of the actinides.** Actinide destruction eliminates concerns with their releases to the ground water and the environment, their possible diversion and use in the spent fuel for weapons construction. Their elimination will also greatly reduce long-term heat loading.

2) **Destroy over 99.9% of the Tc and I.** By transmuting technetium and iodine, two of the major long-term radiotoxicity release hazards can be eliminated.

3) **Separate Sr and Cs (short half-life isotopes).** $^{99}\text{Sr}$ and $^{137}\text{Cs}$ dominate the repository short-term heat loading. These isotopes are not suited for transmutation but will be separated from the remainder of the waste for optimal storage.

4) **Separate uranium.** Uranium is separated from the rest of the spent fuel, stored or re-enriched for further use.

5) **Produce electricity.** The ATW resembles in many ways a nuclear reactor in that it releases energy during actinide destruction (fission) that can be converted into electricity. A small fraction (10-15%) of this electricity will be used to power the accelerator, the rest can be distributed for sale.
In the ATW concept, spent fuel would be shipped to an ATW site where the plutonium, other transuranics and selected long-lived fission products would be destroyed by fission or transmutation in their only pass through the facility. This approach contrasts with the present-day reprocessing practices in Europe and Japan, during which high purity plutonium is produced and used in the fabrication of fresh mixed-oxide fuel (MOX) that is shipped off-site for use in light water reactors. Instead of “reprocessing”, the ATW approach can be fairly characterised as “once-through destruction”. ATW would inhibit plutonium accumulation, proliferation and diversion. The end products of ATW are a more benign fission product waste stream, uranium similar in composition to natural uranium, and electricity. The electricity produced, and the potential cost benefits realised by enhancing the capacity of a repository (and elimination of the need for an additional repository), could offset to some extent the cost of developing and implementing the ATW technology.

Far from being limited to waste destruction, ATW technology also brings to the table new concepts that could be relevant for the next-generation power producing systems. As such, ATW has gained world-wide interest and could be an important component of strategies to deal with international nuclear materials management and promote new, proliferation-resistant, safe reactor technologies.

**ATW system description**

An ATW facility consists of three major elements: 1) a high-power proton linear accelerator; 2) a pyrochemical spent fuel treatment/waste clean-up system; and 3) a liquid lead-bismuth cooled burner that produces and utilises an intense source-driven neutron flux for transmutation in a heterogeneous (solid fuel) core (Figure 1). The concept is the result of many years of development at LANL [3] as well as other major international research centres [4].

The high-power accelerator for ATW would be based on the APT (accelerator production of tritium) accelerator (1.7 GeV, 100 mA, 170 MW proton beam). An accelerator, similar to but smaller than the one now being designed for tritium production would serve as the driver (40 MW) to a subcritical burner, where transuranics and selected fission products are fissioned or transmuted.

In the spent fuel treatment system (Figure 2), uranium and a majority of the fission products are separated from the transuranics and the targeted long-lived fission products by pyrochemical (non-aqueous) processes. The only requirement is the separation of enough uranium (99%) so that no significant new plutonium or other actinides are produced during transmutation. Fission product extraction is not explicitly sought but comes out naturally from the process.

The flow of the spent fuel in the treatment system can be broken down into three basic streams. One stream contains the spent fuel cladding metal, the majority of the fission products from the spent fuel, and the remaining fission products from the transmuted waste, all of which are prepared for permanent disposal. Following the electrochemical extraction of the uranium, a second stream consists of actinides and some cladding zirconium, which is cast into solid metallic fuel elements (“transmutation assemblies”) to be introduced into the subcritical burner for irradiation. The third stream consists of the uranium sent out and stored for possible recycle.

In one reference design concept, a third of the core is extracted and processed every year. In the ATW waste clean-up process, eventually all the fission products in the irradiated waste are partitioned into three forms: active metals, noble metals and lanthanides. This remnant waste is prepared for permanent storage as: 1) oxides in engineered containers for the active metals (including strontium and caesium); 2) oxides for the lanthanides; and 3) metal ingots and oxides for the noble metals
including zirconium. An average of 50 kilogrammes of fission products, per tonne of spent fuel, are discharged as waste after transmutation (including the fission products originally present in the spent fuel), contaminated with less than 100 ppm of transuranics (mostly in the metal oxide waste form). Most of the radioactivity in the discharges would decay before three hundred years, with only weak residual activity of negligible environmental impact remaining afterwards.

The waste burner consists of a heavy metal target (liquid lead-bismuth eutectic (LBE)) producing the high intensity neutron source and the surrounding subcritical core containing the transmutation assemblies (Figure 3). Since significant neutron multiplication and heat production occurs from the fissioning of the waste actinides contained in the surrounding transmutation assemblies, adequate means for heat removal must be present, analogous to critical reactors of similar power level. ATW takes advantage of the exceptional properties of liquid LBE, both as nuclear coolant and as spallation neutron source, for use in the subcritical waste burner. The technology, successfully developed and used in Russia for nuclear submarine propulsion of very fast, deep diving vessels, is becoming accessible to Western researchers and engineers.

The subcritical liquid LBE systems presently being developed at Los Alamos operate in the fast neutron spectrum, to ensure optimal destruction efficiency for the actinides and large neutron availability for transmutation of the targeted fission products. Very low end-of-life inventories are rapidly achieved by burn-down strategies involving gradual thermalisation of the spectrum to exploit the large capture cross-sections of resonances.

Subcriticality does not make ATW by definition “safer” than critical reactors. Rather, subcriticality facilitates tasks that would be exceedingly difficult or inefficient in critical systems. Subcritical systems do not rely on delayed neutrons for control and power change, they are driven only by the externally generated neutron source (i.e. by the ion beam coming from the accelerator). Control rods and reactivity feedback have very low importance: these systems are neutronically (but not thermally) decoupled from their neutron source. Subcriticality therefore allows the ATW system to work with any composition of fuel (or waste) and to greatly relax the required separation in the waste treatment steps. This makes possible, in principle, the destruction of any isotopes (actinides or fission products or mixture of both) with little concern for their neutronic behaviour. Fertile materials are not needed to compensate for the neutronic uncertainties or undesirable reactivity responses of the fuel, and extended burn-up is achieved by increasing the power of the accelerator drive to compensate the reactivity decrease.

Because of its subcritical mode of operation, ATW will be ideally suited as “incinerator” of material that: 1) is not well characterised; 2) burns very poorly or not at all in reactors; 3) has potentially unstable and hazardous reactivity responses; and 4) should not for whatever reason be isolated and placed in reactors. This includes higher actinides such as neptunium (the worst contributor to an oxidising repository long-term performance uncertainties), americium and curium, all isotopes of plutonium and some long-lived fission products. In addition, the neutron-poor thorium-uranium fuel cycle, never successfully implemented in critical reactors, can be used rather straightforwardly in accelerator driven subcritical systems.

**Fuel cycle technology**

Spent fuel treatment technology is derived from pyrochemical processes developed for plutonium production at Los Alamos [5] and the Integral Fast Reactor programme at Argonne [6]. Pyrochemical processes were chosen over the conventional aqueous processes because they are proliferation
resistant – group separations are used instead of single species separations; allow the processing media, molten salts and liquid metals, to be recycled multiple times thus reducing secondary waste; and allow for short turnaround times for waste treatment – radiolysis and decay heat are not significant issues [7]. In addition, the product from the electrochemical processes is easily fabricated into fuel for the system. The central development issue for process chemistry is to establish process scaling information by designing, fabricating and testing various separation systems and then using that information to develop a more detailed material balance for the fuel treatment processes and process plant parameters. An ATW fuel treatment facility would be similar to the fuel cycle facility proposed for the Advanced Liquid Metal Reactor (ALMR) Programme [8]. The following sections provide a brief overview of process chemistry and fuel technology for the ATW system.

**Process chemistry**

The flow sheet, shown in Figure 2, gives an overview of the flow of material from a spent fuel storage facility to the repository. Process technologies are based on modifications of existing technologies so as to achieve the ATW process requirements (see the first part of this paper).

**Metallic fuel**

Existing technology is used wherever possible in the ATW nuclear subsystem. The primary exception is the ATW fuel. The need to eliminate uranium from the waste, the desire to use LWR clad (zircaloy) as the inert fuel matrix and the desire to make processing as simple and waste-free as possible drives the fuel form to a zirconium-based metal matrix with an initial transuranics loading of about 15%. The fuel is a high melting alloy (> 1900 K) and at the operating temperature of the transmutation system is a solid solution of TRU in alpha zirconium. Metallic fuels have long been proposed for use in ALMRs and have been studied in experimental reactor facilities. Much like other development metallic fuels, ATW fuel will require both irradiation and materials compatibility testing. Specific issues include fuel swelling, burn-up limits, fission product, especially fission gas, in-growth, fuel/clad interactions and fuel/clad bonding materials.

**Lead-bismuth eutectic nuclear coolant and spallation target**

Lead-bismuth eutectic (LBE) possesses some unique physico-chemical properties, making it an excellent nuclear coolant and spallation neutron source. LBE’s (44.5 wt% Pb – 55.5 wt% Bi) low melting point (123.5°C), high boiling point (1670°C) and very low vapour pressure allow for a wide operating temperature range, eliminates coolant boiling and enhances circuit safety. The high density of LBE combined with wide permissible temperature range offers extraordinary natural convection cooling capability for enhanced passive safety. LBE’s low chemical activity inhibits violent reactions (fire and explosion) with air and water. The sealed vessels and circuits readily prevent air-borne lead contamination from exceeding established industrial standards (0.01 mg/m³ in Russia, 0.03 mg/m³ in the US). The choice of LBE coolant for the ATW system is based primarily on two factors. First, the LBE can be used as both the coolant and the spallation target. Second, the use of LBE results in a negative overall coolant void and temperature reactivity coefficient [9].

The integration of nuclear coolant and spallation target in the current ATW concept drastically improved the subcritical burner design by simplifying flow configuration, material compatibility and removing target structures in high proton and neutron fluxes. LBE has very high useful neutron
production during spallation and extremely low neutron capture cross-sections. This neutron transparency allows for a widely spaced core with much reduced pressure drop and pumping power requirement. The coolant is also self-shielding against gamma radiation.

A schematic of the ATW nuclear subsystem is shown in Figure 3. The choice of the pool configuration is consistent with the objectives to use proven solutions (the pool configuration was chosen over the loop option for LMRs world-wide) and to maximise safety. The actinide-containing region is 2 m high by 2 m in diameter. An 0.6 m diameter central region contains LBE that is used as the spallation target. The top of the target is located 0.15 m above the mid-plane of the actinide-containing region, and a window separates the inside of the beam tube from the LBE. Passive systems are used to ensure that if LBE temperature exceeds that expected during normal operation the beam tube will be flooded with LBE, effectively removing the neutron source from the actinide-containing region and shutting down the transmutation process.

An intermediate loop could be avoided to reduce cost and in fact some Russian designs place a steam generator directly inside the primary pool. However, it was decided to adopt an intermediate heat exchanger in the ATW concept to contain polonium (produced by neutron capture in bismuth), spallation products and other radioactive isotopes. The secondary coolant is non-radioactive LBE. A minimum 1 m thick LBE reflector surrounds the waste assemblies on all sides. This reflector helps minimise required actinide loading, flattens the power density across the fissioning region, shields the vessel walls from fast neutrons and provides thermal inertia. A core map is provided in Figure 4.

**Conclusions**

ATW destroys virtually all the plutonium and higher actinides without reprocessing the spent fuel in a way that could lead to weapons material diversion. Once demonstrated and developed, ATW could be an essential part of a global non-proliferation strategy for countries that could build up large quantities of plutonium from their commercial reactor waste. ATW technology, initially proposed in the US, has received wide and rapidly increasing attention abroad, especially in Europe and the Far East, with major programmes now being planned, organised and funded. Substantial convergence presently exists on the technology choices among the programmes, opening the possibility of a strong and effective international collaboration on the phased development of the ATW technology.

If the job of nuclear waste destruction has to be done quickly, safely and with reasonable investment, we believe that a dedicated, once-through subcritical burner (ATW) system would provide the most effective option. ATW can provide, within a realistic nuclear technology envelope, a way to destroy the undesired products of nuclear energy generation. This is a new instrument in the field of nuclear systems: it could accomplish the destruction of all transuranics (including plutonium) and long-lived fission products, or only a residual portion, if recycle of Pu in existing critical reactors is deemed acceptable. The technologies introduced and developed for ATW (liquid lead/LBE nuclear coolant, pyrochemical processes, high power accelerators) will also have important applications to, and could well constitute the backbone of, future nuclear systems (both critical and sub-critical).

ATW systems could be used in a series of different scenarios, including the expanded, sustained or declining use of nuclear power. The ability to demonstrate such a flexible means of destruction of waste will be very important in fostering the confidence that a “forever” legacy of waste is not the unavoidable consequence of having once used nuclear power, or by the same token in promoting the acceptance of nuclear power as a viable and environmentally sustainable large-scale energy source.
ATW Consists of Three Major Functional Blocks

Figure 1

ATW Waste Treatment is based on Pyrochemical Processes developed at Los Alamos and Argonne

Figure 2
Accelerator drive (subcriticality) enables versatile and effective nuclear waste destruction

- Power control is not linked to reactivity feedbacks, delayed neutrons or to control rods, but only to the accelerator drive.
- ATW has no need for fertile materials. ATW uses pure transuranic cores.
- Subcritical systems work independently of the fuel composition.
- EOL inventory is not limited by criticality. Possible to have EOL burn down of inventory.
- Neutronics and thermohydraulics are effectively decoupled.

Core map for 2000 MWt ATW burner

200 cm
REFERENCES


[10] Communications and contract reports from the Institute of Physics and Power Engineering (Obninsk) and EDO-Gidropress (Podolsk), Russia.

SESSION III

Reliability of HPPAs – Part I

Chairs: Y. Cho and A. Noda
Operational Experiences at Existing Accelerator Facilities

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Abstract

Over the past several years the author has been conducting a study consisting of literature searches and visits to selected existing accelerator facilities to gather information with the ultimate objective of assembling a database of reliability information for typical accelerator components such as ion sources, focusing magnets, magnet power supplies, RF windows, circulators, high voltage components, etc. The resulting database will be used in support of the design effort for planned high power proton accelerator projects. This presentation describes the major findings and the current status of this ongoing effort.

Generally, most surveyed facilities collect information on beam downtimes and their causes (insofar as these are actually understood). The survey shows that existing facilities consistently operate with availability between 80-90% of scheduled time. However, it should also be noted that the surveyed facilities are normally scheduled to operate only 30-75% of the year. Also, short but frequent interruptions are found to be a typical characteristic of all the large accelerator installations.

Detailed time series of accelerator failure events for several operating cycles have been obtained from two facilities: LANSCE and TJNAF. Such time series data permit statistical estimation of the parameters of the underlying random process which can then be used to generate facility specific reliability predictions and to derive failure and repair rates for some of the system’s components. Examples of such analyses are presented.
Introduction

Successful development of a reliable and maintainable accelerator system requires a systematic application of both the technical expertise and management discipline during all the life cycle phases of the system: conceptual design, demonstration and validation, full scale engineering design and development, production and installation, and operation. In this co-ordinated chain of events, responsibility for achieving the desired level of reliability, availability, maintainability and inspectability (RAMI) is shared by the management, technical specialists, designers, manufacturers, users and the operations support team [1].

In the conceptual design phase, for example, the team makes choices between various system design alternatives using estimates of RAMI performance and projected costs. In the conceptual design phase these estimates must necessarily be based on historical data [2]. In the validation phase, RAMI testing provides the additional information required to confirm those earlier choices. During the full scale engineering design and development phase, the RAMI requirements are firmed up, and the project makes final design decisions and provides adequate demonstration tests to ensure that RAMI requirements will be met. In later phases, RAMI analyses are still required in budgeting for spare parts, repair, shop facilities and personnel training.

RAMI specialists assist the designers in achieving the optimal design that balances reliability and maintainability requirements among subsystems and components. Typical RAMI tools available for this effort include failure modes and effects analyses for determining which low level failure modes are critical to the system’s operation and fault tree analyses for determining the combinations of low level failure modes which can produce critical failures at the system level. Finally, the probabilistic methodology for reliability prediction integrates all available information by developing a model which combines the required production time, the scheduled maintenance plan and the estimated corrective maintenance for comparison with the total calendar time, typically on an annual basis.

Corrective maintenance is the term used to denote production shutdowns forced by random failures that cannot be predicted or prevented by scheduled maintenance. As illustrated in Figure 1, both the loads encountered by the system during its life and the strength of its components are subject to random variability. It is commonly argued that for a population of identical components the rate at which the components are failing over time displays a period of stability between the region of decreasing values during the so-called infant mortality period and the region of increasing values during the wear-out period. The inverse of this constant failure rate that the population exhibits during the stable period is known as the mean time between failures (MTBF).

Since an accelerator is a repairable system, its components are also characterised by the mean down time (MDT), the average time that is required to recover full operation after a failure. System reparability brings with it a considerable level of mathematical complexity into its probabilistic models [3]. A rough estimate of reliability for a non-repairable system can be obtained by summing up the failure rates of its individual components. To the first order of magnitude, one can even approximate the redundant subsystems as perfectly reliable, dispensing with the algebraic complexities associated with the exact calculation. For a repairable system, on the other hand, the analysis is much more complex since it must include the effects of the interactions between the system and the repair policies, maintenance procedures, spare parts policies, etc. Also, it is not just the first failure event, characterised by the mean time to failure (MTTF), but the continuing sequence of failures and repairs, characterised by the system MTBF and the system MDT, that is of interest here. The objective of the predictive analyses is to derive the system MTBF and MDT from its component MTBF and MDT values.
Figure 1. Heuristic arguments for random nature of system failures

The system continually evolves in time, moving from state to state (Figure 2). Each state corresponds to a specific number of system components operating and a specific number of components that have failed and are either undergoing repair or awaiting repair. Even though there is only one state with all the components operating, we can define a certain specific subset of the state space representing functional systems. The states in the complement of this subset in the state space represent failures. The system’s transition from one state to another is governed by transition probability based on the failure and repair rates defined by MTBF and MDT, correspondingly. The probability of the system evolving from its initial state, where all the components are fully operational, to its final equilibrium state passing through all the intermediate time dependent positions, is tracked with a set of differential equations. These are solved as time functions for the calculation of mission reliability for any given length of the mission. Asymptotic limits of these functions are used for calculation of the steady-state availability [4]. The design goal is to assure that the system settles in a form of a limit cycle of failures and repairs (as for an attractor in a chaotic system, the system trajectory is not expected to repeat through the same exact sequence of states). Reliability improvement corresponds to the period of this cycle growing with time.

Figure 2. The evolution of the system in the state space;

system state: \( X = (x_1, x_2, x_3, ..., x_N) \); component state: \( x_i = 0 \) or \( 1 \)
The cycle of operation and repair for a single component is modelled as a superposition of two alternating random processes: one consisting of times between failures and the other consisting of down times as illustrated in Figure 3. Generally, each one of these two processes is Poisson with the MTBF and MDT that can vary with time. Also, the two processes are usually uncorrelated.

**Figure 3. Component failure and repair process**

![Component failure and repair process diagram](image)

**Markov Model:**

- $\lambda \ dt = $ probability of failure in $(t,t+dt)$
- $\mu \ dt = $ probability of repair in $(t,t+dt)$

$\lambda = \frac{1}{MTBF}$

$\mu = \frac{1}{MDT}$

Although the failure and repair processes are generally non-homogeneous Poisson processes or even more generally renewal processes [5], frequently a subclass of such processes called Markov chains is used by the reliability field. This approach assumes that any state of the system depends only on the immediately preceding state [6]. Although the validity of application of this assumption to the system behaviour in the real world can be questioned because undoubtedly the system state is a function of its entire history, it is a very good approximation for most systems.

Next, an assumption is usually made that the system has operated long enough to reach its steady state asymptotic limit. Basically, we assume that the Markov processes describing the system have reached equilibrium. Kolmogorov equations, describing this equilibrium, with time derivatives set to zero, are the basis for the entire approach [7].

A more complex repairable system, consisting of many components, is represented as a set of sockets, each carrying its corresponding part (Figure 4). Each repair corresponds to the replacement of the component in its socket. The analogy of socket and replaceable components should not be carried too far. Fixing a software bug or resetting an electronic power supply can also be viewed in this way.

A Markov model of a system such as an accelerator with thousands of parts is very complex. The number of states in real world systems grows very fast with the number of components: for 100 components, with each in one of two states, the number of possible states is $2^{100} = 1.3 \times 10^{30}$. 
In practice, an approximate approach in which the repairable system is divided into its subsystems, assemblies, and blocks in series of redundant arrangements to the point where each block can be represented by a single elementary Markov process, seems to work rather well. A number of Markov models capable of representing systems with an arbitrary number of components, an arbitrary number of redundancies of either standby or operational type and choice of on-line or off-line repair policies have been derived for application in the accelerator analyses [8].

These probabilistic models use input MTBF derived from average failure rates inferred from observed operation of similar systems in existence and component manufacturer assertions about the predicted failure rates of newly developed equipment in order to generate the top-level failure rate for the entire system. In combination with MDT derived from repair rates estimated by time and motion studies, these are then used to estimate the proportion of time the system will be available for production and the total amount of time that will be needed for corrective maintenance for comparison with the available budget derived from the required production quota.

It must be stressed (even though it may be obvious) that as any other probabilistic methodology, RAMI prediction methodology is only capable of pronouncing judgements about population averages and not about an individual event or a specific system. The role of this methodology is to drive the design towards the reliability oriented goals as an organised activity with the following end products:

- RAMI specifications for all subsystems and components;
- identification of critical items (weak links);
- evaluation of system sensitivities;
- optimal design of system redundancies;
- estimates of maintenance contribution to the life cycle costs;
- identification of areas for potential technology development;
- optimisation of maintenance planning.
From the life cycle cost point of view, the optimisation of system maintenance is perhaps the most important outcome of the RAMI activities. Generally, any system is maintained via a combination of four maintenance modes illustrated in Figure 5. Reactive maintenance is the common situation where no planning has been done at all. Each failure is an individual event which forces the operations into a “brush fire” mode. Loss of production and high cost of repairs are typically the price paid for the “savings” on the maintenance planning. The next step in progression towards better maintenance is called preventive maintenance and consists of periodically scheduled activities ranging from lubrication to replacement of parts.

**Figure 5. Maintenance modes**

In recent years, reliability centred maintenance (RCM) methods have been developed to improve this process even further [9]. The RCM method was developed in the 1960s during the certification of the Boeing 747 and has been used by United Airlines since 1972. This methodology is now credited with containing the maintenance costs for all airlines at a relatively unchanged level over the past two decades. RCM was the result of long-term studies that determined that only 11% of the components of the aircraft fleet showed any sign of increasing failure rate due to ageing. In fact, only 4% of the components displayed both the infant mortality and the ageing regions of the bathtub curve. Most of the components had more or less constant failure rates independent of their length of service. Thus, preventive maintenance based on a rigid schedule was found to waste valuable resources.

RCM employs the “on-condition” and “condition-monitored” approaches to define a predictive maintenance plan. The on-condition maintenance approach determines the condition of the unit by means of repetitive inspections, tests and in-place diagnostics, which monitor the health of the item. The condition-monitored approach relies on statistical analysis of the operating experience to indicate the need for corrective action. For non-safety critical components, RCM may allow run-to-failure as the most cost effective maintenance plan, depending on the results of detailed system analyses. The proactive maintenance mode is the most desired situation where all failures have been eliminated by a careful initial design and subsequent analyses of root causes followed by the corresponding mitigating actions.

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The probabilistic RAMI analysis of repairable systems is a challenging new field requiring an integrated, “holistic” view of the system. The models are incomplete unless they include, besides the detailed representation of the system hardware configuration also the details of the operational doctrine and the repair and maintenance policies with a characterisation of the number and skill levels of the operations and maintenance staff. The real world systems are highly sensitive to details which make the mathematical models very complex: ageing and infant mortality effects, degraded modes (most systems are not just on/off but display a range of deterioration), effects of the environment external to the system, gradual improvement of the operator skills with time and the memory of bad repairs beyond just the immediately preceding state. Since repairs do not really bring the system back to its original condition, future developments will clearly require methodology reaching beyond the simple Markovian systems. Also, the data input into the models are a serious source of uncertainty. This includes the issues such as: applicability of historical statistics to new designs, the accuracy of the industrial database contained in sources such as MIL-HDBK-217 and the fact that new accelerator designs usually contain at least a few elements extending the state of the art for which no historical statistics exist but which may have a significant impact. To obtain the “experimental” statistics necessary to derive the input data and ultimately to understand the significance of the above concerns we initiated the reliability survey of operating accelerator facilities. The results of this survey and preliminary analyses of the collected data are presented in the remainder of this paper.

Accelerator survey

The motivation for the reliability survey of existing accelerator facilities is now particularly urgent in view of several new accelerator projects which are in planning stages: Spallation Neutron Source, Accelerator Production of Tritium, Accelerator Transmutation of (Nuclear) Waste, and the International Fusion Materials Irradiation Facility. The design activities for all these projects will require input data for modelling: failure rate and restoration rates for typical accelerator components. In addition, the structure of the operating and maintenance organisation at the facilities was also studied to understand their role in determining the overall reliability of the system. Most existing accelerator facilities are operated in campaigns (runs) that last typically from several weeks to several months with major modifications and maintenance performed between the campaigns. In these facilities, whose main role is to provide particles for scientific experiments, the period between the campaigns is typically of the order of 3-4 months and above. This extra time is necessary for machine development required for new experiments. During every campaign, the accelerators are usually operated 24 hours a day by several crews of operators working on a rotating-shift schedule. Each facility follows its individually scheduled maintenance plan in a more or less flexible way, depending on the needs of each experiment and the condition of the machine.

A general consensus among the operators is that “preventive maintenance is better than reactive maintenance.” In practice, a combination of reactive and preventive maintenance is used by all facilities. A list of current maintenance tasks, including those dictated by preventive maintenance schedule and the ones due to existing but tolerable failures, is continuously maintained by a maintenance co-ordinator. Maintenance tasks are scheduled for repair during the next maintenance opportunity that is forced either by an upcoming preventive maintenance item or by a failure that cannot be tolerated. Procedures followed in setting up the schedule are also similar across the facilities. Typically, such scheduling involves a team consisting of operators, maintenance personnel and users who keep track of access requirements, repair time and experiment schedule. Clearly, the process is quite complex, but it can be controlled with good results, as reflected by high availability values reported for the above facilities.
All accelerator facilities surveyed maintain some form of record of failures and perform analyses of the gathered statistics to determine the allocation of maintenance resources:

- **ISIS:** The recorded failures are assigned to 80 different categories corresponding to the elements of the accelerator and target by the control room operators using Microsoft Access database.

- **CERN:** Records of downtime events for both major divisions (CPS and SPS/LEP) are published in the form of statistical reports. The recorded failures are assigned to major accelerator subsystems by the control room operators.

- **DESY:** Records of downtime events for HERA from 1996 are recorded in proprietary software on the control room console.

- **LANSCE:** Time history of downtime events and their durations with causes identified in the comment field are collected in a Microsoft Excel file.

- **TJNAF:** Time history of downtime events and their durations with causes identified in the comment field are collected in a Microsoft Excel file.

When all available statistics are combined and displayed in the form of downtime contribution percentage per category, it becomes apparent that the RF systems in linacs are by far the most significant source of downtime in all the facilities (Figure 6).

**Figure 6. Downtime breakdown summary for all facilities combined**

![Downtime contribution summary graph]

As an indication of difficulties with any generalisation between the various facilities, one can compare the overall statistics with the ones plotted in the same manner for a single facility. In Figure 7, ISIS was used as an example. However, each facility plotted separately will show its individual characteristics.
The CERN LEP and SPS facilities provide another example of system behaviour with different characteristics (Figure 8).

Clearly both the similarities and the differences between the reliability behaviour of the various facilities need to be investigated by means of more detailed analyses before we can claim an understanding of the accelerator reliability. The initial progress in these analyses is reported in the next section.
Results from preliminary analyses

At this time, the analyses of the LANSCE data set are the most advanced. The original data set was made available to us in the form of a time series [10]. A sample of this data is illustrated in Figure 9.

**Figure 9. LANSCE performance data (sample)**

<table>
<thead>
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<th>Date</th>
<th>Time</th>
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<th>dT</th>
<th>Area</th>
<th>System</th>
<th>Comment</th>
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<td></td>
<td></td>
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<td>3</td>
<td>linac</td>
<td>805</td>
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</tr>
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<td>3</td>
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</tr>
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<td>1</td>
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<td>line d north spill</td>
</tr>
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</table>

The information recorded for each failure event includes the date and time of occurrence, duration of repair, the additional time needed to bring the system back up, if any, the description of the area and system associated with the failure and additional comments from the operator. The data was analysed in early 1998 and the details of this effort are described in [11], published in this workshop. In summary, the MTBF and MDT estimates were obtained for typical accelerator systems and subsystems:

- 805 RF system;
- DC magnets;
- magnet power supplies;
- pulsed power system;
- water system
- vacuum system.
The MTBF and MDT estimates obtained are presented in Figure 10. A detailed description of the methods of analysis of the data is provided in [11]. Figure 11 shows a sample analysis for the magnet power supplies. In essence, the failure events for the magnet power supplies were extracted from the overall database and the average failure rate limited to this set was calculated. Next, based on the assumption that the failure event probabilities for all power supplies are independent and identically distributed, we divided the above failure rate for the set of power supplies by the number of supplies in the set, obtaining the following failure rate for an individual power supply: \( \lambda = 118 \times 10^{-6} \text{ 1/h}. \) The MTBF = 8 445 h is the inverse of the failure rate. The MDT = 48 min., is calculated as the mean value for the set since every time a failure occurs, the repair corresponds to an individual supply.

Figure 10. Summary of LANSCE analysis results

<table>
<thead>
<tr>
<th>RESULTS OF RELIABILITY STUDY AT LANSCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main System</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>DC Magnets</td>
</tr>
<tr>
<td>Magnet Power Supplies</td>
</tr>
<tr>
<td>Pulsed Power</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Water System</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Figure 11. Analysis of LANSCE magnet power supply failure statistics
The analysis methodology discussed above is applicable to repairable systems with each failure compensated with the corresponding repair. In this case the underlying data structure is simply that of a time series. Other types of data may require a different kind of analysis. For example, failure data for a single component may be provided as statistics for a sample from a population without replacement. This would correspond to the case where we select a random sample from a given population and test individual components. Some of the components fail while others continue operating when the test is stopped for reasons other than failure. For field data commonly obtained for analysis from operating equipment and customer collected statistics, the components may be put in operation at varying times and withdrawn from the test at other times.

For example, as a central element of an RF station in an accelerator but also in a typical radar system or a TV station, the klystron is in the focus of attention of many reliability experts. The most important body of statistical data for high-power CW klystrons in accelerator applications comes from DESY [12]. This facility employs the Philips YK1300/1301/1304 tubes operating at 500 MHz and delivering 0.6-0.8 MW. The data provided covers 80 tubes with various operating times, including 41 failures. The Weibull analysis of this data is shown in Figure 12 where the high voltage operating hours of the klystron are plotted against the corresponding cumulative hazard value.

**Figure 12. Weibull fit to DESY klystron data**

As opposed to a “straight” failure rate calculated as the percentage of the number of equipments in the original population failing per unit time, the hazard rate at any given time is the percentage of equipments that ran all the way to that time (subtracting the items that failed before) and failed at that instant. Therefore, constant hazard rate means that the number of failures per unit time is proportional to the number of units remaining in operation. It is well known that the constant hazard rate corresponds to the exponential failure probability density and that the inverse of the hazard rate equals the MTBF. For constant hazard rate, the cumulative hazard function is proportional to time, \( t \), and equals 1.0 (100%) when \( t = \text{MTBF} \). Thus, as shown in Figure 12, the value of the best-fit straight line corresponding to...
the cumulative hazard of 100% provides an estimate of the MTBF for the sample [13]. The MTBF obtained for the DESY sample is found equal to 18,837 hours. Comparing this value with the MTBF = 11,560 h shown for the LANSCE klystron assembly in Figure 9 one comes to the conclusion that they are not incompatible because the MTBF for an assembly is expected to be lower than for one of the assembly’s components. On the other hand, the klystrons used in LANSCE are different than the ones used at DESY so we are not really comparing “apples with apples”.

Another statistically significant sample is available for the CPI/MPTP VKP-7900 klystron with a multistage depressed collector. This tube produces 64 kW CW RF output power at UHF frequencies (470-810 MHz) and is used in TV transmitters. The statistics collected from a five-year field operation of this tube are provided by [14] and the least-square fit to this set of data gives an estimated 57,544 hours MTBF.

Most manufacturers recommend using 25,000 h for klystron MTBF for tubes of size to be employed in the future high power accelerators, similar to the DESY klystrons [15,16]. Clearly, this value represents a modest extrapolation of the DESY data. While McCune reports higher MTBF, his data corresponds to a smaller size tube manufactured in large quantities (and therefore likely to be more robust).

The ISIS data were not provided as a time series but rather as the total number of failures per category, corresponding to specific subsystems and the total associated downtime. A sample of the data set obtained from ISIS is shown in Figure 13 for the Synchrotron Injector and its subassemblies (ion source, low energy delivery system, linac, high energy delivery system, injector diagnostics and injector services).

**Figure 13. ISIS performance data sample**

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub Sub Area Description</th>
<th>1994-1995</th>
<th>1995-1996</th>
<th>1996-1997</th>
<th>Total 1994-1997</th>
<th>% of Total Number of Faults</th>
<th>% of Total Repair Time</th>
</tr>
</thead>
<tbody>
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<tr>
<td>162</td>
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<tr>
<td>163</td>
<td>Inj Serv Electrical</td>
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<tr>
<td>164</td>
<td>Inj Serv Compressed Air</td>
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<td>0</td>
<td>0</td>
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</tr>
</tbody>
</table>
This type of data can still be used to obtain MTBF and MDT estimates, provided that we also know the total operating time of the system. The MTBF can then be calculated by dividing the total operating time by the number of failures and the MDT by dividing the total downtime by the number of failures. Figure 14 shows the results of such calculations ordered according to ascending values of the MTBF so that the shortest values (most frequent failures) come first. As can be seen, the shortest MTBF, of 2.86 hrs is calculated for the category of nonspecific synchrotron beam loss. Fortunately, the corresponding MDT is only 0.01 h (less than 1 min.). The next category is the accelerating column, with MTBF = 5.99 h, and MDT = 0.02 h, with most events corresponding to sparking. Magnet power supplies compete with the ion source for the third and fourth position, and so on.

Another interesting result which can be obtained from the ISIS statistics is the identification of contributors which are associated with the longest down times. Figure 15 shows the results ordered according to descending values of the MDT. As can be seen, the longest MDT, of 19.37 hrs is calculated for the synchrotron magnets. Fortunately, the corresponding MTBF is also rather long, with 1579.18 h. Linac tanks are the next category with MDT = 8.81 h, and MTBF = 114.86 h. The long MDT for this category is driven by the inclusion of RF window failures with corresponding vacuum pumping of the tank cavities.

It is a notable fact the total contribution of both those kinds of failure events which occur most frequently, but for a very short duration and those failure events which last a long time but occur very rarely, to the overall unavailability is rather small so that the ISIS system can still routinely operate with availabilities above 90% [17].

Based on the survey of data collected so far, we propose the desired format for collecting the failure event records as suggested in Figure 16.
Figure 15. ISIS contributors with the longest MDT

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub Area</th>
<th>Description</th>
<th>Recorded Number of Faults</th>
<th>Recorded Repair Time (h)</th>
<th>Mean Time Between Faults (h)</th>
<th>Mean Repair Time (h)</th>
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<td>221</td>
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<td>154.95</td>
<td>1579.13</td>
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<tr>
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<td>364.17</td>
<td>114.85</td>
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</tr>
<tr>
<td>341</td>
<td>EPB Serv Vacuum Vessels and Pumps</td>
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<td>6.13</td>
<td>6316.60</td>
<td>3.08</td>
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</tr>
<tr>
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<td>Synch Injection Magnets</td>
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<td>154.06</td>
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</tr>
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</table>

Figure 16. Proposed format – desired information

<table>
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<tr>
<th>Date &amp; time</th>
<th>Down-time</th>
<th>Area</th>
<th>System</th>
<th>Sub-system</th>
<th>Assembly</th>
<th>Component</th>
<th>Failure mode</th>
<th>Description of the observed failure mode</th>
<th>Comments</th>
</tr>
</thead>
</table>

The recording of the events including the date and time of occurrence and associated downtime duration in time series sequence is needed for analyses of the type presented above for the LANSCE data. This type of data format can always be converted into any other desired form. Next, it is important that the event be characterised in as much detail as possible. The definition of categories to simplify the task for the operator recording the given failure event is recommended, down to the lowest possible level. The system used in ISIS is an excellent example of implementation of such a scheme. It shouldn’t be difficult to code it so that the assignment can be made by the operator following a hierarchical menu of selections with a series of mouse clicks. A description of the mode of failure is also needed since most components can fail in several different failure modes. Finally, all additional comments that are available should be recorded to help in subsequent root cause analyses. This format will produce a data set of failure events that will lend itself to every analysis imaginable. For this purpose, the software in which this scheme is implemented should also be capable of exporting the data into a standard such as Microsoft Excel or Access.
Future directions

As mentioned above, the reliability methods required for analysis of repairable systems must go beyond the simple evaluation of the time to first failure. In fact, the fundamental problem in the analysis of repairable systems is the ability to distinguish between reliability deterioration and improvement. Proper formulation of this problem requires the formalism of non-stationary stochastic processes rather than cumulative distribution functions. This type of analysis becomes possible, if the data is available in the time series format. This method is based on the understanding that the failures and repairs are a random process. Once we make an assumption concerning the type of the process, we can fit the process parameters to the data.

For example, if we assume that the process is a non-homogenous Poisson type with \( N(t) = \) number of events at time \( t \) as a random variable, then the probability of \( r \) failures in the interval \((t_1, t_2)\) is expressed as:

\[
\Pr[N(t_2) - N(t_1) = r] = \frac{ \left\{ \int_{t_1}^{t_2} \nu(t)\,dt \right\}^r \exp\left( -\int_{t_1}^{t_2} \nu(t)\,dt \right) }{ r! } \]

where \( \nu(t) \) is the rate of occurrence of failures (ROCOF is used by some to denote this quantity to avoid confusion with the “failure rate” already used for the failure hazard function). ROCOF, generally a function of time, can be assumed in the power form:

\[
\nu(t) = \lambda \beta t^{\beta - 1}
\]

and the constants can then be estimated based on the sample.

The knowledge of \( \nu(t) \) allows one to make predictions about the future behaviour of the time series, e.g. the expected number of events or reliability over a given time interval can be predicted as shown in Figure 17. Here, in the left upper quadrant, the cumulative number of failure events is plotted as a function of time for the run called Cycle 71. It can be seen that around the middle of the run, a dramatic reduction in the failure rate is marked by a change of slope of the curve. One cannot see this event so clearly when looking only at the times between the arrivals of events plotted in the right upper quadrant. The values of the \( \nu(t) \) fitted to the data as a function of time are shown in the left lower quadrant. The diminishing ROCOF reflects the diminishing slope of the cumulative number of events curve. The \( \nu(t) \) can now be used to make predictions about the behaviour of the system in the future. For example, the figure in the lower right quadrant shows the calculated value of the expected number of events over eight hours as a function of time that could be extrapolated for any time needed.

A similar type of analysis may be performed for the time series of the repair times. Assuming again that the underlying process is Poisson, we can introduce \( \mu(t) \), the rate of occurrence of repairs (ROCOR) as the parameter of this Poisson process. After fitting it to the data, the knowledge of \( \mu(t) \) allows one to make predictions about the future behaviour of the repairs time series. Figure 18 illustrates this analysis for the repair times for the same Cycle 71 of the LANSCE data. First, in the left upper quadrant, the cumulative number of repairs is plotted as a function of the total cumulative repair time (one has several choices for the abscissa here; the total cumulative time between failures or the total calendar time could also be used in the analysis. The particular choice made here is a kind of canonical selection but one of the other choices may turn out to be better for practical purposes).
It can be seen that this cycle is dominated by a few long downtime events in the beginning of the run (so the Poisson process does not fit this data very well), and a dramatic increase in the repair rate is recorded as a strong a change of slope of the curve mid-way through the run. Again, it is advantageous to plot the cumulative number of repair events because one cannot see this upswing so clearly when looking only at the times between the arrivals of events in the right upper quadrant.

Figure 17. LANSCE Cycle 71 failure time series analysis and performance prediction

Figure 18. LANSCE Cycle 71 repair time series analysis and performance prediction
The values of the $\mu(t)$ fitted to the data as a function of time are shown in the left lower quadrant. The increasing rate reflects the increasing slope of the cumulative number of repairs curve. Again, $\mu(t)$ can be used to make predictions about the future behaviour of the process.

The figure in the lower right quadrant shows down times plotted against the corresponding (i.e. immediately preceding) times between failures and clearly demonstrates the rather interesting fact that there is no correlation between the two.

The type of analysis presented in this section has immediate practical applications in the form of prediction of system behaviour for the same system for which the data has been originally collected. It is necessary to further examine the options available here concerning the type of the process assumed for the analyses. It is already clear that the Poisson process is probably not a very good underlying assumption for the repairs. Study of other options may provide us more insight into the nature of the repairs process. Further development, employing the queuing theory, may lay the grounds for mathematical maintenance optimisation [6] leading to potential substantial improvements in the way the accelerators are operated.

**Summary and conclusions**

In summary, the process of reliability data survey and analysis has been initiated and although much territory remains to be covered, significant progress has been made – we are a long way from the point of departure. We have collected factual information that already allowed for characterisation of the spectrum of the accelerator beam trips.

These data were used to obtain first estimates of the MTBF and MDT estimates via statistical analyses of LANSCE data for typical accelerator components that will be useful in making predictions about reliability and availability characteristics of the future designs: DC magnet power supply, DC magnet, klystron assembly, HV power supply. Both MTBF and MDT are generally shorter than previously expected. As mentioned above, most of the recorded failures are “soft” failures caused by RF arcing which do not require actual replacement of parts, just a reset after a very short duration downtime.

Frequent, short interruptions caused by sparking in the RF system, cavities and waveguides are clearly experienced by all the facilities. It is possible that these interruptions can be eliminated, either by a more conservative design or more attention to cleanliness in the assembly of the high voltage cavities (most sparking is apparently generated via field emission activity enhanced by dust or impurities). In addition, careful examination of the data already collected to identify all the typical accelerator system failure modes and elimination of their corresponding root causes should eventually lead to elimination of all frequent beam trips. Application of sound principles of reliability practice in the design process should avoid most of the other problems with a definite improvement of the reliability characteristics of an accelerator. Design of maintainability into the system as early as possible in the design process will improve availability of the future accelerator systems.

_Acknowledgements_

Generous assistance of many individuals from CERN, DESY, ISIS, LANSCE and TJNAF who supplied the data and their precious time to answer my questions is gratefully acknowledged. Also, I would like to thank Marcus Eriksson for his devotion to the LANSCE data collection and their thorough analyses at Los Alamos during the cold winter of 1998.
REFERENCES


RELIABILITY ASSESSMENT OF THE LANSCE ACCELERATOR SYSTEM

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Abstract
This paper describes the reliability analysis of the accelerator facility at Los Alamos Neutron Science Center (LANSCE) [1]. The goal of the analysis is to present beam failure statistics of LANSCE and identify the root cause of a beam failure. Beam trips and failure causes are assembled using operational data records, accelerator logbook and beam monitor data. Mean time between failure and mean downtime estimates are obtained for typical accelerator components. The results are useful in accelerator reliability modelling and identifying development issues in high power accelerators.
Introduction

The reliability and availability of the accelerator in an accelerator driven system is an important issue. New applications for high power proton accelerators such as the production and destruction of radioactive elements demand high availability, reliability and maintainability. Persistent beam power fluctuations have a negative influence on a hybrid system. In order to estimate and improve the availability and reliability of future accelerator designs, data from existing accelerators are being analysed. The accelerator facility at Los Alamos Neutron Science Center (LANSCE) is the most powerful linear proton accelerator in the world. The accelerator offers enough operating history to supply meaningful reliability data.

The objective of the present data collection and analysis effort is to understand the behaviour of existing operating accelerator facilities so that better, more reliable systems can be designed and built in the future. Previous work has identified the current state of the art lacking in the area of reliability database information for components typically used in RF accelerator systems, such as RF stations, RF drives, RF transport, cooling, vacuum systems, magnets and magnet power supplies. Thus, while it is possible to use the reliability theory to model accelerator systems, the input data currently available for such analyses lacks credibility. This led to the initiation of an effort of data collection and analysis of which this study is one of the tasks. The present work examines the data set of failure events for the LANSCE 800 MeV accelerator facility.

The LANSCE accelerator facility

The LANSCE accelerator delivers two proton beams at 800 MeV: the $^1$H$^+$ and the $^1$H$^-$ beam. The $^1$H$^+$ beam may deliver 1.25 mA current (routine operation is at 1 mA) and the $^1$H$^-$ beam delivers 70 µA. Each injector system includes a 750 keV Cockcroft-Walton type generator. Both ions are accelerated simultaneously in one and the same structure. After acceleration the $^1$H$^+$ and $^1$H$^-$ beams are separated. The $^1$H$^-$ beam is injected into a proton storage ring for accumulation and delivery to the neutron scattering centre or weapons neutron research.

Table 1. The LANSCE accelerator delivers two ion beams

<table>
<thead>
<tr>
<th>Beamline</th>
<th>Energy</th>
<th>Current</th>
<th>Injector (high voltage generator)</th>
<th>Proton storage ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^+$ beam</td>
<td>800 MeV</td>
<td>1.25 mA</td>
<td>Cockcroft-Walton</td>
<td>No</td>
</tr>
<tr>
<td>H$^-$ beam</td>
<td>800 MeV</td>
<td>70 µA</td>
<td>Cockcroft-Walton</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The low energy section of the accelerator is an Alvarez drift tube linac (DTL). The drift tube linac accelerate the protons from 750 keV to 100 MeV. The high energy section is a Side Coupled Linac (SCL). The SCL may accelerate protons up to 800 MeV. Different RF systems are used for the drift tube linac and for the side coupled linac. In the DTL, triode power tubes are used for the generation of RF power while in the side coupled linac klystrons are used. The RF system for the DTL is sometimes referred to as the 201 system since the RF frequency in the drift tube linac is 201.25 MHz. The RF system for the SCL is called the 805 RF system since the RF frequency is 805 MHz.
### Table 2. Different RF systems are used in the DTL and the SCL

<table>
<thead>
<tr>
<th>Linac section</th>
<th>Energy region</th>
<th>RF power</th>
<th>RF frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift tube linac</td>
<td>750 keV-100 MeV</td>
<td>Triode power tubes</td>
<td>201.25 MHz</td>
</tr>
<tr>
<td>Side coupled linac</td>
<td>100 MeV-800 MeV</td>
<td>Klystrons</td>
<td>805 MHz</td>
</tr>
</tbody>
</table>

Ahead of time a beam schedule has been organised with respect to time-sharing between experiments, beam intensity and beam energy. An overall schedule of commissioned beam time for each beamline is set out. Scheduled operation at LANSCE is divided into run cycles. During scheduled operation, the accelerator is operated almost 24 hours per day for an entire run cycle with only a few scheduled breaks. A run cycle is maintained for approximately 5-6 weeks (800-1 000 hours). A large fraction of the year the accelerator is not scheduled due to maintenance activities. Scheduled operation is usually in the region of 2 000-3 000 hours per year, which is about 30% of the year. In reliability assessment of LANSCE the total scheduled beam time is an important factor – beam trips are only analysed if they occur within scheduled accelerator operation.

#### Input data

Beam delivery is measured by current monitors near the targets. If the beam current for some reason is below half the scheduled current the beam is considered as interrupted. This event/trip generates loss of scheduled beam time, commonly called downtime. The operator assigns a failure cause, or downtime assignment, to each trip. The downtime assignment is recorded in the logbook. The failures and downtime assignments are also entered into operational data records. Separate data records are maintained for each beam line or target area. In this investigation beam trips associated with the $H^+$ beam and the $H^-$ beam are analysed. The records obtained cover run cycles 71-76, over the period 1996-97.

The first, and most time intensive, task of this effort was collecting the input data. Thanks to the co-operation of the LANSCE Operations Group, a large amount of data was collected. This included:

- operational data records;
- central control room logbook;
- operations shift supervisor’s summary reports;
- beam monitor data for 1997.

#### Overall LANSCE reliability

In this section, the distribution of beam trips and downtime for the entire LANSCE accelerator facility is presented. The analysis considers scheduled accelerator operation of the $H^+$ beam for 1997 and of the $H^-$ beam for 1996 and 1997. The $H^+$ and the $H^-$ beams are investigated separately. All calculations are based on operational data records or indirectly accelerator logbook data. A histogram of beam trips that occur in the $H^+$ and the $H^-$ beam is presented in Figure 1.

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Figure 1. Beam failure statistics of the LANSCE accelerator facility

Summary of beam trips at LANSCE
(Normalised number of trips per operating year)

<table>
<thead>
<tr>
<th>Duration of beam interruption</th>
<th>Number of trips</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-1 min</td>
<td>3515</td>
</tr>
<tr>
<td>1-5 min</td>
<td>735</td>
</tr>
<tr>
<td>5-15 min</td>
<td>203</td>
</tr>
<tr>
<td>15-60 min</td>
<td>132</td>
</tr>
<tr>
<td>1-5 hours</td>
<td>612</td>
</tr>
<tr>
<td>&gt; 5 hours</td>
<td>1167</td>
</tr>
</tbody>
</table>

H+ beam: 1.6 trips/hour (40 trips per day)
H- beam: 0.8 trips/hour (20 trips per day)

From Figure 1 it is obvious that the H+ beam is exposed to many beam trips with short duration. Seventy-six per cent of all trips in the H+ beam are 0-1 minute long. When comparing the total number of trips in the H- and H+ beams, the conclusion is that twice as many trips occur in H+ beam. When operating, the H+ beam is exposed to 1.6 trips/hour and the H- beam 0.8 trips/hour. The main reason is the larger number of short trips in the H+ beam. For long downtimes (> 5 minutes), almost the same number of trips occur in the H+ and the H- beams. This makes sense since both beamlines utilise, for most of their length, the same accelerating structure. At a closer look, a slightly larger number of long trips occur in the H+ beam. The reason is that the H+ beamline is more complex. It includes the proton storage ring and hence more components are subject to failure.

In Figure 2, the most frequent causes for beam failure and beam downtime in the H+ beam are presented. Two columns are displayed for each individual system. The leftmost column in each system shows the fraction of total number of H+ trips the system is responsible for. The rightmost column shows the equivalent fraction of total downtime. It is a good thing to separate trips and downtime. Trips affect beam stability and produce power fluctuations. Downtime has a negative influence on the overall beam availability.

