9th IEM Meeting Nimes 2006 September 25th to 29th

MEGAPIE Target :
DESIGN IMPLEMENTATION AND PRELIMINARY TESTS OF THE FIRST PROTYPICAL SPALLATION TARGET FOR FUTURE ADS

Ch. Latge1,(CEA) France (christian.latge@cea.fr) F. Groeschel2 (PSI) Switzerland (friedrich.groeschel @ psi.ch)2, P. Agostini3, M. Dierckx4, C. Fazio5, A. Guertin6, Y. Kurata7, G. Laffont1, T. Song8, K. Thomsen2, W. Wagner2, K. Woloshun9

1 CEA Cadarache, 2 PSI Villigen;

3 ENEA Brasimone; 4 SCK-CEN Mol;

5 FZK Karlsruhe; 6 SUBATECH Nantes;

7 JAERI;; 8 KAERI; 9 DOE-LANL

MEGAPIE-TEST

CADARACHE

Introduction 1/2

Partitioning and Transmutation (P&T) techniques could contribute to reduce the radioactive inventory and its associated radiotoxicity.

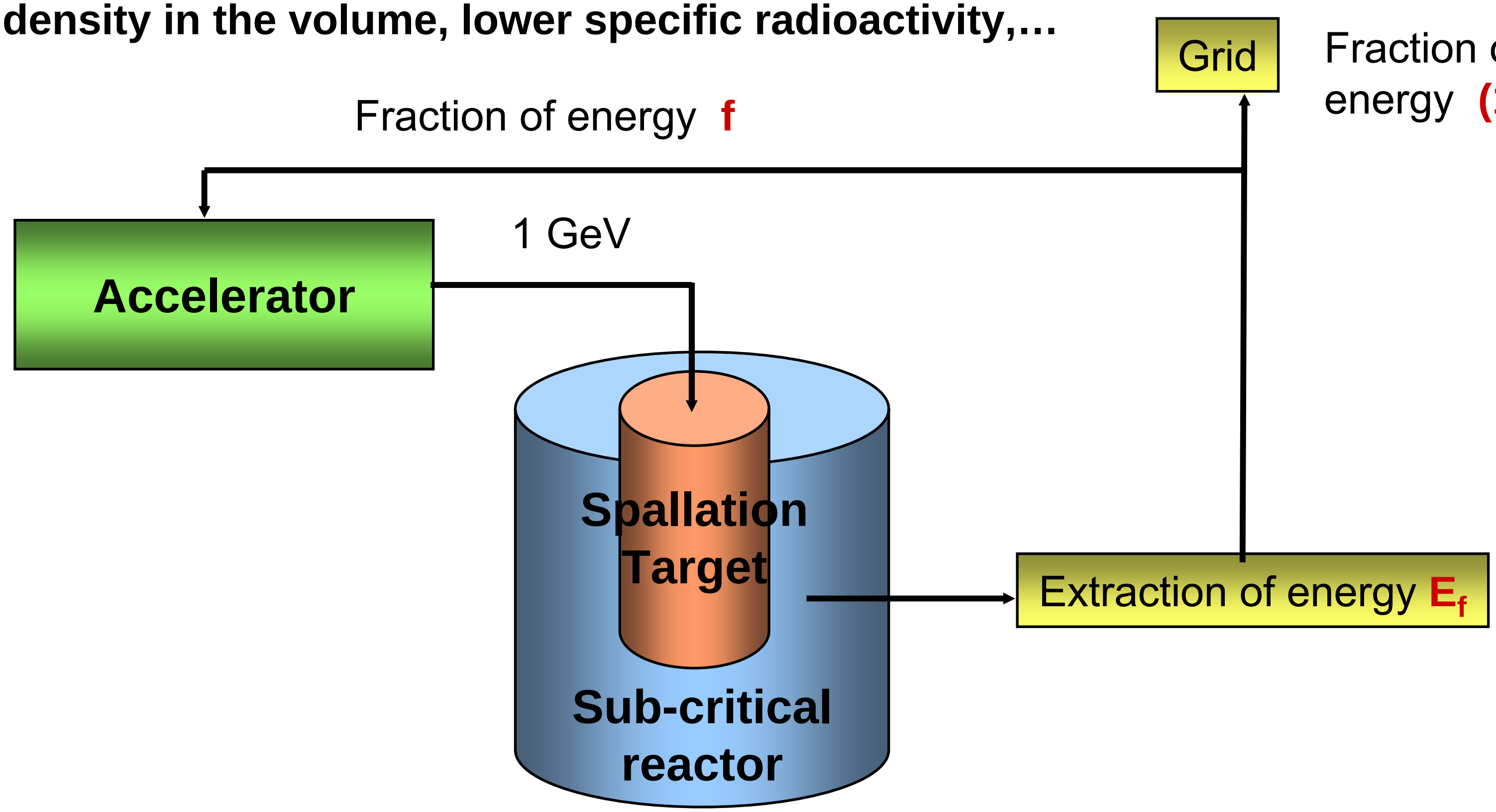
Sub-critical Accelerator Driven Systems (ADS) are potential candidates as dedicated transmutation systems, and thus their development is a relevant R&D topic in Europe.

Following a first phase focused on the understanding of the basic principles of ADS, the R&D has been streamlined and focused on practical demonstration key issues. These demonstrations cover particularly spallation targets of high power.

General consensus :

- up to 1MW of beam power solid targets are feasible from a heat removal point of view.

- for higher power levels, liquid metal targets are the option of choice because of their higher heat removal capability, higher spallation material density in the volume, lower specific radioactivity,…



Introduction 2/2

A key experiment in the ADS roadmap,

MEGAwatt PIlot Experiment (MEGAPIE)

(1 MW) initiated in 1999 in order to design and build a liquid lead-bismuth spallation target, then to operate it into the Swiss spallation neutron facility SINQ at PSI .

It has to be equipped to provide the largest possible amount of scientific and technical information without jeopardizing its safe operation.

Minimum design service life fixed at 1 year (6000 mAh).

Nota : PSI interest lies also in the potential use of a LM target as a SINQ standard target providing a higher neutron flux than the current solid targets. Calculations of the radial distribution of the undisturbed thermal neutron flux for the LBE target in comparison to the former Zircaloy and current steel-clad solid lead target were done with different nuclear codes ; nevertheless, variations between various codes enlightened the necessity of flux assessment by direct measurement.

Main challenges

Three main challenges :

- to design a completely different concept of target in the same geometry of the current spallation targets used at PSI.

- to develop and integrate two main prototypical systems : a specific heat removal system and an electro magnetic pump system for the hot heavy liquid metal in a very limited volume.

- to design a 9Cr martensitic steel (T91) beam window able to reach the assigned life duration.

Choice of Lead-Bismuth

Lead bismuth eutectic (Pb44.5%-Bi55.5%) has been selected, due to its attractive neutronic and physical properties : heat transfer coefficient, low melting point (125°C); nevertheless bismuth induces to the production of activation products i.e. polonium,...

Property		Pb	Bi	LME *	LBE**	Hg
Composition		elem.	elem.	Pb 97.5% Mg 2.5%	Pb 45% Bi 55%	elem.
Atomic mass A (g/mole)		207.2	209	202.6	208.2	200.6
Density (g/cm^3)	20°C	11.35	9.75			10.5
	liquid	10.7	10.07	10.6	10.5	13.55
Linear coefficient of thermal expansion (10^{-5} K^{-1})	solid	2.91	1.75			
	liquid (400°C)	4		4		6.1
Volume change upon solidification (%)		3.32	-3.35	3.3	0	
Melting point (°C)		327.5	271.3	250	125	-38.87
Boiling point at 1 atm (°C)		1740	1560			356.58
Specific heat (J/gK)		0.14	0.15	0.15	0.15	0.12
Thermal neutron absorption (barn)		0.17	0.034	0.17	0.11	389

* LME - lead/magnesium eutectic ** LBE - lead/bismuth eutectic

Choice of T91 for the beam window

Compared to austenitic steel 316L, T91 has :