From Figure 2, it is obvious that an injector failure is the most frequent cause for beam trip. In the H+ beam 77% of all trips are caused by a failure in the H+ injector. The characteristic of the injector failure is the interruption length. It is usually shorter than 1 minute, often in the order of 15-20 seconds, the time it takes to reset the trip and re-energise the Cockcroft-Walton generator. An injector failure is usually caused by electric breakdown in the high voltage column. Since a typical injector failure is short, the injector is not as dominating when it comes to the generation of downtime. While the H+ injector is responsible for 77% of the trips it is “only” responsible for 30% of the downtime. In other words, the injector is the main reason for beam current fluctuations but it has a significantly smaller influence on the overall beam availability. The RF system, including the RF system for the DTL and the SCL, is generating 8% of the trips but is accountable for 23% of the downtime. Hence, a failure in the RF system usually results in a long downtime (> 5 minutes).
Figure 2. Systems responsible for trips and downtime in the H\(^+\) beam

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>Fraction of beam trips</th>
<th>Fraction of downtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(^+) injector</td>
<td>77%</td>
<td>30%</td>
</tr>
<tr>
<td>RF system (201 &amp; 805)</td>
<td>08%</td>
<td>23%</td>
</tr>
<tr>
<td>Target</td>
<td>02%</td>
<td>15%</td>
</tr>
</tbody>
</table>

Summary of trips and downtime in the H\(^+\) beam:

<table>
<thead>
<tr>
<th></th>
<th>Fraction of trips</th>
<th>Fraction of downtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(^+) injector</td>
<td>77%</td>
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<td>08%</td>
<td>23%</td>
</tr>
<tr>
<td>Target</td>
<td>02%</td>
<td>15%</td>
</tr>
</tbody>
</table>

In Figure 3, historical data on overall beam availability and beam schedule for the years 1979-97 is presented [2]. The line graph represents beam availability and the column bars represent the scheduled beamtime. It is important to remember that the availability only measures the availability of the accelerator during scheduled operation. A common misunderstanding is that the availability of the machine gives the year round availability.

Figure 3. Historical availability and scheduled beamtime of the H\(^+\) beam [2]

Figure 3 is interesting in the that sense it shows the relation between beam availability and the length of the operating period. Since a short scheduling period is usually followed by a longer maintenance period, Figure 3 also gives information on the affect of accelerator maintenance on overall availability. When examining this figure, the conclusion is that the scheduled beamtime seems to have little influence on the availability. This means that a long schedule does not have to imply lower beam availability. This is not all true but one obvious example occurred in 1985. In 1985, the
The longest schedule ever was practised. The accelerator was commissioned for 4,500 hours (50% of the year) and it operated with normal availability (83%). In some years the availability actually drops when the accelerator is operated for less time! In 1996, the availability experienced a decline due to a single water leak in one of the targets, otherwise the standard availability of LANSCE is in the region of 80-90%. This level of availability is similar to the availability experienced in other accelerator facilities.

Analysis of beam current

Previous calculations and diagrams presented in this paper were all based on data originating from the accelerator logbook. Similar beam reliability analysis is performed for data originating from beam current monitors. The H⁺ beam current has been analysed during scheduled operation of 1997. The beam current at the end of the H⁺ beamline is inspected and interruptions are registered. A total of 163,000 beam current recordings are included in the analysis. The current analysis will verify previous results and it will present the “true” beam performance. When analysing beam current data it is not possible to investigate the failure cause. Results of the beam current analysis are presented in Figure 4. The histogram includes the total number of beam trips detected in the beam current and the corresponding downtime. For comparison, the total number of trips registered in the logbook during the same time period are also included in the histogram.

Figure 4. Reliability of the H⁺ beam at LANSCE

The trips occurred during scheduled operation of the H⁺ beam for 1997. When analysing the beam current a total of 6,914 beam trips are detected. This number is larger than the number of trips recorded in the logbook (4,655 trips) under the same period of time. From Figure 4 it is clear that the main reason is that a large number of short interruptions (15-20 seconds) are detected in the beam current which are not included in the logbook. This is also confirmed by operating personnel. For example, in difficult periods when the injector is tripping frequently all short beam trips are not recorded in the logbook, instead comments like “continuous arcing in the injector column” are used.

For trips with long downtime (> 5 minutes) it is remarkable how well the results agree even though the underlying data origins from two completely different sources. That is a strong evidence
for the correctness of the results from both analyses. When analysing the beam current it is also evident that practically no interruptions with downtime shorter than 10 seconds occur. In other words, if an interruption occurs it is likely it will last for at least 10 seconds.

Reliability of subsystems and components

In this section the reliability of major LANSCE subsystems and components are investigated. A first cut analysis of the available LANSCE data is performed. Mean time between failure (MTBF) and mean downtime (MDT) for individual subsystems are studied to obtain input data for accelerator reliability modelling (RAMI). Individual failures are thoroughly investigated with the help of logbooks, operational reports, operators and maintenance personnel. In case the cause of a trip is uncertain, experts in particular field are consulted to correctly classify the event. The aim is to detect the root cause, down to components level, of each failure. For this purpose, the raw data is divided into categories corresponding to individual subsystems and subsequently estimates of failure and repair rates are obtained. These categories are listed in Table 3.

Table 3. Classification of subsystems

<table>
<thead>
<tr>
<th>MAIN SYSTEM</th>
<th>SUBSYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>805 RF</strong></td>
<td>Klystron assembly</td>
</tr>
<tr>
<td></td>
<td>High voltage system</td>
</tr>
<tr>
<td></td>
<td>805 tank</td>
</tr>
<tr>
<td></td>
<td>Phase and amplitude control</td>
</tr>
<tr>
<td></td>
<td>Resonance control</td>
</tr>
<tr>
<td></td>
<td>Module control</td>
</tr>
<tr>
<td><strong>DC magnets</strong></td>
<td>Magnet hardware</td>
</tr>
<tr>
<td></td>
<td>Interlocks</td>
</tr>
<tr>
<td></td>
<td>Water cooling</td>
</tr>
<tr>
<td></td>
<td>Vacuum</td>
</tr>
<tr>
<td><strong>Magnet power supplies</strong></td>
<td>Electronics</td>
</tr>
<tr>
<td></td>
<td>Capacitors</td>
</tr>
<tr>
<td></td>
<td>Water cooling</td>
</tr>
<tr>
<td></td>
<td>Interlocks</td>
</tr>
<tr>
<td><strong>Pulsed power</strong></td>
<td>Harmonic buncher</td>
</tr>
<tr>
<td></td>
<td>Deflector</td>
</tr>
<tr>
<td></td>
<td>Chopper</td>
</tr>
<tr>
<td></td>
<td>Kicker</td>
</tr>
<tr>
<td><strong>Water system</strong></td>
<td>Water pump</td>
</tr>
<tr>
<td></td>
<td>Piping</td>
</tr>
<tr>
<td></td>
<td>Other</td>
</tr>
<tr>
<td><strong>Vacuum system</strong></td>
<td>Ion pump</td>
</tr>
<tr>
<td></td>
<td>Piping</td>
</tr>
<tr>
<td></td>
<td>Unknown</td>
</tr>
</tbody>
</table>

Failures corresponding to each subsystem are merged and classified into individual databases. In Table 4, an illustration of the database format for failures in the klystron assembly of the 805 RF system is presented. Similar databases are compiled for each subsystem. The database contain trips that affect both the H⁺ and the H⁻ beams. Failures are only recorded if they occur within scheduled operation.

The database is for practical reasons divided into three major sections. One section deals with the duration of the interruption. It contains the date and time of the beam outage and restoration. It also includes the downtime of each interruption. The second section considers the location of the failure. The area defines the geographical location of the failure [3]. The system and subsystem columns specify in what system and subsystem the failure is located. The third section gives detailed information on the cause of the failure. The cause may be a component failure that needs replacement, a bad condition such as a water flow problem or an adjustment failure that needs to be tuned. In the comment column, extra text has been added to explain the failure.
<table>
<thead>
<tr>
<th>Date &amp; time of outage</th>
<th>Date &amp; time of restoration</th>
<th>Downtime [h:min]</th>
<th>Area</th>
<th>System</th>
<th>Subsystem</th>
<th>Component failure or other reason</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/01/96  02:09</td>
<td>11/01/96  02:29</td>
<td>0:20</td>
<td>LINAC</td>
<td>805</td>
<td>Klystron</td>
<td>Flow switch</td>
<td>Module 21 klystron water not okay. Mechanically agitated flow switch and it made up.</td>
</tr>
<tr>
<td>11/23/96  09:43</td>
<td>11/23/96  09:56</td>
<td>0:13</td>
<td>LINAC</td>
<td>805</td>
<td>Klystron</td>
<td>Water flow</td>
<td>Sector D off. Module 21 klystron water flow tip. The klystron magnet supply value has been opened 1/8 of a turn.</td>
</tr>
<tr>
<td>03/17/97  07:25</td>
<td>03/17/97  07:40</td>
<td>0:15</td>
<td>LINAC</td>
<td>805</td>
<td>Klystron</td>
<td>Ion pump</td>
<td>Module 46 (Sector H) klystron ion pump supply failed. It was replaced.</td>
</tr>
<tr>
<td>05/24/97  07:24</td>
<td>05/24/97  13:14</td>
<td>5:50</td>
<td>LINAC</td>
<td>805</td>
<td>Klystron</td>
<td>Klystron</td>
<td>Module 36 main amplitude crowbar. Sector F tripped a second time and the fire alarm went off. Acrid smell from the capacitor room. Module 36 klystron was replaced.</td>
</tr>
</tbody>
</table>

The main objective of the analyses is to obtain estimates for the MTBF and MDT for typical accelerator components, such as RF amplifiers, HV power supplies, magnets, magnet power supplies, vacuum system components and water cooling components. For illustration the mean downtime estimate as a function of time for the magnet power supplies is presented in Figure 5. Each dot marks a failure in the magnet power supply. Spaces in between dots is the time between failure. The diagram shows the mean downtime estimate at a certain number of failures. The final mean downtime estimate for the magnet power supplies is obtained at the last failure in the diagram.

**Figure 5. Cumulative mean downtime for magnet power supplies**

One indication of sufficient number of entries in the data set is the asymptotic behaviour of the statistical estimators for the desired quantities, such as the cumulative mean downtime which is calculated as the ratio of the cumulative downtime to the cumulative number of events as shown in Figure 5. The conclusion in this case is that further data collection is not necessary, mean downtime estimate appears to be stable at approximately 50 minutes. A similar plot is made for the cumulative mean time between failure in Figure 6.
Cumulative mean time between failure is calculated as the ratio of the cumulative number of failures to the cumulative up time (scheduled time – downtime). As illustrated in Figure 6, the MTBF behaviour for the magnet power supplies is not as smooth as for the cumulative downtime but it appears to converge somewhere in the region of 30 h. With 278 magnet power supplies total in the system, the MTBF estimate for an individual magnet power supply is 8 445 hours, assuming that all supplies have the same failure rate and can be treated as a series system of independent power supplies.

The results obtained via similar analyses for the other subsystems at LANSCE are summarised in Table 5.

**Table 5. Some results of the reliability investigation of subsystems and components**

| RESULTS OF A RELIABILITY STUDY AT LANSCE |
|-------------------------------|-----------------|-----------------|-----------------|
| **Main system**               | **Subsystem**   | **MDT [h:mm]** | **MTBF for all devices [h]** | **MTBF for a single device [h]** |
| 805 RF                        | Klystron assembly | 0:44           | 262                          | 11 560                          |
|                               | High voltage system | 0:18           | 137                          | 960                            |
| DC magnets                    | 0:53            | 290            | 232 280                      |
| Magnet power supplies         | 0:50            | 30             | 8 445                        |
| Pulsed power                  | Harmonic buncher | 0:09           | 44                           | 44                             |
|                               | Chopper magnet  | 0:08           | 291                          | 291                            |
|                               | Deflector magnet | 0:10           | 342                          | 684                            |
|                               | Kicker magnet   | 1:58           | 185                          | 557                            |
| Water system                  | 1:20            | 120            |                              |
|                               | Water pump      | 0:29           | 245                          | 29 506                         |
| Vacuum system                 | 0:48            | 77             |                              |
|                               | Ion pump        | 0:29           | 101                          | 25 308                         |
The MTBF for the klystron assembly calculated from the raw data corresponds to the entire 805 RF system consisting of 44 klystron assemblies. An estimate of the MTBF for an individual klystron assembly was obtained by multiplying this value by 44 as 11 560 hours. This value is not unreasonable when compared with the 20-50 000 hours commonly quoted for the typical klystron tube by itself. A total of 800 DC magnets exist in the LANSCE facility. MTBF for a single magnet is 232 280 hours (=26 years). The DC magnets at LANSCE are very reliable. This is also confirmed by maintenance personnel at LANSCE. Fifty per cent of the magnet failures are water cooling problems inside the magnet. The most frequent failure cause in a magnet power supply is malfunctioning electronic equipment. Most of the power supplies at LANSCE are controlled by manual electronics. Modern power supplies are computer controlled and proves to be much more reliable. MDT for a water pump is 29 minutes and MTBF is 25 300 hours (=3 years). MDT for an ion pump is 29 minutes and MTBF is 25 300 hours (=3 years).

**Failure analysis**

Analysis of failure causes is performed for all major systems. In this section the failure analysis of the RF system is illustrated. In Figure 7, the distribution of trips in the RF system is presented. In Figure 8, on a deeper level, the distribution of trips in the klystron assembly is presented.

**Figure 7. Distribution of trips in the 805 RF system**

All subsystems of the 805 RF system are represented in Figure 7. The high voltage system causes many short interruptions. Usually the high voltage system causes phase or amplitude disturbances to the beam. Twenty-six per cent of the failures in the RF system are unknown. Sometimes when a failure occurs in the RF system it is not possible to point out any specific subsystem (but it is known that the failure occurred in the RF system!). Fifteen per cent of the failures in the RF system are caused by the klystron assembly. In Figure 8, typical failure causes in the klystron assembly are presented.

The klystron assembly includes some other components beside the klystron tube, for example an ion pump, a klystron magnet, etc. Thirty-eight per cent of all failures in the klystron assembly are water cooling problems and 32% are amplitude crowbars. Amplitude crowbars are usually electric sparking in the klystron tube or switchtube (and this may be due to an old switchtube). Most of the downtime occurs when klystron replacement is necessary. During scheduled operation of 1996-97, four klystron replacements occurred.
Conclusions

Operational statistics of the powerful 1.25 mA H$^+$ beam at LANSCE has been obtained using the accelerator logbook and beam monitor data. When the beam current is inspected over a long period of time (2 800 hours), on average 2.4 trips/hour or 60 trips per day are registered. Approximately 75% of all trips are 0-1 minute long. The typical downtime of a beam trip is 15-20 seconds.

In the overall reliability balance of the entire LANSCE accelerator, the injector is responsible for most of the trip events. The injector is accountable for 77% of all trips in the H$^+$ beam. The injector is primarily generating short trips. For long downtimes (> 5 min) the RF system is the largest producer of trips. Upgrading the injector will result in a more stable beam with less interruptions, especially short ones. Upgrading the RF system will result in a better beam availability.

In summary, as a result of the investigation of individual systems, estimates for both MTBF and MDT were obtained for several typical accelerator components: DC magnet power supplies, DC magnets, klystron assemblies, HV power supplies, vacuum system, and water system. The results will be useful in developing preliminary estimates for reliability, availability and maintainability of high power accelerator systems planned in the future. However, before we can fully trust them, they have to be corroborated through comparison with statistics obtained from other facilities. The impact of maintenance activities outside of the scheduled production time needs to be tracked down and included in the estimates as well.

Acknowledgement

The generous assistance of many LANSCE Operations Personnel in performing this work is greatly appreciated. Special thanks are due to Michael Oothoudt and Tim Callaway of LANSCE-6. Also, special thanks are due to Stan Cohen of LANSCE-6 for valuable help with magnet power supplies and John Lyles of LANSCE-5 for help with RF technology.
REFERENCES


OPERATIONAL EXPERIENCES OF THE MOSCOW MESON FACILITY

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Abstract

Construction of a 600 MeV, 500 mA MMF linac has been completed at the INR in Troitsk, 20 km away from Moscow. The linac is operating and has been used for nuclear physics and condensed matter research as well as for isotope production. We have projects aiming toward two more applications: a prototype for nuclear transmutation of minor actinides and a facility for proton therapy.

The parameters of the linac are as follows: proton energy 500 MeV, pulse current 20 mA, pulse duration 150 mks, repetition rate 50 Hz, average current 120 mA.

In 1997-98 the linac provided about 5 000 hours for physics, isotope production and machine development. In 1998, a proton beam was delivered to the pulsed neutron source for the first time. A number of improvements have been implemented having a strong impact on operational efficiency.

One of the most important measures is the creation of a control network for beam diagnostics data acquisition. The new control system offers different types of beam diagnostics monitors: beam current transformers, wire scanners, harps, bunch length and velocity detectors, beam loss monitors, monitors for the measurement of transverse beam density, neutron detectors, etc.

The beam delivery system to the isotope production area includes a bending magnet and a transport channel. The control of beam losses in the vicinity of the bending magnet is a problem of great importance due to the high level of the average beam current. Discrepancies between the beam energy and the magnet current as well as a violation of the correcting elements parameters can lead to instantaneous melting of the vacuum pipe. To prevent such an accident a number of protective measures have been undertaken.

The linac contains two transition regions: 100 MeV and 160 MeV. It is very important to verify the longitudinal bunch length in those regions. The bunch length measurement technique is well established at the INR. Recently, the last modification of the bunch length and velocity detector has been installed at 160 MeV area. The high resolution of the detector allows to monitor the quality of the linac operation. The device uses 100 mkm wire which allows to perform the measurements even at a 50 Hz repetition rate.
The procedure and techniques to control the crucial problem of beam losses at high intensity proton linac are very well developed at the INR. The operational experience of the MMF is useful for R&D and the study of utilisation and reliability of high power proton accelerators.

The Moscow Meson Facility Neutron Complex using a special box for nuclear transmutation study (2.5 MW thermal power), the Pulsed Neutron Source, the Facility for Irradiation Study and the Lead Slowing-Down Neutron Spectrometer could be used for a wide range of tasks in the field of nuclear energy applications. The Institute and the MMF are open to international collaboration.
Reliability of HPPAs – Part II

Chairs: M. Ishihara and C.M. Piaszczyk
Increasingly, accelerators are used for applications in different fields and for purposes they were not originally designed for. This requires large conversion and upgrade programmes, as is the case with the PSI cyclotrons. The most expensive (and extensive) changes usually are required within RF systems. When the emphasis moves toward high beam intensities, the necessary power increase has to be supplied through the RF systems, while, at the same time, the need to keep losses inside the machine at acceptable levels calls for an increase of the acceleration voltages. New concepts have to be developed for such RF systems. If new applications then ask for increased reliability at the same time, it becomes obvious that reliability itself becomes the key issue. Only recently have we concentrated on this topic; some new findings and observations of this process will be presented.
Introduction

When cyclotrons are built for research, they are usually built as unique, one-of-a-kind facilities, remaining prototypes for most of their useful life. Emphasis is placed on continuous enhancements of beam types and specifications. Often, the original focus of the design will be abandoned, following new trends in research, or shifting towards applications in different fields.

The PSI cyclotron facility is proof of this point: originally (30 years ago) conceived as a pure research meson factory (nuclear and particle physics) designed to deliver up to 100 $\mu$A @ 580 MeV (protons), the machines now serve a much wider spectrum of users and applications. The most prominent such field is neutron physics, which is served by the neutron spallation source, SINQ.

At present, our facility is a three-stage design and produces 1.5 mA protons @ 590 MeV. It consists of a 860 keV Cockroft-Walton DC ion source, feeding an injector cyclotron with 72 MeV output energy, and finally a main accelerator, the ring cyclotron, that delivers a continuous beam through two meson production targets, to a neutron spallation source, the SINQ [1].

What makes this facility unique amongst cyclotrons is its ability to produce a high beam current of more than 1.5 mA. In fact, for test purposes (further intensity increase) we have run for over one hour at 1.7 mA; this figure corresponds to a total beam power of 950 kW (CW).

An extensive upgrade programme had to be initiated to supply the required, much higher beam intensity. Designing and building a new injector cyclotron was foremost on the list, followed by the need to replace most of the existing ring cyclotron RF systems [2]. Since the injector cyclotron (II) had already been conceived with much higher beam intensities in mind, only comparably minor modifications were necessary to reach 1.5 mA beam current @ 72 MeV in 1991.

The entire upgrade programme of the ring cyclotron took five years to complete and consisted of upgrading injection and extraction components, and local shielding, but mainly of adding new, higher power RF amplifiers, RF feeder lines and coupling windows to the four acceleration cavities, and a new flat-topping system (everything but the cavity) [3]. At the same time, all active RF power devices (mainly power amplifiers) where removed from the cyclotron vault. This greatly facilitated maintenance, because the large final amplifiers no longer had to be treated as activated equipment, and access for repairs, testing, tuning, etc., was much simplified.

To reduce the number of turns in the machine (from about 310 turns to about 220) in order to minimise extraction losses, the required acceleration voltage per cavity had to be increased to from 450 kV to 730 kV; herewith more than doubling the necessary RF power (cavity losses). Raising the total beam power from 60 kW to about 1 MW, the RF power to be delivered into the beam increased to over 250 kW per cavity. Thus, the sum of RF losses plus beam power resulted in a total power demand of over 550 kW per cavity [4].

The design goal of 1.5 mA beam current at 590 MeV was first reached in September of 1995.

Only after it was shown that such high beam levels could actually be obtained was reliability recognised and addressed as a necessary next step in the development of high power machines. Experience with operating the cyclotrons at high beam currents made us focus on a new set of objectives: reliability and efficiency became the new issues, and a programme was launched to investigate – and possibly eliminate – the major sources of unscheduled interruptions of beam production.
A look at unscheduled beam interruptions (beam interlocks) on the PSI ring cyclotron

Operating statistics of the year 1997 indicated that the total unscheduled downtime for the PSI ring cyclotron amounted to approximately 600 hours (interruptions of > 4 hrs.), or 11% of the planned beam production time [5]. RF problems accounted for about 1/3 of this time (220 hrs.), corresponding to = 4% of the available beam time (for 1996, this number was somewhat better: approximately 1.5%).

Additionally, long hours of unscheduled outage were caused by water leaks at bending magnet coils in beam lines (= 280 hrs.), and failures of vacuum seals between cavities and vacuum chamber (= 100 hrs.).

The rest of the downtime could be attributed to problems or failures of components and devices which could be fixed in less than four hours; but also to RF cavity tuning system problems, which required waiting for about half an hour before a cavity could be turned on again after each spark (because of tuning system range limitation). Not included – because their contribution is negligible compared to the total downtime – are the numerous short (< 1 min.) interruptions in beam production, due to sparking at beam splitters, injection and extraction septa, as well as sparks inside RF cavities or on coupling elements with fast recovery, and all other beam or safety interlocks (typically = 600 to 1 600 per week).

**Categories of beam interruptions**

Looking at beam trip statistics, we noticed that beam trips in our cyclotron could roughly be grouped into three distinct categories, differentiated by the length of the beam interruption:

<table>
<thead>
<tr>
<th>DURATION OF BEAM INTERRUPTION</th>
<th>CATEGORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short beam trips (duration ≤ 1 min)</td>
<td>1</td>
</tr>
<tr>
<td>Medium length beam trips (between &gt; 1 min. to about 1 hr.)</td>
<td>2</td>
</tr>
<tr>
<td>Long interruptions (&gt; 1 hr. – mostly component failures)</td>
<td>3</td>
</tr>
</tbody>
</table>

When investigating the origins of the beam interlocks, we found that the different systems also contributed differently to the categories mentioned above:

<table>
<thead>
<tr>
<th>AFFECTED CYCLOTRON SYSTEM(S)</th>
<th>CATEGORIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrostatic beam defectors</td>
<td>1, 3</td>
</tr>
<tr>
<td>RF systems</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Beam monitoring devices, loss monitors (ionisation chambers)</td>
<td>1</td>
</tr>
<tr>
<td>All other cyclotron components (magnets and power supplies, vacuum and cooling systems, diagnostics, controls)</td>
<td>3</td>
</tr>
</tbody>
</table>

**Sparks at electrostatic beam deflection elements**

Unfortunately, the drop-out rate of electrostatic elements in 1998 has not changed notably compared to 1997, although the beam splitter in the extracted 590 MeV proton beam line has been replaced by a modified design which seems to work more reliable than the previously tested models.
Operation statistics for a typical week in September 1998 reveal that, out of about 1 100 beam trips, about 1 000 can be attributed to electrostatic devices at injection and extraction and to the two beam splitters. Sparking at the high voltage septa causes these interruptions, which typically last < 1 min., and are therefore of Category 1.

Obviously, the sparking behaviour of these DC components is now a limiting factor, and a study to improve the voltage holding capacity by some means has to be initialised in the future. If one looks at the voltage plots of the electrostatic injection and extraction electrodes (EICV and EECV) as well as the beam splitter voltage (EHTV), it does not give a true picture of the frequency of the occurrence of sparks. This is because the sampling rate of the monitoring in this system is = 1 min., and most sparks are much shorter than that (< 500 ms.). The beam current after extraction (MHC1), however, includes all effects (including ionisation chamber interlocks), and typical beam turn-on takes about 40 sec. The plot of MHC1 therefore is a much better indicator of the frequency and duration of beam trips (see Figure 1).

**Figure 1. Voltage of injection and extraction electrodes (EICV & EECV), the beam splitter (EHTV) and the beam current after extraction (MHC1)**

Typical 10-day period in August 1998

**Sparking in RF systems**

A classification of different causes for RF voltage trips into categories looks as follows:

- *Sparking in cavities (including sparking at power coupling windows):*
  
  Usually of short duration (Categories 1 and 2). Automatic recovery, or resettable by operator. In the case of sparking at ceramic coupling windows, the total number of sparks a window can handle safely is normally limited!
• **Failures of coupling windows:**
  Usually of long duration (Category 3), particularly bad if coinciding with cracking of the ceramic window (vacuum leak) and subsequent forced filling of cyclotron with air. Just as bad are water leaks of coupling loops in vacuum. After each such event, it may take several weeks of operation before the sparking rate of the cavities is down to the “normal” value (conditioning!). Figure 2 shows measured drop-out rates for different cases.

• **RF system component failures:**
  − Systems with limited lifetime: (≤ 3 years), e.g. power tubes, RF cavity windows.
  − Systems with “unlimited” lifetime: (> 3 years), no scheduled replacement during expected lifetime of cyclotron, e.g. standard power supplies (PS), high voltage PS, air and water cooling systems, control systems, frequency tuning systems, RF power amplifiers, etc.

**Figure 2. Conditioning effects in ring cyclotron cavities**

*Note: M-sparks = non-recoverable sparks*

**“Non-recoverable” sparks (RF “OFF”) after (uncontrolled) air leak (April 97)**

**Sparks after (controlled) nitrogen filling of cyclotron (May 97)**
Other causes for unscheduled beam interruptions lasting longer than one hour (component failures)

Component failures are usually responsible for unscheduled interruptions of longer duration. To reduce their contribution to the total downtime of the accelerators, one has to focus on the different types of systems separately. Preventative maintenance has to be introduced and performed, in most cases inevitably increasing operating costs. (Power tubes used in final stages of the ring cyclotron RF system cost well over US$ 70 000.00 a piece, for example, so one would be reluctant to replace still functioning tubes by new ones.) Furthermore, high voltage power supplies, as used in RF power amplifiers employing vacuum tubes, are more susceptible to failure than their low voltage counterparts. Means to assist in quick fault diagnostics, ready-to-operate replacement units, fast interchangeability for all critical components and devices are essential in cutting downtime caused by equipment failure. Consequently, all older systems, including RF amplifiers, power supplies, RF control systems and RF interlocks have been converted to a strictly modular design over the past few years.

The components which caused the excessively long interruptions in 1997 (water leaks at bending magnet coils, for example) did not have complete backup units at that time, a situation which has been remedied for those (and other) components in 1998.

The RF system improvement programme

Generally, two ways to reduce the contribution of RF sparking to total beam off-time are possible:

a) Reduce the absolute number of sparks per unit time, for example by conditioning RF cavities. This is a very time-consuming process by itself, and it has to be repeated after each breaking of the cyclotron vacuum. As mentioned before, filling the cyclotron with nitrogen instead of (moist) air makes a great difference, as is illustrated in Figure 2.

b) Analyse sparking mechanisms in cavities and on coupling windows, try to reduce induced damage on ceramic windows and make spark recovery as quick as possible [6].

Additionally, multipacting phenomena in cavities can be a serious problem. In our case, they can prevent RF turn-on for up to half an hour after a spark; some cavities may even become impossible to turn on. Special measures are then needed, like coating critical areas inside a cavity with special materials to reduce the secondary electron emission coefficient (and thus multipacting), and/or fast pulsing of the RF drive. Part of this problem is due to the fact that our cavities are made of aluminium; copper surfaces would show a somewhat lower secondary electron emission coefficient. This property and the fact that redesigned copper cavities can have higher Q and Rp values are amongst the reasons why we are presently designing four new copper cavities for our ring cyclotron [4].

Classes of sparks in cavities, and how to minimise their influence

In all RF resonators at PSI, we observe two different classes of sparks; both of them not causing permanent damage:

- Short (50...250 µs duration) sparks (see Figure 3), which extinguish automatically, even if the RF power into the cavity is not removed for that time. (We call them micro-sparks, or µ-sparks.) Under present operating conditions, we do not even turn off the beam during a µ-spark (≤ 200 µs).
Secondly, there are sparks which do not extinguish for > 3 ms, after which time the amplifier protection circuits turn off the RF drive. After that, pulsing and ramping procedures re-establish full resonator voltage within 4...6 s. (see following Figure 4) This has only become possible after an addition to the cavity tuning system had been designed, allowing the system to lock onto the exact cavity resonance before the pulses are applied.

Figure 4. Cavity voltage, showing RF pulsing and ramping after non-recoverable spark

Sparking around RF couplers and windows, countermeasures

In the past, sparking at couplers limited the lifetime of RF windows; each spark evaporated some metal at the impact points (sputtering). Part of this metal vapour was then deposited on the ceramic surface of the insulator. After a limited number of such sparks (typically a few hundred), this metallic layer became dense enough to be conducting, thus shortening out the RF voltage across the coupling window. The subsequent RF heating of the ceramic window led to cracking, resulting in disastrous air leaks. The required RF power increase made the problem intolerable; lifetimes of weeks at best (at elevated power levels) became the rule.

An extensive study of the problem led to a complete redesign of the coupling elements, and also included electron detection pick-ups at the coupler. This system permits to turn off the RF drive immediately (within µs) after electrons of a spark at the window are detected, drastically reducing the
available energy in a spark, and thus the amount of sputtered material. At the same time, it allows to differentiate between sparks in a cavity (non-destructive) and sparks at coupling windows, which are potentially dangerous because they limit the lifetime of RF coupler windows [6]. The resulting improvement in coupler lifetime is shown in Figure 5.

**Figure 5. RF coupling loop replacement record of ring cyclotron cavities**

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<th>94</th>
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<th>96</th>
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<tr>
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<td>Cavity 2</td>
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<td>Cavity 5</td>
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</tbody>
</table>

Old type loop

New loop

Defective

Replaced without being defective

Shut-down periods

Start of high power operation

**Results**

New coupling loop designs, more refined spark detection, new RF turn-off, turn-on and ramping procedures and improved cavity resonance frequency tuning systems led to a significant improvement of total RF system performance. Furthermore, the inside of the cavities most plagued by multipacting (cavities #1 and #4) were coated with “Aquadag”, a remedy which has helped the other cavities in the past, where it seems to have a permanent effect.

The results of all these measures are clearly visible if one compares the ring cyclotron cavity turn-off statistics of 1997 and 1998. It should be noted that, even in 1997, some new coupling loops had been in operation for over three years, so most of the improvement in the statistics of the year 1998 can be attributed to the improvements to the spark detection, turn-off and turn-on procedures, which became possible mainly through careful study of the sparking mechanisms in cavities and coupling windows.

Comparing the available data for the past two months of operation after the shut-down (July and August 1998) to data from the same period of 1997, it can be seen that the improvements in the RF systems have drastically reduced the number of RF triggered interruptions (compare Figures 6 and 7). In the meantime (August 1998), an error in the start-up system of cavity #2 has been found, so its drop-out rate will now match those of the other acceleration cavities (#1, 3, 4).

The same tendencies can be seen only if events of > 1 min. duration are sampled, by displaying cavity voltages as functions of time. A “typical” (that is: not interrupted by scheduled cyclotron off-time) plot of the four acceleration-cavity voltages for a ten day period in August of 1997 and in September of 1998 is shown in Figures 8 and 9. In both cases, operating beam current was ≈ 1.5 mA.
Figure 6. Number of cavity voltage trips in the ring cyclotron in July and August 1997, grouped according to the duration of the acceleration voltage drop-out

Figure 7. Drop-out data for the same two months July and August in 1998
(Note: Cavity 2 drop-out rate has since been reduced – see text)
The improvements are so significant that now, the cavities are no longer the main culprits in our failure rate “hit list”. That “honour” has now been passed on to the electrostatic devices. A look at the distribution of the duration of cavity voltage trips (Figure 7) clearly indicates that the number of short trips (< 1 min.) as well as longer cavity voltage interruptions have been drastically reduced.
Conclusions

The results shown here illustrate the progress that can be made within a two-year period in cyclotron RF systems if one seriously addresses the problem of reliability. We have only just started to systematically look at the failure rates of the more conventional systems and components, applying strict standards to all systems; introducing rigorous preventative maintenance will certainly improve reliability further. The sparking and discharge problems at high voltages (DC and RF) are still far from being fully understood, so an ongoing research programme is necessary to reduce the frequency of discharges further or, in the end, alleviate them altogether (?). In order to obtain higher beam currents in the future, we wish to increase the cavity voltages to approximately 1 MV per cavity, a goal only obtainable with new cavities. A 1:3 scale working model is now undergoing an extensive power test programme. We hope that a new 1:1 scale cavity will be constructed within the next two years, so that the feasibility of this design can be tested [4].

Acknowledgements

Such an ambitious programme can only be achieved in a team, of course, therefore the author wishes to thank all the colleagues in the RF group and the accelerator division for their great co-operation and efforts, which made this performance possible, and will make further progress possible in the future.

REFERENCES

High availability of the neutron source was the prime design goal in the 5.5 MW long pulse SNQ project worked out in great detail during the first half of the 1980s at the Research Centre Jülich, Germany. On the target side a low load level was ensured by a large rotating structure, whose operating temperature would have been sufficiently low to minimise the effect of thermal cycling due to beam trips. However, since availability is almost exclusively determined by the performance of the accelerator, mainly its RF system, a concept was developed that ensured maximum fault tolerance:

- The high energy part, which accounted for 90% of the 1.1 GeV linac was designed as a β-independent structure to allow operation even with faulty accelerating cells.
- A fast RF phase control system allowed pulse-to-pulse adjustment of the RF phase between cavities to make up for non-accelerating cavities along the linac.
- A very distributed RF system was conceived with automated exchange of RF generators while the accelerator was running.
- The beam optics was achromatic along the whole high energy accelerator and beam transport line.

With these features it became possible to:

- adjust the load (stress) on accelerator components to a level they could endure even after the accelerator was built, or in accordance with growing operating experience;
- operate the accelerator even with several cavities down because only the phase advance in the following cavities needed to be adjusted to keep the bunches stable in the accelerating bucket, which could be accomplished in a matter of milliseconds;
- diagnose and repair defective components off-line while operation of the accelerator continued.

With these features a very high reliability and availability of the accelerator as well as very economic operation was anticipated, because the accelerator excels by low power consumption and no preventive maintenance on the RF system was required.
Introduction

In the past, accelerators were mostly designed as research facilities with the specifications being on the edge of what was considered as technically feasible and with the goal to open up new fields of science. New technical developments were often required to achieve these goals and the users of the facilities were in many cases also involved in their design. As a consequence it was generally accepted that there was a continuous development and improvement of peak performance parameters in order to open up new frontiers in science and research. This situation only changed fairly recently, when accelerators were conceived as purpose-built drivers for facilities to be used by communities of a different background. Examples are synchrotron light sources and spallation neutron sources, whose users demand a high availability and reliability of the source because they consider it as a tool to carry out their research rather than as part of their own experimental equipment. An early example was the SNQ project pursued in Germany in the early 1980s.

SNQ was a spallation neutron source designed as a neutron source for a variety of research applications, the main emphasis being on neutron scattering. The total beam power of the source was chosen as 5.5 MW, thus making SNQ the first pulsed neutron source proposed in the multi-megawatt range. The general concept was to have a full energy linac of 1.1 GeV and to add a compressor ring at a later stage in order to shorten the pulses to the sub-microsecond regime. Since this required H⁻ ions to be accelerated and since no suitable H⁻ ion sources were available at that time, the addition of the compressor ring was considered a future upgrade. In its basic version SNQ would be accelerating protons and would be a long pulse neutron source with a pulse duration and repetition rate of 250 µs and 100 Hz respectively, requiring a pulse current of 200 mA to be accelerated in the linac. Since from its general characteristics SNQ was to be used in a similar way as DC research reactors, albeit with an added benefit resulting from its time structure, it was targeting reactor users as its main clientele. This meant that not only should the scientific potential be significantly superior to that of a high flux reactor, but the availability and reliability should also be similarly high. This consideration was one of the main reasons for ultimately choosing an accelerator concept, which had the promise of very high availability, based on three important features:

- The accelerating structure should be independent of the proton velocity, thus making it possible to continue acceleration without interruption even if some of the cells had failed.
- There should be a very large number of individual accelerating units in order to minimise the overall effect of the failure of one or a few of them and to minimise stress and load on certain sensitive components such as RF beam windows.
- Repair of failed components should be done off-line; it should be possible to exchange the most vulnerable components, namely the RF amplifiers, by a robot while the accelerator was running.

It was for these reasons that, after a coupled cavity disk-and-washer structure had been studied for several years for the high energy part of the linac [1], the concept was changed to a single-cell cavity structure. Detailed arguments for this decision will be given in the section entitled The high energy linear accelerator (HELA).

The concept of the accelerator is described in detail in the SNQ project proposal [2] and parts of the following account are taken from an introductory chapter to the accelerator concept in the Phase B project report originally authored by C. Zettler [3]. Although some of the statements on the low...
energy end may not be completely up to date anymore in view of some relevant developments that occurred since the SNQ project was terminated, no attempt was made to adjust to such new developments because the main emphasis of this paper is on the high energy part (HELA) of the linac.

Main parameters and basic concept of the SNQ accelerator

The general concept

It is now generally acknowledged that a normal conducting linac can operate most economically at high beam current, of the order of 100 mA or more. Thus, although the SNQ-accelerator was to deliver only 5.5 MW time average, its beam current was chosen at 200 mA and pulsed operation at 100 Hz with a duty cycle of 2.5% was envisaged. As shown in [4], a pulsed mode of operation, although probably with longer pulses, should be perfectly acceptable, or even desirable, also for ADS in the field of waste management or subcritical assemblies, since multiplexing between various accelerators and driven devices may be of interest. Clearly such an accelerator, once developed, can also be run at a higher duty factor and deliver more beam power, if needed.

The basic parameters characterising the SNQ linac are given in Table 1, and the concept of the accelerator is shown schematically in Figure 1. Two ion sources operating in parallel with an extraction voltage of ~ 50 keV inject into two radio frequency quadrupole (RFQ) structures. These RFQs run at 100 MHz RF frequency with a relative phase shift of 180 degrees and accelerate the beams to 2 MeV. In a funnelling section, which includes devices for bunching and pulse shaping, the two beams are merged together according to the “zipper principle”. This results in a pulse sequence of 200 MHz. This is the frequency on which the subsequent Alvarez structure operates, which means that each of its RF buckets is filled for optimal accelerating efficiency. At an energy around 100 MeV the Alvarez structure becomes rather inefficient and a single-cell (i.e. uncoupled) accelerating structure will take over for higher particle energies. The main items will be described briefly in the following sections.

Table 1. Basic parameters of the SNQ single-cell linear accelerator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final kinetic particle energy (MeV)</td>
<td>1 100</td>
</tr>
<tr>
<td>DC-beam current during pulse (mA)</td>
<td>200</td>
</tr>
<tr>
<td>Time averaged beam current (mA)</td>
<td>5</td>
</tr>
<tr>
<td>Repetition frequency (Hz)</td>
<td>100</td>
</tr>
<tr>
<td>Beam pulse duration (µs)</td>
<td>250</td>
</tr>
<tr>
<td>Accelerating structures and RF-frequencies (MHz)</td>
<td></td>
</tr>
<tr>
<td>– Alvarez</td>
<td>201.25</td>
</tr>
<tr>
<td>– Single-cell structure</td>
<td>201.25</td>
</tr>
<tr>
<td>Mains power (MVA)</td>
<td>24</td>
</tr>
</tbody>
</table>
Figure 1. Schematic illustration of the SNQ RF accelerator

The injector

The RFQ which has been selected for the low energy end is generally considered a major improvement in accelerator technology. It uses a transverse focusing electromagnetic quadrupole mode, which is polarised by four vanes and can handle beams of very low velocity. Due to a special shaping of the edges of the four vanes, the structure is also able to longitudinally trap protons at low velocities with high efficiency. This bunches the beam and accelerates it to energies much higher than that achievable with DC-acceleration at high beam currents. This structure has, in the meantime, been incorporated in most high current linacs and has been proven a major advancement in linac technology.

The Alvarez accelerator

Alvarez accelerators (drift tube linacs) at 200 MHz have been operating successfully and reliably at various laboratories over many years now and pulse currents up to 300 mA have been achieved, although for a pulse duration short enough to allow running off the stored energy in the cavities. This was not possible in the SNQ Alvarez accelerator. Therefore well controlled distributed power feeding into the structure during the pulses was required, together with the usual measures to achieve a finite group (i.e. energy flow) velocity along the accelerator by two overlapping pass bands.

The beam focusing elements were to be located, as usual, in the drift tubes. Use would have been made of conventional quadrupoles, which offer the advantage of easy, empirical adjustment, or of permanent magnet quadrupoles, provided that it could be proved that there are no problems with radiation. Even a mixed system was not excluded.

The high energy linear accelerator (HELA)

There were a variety of reasons for choosing a single cavity structure with separate RF feeding into each cell for the high energy part of the accelerator:

The main problem that was seen with any coupled cavity structure is that in contrast to electrons which travel at the speed of light already at relatively low energies, the velocity of the protons varies as their energy increases. If, as in a coupled cavity structure, a whole set of cavities is resonating with
fixed RF phases from one common feeder line, the mechanical dimensions of the cavities have to be matched to the velocity of the particles, as in the Alvarez structure (fixed $\beta$-structure; $\beta$ is the ratio between the velocity of the particles and the velocity of light). Hence, if at any position the energy gain is less than the design value, the beam will be out of phase with the RF in the rest of the accelerator, which means that operation cannot continue.

With a single-cell structure, where each cell has its own RF supply, the relative RF phases between the cavities are controlled electronically and can be changed very rapidly (variable $\beta$-structure). Ideally each cell should have its own feed and consequently the RF amplifiers will be relatively low power units and large in number. Thus, if one or a few of them fail, the phases in the following cavities can be readjusted to the new local beam velocity and operation can continue with virtually no interruption. If suitable provisions are made for automatic exchange of RF amplifiers with the accelerator in operation, it will not even be necessary to shut the accelerator down if several amplifiers must be replaced within a short time frame. Maintenance and repair of the amplifiers can then be carried out off-line while the accelerator continues to run. In order to avoid high induced voltage by the beam across the gap of those cavities whose RF feeding had failed, electric damping of the cavity was studied.

Apart from the prospect for a high availability of the accelerator, the single-cell structure also holds promise for several important advantages in other respects, in part because it can accelerate the beam with a variable output energy:

- With respect to the RF supply to the accelerating gap, the optimally distributed feeding points in the single-cell structure offer the important advantage that no energy flow along the accelerating structure is necessary.

- By reducing the voltage across the accelerator gaps, more economic operation of the accelerator becomes possible, although at lower output energy. Since the losses in the accelerator are proportional to the square of the electric field whereas the output energy (and the neutron production) depends linearly on it, optimisation of the operating parameters and cost is possible. At the same time this means that the operating stress can be optimised for high reliability.

- In order to maintain stable output conditions even with several cavities along the HELA not operating, it is possible to have some (detuned) cavities at the end of the linac in standby, which are brought on-line as necessary to ensure the full beam energy without interrupting the operation of the accelerator.

The accelerating cavities (and RF amplifiers), which are all of identical design, can be manufactured in relatively large series. This cannot be done with coupled structures, where in principle no tank will equal any other, except if one tolerates some phase slip between the beam and the RF wave.

Finally, the single-cell concept also offers a non-negligible advantage with respect to the transverse focusing elements. These can be distributed in a much more homogeneous way than with long RF tanks and therefore the beam will be kept small under all circumstances. A smaller beam allows a smaller beam hole. This in turn will lead to a higher shunt impedance of the cells. Preliminary calculations suggest that the transverse beam focusing can be made largely independent of the particle energy. Thus the energy variation described above can be achieved without the need to readjust the
beam optics. In order to come close to a similarly optimum distribution of focusing elements in a
coupled cavity structure, short tanks of the order of 1-2 m would have to be chosen at the low energy
end of the linac.

**The single-cell cavities**

*Parameter optimisation*

The cavities are working in the $E_{010}$ mode. The number of cavities and their design was chosen
based on the following considerations:

- The maximum surface field strength $E_{\text{max}}$ should not exceed the value of 22.5 MVm$^{-1}$ which is
  1.5 times the Kilpatrick limit.
- Enough space should be retained for focusing and diagnostic elements.
- The number of cells should be a multiple of eight. This simplifies the RF power distribution
  at medium and high levels. Also eight single-cell cavities correspond to two transverse
  focusing periods. This lead to 640 cavities for 1 GeV energy gain and an average energy gain
  per cell of about 1.6 MeV. Thus the pulse power requirement per cell is approximately
  500 kW.

Since all cavities should be identical in order to take advantage of series production and to
simplify the exchange of faulty cavities, if ever necessary, the geometrical shape of the cavity has
been optimised for minimum total RF power loss of 640 identical cavities accelerating from 100 up to
1 100 MeV. It was found that the type of cavity chosen has an efficiency only a few tenths of a
per cent lower than cavities optimised at each different $\beta$ along the HELA. In order to standardise the
RF amplifiers, the voltage gradient $E_0$ is identical in all cells. Therefore, the energy gain of the
protons will increase with increasing $\beta$, because the transit time factor $T$ grows from cell to cell and
the synchronous phase $\phi_s$ is held constant through the HELA.

SUPERFISH calculations were made for many different cavity shapes. The geometrical and
electrical parameters of the cavity chosen are given in Table 2, where the RF power loss is increased
by 5% compared to the SUPERFISH values. This allows for additional losses caused by the window,
the tuner and the surface roughness as reported in [5]. The effective shunt resistance per cavity length
is shown in Figure 2.

**Comparison with coupled structures**

For a relevant comparison, an optimised layout for each structure would have to be considered.
Therefore some of the following points, in particular with respect to shunt impedance, which depends
on the RF frequency, may not apply rigorously, if a coupled cavity structure with higher RF
frequency was chosen. Such data are not readily available, but an attempt will be made at the end of
this section to list a few relevant parameters for three different designs. The arguments reported here
are the ones given in the SNQ report, where the single-cell cavities working in $E_{010}$ mode are
compared to coupled structures under equal conditions, namely that the structures 1) work at the same
frequency; 2) accelerate the beam at the same $\beta$; and 3) have the same beam hole diameter.
### Table 2. Calculated parameters of the proposed E₀₁₀ single-cell cavity; a 5% increase in power loss due to windows and surface roughness is included

<table>
<thead>
<tr>
<th>Cavity characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity length</td>
<td>l₀</td>
</tr>
<tr>
<td>Gap length, geometrical</td>
<td>lₚ</td>
</tr>
<tr>
<td>Effective gap length on axis</td>
<td>lₚₑ</td>
</tr>
<tr>
<td>Beam hole diameter</td>
<td>d₀</td>
</tr>
<tr>
<td>Cavity diameter</td>
<td>d₀²</td>
</tr>
<tr>
<td>Resonance frequency</td>
<td>f₀</td>
</tr>
<tr>
<td>Unloaded Q-factor</td>
<td>Q₀</td>
</tr>
<tr>
<td>3-dB bandwidth, unloaded</td>
<td>Δf</td>
</tr>
<tr>
<td>Time constant, unloaded</td>
<td>T= Q₀/πf₀</td>
</tr>
<tr>
<td>Char. impedance (ohmic)</td>
<td>R/Q₀</td>
</tr>
<tr>
<td>Shunt resistance (linac)</td>
<td>2R</td>
</tr>
<tr>
<td>Maximum surface field Eₘₚ to averaged field E₀ ratio</td>
<td>Eₘₚ/E₀</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Structure characteristics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Shunt resistance/cavity length</td>
<td>2R/l₀</td>
</tr>
<tr>
<td>Effective shunt resistance/cavity length</td>
<td>2R'T²</td>
</tr>
<tr>
<td>– at 100 MeV</td>
<td></td>
</tr>
<tr>
<td>– at 350 MeV</td>
<td></td>
</tr>
<tr>
<td>– at 1.1 GeV</td>
<td></td>
</tr>
<tr>
<td>Effective characteristic impedance per cavity length</td>
<td>2R'T²/Q₀</td>
</tr>
<tr>
<td>– at 100 MeV</td>
<td></td>
</tr>
<tr>
<td>– at 350 MeV</td>
<td></td>
</tr>
<tr>
<td>– at 1.1 GeV</td>
<td></td>
</tr>
</tbody>
</table>

### Figure 2. Effective shunt resistance per cavity length for the single-cell and a coupled cavity structure in E₀₁₀ mode

Solid: single-cell cavity with 7 cm beam hole diameter, including 6% additional losses from windows, tuners and surface roughness; dashed: Disk and washer resonator scaled to 201 MHz and 7 cm beam hole diameter including 10% additional losses for an optimised stem configuration
In comparison to other $E_{010}$ mode structures the advantages of the single-cell structure are the following:

a) **Shunt resistance:**

The single-cell cavities have a higher effective shunt resistance than coupled structures provided their accelerating field mode is also of the type $E_{010}$ because the coupling elements dissipate RF power. The dissipation is especially high if resonating elements are employed, as usual, to increase the group velocity in proton accelerating structure:

- In the side coupled structure of the LAMPF accelerator, RF power dissipation in the coupling resonators causes an additional loss in shunt resistance of about 10% [5].
- In the on-axis coupled structure the space requirement and the RF power dissipation in the coupling slots cause an additional loss in shunt resistance between 10 and 20% [5].

b) **Scope for optimisation:**

In single-cell cavities the cell length can be used to maximise the effective shunt resistance per cavity length $R_T^2$. The gain for an optimised cell is 3 to 5% relative to the optimised cell of length $\beta \lambda / 2$ [6].

c) **Sensitivity to tolerances:**

The single-cell cavities have a low sensitivity to field perturbations caused by mechanical and frequency errors in comparison with structures of low group velocity [5].

d) **Stored energy:**

For the same accelerating conditions, the stored energy in a single-cell cavity is lower than in a coupled-structure tank, which results in less damage during sparking.

e) **Beam blow up:**

The single-cell cavities are not sensitive to regenerative beam blow up because the accelerating gaps are separated by drift tubes of at least 0.4 m length and 70 mm diameter, which yields an aperiodic attenuation of intercavity coupling in excess of 110 dB even at $10 f_0$, the tenth harmonic of the working frequency $f_0$.

In summary, apart from their independence from the particle velocity, single-cell structures are also considered advantageous in a number of other respects which are important for economic and reliable operation of an ADS.

As noted above, for a relevant comparison, optimised layouts for the different types of structures would be required. A problem in trying to compare different designs among each other results from the non-standard way of accounting used in different project reports, which leaves it unclear what exactly the contributions are that are included in the numbers given. Table 3 shows data extracted from three different project reports.

As noted before this comparison suffers from the fact that the accelerators were not designed for relative evaluation. In particular the ESS-side coupled cavity linac [7] generates 8% less beam power than the other two but has a pulse structure suitable for injection into a compressor ring, i.e. a fill
Table 3. Comparison of some parameters for different high power linac designs

<table>
<thead>
<tr>
<th>Parameter / Remark</th>
<th>Project</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNQ-SC</td>
<td>SNQ-DW</td>
<td>ESS-CC</td>
</tr>
<tr>
<td>Time average beam power</td>
<td>5.5 MW</td>
<td>5.5 MW</td>
<td>5.1 MW</td>
</tr>
<tr>
<td>Type of HELA structure</td>
<td>Single-Cell</td>
<td>Disk and Washer</td>
<td>Side Coupled Cavities</td>
</tr>
<tr>
<td>RF frequency in HELA</td>
<td>200 MHz</td>
<td>324 MHz</td>
<td>700 MHz</td>
</tr>
<tr>
<td>Peak current in pulse</td>
<td>200 mA</td>
<td>100 mA</td>
<td>64 (107) mA</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>100 Hz</td>
<td>100 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Pulse duration of accelerator</td>
<td>0.25 ms</td>
<td>0.5 ms</td>
<td>1.2 ms</td>
</tr>
<tr>
<td>Mains power requirement</td>
<td>31 MW</td>
<td>(44.3 -5) MW</td>
<td>(34.5+5) MW</td>
</tr>
<tr>
<td>Reference</td>
<td>[3], p.124 (cf. Table 4)</td>
<td>[1], p.121</td>
<td>[7], p.7-2</td>
</tr>
<tr>
<td>Remarks</td>
<td>Auxiliary systems power included, HEBL not included.</td>
<td>Auxiliary systems power included; -5 is for HEBL.</td>
<td>Pulse duty factor 0.6 for ring injection; +5 is for auxiliary syst.</td>
</tr>
</tbody>
</table>

factor of only 60% during the pulse [8]. Although the SNQ-SC linac seems to be fairly efficient in this comparison, it should be borne in mind that, due to its low RF frequency, there is an inherent disadvantage in terms of shunt impedance and mains-to-RF power conversion. So, the apparent competitiveness results from the higher pulse current and associated lower duty cycle. New designs based on the single-cell concept would probably look different in view of various developments that occurred since the SNQ linac was conceived.

Operation parameters and tuning of the single-cell cavity

All cells will work with identical gap voltages. This leads to an energy gain that increases slightly along the HELA because the transit time factor $T$ increases and the synchronous phase $\phi_s$ is kept constant. Thus the total power requirement per cavity will increase along the HELA. The accelerating voltage per cavity increases by 10% from 100 MeV to 350 MeV (about 160 cavities). The further increase is only 3% at acceleration up to 1.1 GeV with the remaining 480 cavities.

A tuning system is foreseen for each cavity in order to fulfil the following two groups of tasks:

1. Tuning to the working frequency to compensate for (a) geometrical errors; (b) fluctuations of pressure and temperature; and (c) variations of the beam current. The compensation of the errors due to these effects can be carried out slowly.

2. Fast detuning in case of failure. Instantaneous shut down of the linac will not be necessary in case of failure of a cavity or its power feeding unit, as fast detuning shall be provided for. This implies that a detuning by approximately 50 kHz must be achieved during a few milliseconds (between two pulses). Otherwise, the beam induced cavity field may cause damages.
Three methods for tuning and their applications discussed in the SNQ study are:

- tuning by plungers;
- tuning by elastically deforming the cavity;
- tuning by a ferrite-loaded-auxiliary resonator or similar device.

The first two methods involve mechanically moving parts and hence are not fast enough to detune a cavity before the next pulse in case of a failure. Although this might be tolerable, it clearly is to be preferred to be able to accomplish the detuning by at least 50 kHz before the next pulse arrives. Plungers that cover a sufficient tuning range would probably reduce the RF efficiency of the HELA considerably and would require a complicated cooling system. Mechanical tuning of the cavity, on the other hand, has virtually no effect on the RF efficiency and cooling requirements but is very slow and should therefore be used only to compensate for fabrication tolerances that might have to be dealt with, if cavity fabrication was to be kept very cheap. In the case of an auxiliary resonator a ferrite-loaded resonator would be coupled to the accelerating cavity. The ferrite would be biased by a DC magnetic field in order to use the gyromagnetic effect. The relaxation loss would be drastically reduced by working at a frequency that is considerably removed from the Larmor frequency. By this method, the HELA structure could be tuned by about 100 kHz. The estimated decrease of the shunt resistance would be less than 0.1%. A further advantage would be that the HELA structure could be tuned and detuned during a time in the submillisecond range and controlled electronically without moving parts. However, such a ferrite tuner must be developed to operate at 200 MHz. Ferrite materials that are suitable for non-reciprocally working at 200 MHz and a high power levels are already developed for use in circulators.

In conclusion it may be stated that the concept of a rapidly tunable single-cell is within the realm of present day technology.

The control system

Failures will occur frequently in the high energy part of the linac due to the large number of components. By far the weakest component is certainly the amplifier chain. Although the failure rate during operation can be reduced by periodic preventive exchange of older tubes, this is a tedious and potentially costly procedure and certainly does not make optimum use of the tubes. On the other hand, with no preventive maintenance and assuming Poisson statistics and a life time of 8 000 h of operation for the RF generator, with the 640 units of a 1.1 GeV accelerator one has to expect up to two failures on average per day. This cannot be dealt with in the conventional way by switching off the linac, diagnosing the error, replacing the faulty component and then returning to normal operation. This would cause intolerably long and frequent shut-down periods. In the SNQ concept automated replacement of a faulty RF generator during operation was foreseen, without switching off the accelerator. This is possible for the reasons exposed below.

The single-cell concept allows operation to continue even if the RF power generator of one or more single-cells have failed. The consequence of a single-cell not accelerating anymore is a change of the phase advance in the following cells. Provided the faulty cell is detuned in order not to be charged up with RF power by the beam, the phase mismatch is 1.3° and 0.2° for all following cells, if the failure occurs at a cell operating at 100 MeV and 350 MeV, respectively. Otherwise the phase
change increases to values of $4.6^\circ$ and $0.7^\circ$ while the batch is passing. The failure of a single-cell can be signalled to the control system and the RF phase in the following cells adjusted. As a result the beam is accelerated to an end energy about 1 MeV below the normal value. (If desired, the correct end energy can be obtained nevertheless by slightly decreasing the absolute value of the stable phase angle, but activation of hot standby cells would be preferred.) The actions to compensate for a faulty RF generator are performed within msec., i.e. between two pulses and operation of the accelerator continues without any interruption. Then, during operation, the error can be further diagnosed and the faulty component may be replaced, either on-line or in a scheduled shutdown.

The single cavity control system which is one part of the three-level linac control system is shown in Figure 3. The inner three control loops to the left of the cavity are conventional. The resonance frequency is kept constant by mechanical tuning. In the other two loops the RF amplitude and phase are stabilised. Because of the options to operate the high energy part of the accelerator at different stable phase angles with small and large RF amplitudes and for different pulse currents, the control loops need input settings (E) for the phase generator, (D) for the amplitude loop, (C) for the amplifier chain, and (B) for the tuner. The phases are set with respect to a 200 MHz reference RF signal which is delayed for each single-cell according to the arrival of the bunches in the centre of its accelerating gap. In a similar way the “switch on” signal is delayed, for example by counting a pre-set number of RF cycles, in order to assure the precise charge-up with RF power when the first bunch of a batch enters the accelerator.

**Figure 3. Block diagram of the single cavity control loops**

![Block diagram of the single cavity control loops](image)

The technologically more advanced control loops are the ones shown on the right hand side of Figure 3. Pick-up signals for the RF phase and beam are fed into the phase generator to determine the actual phase advance $\phi$, which is compared with the setting value (E) in order to properly activate the phase shifter device. The offset value is corrected by the feedback value $\Delta \phi(E)$ which originates from the end energy measuring device at the end of the accelerator.

An even more sophisticated part in the cavity control system is the learn box which observes the error signals during many batches in order to learn how to improve the control or sense irregularities indicating an imminent failure. For this purpose the learn box is provided with the actual phase
advance value and setting value and with the phase generator response. Based on an analysis of this information collected from many batches, the learn box may change directly the setting value for the RF phase and amplitude or, with the support of a computer from a higher level, create a complete new set of parameter values (G) which are better adapted to the actual situation than the original settings.

It is quite clear that the whole single-cell concept with all its advantages would not be possible without these most sophisticated control facilities, which are nowadays available.

**Power consumption**

The large number of small beam focusing elements has the advantage that the electric power consumption of conventional quadrupoles will be substantially reduced. Even more important mains-power savings result from the increased beam intensity but also from the relatively high shunt impedance of the single-cells, particularly at particle energies below ~ 350 MeV.

The design length plays an important role in minimising the total mains-power consumption of the linac. While there is a rather sharp lower limit for the linac length which is determined by the maximum acceptable RF field gradient, it turned out already during the early phase of the SNQ studies that there is a flat minimum of operational costs for a linac which is a little longer than the length which is determined by the installation cost minimum. The latter is, however, also very flat.

This results in an optimum length, at about 0.4 m length per 1 MeV of particle energy gain for the HELA for practically all the types of RF structures considered so far. About twice that value must be taken for the Alvarez accelerator. Based on these data the necessary RF power can be determined and the relevant average factors of the RF power generators as a function of the charge-up time can be applied. A preliminary assessment of mains power requirement is given in Table 4.

It should be noted that the values quoted are obtained with single-cells which are all of absolutely identical design, no matter whether they are used at the low or the high energy end.

While Table 4 gives the details of power consumption for the SNQ single-cell accelerator, the comparison with other concepts shown in Table 3 indicates that it compares favourably to higher frequency coupled cavity structures.

**Conclusions**

The accelerator proposed for the SNQ project carries the potential for intrinsically high availability because it combines the principles of fault tolerance during operation and of off-line repair of defective components with a very high degree of flexibility in adjusting the operating parameters for economic and low stress working conditions. Apart from the features outlined in this paper, the concept also offers important advantages in the way in which the facility can be brought up to specifications and adjusted to operational needs. This is mainly because – and possible only because – the mechanical structure is independent of the velocity of the particles during acceleration. In an ADT application these features may be of particular advantage. The fact that the accelerator operates in a pulsed mode (which is important in order to be able to accomplish the adjustments described while the beam is off) is not seen as a disadvantage for ADT applications, but may turn out to be a highly desirable property for the following reasons:
Table 4. Mains-power consumption  
(in MW, high energy beam line (HEBL) not included)

<table>
<thead>
<tr>
<th>Proton beam power during pulse</th>
<th>220</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEFA</td>
<td></td>
</tr>
<tr>
<td>Total RF power during pulse</td>
<td>328</td>
</tr>
<tr>
<td>Average RF-power:</td>
<td></td>
</tr>
<tr>
<td>- Beam</td>
<td>5.0</td>
</tr>
<tr>
<td>- Cavity walls</td>
<td>3.65</td>
</tr>
<tr>
<td>Power loss</td>
<td></td>
</tr>
<tr>
<td>- Generator</td>
<td>7.0</td>
</tr>
<tr>
<td>- DC supply</td>
<td>2.6</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>5.6</td>
</tr>
<tr>
<td>Alvarez accelerator</td>
<td></td>
</tr>
<tr>
<td>Total RF power during pulse:</td>
<td>30</td>
</tr>
<tr>
<td>- Beam</td>
<td>0.5</td>
</tr>
<tr>
<td>- Cavity walls</td>
<td>0.2</td>
</tr>
<tr>
<td>Power loss</td>
<td></td>
</tr>
<tr>
<td>- Generator</td>
<td>0.7</td>
</tr>
<tr>
<td>- DC supply</td>
<td>0.3</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>0.6</td>
</tr>
<tr>
<td>General supplies</td>
<td>3.1</td>
</tr>
<tr>
<td>Beam optics (conv. quadrupoles)</td>
<td>1.2</td>
</tr>
<tr>
<td>Injector (global)</td>
<td>0.5</td>
</tr>
<tr>
<td>Total mains-power</td>
<td>31.0</td>
</tr>
</tbody>
</table>

1 Including RF-circuit and line losses.
2 Heaters, blowers, vacuum pumps, water cooling.

- In a system with beam multiplexing between several accelerators and driven facilities, as outlined in [4], time gaps in the beam are necessary to activate the beam deflectors without excessive losses and activation.

- If a variation in reactivity of the driven device is to be compensated by adjusting the accelerator power, a pulsed accelerator allows to do this not only by changing the current, but offers the added flexibility of changing the pulse length and even the repetition rate.

In the case of a pulsed accelerator with a $\beta$-independent structure beam power variation can even be accomplished by varying the output energy or by an optimised combination of all four options.

The SNQ accelerator, as outlined briefly in this paper, was originally meant to drive an experimental facility whose main feature was a neutron source for condensed matter research. Apart from allowing several different modes of operation not mentioned here, the concept was chosen to offer optimum flexibility and the highest degree of reliability in terms of not needing to be switched off for every minor fault. This affects mainly shutdowns or interruptions otherwise required to replace or repair faulty components. However, the fact that the option exists to vary the pulse length in order to compensate for a deliberately chosen lower beam energy may turn out to be equally
important. It allows to reduce the field in the cells after the facility has been built and may be viewed as an important way to minimise those short beam trips from which the system normally recovers automatically, but which may still have an adverse effect on the fatigue life of certain components in the driven facility.

Clearly, the concept in its details was based on the technology available at the time of its evaluation. Several important developments have taken place since that time, the most important one being the maturing of the RFQ concept which then was only in its infancy. However, also in other fields, such as RF power generators, new ways are being explored, not only in the high frequency range of klystrons, but also on the 200-300 MHz regime of interest here. This is a very important point because for tetrodes a mean time to failure of only 8 000 hours was anticipated in contrast to 30 000 to 40 000 for klystrons. Accounting also for the fact that klystrons have higher power than tetrodes and a smaller number of them would be required, the average time between failures would be much longer. However, the important point in the concept presented here is that a failure would not affect operation of the accelerator. Any improvement that can be made in the reliability of individual components would, clearly, be an additional advantage, in particular with respect to operating costs.

If adapted to ADS needs, the concept may have to be reviewed in its details, in particular with regards to pulse length and repetition rate, but it appears that it would certainly be worthwhile to consider other alternatives than a superconducting DC linac with high power klystrons only. The question of using superconducting cavities was also considered in the SNQ study and it was concluded that this might be an option if the technology became sufficiently mature. In order to limit the number of cryostats, it was envisaged to have more than one cell in each cryostat, but no detailed assessment was made of the consequences.
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RELIABILITY AND AVAILABILITY OF HIGH POWER PROTON ACCELERATORS

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Abstract

It has become increasingly important to address the issues of operational reliability and availability of an accelerator complex early in its design and construction phases. In this context, reliability addresses the mean time between failures and the failure rate, and availability takes into account the failure rate as well as the length of time required to repair the failure. Methods to reduce failure rates include reduction of the number of components and over-design of certain key components. Reduction of the on-line repair time can be achieved by judiciously designed hardware, quick-service spare systems and redundancy. In addition, provisions for easy inspection and maintainability are important for both reduction of the failure rate as well as reduction of the time to repair. The radiation safety exposure principle of ALARA (as low as reasonably achievable) is easier to comply with when easy inspection capability and easy maintainability are incorporated into the design. Discussions of past experience in improving accelerator availability, some recent developments, and potential R&D items are presented.
Introduction

An accelerator facility requires very high availability in order to carry out its mission effectively, independent of whether it is designed to provide for multi-user research such as synchrotron radiation or particle physics, or whether it is to be used for a single purpose such as an accelerator driven nuclear energy system (ADS). Availability of a facility is defined as the ratio of the actual run time to the scheduled duration of the run. Accordingly, in order to make the availability high, one must not only reduce the failure rate but also reduce the time required to repair the failures.

For an ADS, short mean time to repair (MTTR) is a very important consideration because of the nature of the ADS. If an ADS is used for generating power, reliability of the power station is a requirement. Secondly, one must consider temperature effects on the ADS’s neutron-generating target assembly.

We discuss several concepts associated with availability, followed by some examples from past experience. A brief description of some recent work to improve the availability of an accelerator system and discussions of potential future R&D work are presented.

Reliability

Reliability is a measure of system failure expressed in terms of probability, failure rate or mean time between failures (MTBF). The following is a short discussion of the definitions and some examples of the terms associated with reliability considerations.

If a system consists of a large number of components, and if each component is 99% reliable, then the reliability of the entire system approaches zero as the number of components becomes very large since \(0.99^N \rightarrow 0\) as \(N\) becomes very large.

The probability of a system failure during a period of time, \(dt\), is proportional to \(dt\) with a proportionality constant \(\lambda\). The probability that the system will still be operating after a time \(dt\) is:

\[\Delta P(t) = 1 - \lambda dt\]

Integration of this equation gives:

\[P(t) = e^{-\lambda t} = e^{-1/\tau}\]

where \(\lambda\) is the failure rate, and \(\tau\) is the MTBF. These two quantities are inverses of each other. For a system with a large number of subsystems, the MTBF of the system is:

\[1/\tau_{\text{system}} = \sum_{i=1}^{N} 1/\tau_i\]

The above equation implies that the shortest MTBF dominates in a multi-component system, and that if the system has \(N\) identical subsystems, the MTBF for the system is shortened by a factor of \(N\).

The failure rate, \(\lambda\), is not always constant. Rather, it is a time-varying function, \(\lambda(t)\). One expects to have frequent failures during the commissioning period of a new system, and to have more frequent failures in older facilities. A typical functional expression of \(\lambda(t)\) has the shape of a bathtub,
and is called the reliability bathtub curve (RBTC) as shown in Figure 1. Perhaps the most important consideration related to the failure rate is the built-in stress on the system. A highly-stressed system will have a higher failure rate than a less-stressed system. Judging the acceptable degree of stress in design and construction requires good engineering knowledge and extensive experience.

**Figure 1.** (a) Reliability bathtub curves as a function of design stress; (b) reliability bathtub curves as a function of quality control during construction and preventive maintenance

Figure 1(a) shows three bathtub curves as a function of “built-in design stress levels.” A highly-stressed design would exhibit a higher failure rate. Three bathtub curves show that regardless of the design stresses, newer and older systems have higher failure rates than systems of moderate age. The high failure rate of new systems is attributed to “infant mortality”. The higher failure rate of ageing systems needs no explanation. Proper quality control and inspection during construction can alleviate infant mortality problems, and the failure rate of older systems can be controlled by proper preventive maintenance. Figure 1(b) illustrates the effects of quality control and preventive maintenance. A system that is easy to inspect is also much easier to maintain well, thus good maintenance capability requires easy inspectability. Maintenance and inspection issues are discussed in the next section.

**Availability, maintainability and inspectability**

In order to have high availability, the MTBF should be made as long as possible while the mean time to repair (MTTR) should be as short as possible. The importance of the MTTR is illustrated by the following examples. Suppose there is a system with an MTBF of one day, and the system is scheduled for a 10-day operational period. Case (1): If the system’s MTTR is 10 minutes, then the system would lose 100 minutes out of ten days. Case (2): If the MTTR is one day, then the system would lose five days out of ten due to system repairs.

It is therefore very important to incorporate the capability to do quick and easy repairs or replacements of the hardware that is most likely to have a high failure rate already during the design stage. Redundancy, “hot spares” and “quick disconnects” are some of the options used to shorten the on-line repair time. As noted in the previous section, a superior preventive maintenance plan reduces the failure rate while a well-conceived repair system reduces the time required to repair. The next level of sophistication is designing the capability for easy inspection into the system. Easy inspectability allows both preventive and corrective maintenance to be expedited.
It is possible to expose workers to residual radiation during maintenance and repair activities. The ALARA principle (as low as reasonably achievable) of radiation exposure to workers should be incorporated into the inspection and maintenance plans, and into the equipment designs. Efforts after the fact to limit worker exposure to residual radiation may lengthen the repair time and increase costs.

Some past experiences of accelerator availability

It is worthwhile to review what we can learn from past experience. Three examples described below are used to illustrate methods by which availability issues are addressed at various facilities.

**IPNS experience**

The accelerator system of the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL) consists of a 50 MeV linac and a 500 MeV synchrotron, both operating at 30 Hz for some 17 years. These accelerators were originally built as the injector linac and booster synchrotron for the 12 GeV, zero gradient synchrotron (ZGS) for high-energy physics.

The availability of the IPNS facility has consistently been 95% or better for the past several years as shown in Figure 2 [1]. It has one of the highest availabilities of any accelerator facility of its kind.

**Figure 2. IPNS accelerator system availability since 1981**
The IPNS linac was built in the late 1950s, and was designed to operate at a 0.2 Hz repetition rate. In spite of its age and design parameters, it has been operating at 30 Hz with good efficiency. It may be a highly under-stressed design. On the other hand, the synchrotron was designed for 500 MeV operation at 30 Hz, and was built during the budget-tight waning years of the ZGS programme. As it turns out, the design of the synchrotron was an over-stressed design. The machine had a very high initial failure rate and a very low availability when operating at its design energy.

During the transition from the ZGS programme to the IPNS programme, we made two major remedial actions to reduce built-in system stresses. The first was to re-engineer all pulsed magnets such as kicker magnets and septum magnets. The second was to operate the synchrotron at 450 MeV rather than at 500 MeV, thus reducing stress in the ring magnet and its power supply systems. The lesson is to reduce stresses in the system. The resulting improvement in operation since 1981 is shown in Figure 2.

**PSR experience**

The Los Alamos neutron source, based on an 800 MeV linac and a proton storage ring (PSR), was commissioned in late 1980 to operate at a beam power level of 80 kW by delivering an average current of 100 µA for neutron scattering science. The linac was an existing accelerator that was being operated for the medium energy nuclear physics programme, and the PSR was specifically designed and built for that facility. From the beginning, the facility suffered from marginally acceptable to low availability and low beam power. Figure 3 [2] shows the past performance of the Los Alamos neutron source. It is important to note that the linac had about 80% availability and the PSR also had about 80% availability. The combination of the two resulted in an overall availability of some 65% for the facility. To alleviate the availability difficulty and to reach the original design beam current, a two-step improvement programme is in progress. Performance is expected to improve in the very near future.

**Figure 3. PSR and linac availability and delivered beam current**
**APS experience**

The Advanced Photon Source (APS) is a synchrotron radiation source, not a high-power proton accelerator. However, the APS was designed and constructed for very high availability operation (95% or better) to satisfy user needs. A typical experiment using photons from a synchrotron radiation source may only need a few hours of uninterrupted beam time to collect data from a sample, however the user may have worked many weeks to produce the sample and the sample may be short lived. Accordingly, we decided to design and construct a highly reliable facility. The APS has been operational for the past two years, and has achieved 95% availability.

In a storage ring like the APS, the failure rate is measured by the frequency of beam loss due to a system component trip or malfunction. The time between failures is the stored beam time. As discussed previously, the time between failures should have an exponential distribution $e^{-\lambda t}$. The histogram in Figure 4(a) is a stored-beam-time distribution in 1996 plotted on a linear scale. Figure 4(b) shows the same data and a straight line fit to the data on semi-log 10 scale. The straight line in the semi-log plot indicates that the time between failure goes as $e^{-\lambda t}$, and the slope of the linear fit can be converted to the mean time between failures. The MTBF given by the fit is 2.5 hours.

*Figure 4.* (a) A histogram of the stored beam time distribution for an early operational period in 1996, plotted on a linear scale; (b) the same distribution plotted on a semi-log scale (curve) and the result of a linear fit to the data on a semi-log plot (straight line). The slope of the straight line is the failure rate. The MTBF from the fit is 2.5 hours.

Figures 5(a) and 5(b) show the stored beam time distribution from a 1998 run on a linear and on a semi-log 10 scale, respectively. The straight line in Figure 5(b) is the result of a linear fit to the data on a semi-log scale. This shows that the distribution still has an $e^{-\lambda t}$ shape. The mean time between failures is 14.7 hours obtained from the slope of the line. Note that the time between failures has improved substantially. The improvement in the stored beam time or time between failures demonstrates that the failure rate has improved as predicted by the reliability bathtub curve.

In the next section, we describe work we have done during the design and construction of the APS in order to have a highly reliable and available machine.
Recent work to improve availability

To achieve the availability presented in the previous section, several measures were implemented during the design and construction phases of the APS facility. It could be useful to consider some or all of the measures used in the APS design and construction when designing a high-power proton accelerator (HPPA) for high availability. Short descriptions of these measures are presented below.

Alleviating stressed designs

The failure rate of a facility depends on the degree of design stresses, as was shown in Figure 1. In an era of tight budgets, designers try to get the most performance for the least cost. The following simple example illustrates the dilemma one can face when making a decision on design stresses. Suppose one designs a system that requires a motor. Calculations show that a 97 horsepower motor would be adequate. The question is whether to specify a 100, 150 or 200 horsepower motor in the design. Such decisions depend on the experience of the designers and their willingness to take risks.

To make the risk-taking somewhat uniform at the APS, we decided from the beginning that, although the normal operating energy of the storage ring was 7 GeV, all hardware would be designed to operate at 7.7 GeV. This concept of designing for 10% over the operating energy had its origin at the IPNS and ZGS. Both IPNS and ZGS performed much better at 10% below their design energies.

Reduction in the number of components

It was noted that $0.99^N \to 0$ when $N$ becomes very large. Consequently, reduction of the number of components in a system usually increases the system reliability. However in some cases, increasing the number of components may be desirable for scientific reasons. The following discusses the resolution of a conflict during the APS construction between the desire to reduce the number of components for reliability and the need to increase the number of components for scientific reasons.
The APS storage ring has 400 quadrupole magnets. Each magnet is powered by an individual power supply, thus the system has maximum flexibility. Alternatively, since these 400 magnets are in 10 families, the conventional way would have been to use 10 power supplies and energise each family separately. Doing the latter would reduce the number of the quadrupole magnet power supplies from 400 to 10, but would eliminate scientifically desirable flexibility.

A design decision made was to have 400 quadrupole supplies but to reduce the number of components within the power supplies themselves. Figure 6(a) shows a picture of the original circuit board of a DAC (digital to analogue converter) and Figure 6(b) shows the improved DAC [3]. Such a reduction in the number of components requires very good engineering judgement. In many cases reduction of components may result in a loss of flexibility. Decisions on how much flexibility one can trade off for improved availability, and how to recover lost flexibility, must be made.

**Figure 6. Initial (a) and reduced-component (b) designs of ADCs in the APS power supplies**

![Figure 6](image)

**Spare parts, redundancy and reduction of time to repair**

So far we have discussed methods to reduce hardware system failure rates to achieve high system availability. Next we discuss how to reduce the time required to make on-line repairs. “On-line repair” is any remedial action performed on hardware and software that requires shutting down the
facility system. “Off-line repair” implies that the malfunctioning hardware or software can be removed from the system and replaced with a spare or a redundant part allowing the system to be brought back into operation while the repair of the malfunctioning subsystem is performed later. In this off-line repair mode, the time to repair is the period of time required to replace the component.

There are many ways to design easy-to-repair systems with built-in redundancy. Such features should be designed into the facility from the beginning, since retrofitting systems at a later date can be very costly. Designing in such capability requires sound engineering judgement, generally based on years of experience in operating accelerators, neutron generating targets and reactor systems.

It may be worthwhile to note a couple of examples on the topic of spares and redundancy. All high-power accelerators require high-power radio-frequency sources, regardless of accelerator type. A common concern is how to reduce the time required to make repairs if one of many klystrons or associated power supply systems fails. For a circular machine like the APS storage ring, the solution was to have a “hot spare” installed in the ring. Switching from one to another takes about 10 minutes.

A hot spare RF source for a linear accelerator could be very costly because it requires a completely redundant RF system. However, it is possible to operate the linac with the affected section turned off if the system is designed with phase and energy adjustment capabilities. The design of such a re-phasing capability requires good engineering judgement and a thorough study of the beam dynamics to support re-phasing to obtain the same beam power.

**ALARA concepts and reduction of repair time**

Many accelerator hardware designs have been optimised to minimise radiation exposure to repair personnel, following the ALARA principle. The same design concepts can be used to reduce the time required for repair. An example of this is the quick-disconnect mechanism for accelerator vacuum chamber flanges. Under normal circumstances, nuts and bolts are used to connect and disconnect the vacuum chambers. Making and breaking of these connections is time-consuming work that usually can be avoided in high radiation areas if quick-connect systems are used. Repair time can be significantly reduced.

Another example to reduce radiation exposure to the repair personnel is found at the proton beam transport line just before the neutrino target at FNAL. During normal operation, radiation levels in the neutrino target area can be tens of thousands of rads, thus hands-on maintenance is impractical. A solution to this problem was to install the beam line components on a train with well-engineered rails to support the beam line and align it to the target. When a beam line component or diagnostic element in the line malfunctions, the train is pulled out and allowed to cool down prior to repair, and a new train is inserted so that operation can resume. This kind of idea implements the ALARA concept, and also reduces the time required to accomplish on-line repairs.

With regard to the interface between the proton beam line and the target, this writer would like to question the desirability of doing vertical injection of a proton beam onto the target. Is vertical injection necessary? Horizontal injection would allow much better inspectability and maintainability both for the proton transport system and for its interface to the target system.
Potential R&D work for high availability

There are many R&D topics for high availability goals. Some are facility specific and others are generic. We list here some generic topics that could be collaboratively performed.

**Interface between target and proton beam**

The following topics related to interfacing the target and the beam transport line are of great interest in all high-power proton accelerators:

- window between the target and the beam transport line, window materials and lifetime;
- beam transport line geometry as vertical vs. horizontal injection;
- quick replacement of transport line elements such as magnets and diagnostic equipment;
- self-alignment systems.

**Radiation-hard components**

Since the availability of a facility depends on its mean time between failures and its mean time to repair, we must consider potential failure of system due to radiation damage, and the repair process for radiation damaged components. Hardware elements such as magnets, vacuum joints, ceramic chambers or inserts and certain diagnostic equipment are sensitive to radiation damage. There are two key items that should be addressed in this connection. The first is the failure rate vs. dose rate for such equipment. The second is the engineering design of the repair/replacement process to minimise the repair time and radiation exposure to the repair personnel. It may be worthwhile to note that there have been many radiation damage studies by many laboratories around the world for various purposes. The results of past work should be a good starting point for a comprehensive study for future HPPA systems.

**Conclusion**

The high power proton accelerators now being proposed and designed would provide unprecedented beam power and neutron yields, opening up a new realm of science and technology. In order to make optimum use of such facilities, facility availability resulting from reliability, reparability, maintainability and inspectability, must be addressed during the design of the facility.

Past experience has shown that one must avoid designing over-stressed accelerator systems. A case in point is the IPNS synchrotron that has had trouble free operation at 450 MeV although it was designed for 500 MeV operation.

Reliability statistics obey the $e^{-\lambda t}$ rule. Minimising the number of components in a system helps to reduce its failure rate.
To maximise the availability, both hot and cold spare systems must be addressed during the design. Well-engineered repair processes can incorporate radiation hazard ALARA concepts for the repair personnel at the same time.

Some generic R&D items pertinent to the HPPA are discussed. The R&D could be performed collaboratively.

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Abstract

The Large Electron Positron Collider (LEP), the largest accelerator in the world, is equipped with a superconducting RF system designed at CERN and constructed by European industry. The energy radiated by the circulating beams via synchrotron radiation is replenished by the RF system, which provides a total accelerating voltage of about 3 GV. Very large continuous RF power is thus transferred to the beam; in routine operation it amounts to more than 13 MW at a total beam current mA. The cryogenic installation, one of the largest in the accelerator world, delivers 48 kW at 4.5 K to keep the cavities superconducting. This paper describes the overall RF system, putting emphasis on the design choices and on the problems encountered during their implementation. It also reports on the operational experience with this system, showing that its reliability and performance has enabled LEP to largely exceed the goals set a few years ago.
Introduction

LEP, the largest particle accelerator in the world, is an electron-positron storage ring with a circumference of 26.7 km. Physics of Z0 particles started in 1989 at a collision energy of 45 GeV with a room temperature RF system capable of delivering up to 340 MV at 352 MHz. The subsequent so-called LEP2 project consisted in increasing the collision energy to about the W pair particle production threshold by the adding of superconducting (SC) cavities developed at CERN since 1979.

The basic choices for the LEP SC cavities were made early in the project: 352 MHz (for compatibility reasons and to minimise the critical transverse impedance), four-cell structure with couplers on the beam tube, 4.5 K operating temperature, modular cryostat with easy access to the cavities and ancillary equipment, and thermal and magnetostrictive tuners inside the cryostat (Figure 1) [1].

Figure 1. Exploded view of one RF unit

After an intense period of research and development CERN decided to replace the niobium (Nb) sheet metal, of which the cavities were made, with copper covered with a thin (~1.2 µm) niobium film (Nb/Cu cavities). This approach offers inherent advantages: considerably higher stability against quenching, insensitivity to small magnetic fields and a higher quality factor than that of solid Nb at a given frequency and working temperature (4.2-4.5 K). It is obvious that important savings were achieved by replacing bulk Nb with an Nb layer.

CERN decided in 1990 to transfer the Nb/Cu technology to industry. It awarded the contract for manufacturing the cavities and modules (four cavities assembled together) to three European companies [2]. The entire series production was finished at the end of 1997 and at present 256 Nb/Cu cavities plus 16 solid Nb cavities are installed in the LEP tunnel, providing about 3 GeV total accelerating voltage (Figure 2).

The SC cavity

The four-cell cavity is fabricated from OFHC (oxygen-free) copper, using spinning and electron beam welding techniques. Proper preparation of the copper surfaces (electropolishing, chemical treatment, high purity water rinsing) before welding and before thin film deposition is of the utmost importance. Sputtering the niobium layer is achieved with a magnetron discharge between a high purity niobium cathode and the cavity walls. A high degree of cleanliness (e.g. mounting of the magnetron cathode in a class 100 clean room) is necessary to achieve the required performance of the niobium layer.
The total superconducting surface produced for the LEP2 project amounts to more than 1 500 m$^2$; it must be free of dust particles, since these become electron emitters at high RF fields. Again the importance of clean room work for the final assembly of cavities, couplers and bellows to avoid field emission cannot be overemphasised.

The cavity proper is surrounded by its helium tank and its three tuner bars (see the section entitled The tuning system) and is suspended inside the cryostat (see Figure 1). The latter, with its three wide barrel staves, provides easy access to the cavity as neither a magnetic shield nor an intermediate thermal shield is necessary. Thermal insulation is achieved with superinsulation mattresses alone. Four cavities are assembled together in a common cryostat to form a cryomodule 12.5 m long, including the end elements [3].

Table 1 shows the major parameters of the LEP2 cavities, the most critical being the quality factor $Q_0$ at the operating field (6 MV/m). This is the parameter which is measured during the acceptance tests made at CERN for all cavities and modules produced by industry.

**RF couplers**

**RF power coupler**

The power couplers of the LEP2 cavities [4] are located on the enlarged beam tubes to avoid ports on the cavity cells themselves. The open end of the inner conductor of a coaxial line protrudes slightly inside the beam tube, close to the end cell. At the other end of the coaxial line a cylindrical RF window derived from those used in the LEP copper RF system is part of a waveguide-to-coaxial transition (Figure 3). While the inner conductor of the line is at ambient temperature (air-cooled) along its whole length, the outer one is subject to the full temperature gradient from cavity to outside. It is made of a thin-walled stainless steel tube, copper-plated by sputtering. To avoid any welds in this critical area, this tube and its end flanges are machined out of a single forging. Helium gas cooling channels are provided on the outside of the tube.

The major problem found with this type of coupler is multipacting (resonant electron loading) in the coaxial line. To completely suppress any multipacting in the coaxial line during operation of the couplers, a DC bias voltage of + 2.5 kV is applied to the inner conductor [4]. In this way no resonant electron discharge can occur; this is obvious when the DC voltage is larger than the peak RF voltage in the line, but it can also be confirmed by simulations for lower DC voltages. No DC current is
Table 1. LEP2 cavity parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Frequency</td>
<td>352.209 MHz</td>
</tr>
<tr>
<td>Operating field</td>
<td>6 MV/m</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>10.2 MV</td>
</tr>
<tr>
<td>Number of cells</td>
<td>4</td>
</tr>
<tr>
<td>Effective length (four cells)</td>
<td>1.702 m</td>
</tr>
<tr>
<td>Modular length (between cryostat flanges)</td>
<td>2.553 m</td>
</tr>
<tr>
<td>Diameter: equator</td>
<td>755 mm</td>
</tr>
<tr>
<td>Diameter: iris</td>
<td>241 mm</td>
</tr>
<tr>
<td>Relative pass band $2(f_p-f_0)/(f_p+f_0)$</td>
<td>1.76%</td>
</tr>
<tr>
<td>$E_{ep}/E_{acc}$</td>
<td>2.3</td>
</tr>
<tr>
<td>$B_{pk}/E_{acc}$</td>
<td>3.9 mT/(MV/m)</td>
</tr>
<tr>
<td>$R/Q (R=V^2/2P)$</td>
<td>232</td>
</tr>
<tr>
<td>Field flatness tolerance $dE/&lt;E&gt;$</td>
<td>± 5%</td>
</tr>
<tr>
<td>Tuning sensitivity</td>
<td>+ 40 kHz/mm</td>
</tr>
<tr>
<td>He pressure sensitivity</td>
<td>&lt; 10 Hz/mbar</td>
</tr>
<tr>
<td>Tuning range: slow</td>
<td>50 kHz</td>
</tr>
<tr>
<td>Tuning range: fast</td>
<td>1.6 kHz</td>
</tr>
<tr>
<td>$Q_0$ at operating field (4.5K)</td>
<td>&gt; 3.2 × 10^9</td>
</tr>
<tr>
<td>$Q_0$ at low field (4.5K)</td>
<td>&gt; 6.4 × 10^9</td>
</tr>
<tr>
<td>RF losses at 6 MV/m and 4.5 K/cavity</td>
<td>&lt; 70 W</td>
</tr>
<tr>
<td>Cryogenic standby losses per complete module</td>
<td>&lt; 90 W</td>
</tr>
<tr>
<td>$Q_{ext}$ of RF coupler (nominal)</td>
<td>2 × 10^6</td>
</tr>
<tr>
<td>Loss factor for a complete module (four cavities and two end tapers) at $\sigma_z = 10$ mm: longitudinal</td>
<td>5 V/pC</td>
</tr>
<tr>
<td>Loss factor for a complete module (four cavities and two end tapers) at $\sigma_z = 10$ mm: transverse</td>
<td>8 V/pC.m</td>
</tr>
</tbody>
</table>

Figure 3. Layout of the 75 Ω fixed coupler for LEP2
drawn by the coupler and a simple high-voltage DC supply feeds eight cavities in parallel. For the LEP2 project, the nominal RF power per SC cavity at full beam current (under matched conditions) is 120 KW at 352 MHz. On the experimental test set-up, using a single-cell superconducting cavity equipped with two RF couplers, RF power of more than 500 KW CW was transferred from the input to the output coupler via the cavity [4]. In pulsed mode, up to 700 kW were achieved, showing that the couplers are overdimensioned for LEP2 use.

**Higher-order mode (HOM) couplers**

The circulating beam deposits electromagnetic energy in each cavity in the form of higher-order modes (HOMs). Since for SC cavities the natural attenuation is extremely small, this energy has to be removed by special means. In the LEP2 SC cavities this is achieved by using HOM couplers [3] to take the extracted energy outside the cryostat, where it is dissipated in room-temperature loads. The effectiveness of HOM couplers is most critical with the short bunches of LEP (RMS half length 8-10 mm).

An additional function of the HOM couplers is to reduce the impedance seen by the beam at each HOM frequency in order to minimise the risk of coupled bunch instabilities and to reduce the power deposited by the beam (avoiding resonant build-up). Each LEP2 cavity is equipped with two higher-order mode couplers. They are of the “hook” type in which a series notch filter at the RF frequency is established with the inductance of the “hook” and its capacitance to the wall of the cavity port. The connecting RF line between the cold coupler and the cryostat wall is a 25 cm “rigid” coaxial line made of two thin stainless steel copper-plated tubes. Finger contacts at either end of the line allow some mechanical displacements during cool-down. It was demonstrated experimentally that more than 850 W can be transmitted through the HOM coupler and its line at 630 MHz (frequency of the dominant longitudinal HOM of the LEP2 cavity). Above 2.2 GHz (cut-off frequency of the 10 cm diameter beam tube) HOM power may propagate outside the SC cavity module.

**The tuning system**

The cavities are made from sheet metal and have, after electron-beam welding, frequency deviations up to 200 KHz and unequal field distributions. They are corrected during the fabrication process by unelastic deformation. Individual cells are adjusted in length to obtain a flat field distribution (± 5% deviation in field) and the observed frequency variations (200 kHz) correspond to a change of a 5 mm in the total length of the cavity.

The very narrow cavity bandwidth (± 90 Hz at $Q_{es} = 2 \times 10^6$) requires a very precise tuning system; this is based on the combined magnetostrictive and thermal effects of nickel tubes attached to the cavity. Three very rigid arms with 120° spacing are welded to the end flanges of the cavity and to the ends of the He tank. They are connected by three longitudinal, 2 m long nickel tubes forming a very rigid cage around the cavity. The total range of the fast tuner (magnetostrictive effect) varies from unit to unit between 1.6 and 2 kHz; a typical rise time is 50 ms for a step current change.

The coarse slow tuner is based on the controlled thermal expansion of the nickel tubes, which are cooled by a fixed flow of helium gas and heated in a controlled way at their centres. The slow tuning range is about 50 kHz and the speed greater than 8 Hz/s.
The RF power system

The LEP RF system is based on high-power klystrons (1.3 MW), each feeding eight SC cavities via a circulator and a series of symmetrical magic tee splitting stages [7]. The circulator is terminated on its third port by a 300 KW load (Figure 4). Each RF unit, comprising two klystrons fed by a common high voltage (HV), is totally self-contained and can be operated independently of the rest of the system. Since each klystron supplies eight cavities, the RF controls for the two groups of eight cavities were designed to be independent from each other. Therefore eight cavities are controlled by a single RF interlock trip. High-voltage interlocks are provided, which however can still switch off the whole unit of 16 cavities.

Figure 4. Layout of twin RF units sharing one common klystron supply

Regulation circuits for each klystron include a fast phase loop to suppress spurious phase modulation (essentially due to HV supply 600 Hz ripple) at the klystron output and a slow amplitude control acting on the modulator anode of the tube. The latter is used to control the sum of all eight cavity voltages. To avoid beam instabilities and to control to some extent microphonic effects in the cavities, an additional fast (few kHz) RF loop is also available. It regulates the vector sum of the eight cavity signals (vector sum feedback loop).

The total voltage available for acceleration in LEP is regulated by a software controller (Global Voltage Control), which adjusts the power in each klystron to achieve the desired total voltage taking into account unavailable klystrons and/or cavities.

The cryogenic system

The cryogenic system at each of the four acceleration points of LEP consists of a cryoplant with an equivalent cooling capacity of 12 KW (at present updated to 15 KW) at 4.5 K and its associated liquid helium (LHe) distribution system to supply the superconducting four-cavity module [3]. The He compression group, purifiers, low-pressure balloons and the He gas storage vessels and infrastructure equipment are installed in surface buildings and outside at each interaction point.

To fit into the available underground space, the cold box equipment is divided in two parts linked by a transfer line at about 20 K. A large cold box is situated at ground level and a smaller one in the machine access shaft, at the tunnel level.
The cold boxes are interconnected by transfer lines through the access shaft at between 50 and 140 m depths. From the smaller cold box the modules are cooled on each side through pairs of about 250 m long separate transfer lines, one for the LHe supply and one for the cold gas return. The cavities are cooled by a bath of boiling liquid helium (LHe) kept at 1.250 bar (absolute) at 4.45 K. A small percentage of the evaporated He is used for intercepting heat conducted along the RF couplers, tuners and beam tube transition cones.

Performance and reliability

Cavities

Like in any RF system, the SC cavities must be reconditioned after a long interruption. This is the case in particular at the end of the annual long machine shutdown. One or two weeks are dedicated to cavity conditioning at the start of a new run.

Cavity conditioning can be a simple RF processing, i.e. a gradual increase of the RF field, limited by the vacuum level in the cavity and RF coupler. To reach the highest fields it is often necessary to use pulse processing (few ms long RF pulses at 100 ms intervals). A good indication of the quality of the cavity is the level of radiation produced by the spurious electrons (from the emitters, dust particles) accelerated all along a module. Typical levels range from a few krad/h to 50 krad/h. In the most difficult cases, even in the LEP tunnel, helium processing is used. With all these techniques the available accelerating field in LEP is significantly above its design value of 6 MV/m. In the coming years (1999-2000) it is foreseen that the cavities will be run up to an average field of 6.7 MV/m to reach an energy of 100 GeV.

Cryogenic measurements of the cavity quality factor $Q_0$ (the only measurements of $Q_0$ available when the cavities are installed) do not show any sign of degradation of the quality of the niobium layer. There was only one incident which required removal of a module out of the tunnel. This module was accidentally exposed to a fast flow of clean nitrogen, following a human error in controlling the vacuum valves. Normally the cavities are vented to atmospheric pressure with a very slow flow of nitrogen to avoid transport of dust particles. The module was removed from the beam line (two-day operation) and completely disassembled. Each cavity was rinsed separately with ultrapure water and subsequently RF tested ($Q_0$ vs. $E$ curve) to check again its performance. The module was then reassembled and reinstalled in LEP (the total duration of this repair was about one month).

Couplers

The RF couplers were all conditioned on a warm test stand, in the travelling wave mode, at up to 200 kW prior to their installation on the SC modules. This guarantees a high safety margin during operation, and in fact, no serious incident with the RF couplers ever occurred. During cavity conditioning, the DC bias on the inner conductor is switched off to let multipacting discharges clean the coupler surface. Progress of conditioning is monitored by a vacuum gauge in the coupler, a gauge which is also part of the RF interlock system.

For the HOM couplers, made of solid niobium, there is a risk of quench, in particular if spurious accelerated electrons impinge on the hook surface. Temperature sensors at the base of the hook would detect a quench and trigger the interlock system. At the present intensities (6 mA) and bunch lengths
(σₜ > 8 mm), the vast majority of HOM couplers shows no sign of temperature increase. However a few of them (five to six) exhibit a slow temperature rise which is at the moment still under investigation.

Another effect of the higher-order modes excited by the beam in the cavity manifested itself recently. The small antennas used to monitor the RF field in the cavity also pick up the HOM fields at very high frequencies (~1 to 7 GHz). A substantial fraction of the power is dissipated in well-insulated cables inside the cryostat. As a result, a number of cables were burned. A campaign to replace these cables by thicker ones during the next shutdown is in preparation. Thanks to the cryostat design having a good accessibility this operation can be done in the tunnel without moving the modules.

**Tuning system**

The SC cavities have a very small bandwidth (± 90 Hz) and are therefore sensitive to microphonic effects. A mechanical excitation was found in the turbulent flow of helium in the input manifold of the cryostat and was rapidly corrected. Ponderomotive instabilities are observed with beam, when the cavity becomes detuned to compensate the reactive part of beam loading. They manifest themselves as strong oscillations (up to 50% of the cavity voltage) at the main mechanical cavity resonance (around 100 Hz). These instabilities, which may be incoherent from cavity to cavity, cannot be suppressed by the RF system, because a single klystron drives eight cavities. They are avoided by changing the tuner set points in such a way as to bring the cavities back to resonance, even in the presence of beam loading. Optimum set point values for each cavity are determined by software for a given beam current and energy.

Two other different methods have been recently tested to avoid ponderomotive instabilities: a small bandwidth feedback loop, working in parallel to the normal slow tuning loop, can effectively damp the cavity mechanical resonances around 100 Hz and raise the instability threshold. One can also reduce the effective sensitivity of the cavity to Lorentz force detuning (the primary source of ponderomotive instabilities) by using a feedforward link from cavity voltage to magnetostrictive tuner. Both methods have been successfully tested.

**RF power system**

The 34 klystrons driving the SC modules have so far accumulated between 2 000 and 10 000 operating hours, with an average of about 4 000 hours. The average life-time of these high power klystrons is expected to be 18 000 hours; in the LEP copper RF system one tube reached more than 28 000 hours. Eight klystrons have been replaced since the beginning of LEP in 1989. To replace one klystron takes about half a working day.

In an SC cavity system a high-power reflected pulse (four times the incident power) is generated at each abrupt RF switch-off. These pulses caused damage in the 50 Ω coaxial to waveguide transitions which are installed between the circulators and their loads. In some cases the circulator itself had also been damaged. This problem has now disappeared with new 10 Ω transitions replacing the old ones.

Arcing in the waveguide system has been sometimes observed, possibly due to higher order modes excited by the beam itself. Arc detectors are installed in the waveguides; they are part of the global interlock system.
The electrical length of the waveguides, between circulator and SC cavities, must be adjusted accurately (less than a few degrees of RF phase), since otherwise beam loading leads to a large imbalance in cavity voltages during operation. In extreme cases (e.g. at injection) where a cavity voltage gets so low that the tuner no longer works, the entire RF unit will trip off. At high energy some cavity voltages will exceed their limits, leading again to RF trips if the electrical lengths of waveguides are not properly adjusted. A tedious programme of adjustments is under way to minimise these effects.

**Cryogenic system**

The cryogenic system in itself is very reliable. During the years 1996 and 1997 the beam time lost due to the cryogenic system was less than 1% of the total (~ 4 000) running hours.

Three interruptions of cooling helium supply occurred in 1996. One was due to a turbine stop (two hours lost for RF operation), while the other two were of outside origin, stop of cooling water and general power failure affecting all LEP installations. Table 2 summarises the failures and associated downtime during physics in 1997 [5].

<table>
<thead>
<tr>
<th>Failure type</th>
<th>Place</th>
<th>RF downtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency stop</td>
<td>IP4</td>
<td>16 h</td>
</tr>
<tr>
<td>Power cut</td>
<td>SPS</td>
<td>3 h</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>IP8</td>
<td>6 h</td>
</tr>
<tr>
<td>Motor bearing</td>
<td>SPS</td>
<td>5 days</td>
</tr>
</tbody>
</table>

As illustrated by the preceding table, and also from general experience, the most troublesome incidents with the cryogenic system are due to outside sources, i.e. to either power or cooling water interruptions. The time needed to recover from a failure is practically proportional to its duration, according to the empirical formula [6]:

\[
\text{Time to recover} = 3 \text{ hours} + 7 \times \text{failure duration}.
\]

**Overall reliability**

The LEP2 RF system is a highly complex piece of equipment distributed over four geographical zones separated by long distances. Access to the equipment is not easy, all electronic control chassis being installed in remote underground areas. There are about 500 19" racks of electronic equipment to control the entire RF system, and over 9 000 interlocks which can trip an RF unit or its high voltage power supply. It is therefore not surprising that a variety of problems are recorded, due to equipment failure, software bugs or sometimes of unknown origin [7].

At the beginning of LEP2 exploitation, the average time between RF trips was 1h1/2; at present it is doubled (3 h), which indicates a significant improvement of the reliability of the overall system.

Moreover, not all RF trips lead to beam loss. LEP can operate with up to two klystrons being switched off. In most cases after a trip the Global Voltage Control can restore satisfactory operating conditions in a short time (mainly limited by the speed of data transmission).
Figure 5 gives an idea of the overall reliability of the RF system, as seen by its user, namely the operations group in charge of the running of LEP. In 1997, the total number of hours lost was 339, over the total running time of LEP (4000 hours). Only 7% of the 339 hours LEP downtime can be attributed to the RF system. Those lost hours were mainly due to problems requiring major interventions on the waveguide system (klystron, circulator or water load to be replaced) or urgent accesses in the machine tunnel.