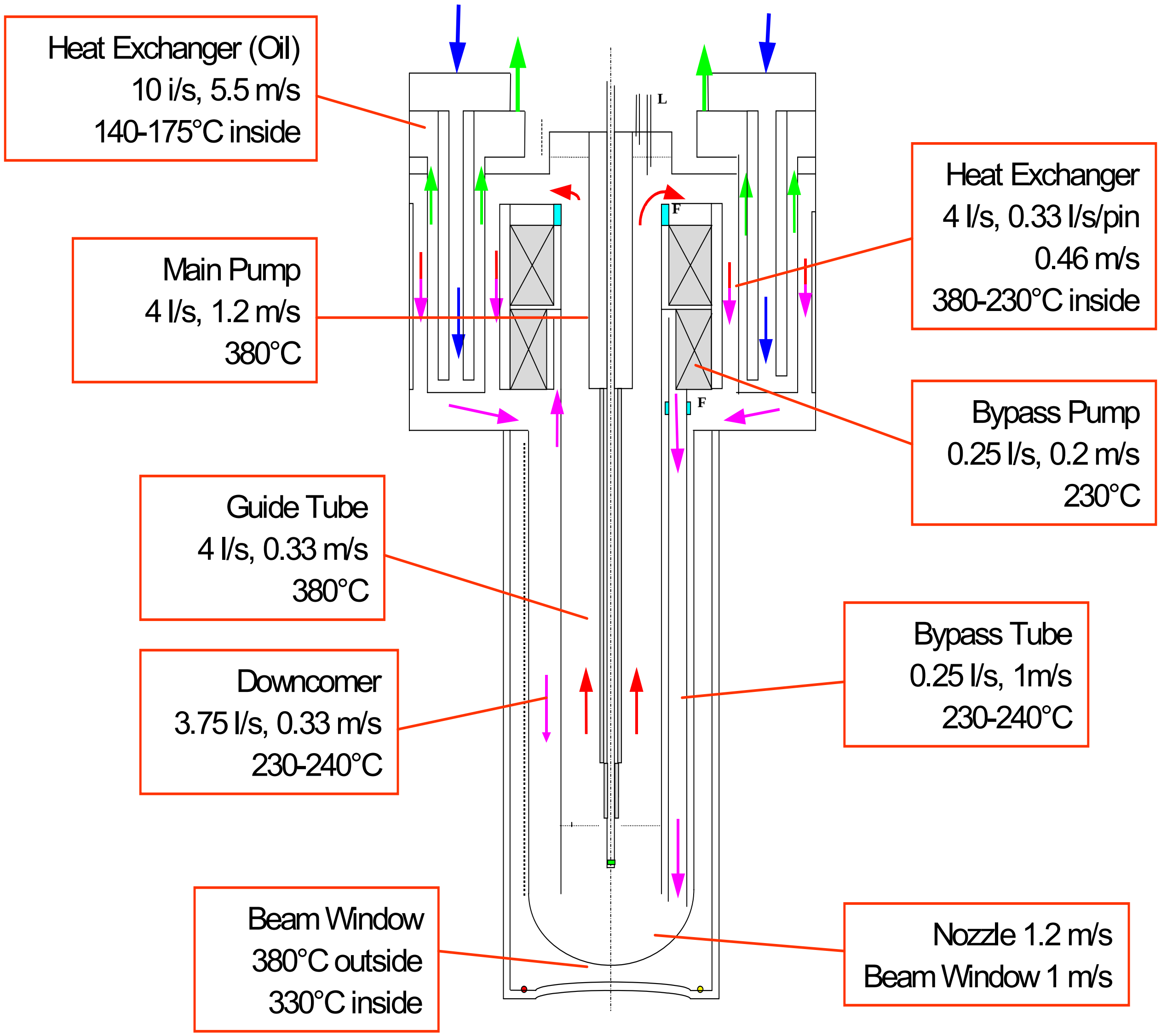
- higher strength.
- much better resistance to heat deposit (due to a lower thermal expansion coefficient and a higher thermal conductivity). As a result, thermal stresses are about twice as high in 316 as in T91 for a given geometry and heat deposit.
- better corrosion resistance in Pb-Bi due to a low nickel content.

Furthermore, for applications under irradiation up to high doses at temperatures higher than about 400°C, T91 has additional advantages over 316 :

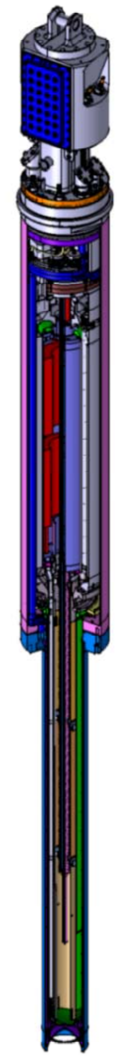
- much lower swelling.
- better resistance to the “high temperature helium embrittlement” phenomenon.

Of course, the main weakness of martensitic steels is the existence of the Ductile-to-Brittle Transition temperature (DBTT) which is shifted as a result of irradiation. This shift is small for 9Cr martensitic steels up to high doses at irradiation temperatures higher than 400°C. At lower irradiation temperature, a significant DBBT shift occurs.

(T91 : (0.1C, 0.32Si, 0.43Mn, 8.73Cr, <0.01W, 0.99Mo, 0.19V, 0.031Nb, 0.029N, 0.24Ni))



Heat Exchanger (Oil)
10 i/s, 5.5 m/s
140-175°C inside
Main Pump
4 l/s, 1.2 m/s
380°C
Guide Tube
4 l/s, 0.33 m/s
380°C
Downcomer
3.75 l/s, 0.33 m/s
230-240°C
Beam Window
380°C outside
330°C inside
Heat Exchanger
4 l/s, 0.33 l/s/pin
0.46 m/s
380-230°C inside
Bypass Pump
0.25 l/s, 0.2 m/s
230°C
Bypass Tube
0.25 l/s, 1m/s
230-240°C
Nozzle 1.2 m/s
Beam Window 1 m/s
L
F
F



MEGAPIE – Target main characteristics

Beam energy:	575 MeV
Beam current:	1.74 mA (design)
Length:	5.35 m
LBE volume:	~ 82 l
Weight:	~ 1.5 t
Wetted surface:	~ $8m^2$
Gas expansion volume:	~ 2 l
Insulation Gas:	0.5 bar He

Deposited heat:	650 kW
Cold temperature:	230 – 240°C
Hot temperature:	380°C
Design temperature:	400°C
Operating pressure:	0 – 3.2 bar
Design pressure:	16 bar
Total LBE flow rate:	4 l/s
By-pass flow rate:	0.25 l/s

The MEGAPIE project : support to design

The preparation of the complete design of the target with ancillary systems required first the **definition of critical issues and required R&D needs** which are inherent in the design and operation of a spallation target.

- An answer to target specific critical issues was given using **analytical, numerical and experimental approaches**.
- The results of these dedicated studies contributed to the **validation of the design and operating options** .
- Moreover, these studies also contributed to **safety and reliability assessment** of aspects which might endanger the integrity and operability of the target.

Support to the MEGAPIE design has been mainly devoted to the following fields :

- Neutronics
- Materials
- Structure Mechanics
- Thermal hydraulics
- Mass and heat transfer
- Liquid Metal Technology

CADARACHE

MEGAPIE : Main Results

The Megapie target has been designed and successfully manufactured in France*, under the QA of PSI, with the Design Support activities of the MEGAPIE partnership.

*** Pumps designed and manufactured in Latvia.**

A very large amount of experimental tests, calculations, projectstudies have been carried out in various fields.

It has been demonstrated that:

- the target is coolable
- there are no major problems linked to liquid metal technology
- corrosion is limited and window lifetime has been estimated to an acceptable value (23 weeks).
- no critical points for ancillary systems have been evidenced
- irradiated target handling and waste management is well defined,
- safety demonstration is possible.

CADARACHE

MEGAPIE – Target components

Target window: T91, 1.5 mm

Target heat exchanger
12 pin LBE – Diphyl THT

Target head
Connector interface to ancillary systems

Main and by-pass tube
LBE flow guide

Ancillary systems

Ancillary systems were designed by PSI, ENEA and Ansaldo.

Heat removal system, HRS, with Diphyl THT® oil a cooling medium and an intermediate water loop,

Cover Gas System, CGS, to cope with the overpressure in the target and to assure the confinement of all radioactive gases produced by the spallation process (about 8 liters) and a regular and controlled venting. (gases collected in the target expansion tank and periodically evacuated via filters into a decay tank).

LBE Fill and Drain System, F&D, with a double containment and an appropriate system for disconnecting the tubes after operation.

Beamline adaptations including advanced beam monitoring : implementation of Catcher, funnels, collimator slit, VIMOS (beam position visualization system).

Handling devices for the target decommissioning, storage, dismantling and disposal.

Integral Tests

Integral Test: **September to December 2005**

–to integrate the target and the ancillary systems,

– to carry out LBE filling and draining operations,

– to check the operability of the main components of the target,

– to check and calibrate the instrumentation (mainly flow-meters)

– to determine the thermal hydraulics characteristics of the system,

– to simulate heat deposition (with a heater)