**Figure 5. LEP downtime for 1997**

![Pie chart showing LEP downtime for 1997]

The 12% downtime attributed to the cryogenic system is for a large part not related to the cryoplants dedicated to the RF system, but to the cryogenics needed by the particle detectors installed in the four collision points of LEP. As mentioned already, most of the cryogenic downtime quoted here can be attributed to power or cooling water failures.

**Conclusion**

The large scale application of SC RF technology in LEP has demonstrated the robustness of superconducting cavities and their couplers in an industrial-like environment. The same conclusion can certainly be drawn for SC cavities of future proton machines for which in fact some of the LEP problems would not even exist (e.g. those related to higher-order modes and to some extent those related to ponderomotive instabilities).

The overall LEP RF system is still in a stage of improvement, following our experience gained with beam during the last two or three years, and its reliability will certainly continue to improve. It must be emphasised that LEP, and in particular its RF system, is at the same time an industrial plant of large size and a prototype equipment in continuous evolution and always pushed to its limits by the demands of high energy physicists. Despite these somewhat conflicting requirements the LEP RF system has already achieved a performance and a reliability record which just a few years ago looked almost impossible to attain.
Acknowledgements

It is a pleasure to acknowledge all the people who engineered, constructed and put into operation the LEP2 RF system. The success of this undertaking would not be possible without their ability, competence, dedication and long-lasting commitment.

We are grateful to O. Brunner and Ph. Gayet for very useful discussions.

We are indebted to Prof. V.L. Telegdi for his helpful advice and critical reading of this paper.

REFERENCES


SESSION IV

New Accelerators for ADS – Part I

Chairs: M. Inoue and P.K. Sigg
HIGH INTENSITY PROTON LINEAR ACCELERATOR FOR NEUTRON SCIENCE PROJECT

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Abstract

JAERI has been proposing the Neutron Science Project (NSP) which will be composed of a high intensity proton accelerator and various research facilities. With an energy of 1.5 GeV and a beam power of 8 MW, the accelerator is required for basic research fields and nuclear waste transmutation studies. The R&D work has been carried out for the components of the accelerator. In the low energy accelerator part, a beam test with an ion source and an RFQ has been performed with a current of 80 mA and a duty factor of 10% at an energy of 2 MeV. A 1 m long high power test model of DTL has been fabricated and tested with a duty factor of 20%. In the high energy accelerator part, a superconducting (SC) linac has been selected as a main option from 100 MeV to 1.5 GeV. A test stand for SC linac cavity with equipment of cryogenics, vacuum, RF source and cavity processing and cleaning system has been prepared to test the fabrication process and physics issues. The vertical tests of $\beta = 0.5$ (145 MeV) and $\beta = 0.89$ (1.1 GeV) single cell SC cavities have been made resulting in a maximum electric field strength of 44 MV/m and 47 MV/m at 2K, respectively.
Introduction

JAERI has been proposing the Neutron Science Project which aims at exploring the fields of basic science and nuclear technology using a high intensity proton accelerator [1]. The design studies are being carried out for a high intensity pulsed and CW spallation neutron sources for basic research fields of material sciences, etc., and for accelerator-driven transmutation technology of long-lived radioactive nuclides from nuclear power generation as a part of the OMEGA programme (Option Making Extra Gains of Actinides and Fission Products). A conceptual layout for the NSP proton accelerator is given in Figure 1.

Figure 1. A Conceptual layout of the JAERI NSP-LINAC

JAERI had originally planned to build a pulsed linac with an energy of 1.5 GeV and a peak current of 100 mA with 10% duty factor. The design study has been made to confirm technical feasibility to accelerate high peak current with high duty operation from the beam dynamics point of view. In this accelerator development, the R&D work has been performed on high brightness ion source, radio frequency quadrupole linac (RFQ), drift tube linac (DTL) and RF source, as well as the conceptual design of the whole accelerator's components.

JAERI has changed the original plan by proposing an option of superconducting (SC) linac to meet requirements for a variety of basic research fields mentioned above and an ultimate goal for waste transmutation [2]. This SC linac will be operated in pulse as a first stage for the spallation neutron source and upgraded to CW for engineering test as a second stage. These two operational modes, pulse and CW operation, will be realised by a time sharing manner, not simultaneously, and is the most challenging technical issue for the accelerator development. A specification of the JAERI NSP LINAC is given in Table 1.

The SC linacs have several favourable characteristics as follows: the large bore radius results in low beam loss, the length of the linac can be reduced, and high duty and CW operation can be made for engineering purposes. The AC power requirements for various operational conditions as a function of accelerator length is shown in Figure 2. The accelerator length is determined by the average accelerator gradient. Our reference value is located in the range of about 2 MV/m. For the case of CW operation, normal conducting (NC) linac requires 14 times more AC power than SC linac while 10% more for duty 10% pulse operation. The inexpensive operation cost with the SC option is expected in comparison with NC option in particular for the case of CW operation.
Table 1. A specification of JAERI NSP LINAC

<table>
<thead>
<tr>
<th>Particles:</th>
<th>Negative and positive hydrogen ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy:</td>
<td>1.5 GeV</td>
</tr>
<tr>
<td>Beam current:</td>
<td></td>
</tr>
<tr>
<td>1st stage:</td>
<td>Pulse average 1 mA, peak 16.7 mA</td>
</tr>
<tr>
<td></td>
<td>(duration 2 ms, repetition rate 50 Hz)</td>
</tr>
<tr>
<td>2nd stage:</td>
<td>CW &lt; 5.33 mA</td>
</tr>
<tr>
<td></td>
<td>Pulsed average &lt; 5.33 mA, peak 30 mA</td>
</tr>
<tr>
<td>Low energy:</td>
<td>RFQ &amp; DTL/SDTL normal conducting linac: 200 MHz</td>
</tr>
<tr>
<td>High energy:</td>
<td>Superconducting linac: 600 MHz</td>
</tr>
<tr>
<td>Chopping:</td>
<td>60% (intermediate pulse width of 400 ns)</td>
</tr>
</tbody>
</table>

Figure 2. The AC power requirement for SC linac and normal conducting linac; (a) and (b) show the cases of CW operation and pulse operation, respectively

Several R&D items have been studied for high intensity accelerator development: 1) the beam dynamic calculation; 2) the development of ion source and the fabrication of high power test models for CW-RFQ and CW-DTL; 3) the SC cavity development; and 4) high power RF source development.

2 MeV RFQ beam test and DTL high power test

The R&D work for the low energy portion has been carried out as a first step in the development with a positive hydrogen ion source and a pulsed RFQ. This R&D RFQ is a four-vane type and designed to accelerate 100 mA (peak) of protons to 2 MeV with a duty factor of 10%. The low power tuning, the high power conditioning and the beam tests were carried out [3]. The layout of the 2 MeV RFQ and the R&D results are shown in Figure 3. The proton beam from the 100 keV ion source was focused by the two solenoids to match the RFQ acceptance. The maximum RFQ output current, which was currently achieved, was 80 mA at the ion source extraction current of 155 mA with 10% duty factor. The transmission in the low energy beam transport (LEBT) from the ion source to the RFQ was about 65% with the proton fraction of about 80% in the ion source beam. The maximum
transmission rate through the RFQ was obtained to be 90% at the most optimum ion source condition. The RMS emittance values from the ion source and RFQ are minimum to be 0.15 \( \pi \) mm.mrad and about 0.62-0.76 \( \pi \) mm.mrad at the beam current of 170 mA, respectively. These emittance values are not satisfactory and the further improvement is needed.

**Figure 3. The R&D results of low energy accelerator parts**

A 1 m long R&D DTL high power test model with nine cells for mock-up of the first part of the DTL has been fabricated to study the RF characteristics and the cooling capabilities. The 20% duty operation was achieved with a RF power of 128 kW. Further tests of CW operation with this high power test model is being prepared. The 1/3 scaled DTL cold model installed with post couplers and 60 DT cells, which corresponds to the energy region of 2-10 MeV, was also fabricated. The effects with post coupler such as field distribution, the detuning sensitivity and mode spacing were tested. The parameters of post coupler configurations (total numbers and positioning) has been obtained for stabilisation of the accelerating fields [4].

**Low energy part below 100 MeV for the NSP linac**

**New design for the low energy part**

In order to realise the short pulse for basic research with the proton storage ring and the final CW operation, new R&D is being carried out including negative ion source and CW RFQ/CW DTL in addition to the SC linac development. At the high energy part of DTL, the SDTL (separated type of DTL) proposed by Kato (KEK) [5], has been studied. The SDTL, which has higher shunt impedance and simpler mechanical structure than DTL, is an attractive option for CW operation in the energy region of 50-100 MeV where the SC linac can not be applied.

**Ion source**

A negative ion beam is required for basic research to inject the beam into the storage ring which produce 1 \( \mu \)s pulse. The beam extractor of the existing positive ion source used for previous beam experiment was modified to produce negative ion beams from source ion plasma by providing the
transverse magnetic field. The characteristics of the negative ion beam have been examined with the maximum observed beam current of 21 mA at an arc discharge power of 35 kW [6] with caesium inserted.

A new negative ion source has been fabricated to accumulate experimental data to fulfil the requirement to the NSP linac. A plasma chamber is installed outside the insulator to easily change the configuration of the cusp magnet fields. The vacuum pumping system is also improved. The preliminary data have been obtained to be 11 mA beam extraction without caesium from the test experiment.

**RFQ for pulse and CW operation**

The low energy part should be capable for the CW mode operation as well as the pulse mode, because the SC linac has been operated with CW. The scheme to prepare two independent RFQs together with ion sources for pulse and CW operation is considered to meet these two different operational conditions [7]. The pulse mode RFQ is optimised at a beam current of 30 mA. A maximum peak electric field of 1.65 Ek is chosen. The CW mode RFQ is optimised below a current of 10 mA with lower electric filed of 1.5 Ek. The beam simulation is performed with the PARMTEQ and PARMTEQM codes. The similar performance for transmission rate and transverse and longitudinal emittances were obtained with the calculations. Because the most important problem for the R&D RFQ was found to be the RF contact between vane and tank, the RFQ will be made as integrated type by brazing between vane and tank. The high power model 50 cm long was fabricated and tested with a power of 60 kW and a duty factor of 20%.

**CW DTL/SDTL**

The parameters for the CW DTL are also re-evaluated to match the CW operation for the SC linac design concept. The SDTL concept has been also adopted to improve the performance for CW operation. A relatively low accelerator gradient of 1.5 MV/m is taken in order to reduce the RF power consumption and the RF heating. The expected maximum magnetic field gradient for the focusing magnet is about 50 T/m using the hollow conductor type Q-magnet. The end point energy for the SDTL is 100 MeV which is determined from the beam dynamics and mechanical consideration of the high $\beta$ structure. The beam dynamics study is conducted to obtain the optimised parameters for each accelerator structure. An equipartitioned design approach is taken for the DTL/SDTL to maintain the good beam quality and to prevent emittance growth causing beam losses.

**High energy accelerator part**

**The layout of the superconducting linac**

In the SC linac part, the proton velocities $\beta$ (the ratio of the particle velocity to the light velocity $\beta = v/c$) gradually change from 0.43 (100 MeV) to 0.92 (1.5 GeV). Accordingly, the length of the cavity has to be changed to match the resonant frequency and to prevent the phase slip. The number of the cavities with the different length, however, is limited because the capital and maintenance costs increase as the number increases. The cavities, therefore, are classified into several sections where all cavities have the same length.
In order to determine the layout of the SC accelerating structure, several cases of the SC linac have been studied [8]. The cavities in each $\beta$ section are made with five identical cells and designed at the specific beam energy but also can be operated at slightly different beam energy with lower efficiency. The maximum peak surface field is set to be 16 MV/m. Two cavities are laid in one doublet focusing period.

Figure 4(a) shows the linac length and number of the cavities and compares the reference case where each cavity has different $\beta$ values (281 sections). Figure 4(b) shows the RMS emittance growth calculated by the modified PARMILA. The emittance growth in the transverse direction is independent of the number of the sections, while the longitudinal emittance decreases as the section number increases. The section number of eight has been selected where the linac length and emittance growth are almost saturated. The conceptual layout and basic parameters of the superconducting linac are shown in Figure 5. The structure of the cryomodule, input/HOM couplers and tuning devices, etc., are being designed based on the KEK-TRISTAN (high energy $e^+, e^-$ colliding machine) experiences.

**Figure 4.** SC linac length and RMS emittance growth as a function of the number of sections; in the reference case, each cavity has different $\beta$ values (281 sections)

**Figure 5.** Basic parameters for superconducting (SC) linac

Using these parameters, some detailed calculations for the beam dynamics have been made. The equipartitioned design approach is also taken for the SC linac. The design and beam simulation results of the SC sections such as wave numbers, the beam sizes and the equipartitioned factors are shown in Figure 6. The equipartitioning factor of about 0.9 shows the design parameters nearly equipartitioned. There is only 1% increase of the transverse and the longitudinal RMS emittances. The error analyses on the performance of the linac with RF variations and quadrupole magnet misalignment were studied. Figure 7 shows examples presenting the longitudinal emittance diagram and energy dependence with RF amplitude and phase errors. From these error analyses, the accuracy of those RF amplitude and phase should be within 1% and 1 degree range.
Figure 6. Design and beam simulation results of the SC linac sections

Figure 7. The longitudinal emittance at the output energy and growth as a function of the energy with RF amplitude and phase error. The 2-3% errors are assumed in the calculations.

Another major concern is the strength of the cavity under the vacuum load for the low $\beta$ ($\beta < 0.7$) region. The mechanical structure calculations with the ABAQUS code have been made to determine the cavity shape parameters as well as electromagnetic ones with the SUPERFISH code.

Fabrication and test of a superconducting cavity

The test stand for a superconducting cavity development with the cryostat 80 cm dia. × 350 cm long and a clean room has been constructed [9]. Two sets of single SC test cavities have been fabricated for $\beta = 0.5$ which corresponds to the proton energy of 145 MeV. Fabrication process such as cold rolling and press of pure niobium metallic sheet, electron beam welding, surface treatment (barrel polishing, electro-polishing and high pressure water rinsing, etc.) have been performed based on the KEK experiences for 500 MHz TRISTAN cavity. Vertical tests have been conducted to examine the RF and mechanical properties. Figure 8 shows the results of performance test for two prototype cavities. The measurements were made several times for each cavity. The maximum surface
peak field strength of 24 MV/m at 4.2 K and 44 MV/m at 2.1 K have been successfully obtained for the second cavity. The Q values of $2.8 \times 10^{10}$ at 2 K and $7.3 \times 10^8$ at 4.2 K were obtained at $E_{\text{peak}} = 16$ MV/m [10]. This result was reconfirmed at the recent second experiment although the Q values this time were lower: $1 \times 10^{10}$ at 2 K because some deterioration of the surface condition occurs during the intermediate period. Those test results have satisfied the specification for the conceptual layout of the superconducting linac.

**RF sources**

The RF sources are the main components to determine availability and reliability, and are the most costly parts for the accelerator system. Two frequency choices, 200 MHz and 600 MHz, have been selected in the conceptual study for low energy and high energy part, respectively, where total peak RF powers of about 300 kW for RFQ, 9 MW for DTL/SDTL and 25 MW for SC linac are required for pulse operation. Due to the different two mode operations and gradual upgrade path, optimisation for RF configuration is one of the most important technical issues. An RF system based on the grid tube (tetrode) klystron and IOT has been carried out [11]. As an example, Figure 9 shows RF power requirements for eight different $\beta$ sections for each operating condition in the SC linac.

**Summary**

The R&D work for the prototype linac structures has been performed. The good performances of the components such as ion source, 2 MeV RFQ and RF source have been achieved. The test stand for the SC cavities was constructed. The vertical SC cavity test has been successfully conducted resulting in the satisfactory maximum surface electric field strength for the SC proton accelerator. The design work on the RFQ and DTL/SDTL as well as SC cavities for the CW operation is performed.
Figure 9. Beam loading for each cavity

Acknowledgements

The author would like to thank all the members of Proton Accelerator Laboratory and Proton Ring Laboratory for contributing to the work presented in this paper. The discussions and help on the SC cavity development from Drs. S. Noguchi, K. Saito, H. Inoue and E. Kako of KEK are greatly appreciated. Thanks to Drs. T. Kato and Y. Yamazaki of KEK, and Dr. R.A. Jameson of LANL concerning the beam dynamics calculations and accelerator system optimisation.

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ACTIVITIES ON THE HIGH CURRENT SC PROTON LINAC FOR THE TRASCO PROJECT

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Abstract

An R&D programme, TRASCO, has started in Italy on an accelerator driven system for nuclear waste transmutation. The large flux of spallation neutrons from a high current CW proton linac accelerator is intended to drive a subcritical system to transmute nuclear waste, while producing energy. Our specific task is to develop, together with the national industry, a design of the proton accelerator, along with prototype development for its most critical components.

The present reference design follows from that proposed at LINAC’96 and revised at PAC’97. A 1.6 GeV linac, operated at 25 mA, allows to reach 40 MW of beam power. A beam power upgrade is achievable using additional couplers per cavity. This design is based on a normal conductive low energy part, which includes a proton source, a RFQ and a DTL, followed by a three-section superconducting linac, at the 352 MHz LEP frequency. The three sections use five cell bi-elliptical cavities, designed to match the proton beam at the normalised velocities $\beta = 0.5$, $0.65$ and $0.85$.

A design for bi-elliptical (both at the iris and at the equator) cavity geometry has been carried out and a two year R&D activity to be performed by INFN will be dedicated to the fabrication of copper and niobium prototypes of the cavities. The $\beta = 0.5$ and $\beta = 0.65$ sections will use thin niobium cavities, copper sprayed for mechanical stability. For the high $\beta$ section, the sputtering technique will be preferred, in order to reduce the structure costs. A collaboration with CERN is being established to jointly develop a full five cell sputtered cavity for the $\beta = 0.85$ section, while performing chemical treatments and test on the other prototypes.

In this contribution we present the work that has been carried out so far, including the results from preliminary beam dynamics simulations. A discussion on the expected linac reliability will also be given, on the basis of the parameter choice and of the experience gained with the operation of similar cavities and plants.
Introduction

The generation of a high neutron flux with a broad energy spectrum by means of a high current proton beam impinging on a spallation target opens new perspectives in the use of high energy, high current proton accelerators [1,2]. A CW proton beam power in excess of a few tens of MW could provide the neutron flux to a subcritical nuclear reactor, allowing the design of a new, intrinsically safe, scheme for the nuclear energy production, where the closure of the fuel cycle has been obtained. In the subcritical system the high neutron flux in excess allows the incineration of the nuclear waste (actinides and long-lived fission fragments) produced by conventional critical reactors, leaving no substantial amount of radiotoxic waste at the end of the cycle.

The TRASCO project

TRASCO is a two year, 10 M$ programme in which the INFN, the ENEA and Italian industries will work on the design of an accelerator driven waste transmutation subcritical system. TRASCO is an Italian acronym for Transmutation (TRASmutazione) of Waste (SCOrie).

This programme is in line with the growing European consensus, promoted by Carlo Rubbia through the idea of the Energy Amplifier [2], on a long term reconsideration of the civil use of nuclear power, based on a final solution of the waste accumulation problem. While similar programmes are underway in the USA [1] and in Japan [3], in Europe the various national efforts [4] are co-ordinating through the signature of Memoranda of Understanding, like the one recently signed by the INFN, the CEA and IN2P3 for a common effort in accelerator technology development. Another MOU signed with the CERN group led by E. Chiaveri will allow us to use the wide experience gained so far in the production and commissioning of the LEP2 cavities. The cavity prototypes planned for TRASCO will be treated and tested at the CERN premises.

The aim of this preliminary, and short-termed, programme is to set the feasibility of a high beam power proton linac based, whenever possible, on established technologies and particularly the “cheap” CERN technology developed for the LEP2 superconducting cavities. This is an extremely attractive option, since it allows the possibility to make use of large and expensive facilities existing at CERN and at various European companies for the studies on prototypes.

The low energy part of the TRASCO linac (up to 100 MeV)

The low energy section of the machine, up to 100 MeV, is under study by two INFN groups, at the National Laboratories in Legnaro (LNL) and Catania (LNS), in the framework of the collaboration with CEA and IN2P3.

A working prototype of the source is in operation at Saclay, and the main objective of the collaboration is the improvement of the source reliability and availability. A second improved version of the source will be designed and assembled at LNS in the context of the TRASCO programme and its collaborations.

The design and development of the CW, 5 MeV, RFQ, similar to the one developed for APT at LANL [5], is considered one of the major technological tasks. An aluminium full-scale prototype of the first section, based on a preliminary design performed at LNL, has been constructed and will be tested in the framework of the collaboration with France to gain experience in view of the final
commonly engineered design. The construction of the first section (up to 2 MeV) of the real RFQ is part of the TRASCO programme. A picture of the LNL aluminium model of the RFQ is shown in Figure 1.

**Figure 1. The aluminium model of the RFQ prototype under RF test at LNL**

The medium energy part, up to 100 MeV, is in study by INFN/LNL and CEA/SACLAY, and will take advantage of a contract signed with a qualified industry. This reference option is based on the use of the DTL technology, with the focusing elements incorporated in the accelerating electrodes [6].

An alternative superconducting design is being considered at LNL [7] according to an architecture based on independently phased resonators. This second option is interesting for LNL in view of even other possible applications, as the production of radioactive nuclei to be accelerate in the ALPI booster. This design takes advantage of the wide experience of LNL in the design and operation of low beta superconducting cavities for heavy ions.

**The high energy part of the TRASCO linac (100 MeV-1.6 GeV)**

The reference linac design for the high energy section of the TRASCO linac has been set in Refs. [8] and [9]. The 25 mA, 100-1 600 MeV linac is split three sections, with synchronous cavity $\beta$ of 0.5, 0.65 and 0.85. The transverse focusing is provided by a periodic doublet lattice, with cell length of 8, 11.2 and 15.3 m, respectively. Figure 2 shows the focusing cell in the three linac sections.

**Criteria for linac sectioning**

The choice of the synchronous cavity $\beta$ for the three sections determines the linac performance, in terms of acceleration efficiency and beam dynamics behaviour. The acceleration efficiency is described by the ratio of the energy gain of a generic particle, $\Delta W$, with respect to that of the synchronous one. This defines the Transit Time Factor (TTF) of a cavity and can be written as:

$$\Delta W = q\Delta V_{acc} = qE_{acc}L_{act}T(\beta,\beta_c)\cos \phi_s$$

where $L_{act} = N\lambda\beta_c/2$ is the definition of the active cavity length, $E_{acc}$ is the accelerating gradient for the particle at $\beta = \beta_c$, that is defined as: $E_{acc} = \Delta V_{acc}^{max}/L_{act}$ and $\phi_s$ is the synchronous phase.
Figure 2. The doublet focusing cells of the three linac sections

Above: $\beta = 0.5$ section (with two cavities per cryomodule and 8 m of period length).
Middle: $\beta = 0.65$ section (with three cavities per cryomodule and 11.2 m of period length).
Bottom: $\beta = 0.85$ section (four cavities per cryomodule and 15.3 m of period length).

In this definition the transit time factor is normalised to 1 at the nominal particle velocity $\beta = \beta_c$. Note also that the geometrical cell length is not equal to the defined active length of the cell. As a matter of fact, we chose to indicate the $\beta$ values for the cavities not from the cell to cell distance, but from the behaviour of the transit time curve of the whole (end-cell compensated) cavity in the desired energy range, as shown in Figure 3 for the $\beta = 0.65$ cavity. In particular, the geometrical $\beta$ values for the three structures are: 0.475, 0.623 and 0.826.

Figure 3. The dotted curve is the transit time curve of the cavity chosen for Section II of the linac, as computed from the SUPERFISH fields, the two thin lines are the TTFs for an ideal cavity (sin-like fields) with $\beta = 0.652$ and 0.648. All the curves are normalised to 1 for a particle with $\beta = 0.65$.

The procedure for determining the $\beta$ values and the transition energies of the three sections depends strongly on the operating range allowed by the cavities. Our criteria sacrifice some RF efficiency in the first part of each linac section for improved average (real estate) acceleration gradient. Since the $\beta$ changes most rapidly at low energies, the initial few cavities in each section are used for velocity matching by operating them at lower RF power than the following. Such an
approach allows all section cavities to operate closer to the maximum accelerating gradient (see Figure 4), while the best klystron efficiency is set for the majority of a section cavities which, in the last part of each section, operate at a constant energy gain. Moreover, the smooth ramping of the effective energy gain at the entrance of each linac section helps the beam matching between the different lattice periods. In the high energy section the energy gain per cavity of 10 MeV and a better packing factor allows a real estate gradient of 2.6 MV/m.

Figure 4. Chosen cavity energy gain vs. beam energy (solid) and energy gain corresponding to 16 MV/m peak field (dashed)

Beam dynamics simulations

Beam losses in a high beam power accelerator should be kept to a minimum, in order to avoid component activation and “hands-on” maintenance. Hence, the performance of the linac needs to be validated with simulation codes. The results of extensive simulations, based on a new code [10], were presented at the LINAC’98 Conference [11]. In Figure 5 we show the RMS, 90% and 100% emittances for the nominal current of 25 mA, and a typical simulation of $10^5$ particles. The two transitions have been used for beam matching across the three sections. With this proper matching procedure the RMS emittance growth is limited to below 10% and the total emittance increases by a factor smaller than two.

Figure 5. The RMS, 90% and total (100%) emittances along the linac. The solid curves are the transverse emittances (left axis), and the dashed curve is the longitudinal emittance (right axis). The simulation has been performed with $100 \ 000$ particles.
The ratio between the beam aperture and the transverse RMS beam size is well above 25 all along the linac. This, together with the small number of betatron wavelengths in the linac (few tens), gives us confidence that in this design beam losses in the SC linac would not be a serious problem.

The simulations were performed for a nominal current of 25 mA, the goal being that of a driver for a prototype transmutation plant. An increase of the linac current up to 100 mA has not been studied yet in full detail. For currents greater than 50 mA a shorter focusing period should be provided in the first linac section, for example using superconducting quadrupoles in the cryomodules. A DTL extension to higher energies is less favourable, due to the higher reliability of the SC linac, explained in the following.

Reliability of the proposed design

Having assessed that the basic design does not show serious limitations in achieving the objectives for a transmutation plant, we are now planning the inclusion of spare linac focusing cells in order to achieve full reliability in the case of klystron or cavity/coupler faults.

In spite of the demonstrated high reliability of the existing large scale superconducting RF accelerators (LEP, CEBAF, HERA and TRISTAN), a driver for a nuclear waste transmutation plant needs to satisfy the stringent requirements imposed by its specific use. In particular, a beam stop due to any failure of one of its components causes an interruption of the spallation neutron flux sustaining the subcritical system. If this interruption exceeds a fraction of an hour (the exact time depending on the details of the core design), the fuel bar poisoning rises, i.e. a new start-up procedure needs to be performed and the waste cleaning process is partially lost.

For these reasons we are considering a linac design which includes two spare cryomodules for the low and intermediate energy sections. These two sections are the most critical, since they need to provide the correct transition energy to the following sections. A 10% spare contingency of three additional cryomodules is planned for the (less critical) high energy section. The lengthening due to the contingency hardware is around 80 m, for a new total length of 800 m. The updated section parameters are presented in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Summary of the SC TRASCO linac parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td><strong>Section length [m]</strong></td>
</tr>
<tr>
<td><strong>Injection energy [MeV]</strong></td>
</tr>
<tr>
<td><strong>Cell period [m]</strong></td>
</tr>
<tr>
<td><strong># focusing cells/section</strong></td>
</tr>
<tr>
<td><strong>Max. ΔE/cavity [MeV]</strong></td>
</tr>
<tr>
<td><strong>Eacc [MV/m]</strong></td>
</tr>
<tr>
<td><strong># cavities/section</strong></td>
</tr>
<tr>
<td><strong># cavities/cryomodule</strong></td>
</tr>
<tr>
<td><strong># cryomodule/klystron</strong></td>
</tr>
<tr>
<td><strong>Beam power/cryomodule [kW]</strong></td>
</tr>
</tbody>
</table>

* The additional focusing cells indicated after the plus sign are the needed contingency required for the linac reliability.
In the case of failure, a spare component will take the place of the faulty, and the beam will be back on the target in the time required by the reactor design. Some of the components, e.g. the klystrons, can be repaired or replaced during the linac operation, while others, like the cavities or the RF couplers, need to wait for the planned reactor maintenance shutdown.

The best use of these spare components when they are not needed (whether they are kept on or off at all times) needs to be analysed on the basis of both capital and operational costs.

**R&D activities on the TRASCO superconducting cavities**

The SC linac design uses five cell structures in the three different sections, at the synchronous values of $\beta = 0.5$, 0.65 and 0.85 [12]. The choice of the number of cells per structure is motivated from a compromise between the structure efficiency and its operating energy range, because the energy acceptance narrows as the number of cell increases. Five cell structures give the highest active length per cavity, compatible with a three section linac design. The efficient energy for such a scheme ranges from 100 MeV to 1.7 GeV.

The cavities have been designed with an elliptical iris and an elliptical equator, on the basis of electromagnetic and mechanical considerations. A sketch of the geometry is presented in Figure 6. The end cells have been modified with respect to the inner cell geometry in order to achieve field compensation. The magnetic volume reduction needed for compensation is obtained by slightly increasing the angle $\alpha$, with fixed iris radius ($R_{\text{iris}}$) and d (see Figure 6).

**Figure 6. Reference geometry for the cavity shapes**

In Table 2 we report the main electromagnetic characteristics of the three structures: the ratio between the peak electric field on the cavity surface with respect to the accelerating field, the ratio of the maximum magnetic field with respect to the accelerating field and the cell to cell coupling. The geometrical parameters of the structures and the operating values for the accelerating gradients in the linac design have been chosen in order to limit the maximum surface electric field below
16 MV/m and the maximum surface magnetic field below 40 mT. A cell to cell coupling of 1.7% has been required to the structure. Table 3 reports the geometrical dimensions of the internal cells of the cavities. The cavity shapes have been extensively investigated with the codes SUPERFISH and OSCAR2d [13].

Table 2. Main electromagnetic characteristics of the three structures

<table>
<thead>
<tr>
<th>$\beta_c$</th>
<th>$E_p/E_{acc}$</th>
<th>$B_p/E_{acc}$ [mT/MVm$^{-1}$]</th>
<th>Cell to cell coupling [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>3.4</td>
<td>8.1</td>
<td>1.8</td>
</tr>
<tr>
<td>0.65</td>
<td>2.7</td>
<td>6.5</td>
<td>1.7</td>
</tr>
<tr>
<td>0.85</td>
<td>2.3</td>
<td>4.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Table 3. Geometrical parameters (in mm) for the internal cell geometry at the working cryogenic temperature

<table>
<thead>
<tr>
<th>$\beta_c$</th>
<th>0.5</th>
<th>0.65</th>
<th>0.85</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>47.1</td>
<td>71.6</td>
<td>131.3</td>
</tr>
<tr>
<td>B</td>
<td>80.1</td>
<td>121.8</td>
<td>196.9</td>
</tr>
<tr>
<td>a</td>
<td>33.4</td>
<td>44.8</td>
<td>35.4</td>
</tr>
<tr>
<td>b</td>
<td>60.1</td>
<td>89.6</td>
<td>56.7</td>
</tr>
<tr>
<td>d</td>
<td>26.8</td>
<td>32.8</td>
<td>26.8</td>
</tr>
<tr>
<td>L</td>
<td>101.1</td>
<td>132.6</td>
<td>175.7</td>
</tr>
<tr>
<td>D</td>
<td>392.2</td>
<td>392.7</td>
<td>385.2</td>
</tr>
<tr>
<td>$R_{iris}$</td>
<td>99.4</td>
<td>109.3</td>
<td>114.3</td>
</tr>
</tbody>
</table>

The operating accelerating fields will be 4.6, 5.7 and 6.7 MV/m, respectively. These are consistent values with respect to the CERN operational experience, and the gradient improvements gained through the R&D driven by the TESLA Test Facility [14] will allow a safety margin for operation and/or a cost reduction by easing the material requirements.

A synchronous phase of 30 degrees was chosen to provide the necessary longitudinal focusing.

**Mechanical issues of the structures**

The behaviour of the bulk niobium and copper cavities under vacuum has been investigated with structural analysis tools, in the elastic and in the elastoplastic regimes. This analysis led to the choice of an elliptical equator, so as to achieve a more homogeneous stress distribution along the geometry with respect to the usual elliptical iris and round equator design.

Only the lower $\beta$ cavities are unstable under vacuum and need stiffening to ensure mechanical stability. The preliminary results obtained recently in France [15] for the structural stiffening of thin niobium cavities via copper spraying with a plasma jet are very promising. In particular, two single cell cavities at 3 GHz made with a RRR = 40 niobium sheet of 0.5 mm reached around 30 MV/m of surface peak field. No performance deterioration has been measured after the copper spray deposition.
On this basis, we decided to use this technology as the reference for the lower $\beta$ cavities, given our low operating peak surface fields (16 MV/m). Figure 7 shows a summary of the stress calculations for the two lower $\beta$ cells under vacuum, in the case of copper spray stiffening on a 2 mm niobium sheet. The copper thickness ranges from 3-18 mm.

**Figure 7. Stress analysis for the $\beta = 0.65$ (left) and $\beta = 0.5$ (right) copper sprayed cavities.**

Units for the stresses indicated in the scale on the right are kgf/mm$^2$.

---

**Cavity prototypes**

The construction and test of prototypes of the cavities with different geometry, required for the three-linac section, is one of the important task of the TRASCO programme. In particular the two-year programme on cavity prototypes includes:

- Construction and test of a full $\beta = 0.85$ five cell cavity. This cavity, now under construction at CERN in the framework of the MOU recently signed, is built according to the TRASCO design and takes advantage of the experience gained at CERN on cavity fabrication, sputtering and test. The cold tests are expected by Spring 1999.

- Construction and test of some (4-6) single cell cavities, according to the design of the lower beta structures. These cavities are expected to qualify the already mentioned technology [15] of the external copper plasma deposition on a completely treated thin niobium cavity. Reactor grade niobium (RRR = 40) of 2 mm thickness has been chosen and ordered for this purpose. On the basis of the experience gained so far [14], we decided to check the niobium sheets with the eddy current technique, to avoid inclusions of foreign materials, and to afer the electropolishing with respect to the usual buffered chemical polishing (BCP). The 800°C heat treatment is foreseen and the final high pressure water rinsing will be applied. This part of the programme will be performed with the Italian company ZANON and will use the CERN competencies for chemistry and cold tests.

- Construction and test, with ZANON, of a second full $\beta = 0.85$ five cell cavity. This cavity should also be equipped with a cryostat and with prototypes of the major ancilliary components, as couplers and tuners.
These three objectives are considered particularly important to qualify the chosen technologies and to demonstrate the real cavity performances we can expect. A precise estimation of the linac cost will also be possible after this R&D programme.

**High order modes and multipactoring**

The excitation of high order modes in the five cell structures can be of some concern due to the very high current foreseen for the linac. The analysis of the first bands, performed with the OSCAR2d code [13], shows very low R over Q values for all the high order modes, due to the crossing of the TM011 and TM020 bands. This results in a strong decrease of the shunt impedance of the modes.

The choice of a beam tube diameter equal to the inner irises diameter helped in easing the high order mode behaviour of the accelerating structure. The RF field freely propagates through the cavity for any frequency above the beam tube cut off and no trapped “tube modes” are expected.

Possible electron loading effects (multipactoring) were investigated too. As expected the elliptic shape of the equator resulted in a very safe cavity operation. Indeed, the choice of the elliptical equatorial shape gives a stronger longitudinal component of the electric field along the surface, which pushes the electrons strongly towards the cavity equator and brakes the resonant conditions.

**Preliminary design of the cryomodules**

Based on the expertise gained in the design of the second and third generation of TESLA Test Facility (TTF) cryostats [16] we have started the design of the cryomodules for the superconducting linac. The design is still at a preliminary stage, but various solutions have been chosen because of their success in the TTF cryomodule design.

The cryostat has a single thermal shield, made by a 1 mm copper sheet supported by a stainless steel frame. The thermal shield is cooled by two symmetrical helium pipes connected through the new “finger-welding” scheme [16] that has been successfully tested at TTF [14]. This design reduces production costs and pre-assembling time.

Following the scheme developed for LEP2 at CERN, the cryomodule will be extremely modular, each module holding a single cavity in a stainless steel frame. The vacuum vessel is open, similar to that one used in the LEP2, with a thin stainless steel sheet closing it, to guarantee easy access. Figure 8 shows the cryostat preliminary design.

**Conclusion**

We have summarised here the major activities on the high current proton linac foreseen for the TRASCO project that has been recently funded in Italy. These activities are at the beginning and the growing interest of the international community suggests that some of them will be modified because of a better co-ordination between the different subjects and nations involved.

The framework we have recently set through the Memoranda of Understanding signed by the INFN with the CEA and IN2P3, for a common effort in the accelerator technology development, and with CERN, for cavity development, is a good starting point.
Acknowledgements

I would like to conclude by thanking all the members of the TRASCO group for the excellent work done so far, a small part of which I have summarised in this paper.

REFERENCES


[4] See the contributions of M. Salvatore and M. Napolitano at this workshop.


Abstract

The report is devoted to the design of superconducting linear accelerator as a driver of nuclear power installations of a new generation – accelerator driven systems (ADS). The purpose of the research is the development of a CW mode 1 GeV, 30 mA proton superconducting linear accelerator. Superconducting cavities are used in the main part of the accelerator from 50 MeV up to 1 GeV. The main statements used in this design are discussed. Beam dynamic simulation results are presented.
Introduction

Proton linear accelerators are the base of safe electronuclear power installation (accelerator driven power system – ADS). Such installations are dedicated to various purposes: weapons plutonium conversion, “energy amplifier”, transmutation of radionuclear wastes, etc. [1-3]. A set of demands is placed on accelerators according to its functions. For the most ADS CW mode linear accelerator for the energy of 1 GeV and current up to 30 mA is demanded.

At the moment there are not problems of fundamental nature in such linac construction. That is why the main problems have economic and technical aspects [1-3]: high economic efficiency (total electric efficiency >50%), its reliability and radiation purity, the linac design must permit modernisation with changing of beam performances demanded, linac design must apply perspective methods and materials tested in actual practice.

Scheme and main requirements for linear accelerator

The most expedient way of obtaining proton beams demanded for ADS is through a linear accelerator with superconducting (SC) accelerating resonators.

The scheme of CW proton and negative ions of hydrogen linear accelerator (LAP) for the energy of 1 GeV and current up to 30 mA with superconducting accelerating resonators (SCR) in the main part is shown in Figure 1.

Figure 1. 1 GeV, 30 mA CW linac scheme

<table>
<thead>
<tr>
<th>IAP</th>
<th>First part</th>
<th>Second (main) part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector</td>
<td>RFQ</td>
<td>DTL</td>
</tr>
<tr>
<td>352 MHz</td>
<td>352 MHz</td>
<td>1 056 MHz</td>
</tr>
<tr>
<td>7.2 m</td>
<td>55 m</td>
<td>400 m</td>
</tr>
<tr>
<td>100 keV</td>
<td>5 MeV</td>
<td>50 MeV</td>
</tr>
</tbody>
</table>

The following main statements are used in its design.

1. **Reliability.** Analysis of proton linac operation reveals that the principal reasons for their downtimes are malfunctions in high voltage injectors and in the RF power supplying systems. In order to solve the problem of proton linac reliability, it would be necessary to fulfil at least two conditions, viz., it is necessary to create reliable amplifying electron devices of large unit output power capacity, thereby reducing essentially the number of RF driving channels to a level not exceeding markedly that now running in linacs of meson facilities, and to refuse from the use of high voltage injectors. So the main requirements are low voltage injector, CW mode and decreased number of RF channels.

2. **Economic efficiency.** With respect to accelerator operation efficiency, it is necessary that total efficiency of high current accelerator be no less than 50%. Since efficiency of RF systems is about 70%, than cavity efficiency (\(\eta_c\)) has to be rather high (70-80). Cavity efficiency can be estimated by the formula:
\[ \eta_c = \frac{1}{1 + \frac{E_a}{I_b} Z_{\text{eff}} \cos^2 \varphi_s} \]

where \( I_b, E_a, Z_{\text{eff}}, \varphi_s \) are beam current, a voltage corresponding to particle energy gain per cavity unit length, effective shunt impedance of the cavity unit length, and synchronous phase, respectively. Power consumed by the other linac systems (focusing, vacuum, control, etc.) amounts to relatively small part. So the high value of \( \eta_c \) occurs with acceleration of high current. The following relationship should be fulfilled:

\[ E_a \cdot I_b >> \frac{E_a^2}{Z_{\text{eff}} \cos^2 \varphi} \]

So it is essential that power for beam acceleration is far in excess of power dissipated in cavity walls. As calculations indicate, with ordinary parameters of “warm” cavity and acceleration rate of about 1 MeV/m, \( \eta_c \) may be as much as 70% with the currents of the order of 80 mA. For high efficiency with lower intensities pulse mode operation of linear accelerators is demanded, that takes place in all modern proton accelerators, or CW mode and superconducting cavities are demanded. For currents of 10-50 mA it is appropriate to use an accelerator with superconducting cavities. Superconducting proton linac has crucial advantages over “warm” linear accelerator in the range of middle currents of the order of ones and tens mAmps. RF power requirements are significantly lower and consequently cost of linac construction and exploitation decrease; accelerator reliability increase and length decrease by no less than two times as well. Therefore the main requirements are superconducting cavities in the main part of the linac and short length because of the high accelerating rate.

3. Radiation purity. Beam losses are not more than \( 10^{-4} \) [4] because of acceptance reserve of accelerating-focusing channels.

Linac consists of three parts. Initial part – RFQ structure, accelerating field frequency \( f_1 = 352 \) MHz. First part – three DTL resonators, frequency \( f_1 = 352 \) MHz. Main part – accelerating structure consists of 248 nine-cell axially symmetric cavities with elliptical shaped cells excited at the frequency \( f_2 = 1056 \) MHz. The accelerating rate is 5 MeV/m. (Now the possible accelerating rate of 15 MeV/m is considered.)

Odd frequencies ratio \( f_2/f_1 = 3 \) allows if necessary to simultaneous acceleration of protons and negative hydrogen ions.

The main parameters of the linac are presented in the Table 1. The parameters will not change in the case of acceleration of hydrogen negative ion beam.

The RF system and automatic control system are proposed as classic linac. For a decrease in the number of RF channels the possibility of excitation of several SCR in the main part by one RF amplifier is considered (see Figure 2). Klystrons are used as RF amplifiers (1.3 MW klystrons in initial and first parts, 400 kW klystrons in main part).

In order to provide superconductivity in the SCR, its surfaces by layer are cooled to 2 K by liquid helium. The total thermal power removed by helium is 5 kW.

The module of the main part of the linac with two SC cavities and a PM quadrupole lens is shown in Figure 3.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial part</th>
<th>First part</th>
<th>Second part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of accelerator, resonator</td>
<td>RFQ</td>
<td>DTL</td>
<td>9-cell resonators</td>
</tr>
<tr>
<td>Injection energy, MeV</td>
<td>0.1</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Output energy, MeV</td>
<td>5</td>
<td>50</td>
<td>1000</td>
</tr>
<tr>
<td>Frequency of accelerating field, MHz</td>
<td>352</td>
<td>352</td>
<td>1056</td>
</tr>
<tr>
<td>Number of resonators</td>
<td>1</td>
<td>3</td>
<td>248</td>
</tr>
<tr>
<td>Period of focusing, m</td>
<td>$\beta \lambda$</td>
<td>2$\beta \lambda$</td>
<td>14$\beta \lambda$</td>
</tr>
<tr>
<td>Acceptance, specified, $\pi$ cm-mrad</td>
<td>0.27</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Effective emittance, specified, $\pi$ cm-mrad</td>
<td>0.1-0.15</td>
<td>0.15-0.3</td>
<td>0.3-0.4</td>
</tr>
<tr>
<td>Equilibrium phase, degree</td>
<td>-(40+35)</td>
<td>-30</td>
<td>-30</td>
</tr>
<tr>
<td>Phase width, degree</td>
<td>360-36</td>
<td>36+20</td>
<td>60+20</td>
</tr>
<tr>
<td>Pulse spread at output, %</td>
<td>0.32</td>
<td>0.1</td>
<td>0.04</td>
</tr>
<tr>
<td>Resonator length, m</td>
<td>7.2</td>
<td>18.5-17.6</td>
<td>0.4-1.12</td>
</tr>
<tr>
<td>Diameter of resonator, cm</td>
<td>20.2</td>
<td>55.0</td>
<td>29-26</td>
</tr>
<tr>
<td>Aperture diameter, mm</td>
<td>5</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Accelerator length, m</td>
<td>7.2</td>
<td>55</td>
<td>400</td>
</tr>
<tr>
<td>Power for beam, MW</td>
<td>0.15</td>
<td>1.35</td>
<td>28.5</td>
</tr>
</tbody>
</table>

**Figure 2. Scheme of RF power supply of resonator set from one amplification channel (with automatic control system and redundancy)**
Results of beam dynamic simulation

Codes of the LIDOS.Advisor package [5-8] were used for beam dynamic calculation. The main problem is to prevent particle losses in the high-energy accelerator part. Two main dangerous effects leading to an increase in transverse beam size would be set: influence of phase motion on transverse one and random errors (within the limits of tolerances) in tuning and installations of channel elements. The first effect is the peculiar features of the superconducting channel. In an ordinary “warm” channel, the influence of phase motion on transverse one is weak effect, but in this case this influence is rather high because of the high amplitude of the accelerating field. This effect is most conspicuous in the high-energy accelerator part with low (50-100 MeV) particle energy.

The High Beta Linac (HBL) part of the LIDOS.Advisor package makes it possible to determine the main channel parameters, demanded tolerances for elements installation, and reveals the influence of various factors on beam parameters in the channel and at accelerator output. Initial and final particle energy, distribution of accelerating field amplitude and equilibrium phase along the accelerator, emittance and current are specified as initial information. Mean-squared errors of position of focusing lens ends, focusing fields, rotation of lens median axes, amplitude and phase of accelerating fields are used as additional initial data. Based on these data, channel random realisation are calculated and statistic characteristics of beam parameters are derived. Simulations on the basis of LIDOS.Advisor.HBL show that the mismatching factor of transverse beam sections increases the boundaries of longitudinal oscillation separatrix up to the 1.8-2 in the considered case. If beam phase width at the channel beginning is 50°, then maximal mismatching is 1.5. Beam phase characteristics at the accelerator output for the channel without disturbances and superposed beam phase portraits obtained with 50 channel random realisation are shown in Figures 4 and 5.
The phase width of the initial beam is 50°. Initial data were as follows: error of cavity field amplitude: 1%; error of cavity phase: 1°; transverse displacement of quadrupole lens ends: 50 mkm; error of magnetic field gradient in the lenses: 1%; rotation of lens median axes: 0.5°. Statistic characteristics of beam parameters obtained in 50 random realisation are shown in Figure 6.

Results analysis shows that because of the influence of longitudinal phase oscillations and under the influence of random errors transverse beam size with high confidence coefficient will not exceed 5.5 mm. In this case the size of matched equilibrium section in the channel without errors is 3 mm.

Fulfilled investigations verify the efficiency and reliability of the described scheme as well as its practical feasibility.
Figure 6. Statistic characteristics of beam parameters obtained in 50 random realisations

REFERENCES


New Accelerators for ADS – Part II

Chairs: M. Mizumoto and C. Pagani
The use of cyclotrons to produce high intensity beams offers many advantages with respect to linear accelerators: compactness, lower cost and higher electrical-beam power conversion efficiency. According to the positive experience of the PSI laboratory, the cyclotrons proposed up to now to deliver high intensity beams are based on extraction by electrostatic deflectors. In this case a large extraction radius and high energy gain per turn are required. An alternative method based on acceleration of $\text{H}_2^+$ ions is proposed here. The binding energy of a $\text{H}_2^+$ molecule is about 20 times higher than $\text{H}^-$, and also allows to use very high magnetic fields at energies as high as 1 GeV/n. The maximum beam current achievable with these cyclotrons is extrapolated from the experimental results obtained by $\text{H}^-$ commercial cyclotrons. The main advantages, i.e. easy operation, high reliability and electrical conversion efficiency and the technological problems of this alternative method are presented.
Introduction

Proposals for construction of accelerators driven systems (ADS), to be used as an energy amplifier or for waste transmutation, have stimulated the study of an accelerator complex based on cyclotrons [1]. The main goals to be achieved by these accelerator complexes are: an energy of 1 GeV and a current of ≥10 mAmp. The cascades cyclotrons accelerator complex recently proposed is a natural upgrading of the PSI accelerator complex [2,3]. Unfortunately, the beam extraction from cyclotrons is a difficult process if an efficiency as high as 100% is required. The beam losses at extraction are due to the interception of the beam particles with the electrostatic deflector. To achieve an extraction efficiency near 100%, it is straightforward process to increase the separation among the beam orbits and reduce the beam halos in the radial plane. Increasing the size of the extraction radius of the cyclotrons and the energy gain per turn allows to obtain larger separation among the orbits and at the same time to reduce the growth of the longitudinal beam size due to the space charge effects and then also the beam energy spread [2]. In this paper an alternative method based on acceleration of \( \text{H}_2^+ \) and the extraction by stripper is proposed. The \( \text{H}_2^+ \) molecule after the acceleration process inside the cyclotron is broken into two free protons when it crosses the stripper placed at the extraction radius. These protons run along an inner circular trajectory with R ≈ Rex/2 and escape the region of magnetic pole of the cyclotron. The acceleration of \( \text{H}_2^+ \) molecule has the following advantages:

- beam extraction by stripper and elimination of the electrostatic deflector of extraction;
- lower voltages on the acceleration electrodes;
- reduction of space charge effects;
- use of high magnetic field becomes possible.

The elimination of the deflector also allows to extract the beam without any beam losses if the cavities operate with low voltages (500 kV). If such is the case, an easier and more reliable operation mode of cyclotron is achieved. The stripping process is normally used by some cyclotron laboratories [4] to extract light and medium ions, by TRIUMF cyclotron to extract \( \text{H}^- \) at energies as high as 520 MeV (200 kW) and in many commercial cyclotrons to extract \( \text{H}^- \) or \( \text{D}^- \) beams with beam power of about 40 kW. Unfortunately the extremely low binding energy of \( \text{H}^- \) ions prevent the use of a high magnetic field for high energies due to the high losses produced by electromagnetic stripping. The binding energy of \( \text{H}_2^+ \) ionised molecule is ≈16.3 eV, about 20 times higher than \( \text{H}^- \), and allows to use a very high magnetic field at energies as high as 1 GeV per nucleon. Of course the magnetic rigidity of \( \text{H}_2^+ \) is twice the magnetic rigidity of a proton beam having the same velocity. Thus, it is mandatory but feasible to use higher magnetic fields produced by superconducting magnets to accelerate this molecular beam. Up to now the superconducting cyclotrons have been dedicated to the acceleration of ion beams to be used for nuclear experiments and limited at low intensity beams. Although some projects like MSU and EXCYT [5,6] plan to increase the beam intensity of extracted beams, the expected upper limit is of some kW. This limit is mainly due to the poor separation between the orbits at the extraction radius and to the use of electrostatic deflectors in compact superconducting cyclotrons.