– to characterize the heat transfer and hydraulic behavior at the window,

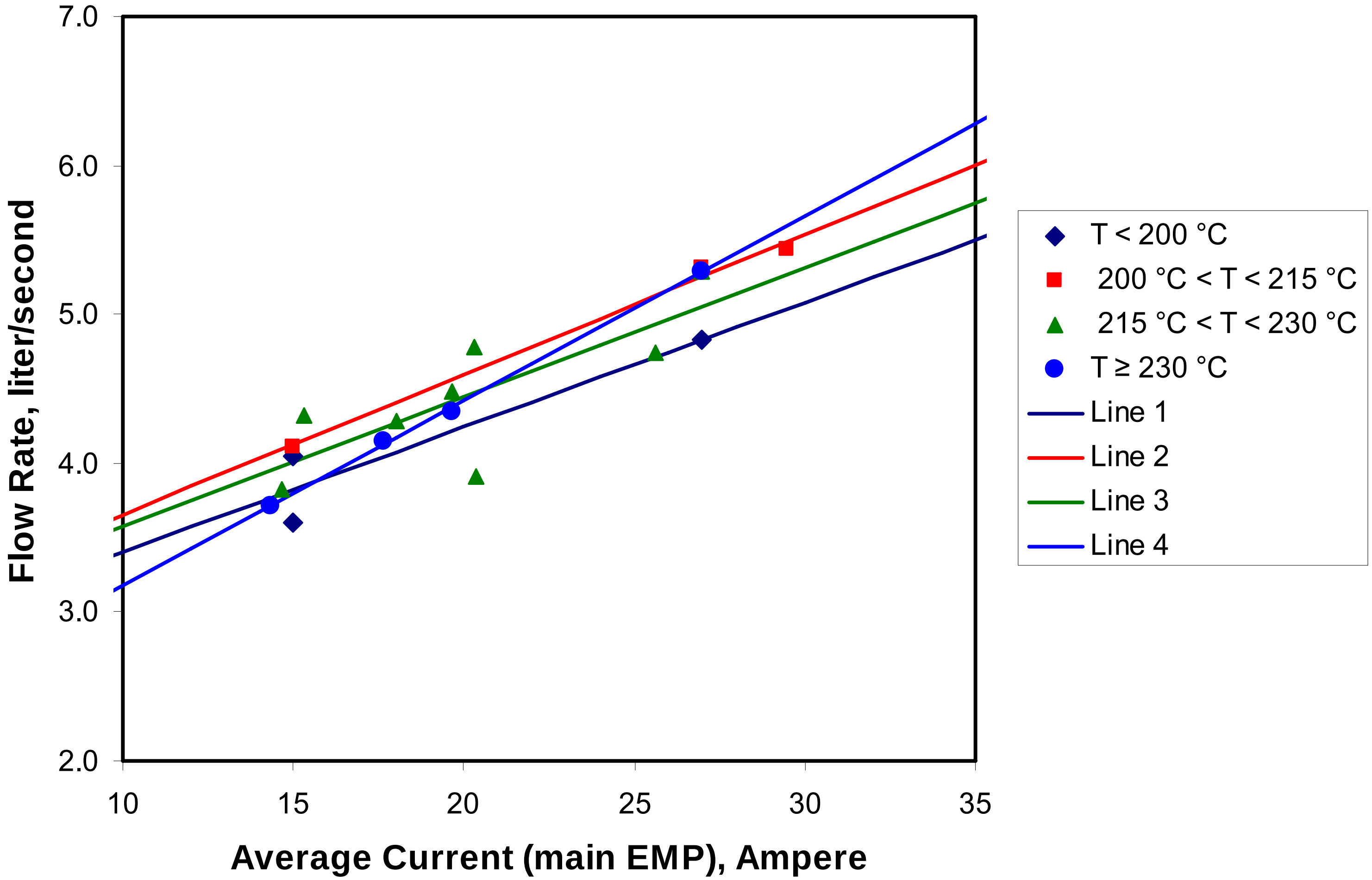
– to obtain the vital parameters for system control,

– to provide enough information for licensing the target for irradiation test,

– to gather technical and scientific data for model verification, in order to be able to extrapolate the Megapie experience for the future ADSs

Transfer to SINQ: **January to March 2006**

Main characteristics of the main EMP



CADARACHE

Thermohydraulic tests : results for control system

Four tests → set of the data for the system characterization.

Requirements for the control of the target for an efficient and safe control :

- **Keep the target (window) at a constant temperature of 230°C :**
  - → not too low to have a safe margin before freezing,
  - → not too high to limit thermal stress on the heat exchangers.

- **Limit temperature excursions during beam transients** : beam on / off operations, beam trips and interrupts.

- **Assure stable target temperature in the three reference operating cases :**
  - isolation (target isolated from heat removal system),
  - hot standby (awaiting beam operation) and
  - full beam power.

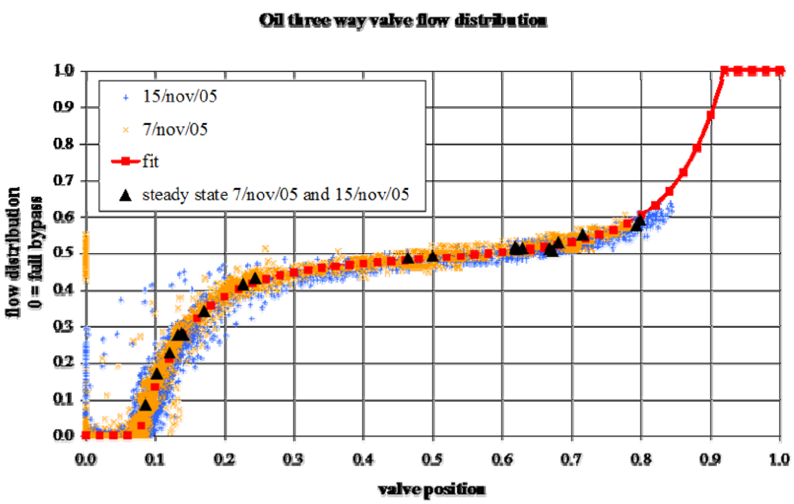
Thermohydraulic tests : results for control system