Extraction by stripping does not require single turn extraction, and allows to use lower energy gain per turn during the acceleration process. The reduction of the voltage on the DEES from typical values of 1 MV for a single turn extraction of 1 GeV beam, down to 0.5 MV, gives a reduction of a factor 4 on the thermal power losses, making the design of the cooling system of the cavities a little less difficult a task.
Hereunder, to demonstrate the feasibility of extraction by stripping of $\text{H}_2^+$, a simulation using the measured magnetic field of our K800 compact superconducting cyclotron is presented. Moreover some considerations on the possible use of larger compact and/or sector separated superconducting cyclotrons to accelerate high current beam at high energies, the main limits due to the interactions with the molecule of the residual gas and to the electromagnetic stripping of $\text{H}_2^+$ are discussed.

**Extraction by stripping**

In the near future, upon the installation of the axial injection system, the LNS superconducting cyclotron will be able to accelerate $\text{H}_2^+$ up to 100 MeV/amu: the beam will be extracted by electrostatic deflectors and magnetic channel with a typical extraction efficiency of $30 \div 70\%$. To extract $\text{H}_2^+$ by stripping a new extraction path across the cryostat and the yoke is mandatory. So it will not be possible to upgrade our cyclotron, because to build a new extraction channel it would be necessary to dismount the cyclotron and the cryostate itself. Anyway we can use the measured magnetic field and characteristics for extrapolation for a new compact superconducting cyclotron.

To check the feasibility of stripping extraction in compact superconducting cyclotrons the trajectories of $\text{H}_2^+$ inside our K800 cyclotron were studied. The magnetic field was interpolated from the measured magnetic field maps. The stripper foil, simulated by a sudden change of charge state, was placed at different angles inside a hill. We found that for an enough large angular range of stripper positions the stripped particles escape from the cyclotron magnetic field in one turn. In Figure 1 three different trajectories for three different stripper positions are shown. According to our simulations small variations of the extraction radius have negligible effects on the extraction trajectory. The stripper position has a strong effect on the size of the beam envelope. This is mainly due to the different strength of focusing field crossed by the different trajectories. However a position which minimises the beam envelope in both the radial and axial plane along the whole trajectory was found. The radial and axial beam envelope along the better extraction trajectory is shown in Figure 2.

The beam envelope has a maximum in the region where the trajectory crosses the cryostat. The insertion of a small magnetic channel at $R = 100$ cm, quite far from the last accelerated orbit is sufficient to focus the beam and maintain its size below 10 mm in both the transversal directions up to the outer radii. Although for each cyclotron the extraction trajectories are different, the present simulation confirms the experience of other laboratories [4], also proving the feasibility of this extraction process for compact superconducting cyclotrons.

**Figure 1. Trajectory of the last accelerated orbit of $\text{H}_2^+$ and extraction trajectory of the proton beam produced by the stripper**
Figure 2. Beam envelope along the extraction trajectory without and with the magnetic channel, dotted and continuous line, respectively.

Acceleration of $H_2^+$ with cyclotrons

Compact superconducting cyclotron

To check the feasibility and the limits of the proposed method, the design for a new conservative compact superconducting cyclotron is in progress. The preliminary parameters of this new cyclotron are presented in Table 1. It is based on the design of our existing K800 cyclotron but with a lot of simplifications and some upgrading. The new cyclotron has to accelerate a single kind of particle with $q/A = 0.5$ at a fixed energy of 100 MeV/amu, while the present cyclotron has to accelerate any kind of particles in a broad energies range. The main advantage of the new cyclotron are thus: single frequency, few trim coils with small size and small power, fixed operation mode of the power supplies of the main coil, low liquid helium consumption, larger gap in the median plane and across the cryostate and more accessibility at the median plane. This compact cyclotron for 100 MeV/n $H_2^+$ is also a very appealing accelerator for the production of exotic ions. Moreover this cyclotron should be able to accelerate deuterons and fully stripped light ions ($q/A = 0.5$, $A \leq 32$) at fixed energy of 100 MeV/n. If a beam power up to $10 \div 20$ kWatts is required, these beams could be extracted by electrostatic deflectors placed inside the valley. This cyclotron is proposed as primary accelerator of our upgrading programme of the EXCYT project to produce exotic ions beams at LNS.

This compact superconducting cyclotron (CSC), without any pre-injector cyclotron, could be used as injector for the ring cyclotron proposed in Refs. [2,3]. This cyclotron is able to deliver a proton beam of 100 MeV and extensions at higher energy as 150 MeV or more are realistic too. The intensity limitation due to the electrostatic extraction process is then overcome by this kind of cyclotrons.

Let us now evaluate the upper intensity limits for $H_2^+$ compact cyclotrons. The main constraints on the maximum beam current delivered by cyclotrons are due to the defocusing of the beam in the early stage of acceleration due to the space charge forces. The dynamic of $H_2^+$ in a compact cyclotron is similar to the acceleration process of $H^-$ if the magnetic field, the accelerating voltage, injection energy are properly scaled. So we could extrapolate the effect of space charge for the $H_2^+$ beam from corresponding figures for $H^-$ cyclotrons. In both cases the space charge effects are strongest in the first turns. So the main limit to the maximum current delivered by a compact cyclotron equipped with extraction by stripper are due to the central region. According to the evaluation accomplished in [8],

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Table 1. Main characteristics of the new superconducting cyclotron and comparison to CS K800

<table>
<thead>
<tr>
<th></th>
<th>New proposal</th>
<th>CS K800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions</td>
<td>(H_2^+)</td>
<td>Any kind</td>
</tr>
<tr>
<td>Q/A</td>
<td>0.5</td>
<td>0.5 + 0.05</td>
</tr>
<tr>
<td>Maximum energy</td>
<td>100 MeV/amu</td>
<td>5 (\div) 100 MeV/amu</td>
</tr>
<tr>
<td>Injection energy</td>
<td>100 keV</td>
<td>30 keV</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>3</td>
<td>2.2-4.8</td>
</tr>
<tr>
<td>Sectors/cavities</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Power harmonic coils</td>
<td>(\leq 5) kW</td>
<td>100 kW</td>
</tr>
<tr>
<td>Useful hill gap</td>
<td>34 mm</td>
<td>24 mm</td>
</tr>
<tr>
<td>Extraction</td>
<td>Stripper</td>
<td>Elec. defl.</td>
</tr>
<tr>
<td>Frequency</td>
<td>72</td>
<td>15 + 48</td>
</tr>
<tr>
<td>Harmonic</td>
<td>(h = 3)</td>
<td>(h = 1,2,3)</td>
</tr>
<tr>
<td>Accelerating voltage/turn</td>
<td>600-1 000 kV</td>
<td>300-600 kV</td>
</tr>
<tr>
<td>RF power/cavity</td>
<td>(\leq 50) kW</td>
<td>40 kW</td>
</tr>
<tr>
<td>Ampere turns coil (\alpha/\beta) (At)</td>
<td>(1 950 \times 1 750/780 \times 1 260)</td>
<td>(1 950 \times 1 976/1 750 \times 1 368)</td>
</tr>
<tr>
<td>Coil (\alpha), diameters</td>
<td>(\Phi_{in} = 2 017, \Phi_{out} = 2 322) (Z_i = 76, Z_f = 425)</td>
<td>(\Phi_{in} = 2 000, \Phi_{out} = 2 331) (Z_i = 62, Z_f = 425)</td>
</tr>
<tr>
<td>vertical size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coil (\beta), diameters</td>
<td>(\Phi_{in} = 2 017, \Phi_{out} = 2 322) (Z_i = 433, Z_f = 684)</td>
<td>(\Phi_{in} = 2 000, \Phi_{out} = 2 331) (Z_i = 433, Z_f = 684)</td>
</tr>
<tr>
<td>vertical size</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L He</td>
<td>(\leq 15) lt/h</td>
<td>25 lt/h</td>
</tr>
</tbody>
</table>

the TR30 compact cyclotrons for \(H^-\) are able to accelerate a maximum of 3.3 mA. This experimental intensity limit is due both to the vertical space charge tune shift and to the longitudinal space charge effect. Both these effects give quite similar upper limits. Moreover both the longitudinal and vertical limits as shown in [8] scale as the cube of size of the central region. According to these considerations the TR30 compact cyclotron for \(H^-\) with central region scaled up of a factor 1.44 should increase the current upper limit to 6.6 mAmp. If the central region of \(H^-\) compact cyclotron is scaled up to the magnetic rigidity of \(H_2^+\) ions, doubling the magnetic field, the injection energy and the RF voltage (see Table 2) the intensity limit should be two times higher than the \(H^-\) case, as a consequence of the reduced charge to mass ratio \(q/A = 0.5\) of the \(H_2^+\) ion. The injection energy and the RF accelerating voltage are quite close to the parameters of our proposed compact superconducting cyclotron.

Table 2. Expected upper current limit, due to the space charge and central region effects for compact cyclotrons

<table>
<thead>
<tr>
<th></th>
<th>Einj. (keV)</th>
<th>(E_{in}/\text{turn}) (keV)</th>
<th>Bo (Tesla)</th>
<th>Imax (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR-30</td>
<td>25</td>
<td>208</td>
<td>1.9</td>
<td>3.3</td>
</tr>
<tr>
<td>TR-30 scaled up</td>
<td>50</td>
<td>416</td>
<td>1.9</td>
<td>6.6</td>
</tr>
<tr>
<td>CSC- (H_2^+)</td>
<td>100</td>
<td>832</td>
<td>3.8</td>
<td>13/26 *</td>
</tr>
</tbody>
</table>

* Proton beam current after the stripper.

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If a proper scaled central region, according to the TR30 cyclotron, can be realised a maximum beam current higher than 10 mA of protons is feasible. Moreover a significant advantage for injection of H$_2^+$ could be the higher injection energy and the better emittance and higher currents of H$_2^+$ source as compared to the H source. To deliver a good beam quality for the next acceleration step inside the ring cyclotron, a two-stage phase selection, to reduce the natural large 70° acceptance phase to 20° RF, should be performed. The first phase selection, to reduce the accepted phases down to 40° RF have to be done at early turns using the posts of central region. Here about 80% of the beam intensity should be stopped. Assuming an injected DC beam current of 50 mAmp of H$_2^+$ with an injection energy of 0.1 MeV a beam power of about 20 kW has to be removed. Moreover a proper shape of magnetic field could produce a correlation between the phase of the particle and its radial position. So a second stage of phase selection using movable slits should be able to define a final beam phase width of 15° RF. To prevent activation of cyclotron components this second stage has to be installed at a radius where the beam energy is lower than 6-8 MeV/n. The expected beam reduction at this location should be 50% and to obtain a H$_2^+$ beam current of 5 mA, 50 kW beam power should be removed. The gain per turn, after the phase selection, has to be increased up to the extraction radius to allows a phase compression down to 10° RF. The previous considerations are based on unbunched beam. The use of a buncher together with a higher injection voltage should reduce at least by a factor two the required injected current and the power loss at the phase selection positions. The most serious problems to use superconducting compact cyclotrons is the transfer of the 1-2 MW power at beam. In a three-sector CSC with three accelerating cavities about 0.5-0.8 MW have to be transferred to each cavity by a proper coupler. Moreover large cryo-panels have to be installed in the valleys or inside the DEEs to reach a good vacuum of the order of 10$^{-8}$ torr, to minimise the beam loss for interaction with the residual gas (see Table 3). Design of a similar CSC for a 110 MeV/amu has also been proposed by Mandrillon [13]. This is a four-sector cyclotron which could offer some further advantages due to higher energy gain per turn and more space for RF cavities and vacuum pumps.

### Table 3. Estimated current loss due to interactions with residual gas for TRIUMF and other cyclotrons projects

<table>
<thead>
<tr>
<th></th>
<th>$E_{\text{max}}$ (MeV/n)</th>
<th>$\Delta E/\Delta n$ (MeV)</th>
<th>$R_{\text{n}}$ (m)</th>
<th>$I_{\text{max}}$ (mA)</th>
<th>Vacuum (torr)</th>
<th>$T$ (%)</th>
<th>$I_{\text{loss}}$ ($\mu$A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIUMF</td>
<td>520</td>
<td>0.34</td>
<td>7.8</td>
<td>0.4</td>
<td>$2 \times 10^8$</td>
<td>1.64</td>
<td>6.6</td>
</tr>
<tr>
<td>CR-Cyc</td>
<td>100</td>
<td>1</td>
<td>1.65</td>
<td>5</td>
<td>$10^3$</td>
<td>0.07</td>
<td>3.5</td>
</tr>
<tr>
<td>Eulima</td>
<td>400</td>
<td>2</td>
<td>2.2</td>
<td>10</td>
<td>$10^3$</td>
<td>0.08</td>
<td>8</td>
</tr>
<tr>
<td>Dubna</td>
<td>800</td>
<td>4</td>
<td>3.21</td>
<td>10</td>
<td>$10^3$</td>
<td>0.07</td>
<td>7</td>
</tr>
<tr>
<td>RS-Cyc</td>
<td>1000</td>
<td>6</td>
<td>6.5</td>
<td>10</td>
<td>$10^3$</td>
<td>0.12</td>
<td>12</td>
</tr>
</tbody>
</table>

### Ring superconducting cyclotron

The spiral angle for a compact cyclotron has to be increased enormously to produce enough axial focusing for beam energies higher than 200 MeV/n. These higher energies are then achievable only by ring superconducting cyclotrons (RSC) which could produce larger flutter values and enough axial focusing. A ring superconducting cyclotron able to accelerate deuteron beam up to 1600 MeV has already been proposed [9] (injection energy 100 MeV, extraction radius 3.21 m, energy gain 4.6 MeV/turn, eight sectors/cavities, weight $150 \times 8 = 1200$ tonnes). This accelerator needs the sophisticated orbit expansion process to obtain enough separation at extraction, but the same ring cyclotron could be used to accelerate H$_2^+$ up to energy of 800 MeV/n using a lower voltage of
500 KV and the simpler and safer extraction by stripper method. The main doubt about this ring superconducting cyclotron is the feasibility of the high magnetic field inside the sectors, about 8 T, while no loss due to electromagnetic stripping is expected. The beam losses due to the interaction with the residual gas for the TRIUMF cyclotron, for the compact and ring superconducting cyclotrons (see Table 3) show that the required vacuum values are feasible anyway.

To overcome the technological problems of 8 T magnets it is interesting to investigate a solution based on sector magnets with a more realistic magnetic field of 4 T (see Figure 1). If we assume a ring cyclotron similar to the PSI cyclotron of 1 GeV [2], the so-called “dream machine”, but with a magnetic field of 4 T instead of 2.1 T, this become a scaled cyclotron able to accelerate $H_2^+$ at 1 GeV/amu. The PSI cyclotron proposal is based on 12 sectors to allow the installation of eight accelerating, two flattopping cavities, and the injection and extraction path. The cyclotron for $H_2^+$ don’t need the flattopping cavities so the numbers of sectors could be reduced to 10, and it becomes possible to increase the size of the valley and have more room for the cryostate of the superconducting coils. The installation of a stripper foils system in a valley allows the beam extraction without the electrostatic deflector and with an efficiency of 100%. Figure 1 shows three families of cyclotrons: rings for protons with extraction of a single turn by electrostatic deflectors, cyclotrons for H with extraction by stripper, and superconducting cyclotrons which could be modified to extract $H_2^+$. The proposal for large superconducting cyclotron like EULIMA [7] and the accelerator for deuteron [9] are shown as extensions of the compact superconducting cyclotrons. Moreover the proposed new family of superconducting ring cyclotrons with a mean field of about 1.8 T and larger extraction radius is shown as well. The advantages of this new kind of accelerator consist mainly in their easy operation mode, their higher reliability, the beam continues to come out if one or more cavities are down, and their higher conversion efficiency from electrical to beam power.

**Figure 1:** Energy vs. extraction radius for large cyclotrons in the world, and for some proposed cyclotron projects, labelled by *. The maximum energies vs. extraction radius for the new family of ring cyclotrons for $H_2^+$ with $B_{\text{int}} = 4$ T and $\langle B \rangle = 2$ T are also shown.
Limits

Of crucial importance for the design of the above cyclotrons is the surviving probability of the $\text{H}_2^+$ molecule in the high magnetic field. The binding energy of the last electron is of 16.3 eV, about 20 times larger than the binding energy in the $\text{H}^-$ case. This binding can be broken by the electric field which results from the motion of the ion in the magnetic field. The equivalent electric field in the rest frame of the $\text{H}_2^+$ molecule, due to the magnetic field $B$ is given by the relativistic transformation of the electromagnetic field [10]:

$$\epsilon = 3 \cdot \beta \cdot (1 - \beta^2)^{-1/2} \cdot B \cdot 10^{-2} \text{ MV/cm}$$

where $\beta = v/c$, and $B$ is the magnetic field in Tesla.

The probability $D$ to remove the electron which binds the two protons of the $\text{H}_2^+$ molecule depends upon the binding energy $W$ of the electron and by the applied electric field $\epsilon$.

A useful formula suggested in [11] is:

$$D = \exp(-\alpha/2\alpha) , \alpha = \frac{4}{3} \sqrt{2m/e} W^{3/2} / \epsilon$$

where $m$ and $e$ are the mass and the charge of the electron respectively, and $h$ is the Plank constant. According to this equation the probability of removing the electron scales according to $W^{3/2}/\epsilon$. Since the binding energy of $\text{H}_2^+$ is about 20 times the binding energy of $\text{H}^-$, the electric field should be 90 times higher than for an $\text{H}^-$ ion of same velocity. This means that to accelerate $\text{H}_2^+$ up to an energy of 2 GeV it will be possible to use a magnetic field as high as 10 Tesla without significant dissociation. Another serious problem in the acceleration of the $\text{H}_2^+$ is the interaction with the residual gases. As is well known, due to the interactions with the molecule of the residual gas, ions could lose the orbital electron along the acceleration path. The fraction of particles which survives is [12]:

$$T = N/N_0 = \exp\left(-3.35 \times 10^{16} \int \sigma_i(E) P \, dl\right)$$

where $P$ is the pressure (torr) and $L$ is the path length in cm.

The cross-section of electron loss [12] is:

$$\sigma_i(E) = 4\pi a_0^2 \left(v_0/v\right)^2 \left(Z_i^2 + Z_t\right)$$

where: $v_0$ and $a_0$ are the velocity and the radius of the orbit of Bohr respectively, and $Z_i$ is the atomic number of the residual gas. This formula gives a result in quite good agreement with experimental data and is anyway useful to estimate the expected beam loss in comparison with the parameters of the TRIUMF cyclotron. As shown in Table 3, to maintain the amount of loss during the acceleration at the same level as the TRIUMF cyclotron, the vacuum has to be $10^{-8}$ torr, two times better than the vacuum of TRIUMF cyclotron. The proposed high energy cyclotrons discussed here are more compact and smaller than the TRIUMF, and thus achieving a better vacuum seems feasible. Anyway
it is very important to have some measured values of the cross-section for electron stripping of H$_2^+$ across residual vacuum gas. We plan to measure these cross-sections next year when our laboratory will be equipped with an H$_2^+$ beam of 100 MeV/amu.

**Power conversion efficiency**

A very important parameter for high current accelerators is their conversion efficiency from electrical power to beam power. For a ring cyclotron based on the PSI-proposed “dream machine”, the expected overall conversion efficiency is 44% [2], according to the following formula:

$$\varepsilon_{\text{tot}} = P_{\text{be}} / (P_{\text{b}} + P_{\text{fl}} + P_{\text{loss}}) / \varepsilon_{\text{ac}} + P_{\text{other}}$$

where:

- $\varepsilon_{\text{ac}} = 75\%$ is the AC/RF conversion efficiency optimised;
- $P_{\text{be}} = 10$ MW is the total beam power;
- $P_{\text{b}} = 9$ MW is the beam power transferred by the cyclotron;
- $P_{\text{fl}} = 1$ MW is the power absorbed by the flat-top cavity;
- $P_{\text{loss}} = 4$ MW is the thermal loss on walls of the eight cavities, 1 MV peak voltage, 1 MΩ shunt impedance;
- $P_{\text{other}} = 4$ MW for injector, preinjector, magnets, etc.

A cyclotron for H$_2^+$ can be operated with a lower voltage than a cyclotron which needs well separate turn. To maintain the residual gas beam losses at an acceptable level, a ring cyclotron for 1 GeV beam could be equipped with eight cavities, peak voltage 750 kV (see Table 3). According to the present data of PSI the wall losses are then of 280 kW for each cavity copper made. The reduced wall losses have a strong influence on the overall efficiency of the complex that became of $\varepsilon_{\text{tot}} = 53\%$ if we consider that the flattopping cavities are unnecessary. Of course if new kind of cavity with higher shunt impedance as proposed by Mandrillon [3] became available the overall conversion efficiency is further increased.

**Conclusion**

A lot of work has to be done to evaluate the difficulties related to the construction of H$_2^+$ cyclotrons to achieve energies as high as 1 GeV in particular on the feasibility of sectors magnet for ring cyclotrons able to produce magnetic fields of 4 T. However as presented here, it is now also possible to construct cyclotrons able to deliver high intensity proton beams with energies of 100-150 MeV according to the experience of the already existing compact superconducting cyclotrons. Figure 1 shows the maximum energies of the existing three families of cyclotrons: rings for protons, cyclotrons for H$^-$ and superconducting cyclotrons for H$_2^+$ (constructed or proposed). The maximum energies vs. extraction radius for the new family of ring cyclotrons for H$_2^+$ with $B_{\text{wall}} = 4$ T and $<B>$ = 2 T are also shown.
Current technological limits prevent the design of a ring cyclotron for $\text{H}_2^+$ of smaller size, which could be achievable in future, anyway the advantages related to the easy operation mode and to the higher reliability of the acceleration and extraction of $\text{H}_2^+$ are quite evident. The reasons of the success of $\text{H}^+$ commercial cyclotrons are their reliability and easy operation mode. Also for the cyclotrons dedicated to drive more or less complex plants it is necessary to guarantee a high level of reliability and easy operation mode independent of the skill of the operators. We believe these goals are also achievable by large cyclotrons when they are designed to accelerate $\text{H}_2^+$ ions to be extracted by stripping.

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SUPERCONDUCTING SEPARATED ORBIT CYCLOTRONS

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Abstract

A separated orbit cyclotron (SOC) is in principle a linac rolled up along a fixed spiral orbit. The quadrupole lenses with superimposed bending fields form individual, independent channel magnets. Radially neighbouring RF cavities are joined together, so that each big cavity accelerates several beams in parallel. Recently the feasibility of a SOC was demonstrated with the TRITRON. An ion beam was accelerated continuously along six turns by six superconducting RF cavities and 75 superconducting channel magnets. The remarkable features of the TRITRON are the excellent stability, reproducibility and reliability of all six cavities and the magnets. Based on the good results a system of three superconducting SOCs is proposed to accelerate protons up to 1 GeV with beam currents of 10 mA at least.
Introduction

In recent years an increasing demand for proton beams with average currents of more than 10 mA and energies of the order of 1 GeV arose, for instance for the production of high neutron fluxes, for accelerator driven nuclear power plants and for transmutation of nuclear waste [1]. In principle two types of accelerators are possible to obtain such beams: linacs and cyclotrons.

A linac consists of many single RF cavities with quadrupole magnets in between, providing strong transversal focusing. Longitudinal focusing is obtained by phase variations in the RF cavities due to velocity deviations. The length of the linac is of the order of 1 km.

Cyclotrons are much more compact, thus the costs of buildings and shielding would be much less. In modern isochronous cyclotrons the beam is bent by big magnets with a field radially increasing on the average, which ensures a constant revolution frequency of the particles, independent of their velocity. To obtain axial focusing the pole face has to be subdivided into spiral shaped sectors. In the intermediate sectors accelerating RF gaps are installed. The RF frequency must be a harmonic of the revolution frequency. The bunch has to cross the gap at the phase of maximum voltage. Because of the velocity independence of the revolution frequency there is no longitudinal focusing. The maximum current which can be achieved is limited finally by beam losses at the extraction, respectively by the radial width of the bunches and the turn separation at the extraction element. The turn separation is proportional to the accelerating voltage per turn. The maximum accelerating voltage is limited due to the restricted space for the RF structure in the narrow magnet gaps respectively intermediate sectors. The radial width of the bunches depends on the energy spread of the particles in a bunch: particles with less energy need more revolutions compared to those with more energy. The energy spread itself depends on the length of the bunches: particles crossing the RF gap to early or to late will always gain somewhat less energy compared to the central particle. Finally the length of the bunch is a function of the total charge contained in it. Recently in the ring cyclotrons at the Paul Scherrer Institute, Switzerland, a proton beam was accelerated to an energy of 590 MeV with an extracted current of 1.5 mA. From the experience with this machine it is expected that with a somewhat larger cyclotron proton beams of 1 GeV and 10 mA should be feasible [2]. However, this might be the upper limit for beam currents from conventional isochronous cyclotrons.

To overcome these problems F.M. Russell proposed as early as 1963 the principle of the separated orbit cyclotron (SOC) [3]. Though called a cyclotron, it bears much more resemblance with a linac, at least with respect to the beam dynamics. In the case of a linac one could save costs of buildings and shielding by folding it by means of bending magnets. A most regular folded linac will end up at a spiral orbit. The bending magnets should be rather narrow in radial direction, so that they can be placed in groups, forming flat sectors. These channel magnets can have alternating gradients, providing strong transversal focusing. Then the magnetic field will not be isochronous locally. Therefore velocity differences will cause phase shifts with respect to the RF cavities and thus longitudinal focusing. An extraction element is not needed, the beam just leaves the last channel magnet. In principle one should be able to attain beam intensities comparable to those in a linac.

The key to strongly separated orbits is a considerably increased accelerating voltage per turn, resulting in a turn separation of several cm. In the intermediate sectors the radially neighbouring cavities can be joined into a common big one, which accelerates several beams in parallel. In this manner the number of single cavities is reduced.

Immediately after the principle of the SOC had been invented, strong activities started to realise it, though with normal conducting magnets and cavities at that time [4]. However, a small
experimental test ring never came into operation. To put this concept into action superconductivity was needed. Using the high current density in superconducting coils, the cross-sections of the channel magnets and thus the turn separation can be made less than 10 cm. The channel magnets will occupy not much more space than really needed, leaving it to optimise the shape of the RF cavities with respect to losses and peak fields. The required accelerating voltages can be obtained best with RF superconductivity, because then the maximum voltage is limited by field emission, and not by cooling the dissipated heat as in conventional cavities. In view of the high accelerating voltages used the saving of dissipated RF power is an additional advantage of superconductivity. Note that for RF superconductivity the magnetic background fields have to be less than $10^{-4}$ T. Therefore the short range of the fringe fields of the channel magnets is important.

The TRITRON

According to the preceding considerations a small prototype of a separated orbit cyclotron, the TRITRON, was designed at the Beschleunigerlaboratorium of the University of Munich and the Technical University of Munich [5-7]. The purpose of this project was to study the beam dynamics of such a machine theoretically, to develop the technology and to demonstrate the feasibility of the principle of this new type of cyclotron. It is a rather small machine with the existing MP-tandem as injector, thus not a high current prototype device.

Figure 1 shows cross-sections, and Table 1 summarises some of the data regarding TRITRON. The injection radius is 66 cm, the extraction radius 145 cm, the energy gain factor is about 5. Six sector-shaped RF cavities (170.7 MHz) with 20 beam holes provide an acceleration voltage of 3 MV on the last turn. When the project was started it was unknown whether superconducting cavities of the type needed would operate at all. In order to keep the acceleration voltage low, the turn separation was chosen as small as possible (40 mm) resulting in an aperture of the magnetic channels of only 10 mm. Altogether 240 channel magnets with alternating gradients are arranged in 12 flat sectors, guiding the beam along 20 turns. Arrays of 20 small superconducting axial steerer magnets are positioned in three of the intermediate sectors. The radial and axial beam positions are measured by wire scanners installed in each second intermediate sector. The machine is hanging on a torus-like liquid helium reservoir under the upper half of the cryostat. The cavities and magnets are cooled indirectly by pipes connected to the torus. An additional pipe system for forced helium flow provides the cooling from 300 K to 4.5 K. The insulating vacuum of the cryostat is the same as for the beam, there is no separate vacuum chamber. Therefore the cavities are floated by normal laboratory air each time the cryostat has to be opened.

The cavities (see Figure 2) are produced by an electroforming technique from copper [6] and then electroplated with a thin layer (<5 $10^{-3}$ mm) of Pb$_{96}$Sn$_{4}$, which becomes superconducting below 7.5 K. Each cavity consists of two halves, connected in the plane of the particle orbits. No RF currents should cross the flat joint in the fundamental mode. The total length of the cavity is 1.233 m. The gap width is 62 mm at the first orbit, and 128 mm at the last. The maximum E-field is at the 13th beam hole, the maximum voltage at the 18th hole. The diameter of the beam holes is 13 mm. The ratio $E_{\text{peak}}/E_{\text{max}}$ is less than 1.5. Figure 3 shows the radial characteristics of the amplitudes of the electric field E and the accelerating voltage U. The calculated E-curve was obtained by the MAFIA code.

Though not being handled under special clean room conditions the quality of the cavities stayed constant since the original electroplating procedures during the years 1990 to 1992. Typical curves of the quality factors versus the RF voltage at the last beam hole are shown in Figure 4. At voltages of
Figure 1. Cross-sections of the TRITRON cryostat

V: vacuum vessel, S: 80 K-shield, M: magnet sector, R: RF cavity, He: helium reservoir, T: support
Table 1. General design data of the TRITRON

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy gain factor</td>
<td>4.9</td>
</tr>
<tr>
<td>Injection radius</td>
<td>0.66 m</td>
</tr>
<tr>
<td>Extraction radius</td>
<td>1.45 m</td>
</tr>
<tr>
<td>Turn separation</td>
<td>40 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>19.8</td>
</tr>
<tr>
<td>Magnet data:</td>
<td></td>
</tr>
<tr>
<td>Number of magnet sectors</td>
<td>12</td>
</tr>
<tr>
<td>Number of chan. magnets/sector</td>
<td>20 (19)</td>
</tr>
<tr>
<td>Bending angle per channel</td>
<td>30°</td>
</tr>
<tr>
<td>Sector angle</td>
<td>20°</td>
</tr>
<tr>
<td>Bending radii</td>
<td>430...942 mm</td>
</tr>
<tr>
<td>Geometrical aperture</td>
<td>10 mm</td>
</tr>
<tr>
<td>Max. induction: sector channels</td>
<td>1.7 T</td>
</tr>
<tr>
<td>3rd inject. chan.</td>
<td>2.4 T</td>
</tr>
<tr>
<td>Normal. rad. gradients 1/B dB/dr</td>
<td>3.6/- 4.9 m⁻¹</td>
</tr>
<tr>
<td>Betatron oscillat. numbers Qₓ</td>
<td>1.2 ... 1.6</td>
</tr>
<tr>
<td>Qᵧ</td>
<td>0.8 ... 1.7</td>
</tr>
<tr>
<td>Synchrotr. oscill. numb. (incoh.)</td>
<td>0.2</td>
</tr>
<tr>
<td>Cavity data:</td>
<td></td>
</tr>
<tr>
<td>Number of cavities</td>
<td>6</td>
</tr>
<tr>
<td>Fixed RF frequency</td>
<td>170.7 MHz</td>
</tr>
<tr>
<td>Harmonic numbers</td>
<td>14 ... 55</td>
</tr>
<tr>
<td>Total radial length</td>
<td>1233 mm</td>
</tr>
<tr>
<td>Radial gap length</td>
<td>85 cm</td>
</tr>
<tr>
<td>Gap width injection/extraction</td>
<td>62/128 mm</td>
</tr>
<tr>
<td>Aperture of the beam holes</td>
<td>13 mm</td>
</tr>
<tr>
<td>Maximum gap voltage</td>
<td>0.53 MV</td>
</tr>
<tr>
<td>Maximum accelerating field</td>
<td>4.7 MV/m</td>
</tr>
<tr>
<td>Peak field to max. gap field</td>
<td>&lt; 1.5</td>
</tr>
<tr>
<td>Unloaded quality factor</td>
<td>3.7 10⁶</td>
</tr>
<tr>
<td>Dissipated power per cavity</td>
<td>6 W</td>
</tr>
<tr>
<td>Surface resistance</td>
<td>2.5 10⁻⁷ Ω</td>
</tr>
</tbody>
</table>

Figure 2. Two halves of a cavity, the left one with cooling pipes attached on both sides
500 kV the dissipated heat per cavity is about 5 W. In order to remove multipacting at all levels the cavities have to be conditioned with RF pulses each time they had been exposed to air. Coarse tuning is made by mechanical deformation, fine tuning by sapphire rods (slow) and piezoelectric actors (fast). An electronic control system provides for stability of phases (1°) and amplitudes (10⁻³). The reproducibility is of the same order. Actual phase and amplitude settings are made by observing the shift of the radial position of the beam half a betatron-oscillation downstream of the cavity.

Each of the 12 magnet sectors contains 20 or 19 channel magnets. Each sector consists of two sheets of steel (30 mm thick), with curved slots every 4 cm (see Figure 5). All pieces made from steel are Ni plated to avoid rust. The coils consist of 2 × 13 windings of a Rutherford-type cable, including a separate gradient winding in each half-coil (indicated black in Figure 5). The half-coils were wound directly into the slots and then vacuum impregnated with epoxy in situ. A copper profile shields the coil from beam losses. Flat disc springs between the copper profile and the coil prevent the coil from cracking of from the steel [10].

The currents of the 240 magnetic channels have to be adjusted individually according to the respective momentum of the central particle of the bunch. This is accomplished by just one single power supply by bypassing the difference of the current of an individual channel and the main current.
in controllable superconducting switches across each coil. The fields are reproducibly correlated to the currents in the coils. There are neither leakage effects of the currents in the superconducting switches, nor hysteresis effects of the steel, nor magnetisation effects of the superconductor, nor cross talking effects from neighbouring channels observed ($\Delta B/B < 10^{-4}$). Once the optimum field settings for a certain injection energy is found on the first two turns, e.g. with the cavities switched off, it can be used for further runs without any variations. The beam will appear immediately at the end of the second turn again with good transmission, as soon as the proper injection energy has been chosen, even if the magnets had been warmed up in the meantime. This stable and reproducible tuning facilitates the beam funnelling considerably.

**The commissioning**

All components of the TRITRON (see Figure 6) work very reliably, which can be seen from the fact that the cryostat was kept cooled below 80 K at least since January 1997 except for three short warm-ups for minor repairs of (1) broken wires of some probes; (2) problems with the driving linkage of a RF antenna of one cavity; and (3) a broken piezoelectric actuator of the fast fine tuning system of one cavity. These failures can be considered as typical troubles during the initial test phase.
Since January 1997 the TRITRON project had in total 10 weeks of beam time from the tandem injector. For all tests $^{32}\text{S}^{+16}$-ions were injected with typical currents of 10 pnA and an energy of 40.3 MeV (corresponds to $h = 47$), a relative energy spread of $8 \times 10^{-3}$, and a bunch length of 200 ps. Due to the small geometrical aperture of the channel magnets (10 mm) the injection phase and energy of the beam has to be stable within $\pm 1^\circ$ resp. $\pm 4 \times 10^{-5}$. Most of the beam time was needed to prepare the tandem to fulfil these requirements.

The following procedure was used to adjust the magnet currents and the RF cavity voltage phases resp. amplitudes in the TRITRON in a manner such that steady acceleration would result:

1. Still without voltage in the cavities, the currents of all magnets on the first two turns are adjusted to get the beam well guided to the end of the second turn.

2. The first cavity is switched on with a rather high voltage. The beam will be accelerated or decelerated according to the effective phase of the cavity voltage at the passage of the bunches. An energy shift causes betatron oscillations of the whole bunch, which can be detected as radial position shift most sensitively half a betatron oscillation downstream of the cavity (0.4 turn). By this method both zero phases can be determined. From the radial broadening of the beam the (focusing) zero phase with increasing voltage can be distinguished from the defocusing one. Furthermore the radial broadening possibly gives informations about the tilt of the longitudinal phase ellipse. Finally the actual phase setting of say $60^\circ$ with respect to the focusing zero phase is put on the cavity.

3. The currents of all magnets downstream of the cavity are increased by a pre-calculated value, which corresponds approximately to a specific velocity increase of the bunches according to an isochronous motion. Then the voltage amplitude of the cavity has to be adjusted until the beam is well centred again in the succeeding channels.

The same procedure has to be applied to the remaining cavities. If the last cavity has been set, the beam has to be funnelled by adjusting the currents of the magnets on the succeeding turns. If the specific energy gain per cavity on the first turn had been chosen appropriate to the injection energy, the momentum of the bunches resp. the bending power (Br) of the magnets will increase approximately linearly with the magnet number. However, generally the specific energy gain will be missed and the energy of the bunches will execute coherent oscillations with respect to the ideal course. At the worst there will be no steady acceleration at all. Then the phases and amplitudes of the cavity voltages have to be adjusted again starting with a different specific energy gain.

Following this procedure the beam was guided along several turns with continuously increasing energy. Up to now the beam passed through 75 channel magnets to a maximum of six turns, finally having an energy of 72 MeV. The currents in the channels respectively the Br-values follow a straight line with small deviations. These deviations show two oscillations corresponding to two coherent synchrotron oscillations with the expected number 0.5 per turn (see Figure 7).

The observed betatron-oscillation numbers and the momentum compaction factor were in agreement with theory as well. In continuing to more turns the main problems are caused by different long-term instabilities of the tandem, which make the funnelling process through the narrow channels along many turns difficult. This is not a principal limitation, but a consequence of the conservative design of the TRITRON as a prototype machine with rather small turn separation and narrow geometrical aperture.
Figure 7. The relative deviations from linear increase, $\Delta Br/(Br)$, versus the magnet number of turn 2 to 5, showing two coherent synchrotron oscillations

Future developments

Based on the good results of the superconducting cavities future separated orbit cyclotrons can be planned with enlarged turn separation, say 10 cm, which would leave a geometrical aperture for the beam of about 4.5 cm. This would reduce the requirements on the stability of the injector considerably and make the acceleration of high intensity beams with low losses much easier.

A system of three superconducting SOCs will be considered, with the injection energies 20 MeV, 106 MeV and 393 MeV, and the extraction energy at the last ring of 1 GeV. All cavities are assumed to be equal and about twice as large as the present TRITRON cavities. Larger cavities with a weight of > 3 tonnes would be difficult to handle and to fabricate. The accelerating gap length shall range from 20 cm at the first and 40 cm at the last beam hole. Sixteen beam holes with the radial distance of 150 cm from the first to the last are planned. The acceleration lips are vaulted asymmetrically with respect to the radial axis, so that one flat magnet sector can be installed in the concave side without loosing space in a most dense arrangement of the cavities along a ring, as shown in Figure 8. The cut-off bores in the accelerating lips with a diameter of 45 mm will have a length of 120 mm. The overall length of the cavities will be about 3 m. The frequency in the fundamental mode is calculated with a special code to be 90 MHz [11]. At the last beam hole a maximum voltage of 2 MV is assumed corresponding to a field in the gap of 5 MV/m and a maximum gap field of 5.8 MV/m near to the tenth beam hole. From the results with the TRITRON cavities the dissipated heat in the cavity walls is estimated to be < 36 W. Some data of the three rings are presented in Table 2. In total 65 cavities are needed. The maximum power, which has to be transmitted to a 10 mA proton beam is less than 170 kW per cavity. Present input couplers for superconducting cavities are operated routinely at up to about 200 kW. However, the development of couplers for transmitted powers of about 800 kW is making good progress (e.g. at KEK and Cornell).

The limiting effects for the beam current are similar to those known from proton storage rings. The beam creates fields, the space-charge fields and those from image currents on the beam-tube walls, which act back on the beam itself. All related effects depend mainly on the longitudinal and transverse coupling impedances. Pure inductive and capacitive impedances cause real, intensity dependent shifts of the betatron and synchrotron oscillation numbers, and some change of the bunch
Figure 8. Schematic view of a large separated orbit cyclotron ring

Table 2. Some parameters of a system of three superconducting SOCs for a maximum energy of 1 GeV

<table>
<thead>
<tr>
<th>For all three rings</th>
<th>Ring</th>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn separation</td>
<td>10 cm</td>
<td>Injection energy</td>
<td>17.4</td>
<td>106</td>
</tr>
<tr>
<td>Geometrical aperture</td>
<td>45 mm</td>
<td>Extraction energy</td>
<td>106</td>
<td>393</td>
</tr>
<tr>
<td>Drift length cav./chan. magn. at extr.</td>
<td>18 cm</td>
<td>Injection radius</td>
<td>122</td>
<td>259</td>
</tr>
<tr>
<td>Max. induction in the channel mag.</td>
<td>1.75 T</td>
<td>Extraction radius</td>
<td>282</td>
<td>419</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bending radius at extr.</td>
<td>87</td>
<td>180</td>
</tr>
<tr>
<td>Cavities: total length</td>
<td>3 m</td>
<td>Transit time fact. at inj.</td>
<td>0.83</td>
<td>0.97</td>
</tr>
<tr>
<td>Radial distance 1st...16th beam hole</td>
<td>150 cm</td>
<td>at extr.</td>
<td>0.88</td>
<td>0.95</td>
</tr>
<tr>
<td>Gap width at injection</td>
<td>20 cm</td>
<td>Accel. voltage/turn, inj.</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>40 cm</td>
<td>extr.</td>
<td>9</td>
<td>33</td>
</tr>
<tr>
<td>RF frequency</td>
<td>90 MHz</td>
<td>Number of sectors</td>
<td>8</td>
<td>18</td>
</tr>
<tr>
<td>Accelerating voltage at extraction</td>
<td>2 MV</td>
<td>Number of cavities</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>Maximum accel. field in the gap</td>
<td>5.8 MV/m</td>
<td>Number of turns</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Dissipated heat per cavity</td>
<td>&lt; 36 W</td>
<td>Harmonic number</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transfer power/cav.</td>
<td>130</td>
<td>170</td>
</tr>
</tbody>
</table>

dimensions. A resistive impedance causes imaginary frequency shifts and eventually instabilities, with the time constant of growth proportional to one over this frequency shift. In SOCs the beam is running either in a copper tube inside of the channel magnets, or in a cavity gap. The influence of the slits between the tubes and the cut-off bores of the cavities is assumed to be negligible.

The resistive wall effect of the copper tubes is expected to be much less compared to that of stainless steel vacuum chambers normally used in storage rings. The surface resistance of cold copper at 500 MHz for example is about 40 times less than that of the stainless steel at room temperature (anomalous skin effect). The reactive part of the impedance in the SOCs is mainly determined by the space charge effect. It decreases strongly with increasing particle energy. It can be overcome by
choosing the injection energy sufficiently high. In addition rather large shifts of the betatron oscillation numbers are admissible due to the insensibility to resonance problems. Longitudinally the high accelerating voltage per turn causes unusually high synchrotron oscillation numbers, so that rather large shifts are admissible here also.

The superconducting cavities are traversed by 16 bunches in parallel, radially distributed along a large range. So the excitation of higher-order modes by the beam has to be expected. Some special features of the cavities may be helpful to overcome these problems. First the cavities are single cells, resulting in a simple line spectrum without broad passbands. Thus there will be a certain chance to detune the cavity with respect to the frequency of a higher-order mode, which may be excited by the beam. Secondly, the quality factor of all modes with surface currents crossing the horizontal plane of symmetry are reduced due to the poor flat RF joint. Finally, the cavity volume is accessible from all sides to install higher-order mode couplers in an effective manner, avoiding trapped modes as in some multicell cavities. The interaction of several parallel high intensity bunches with a superconducting cavity of the TRITRON type can be investigated experimentally by triggered electron pulses through the beam holes, and theoretically by means of computer codes. So far various storage rings with superconducting multicell cavities operate stable with beams of about 50 mA.

Conclusions

The results of the test runs demonstrate that the principle of a separated orbit cyclotron works as anticipated. The beam dynamics correspond to theory. The experience of the last year proves a very stable, reproducible and reliable operation of all components. No ageing effects were observed during a period of more than six years. This concerns particularly the superconducting switches and joints of the magnet system, and the superconducting cavities, which are handled under normal laboratory air conditions.

Acknowledgements

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FFAG SYNCHROTRON FOR AN ACCELERATOR DRIVEN SYSTEM

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Abstract

Fixed-field alternating gradient (FFAG) synchrotron is proposed for accelerator driven systems of nuclear energy breeding and transmutation of nuclear waste. A preliminary design of 1.5 GeV and 10 MW beam power FFAG synchrotron is presented.
Introduction

One of the most important issues in realising an accelerator driven system (ADS) for energy amplifier is the electrical power efficiency during operation of the accelerator. The operational electric power efficiency of the accelerator is defined by the ratio of the total beam power to the total electric power requested for operation of the whole accelerator system. In order to make the ADS in a realistic manner, the electrical-power efficiency should be at least more than 30%. The beam power can be expressed by the product of the beam energy and the average beam current. The requested beam power for ADS would be at least 10 MW. Since a beam energy of 1-3 GeV is most practical for ADS if the accelerated particles are protons, the average beam current should be about 10 mA.

The accelerator comprises mainly the magnet and the RF accelerating systems. During operation, the 80-90% of the total electricity of the accelerator is dissipated for these two systems. The electric power consumed by the magnet system can be dramatically reduced by using a superconducting technique, and can become negligibly small. On the other hand, the electric power dissipated by the RF accelerating system would still be an issue even if a superconducting RF system is applied.

The RF electric power for the accelerating cavity system is given by:

$$ P = \frac{V^2}{R_s L} $$

Here, $V$ is the total RF voltage requested for beam acceleration, $R_s$ the effective shunt impedance of the accelerating cavity per unit length and $L$ the total length of the accelerator. In a linear accelerator, the total length of the accelerator should be kept small because of the site limitation and also to minimise the initial construction cost. Thus, a superconducting RF cavity system is inevitably essential in a linear accelerator system to reduce the total RF power requested for operation by increasing the effective shunt impedance.

However, it is rather difficult to reduce the total length to less than 1 km for a 1 GeV proton linear accelerator, even when a superconducting RF system is used. On the other hand, for a cyclic accelerator, such as cyclotron or synchrotron, the situation is more reluctant, because the cyclic accelerator is regarded as being a very long accelerator. More than 50% electric power efficiency seems to be possible in a cyclic accelerator, even if the normal conducting RF cavity is used.

Accelerator for ADS

For ADS, a cyclotron with superconducting magnets has been discussed so far as a possible candidate for the cyclic accelerators. This is believed mostly because of the experience at the PSI cyclotron, which has obtained about more than 1 MW beams so far. As for a synchrotron, it has been thought that it would be almost useless for ADS because the operation is a pulsed mode and the average beam current is small. The magnetic field is time varying according to beam acceleration in the synchrotron, and the eddy-current power loss in the magnets becomes serious when the repetition rate of the accelerating cycle is increased. On the other hand, the accelerated particle number per pulse is limited by the space-charge effect. Practically, the maximum repetition of the rapid cycling synchrotron is limited to be less than 50 Hz or so. Therefore, the maximum available beam power
would be at most about 1 MW [1]. However, the beam in the synchrotron is stable, because it is strongly focused in the transverse and longitudinal directions, and the instantaneous beam current in the ring becomes very large.

**FFAG synchrotron**

A multi-orbit synchrotron (MOS) using fixed-field alternating gradient (FFAG) focusing seems to be very attractive for this purpose, because the repetition rate of the accelerating cycle could be raised ten times or more compared to that of the ordinary synchrotron.

The idea of a MOS using a FFAG was proposed independently by Ohkawa, Symon and Kolomensky in the early 1950s, and electron-beam machines demonstrating this principle have been successfully built in the MURA project [2]. However, no practical proton-beam machine has been built so far.

In MOS with FFAG focusing, where the magnetic field is constant in time, the shape of the magnetic field should be such that the betatron tunes for both the horizontal and vertical planes should be constant for all closed orbit, and departing from all of the dangerous resonance lines. The condition above is called “zero-chromaticity”.

\[
\frac{\partial}{\partial \theta} \left( \frac{K}{K_0} \right)_{\theta=const.} = 0, \quad \frac{\partial}{\partial p} \left( \frac{K}{K_0} \right)_{\theta=const.} = 0
\]

A magnetic field satisfying the scaling conditions described above must generally have the form:

\[
B(r, \theta) = B \left( \frac{r}{r_0} \right)^n \left( \theta - \zeta \ln \frac{r}{r_i} \right)
\]

where \(\zeta\) is a spiral angle. If \(\zeta\) is zero, the magnetic field does not depend on, and the corresponding orbit points are distributed on a radial vector. The type of having this magnetic shape is called “radial sector”. On the other hand, if \(\theta\) behaves in a logarithmic manner, such as:

\[
\theta - \zeta \ln \frac{r}{r_i} = const.
\]

the orbits remain geometrically similar, but move around the beam centre towards larger radii. This type is called “spiral sector”.

One of the most difficult technical issues to realise a high-repetition MOS is RF acceleration. The requested accelerating RF voltage per one turn is:

\[
\Delta V = 2\pi(1 + n) \left( \frac{\partial r}{\partial t} \right)_p
\]
Here, $\frac{\partial r}{\partial t}$ is the orbit excursion rate. In the case of a 1 GeV MOS with a repetition rate of 1 kHz, the requested RF voltage becomes almost 1 MV. This is a rather difficult number if an ordinary ferrite-loaded RF cavity is applied, which has been conventionally used for the proton synchrotron so far. In the ordinary ferrite-loaded RF cavity, the maximum accelerating field gradient is at most 10 kV/m or so. Therefore, more than 100 m long straight sections are necessary for the RF cavities in the ring, although the total circumference of the 1 GeV MOS would be less than 150 m.

Recently, a new type of high-gradient RF cavity using a high-permeability magnetic alloy has been developed at KEK for the JHF project, and a field gradient of 100 kV/m has been successfully achieved [3]. Using this high-gradient cavity, the most difficult technical issue in realising a high-repetition MOS can be solved. The fundamental parameters and the beam parameters of a preliminary design of the 1.5 GeV and 10 MW beam power MOS are listed in Table 1 and Figures 1-3.