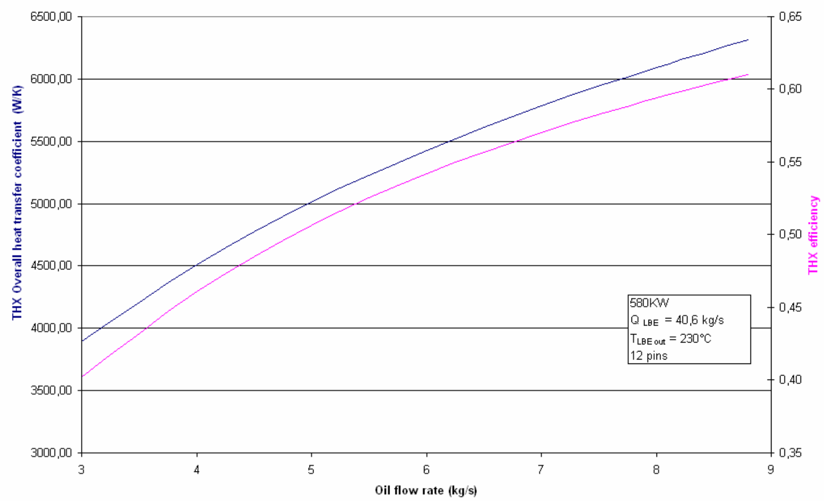
During the integral tests, it was seen that :

- the characteristics of the oil three-way valve are highly non-linear, and

- the target heat exchanger performance was better then expected (20 to 40 % according different evaluations);

→ main consequence : only about 40% oil flow through oil/water heat exchanger during full beam power operation



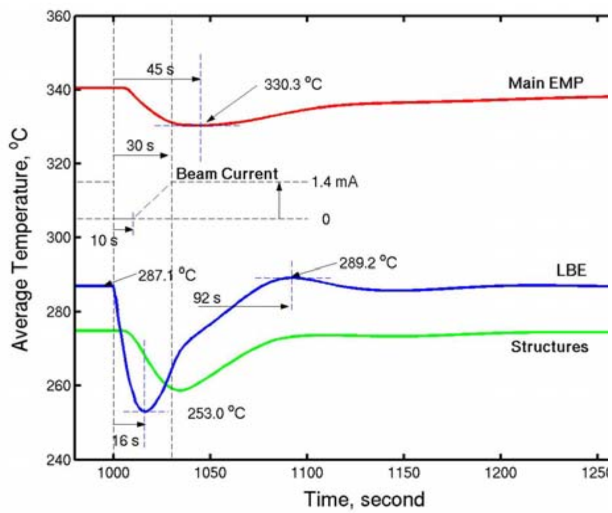


Oil three way valve characteristics

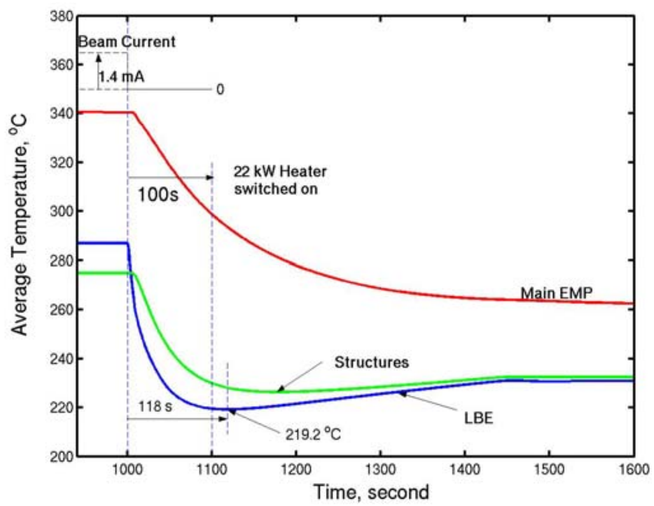
Influence of oil flow-rate on Heat transfer coefficient

Integral test : beam trip simulation

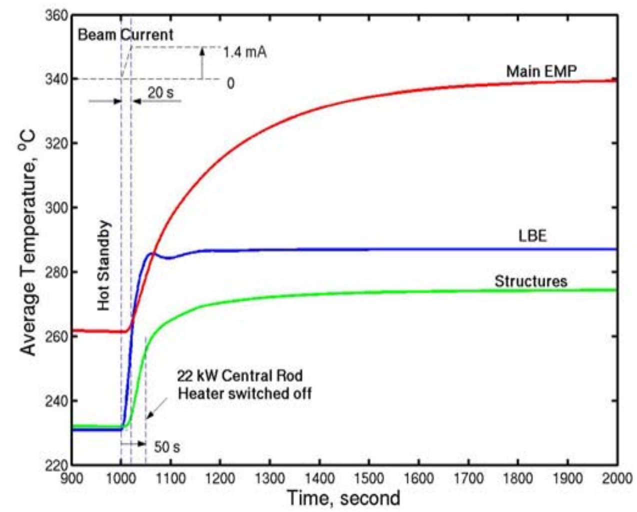
<u>Main assumption for the system characteristics analysis :</u> main LBE flow rate computed from the heat balance of known power input.
→test simulating a beam trip (average temperatures of LBE, target structures, and main EMP) and showing the capacity of the Heat Removal system to react to the transient situation.