REFERENCES

Table 1. Fundamental parameters of 1.5 GeV FFAG synchrotron

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1.5 GeV-10 MW multi-orbit synchrotron</th>
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<tbody>
<tr>
<td>Injection energy</td>
<td>0.25 GeV</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>1.5 GeV</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>$5.5 \times 10^{13}$ ppp</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>750 Hz</td>
</tr>
<tr>
<td>Average beam current</td>
<td>6.6 mA</td>
</tr>
<tr>
<td>No. of sectors</td>
<td>16</td>
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<tr>
<td>Circumference factor</td>
<td>2.68</td>
</tr>
<tr>
<td>Beam curvature</td>
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<tr>
<td>injection</td>
<td>4.54 m</td>
</tr>
<tr>
<td>extraction</td>
<td>5.0 m</td>
</tr>
<tr>
<td>Average beam radius</td>
<td></td>
</tr>
<tr>
<td>injection</td>
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<tr>
<td>extraction</td>
<td>13.4 m</td>
</tr>
<tr>
<td>Magnet pole radius</td>
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<tr>
<td>injection</td>
<td>12.2 m</td>
</tr>
<tr>
<td>extraction</td>
<td>13.4 m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td></td>
</tr>
<tr>
<td>injection</td>
<td>0.536 T</td>
</tr>
<tr>
<td>extraction</td>
<td>1.5 T</td>
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<tr>
<td>Field index</td>
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</tr>
<tr>
<td>Effective field index</td>
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<td>Spiral angle</td>
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<tr>
<td>Fractional angle</td>
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<tr>
<td>Betatron oscillation tune</td>
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<td>horizontal</td>
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<tr>
<td>vertical</td>
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<tr>
<td>Momentum compaction factor</td>
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<tr>
<td>Transition gamma</td>
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</tr>
<tr>
<td>Max. RF voltage</td>
<td>0.56 MV</td>
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<tr>
<td>RF frequency</td>
<td></td>
</tr>
<tr>
<td>injection</td>
<td>2.39 MHz</td>
</tr>
<tr>
<td>extraction</td>
<td>3.3 MHz</td>
</tr>
</tbody>
</table>
Figure 1. Schematic diagram of 1.5 GeV FFAG synchrotron

Figure 2. Beam parameters of 1.5 GeV FFAG synchrotron
Figure 3. High gradient RF cavity with high permeability magnetic alloy (FINEMET)

*RF field gradient: 50 kV/m, frequency: 3 MHz*
SESSION V

Beam Trips/Fluctuations: Effects on ADS and ADS Resistance

Chairs: H. Takahashi and H. Takano
EFFECTS OF ACCELERATOR BEAM TRIPS ON ADS COMPONENTS

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Abstract

Frequent beam trips as experienced in existing intense proton accelerators may cause thermal fatigue problems in ADS component materials, leading to degradation of their structural integrity and reduction of their lifetime. Analytical studies are underway to investigate the effects of beam trips on ADS components, with objectives to formulate ADS design considerations and R&D needs, and to determine the requirements of accelerator reliability. Preliminary analyses were made on thermal and structural responses of a fuel pin, a beam window and a spallation target for the experimental facilities planned under the Neutron Science Project. It is estimated that fatigue damages to the fuel cladding and the beam window caused by beam trips are negligible.
Introduction

France, Japan and several other countries are making efforts to develop accelerator driven systems (ADS) for nuclear waste transmutation and power generation. There are some proposals to construct small-scale experimental systems to demonstrate the ADS technologies toward the development of full-scale ADS. An experimental programme is being planned for the demonstration of accelerator driven transmutation technology in the JAERI Neutron Science Project. A pre-conceptual design study is being made for a 30-60 MWt experimental system and a 7 MWb target experimental facility [1].

One technical issue that has recently attracted attention is the negative impact of temporal changes in beam intensity (trips and fluctuations) on ADS. It is recognised that proton beams from existing intense proton accelerators trip (suddenly stop) very frequently. Such frequent beam trips may cause thermal fatigue problems in ADS component materials, leading to degradation of their structural integrity and reduction of their lifetime. They can also badly erode the availability and the capacity factor of ADS, resulting in poor economics.

In the development of accelerators for ADS, it is vitally important to establish the technologies to achieve a very high degree of reliability. On the other hand, it is also important in the development of target/core sub-systems of ADS to design structural components to withstand possible thermal fatigues due to beam trips and fluctuations. An important step in the ADS design study is to determine the magnitude of the effects of beam trips on susceptible components to severe thermal fatigue problems. The investigation will provide a database for formulating ADS design considerations and R&D needs, and requirements of accelerator reliability.

This paper briefly discusses the effects of beam trips on ADS generally, and describes the preliminary analysis on thermal and structural responses of a fuel pin and a beam window under the specific conditions in the planned experimental facilities.

Effects of beam trips on ADS

The configuration of ADS can be varied depending on the degree of reliability of the accelerator sub-system relative to that of the target/core sub-system. If achievement of a higher reliability of ADS as a whole would be the primary design, a sub-system with lower reliability should be multiplexed for fault tolerance or redundancy.

In a case when the reliability of the accelerator is higher than that of the target/core, the configuration of ADS would be a combination of one accelerator module and multiple target/core modules as shown in Figure 1(a).

In a case when the reliability of the accelerator is comparable with that of the target/core, ADS would combine one accelerator module with one target/core module as shown in Figure 1(b).

With the technology at present and in the near future, the accelerator is much less reliable than that of the target/core. In such cases, multiple accelerator modules would be required to operate one target/core module as shown in Figure 1(c).
Various system configurations that combine multiple accelerator modules and multiple target/core modules can be imagined, when both degrees of reliability of the accelerator and the target/core are lower than those required.

A trip of proton beam causes a sudden decrease in the flux of emitted neutrons from the spallation target together with a sudden decrease in the heat deposition in the spallation target and the beam window. In the subcritical core, the decrease in source neutrons results in a drop of the core neutron flux, which in turn results in a drop of the core heat generation due to fission reactions down to a decay heat level. If the cooling system continues in operation after the beam trip has occurred, the decrease in the heat deposition and the heat generation lead to a decrease in the temperatures of the window, the target and the core. It also leads to a decrease in the coolant temperature rise through the core decreases, which eventually causes a decrease in the temperatures of almost all the components in the primary system, the heat transport system and the energy conversion system with certain delays.

A decrease in the core neutron flux changes the subcriticality of the core. The level of the neutron flux determines the balance between rates of production and decay of a reaction product nuclide, and thus changes the concentration of the nuclides. The change in the concentration of a nuclide with a large neutron capture cross-section or a large neutron fission cross-section affects the effective neutron multiplication factor of the core. The temperature change caused by a beam trip has an influence on the subcriticality of the core through a variety of mechanisms, such as axial fuel expansion, coolant density change, Doppler effect, fuel-element bowing and radial core expansion.

The load factor or capacity factor of ADS will be badly eroded by frequent beam trips unless the mean shutdown time is sufficiently short. The time required to bring back to the full-power operating conditions would also be influential to the load factor of capacity factor. The required time for restart
depends on the initial condition (cold standby condition, hot standby condition, or near full-power operating condition) and the imposed limit on the rate of power or temperature rise. If sudden temperature drops due to beam trips are tolerable for a sufficiently large number, there will be nothing to limit the rate of temperature rise at restart in principle. It will be possible to design the 30-60 MWt system so that the temperatures can be restored within about 1 minute in the liquid-metal primary and secondary loops, and within about 30 minutes including in the steam turbine cycle.

Frequent beam trips will exacerbate the operational cost of ADS. The operational cost will be increased relatively by the reduced load factor. If some components in the system would require inspection, repair or replacement before restart, this would increase the operational cost absolutely.

The effect of a beam trip may have a regulatory and social aspect. A beam trip of ADS looks analogous to a scram of a conventional critical reactor. The consequences of a beam trip in a subcritical core are very similar to that of a scram in a reactor core. The safety implication is, however, quite different between the beam trip and the scram. This similarity may often lead to a misconception of the safety implication of beam trips for the general public and for regulatory authorities.

**Effects on structural integrity and lifetime of components**

One of the most important effects of beam trips is the thermal fatigue of ADS component materials. A beam trip changes temperatures in ADS components. The change in temperatures causes change in thermal stresses and thermal strains in the components.

Nearly all materials expand as they are heated. The thermal expansion is single valued and reversible for heating to temperatures well below the melting point. For most metals, the expansion is almost isotropic. The thermal stress $\sigma$ is generally expressed in the form $\sigma = c \varepsilon \alpha \Delta T$, where $E$ is the modulus of elasticity, $\alpha$ is the coefficient of thermal expansion, and $\Delta T$ is the temperature difference. The constant of proportionality $c$ depends on the condition of mechanical restraint and temperature distribution, and Poisson’s ratio. Large temperature difference in materials with high modulus of elasticity and high coefficient of thermal expansion results in large thermal stress.

Repeated temperature changes called thermal cycling due to frequent beam trips can cause thermal fatigue in the component materials. Damages caused by thermal fatigue can lead to the degradation of their structural integrity and reduction of their lifetime. Rather frequent replacements of the damaged components and/or some special design measures to alleviate the problem might be required if the accelerator reliability could not be sufficiently improved.

**ADS components subjected to thermal fatigue**

There are various types of mechanism to cause thermal stress. They can be divided into the following four classes: externally restrained thermal expansion or contraction of a structural element, temperature difference among structural elements, non-uniform temperature distribution or temperature gradient in a structural element, and combination of materials with different coefficients of thermal expansion.

Virtually all the components in the primary system, the heat transport system and the energy conversion system of ADS suffer from thermal cycling caused by beam trips to a greater or lesser extent. Figure 2 illustrates the experimental system that has been proposed under the JAERI Neutron...
Science Project. The main goals of the experiments are: to demonstrate the integrated operation of spallation target and subcritical fast-spectrum core driven by an intense proton beam, to demonstrate the minor actinide transmutation performance, to test the instrumentation and control system, to test the integrity of minor actinide fuel, to verify the system design concept and to verify the operational safety of the system.

The experiments are planned with a 30 MWt UO$_2$ core for the first step and then with a 60 MWt UN core for the second step. The design of the experimental system is based on the current sodium-cooled fast breeder reactor technology. A 1.5 GeV proton beam is injected through the beam window into the target region located at the centre of the subcritical core. The target consists of a cluster of target sub-assemblies with multi-layers of tungsten disk. The annular fuel region around the target consists of fuel sub-assemblies, each being formed by a hexagonal bundle of fuel pins containing fuel pellets. The beam tube is vertically inserted into the target/core vessel down to just above the target. The bottom end of the tube forms the beam window of a hemispherical shell. The target and fuel sub-assemblies are cooled by forced upward flow of primary sodium coolant. Impinging sodium flow from the target exit cools the beam window. The heat generated is transferred to a secondary sodium loop via an intermediate heat exchanger, and then discharged to the atmosphere through an air cooler. An auxiliary cooling system with sodium-potassium eutectic loop is provided as an independent means of removing decay heat. The primary system has a loop-type configuration. The experimental system does not involve electric power generation.

Major components which are highly susceptible to severe thermal fatigue problems are: beam window, spallation target, fuel pellets, fuel cladding, core barrel, target/core vessel, coolant outlet nozzle, main coolant piping, in intermediate heat exchanger (heat transfer tubes and tube plate), etc. Such components with internal heat generation as the beam window, spallation target and fuel pellet generate significant heat, and thus create a large temperature gradient to remove it by conduction. The fuel cladding and heat transfer tube in the intermediate heat exchanger are subjected to a large
temperature gradient for high flux heat transfer. In general terms, these components are relatively small in size, simple in shape and generic in design. Other components have relatively large dimensions and complex geometry, depending on particular designs. The thermal stress problem in such larger-scale components is often much more severe than that in smaller-scale ones. The evaluation of the structural integrity of such components would require detailed design, and the results should be difficult to be generalised.

There are several methods of mitigating thermal stresses on such structures. They can be divided into four main groups: attenuation of heat flux, modification to thermal characteristics of the structure, thermally non-redundant structures and selection of materials.

Thermal stresses depend on the heat flux. Insulation and artificial heating or cooling on the surface can reduce heat input and output, and thus attenuate the heat flux. The thermal characteristics of a structure subject to heating or cooling can generally be expressed as the Biot number $B = hl/\lambda$; where $h$ is the heat transfer coefficient, $l$ is the characteristic length in the direction of heat conduction and $\lambda$ is the thermal conductivity. A small Biot number can reduce the magnitude of thermal stresses. Structures with least restraint against thermal expansion such as bellows-type joints, flexible joints, etc., will not suffer high thermal stresses. Material with a small thermal shock resistance parameter $\lambda \sigma_{ult}/\alpha E$, where $\sigma_{ult}$ is the tensile strength, will generally have better thermal and structural characteristics.

Analytical studies on effects of beam trips

Preliminary analyses were made on thermal and structural responses of a fuel pin and a beam window for the experimental facilities planned under the Neutron Science Project.

Analysis of fuel pin

Two-dimensional thermal-hydraulic and structural analysis was made on the single fuel pin with the average power of the planned 60 MWt experimental system. Design parameters used for the analysis are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Parameters used for the fuel pin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
</tr>
<tr>
<td>Bond</td>
</tr>
<tr>
<td>Cladding</td>
</tr>
<tr>
<td>Pin diameter (OD/ID)</td>
</tr>
<tr>
<td>Pin pitch</td>
</tr>
<tr>
<td>Pellet diameter</td>
</tr>
<tr>
<td>Pellet density</td>
</tr>
<tr>
<td>Active core height</td>
</tr>
<tr>
<td>Coolant</td>
</tr>
<tr>
<td>Coolant temperature (in/out)</td>
</tr>
<tr>
<td>Linear power rating</td>
</tr>
</tbody>
</table>
Figures 3(a) and 3(b) show the axial distributions of the temperatures along the fuel pin on a steady state nominal operating condition together with the distribution of the linear power rating used as inputs. The maximum in the clad temperature distribution occurs at the core exit, whereas the fuel surface and fuel centre temperatures have their maximum values at an axial distance of about 65 cm from the core inlet. The maximum temperatures of clad, fuel surface, and fuel centre are about 440°C, 600°C and 1520°C, respectively.

Figure 3. (a) Axial distribution of coolant temperature and clad temperature, and (b) axial distribution of fuel surface temperature and fuel centre temperature

The tangential stress at the fuel pellet surface \( \sigma_{\theta} \) was evaluated as \( \sigma_{\theta} = \alpha f E f Q / 8 \pi (1 - \nu_f) \lambda_f \), where \( \alpha \) is the coefficient of thermal, \( E \) is the modulus of elasticity, \( Q \) is the linear power rating, \( \nu \) is the Poisson’s ratio, \( \lambda \) is the thermal conductivity, and the subscript \( f \) refers to the UO\(_2\) fuel. The tangential stress of the fuel clad \( \sigma_{\theta} \) was evaluated as \( \sigma_{\theta} = \alpha c E c \Delta T / 2 (1 - \nu_c) \), where \( \Delta T \) is the temperature difference across the clad, and the subscript \( c \) refers to the clad. The strain \( \varepsilon \) was calculated from \( \varepsilon = \sigma / E \). The radial displacement \( \delta r \) was calculated from \( \delta r = r (1 + \alpha \Delta T) \) to check the mechanical interaction between the fuel pellet and the clad.

Figures 4, 5 and 6 depict the axial distributions of fuel pellet stress, fuel clad stress and fuel clad strain, respectively, on the steady state normal condition. These distributions are almost similar to that of the linear power rating. It should be noted that the results are valid only when the stress stays within the elastic limit. The calculated fuel pellet stress is far beyond its tensile strength, causing cracks in the fuel pellet as discussed later.

The beam trip transient assumed for the analysis is schematically illustrated in Figure 7. The steady state normal operation at the nominal power is assumed before the beam trip. The beam trip occurs at 0 s, and the thermal power abruptly drops at 0 s from 100% to 0%, while the coolant flow rate and the coolant inlet temperature remain unchanged after the beam trip at their initial values (100% and 340°C, respectively). The decay heat is not accounted for in this analysis. The temperatures will start to decrease on the power drop.

Figure 8 shows the response of the fuel centre temperature, the fuel surface temperature, the fuel clad temperature, and the coolant temperature at their respective locations of maxima during the beam trip transient. Figures 9, 10 and 11 show the response of the maximum fuel pellet stress, the maximum fuel clad stress and the maximum fuel clad strain.
Figure 4. Axial distribution of fuel pellet stress on the normal operating condition

Figure 5. Axial distribution of fuel clad stress on the normal operating condition

Figure 6. Axial distribution of fuel clad strain on the normal operating condition
Figure 7. Beam trip transient

Figure 8. Temperature response during the beam trip transient

Figure 9. Response of the fuel pellet stress during the beam trip transient
The temperatures start to fall at 0 s, asymptotically approaching toward the coolant inlet temperature of 340°C. After about 10 to 15 s into the transient, the fuel pin becomes nearly isothermal. The fuel pellet stress, the fuel clad stress and the fuel clad strain decrease monotonically with time from the initial value to 0. Unusual behaviour or increase of the strain and stress, which may happen in high Biot number cases, is not seen during this rapid transient.

The peak fuel temperature is 1 520°C, sufficiently lower than the melting point of around 2 800°C. Tensile strength of UO$_2$ fuel pellet is around 1 000 kg/cm$^2$ at 1 500°C. The peak tensile stress of the fuel pellet is 3 700 kg/cm$^2$. It is predicted that one or two radial cracks are formed for linear power ratings below 200 W/cm (Figure 12). The cracks relieve the thermal stress and prevent further crack formation and propagation. It is predicted there are no possibilities of tensile/creep rapture of the 316 SS cladding, since the internal pressure of fuel pin due to gaseous fission product release is estimated to be low. With an appropriate gap, fuel clad mechanical interaction is expected not to occur. The major factor that can affect the integrity of cladding is identified to be fatigue caused by thermal cycling. The maximum thermal strain of the cladding is calculated to be $2.3 \times 10^{-4}$. The design fatigue strain range of 316 SS at $10^7$ cycles is $10^{-3}$ at 430°C (Figure 13). It is concluded that fatigue damage to cladding is negligible.
Figure 12. Estimation of crack patterns in fuel pellet

<table>
<thead>
<tr>
<th>linear power</th>
<th>computational domain</th>
<th>zones where principal stress exceeds 10 kg/mm²</th>
<th>possible pattern of cracking</th>
</tr>
</thead>
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<tr>
<td>100 W/cm</td>
<td>![Pattern]</td>
<td>![Pattern]</td>
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<tr>
<td>200 W/cm</td>
<td>![Pattern]</td>
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<tr>
<td>300 W/cm</td>
<td>![Pattern]</td>
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</table>

Figure 13. Design fatigue strain range, $\varepsilon_f$, 304 SS and 316 SS – elastic analysis (ASME code case N-47)

Analysis of beam window

Two-dimensional thermal-hydraulic and structural analyses were made on the beam window of the planned high-power target experimental facility. The beam window is a hemispherical cap made of 316 SS, having a radius of 120 mm and a thickness of 1 mm. The incident proton beam with a power of 7 MW has a diameter of 200 mm and a uniform profile. The beam window is cooled by upward flow of Na coolant at 440°C. The operating pressure of the coolant at the level of the beam window is 3 MPa. A model for the analysis is shown in Figure 14, and parameters are summarised in Table 2.
Figure 14. Calculational model and boundary conditions for the beam window analysis

![Model of Beam Window](image)

Table 2. Parameters used for the beam window analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Beam power</td>
<td>7 MW</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>200 mm</td>
</tr>
<tr>
<td>Current density distribution</td>
<td>Uniform</td>
</tr>
<tr>
<td>Window material</td>
<td>316 SS</td>
</tr>
<tr>
<td>Window diameter</td>
<td>240 mm</td>
</tr>
<tr>
<td>Window thickness</td>
<td>1 mm</td>
</tr>
<tr>
<td>Coolant</td>
<td>Sodium</td>
</tr>
<tr>
<td>Coolant pressure</td>
<td>~ 0.3 MPa</td>
</tr>
<tr>
<td>Coolant temperature</td>
<td>440°C (normal operation, upstream)</td>
</tr>
</tbody>
</table>

The maximum operating temperature of the beam window is 525°C, and the temperatures at evaluated cross-sections are in the range from 340 to 515°C. The maximum stress occurs at the edge of the beam, and is about 16 kg/mm², twice the stress on the centre. Evaluation was made according to “High-Temperature Design Guideline for FBR Prototype Class 1 Components” (STA) and “Technical Standard for Structures of Nuclear Facilities for Power Generation” (MITI) for a high-temperature operating time of 8 760 h (1 year).

All stresses and strains calculated are well within their allowable limits, and the allowable number of operating cycles is greater than $10^6$. It is evaluated that fatigue damage to the beam window is negligible.
Concluding remarks

Effects of beam trips on ADS were briefly discussed. There could be many aspects of the accelerator beam reliability issue. From the technical point of view, one of the most important problems is the thermal fatigue of ADS component material, which has recently attracted much attention. Thermal fatigue could lead to degradation of their structural integrity and reduction of their lifetime.

As an attempt to investigate the effect of beam trips on ADS component, preliminary analyses were made on the thermal and structural response of the fuel pin and the beam window of experimental facilities planned under the JAERI Neutron Science Project. Fatigue damages to the fuel clad and the beam window caused by beam trips were estimated to be negligible.

It should be noted that the results are not generally applicable, but specific to the case of the planned experimental facilities. They are designed to operate at lower values of the heat load, the operating temperature level, and the core temperature rise than those employed in current FBR design practice. Higher heat load and elevated temperature could complicate the problem, and larger-scale structures not analysed here could have much severer thermal stresses.

More detailed design and further analyses are needed to formulate design considerations, R&D needs and the requirements of accelerator reliability.

REFERENCES

FAILURE MODES OF ELEVATED TEMPERATURE STRUCTURES DUE TO CYCLIC THERMAL TRANSIENTS

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Abstract

In the case of low pressure power plants, designers should pay attention to thermal transient stress, which is sometimes the main loading to components. Temperature fluctuation caused by power change of plant systems enforces cyclic thermal transients to structures, where thermal fatigue or creep fatigue damage will be accumulated during the plant’s lifetime. When severe thermal stress is enforced, there is possibility of crack initiation and propagation at structural walls.

This paper discusses failure modes of elevated temperature structures due to cyclic thermal transients, through design experiences at FBR plants and structural strength tests.

Thermal transient problems can be classified from the point view of time constants of fluid and structures. When the frequency of temperature fluctuation is higher than the time constant of structures, the main cause of thermal stress is the temperature gradient across the thickness of the wall, which generates bending and peak stress. This phenomenon appears in thermal stripping, where the failure mode is high cycle fatigue. If the frequency is much higher than the time constant, the structure can not respond and temperature amplitude is diminished, leading to a small amount of thermal stress. On the other hand, if frequency or rate of temperature change is lower than the time constant of the structure, the temperature gradient in the wall thickness is gentle and mitigates bending and peak stress. In this case, another stress mode caused by differences of wall average temperature in structures becomes dominant and membrane and bending stress are induced. This mode appears in thermal transient and thermal stratification problems, in which failure modes are creep fatigue and progressive deformation.

In the case of ADS, the accelerator target and fuel have a second order of time constants, and plant components have longer time constants than minutes. The target and fuel have a common sensitivity to beam trip frequency, and plant structure has a different one. Therefore, the target and fuel should be treated separately from other components.
Introduction

Structural integrity assessment is an important step in the design towards demonstrating safety and reliability of nuclear components. In the case of elevated temperature and low pressure power plants such as Fast Breeder Reactors (FBRs), attention should be paid to thermal transient stress, which is sometimes a main loading to components [1]. Since the sodium coolant of a FBR has a high boiling point (about 1155 K) and an excellent heat conductivity with small heat capacity, the temperature difference between the hot (~825 K) and cold sodium in the heat transport circuit is large (~150 K) and the operating pressure is low (~2 MPa). Temperature fluctuations caused by a power change in the plant systems enforce cyclic thermal transients to the structures, where thermal fatigue or creep fatigue damage will be accumulated during the plant’s lifetime. When severe thermal stress is enforced, there is a possibility of crack initiation and propagation at the structural walls. This paper discusses failure modes of elevated temperature structures due to cyclic thermal transients, from design experiences from FBR plants and structural strength tests.

Expected failure modes due to thermal transients in fast breeder reactors

(i) Thermal transient loading due to plant operation

Transient operation of plants induces cyclic thermal transients of the coolant in circuits as shown in Figure 1. Since each structure has its own response characteristics with regard to a temperature change of the coolant, the same thermal transient condition generates different levels of thermal stress in each structure. For example, a main factor of thermal stress at pipes (Figure 1) is temperature gradients in the structural walls. This gradient decays rapidly from heat conduction in the wall, and the time constant of decay is usually shorter than the transient periods. Therefore, generated thermal stress becomes smaller compared with temperature amplitude. On the other hand, the Y-piece between a vessel wall and a support skirt (Figure 1) has long time constant. A vessel can respond quickly to a temperature change in the coolant, however a skirt can not since this portion of the structure does not come into contact with the coolant. As a result, large temperature differences exist between the two parts, which generates severe thermal stress when they come together. The number of cycles during a lifetime is usually less than four hundred, however, stress levels sometimes exceed the yield stress and cause low cycle fatigue crack initiation and propagation. In the case of elevated temperature operation conditions, residual stress generates creep damage during relaxation and the failure mode becomes creep fatigue.

(ii) Thermal stratification and free surface moving

When the plant is shut down, both the temperature and the flow rate of the coolant decrease. Cold sodium enters into the upper plenum of a reactor vessel and a stratified layer appears between the upper hot sodium and the lower cold sodium (Figure 2). This layer enforces a severe temperature gradient in the vertical direction of the vessel wall. A similar situation exists at the free surface of the sodium in a vessel, as the sodium temperature remains at operating temperature, while the top level of the vessel usually connects directly to the room temperature of the building (Figure 2). The movement the of stratified layer or the free surface enforces cyclic hoop and axial stress on a vessel wall, leading to progressive deformation by thermal ratcheting and creep fatigue damage.
Figure 1. Creep fatigue failure caused by thermal transient loading due to plant operation

![Diagram showing thermal stress and fluid temperature over time.]

Figure 2. Thermal ratcheting due to thermal stratification and free surface moving

![Diagram showing thermal stratification and free surface movement.]

(iii) *Thermal stripping*

When mixing between high temperature and low temperature liquids occurs, random temperature fluctuations result from incomplete mixing, where typical frequency is 0.1-2 Hz and the amplitude about 30-100 K. These temperature fluctuations induce nearby structures to crack from high cycle fatigue damage and subsequent crack propagation. This phenomenon is called thermal stripping. Examples are upper core structures exposed to the high temperature sodium from fuel assemblies and the low temperature sodium from control rods, as well as the T-junctions of hot and cold pipes.
Figure 3. High cycle fatigue modes due to thermal stripping

The above mentioned thermal transient and failure modes are summarised in Table 1. When the frequency of temperature fluctuation is higher than the time constant of the structures, the main cause of thermal stress is the temperature gradient across the wall thickness, which generates bending and peak stress as indicated in Figure 4. This mode appears in thermal stripping and is briefly described in Figure 5, which shows the temperature profile across wall thickness under sinusoidal temperature fluctuation with constant amplitude and heat convection factor. If the frequency is much higher than time constant of the structures (10 Hz in Figure 5), then the structure can not respond and the temperature amplitude is reduced, leading to reduced thermal stress. On the other hand, when the frequency or rate of temperature change is lower than the time constant of the structure, the temperature gradient in the wall thickness is gentle and mitigates bending and peak stress. In this case, another stress mode caused by different wall average temperature in structures becomes dominant and generates membrane and bending stress. This mode appears in thermal transient and thermal stratification problems.

<table>
<thead>
<tr>
<th>Thermal transient mode</th>
<th>Thermal transient</th>
<th>Thermal stratification</th>
<th>Thermal stripping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature amplitude</td>
<td>~150 K</td>
<td>150–500 K</td>
<td>30-100 K</td>
</tr>
<tr>
<td>Transient rate/</td>
<td>0.005-15 K/sec</td>
<td>0.005-1 K/sec</td>
<td>0.1-100 K/sec</td>
</tr>
<tr>
<td>frequency of fluctuation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time constant of</td>
<td>10-1 000 sec</td>
<td>100-10 000 sec</td>
<td>1-100 sec</td>
</tr>
<tr>
<td>structural response</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle numbers</td>
<td>300-400 cycles</td>
<td>300-400 cycles</td>
<td>1 000 000-10 000 000 cycles</td>
</tr>
<tr>
<td>Failure mode</td>
<td>Low cycle fatigue crack initiation and propagation</td>
<td>← iibid. Progressive deformation due to thermal ratcheting</td>
<td>High cycle fatigue crack initiation and propagation</td>
</tr>
</tbody>
</table>
Structural strength tests

In order to develop structural design evaluation methods of creep fatigue, crack initiation and propagation due to thermal transients, structural strength tests have been conducted at the Oarai Engineering Centre of the Power Reactor and Nuclear Fuel Development Corporation [2]. Small-scale models of fundamental structures and medium-size components, approximately 2 m high, were tested. Typical materials used were SUS304 and 2¼Cr-1Mo. By using sodium loops as in Figure 6, these models were exposed to cyclic thermal transients by allowing high temperature (typically 600°C) and low temperature (typically 250°C) liquid metals run though alternatively. During thermal transients, the temperature history of the liquid metal and the structures were monitored and used as input to the structural analysis mesh models shown in Figure 7.
After tests, many cracks were observed on the surfaces of the test models. The depth and surface of the cracks were measured (Figure 7). Microscopic inspection showed that failure modes were due to thermal fatigue when repeated periods were short and to be creep fatigue if periods were long. Macroscopic inspection revealed that crack stopped under pure displacement controlled loading. However, crack propagated though the wall when combining load controlled and displacement controlled loading (so-called elastic follow-up).
Thermal-hydraulic and thermal-mechanical analysis methods

In order to simulate thermal transient phenomena in fast reactor plants, where the main loading is thermal stress induced by transient operation of the plant, a conventional design procedure uses several different analytical codes as shown in Figure 8. First of all, the one-dimensional plant dynamics simulation codes predict the thermal boundaries of the components. Next, multi-dimensional thermal-hydraulic analysis in components under former boundaries is performed and the thermal responses of the structures are calculated through structural analysis codes. The corresponding temperature distributions finally lead to calculation of thermal stresses, using stress analysis codes. This step-by-step procedure requires both a considerable amount of manpower to ensure interfaces among codes and a large amount computation time, the total turn around time sometimes extending to as much as one month per analytical case.

**Figure 8. Conventional and proposed analysis procedures of thermal transient stress**

To perform a trial and error approach to obtain the optimum plant design, the author proposed a new design procedure, based on an integrated analysis code named PARTS (Programme for Arbitrary Real Time Simulation) for the simulation of both thermal-mechanical behaviours of structures and plant thermal-hydraulic dynamics [3].

Strength evaluation methods

Elevated temperature design codes for FBRs include procedures to predict fatigue and creep fatigue damage from stress and strain obtained in thermal-hydraulic and thermal-mechanics analysis [4,5,6].
Fatigue crack initiation is avoided when limiting the fatigue damage factor, which is evaluated by strain range $\varepsilon_t$, cycle number $N$, fatigue curve $N_f$, and the following equation:

$$D_f = \frac{N}{N_f(\varepsilon_t)}$$

(1)

In the case of the allowed strain range $\varepsilon_{it}$ ($i = 1,2,3,...$), accumulated fatigue damage can be evaluated by the linear summation rule (Miner’s rule):

$$D_f = \sum \frac{N_i}{N_f(\varepsilon_{it})}$$

(2)

Creep fatigue crack initiation is prevented by limitation of the creep fatigue damage factor:

$$D = D_f + D_c$$

(3)

Creep damage $D_c$ is evaluated from the following equation (time fraction rule) containing stress history $\sigma_i(t)$ and the corresponding rapture time $t_R(\sigma_i)$:

$$D_c = \sum \frac{t_i}{t_R(\sigma_i)}$$

(4)

An alternative method is the ductility exhaustion method using accumulated creep strain $\varepsilon_i$ during an operation period and the ductility limit of the material $\varepsilon_R$ [5].

$$D_c = \sum \frac{\varepsilon_i}{\varepsilon_R}$$

(4)

Elevated temperature structural design codes pay attention to strain concentration at structural discontinuities due to creep and plasticity, since it leads to enlarge creep fatigue damage of material. These codes categorise stress to a load-controlled type, caused by the equilibrium between external load and displacement-controlled stress, associated with the compatibility of geometrical continuum (Figure 9). In the case of displacement-controlled stress, strain is constant even at plastic conditions and creep deformation occurs. Conversely, load-controlled stress is constant during deformation. Thermal stress is usually treated as displacement-controlled, except for structural discontinuity portions, where creep strain occurs mainly at high stress and flexible portions, and the elastic strain of surrounded portions relaxes. At structural discontinuities, this strain redistribution makes stress condition something intermediate between load-controlled and displacement-controlled, so-called elastic follow-up (Figure 9). Since elastic follow-up enlarges the strain range and reduces the stress relaxation rate, as broken line shows in Figure 1, it should be appropriately taken into account for strength evaluation [8]. If elastic follow-up parameter “q” (as defined in Figure 9) can be obtained, then a precise prediction is possible. An example of creep fatigue prediction on thermal experimental tests (Figure 7) is shown in Figure 10, which compares cracks and predicted creep fatigue damage. This damage implies that values over one (1) correspond to crack initiation. Conventional methods use conservative elastic follow-up parameters and new methods adopt rationalised ones.
Discussion

Thermal transient problems can be classified from the point of view of time constants of fluids and structures. When the time constant of a structure is much smaller than one of a fluid, the whole temperature of the structure can respond to a change in fluid temperature, and thus thermal stress caused by the temperature gradient is small. On the other hand, when the time constant of a structure is much larger than that of a fluid, the temperature gradient across the wall thickness becomes the main cause of thermal stress. If the time constant of the fluid and the structure is close to the same, large thermal stress is induced by both differences in wall average temperature and the temperature gradient across the wall thickness.
In the case of ADS, the accelerator target and the fuel have a second order of time constants, and plant components have time constants longer than just minutes. The target and the fuel have a common sensitivity to beam trip frequency, and the plant structure has a different one. Therefore, the target and the fuel should be treated separately from other components.

Thermal transient stress would be reduced if the time constants of the components could avoid periods of temperature fluctuation. To this end, some ideas include:

- a thermal linear to enlarge the time constants of the components;
- a large liquid plenum to enlarge the time constants of plant dynamics;
- rapid automatic recovery of the beam (with plural beam sources?).

Some ideas for attenuation of the temperature amplitude are:

- a rapid downward coast of the coolant’s flow rate;
- a large liquid plenum for attenuation of high cycle fluctuation.

**Conclusions**

Thermal transient problems and associated failure modes experienced in FBRs were categorised into: creep fatigue failure caused by thermal transient loading due to plant operation, thermal ratcheting induced by thermal stratification and free surface moving, and high cycle fatigue modes due to thermal stripping. The main difference between these modes is due to the frequency of temperature change and the relative time constants of the structures.

For strength evaluation, thermal stress can be usually treated as displacement-controlled. However, elastic follow-up at structural discontinuities enhances strain in spite of thermal stress, and attention should be given to these parts.

**REFERENCES**


THERMOMECHANICAL ANALYSIS OF AN ATW FUEL ELEMENT UNDER AN ACCIDENT SCENARIO

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Abstract

The integrity a fuel element in the ATW system is being evaluated under an accident scenario in which the accelerator is ramped to full power instantaneously creating a hyperbolic tangent neutron flux profile. Under this scenario, severe thermal transients will arise in the fuel and the fission heating of the fuel will occur faster than thermal strains can be relieved by material deformation. The thermal shock will produce vibrations leading to high stresses in the fuel and supporting structure. This analysis may have additional implications with regard to the effects on accelerator trip events on the integrity of the ATW reactor system.

ABAQUS, a transient-dynamic finite element code, is being used to determine the time dependent stresses and displacements due to thermal shock loads. A normalised measure of stress (NS) is being evaluated at a time when the peak tensile strength is reached. The normalised measure of stress is the ratio of the von Mises (effective) stress to the temperature dependent tensile strength in each finite element. NS values of greater than one indicate that the tensile strength has been exceeded and that failure is expected. Because of the preliminary stage of the investigation, many physical details such as the mechanical interaction of the expanded fuel and the cladding, which would affect the thermomechanical behaviour of the fuel elements, are neglected. Parametric studies are being conducted in which the temperature rise parameters, fuel dimensions, and material assumptions are varied. Further analyses will include sensitivity studies to determine the optimum fuel design and driver ramp-up protocol to ensure that the fuel matrix will remain in the elastic or near-elastic range.
REFERENCES


The reliability of accelerators for industrial use such as energy production or transmutation of radioactive material can be extensively increased by taking into account the safety factor of reducing the electric field strength for acceleration cavity. To keep energy cost low, the accelerator should be in hand on maintenance by minimising the beam loss. The two methods of spreading proton beam are described. Although the CW beam is most favourable for accelerator driven reactor, the use of pulsed spallation neutron for this ADR such as the induction linac and fixed field alternating gradient accelerator (FFAG) are discussed with the fatigue problem of the solid fuel due to periodic shock by the pulsed operation of accelerator. The control of reactor power by neutron absorber is discussed in comparison with the approach used by accelerator power, and the non-proliferation problem is mentioned for accelerators.
Introduction

For accelerators to be used successfully in industry, especially in energy production, it is mandatory that they be almost free from trips. When we proposed accelerator fuel production [1] in the International Nuclear Fuel Cycle Evaluation (INFCE) study in 1977, the first objections came from physicists who had had experiences in their early experiments. Today, however, the National Synchrotron Light Source has contributed to the study of solid state, material science and biological science by providing a very stable beam with high luminosity (relativistic heavy ion collider) which can make high luminosity to obtain many events for scare events. However, these are not electric power production accelerators. The reliability of alternating gradient synchrotron (AGS), which was commissioned in 1960 by the invention of Courant and Schneider’s Strong Focusing Principle is also not adequate for industrial use. The main purpose of this machine is to achieve high energy to discover new particles or events. Although its reliability is also important, it was designed to achieve as high electric fields as possible with minimum cost. Thus, the acceleration cavity and the other devices were operated at maximum capacity, so that it is prone to trip with small irregularities in performance. For industrial devices such as electric power producers, the same safety factor is used and not operated in the maximum capacity.

The radiation hazard in the high current accelerator makes it difficult to repair or replace failed parts. The use of robotics devices is still in its infancy, and they are very expensive. Therefore, beam loss should be minimised or localised so that the accelerator can be repaired by hands-on maintenance.

Although for energy production using the subcritical reactor, continuous wave (CW) operation is preferable, the accelerator system for producing the pulsed proton beam has been studied due to the recent interest in the pulsed neutron source. The short-pulsed beam is created by compacting the partial CW beam to generate a pulsed spallation neutron source.

Using accelerators for producing energy or transmuting minor actinide and long-lived fission products should not be expensive, so that nuclear energy can be competitive with other energies such as that produced by oil, natural gas and coal. By running the nuclear reactor under small subcritical condition, we can run it more safely, and can produce hard neutron energy spectrum. Thus, neutron economy can be increased, which means we can use the necessary neutrons for producing the fissile material from fertile material or transmuting the minor actinide (MA) and long-lived fission products (LLFP) at reasonable cost. To use this system, the reliability of accelerator operation is an absolute necessity.

Tripping of the accelerator

Although very short trips of the beam do not affect power production due to the large heat capacity of the subcritical reactor, the lack of the beam for short intervals creates a loss of heat generation and causes a thermal shock to the reactor’s elements.

One cause of tripping of the accelerator is the sparking of a cavity caused by applying a high electric field, which generates flakes from the impurities, defects or dust on the cavity’s surface, and causes electric avalanches. Figure 1 and Table 1 show experimental data on the X-ray doses and spark rates obtained at CERN and Fermi Laboratory during conditioning.
Near the Kilpatrick electric field, the radiation dose rate from X-rays and electrical breakdown increases, with the electric field strength (E) of $E^{1.5\pm0.3}$ power and $E^{1.9\pm1.2}$ power [2]. A small reduction in the electric field drastically reduces dose rates from X-rays and probabilities of sparking, while the length of an accelerating particle’s track is inversely proportional to E. Thus, by slightly lowering the accelerating field and lengthening the accelerator beam’s track, the occurrence of electrical breakdown in the cavity can be reduced without incurring a big economical penalty. To prevent electron avalanches, cleaning the cavity’s surface by injecting clear water, eliminating impure materials which make flakes, and conditioning are essential.

Another cause of tripping is the breakdown of the coupler between the wave-guide to the cavity, and the RF windows for its transmission. This cause can be eliminated by reducing the high gradient in the electric field caused by sharp edges.

**Spread of the proton beam and its shape**

To avoid the radiation damage of beam windows by the high intensity injection of the proton beam, the proton beam should be spread to reduce the frequent replacement of beam windows and targets. Spreading the beam can be achieved by using quadrupole and octapole magnets [3]. According to our analysis, a long expansion length of 17 m is required before injecting the 1.5 GeV proton beam with a spread of 15 cm x 20 cm into the target assembly for the proton beam. When the beam power is higher, and a wider window is required, much longer beam expansion is needed, and horizontal injection is preferable to vertical injection for a deep subcritical reactor. Horizontal injection was adopted in our light-water fuel regenerator [4] and in Los Alamos National Laboratory’s accelerator tritium producer [5]. The analysis shows that the spread of the beam has some peaking at its edge, which is not desirable for radiation damage of beam windows, and non-uniformity of the heat deposition.

Another way to spread the beam is to use rastering beams. We estimated the power required to raster 1 GeV energy proton (momentum $p = 1.807$ GeV/c, $\gamma = 2.066$, $\beta = 0.875$, $B\rho = 5.657$ Tm) to cover the targets front surface dimension of 7 cm height and 20 cm width. When the 1 m length quadrupole magnet is placed at 10 m upstream from the target windows, the sweep angles that cover the surface is 0.0133 mrad, and integral of B dl is 0.0755 Tm. The sweeping time of 550 nsec with intervals, the power required is calculated as 12 KW due to large impedance for eddy current. If we use the magnet with a two-meter length, the power can be reduced by four. Although the beam is peaking at the upper and bottom edges, the peak is much milder than in the case of non-rastering static. To reduce beam loss and the associated high radiation field, a carefully designed magnetic field is needed.

Another caution in using the electric magnet for spreading the beam is a cut-off in the electricity for the magnet. When cutting-off occurs, the spread of the beam is shrunken, and a high intensity beam could instantaneously melt the windows’ material, making a hole. To prevent such an accident, some part of the expanding magnet should use a permanent magnet. The magnetic field created by the permanent magnet is 0.2 Tesla; thus, we can design the configuration such that the beam is still spread, even in this accidental situation. Also, the sharp edges created in tailoring the beam [3] should not contribute to radiation hazards in the target’s design.
A liquid-fuel target without windows can alleviate many of the problems associated with radiation damage, and also mitigate the sharply peaked heat-generation from a localised spallation source.

Use of induction linac and fixed field alternative gradient accelerator (FFAG) [6]

To accelerate the high current proton beam in CW mode, a linear accelerator with a regular conductor acceleration cavity is most suitable, but for the low-power accelerator, the superconducting linac is required to increase the acceleration efficiency. For non-proliferation, due to the simple extension capability of a high power accelerator, this is a problem.

We proposed to use the cyclotron for a low-powered CW beam to run the large-powered subcritical reactor with a slightly subcritical reactor with $k = 0.99-0.98$. The cyclotron can accelerate only a limited small current beam; but it is more cost-effective, and also large real estate is not required as with the linac.

Recent explosive improvement in calculational power enable us to use the pulsed spallation neutron as the neutron source for many applications of neutron scattering. For the application of pulsed spallation neutron sources, two groups of accelerator architectures can be considered. One group uses RF linear accelerators, which inject into compressor rings, either rapid-cycling synchrotron or accumulator rings. The other group uses more exotic machines, induction linacs and fixed-field alternating gradient accelerators, which avoid some of the most fundamental technical risks, of a development of high-intensity, negative-ion sources and the control of very low-level beam losses during injection into the compressor rings.

Induction linacs have the capability to accelerate microsecond-long, and even shorter pulses, at high repetition rates, and with large accelerating gradients (1 MV/m). They can accelerate large beam intensity, few tens of amperes, as directly derived from low duty-cycle, positive-ion sources. Induction linacs need no compressor rings, since beam pulses of the desired short length and power can be directly generated at the exit. Unfortunately, full-energy induction linacs are long and expensive. However, the linac can also be used as an injector to a rapid-cycling synchrotron, or an FFAG machine, thus removing the concerns and problems associated with the multi-turn injection and the development of negative-ion sources, since the positive-ion beam can be injected in one single turn. The major technical risk is the development of the (positive) ion source, which considering the large beam intensity also has a large beam emittance, the early stage of acceleration, the overall length and the cost. The technology, which is very mature and sophisticated, is not that well-known to the community of majority of the accelerator experts who prefer working on accumulators, synchrotron and RF linacs. In the past there has been a tendency to prematurely dismiss the technology as a stand-alone application to pulsed spallation neutron sources. However, we believe that if used as a low-energy injector to an FFAG accelerator, as explained below, the induction linac has very attractive features.

Fixed-field alternating gradient (FFAG) accelerators

FFAG accelerators were also proposed in the past as possible spallation neutron sources. They need an injector, usually a modest RF linac, but otherwise they can provide most of the acceleration once the beam velocity has reached a large enough value. Their good feature is that they provide acceleration in a constant (fixed) field environment. In the past, the use of an FFAG was
based on the idea to inject 300-500 turns, pulse trains arriving, from the injection linac. During that time, the RF system of the FFAG was turned off. When the DC beam in the FFAG had reached the space charge limit, the RF was turned on slowly and the beam adiabatically captured into the RF bucket. Then the beam was accelerated to full energy, spiralling out to the extraction radius, where it was kicked out, in one shot, and directed onto the neutron production target. The output power of such a linac-FFAG combination is determined by the space charge limit at the injector, the FFAG’s repetition rate and its output energy. The major technical difficulties for the past linac-FFAG combination were the low-loss requirement for the multi-turn injection, the loss-free adiabatic trapping of the injected beam and the disposal of the excited $H^0$-states at a suitable beam stop. The design of the sector magnets and the RF cavity is also not trivial. Most of these problems can be removed by using an induction linac as the injector. Because of the initial short beam pulse length, there is no need for multi-turn injection, which considerably simplifies the design.

The technology of FFAG accelerators is also old, but recently has reached its maturity and attained a certain level of sophistication. Several new features can be incorporated, for example, long drift spaces can be inserted. To minimise the cost of the magnets, transverse focusing may be obtained not only with a conveniently chosen field profile, but also with the shaping of the entrance and exit angles of the bending magnets. With specially adjusted focusing elements, it is also possible to introduce isochronism and zero, or small dispersion regions to locate more compact RF cavities for acceleration.

**A scenario based on an induction linac injecting into a FFAG accelerator**

Figure 2 and Table 2 show the best combined features of the induction linac and the FFAG accelerator. The combination in sequence of the two types of accelerator complement each other’s features, removes some of their major technical difficulties, and, most importantly, eliminates problems peculiar to negative-ion sources and multi-turn injection.

The design construction and operation of this induction linac should not present insurmountable difficulties. Also, considering the very short beam pulse length and the large ratio of inner core diameter to beam size, no problems of radiation activation due to latent beam losses are expected. Such a short beam pulse can be injected in one turn in a circular accelerator for further acceleration. The circular accelerator could be a FFAG accelerator, because it avoids fast-ramping magnetic fields, as in the case of synchrotron, which requires a complicated vacuum system and vacuum chamber, and limits the pulse repetition rate.

The actual value of the injection energy, between 260 and 600 MeV, can be chosen as a compromise between conflicting requirements. One would prefer a large value of the injection energy to avoid too severe space-charge effects, to reduce the cost of the FFAG accelerator, to narrow the required momentum acceptance and thus the size of the magnets. On the other end, high-energy induction linacs are long and more costly. The optimum choice can be determined only after careful trade studies. Table 3 summarises typical parameters of the FFAG accelerator for a range of injection and final energy values.

As discussed before, the CW machine is preferred for energy production because no shock occurs. However, if we can increase the frequency of 50 Hz to 1 000 Hz beam pulse, the shock pulse can be reduced by 20. If we can take out the slow extraction of beam, we can make a CW-like beam operation for the reactor.
The effects of the shock due to this high-frequency pulsed proton to the subcritical reactor was studied by using the spatial and time-dependent code. Again the small sub-criticality can reduce the fatigue caused by periodic shock.

**Fatigue of solid fuel**

When the pulsed neutron is injected into the subcritical reactor, a shock wave is created, even though the delayed neutrons somewhat reduce the shock intensity. When solid fuel is used, the repeated shock might cause the fatigues of the fuel; its cycling time for one replacement will be shortened, which makes the plant factor small. We studied the fatigue of fuel in the old, fast-pulsed reactor program which was run successfully for more than 40 years in the Dubna pulsed reactor. By running it sub-critically (not super-critically) and using the pulsed spallation neutron source, we safely operated it although the delayed neutron caused a wider pulse.

We performed the integrity test of the fuel using the fatigue test facility [8], applying the shock corresponding to the 30-MWt, 50 Hz pulsed reactor to uranium carbide fuel. To obtain high conductivity, the spherical uranium carbide fuel of 1 micron diameter with a graphite sheet was compressed to form fuel rods.

Our experiment, applying the periodic shock into the uranium carbide fuel, was maintained by more than one month due to the high conductivity of the fuel. The failure of integrity of fuel depends on its temperature. The high fuel temperature of a power reactor might strongly affect the integrity under fatigue due to fluctuation of power, especially for irradiation conditions.

**Variable beam power**

In some designs for the accelerator-driven reactor, the use of proton-beam power to control reactor power was suggested. Using such power can be done easily for a small reactivity change. However, for a large reactivity change, like the burn-up of fuel, a large change in the accelerator’s power beam is required. It is uneconomical though, because the full capacity of an expansive accelerator facility is not used unless the beam is split to run the other subcritical reactor. Without a neutron absorber, such as control rods, the neutron economy can be increased. A reactor without the control rods becomes a simple mechanical system which confers an economical benefit, but this benefit is not large enough to compensate for the economical penalty of the high cost of an accelerator facility. The use of control rods is much more economical.

When sub-criticality is changed by a large amount, the spatial distribution of heat generation for the localised spallation neutron source will be changed; then, a simple change in the accelerator’s power cannot accommodate it unless the subcritical reactor is a liquid-fuelled reactor. The slow response time of the control rods can be sufficient to adjust to the slow change in power due to subcritical operation, and a fast change in power, which maybe needed in an emergency, can be done with the accelerator.

A high-powered accelerator with a high current creates a high wake field besides an accelerating RF, and the temperature of the accelerating cavity will be affected by the change in power. A large change in beam current is not desirable in terms of the beam’s stability, and the beam halo created by phase mismatch increases the radiation level, an effect which should be avoided. The jittering of an
unstable beam creates fluctuations of fission power in the reactor. This occurrence should also be avoided as much as possible so that the plant can have a long life, which is very important for its overall economy.

Non-proliferation problem

We would like to have a linear accelerator, which can increase the beam current more easily, so that we can produce the fissile material with deep sub-criticality effectively. We proposed tritium production using the high-power accelerator in place of the reactor. According to the demand for the tritium, we can easily adjust the accelerator’s power, producing the tritium without producing the fission products.

However, for non-proliferation, the weapons’ fissile material can be produced in a short time, the development of the linear accelerator has to be counter-balanced by the proliferation problem of weapons material.

Conclusion

Accelerator technology has impressively improved, and accelerators are utilised in many fields. The maturity of the technology has been established by this extensive use. So far, accelerators are used mostly for scientific research, with their reliability a secondary consideration to their high performance. However, for industrial use, especially in the sector of electric power production, reliability is the first priority and high performance the secondary one. We have the ability to construct very reliable, economical accelerators.

Acknowledgements

The authors would like to express their thanks to Drs. A. Luccio and J. Niederer for valuable discussion, and Dr. A. Woodhead for editorial work. This work was performed under the auspices of the US Department of Energy under Contract No. DE-AC02-76-COH016.
REFERENCES


Figure 1. Experimental data (during conditioning) of X-ray dose and spark rate

![Graph showing X-ray radiation at 3.6 meters](image)

Table 1. Experimental data (during conditioning) of X-ray dose and spark rate

<table>
<thead>
<tr>
<th>Source</th>
<th>X-ray Dose Rate/hr</th>
<th>Spark Rate/pulse after 4 * 10^6 REF Pulse</th>
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<tbody>
<tr>
<td>CERN (for a 200 MHz cavity)</td>
<td>0.3 * (E/12 MV/m)^1.9</td>
<td>0.7 * 10^X</td>
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<tr>
<td>FERMI laboratory (for prototype #1, 6 cells of the 805 MHz cavity)</td>
<td>0.3 * (E/12 MV/m)^1.9</td>
<td>0.7 * 10^X</td>
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(Data quoted or deduced from P.E. Fangesras, et al., PAC-87, p. 1719)
Table 2. Requirement and induction linac parameters

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Value 2</th>
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<tr>
<td>Average beam power</td>
<td>5 Mw</td>
<td></td>
</tr>
<tr>
<td>Repetition rate</td>
<td>200 Hz</td>
<td></td>
</tr>
<tr>
<td>Final energy</td>
<td>1 GeV</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Average beam current</td>
<td>1.25 mA</td>
<td>0.42 mA</td>
</tr>
<tr>
<td>Positive-ion source</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse length</td>
<td>2 µs</td>
<td></td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.04%</td>
<td></td>
</tr>
<tr>
<td>Peak current</td>
<td>12.5 A</td>
<td>4.2 A</td>
</tr>
<tr>
<td>Normalised emittance</td>
<td>$30 \pi \text{ mm mrad}$</td>
<td>$10 \pi \text{ mm mrad}$</td>
</tr>
<tr>
<td>2 induction linac</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final energy</td>
<td>260 MeV</td>
<td>600 MeV</td>
</tr>
<tr>
<td>Final pulse length</td>
<td>0.15 µs</td>
<td>0.1 µs</td>
</tr>
<tr>
<td>Initial accel. gradient</td>
<td>36 kV/m</td>
<td></td>
</tr>
<tr>
<td>Final accel. gradient</td>
<td>1 MV/m</td>
<td></td>
</tr>
<tr>
<td>Total length</td>
<td>380 m</td>
<td>720 m</td>
</tr>
<tr>
<td>Internal core diameter</td>
<td>60 cm</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. FFAG accelerator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy</td>
<td>1 GeV</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>260 MeV</td>
<td>600 MeV</td>
</tr>
<tr>
<td>Circumference</td>
<td>200 m</td>
<td>200 m</td>
</tr>
<tr>
<td>Packing factor</td>
<td>40%</td>
<td>40%</td>
</tr>
<tr>
<td>Bending radius</td>
<td>12.74 m</td>
<td>12.44 m</td>
</tr>
<tr>
<td>Bending field</td>
<td>1.95-4.44 kg</td>
<td>3.19-10.01 kg</td>
</tr>
<tr>
<td>Momentum aperture</td>
<td>± 40%</td>
<td>± 50%</td>
</tr>
<tr>
<td>Max. dispersion</td>
<td>2.0 m</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Max. beta function</td>
<td>20 m</td>
<td>20 m</td>
</tr>
<tr>
<td>Magnet aperture</td>
<td>1.6 m</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Magnet gap</td>
<td>30 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Space-charge $\Delta v$</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Normalised emittance</td>
<td>$400 \pi \text{ mm mrad}$</td>
<td>$220 \pi \text{ mm mrad}$</td>
</tr>
<tr>
<td>Acceleration period</td>
<td>5 ms</td>
<td>5 ms</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>RF frequency</td>
<td>0.93-1.31 MHz</td>
<td>1.19-1.46 MHz</td>
</tr>
<tr>
<td>RF peak voltage</td>
<td>500 kV</td>
<td>600 kV</td>
</tr>
</tbody>
</table>
Abstract

Even under the assumption that the reliability of future high power accelerators built for industrial applications can be improved by two orders of magnitude over what is routine at current research accelerators, the question still remains as to what the effects of beam trips on a driven subcritical reactor would be and how the system could be optimised for maximum service life and economic operation. Based on information from research spallation neutron sources built and studied so far and on results from a fast reactor study, the present paper discusses the likely thermal shock levels resulting from beam trips of different duration on the target system and on the subcritical assembly surrounding it. Since a possible method of mitigating the effect of beam trips would be to multiplex beams from different accelerators into a number of target stations, which would require pulsed accelerators to be used, the effect of pulsed beams on the driven system is also considered. In view of the fact that the number of permissible cycles increases by an order of magnitude as the maximum stress is reduced by a factor of two, the larger number of partial beam losses in such a system should not be a problem. It would, in addition, have a number of other advantageous features, some of which are listed in the paper.
Introduction

Reliability of the whole system, accelerator plus driven assembly, is of prime importance in future applications for simultaneous waste management and power generation. This is not only for technical, economical and safety reasons but also, and probably most importantly, for reasons of licensing and public acceptance.

So far spallation neutron sources have been built exclusively as facilities for basic research and all of them are of relatively low beam power, less than 1 MW. Although overall availability is, of course, a concern in view of the usage of these facilities in a large number of research programmes, the question of short beam trips has, in general, not received much attention. They do not contribute significantly to beam time lost and experiments are done with pre-set monitor counts for the incident beams anyway. Although efforts have been going on to improve the performance of the driving accelerators, the emphasis was mainly on running at high currents, which naturally goes along with high loads on the accelerator components. It is mainly for this reason that the two existing high current accelerators, the 800 MeV linac at LANSCE, Los Alamos, USA and the 600 MeV cyclotron at PSI, Switzerland, which run at 1 and 1.5 mA beam current respectively, have been suffering from large numbers of beam trips. This raised the question as to the reliability of accelerators which would drive high power targets for nuclear applications, in particular subcritical assemblies. At their present performance, beam trips of more than one minute duration occur in above two accelerators at a rate of a few hundred per week, with shorter ones being even more frequent, in particular at the PSI cyclotron (see below). The spallation target of the neutron source SINQ driven by the PSI accelerator is the one operating at the highest power level world-wide. It is, therefore, an important test bed for possible effects of beam trips on a high power target and we will give a short account on the operating experience and ongoing development work at this facility. We will also use results from model calculations carried out at PSI for the 5 MW beam power spallation neutron source ESS currently under evaluation in Europe. With regard to the driven facility we will use results on scram calculations obtained for the projected European fast reactor (EFR). Taken together, this allows us to draw some conclusions on required operating conditions and derive some thoughts on possible ways of circumventing difficulties that seem to persist, even if significant improvements in the stability of accelerator operation will be realised.

The model used for the facility

Since no detailed conceptual design exists at present for a driven subcritical assembly, we base our discussion on a model as shown in Figure 1.

As in the “pool” design of liquid metal cooled fast reactors a pumping system for the core coolant and an intermediate heat exchanger are included inside the containment of the reactor vessel. The coolant, after taking up the heat dissipated in the subcritical assembly (SCA) flows through the above core structure (ACS) into the hot coolant pool, from where it passes through the intermediate heat exchanger (IHX) into the cold pool below. The pump drives cold fluid through a lower plenum with a diagrid for optimum flow distribution into the core. The ACS has a similar function as in the fast reactor: it supports numerous sensors, mainly thermocouples, to survey the correct operating conditions, as well as the control rod drives (which are still assumed to be required to sustain the right degree of subcriticality and desired power distribution over the service period of the core).
Figure 1. Scheme of the model used to discuss the effects of beam trips on a driven subcritical reactor. Separate cooling loops are assumed for the target and the core.

It is assumed that there will be separate cooling loops for the SCA and the target, which is taken as a liquid metal target with a beam injection window. No pool is assumed to exist in the target loop; the target material is assumed to flow through appropriately sized pipes directly to its intermediate heat exchanger and pump (not shown in Figure 1).

We also discuss the case of a pulsed accelerator driving the facility. Arguments for this will be given at the end of the paper.

We will start the discussion by considering some materials issues and questions of flow configuration in the target, using data from SINQ and ESS.

Operating experience and ongoing development at the SINQ spallation neutron source

The accelerator facilities at PSI and their related experimental areas, in particular the spallation neutron source SINQ, have been described in detail elsewhere [1,2,3], and only a brief outline will be given here. The main parameters are listed in Table 1.

SINQ is driven by a cascade of three accelerators, feeding into one another and producing a proton beam of 1.5 mA at 590 MeV. These are a Cockroft-Walton pre-accelerator of 870 keV, an isochronous injector cyclotron of 72 MeV and the final isochronous ring cyclotron of 590 MeV. The beam is transported over a long distance with several splitters and internal targets to supply protons, pions and muons to a variety of experimental facilities before it finally hits the SINQ neutron target. While the 6 cm thick graphite target, called “E” is the most important component as far as beam attenuation is concerned, loss monitors all along the beam line and at various installations are provided to trip the beam in case unforeseen losses occur anywhere along the beam line, in order to prevent excessive activation of the components and the beam tunnel. So, apart from beam trips caused by the accelerators themselves, some causes of which are discussed in Ref. [4], the run permission can also be denied by the secondary installations. Such trips usually require corrective operator action
Table 1. Main parameters of the SINQ spallation neutron source

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Target station</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Eight sector isochronous cyclotron, 590 MeV, 51 MHz</td>
<td>• Vertical beam injection from underneath with collimator below target</td>
</tr>
<tr>
<td>• Injector: 4 sector isochronous cyclotron, 72 MeV</td>
<td>• Mark 1 target: zircaloy rods, D₂O cooled</td>
</tr>
<tr>
<td>• Proton beam current 1.5 mA</td>
<td>• Goal: liquid heavy metal; expected gain &gt;2</td>
</tr>
<tr>
<td>• Beam after pion target (6 cm graphite): 570 MeV</td>
<td>• 2 m diameter heavy water moderator and reflector; beam tubes tangential to target</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam on target</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>• 0.85 mA, 570 MeV currently available for SINQ</td>
<td>• 4 twin beam tubes (3 thermal, 1 cold)</td>
</tr>
<tr>
<td>• Two-dimensional truncated Gaussian distribution σₓ = 3.3 cm, σᵧ = 3.83 cm</td>
<td>• 25 litre liquid deuterium cold moderator</td>
</tr>
<tr>
<td>• Maximum current density 17 µA/cm², if all beam passes through pion target E</td>
<td>• 7 cold neutron guides, supermirror coated</td>
</tr>
</tbody>
</table>

and are of a duration of longer than one minute. The majority of the beam trips occurring at SINQ, however, are of short duration and the accelerator recovers from them automatically. As an example, Figure 2 shows the beam intensity recording over a period of 24 hours on 16-17 October 1997, during which no major interruptions occurred and where the accelerator scored a highly satisfactory availability of 97.7%. The fact that the current level is only 830 microamperes, while the accelerator was running at 1.5 mA is due to the losses associated with the operation of the target “E”, which causes some attenuation and significant scattering such that, after recapturing and scraping for further low loss transport, only about 56% of the original intensity can be rescued.

**Figure 2.** Sample recording of the beam intensity at SINQ over a 24 hour period with excellent overall availability (98%). The recordings are taken at intervals of 1 minute.

![Beam intensity recording](image)

The beam is injected into the SINQ target vertically (from underneath) and the forward and return flows of the coolant are concentric inside a double-walled and separately cooled target container. A schematic drawing of the present target is shown in Figure 3.
Figure 3. Schematic representation of the present SINQ target made up of an array of heavy water cooled rods

The coolant flows downwards in the space between the target case and the container and returns through the rod assembly. The container is a double-walled structure with its own coolant flowing between the two shells. The target is inserted inside the boundary tube in the centre of a large moderator tank.

In its present configuration the target is made up of zircaloy-2 rods, because insufficient data on materials behaviour under the pertinent operating conditions was available to design a more efficient target system based on lead filled tubes or on liquid lead-bismuth. In order to generate such a database a large number of materials test specimens have been mounted in some of the rods of the present target [5], and also prototypic composite target rods have been incorporated. Some of these experimental rods are equipped with thermocouples to monitor the irradiation temperatures and the response to beam trips. Figure 4 shows a temperature recording of some of these thermocouples during two short beam trips. The thermocouples are located at different positions in the target in the centre of rods of different designs. It is obvious that the temperature in all rods drops to a level close to the coolant temperature within less than 20 seconds. Irradiating the materials at realistic conditions with respect to spectral characteristics and thermal history is very important, because the effects on mechanical properties are strongly dependent on these conditions. This can, for example, be seen from Figure 5, which compares the results of in beam and post irradiation fatigue tests on a martensitic steel (MANET) carried out at the PSI proton irradiation facility PIREX [6].

Anticipating positive results of these experiments it is intended to use lead filled steel rods in the next target as an intermediate step to a liquid metal target with lead-bismuth eutectic as target material. Apart from producing a 2.5 times higher neutron flux than the present target, the liquid metal target is also expected to help reducing the radioactivity in the SINQ cooling water plant room [7] and to serve as an important test bed for future high power liquid metal targets. The peak proton current density in SINQ is presently about 17 µA/cm². In a future ADS one would expect it to be roughly five times higher.

Results of the ESS liquid metal target study

Time average temperatures in the target and window

The power deposition in steel is of the order of 2.3 W/g per µA /cm², resulting in a surface heat flux of about 18 W/cm²/µA per mm thickness of a window cooled on one side only. For 100 µA /cm² and 1.5 mm window thickness this means a peak heat flux density of the order of 270 W/cm², which
Figure 4. Temperature recording in the centres of different test rods in the SINQ target during two short beam trips

The rods labelled “experimental” contain a large number of miniaturised test specimens of different types and materials. The rod labelled “lead” is a prototype rod made from a lead filled steel tube as intended for use in the next target.

Figure 5. Fatigue behaviour of MANET steel irradiated in the PIREX facility with 590 MeV protons

is a fairly substantial heat load. Detailed CFD studies carried out for the 5 MW beam power liquid mercury target of the European spallation source project (ESS) [8,9] with 80 µA/cm² can be used to illustrate the situation. The design of this target is shown schematically in Figure 6. It was found that, with about 23% of the target material entering from the bottom channel, adequate window cooling could be secured [10].
Figure 6. The ESS mercury target with three inlet channels at the bottom and both sides of the target. The window is cooled by the flow from the bottom channel. The target material is heated by the beam as it flows out through the main channel.

The resulting temperature distribution is shown in Figure 7 for a peak current density of $80 \mu A/cm^2$ of 1.3 GeV protons. The first four points on the plot are in the window, showing that the temperature gradient across the 1.5 mm thick window is as high as 50 K and that the maximum temperature in the window is about 127 K above the coolant temperature at inlet. This characterises the thermal quench that would have to be anticipated at each beam trip, even very short ones. In the ESS concept the target material is heated up by the beam as it flows away from the window, reaching its maximum temperature of nearly 150 K above inlet at a distance of roughly 40 cm from the window. It is important to note that, if the flow were reversed, the temperature rise in the window would be relative to the maximum coolant temperature and the peak value reached would be about 215 K above the coolant inlet temperature. This would also be the amplitude of the quench at each beam trip lasting long enough (of the order of 1 second) for the unheated coolant to reach the window. Thus, while all beam trips generate the same quenching amplitude in the flow configuration as designed, in a reversed flow configuration one would have to distinguish between very short trips (less than one-tenth of a second), in which the amplitude of the quench would be the same as above (although at a higher temperature level) and longer ones, in which the amplitude of the quench would also include the temperature difference between inlet and maximum in the coolant.

Figure 7. Calculated temperature distribution in the window and the target material along the beam axis of the ESS target at a mercury flow rate of 175 l/s. The first four points are in the 1.5 mm thick window.
**Effect of pulsed heat input**

ESS is designed as a short pulse neutron source, which means that the power is deposited at a level of 100 kJ per pulse within 1 µs. In such short times the volume expansion from the resulting temperature rise cannot be accommodated by the liquid and a pressure wave is generated that travels outwards to the walls and produces cyclic stresses upon impact [11,12]. The amplitude of these stresses is roughly proportional to the height of the rising edge of the power pulse. So, while quite severe effects must be anticipated for pulses of 1 µs duration, the problem is much less serious if the same power is deposited in pulses of 250 µs or more, as can be seen from the results reproduced in Figure 8, which were obtained for targets of elliptic cross-section [11]. In a pulsed ADS driver pulses would most certainly be even longer than 250 µs, probably 1 ms or more. Therefore no pressure wave effects in the target would have to be anticipated.

**Figure 8. Stress in the target container resulting from pulsed heat input at a level of 100 kJ per pulse (60 kJ dissipated in the target) for a pulse duration of 1 and 250 µs**

![Stress in the target container](image)

**Conclusions for an ADS target**

For very short beam trips (0.1 sec or less) essentially only the beam window will undergo a thermal cycle whose amplitude depends on the duration of the trip but can be as much as 100 K. This window will have to be designed for thermal fatigue. Based on the results shown in Figure 5, at least a reduction factor of two in the number of permissible cycles relative to the design codes for the unirradiated material will have to be allowed for. This beam window will have to be designed for regular exchange and the exchange intervals may have to be scheduled according to the frequency of all trips, even very short ones. The remainder of the target loop will certainly feel the effects of those beam trips, which are long enough for the coolant to traverse the heating zone of the beam. Since no pool is likely to be provided, this affects all components of the loop. There will be some damping of the quench rate as the colder fluid picks up heat from the heated components and walls it passes by, but this effect will be minimal. For beam trips longer than one second, one will generally have to allow for a full temperature swing of the whole loop, the amplitude of which equals the average temperature rise the coolant usually experiences on its passage through the target.

Pulsed operation of the accelerator at a repetition rate of one or a few hundred Hertz will generate temperature cycling of the order of a few degrees only in the target window and will not be sensed by the remainder of the loop at all.
Considerations for the driven facility (subcritical core)

Analogy between beam trips in an ADS and scrams in an LMFR

Power transients in a multiplying assembly are governed by the reactor kinetics equation. In terms of the neutron population, \( P(t) \), the point reactor approximation to this equation reads

\[
\frac{dP(t)}{dt} = \frac{\rho(t) - \beta_{\text{eff}}}{\Lambda} P(t) + \sum_j \lambda_j c_j(t) + Q(t)
\]

where \( \beta_{\text{eff}} \), \( \Lambda \), \( (\lambda_j c_j) \), and \( Q \) are the effective delayed-neutron fraction, the mean neutron generation time, the delayed neutron source from the \( j \)th delayed neutron group (given by the product of the decay constant and the effective number of delayed-neutron precursors), and the external neutron source, respectively. The reactivity, \( \rho \), is essentially equal to the relative change in the effective multiplication factor, i.e. \( \rho = (k-1)/k \).

For a critical reactor, for which the external neutron source is zero, a scram means changing the reactivity from zero to \( \rho_c \), the control rod reactivity. A beam trip in an ADS operating at constant subcriticality level \( \rho_s \), on the other hand, means switching the external neutron source suddenly from the steady state value \( Q_s \) to zero. As regards the solution of the equation, it is obvious that the instantaneous scram and the beam trip are equivalent. Assuming a negligible beam switch-off time, the neutronic response to a beam trip can thus be treated with the well known formalism of a reactor scram, with a negative reactivity insertion corresponding to the subcriticality.

Kinetic parameters and reactivities for three typical cases are compared in Table 2. The cases are: a realistic scram (control rod insertion time \( \tau_c = 1 \text{ s} \)) for the European fast reactor (EFR) (Figure 9), [13] a beam trip for a U/Pu fuelled subcritical reactor with the characteristics of the EFR, and a beam trip for a Th/\(^{233}\)U fuelled subcritical reactor with the characteristics of the energy amplifier [14]. They are abbreviated LMFR ADS(U), and ADS(Th), respectively.

<table>
<thead>
<tr>
<th>Case</th>
<th>( \beta_{\text{eff}} ) (%)</th>
<th>( \Lambda ) (( \mu \text{s} ))</th>
<th>( \rho )</th>
<th>( \tau_c ) (sec)</th>
<th>( \rho/\Lambda ) (( \mu \text{s}^{-1} ))</th>
<th>( \beta_{\text{eff}}/\left(\beta_{\text{eff}}-\rho\right) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS (U)</td>
<td>0.36</td>
<td>0.40</td>
<td>-0.03</td>
<td>0</td>
<td>-0.075</td>
<td>0.11</td>
</tr>
<tr>
<td>ADS(Th)</td>
<td>0.33</td>
<td>0.66</td>
<td>-0.03</td>
<td>0</td>
<td>-0.045</td>
<td>0.10</td>
</tr>
<tr>
<td>LMFR</td>
<td>0.36</td>
<td>0.40</td>
<td>-0.08</td>
<td>1</td>
<td>-0.2</td>
<td>0.043</td>
</tr>
</tbody>
</table>

For an instantaneous scram or beam trip, one expects the power to decay rapidly with the “prompt” decay constant \( \rho/\Lambda \) to a level of approximately \( \beta_{\text{eff}}/\left(\beta_{\text{eff}}-\rho\right)P(0) \), dominated by the delayed neutrons with much longer decay time constants. The calculated power transients shown in Figure 9 confirm this behaviour (since the ADS parameters and hence responses are nearly identical, the ADS(U) curve only is retained in the figure). As indicated before, a negligible beam switch-off time \( \tau_c \) is assumed in the calculation. This is, however, justified because the beam vanishes within a microsecond or less, i.e. a time span which is short compared with \( \Lambda/\rho \). The LMFR curve in Figure 10 shows that, for a realistic scram, the initial response is correlated with the relatively long control rod insertion time, and that the power drops to a lower level than in the ADS case. Taking into account the heat transfer from the fuel to the coolant, however, the effect of the scram and the beam trip on the core outlet temperature will be very similar.
Figure 9. Schematic representation of the EFR primary cooling circuit

Figure 10. Neutronic response of the system with uranium fuel to the shutdown cases postulated in Table 2

Figure 11 shows the temperature transients in case of a scram for the 1.4 GWe European fast reactor (EFR) (Figure 9) at the points of core exit and at the inlet to the intermediate heat exchanger (IHX). It can be seen that, while the initial temperature drop at core exit, and hence in the above core structure (ACS) occurs within some 20 seconds, there is some buffer effect of the hot pool for the IHX, for which the initial temperature drop happens with some delay and takes about 150 seconds to complete. As marked in Figure 11, it is assumed that the pumps are tripped at the instant of the scram and are coasting down to 25% of their normal working speed. Without reduced pumping power the temperature drop would be even more severe.
Figure 11. Temperature evolution in the primary cooling circuit of the EFP (Figure 9) in case of a scram

Conclusions for beam trips in an ADS

On the basis of the above comparison the effect of a beam trip in an ADS can be judged as follows: Trips of more than 20 seconds duration will inflict a full (more than 100 K) temperature quench on the ACS. For shorter trips the amplitude of the quench becomes progressively smaller. Similarly, the IHX will suffer a full temperature quench for beam trips longer than about 100 seconds. The cool-down after the initial quench occurs at a rate which is probably slow with respect to the thermal inertia of the components and is, therefore, comparatively harmless. It should be emphasised that it is because of the suspected effects of a quench on the ACS and IHX that the number of tolerable scrams per year has been set to less than three (!) in most LMFRs (one for the EFR). Even under the assumption that the reliability of accelerators driving future ADS would improve by two orders of magnitude over what is currently achieved in high current research accelerators in terms of trips longer than 1 minute, of the order of 100 trips per year would still have to be anticipated. In view of the time response of the driven system it would seem extremely important that automatic recovery from short trips due to sparking in RF cavities (which presently takes about 20 seconds at the PSI cyclotron, cf. Figure 4) be sped up as much as possible, e.g. to the order of 0.1 sec, as appears to be feasible [4]. In this case the short trips should not affect the driven core or the target system in a serious way.

Effect of pulsed accelerator operation

It is clear from the foregoing discussion that pulsed operation of the accelerator with pulse repetition rates of the order of 100 Hz or more would not affect the temperature in the cooling circuit of the core at all. This is not automatically true for the fuel itself, in which the power would be released in correspondingly short pulses. According to Table 2 and Figure 9, the amplitude of power cycling would be exp(-0.075*10 000), for a shutdown of 10 ms duration, which is a complete drop to the delayed neutron power level. On the other hand, a noticeable change in fuel temperature by heat conduction takes of the order of a few seconds and the temperature of the cladding will be kept stable by the surrounding coolant. It can, therefore, be concluded that use of a pulsed accelerator would have no appreciable effect on the temperatures in the fuel. In this context it may be noted that the plutonium oxide-fuelled and sodium-cooled pulsed reactor IBR2 in Dubna, Russia, has been operating
safely for significantly over 10 years on the same fuel at an average power level of 2 MW and with pulses of about 2 GW at 5 Hz repetition rate. This is a much more severe thermal load than would ever have to be anticipated on the fuel of an ADS by pulsed accelerator operation.

**Options to accommodate beam trips in an ADS**

Although one can certainly anticipate significant improvements in the reliability of high power accelerators built for industrial applications over what is presently routine in research facilities, it does not seem justified, at present, to assume that these complex systems would reliably operate with significantly less than 100 unscheduled trips per year. Even in fault tolerant low stress designs based on the principles outlined in Ref. [15], a failure rate as low as less than three per year seems highly unlikely. While reviewing the design of the subcritical core and its ancillary systems with respect to their resistance to thermal shocks may bring about some improvement on the reactor side, it is difficult to imagine that the tolerable number of unscheduled shutdowns could be reconciled with the performance of any single accelerator. As a possible way out it is sometimes proposed to use more than one accelerator to drive an ADS. With two accelerators the probability of simultaneous tripping of both would already be significantly reduced, if the facility would be shut down in a controlled way in case one of them develops a more serious problem. With only one of the two tripping, the power drop would be to a level of 55% rather than 11% (cf. Table 2) as in the case of a single driver. Since, according to the ASME design code, the number of cycles stainless steel can endure increases by an order of magnitude or more if the stress amplitude is halved (Figure 12), this will be a significant improvement, although the rate of partial trips would, of course, double. Nevertheless, a very careful analysis would be required to judge the actual benefits of this solution for the structure concerned and also in terms of economy and availability. Of course, postulating a larger number of accelerators to drive a single subcritical system becomes increasingly unrealistic.

**Figure 12. Allowable stress in stainless steel 316LN as a function of load cycles (ASME)**

The situation might, however look very different if one takes into account that, in an equilibrium situation, several ADS might be required to handle the waste generated by a country’s suite of nuclear power units. In this case, combining them in a transmutation park would seem an almost natural thing to do for a variety of reasons. Such a concentration would not only allow to make optimum use of the required support facilities but would also open up the opportunity to multiplex beams from all accelerators into all driven facilities. Such a scheme, using three accelerators and four ADS, is shown schematically in Figure 13.
Merging beams into a common injection line can be achieved by a “funnelling” system or by fast pulse kickers. In view of the difficulties in designing a funnelling system already at low energies, and of switching individual bunches into different beam lines, it is assumed that the second method will be employed, which requires pulsed operation of the accelerator. The pulses from each accelerator would be split equally among all driven facilities in a switchyard. Assuming that \( n \) accelerators would supply beams to \( m \) ADS, the beam power per ADS would be:

\[
P_{b,ADS} = \frac{n}{m} \times P_{b,ACC}
\]

If the pulse repetition rate of each accelerator is one or a few hundred per second, a trip in any one accelerator would affect all ADS, but at a level of only \( 1/n \) relative to the effect a trip would have if only a single accelerator were used. In this way the amplitudes of the thermal cycles could be reduced to a level below the endurance limit of the structures. It may be noted that such a combination would also have other advantages. They include:

- There is no need to match the power of the accelerator to the level of subcriticality of the ADS, since \( n \) and \( m \) need not be equal. With a suitable match between the power and availability of the accelerators and their number, even extended downtimes of one accelerator for maintenance need not impede operation of the facility.

- There may be good reasons for having subcritical assembly units of moderate power only, all of which cannot be discussed in full in the frame of this paper, but one of them might well be the difficulty of managing the power distribution in a large driven core.
• It may be assumed that the requirements in terms of downtime for maintenance are different for the ADS and the accelerators. This can be taken care of by a suitable choice for the numbers of the two types of units. In this way optimum use of both the accelerators and the ADS can be achieved.

• The ADS may be in different states of “burn-up”, i.e. require different beam power to achieve nominal operating characteristics. Rather than running one accelerator below its capabilities, this can be taken care of by a suitable pulse management.

• Etc.

The fact that, in order to accomplish such beam management, the accelerators must operate in a pulsed mode would not have an adverse effect on the service time of the ADS as discussed above. The switching would be accomplished by beam kickers which are activated between the pulses and would therefore be loss free. No very stringent requirements must be imposed on the pulse duration except that the gaps should be long enough to switch the kickers safely, for which 1 ms should be plenty. Apart from this the duty cycle of the accelerators can be optimised following arguments of economy and reliability. Since it is possible to control the pulse length on a pulse-to-pulse basis (more easily than the current level), supplying different beam power to the various ADS should not be difficult.

Conclusions

Although more thorough analyses based on a conceptual design of an ADS are indispensable in order to draw final conclusions, it seems that, apart from designing for low stress levels and maximum fault tolerance in the driving accelerator, two ways can be followed to mitigate the effect of beam trips on an ADS:

1) Make sure that the accelerator can recover from short beam trips in a matter of a few tenths of a second. In this case those trips will not affect the target or the driven core in a serious way due to the thermal inertia of the components involved.

2) Use a distributed system of accelerators and subcritical assemblies with beam multiplexing between them. In this case the temperature drops in all driven systems caused by a trip in any one of the accelerators, even if their number would not be very large, should cause stress amplitudes in the driven facilities which stay below the endurance limit and thus allow a much larger number of trips to be tolerable than the number of full power scrams that are allowed in LMFR designs.

There are several other arguments in favour of such beam multiplexing and the technique should certainly be developed. In this context it is worth mentioning that, in the next generation of accelerators for research neutron sources the same techniques will be required to combine beams from more than one compressor ring and to distribute them between different target stations, as proposed, for example, for the European spallation source [9], but also for similar projects in the US and in Japan. In this sense, although subcritical “booster” targets have briefly been considered for pulsed neutron sources [16, 17] but are not presently proposed for any of the new facilities, the synergy between next generation research neutron sources and ADS actually goes beyond the common problems in accelerator reliability and liquid metal spallation target design.
REFERENCES


SESSION VI

Interface Technology

Chairs: V. Bellucci and T. Shibata
THERMAL RESPONSE OF THE IFMIF LITHIUM LOOP AT BEAM TRIP

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Japan Atomic Energy Research Institute (JAERI)

Abstract

The thermal response of liquid lithium (Li) at beam trip has been studied by modifying a computer code. This is a part of the design activity of the International Fusion Materials Irradiation Facility (IFMIF), which will provide high flux, high energy neutron irradiation fields for testing and development of fusion materials by deuteron-Li reaction in the target. By the accelerator system, two deuteron beams are focused onto a liquid Li target. An existing computer code for reactor transient response has been modified to deal with Li, and the transient analysis has been performed for thermal response of IFMIF primary Li loop in cases of one and two beams trips.
Introduction

Outline of IFMIF

Intense neutron flux at the energy 14 MeV in a D-T fusion reactor will damage and activate reactor materials because of the displacement of atoms and the nuclear reactions including the generation of gaseous elements. A neutron source to provide an intense neutron irradiation field simulating the fusion reactor condition has been required for the development of the low-activation and damage-resistant fusion reactor materials.

The design activity of the International Fusion Materials Irradiation Facility (IFMIF) [1] to provide such a neutron irradiation field started in February 1995 under the auspices of the International Energy Agency (IEA). Figure 1 shows the schematic layout of the IFMIF. Deuterons (D⁺) are accelerated by two accelerators. Two D⁺ beams at 30-40 MeV with a total current of 250 mA are focused onto a high-velocity liquid lithium (Li) target that flows in vacuum. Neutrons are generated by D-Li stripping reaction within the Li target flow. Candidate materials will be placed in the test cell behind a concave back-wall and irradiated in the intense neutron field.

IFMIF target flow and Li loop

A schematic of the IFMIF target assembly is shown in Figure 2. The two D⁺ beams will be focused onto a rectangular region (50 mm high × 200 mm wide) of Li target. Most of the kinetic energy of the D⁺ beam power (> 95%) is deposited and turned into heat within the Li target flow.

The liquid Li target system should remove the generated heat (max. 10 MW) to keep the stability and the integrity of the target flow itself. The Li target flows in high vacuum of 10⁻³ Pa. The temperature increase in the Li target should thus be well suppressed to avoid both the voiding in the target and the significant vaporisation at the free surface. To meet these conditions, the liquid Li flows at high speed (10-20 m/s) along a concave back wall. Depthwise static pressure distribution due to the centrifugal force results in a significant increase in the saturation temperature along with the depth.

A schematic of IFMIF target heat removal system is shown in Figure 3. As shown in this figure, the system has two targets. This system consists of primary Li, secondary organic oil and tertiary water loops to avoid direct reaction of Li and water. Only one target will be irradiated by two D⁺ beams at the same time. In the other target, decay heat will be removed by Li flow with a lower flow rate (10% of that in the irradiated target).

Beam trip

To perform a total facility availability of 70% over a calendar year (8 760 h), the availability in scheduled operation (7 600 h) has been allocated to the main IFMIF subsystems as shown in Table 1.

The D⁺ beam(s) trip is one of unscheduled downtime of the accelerator facilities. On the primary loop of Li, steep temperature change may cause thermal shock on the Li components and flow instability. Some long time of beam(s) trip will affect the thermal control of the loops. Therefore, the thermal transient analysis has been performed to clarify the thermal response of the Li loop after beam(s) trip.
Table 1

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test facilities</td>
<td>97.5%</td>
</tr>
<tr>
<td>Target facilities</td>
<td>95.0%</td>
</tr>
<tr>
<td>Accelerator facilities</td>
<td>88.0%</td>
</tr>
<tr>
<td>Conventional facilities</td>
<td>99.5%</td>
</tr>
<tr>
<td>Central control system and common instrumentation</td>
<td>99.5%</td>
</tr>
<tr>
<td><strong>Total (product)</strong></td>
<td><strong>80.7%</strong></td>
</tr>
</tbody>
</table>

Modification of the computer code

An existing computer code for water systems has been modified to deal with the Li system.

**RETRAN**

One of the computer codes RETRANs [2] was chosen for the analysis of thermal response of the IFMIF Li loop. RETRANs have been developed, with the support of the Electric Power Research Institute (EPRI), for transient thermal-hydraulic analysis of complex fluid flow in light water reactor (LWR) plants. RETRAN-02 can deal with two phase, supercritical, super heated states, heat exchangers and pumps. Furthermore, RETRAN-02 was modified into RETRAN-02/RR in JAERI mainly to be more accurate under low pressure conditions [3].

**Data of Li properties**

RETRANs can deal with only water as fluid (liquid and gas). IFMIF target heat removal system consists of three fluids: Li, organic oil and water. Therefore, the physical properties of Li and organic oil should be added. At first, the following data of Li properties [4] were collected and applied to RETRAN-02/RR for analysis of thermal response of the primary Li loop:

- \( T - P - \rho_{[\text{liquid}]} - C_p_{[\text{liquid}]} - H_{[\text{liquid, gas}]} \) at saturation condition
- \( \rho_{[\text{gas}]} , C_p_{[\text{gas}]} , H_{[\text{gas}]} \) at some points of \((T, P)\)
- \( P_c , T_c , \lambda , \mu \)

where \( T \) is temperature, \( P \) is pressure, \( \rho \) is density, \( C_p \) is specific heat, \( H \) is specific enthalpy, suffix \( c \) is critical state, suffix \( s \) is saturation, \( \lambda \) is heat conductivity and \( \mu \) is viscosity.

**Modification of algorithm and approximation**

In RETRAN-02/RR for water, \( H_s \) (H of saturated liquid and gas) are approximated as polynomials in \( \log(P) \) or \( (P_c - P)^{0.4} \). On the other hand, in the RETRAN for Li, \( H_s \) was modified to be approximated as polynomials in \( T_s \) (T at saturation).
In RETRAN-02/RR, $Ps$ (saturation pressure) is approximated as $Ps = Pc \cdot e^{ARG}$, where ARG is a rational expression in $T$. On the other hand, in the RETRAN for Li, $Ts$ is approximated with the following relationship:

$$Ts = \left\{ C_2 / \left[ C_1 - \log(P) \right] \right\} - C_3 \quad (1)$$

in which $C_1$, $C_2$ and $C_3$ are the constants, and $C_1 = 22.71826779$, $C_2 = 1.794715352 \times 10^4$ and $C_3 = 2.617603890 \times 10^2$. ($Ts$ and $P$ are in units of °C and Pa, respectively.)

Water is such a usual substance in reactor fields that there are liquid and gas data of $\rho$ and $T$ at some points of $(P,H)$. For example, a value of temperature, $Tk$, is given at every combination of $(Pi,Hj)$, where $i$, $j$ and $k$ are ordinal numbers of $P$, $H$ and $T$ respectively. In RETRAN-02/RR, $T$ of liquid and gas are approximated as polynomials in $P$ and $H$. Coefficients of the polynomials, $C$, are given with solving an inverse matrix problem of that expressed with some $Ti$ and some $Pj$:

$$T = M \cdot C \quad (2)$$

where elements of matrix $A$ are expressed as $Pi^{im} \cdot Hj^{ip}$, elements of matrix $T$ depend on $i$ and $j$. On the other hand, for liquid Li, data $T$, $P$ and $H$ are given only at saturation. Elements of matrix $A$ are expressed with chosen $Pi$ and $Hi$ (not $Hj$), elements of matrix $T$ depend on $i$ only. In the RETRAN modified for Li, $T$ in liquid is approximated as a polynomial in $H$ and $\log(P)$, $T$ in gas is approximated as a polynomial in $H$ and $P$. Specific volume ($1/\rho$) of liquid Li was modified to be approximated as a rational expression of $H$ and $\log(P)$. Specific volume of gas Li was modified to be an ideal gas as $P/\rho = RLI \cdot T$, where $RLI$ is a constant given with gas constant and average molecular weight of 6.941 g/mol. Specific heat is given by $Cp = 1/(\partial T/\partial H)P$.

In the RETRAN modified for Li, kinematic viscosity is approximated as $\nu = e^{POL}$, where $POL$ is a polynomial in $T$. Heat conductivity ($\lambda$) is approximated as polynomial in $T$.

**Calculation for Li loop**

With the RETRAN modified for Li, one-dimensional transient thermal analysis has been performed for thermal response of the primary loop of IFMIF target after one and two beams trips.

**Input condition**

The calculation model is shown in Figure 4. The flowing Li of 250°C, 73.5 kg/s is heated by two $D^+$ beams of a total power of 10 MW. The trips of one and two beam(s) at $t = 10$ s were supposed. No change in the temperature of second loop (220°C) was also supposed. The heat transfer coefficient ($h$) was automatically given to cool Li into 250°C under the normal condition mentioned above. The length, diameter, volume and height from floor were inputted for every element (pipe, tank and heat exchanger).
Results and discussion

Figure 5 shows Li temperatures in case of two beam trip. During normal operation (beam power is 10 MW, \( t < 10 \) s), Li temperatures were constant 542°F (283°C) after beam irradiation and before Li cooler, and also 482°F (250°C) after Li cooler and before beam irradiation. Even with the large amount of Li (1.18 m³) in the quench tank, Li temperatures rapidly changed after two beams trip (beam power is 0 MW, \( t > 10 \) s). Li temperatures became uniform near the temperature of the secondary loop 220°C within a few minutes. More discussion would be required about the effect of rapid change of Li properties upon the flow condition. For example, the kinematic viscosity of Li would change from 1.11 m²/s (\( T = 542\)°F) to 1.01 m²/s (\( T = 482\)°F) within a few minutes. Also, more discussion may be required about control method of Li temperature or shut down process of the Li cooling system.

Figure 6 shows Li temperatures in case of one beam trip. The hotter and colder Li temperatures would become about 485°F (252°C) and 455°F (235°C) respectively also within a few minutes after the beam trip.

Summary

At this stage, the code modification and the transient analysis for thermal response of the IFMIF Li cooling system are summarised as follows. A reactor transient code RETRAN-02/RR was modified to apply to the Li loop with changing liquid properties and their approximation expression and algorithm. After this modification, thermal responses of the IFMIF Li loop were roughly studied in the cases of one and two beam(s) trips.

RETRAN-02/RR should be modified to deal with Li, organic oil and water at the same time. To improve the database of these fluids in broader regions is recommended for more accurate approximation. After this modification, the analysis would be performed for the IFMIF Li cooling system totally including primary, secondary and tertiary loops. Through such an analysis, the control method of Li temperature or shut down process of Li cooling system would be clarified.

REFERENCES

Figure 1. Schematic layout of IFMIF

Figure 2. Schematic of IFMIF target assembly
Figure 3. Heat removal system

Figure 4. Calculation model
Figure 5. Temperature transition (two beam trips)

Figure 6. Temperature transition (one beam trip)
An oscillating thermal stress of the target due to the pulsed heat generation and the effect of a beam trip caused by the loss of coolant water are described for the micropulsed mercury target at the performance of 1.5 GeV, 50 Hz and 5 MW. Thermal stresses in the axisymmetric window model will become a steady state in a couple of seconds. The window expanded with oscillating at 50 Hz, however, amplitude was very small. The maximum stress was 90 MPa for 47 µA/cm² beam density. Decay constants were 10 s for loss of cooling water (LOC) and 5 s for the normal beam stop (SCRAM).
Introduction

JAERI has been developing a short-pulsed mercury target at the performance of 1.5 GeV, 50 Hz and 5 MW. In the target the particles produced in the course of spallation reaction generate an intense nuclear heat. The short-pulsed protons, at a frequency of 50 Hz (the duration of one pulse is 1 μs and the period between pulses is 20 ms), will load pressure waves to the target and stress waves to the target container. They transmit at the speed of sound and have a very high frequency component in the waves. They will decay out soon due to absorption of kinetic energy.

On the other hand there is another stress acting on the target container as a substantial force. It is a thermal stress that is caused by a cyclic heat generation in the target material. The heat generation will often be interrupted by a beam trip.

In the following an oscillating thermal stress of the target due to pulsed heat generation is studied, and then the effect of a beam trip caused by the loss of coolant water will be discussed.

Model parameters

Figure 1 shows the mercury target. Neutronics calculation were done by using NMTC-JAERI under the conditions listed in the table below [1].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam power</td>
<td>5 MW</td>
</tr>
<tr>
<td>Power frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>1.5 GeV (3.3 mA)</td>
</tr>
<tr>
<td>Beam pulse duration</td>
<td>1 μs</td>
</tr>
<tr>
<td>Beam profile: Rectangular</td>
<td>4.68 cmφ</td>
</tr>
<tr>
<td>Beam density</td>
<td>48 μA/cm²</td>
</tr>
<tr>
<td>Target size</td>
<td>12.85 cmφ × 2 000 cmL</td>
</tr>
</tbody>
</table>

Figure 1. Proton beam profile and target geometry

Figure 2 shows the distribution of energy deposition in the mercury target. The deposited energy in the target window per pulse is calculated to be 21.3 J/cm³ and distributed homogeneously in the solid material.
Figure 2. Energy deposition in the mercury target to the axial direction [1]

Mercury and the water as illustrated in Figure 3 cool the target plate. A generated heat will diffuse in the plate and disperse to the coolants through heat convection. Heat transfer coefficients were determined by the Dittus-Boelter equation for water cooling [2]:

$$Nu = 0.023Re^{0.8}Pr^{0.4}$$  \hspace{1cm} (1)

and the Subbotin equation for liquid metal cooling [2]:

$$Nu = 5 + 0.025Pe^{0.8}$$  \hspace{1cm} (2)

where $Nu = \frac{\alpha L}{\lambda}$, $Re = \frac{UL}{\nu}$, $Pr = \frac{C_p \eta}{\lambda}$, $Pe = \frac{U \cdot d}{a}$, $\alpha$ is heat transfer coefficient (W/m$^2$K), $\lambda$ is heat conduction coefficient (W/mK), $\nu$ is kinematic viscosity (m/s), $\eta$ is viscosity (Pa s), $a$ is heat diffusion coefficient (m$^2$/s), $C_p$ is specific heat at constant pressure (J/kg K), $L$ is typical length (m), and $U$ is velocity (m/s).

Figure 3. Heat transfer through the plate
Table 1 shows the material properties of the water and mercury at room temperature, respectively. Heat transfer coefficients are determined to be 10 kW/m²K at a velocity of the water flow of 2 m/s and 5 kW/m²K at a velocity of the mercury flow of 0.5 m/s tentatively [3]. Temperatures of the water as well as mercury are set to 0°C. The plate thickness is 1.5 mm.

Table 1 Material properties of coolant target materials

<table>
<thead>
<tr>
<th>Items</th>
<th>H₂O</th>
<th>Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>997</td>
<td>1.329 × 10⁴</td>
</tr>
<tr>
<td>Heat transfer coefficient (W/mK)</td>
<td>0.61</td>
<td>11.0</td>
</tr>
<tr>
<td>Specific heat at constant pressure (J/kg K)</td>
<td>4.18</td>
<td>0.137</td>
</tr>
<tr>
<td>Viscosity (Pa s)</td>
<td>854</td>
<td>1.17 × 10⁻³</td>
</tr>
<tr>
<td>Kinematics viscosity (m/s)</td>
<td>8.57 × 10⁻⁷</td>
<td>–</td>
</tr>
<tr>
<td>Heat diffusion coefficient (m²/s)</td>
<td>1.47 × 10⁻⁷</td>
<td>6.04 × 10⁻⁶</td>
</tr>
</tbody>
</table>

A calculation model is a part of the target window structure modelled as an axisymmetric hemispherical shape as shown in Figure 4 where z is a symmetric axis in the cylindrical co-ordinates \((r, \theta, z)\). In the course of the spallation reaction in the plate a heat will be generated, and the temperature rise \(\Delta T\) during 1 µs is estimated to 5.3°C by the next relationship:

\[
\Delta T = \frac{DQ}{C_p \rho}
\]  

(3)

where \(\Delta Q = 21.3 \text{ J/cm}^³\), \(\rho = 7.89 \text{ g/cm}^³\) and \(C_p = 0.511 \text{ J/gK}\). In the following calculations the ABAQUS 5.7 standard [4] was used.

Figure 4. Calculation model for thermal stress

Single pulse

Figure 5 shows a time structure of micropulses used in the calculation. Figure 6 shows the temperature at the centre of the model \(r = 0\) at \(N = 1\), one pulse. The temperature drop at a time of 20 ms, when a next pulsed beam deposits heat in the plate is reduced by 15% at the water side. The maximum temperature is located in the plate. The temperature rise will diminish to zero within 5 s.
Figure 5. A time structure of micropulses

Figure 6. Temperatures at a centre $r = 0$

Multipulses

Figure 7 shows temperature rises by accumulated pulses. The temperature rise saturates at a time of a couple of seconds although an oscillation due to a pulsed injection of protons was observed. In the steady state after a couple of seconds a dispersing heat balanced with heat generation. In the described model a beam was stopped at 5 s and continuously cooled. The temperature diminishes within another five seconds. Figure 8 shows the displacement of the target window at $r = 0$ to $z$ direction. The apex of the window oscillates at a frequency of 50 Hz and expands 0.13 mm to the waterside. Figure 9 shows the stress to the $\theta$ direction. The maximum stress occurs at the waterside and is estimated to be 90 MPa. As is shown in Figure 10, the radial stress $\sigma_r$ distributes in the same manner with $\sigma_\theta$.

Beam trip

The next plots will show the result of case study for the loss of the cooling water (LOC). At a time of 5 s it is assumed that the water cooling does not work effectively. Simultaneously the beam is tripped. Figure 11 shows the temperature and time relation. Heat diffuses to the waterside from the location of midplate at the maximum temperature and the waterside temperature will increase by 20°C. As long as mercury flows heat will decay out within 10 s.
Figure 7. Temperature rises by accumulated pulses and the temperature recovery due to the normal beam stop

Figure 8. Expansion of the window to z direction

Figure 9. Stress-time at the window
Figure 10. Stress distributions in the window section at a time of 5 s

Figure 11. Transient temperatures at the beam stops

Figure 12 shows the transient thermal stress induced during LOC in comparison with the case of normal beam stop. According to the redistribution of stresses in the cross-section at the window, the stress at the waterside decreases straightway and the stress at the mercury side arises gradually.

Summary

Through analyses of the thermal stress a thermo-mechanical behaviour of the target window was made clear.

Thermal stresses in the axisymmetric model of the target widow will become a steady state in a couple of seconds but oscillate at 50 Hz. The window will also expand while oscillating at the same frequency. However, the amplitude is very small. The maximum stress was 90 MPa for 48 $\mu$A/cm$^2$ beam density.
Decay constants were 10 s for loss of cooling water (LOC) and 5 s for the normal beam stop. For the case of LOC, heat in the window is possibly removed by the mercury flow within 10 s. Redistribution of the temperature and the stresses in the window occurs and the stress will be balanced in the structure.

REFERENCES


FATIGUE BEHAVIOUR OF WINDOW AND RODS

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Abstract

The current CEA project pertains to feasibility studies of an internal source of neutrons used for irradiations of various natures.

An external source generates the necessary protons thanks to a particle accelerator that delivers a high energy proton beam: 600 MeV, 40 mA.

The target is composed of rod assemblies and the spallation material is lead contained in aluminium cladding cooled by low pressured tepid water.

The interface between the accelerator and the target named “window” must both ensure tightness between the accelerator and the target and maintain a differential pressure while being as thin as possible to avoid a too great dissipation of the incident beam. In this respect, the interface is made of Inconel of low thickness in order to be as transparent as possible of the proton beam whose average power density is about of 10 µA.cm⁻², and is cooled by forced convection water of the target.

An analysis of nominal and incidental situations of the facility operating mode has been conducted, especially in order to evaluate the consequences of abrupt and frequent shutdown or tripping of the accelerator on the thermomechanical behaviour of the spallation rods and the window, as well as in terms of thermal fatigue.
Introduction

The current CEA project pertains to feasibility studies of an internal source of neutrons used for irradiations of various natures.

An external source generates the necessary protons thanks to a particle accelerator that delivers a high energy proton beam: 600 MeV, 40 mA.

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Two windows are used to separate the accelerator from the target. The first one near the target isolates the core and the second isolates the accelerator. The window near the core is called the hot window and the second is the cold window. Between the two windows, the zone does not need a high quality vacuum. In case of leak before break the pressure inside this region increases and it is possible to slowly stop the device. The hot window is cooled on the outer face by the coolant of the target while the cold window is cooled by inner channels. The mechanical stresses on the hot window are higher than those of the cold window. Thus, the hot window is more difficult to design. Materials used are Inconel 718 for the hot window and aluminium alloy for the other. The maximum Inconel temperature is 522 K.

In the target, lead rods with aluminium alloy cladding are used and cooled by water.

An analysis of nominal and incidental situations of the facility operating mode has been conducted, especially in order to evaluate the consequences of abrupt and frequent shutdown or tripping of the accelerator on the thermomechanical behaviour of the window and spallation rods, as well as in terms of thermal fatigue.

Thermomechanical studies of spallation rods

Problem status

The spallation rod consists of a lead matrix cladded with an aluminium alloy. The lead viscoplasticity being highly activated with temperature (\( \theta = 0.65 \theta_{\text{melt}} \) in nominal conditions), the initial matrix-cladding gap is assumed to be closed under normal operating conditions. Nevertheless, during the operating cycle, the lead matrix will swell due to spallation gas accumulation and will consequently load mechanically the cladding. In transient conditions, due to proton beam trippings, the cladding may be fatigue damaged by stress variations. The considered trip frequency has to be sufficiently low so that, despite the thermal inertia of the materials, the temperature variations may be significant in the rods.

Thermomechanical studies have been performed to verify, either in nominal or in transient conditions, if the cladding solicitation respects the conception criteria.
Material properties

Lead characteristics

At temperature conditions of the target, damage effects due to neutron or proton irradiation are not have a significant effect on the lead mechanical properties. Thus the considered characteristics are those of the non-irradiated material. Furthermore, transmutation product effect is taken into account by means of a swelling mechanism of the lead matrix with spallation gases.