(a) during beam trip

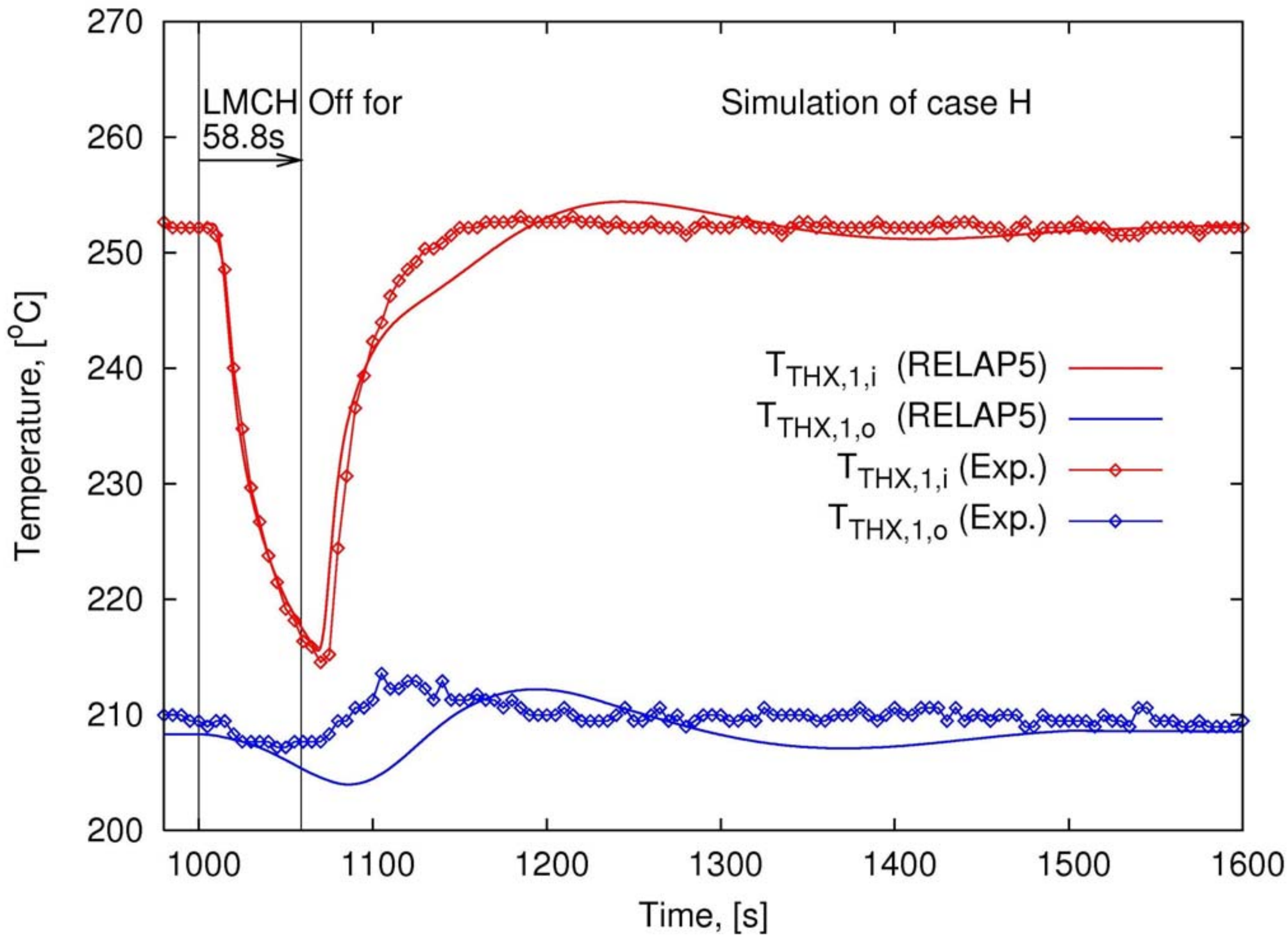


(b) during beam interrupt



(c) restarting from how standby

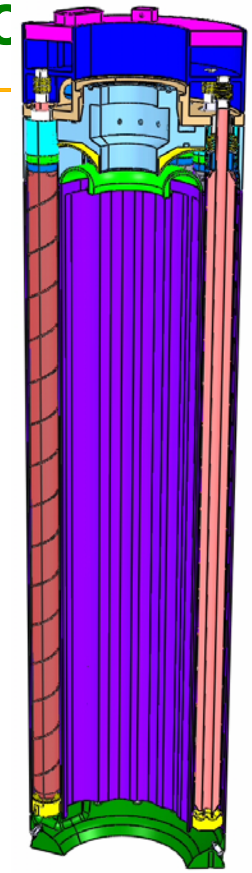
Experimental / calculated temperatures for an unprotected trip