The lead viscoplastic behaviour follows the law proposed by Hofman [1]. An activation energy term is added to introduce the material creep dependence with temperature. The lead creep phenomenon being supposed to be based upon a self-diffusion mechanism, the lead self-diffusion energy is considered in the creep law (1).

\[
\dot{\varepsilon} \left( s^{-1} \right) = 1.347 \times 10^7 \exp \left( -\frac{12,000}{T(K)} \right) \sh \left[ 2.48 \sigma \text{ (MPa)} \right]
\]  

(1)

A significant quantity of gases is produced by spallation reactions. An estimation of the lead matrix swelling is done based upon the following assumptions:

- all produced gases precipitate in bubbles;
- bubbles are in equilibrium with the lead surface tension;
- the perfect gas law is applicable;
- the swelling corresponds to the bubbles volume.

Considering large bubbles \((r = 0.1 \mu\text{m})\), the swelling law is given by (2):

\[
\frac{\Delta V}{V} = 3 \times 10^{-8} \ q(\text{ppm}) \ T(K)
\]

(2)

with \(q\): gas quantity.

Aluminium alloy characteristics

Aluminium alloys are usually used in pool reactors as structure or cladding materials. The temperature conditions of the spallation target being close to those of pool reactors, a compilation of data relative to characterisations of in-pool reactor irradiated aluminium alloys has been carried out. As their in-service evolutions have proved to be satisfactory up to high doses (except for some alloys, with more than 3% magnesium, which have been subjected to corrosion), aluminium alloys of series 5xxx and 6xxx have been selected as candidates for the cladding and the structure of the target. More specifically, the 6061-O alloy, which would present significant residual ductility for the dose corresponding to one operating cycle of the target, seems to be well adapted to the specific displacement controlled loading condition of the spallation rod cladding.
Irradiation produces hardening and loss of ductility for aluminium alloys. Plastic characteristics of 6061-O alloy, at non-irradiated state and for a fluence equivalent to an operating cycle, are given in Table 1.

### Table 1. Plastic characteristics of 6061-O aluminium alloy

<table>
<thead>
<tr>
<th></th>
<th>Rp₀₂ (MPa)</th>
<th>Rₘ (MPa)</th>
<th>At (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-irradiated</td>
<td>55</td>
<td>124</td>
<td>30</td>
</tr>
<tr>
<td>One operating cycle</td>
<td>191</td>
<td>225</td>
<td>15.7</td>
</tr>
</tbody>
</table>

In normal operating conditions (low temperature, small stress), creep is activated by the neutron flux. Nevertheless few data are available for irradiation creep. However, for pure aluminium, Table 2 gives the in-pile versus thermal creep rate ratios for stress values ranging from σ/2 to σₚ.

### Table 2. \(\dot{\varepsilon}_{irr}/\dot{\varepsilon}_{th}\) ratios for neutrons flux \(\Phi_r = 1.4 \times 10^{16} \text{ n m}^{-2} \text{ s}^{-1}\)

<table>
<thead>
<tr>
<th></th>
<th>353 K</th>
<th>393 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>σ/2</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>3/4 σₚ</td>
<td>29</td>
<td>10</td>
</tr>
<tr>
<td>σₚ</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

From these values and the thermal creep data of 5454-O alloy (characteristics close to 6061-O alloy ones), an evaluation of the irradiation creep law is obtained in applying the same \(\dot{\varepsilon}_{irr}/\dot{\varepsilon}_{th}\) ratios:

\[
\theta = 366 \text{ K} \Rightarrow \dot{\varepsilon}(\text{s}^{-1}) = 1.3 \times 10^{-44} \left[\sigma(\text{MPa})\right]^{17}; \quad \theta = 394 \text{ K} \Rightarrow \dot{\varepsilon}(\text{s}^{-1}) = 3.2 \times 10^{-37} \left[\sigma(\text{MPa})\right]^{13.8}
\]

**Thermomechanical study in nominal conditions**

In nominal conditions, the spallation rod cladding is loaded by the mechanical interaction due to the lead matrix swelling. The thermomechanical study has been conducted for the warmest rod. The temperatures in this rod and the corresponding swelling rate distributions in the lead matrix are plotted in Figures 1 and 2. The hot zone corresponds to the rod part directly subjected to the proton beam, where 97% of the total rod power is settled.

Due to friction effects between the lead matrix and the cladding, no relative axial displacement is possible between lead and cladding, the shear resultant at the interface being large enough to equilibrate the cladding axial traction. So a generalised plane strain condition is used to determine the stress state in the rod mid-plane, which results of the equilibrium between the lead matrix swelling rate and the cladding irradiation creep rate: the stabilised circumferential stress in the cladding is \(\sigma_{θθ} = 90 \text{ MPa}\).

RCC_MR rules are then used to evaluate the cladding creep damage. In a first step, the time to rupture for the calculated stress value majored by a coefficient 1.1, is determined using the stress versus time to rupture data available for 5454-O alloy (Figure 3).
Figure 1. Isotemperatures in nominal conditions
(radial frame amplification: $\approx 100$)

Figure 2. Swelling rate in the lead matrix
(radial frame amplification: $\approx 100$)

Figure 3. Stress versus time to rupture for 5454-O aluminium alloy
In a second step, the fatigue usage factor that corresponds to the ratio between the hold period (here the cycle period) and the time to rupture, is determined. The obtained fatigue usage factor, \( w = t/\tau, (\sigma/0.9) = 0.16 \), respects the RCC_MR criterion (\( w < 1 \)).

**Thermomechanical study in case of proton beam trippings**

The analysis of some operating conditions of experimental accelerators shows that different proton beam trips may occur:

- shutdown with almost immediate recovery (high frequency tripping);
- shutdown followed by a break period before recovery (typical break period \( \approx 20 \text{ min.} \)).

To analyse the mechanical damage produced by such proton beam trips, an evaluation of the thermal inertia of the rods has been firstly done.

A transient thermal resolution has been performed to model the temperature drop after a beam shutdown. The central temperature decrease versus time is plotted in Figure 4: it shows that the temperature variation after 0.1 s is not significant and that the total temperature drop lasts almost 1 s. Thus beam trips with a frequency higher than 10 Hz will induce no significant stress variation in the rods and consequently no fatigue damage problem.

![Figure 4. Rod central temperature versus time after a shutdown](image)

For a beam shutdown followed by a break period longer than 1 s, the stress varies from the nominal value to a value nearly equal to zero due to the internal gap reopening, when the rod temperature drops. If during a long break period, the gap partially closes due to a lead creep mechanism under the matrix weight, the cladding stress would be higher at the beam recovery. An evaluation of the extra cladding loads has been done for a typical break period equal to 20 min.: the gap reduction due to the lead creep mechanism remains small and also the corresponding stress increases after beam recovery (Figure 5).

Furthermore, the number of such beam shutdowns being limited during an operating cycle, the stress cycling (\( \Delta \sigma = 90 \text{ Mpa} \)) should not induce significant fatigue damage.
Figure 5. Circumferential stress versus time; simulation of a shut down with 20 min. break period

Thermomechanical studies of the hot window

The hot window has to be as transparent as possible to the proton beam. With the cold window, it creates an intermediate vacuum space between the HPA and the pressurised target.

The purpose of this study is to demonstrate the technical feasibility of the hot window according to the French code for Liquid Metal Fast Reactors RCC_MR [3]. This code is published by the AFCEN (French Society for Design and Constructions Rules for Nuclear Island Components) and establishes a complete set of design and construction rules.

The hot window is roughly divided in two parts, the framework, in stainless steel, and the cylindrical bottom, in Inconel 718. It is cooled by a net of channels except for the cylindrical bottom, which is cooled thanks to a 3 mm blade of water. This cooling evacuates the heat source (increasing function of the hot window thickness) produced by the proton beam, the neutrons of spallation and the gamma radiation.

Solicitations that undergo the hot window are due to:

- external pressure (the cooling water);
- temperature effects, in steady state and transient state (start-up and shutdown of the beam).

It results that the problematic of the design is to find the minimal hot window thickness resisting to the pressure effect, so, on one hand, to be as transparent as possible to the beam, and on the other hand, to limit induced thermal stresses.

Design criteria

An elastic analysis of the mechanical stresses induced by secondary and primary loadings for Class 1 is presented for the nominal situation. Consequently, the value of the maximal allowable limit stress $S_m$ is the minimal value of \( \{2/3 \, R_{0.002}(293 \, K), \, 0.9 \, R_{0.002}(\theta) , \, 1/3 \, R_m(293 \, K), \, 1/2.7 \, R_m(\theta)\} \) where $R_{0.002}$ is the 0.2% conventional yield strength and $R_m$ is the ultimate strength and $\theta$ the temperature.
The mechanical design of the Inconel part of the hot window is analysed for monotonic loadings (type P), cycle loadings (type S), buckling (external pressure) and fatigue by applying level A criteria. The aim of level A is to protect the component against the following damages:

- immediate or time dependent excessive strain;
- immediate or time dependent plastic instability;
- immediate or time dependent fracture;
- elastic or elastoplastic buckling, immediate or time dependent;
- progressive strain;
- fatigue;
- fast fracture.

**P-type damage**

P-type damage denotes damages in structure which can result from application of a steadily and regularly increasing loading as the external pressure. Criteria to verify are:

\[
\begin{align*}
\overline{P}_m & \leq S_m(\theta_m) \\
\overline{P}_L & \leq 1.5 S_m(\theta_m) \\
\overline{P}_m + \overline{P}_b & \leq 1.5 S_m(\theta_m)
\end{align*}
\]  

(3)

where \( \overline{P}_m \) is the general primary membrane TRESCA (maximum shear stress) stress, \( \overline{P}_L \) is the local primary membrane TRESCA stress, \( \overline{P}_m + \overline{P}_b \) is membrane plus bending TRESCA stress, and \( \theta_m \) is the average temperature in the thickness during the studied loading.

**S-type damage**

S-type damage denotes damages that result from repeated (cyclic) application of loadings at the shutdown or start-up of the beam. Criterion to verify is:

\[
\text{Max } \left[ \overline{P}_L + \overline{P}_b \right] + \overline{\Delta Q} \leq 3 S_m[\text{Max } \theta_m] \tag{4}
\]

where \( \overline{\Delta Q} \) is the range of secondary TRESCA stress.

**Buckling**

When creep is not significant, the buckling risk of structure is present, if no buckling occurs for a loading equal to 2.5 times the actual loading. This coefficient has to be obtained by taking account of:
• geometrical imperfections the most severe allowed by imposed tolerances;
• minimal imposed thicknesses after deduction of the over thickness anticipating the corrosion;
• minimal tensile properties at considered temperatures.

**Fatigue**

This method calculates a rate of fatigue $V_A(\Delta \varepsilon)$ that has to remain less than 1. It provides an estimation of the actual equivalent strain range $\Delta \varepsilon$ resulting from an elastic analysis. This is obtained by evaluating the amplification of the strain due to plasticity with the help of cyclic curves. However, no Inconel 718 fatigue curve of this kind is allowable but a curve that provides, for a given equivalent stress range $\Delta \sigma$ and a given temperature, the maximal number of authorised cycles. This curve comes from the material database of PETTEN (Netherlands).

![Figure 6. Number of cycles to failure for Inconel 718](image)

**Material properties of Inconel 718**

The material properties are tabulated in Table 3.

**Table 3. Mechanical characteristics of Inconel 718**

<table>
<thead>
<tr>
<th>$\theta$ (°C)</th>
<th>$\lambda$ (W/mK)</th>
<th>$\alpha$ ($10^{-6}$/K)</th>
<th>$E$ (GPa)</th>
<th>$R_{0.2}$ (MPa)</th>
<th>$R_m$ (MPa)</th>
<th>$S_m$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>11.25</td>
<td>10.3</td>
<td>201.2</td>
<td>1 078.7</td>
<td>1 359.7</td>
<td>453</td>
</tr>
<tr>
<td>50</td>
<td>11.75</td>
<td>10.9</td>
<td>199.9</td>
<td>1 081.3</td>
<td>1 367.0</td>
<td>453</td>
</tr>
<tr>
<td>100</td>
<td>12.59</td>
<td>11.9</td>
<td>197.5</td>
<td>1 082.9</td>
<td>1 374.0</td>
<td>453</td>
</tr>
<tr>
<td>150</td>
<td>13.42</td>
<td>12.7</td>
<td>194.9</td>
<td>1 080.7</td>
<td>1 374.5</td>
<td>453</td>
</tr>
<tr>
<td>200</td>
<td>14.26</td>
<td>13.4</td>
<td>192.2</td>
<td>1 074.9</td>
<td>1 368.6</td>
<td>453</td>
</tr>
<tr>
<td>250</td>
<td>15.09</td>
<td>14.0</td>
<td>189.3</td>
<td>1 065.5</td>
<td>1 356.2</td>
<td>453</td>
</tr>
<tr>
<td>300</td>
<td>15.93</td>
<td>14.4</td>
<td>186.3</td>
<td>1 052.5</td>
<td>1 337.4</td>
<td>453</td>
</tr>
</tbody>
</table>
The Poisson ratio, in the range of temperature is 0.28. The density and the specific heat are constant. Their respective values are 8 200 kg/m$^3$ and 460 J/kg K.

**Elastic analyses**

Computation is done by means of the finite elements code CASTEM 2000 of the Mechanics and Technological Department of the CEA.

**Computing assumptions**

Assumptions and specifications used to design the hot window are presented. Loadings come from neutronic and thermohydraulic studies done by the CEA/DMT. The thermohydraulic study gives a pressure drop of 0.2 MPa. The inlet pressure is 0.6 MPa but the hot window is designed for a fluid pressure of 0.7 and 1 MPa. The neutronic study provides the heat source per unit of volume per unit time.

**Methodology**

The methodology of the design computation is the following:

1. **Buckling analysis at 293 K**
2. **Computation of the nominal state**
3. **Buckling analysis of the expanded structure**
4. **Thermal shock analysis**
5. **Acceptable structure**

- Provide a nominal thickness of the hot window
- The structure should verify the RCC_MR criteria
- Compute the number of cycles to failure

Only ¼ of the hot window is meshed because the structure and the loadings are symmetrical. The solid is isotropic and meshes with shell elements (COQ3 for the thermal analysis and DKT for the mechanical analysis). The finite element mesh is presented in Figure 7.
Boundary conditions

Mechanical boundary conditions:
- external pressure is 0.7 MPa or 1 MPa;
- clamped where the hot window is linked to the framework;
- symmetry conditions.

Thermal boundary conditions:
- heat source;
- heat transfer coefficient of the cylindrical part of the hot window: 36 000 W/m²K;
- heat transfer coefficient of the other part of the hot window: 10 000 W/m²K.

To compute the thermal transient, the cyclic thermal loading is defined as follows:
- the system is firstly in its nominal situation;
- the beam is shutdown;
- the steady state is reached;
- the beam is started up, \( P(\bar{x}, t) = P(\bar{x}) \left( 1 - e^{-t/\tau} \right) \) where \( \tau = 10^{-3} \) s;
- the new nominal state is reached.
Discussions of results

Results are presented in Table 4.

Table 4. Results of elastic analysis

<table>
<thead>
<tr>
<th></th>
<th>0.7 MPa</th>
<th>1. MPa</th>
<th>limit stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Window thickness</td>
<td>3.8 mm</td>
<td>4.4 mm</td>
<td></td>
</tr>
<tr>
<td>Max. temperature</td>
<td>480 K</td>
<td>522 K</td>
<td></td>
</tr>
<tr>
<td>Membrane tempera</td>
<td>447 K</td>
<td>480 K</td>
<td></td>
</tr>
<tr>
<td>Min. temperature</td>
<td>351 K</td>
<td>365 K</td>
<td></td>
</tr>
<tr>
<td>$P_m$</td>
<td>90 MPa</td>
<td>93 MPa</td>
<td>453 MPa</td>
</tr>
<tr>
<td>$P_m + P_b$</td>
<td>300 MPa</td>
<td>365 MPa</td>
<td>679 MPa</td>
</tr>
<tr>
<td>$\Delta \sigma$</td>
<td>625 MPa</td>
<td>814 MPa</td>
<td>1359 MPa</td>
</tr>
<tr>
<td>$\Delta \sigma$</td>
<td>450 MPa</td>
<td>629 MPa</td>
<td></td>
</tr>
<tr>
<td>Nb cycles to fail</td>
<td>$&gt; 10^6$</td>
<td></td>
<td>100 000</td>
</tr>
</tbody>
</table>

The buckling analysis imposes thicknesses according to the pressure of the cooling circuit. Maximal temperatures are upon the vacuum side and minimal are upon the cooled side. The thermal field follows the heat source field. For P-type damages, maximal stress occurred at the connection of the shell with its stiffener. The classification of stresses considers that, in this geometrical zone, the membrane stress is a local primary stress while the bending stress is a secondary stress. It follows that this high value of stress is not to take into account in P-type damage analysis.

Conclusions and perspectives

An analysis of nominal and incidental situations of the facility operating mode has been conducted, in order to evaluate the consequences of abrupt and frequent shutdown or tripping of the accelerator.

Thermomechanical studies of the spallation rod show that either in nominal or in transient conditions, the cladding solicitation respects the conception criteria. Beam trips with frequency higher than 10 Hz should not induce significant stress variation in the rods and fatigue damage problems would be avoided considering a limited shutdown number.

Elastic analyses with regard to RCC_MR have been done for the hot window. These analyses are not exhaustive and show that in the framework of the retained assumptions, the hot window in Inconel 718 verifies the RCC_MR Class 1 criteria. For a pressure of 0.7 MPa, the required thickness is 3.8 mm, while for a pressure of 1 MPa, the required thickness is 4.4 mm.

Concerning the lead swelling law, experimental data would be necessary to confirm the assumptions taken into account in the formulation. Furthermore, complementary analyses will have to be realised in order to estimate the radiation effects on materials with regard to progressive strain, fatigue damages and time to rupture data.
REFERENCES


THERMOMECHANICAL STRESSES ON THE BEAM WINDOW

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Abstract
The Centre for Advanced Studies, Research and Development in Sardinia (CRS4) is participating in an Italian R&D programme, together with Ansaldo, the ENEA and the INFN, devoted to the design of a 80 MW prototype of the energy amplifier proposed by C. Rubbia. The use of advanced numerical tools has been of practical support in the design of critical elements of the machine such as the fuel element and the beam target. The aim of this work is to study the sensitivity of beam window stresses to the beam distribution, size and interruption. In order to compute thermal stresses, the heat deposition in the window and in the coolant generated by the interaction with the proton beam is calculated and used as input data for the fluid dynamic simulation of the natural convection flow of the target coolant.
Introduction

The energy amplifier (EA) [1,2] is a nuclear system in which a beam target, driven by a proton accelerator, supplies an external source of neutrons to the subcritical core. The beam target represents one of the main technological problems related not only to the design of the EA, but to all high power spallation sources currently under study or in construction worldwide [3,4].

Neutrons come from the interaction of a high power proton beam with the material contained in the target. Such interaction, called spallation, has the undesirable effects of producing a large quantity of heat (typically some MW concentrated in a small volume) and inducing intense radiation damage in the structural materials. Liquid metals are currently considered the best choice in terms of target materials since they satisfy the important criteria of being the spallation medium and the cooling fluid at the same time, and since their structural and thermal properties are not degraded by the radiation damage induced by proton interactions. Nevertheless, the corrosion of structural materials in a liquid metal environment is an important problem. Given the fact that the primary cooling loop of the EA is made of lead-bismuth eutectic (LBE), we consider the same coolant for the beam target. The LBE flow is driven by natural convection whose efficiency depends on the target height (which is related to the dimensions of the EA) and on the fluid dynamic design of the coolant circuit.

In the EA prototype target a window separates the internal part of the beam pipe from the coolant. Configurations using a beam window have additional problems of beam window cooling (in the window the highest temperatures and stresses are reached) and radiation damage induced in the window material. This damage is of a slightly different nature from that induced in the other structures, since the window is exposed not only to backscattered high-energy neutrons, but also to the high-energy proton flux. While steels for low power applications keep a sufficient structural resistance and are suitable candidates for the EA prototype [3-5], refractory alloys or more advanced materials are mandatory for high power applications [6,7].

The EA prototype target

The EA prototype target [5] is an axial symmetric device consisting of a “beam pipe” enclosed in a coaxial “container” (see Figure 1). The beam pipe is made of martensitic HT-9 steel and is a vertical cylinder of 10 cm radius, 635 cm height and 3 mm thickness closed at the bottom by an HT-9 “window”. The window has a hemispherical external surface and an ellipsoidal internal surface so that the thickness varies from a minimum of 1.5 mm in the beam pipe axis to a maximum of 3 mm in the junction with the cylindrical part of the beam pipe. The window is tapered in order to reduce the beam heating in the beam pipe axis. The container is a vertical cylinder of 27 cm radius and 724 cm height with a hemispherical bottom. The region between the beam pipe and the container is filled with LBE and “vacuum” is made inside the beam pipe.

Having neglected the heat flux through the beam pipe and the container, the heat produced in the window and in the coolant is removed by a natural convection flow. This flow is guided by the “flow guide”, that is, a 17 cm internal radius cylinder laying between the beam pipe and the container. The flow guide separates the internal hot flow rising from the spallation region from the external cooled flow downcoming from the heat exchanger positioned on the top of the downcoming duct. In the spallation region the flow guide assumes a funnel shape which accelerates the flow and enhances the cooling of the window. The flow guide is made of two HT-9 layers 1 mm thick separated by a 1 mm layer of insulating material (zirconium oxide). The heat exchanger is located 25 cm from the container top, is 45 cm in height and its outlet temperature is set to 180°C.
Neutronic analysis

The proton beam is injected through the top of the beam pipe and interacts with the window, the coolant and the flow guide. The proton energy is 600 MeV and the beam size is assumed to be a circular spot of radius $r_0 = 7.5$ cm (the window radius allows a correct defocusing of the beam spot in order to prevent localised high power densities in the target materials). The beam current density is given by the three-dimensional parabolic profile:

$$J = \frac{2I_0}{\pi r_0^2} \left(1 - \frac{r^2}{r_0^2}\right)$$

where the beam current $I_0$ ranges from about 2 to 6 mA. In the following we assume the maximum beam current to be 6 mA, corresponding to a beam power of 3.6 MW.

The FLUKA Monte Carlo code [8,9] is employed to calculate the heat source distribution, taking into account not only the electromagnetic interactions, but all kind of nuclear reactions induced by both protons and secondary generated particles. A $40 \times 70$ orthogonal grid is used for the FLUKA simulation. The heat generated inside the funnel is calculated by applying the distribution for the coolant multiplied by the ratio between the flow guide density and the coolant density. According to the FLUKA computation, inside the window the proton beam deposits in the form of heat about 22 kW (i.e. 0.6% of the beam power). The heat production in the coolant and in the flow guide is 72% and 1% of the beam power respectively, the rest of the beam energy being contained in the particles escaping the system or in the binding energy of the target nucleus. Figure 2 illustrates the contours of the beam power released in the LBE.
Fluid dynamic analysis

The turbulent natural convection flow of the coolant and the thermal field in solids are simulated using the STAR-CD fluid dynamic code [10] where the heat source distribution calculated by the FLUKA code is used as input data. The vacuum inside the beam pipe is simulated by means of air at very low pressure. The heat exchanger is modelled as a thermal sink uniformly distributed. The numerical model employs a third order scheme for the spatial discretisation of the convective terms. The Chen $k$-$\varepsilon$ model with a two-layer algorithm in the near wall region accounts for turbulence effects. The radiative heat flux through the beam pipe and the pressure losses in the heat exchanger are neglected. The container walls are assumed to be adiabatic.

The IDEAS CAD and mesh generator [11] is employed to create a mixed structured/unstructured mesh. The fluid regions near the walls are meshed with structured grids, easier to handle and more suitable for the application of the turbulent near-wall algorithms. Structured meshing is also used for the discretisation of the solids. The total number of cells is about 14 000 and the discretisation is very accurate in the funnel zone, especially next to the window stagnation point.

Figure 3 shows the computed velocity and temperature fields in the funnel region. The recirculation zone in the downcoming duct increases the temperature and reduces the natural convection pumping. However, the target height and the flow acceleration due to the convergent funnel shape generate the coolant velocity necessary for cooling the beam window to a maximum temperature of 427 °C.

Structural analysis

The MSC/NASTRAN structural code [12] is employed to calculate the stresses induced in the window/pipe system by using a linear (elastic) model applied to the same window/pipe grid used for the fluid dynamic simulation. The temperature field is assigned to the elements of the model and the coolant hydrostatic pressure distribution is applied onto the external surface.
Figure 3. Velocity and temperature fields in the funnel region

The maximum Von Mises stress is 109 MPa, the maximum “meridional” (i.e. tangent to the window profile) stress is 102 MPa and the maximum “hoop” (i.e. perpendicular to the plane of study) stress is 101 MPa. The maximum window temperature is 427°C which corresponds to an ultimate tensile strength (UTS) of 610 MPa (this value is conservative due to the UTS decrease when the temperature increases). The values of temperature and stress are within the HT-9 application range described in [13].

Beam distribution effects

The window stresses sensitivity to the beam distribution is studied by considering Gaussian and uniform distributions having the same proton energy and beam current of the parabolic distribution given by Eq. (1) (see Figures 4 and 5). The corresponding heat flux to be removed from the window decreases in the beam axis according to the smaller window thickness.

Figure 6 shows the temperature distributions on the internal (window/vacuum) and external (window/coolant) surfaces as a function of the angle $\alpha$ between the target axis and the window (or pipe) circumference orthogonal to the axis (the proton beam crosses the window up to an angle of 48.6°).

The Gaussian distribution leads to window temperatures out of the HT-9 application range. With respect to the parabolic distribution, the Gaussian and uniform distributions have greater temperature gradients and therefore greater stresses close to the beam axis and edge respectively, as illustrated in Figures 7 and 8 where the meridional and hoop stress components in the internal and external window fibres are reported. The maximum Von Mises stresses are 189 and 149 MPa for the Gaussian and uniform distribution respectively. The Gaussian distribution produces stresses out of the HT-9 application range. The thinner part of the window, which is also the most loaded in the non-uniform distribution case, undergoes strong bending moments (depending basically on the temperature gradient along the thickness).
Figures 4 and 5. Assigned proton beam particle distributions and corresponding heat flux calculated by FLUKA in the window for different beam distributions

Figure 6. Temperature distributions on the internal and external window surfaces

Figure 7. Meridional stress components in the internal and external window fibres
Beam size effects

One of the most dangerous accidents expected in the beam window is a reduction of the beam size. In order to analyse such an effect we reduced the beam spot radius down to a dimension of 3 cm. Figure 9 shows that the maximum temperatures reached on the external and internal window surfaces in the beam axis are immediately out of the utilisation range of a HT-9 steel.

The corresponding maximum meridional, hoop and Von Mises stresses normalised with respect to the UTS are shown in Figure 10 and also illustrates that stresses are immediately out of the application range when reducing the spot size.

Figure 9. Temperature on the window surfaces in the beam axis vs. beam radius
Beam interruption effects

When the beam is interrupted, window temperatures decrease to the heat exchanger exit temperature. The beam interruption transient is calculated by a structural analysis decoupled by the fluid dynamic transient. The MSC/NASTRAN code is used where the coolant temperature is supposed to decrease from 360°C (see Figure 6) to 180°C in 0.15 s, according to the coolant velocity field near the window. The window/coolant heat flux is computed by using a heat transfer coefficient of 20 000 Wm⁻²K⁻¹ obtained by a forced convection fluid dynamic analysis of the window flow without the LBE heat source. Figures 11 and 12 show the maximum temperature and Von Mises stress in the window during the transient.

Figures 11 and 12. Maximum window temperature and Von Mises stress during the beam interruption transient

Under the approximation done on the coolant temperature transient, each beam interruption longer than about 4.5 s produces a stress cycle whose maximum Von Mises stress is 175 MPa. By neglecting the creep damage, the fatigue life may be determined from a design curve based upon strain cycling fatigue data generated at the maximum temperature [14]. In [15] a design curve for medium-strength pressure vessel steels is given, leading to a number of cycles to failure equal to 10⁵. However to predict thermal fatigue life with a higher degree of accuracy it is necessary to simulate the coupled thermal and fluid-dynamic transient and to acquire data about the thermal stress behaviour of the specific steel, the irradiation damage and the corrosion effects.
Conclusions

Extensive numerical calculations have been performed to study the thermo-fluid dynamics and the structural loads on the EA 80 MW prototype target. In the limits of the geometrical constraints of the system, a thermal hydraulic optimisation of the target allows the use of natural convection. The relatively low power beam of the machine (600 MeV of beam energy and 2-6 mA of beam current) allows the use of a martensitic steel in the beam window. This greatly alleviates the problems related to the construction, the assembly and the operation of the window under intense proton irradiation.

When changing the uniform beam distribution from parabolic to Gaussian or uniform, window temperatures and thermal stresses increase and eventually go out of the steel application range. When reducing the beam size temperatures and stresses still increase but in this case are immediately out of the steel utilisation range.

A simplified study of the fatigue damage induced by cyclic beam interruptions (longer than about 4.5 s) leads to predict the allowable number of interruptions to failure. In this analysis the more critical points remain a need of data on steel thermal cycle fatigue, irradiation damage and corrosion.

REFERENCES


SESSION VII

Working Group Reports
SUMMARY OF DISCUSSIONS IN WORKING GROUP 1: ACCELERATORS

N. Watanabe

N. Watanabe chaired the panel session with G. Bauer and M. Napolitano. The commentators include J. Brochard, Y. Cho, M. Hron, T. Mukaiyama, M. Salvatores and T. Yamazaki.

This session started with the parallel session reports, first from the accelerator group, led by M. Napolitano, and then from the ADS group, led by G. Bauer. Topics discussed (arranged by moderators) are as follows:

I. Confirmation for common agreement:
   1) required accelerator reliability (towards final agreement);
   2) achievable accelerator reliability (towards final agreement);
   3) how to cover the gap if it exists (?);
   4) necessary R&D in accelerator (towards an extremely reliable HPPA);
   5) necessary R&D in ADS side (towards an ADS resistant to beam trips and fluctuations);
   6) HPPA type suitable for ADS (i.e. linear vs. ring);
   7) one high powered accelerator vs. several medium-powered ones;
   8) suitable type of subcritical reactor for ADS.

II. Utilisation (common use) of HPPAs:
   1) dedicated vs. multi-use (i.e. dedicated: SNS, ESS, etc.; multi-use: JAERI);
   2) common use between other fields (i.e. basic science/energy science; hybrid-neutron source/muon catalysed fusion as a 14 MeV neutron source);
   3) merits and demerits;
   4) technical problems.
III. Possible future collaboration:

1) International collaboration (on what?):
   a) accumulation of database in existing medium/high power accelerators;
   b) material irradiation and testing;
   c) further analyses on the effects of beam trips and fluctuations on ADS;
   d) etc.

2) Interdisciplinary collaborations (on what?):
   a) same as b), above;
   b) R&D of high power targets;
   c) remote handling;
   d) etc.

3) Between what communities?

Summary of discussion

The major discussions are summarised as follows:

1) Reliability of the system
   Regulatory requirements are to be considered. They should be comparable to “reactor”. If unscheduled faults happen once, a long period will be lost. Especially at the beginning of commissioning it should be very stable. Power control must be studied.

2) R&D needs in HPPA
   MTBF is not important at present. The requirements from ADS are completely new for the accelerator community.

3) R&D needs in ADS
   System analysis is required on the reference subcritical system as well as safety analysis.

4) Linear vs. circular accelerators
   It depends on current, power, energy. A linac is for several ten mA and cyclotron is for less than 10 mA. Beam shape and “halo” are also to be considered. At the same time, a good core with stable $k_{in}$ is necessary.

5) Multiplexing vs. single accelerator
   This is to be considered from cost, reliability, the number of components. The system test facility may be one accelerator and transmutation plant has options. The key question is economy in commercial operation, including repairing and maintenance cost.
A multi-use facility, such as JAERI-NSP and JHF, aims toward multi-disciplinary or cross-disciplinary. Secondary particles such as neutrons and muons are also the purpose of HPPA utilisation. T. Yamazaki showed an example of multipurpose use of an HPPA in the proposed JHP (now JHF) in four basic science fields: kaon physics, unstable nuclear beam physics, muon science and neutron scattering.

6) **Dedicated or multi-use facility**

Many facilities are not allowed especially for small island (as in Japan). But ADS is not in this domain. It is important to make a dedicated facility to demonstrate a promising system to society.

7) **Possible collaboration**

International collaboration is fruitful to contest the ideas and to reduce the R&D cost. A large amount of R&D could be shared. The framework of the OECD/NEA is also useful.
SUMMARY OF DISCUSSIONS IN WORKING GROUP 2: ADS AND SUBSYSTEM

G.S. Bauer and Y. Oyama

Definition of scope

The group agreed that it was necessary to distinguish between a full-scaled transmutation plant (TP) and a system test facility (STF) which would be a precursor to the TP and is the only facility whose construction could be considered in the near future.

Transmutation plant

Such a plant would be used for routine transmutation of long-lived radioactive waste and would be capable of coping with the waste emerging from a country’s suite of nuclear power generating facilities. In that case beam multiplexing between several accelerators and different ADS of relatively low power would be conceivable, which would be expected to significantly reduce the impact of a beam trip in any one accelerator. Such multiplexing might be desirable for a variety of reasons, as discussed, e.g. in [1]. It would allow to apply current design criteria of LMFBR in terms of the number of permissible unscheduled fast shutdowns per year. Since this would be a commercial facility, it would have to be optimised in terms of cost and reliability. In particular, such a plant might use fuels currently not available or still in a state of development.

Multiplexing being a new concept, there are a number of questions in this context that need to be answered. They relate to the overall size of the plant and its sub-units as well as to detailed studies of the effect of pulsed beam operation on the driven core and optimum/acceptable pulse parameters.

Systems test facility

The main purpose of the STF would be to explore the merging of an accelerator and a subcritical reactor, to demonstrate that safe and reliable operation can be achieved and to generate the database necessary for the final construction of a TP. In this case only one accelerator can realistically be planned to drive the reactor. The very high reliability required for this accelerator may therefore justify a certain degree of “over-design”. It is conceivable that there would be a limitation on the maximum number of unscheduled trips in the STF which would limit its service time without thorough inspection for possible damage that might have resulted. In order to enable such inspection, but also in order to make possible experiments necessary to produce the required database, a high degree of flexibility should be designed into such an STF, but its design would most likely be based on known fuel. Development of new fuels might be envisaged over the course of the STF’s service time. An important question that should be settled early on is the required power level and the degree of
subcriticality that will be used. This should, of course, be representative for a module of the later TP in order not to introduce any significant uncertainty that might result from another large extrapolation. The following discussion is with reference to the STF only.

**The driven facility and its spallation target**

With respect to the response to a beam trip, it turned out that one can distinguish between quick response components (within a second or less) and slow response components (of the order of a minute) in the system. Examples of the former category are the beam window (BW) and the fuel core (FC), whereas the above core structure (ACS), primary coolant piping (PCP, as part of or independent of the ACS) and intermediate heat exchanger (IHX) belong to the latter one.

Although some ADS proposals foresee to use the same loop for the spallation target and to cool the subcritical reactor core, the group decided to base their analysis on the assumption that both loops would be separated and operating independently of each other. The driven facility (DF) includes the subcritical core and its cooling loop, whereas the beam window and target boundary tube (target containment) are part of the spallation target loop. So, fast and slow response components will be present in both subsystems.

**The spallation target loop and beam window**

The spallation target loop is characterised by a relatively small amount of coolant (spallation material) in the circuit. The flow is more or less directly from the heated zone to the heat exchanger and pumps. Any change in temperature will, therefore, be felt in full by the connecting pipes and by the heat exchanger. The most highly loaded component, however, will be the target window, in which a significant amount of heat will be generated and which must be cooled intensely. The heat generation is of the order of 15 W/cm$^3$ per mA/cm$^2$ of beam current density [2]. Realistically, up to 100 mA/cm$^2$ will have to be anticipated, which leads to a heat flux density of 150 W/cm$^2$ per mm of window thickness in the case of single-sided cooling. In the case of the ESS target [2] with 80 mA/cm$^2$ the temperature gradient across the 1.5 mm thick window was found to be 55 K and the temperature on the inside of the window was about 80 K above the inlet temperature of the coolant. The maximum temperature reached on the beam axis in the target material (Hg) was 140 K above the coolant inlet temperature. Taking this as an example and assuming that the window cooling medium is the target material, two cases may prevail:

(a) **Target material flow towards the window**

In this case the relevant coolant temperature is the maximum temperature in the target material and the peak temperature in the window will be some 230 K above the forward flow temperature of the target material. In case of a beam trip it will take of the order of a second for cold material to reach the window. This means that for very short beam trips (of the order of 0.1 second) the amplitude of the thermal quench in the window will be of the order of the temperature difference between the window and the target material, but the quench rate will be high. For longer duration of the trip (more than two seconds) a complete cool down to the

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1 For an ADS with 100 MW thermal power and 5 mA proton beam current (ca 5 MW beam), this means that the footprint of the beam is about 100 cm$^2$, accounting for a peak-to-average ratio of 2.
forward flow temperature of the window will occur, leading to a higher quench amplitude, although with a longer time constant. A characteristic time for the change of temperatures and stress in the beam window of the order of a few seconds was also reported by Kikuchi [3] for the mercury target under development at JAERI.

(b) Target material flow away from the beam window

With the target material flowing away from the beam window, special design measures may be necessary to ensure adequate cooling of the window [2], but the temperature jump after a beam trip will be smaller than in Case (a) for longer trips.

For very short trips the amplitudes and rates of change will be the same in both cases, although the temperature level will be lower in Case (b) than in Case (a). The question of whether a higher or lower operating temperature of the window is to be preferred is not easily answered, because it depends on the properties of the window material and their evolution under irradiation. The latter is only poorly known for the conditions prevailing in a spallation target and is the subject of current R&D efforts on an international scale.

An obvious way to reduce the effect of thermal cycling on the beam window is to reduce the current density as in the system discussed by Takizuka [4]. This has to be balanced against the mechanical stability of a larger window in the case of constant required overall beam current. Since the beam cross-section and profile may also affect the coupling between the target and the DF, careful analysis of this question is required, but there is certainly scope for optimisation.

In any case, the target window will have to be designed as an exchangeable element, but the consequences of frequent thermal quenches might well be an unacceptably short service lifetime, if the amplitude is high. Due to the small thermal inertia of the target window and the “slow” gradient of temperature change along the pipes and in the heat exchanger (ca. 2 seconds) of the target loop, no special protocol for restart of the beam will be required for the target loop.

The driven facility (subcritical core and its cooling loop)

No detailed information was available on the effect of beam trips on the fuel assembly. It was assumed, however, that the fuel rods themselves would be able to stand a relatively large number of thermal cycles during their service life. The strongest concern was about the effect of thermal cycles on the ACS, the PCP and the IHX. Typically the temperature rise of the coolant on its passage through the core will be of the order of 150 K and the time it takes to flow through the core will be less than 1 second. However, due to the thermal inertia and afterheat the initial temperature drop at the core exit in case of a scram occurs within about half a minute. For the case of the PCP at the Monju fast reactor, Kashara [5] quoted a characteristic decay time of the stress of 40 seconds. While the exact number depends, of course, on the reactor type, this determines more or less the quench rate of the ACS and PCP in case of a beam trip. For beam trips of the order of 1 second or less, the effect on the ACS will be negligible, whereas a full quench by about 120 K will occur if the beam trip is longer than half a minute. Due to the fact that, in some designs, like the EFR, a relatively large pool of hot coolant is located between the core and the IHX, a certain degree of additional thermal inertia is introduced. This means that a change in core outlet temperature will be felt at the IHX with a time delay of the order of 1 minute and that the slope of the temperature drop will also be smaller than at the ACS. By suitable design measures this damping effect might even be enhanced. As compared
to the target window, no extreme heat loads occur in the core or in the components of the DF and
temperature quenches will generally be less severe. Also the change of materials properties in the fast
neutron spectrum are better known than in the spallation spectrum at the target window. In order to
protect the core and to ensure operational safety of the facility however, a special restart protocol may
have to be followed after a significant cool down of the driven facility, i.e. a beam trip lasting longer
than half a minute. This would probably be a request to the accelerator control system.

Classification of beam trips ("unscheduled" beam loss)

From the foregoing discussion it became obvious that two kinds of beam trips should be
considered, depending on their duration. Although the limit between what should be classed as short
or long trips could not be specified precisely without a more detailed analysis, the final criterion will
be their effects and allowed frequency of occurrence.

Short beam trips

Beam trips that will only affect the heat generation in the target window and in the fuel of the
driven facility and that will not lead to significant variations in the temperature of the target material
or the core coolant will be classed as “short”. These will be trips that might result from a short spark
somewhere in the accelerator system. It would be a requirement that the accelerator should recover
from such events within less than a second or, better, less than 100 ms. Under these circumstances,
trips can be tolerated at rates significantly larger than what is acceptable for longer trips. Such trips
would be considered a design feature of the facility, but still a limitation on their total number might
have to be imposed within the service life of the fuel or the target window, both of which are
components whose regular replacement must be envisaged in any case. The ACS, PCP and IHX will
be virtually unaffected by such trips.

Longer beam trips

Incidents leading to extended loss of beam over periods that cause a significant drop in the
coolant temperature might have to be classed as "unscheduled fast shutdowns". According to current
practice such incidents must be reported to the authorities and, in general, require an investigation
into their cause and potentially corrective measures to prevent them from happening again. Such trips
must clearly be kept at a minimum. This will require regular preventive maintenance of accelerator
components with limited lifetimes. For trips of this type restrictions may have to be applied that are
similar to current restrictions on the occurrence of reactor scamps in LMFRs. A slow and controlled
restart will be required after such trips. With respect to the most affected components, the ACS on the
one hand and the PCP and heat exchanger of the target loop, trips of more than 20 seconds, but
certainly more than 1 minute might have to be classed as “long”.

Trips of intermediate duration

Clearly, what was classed as “short” will be trips from which the accelerator system recovers
automatically, whereas “long” trips in the above sense will require operator intervention. In between
these two obvious cases there is a class of trips whose effects cannot be assessed without detailed
analysis of a given reference system and its various thermal constants. Such a system does not exist at present, but the group strongly felt that there was a need to create one in the near future. Based on the above criteria of distinction, a time limit may have to be defined which automatically prevents the accelerator from restarting, if it is exceeded.

**Unresolved or not finally resolved issues**

The following topics were not discussed in any detail during the time available for the deliberations of the working group but were identified as relevant in the context of a subcritical device and its driving accelerator.

**Pulsed accelerators**

Pulsed operation of the accelerator in the sense that gaps are introduced in the beam which allow switching of deflection devices would likely become a necessity if more than one accelerator was used to feed a DF, as was pointed out as an option by Watanabe [6]. While cyclotrons deliver an intrinsically continuous beam in which such gaps would have to be introduced on purpose, linacs can be operated in continuous or pulsed mode. At present continuous superconducting linacs are the preferred solution in several ADS concepts but, so far, no such accelerator has yet been built for protons. For normal conducting linacs in the power range of 5-10 MW pulsed (low duty cycle) operation is much more economical than CW operation. The question of what the effect of such pulsed operation would be on the DF could not be answered during the session. On the other hand, pulsed accelerators would also give extra possibilities in controlling the beam power via the pulse length (see below) and would open up the possibility of multiplexing between several accelerators and DFs. Arguments for doing so were given in Ref. [1].

**Degree of subcriticality**

The question of what the value of $k_{eff}$ in the DF should be depends on the desired safety margin on the one hand, but on the other also affects the required accelerator power and hence cost quite severely. Other factors of influence are the type of fuel used, details of the facility design and the degree of loading with neutron absorbing materials. These decisions can only be based on detailed studies. Nevertheless they are also important in the context of the effect of beam trips, because of their influence on the amplitude of the temperature surge.

**Other issues to be considered**

The following topics were not discussed in any detail but were identified as relevant to the general topic of the interface between a subcritical device and its driving accelerator:

- Is the required level of reliability comparable to what is current practice at reactors (less than four fast trips per year)?
- Extent to which control rods are required in a driven facility (DF):
  - safety device for long time shutdown;
- compensation for burn-up:
  \(\Rightarrow\) by control rods;
  \(\Rightarrow\) by accelerator power.

- Possibility of beam power surges:
  - cannot be allowed; is it a possibility? how to exclude?

- Control of beam power based on data (request) from DF (n-flux, T, ?):
  - how:
    \(\Rightarrow\) by energy;
    \(\Rightarrow\) by current;
    \(\Rightarrow\) by pulse rate;
    \(\Rightarrow\) by pulse length.

- Beam veto by DF (under what conditions must the beam be shut down by request from the DF?)

- Effects of partial loss of beam (LoB) in multiplexed systems (several accelerators feeding into one target):
  - allowable steps (necessary number of accelerators?).

- Feedback of electricity or independent supply from grid:
  - automatic power reduction on accelerator if heat sink is not available (how to accomplish?).

**Conclusions**

While the field to be covered in the general context of the interfacing between accelerators and driven facilities is clearly much wider than what can be dealt with in 1½ hours of group work, the working group arrived at some important conclusions.

- With respect to their effect on liquid target material and reactor coolant temperature, trips may be classed as “short” or “long”. Short trips will not affect the temperature of the loop by a significant amount but may be important for the final service life of exchangeable components such as fuel assembly and target window. The number of long trips will have to be restricted to a figure which must be obtained from a detailed analysis of a reference concept. Automatic recovery of the accelerator from minor disturbances (sparks) should be as fast as possible, certainly less than 1 sec.
• It is not possible, nor necessary at the present time, to treat the case of a final transmutation plant. Attention should be focused on the more near term question of a systems test facility. Requirements to the accelerator driving the STF will be equally stringent as in the final TP.

• An STF could be designed to a certain number of long trips, whereas a TP must be designed for a given number of service years. Multiplexing between different accelerators and driven units might help to reduce the number of long trips.

• It is an important task for the community to define a reference design for a STF soon in order to be able to analyse interface issues to the driving accelerators in more detail.

REFERENCES


SESSION VIII

Closing Session
WORKSHOP SUMMARY

M. Salvatore

The panel discussions have covered most of the essential points raised during the workshop, and in particular Dr. Bauer and Professor Napolitano’s reports on the separate working sessions held yesterday have already given relevant indications of what has been accomplished at this meeting.

I will attempt, however, to present a quick summary and express some personal ideas and proposals as regards this workshop.

The workshop began with a review of some of the major programmes. The most significant points include:

- The announcement that the SNS project is securely funded with a relatively tight time schedule for construction (2005).

- The KEK/JAERI joint project for an integrated facility which is close to being funded opens new perspectives in Japan and elsewhere.

- Finally, if we consider the continuous progress of the SINQ installation in PSI-Switzerland, we have a new vision in the field of accelerator applications and neutron sources that would have been difficult to foresee only three to four years ago. At that time, the possibility for advancement in this domain seemed relatively obscure.

The presentations made by JAERI (Centre for Neutron Science), as well as by Korea and China, seem to indicate that the “multi-purpose” approach for ADS development is gaining ground, and Professor Niimura’s excellent presentation was an enlightening example of a potential user with strong scientific interests.

The emphasis, however, remains on HPPA development. In the case of accelerator driven transmutation, a similar importance should be placed, in my opinion, on the development of appropriate materials and fuels for transmutation.

One of the main issues of the workshop was the “reliability” of accelerators, in particular in the context of their coupling with a near-critical multiplying fission reactor. It is clear that “reliability” means different things for different user communities and that arriving at a mutual understanding is necessary.

Questions of “availability”, “beam trips” and also “reliability of the diagnostics systems of the sub-critical core coupled to the beam shutdown system” are relevant and connected issues.
In fact, before giving my impressions on the beam trip aspect, I would like to emphasise once more that a reliable sub-critical core system control, designed to know the source level and the status of global and local power inside the sub-critical core, is of the utmost importance with regard to safety. This also applies to the definition of the appropriate system for beam shutdown in case of an abnormal situation inside the core. Also in the domain of safety, it is easy to imagine that we will have to consider scenarios of system failure with regard to beam shutdown. Under such circumstances, some kind of automatic feedback (as in the case of coupling the power generation system to the accelerator power source) could be worth examining.

It is probable that we will need an accelerator able to deliver current over a wide range of intensities (perhaps 5-15 or 3-10 mA or even 10-30 mA). An unwanted injection of the entire beam current reserve when operating at the lowest intensity regime, though it seems unlikely, will also probably be the object of a specific safety demonstration. This means that this preoccupation should enter into the specification for the accelerator output control.

Finally, it should be noted that the multiple accelerator feed concept has been advocated, as well as the use of pulsed accelerators to feed ADS. For my part, I would like to remind the interested parties to reduce current intensity demands.

All of the topics mentioned above require further reflection, and should be accordingly accounted for in R&D programmes.

As far as beam trips, the original worry expressed by Professor Watanabe seems to correspond to potentially real problems related to the safety and the material performance of the sub-critical core. Preliminary evidence was presented by the reactor community, and this data should be confirmed and generally agreed upon.

As chairman of the Nuclear Science Committee, I believe that certain follow-up activities in this area, sponsored by the NEA, are warranted. Such activities could take the form of the following initiatives:

- The launch of an international benchmark to assess on one or two representative geometries the effects on the structures of “short” beam trips followed by recovery (20-120 sec range).
- The organisation of another workshop in approximately one year’s time so as to provide a forum for the two communities, as was so successfully done here.
- Discussion of a joint effort for an experimental verification (if possible under irradiation).

The clear message of this workshop is that international collaboration in this domain is mandatory, in particular at this phase of exploratory studies.

Not being an expert on accelerators, I have a good excuse to refer to the informative discussion just held on accelerator performances, and not to provide any kind of summary beyond what Professor Napolitano has already presented.

Finally, I would like to conclude with warm thanks to our hosts at JAERI for preparing and running a very successful meeting. I would like to express my appreciation to Professor Watanabe, who proposed this delicate – and crucial – subject.
I would also like to thank the JAERI Nuclear Science Centre staff, who provided us with the means to fully benefit from our participation and to enjoy our stay in beautiful Japan.

I do not know if we will be able to meet the challenge issued by Professor Saito for “a renewal era for clean nuclear energy”, but I am convinced that you will share with me the feeling of having contributed in some small way to the progress of a worthwhile area of research.
CLOSING ADDRESS

Dr. Kunihisa Soda

First of all, on behalf of the vice president of JAERI, Mr. Matsuura, and on behalf of the Japan Atomic Energy Research Institute, I would like to thank all those who participated at this workshop. As Dr. Salvatores mentioned, I believe this meeting has been of great interest to all parties involved, and has been particularly successful in that sense. This is one of the first occasions that accelerator experts and nuclear technology experts have been brought together and that, if nothing else, is a significant accomplishment. I would like to highlight, however, the need for more contact with experts in the domain of nuclear technology, especially with regard to nuclear safety and engineering. My own career has been devoted to reactor safety, and I must admit that if I were asked to authorise construction of an ADS, I would probably request extremely detailed data, or require extensive analysis based on specific data. The meeting to be held next year will hopefully address this type of issue more fully.

As far as JAERI's activities are concerned, some of you will visit the JAERI Tokai site this afternoon. On the occasion of this visit, I take the opportunity to inform you of the re-organisation of our departments to allow a greater focus on energy research. One of our new departments will be devoted to Energy Systems, and others include the Department of Material Science and the Centre of Neutron Science. These three departments are intended to develop proposals for future energy sources that should include ADS and many other various kinds of research. I hope that over the course of the next century we will be able to discover new, economical and sustainable energy sources that will permit our continued presence on this earth.

Finally, I thank everybody who contributed to the organisation of the workshop, especially the staff of the Centre of Neutron Science. Without their hard work and dedication, this meeting would not have been the success I believe it to be. I thank you again and I hope you enjoy your stay in Japan. Thank you very much.

I now officially declare this workshop closed.
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