RELAP model more or less verified but could be improved by a better estimation of :

- the thermal masses of LBE and structures (Cp,…)
- the heat transfers coefficients (using T of the main and bypass EMPs,),

Integral tests : THX design validation



Sufficient capacity of the Heat Removal System to cope with about 600 kW of heating in the target and flexible to the changes, though the operating conditions might be differed from the predictions.

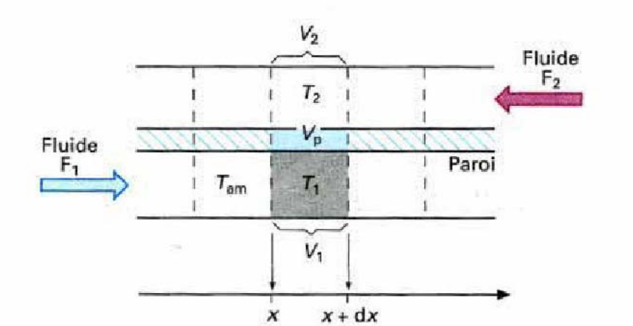
But : after the integral tests, bypass flow conditions still to be determined

Analysis of the experimental data of the LBE-oil thermal exchanger of the target (with analytical heat exchanger calculations (Global model, ε-NUT, and numerical model (1D), finite volumes) :

→For each of the 4 campaigns, computed values in agreement with the corresponding experimental results.(maximum variance between calculations and experiments very low, and
below the accuracy of the model is about 20%).

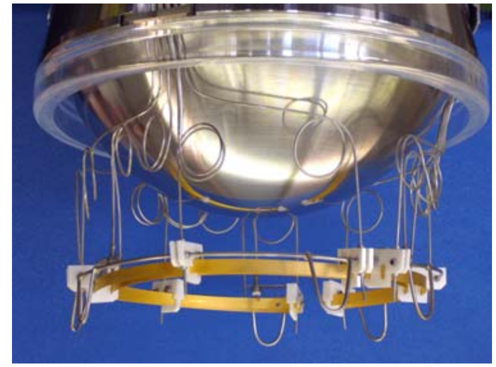
→Thus, THX heat transfer model used to its design, validated, even if some uncertainties hang over flow rates assessments.

→Parametric study of sensitivity : large margins on the THX thermal exchange capacity.



Full scale leak test

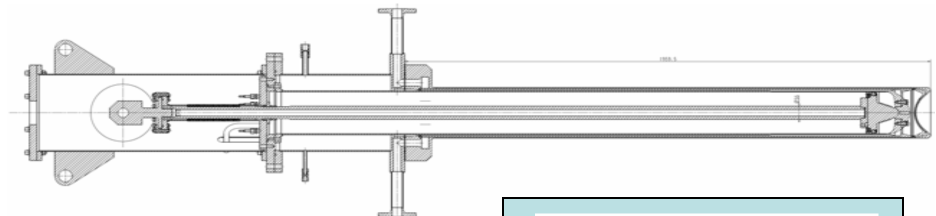
Main goals : to validate :
- the design of the Lower Target Enclosure (LTE) under worst case leak conditions,
- the leak detector system, implemented in the lower part of the LTE.



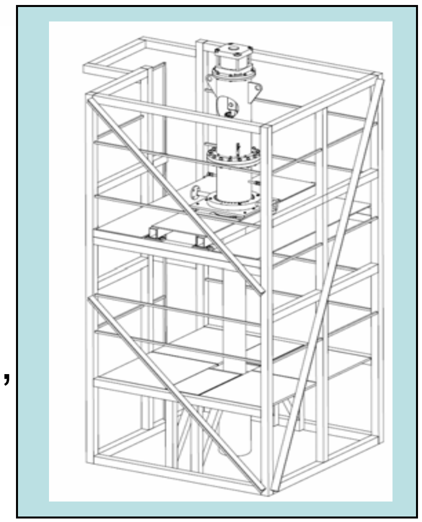
2 different sensors implemented :

- Thermocouples (9 individual and independent sensors, 3 electrically preheated) as main leak sensor, and,

- Stripe sensors type “AC impedance” (3 separate units)

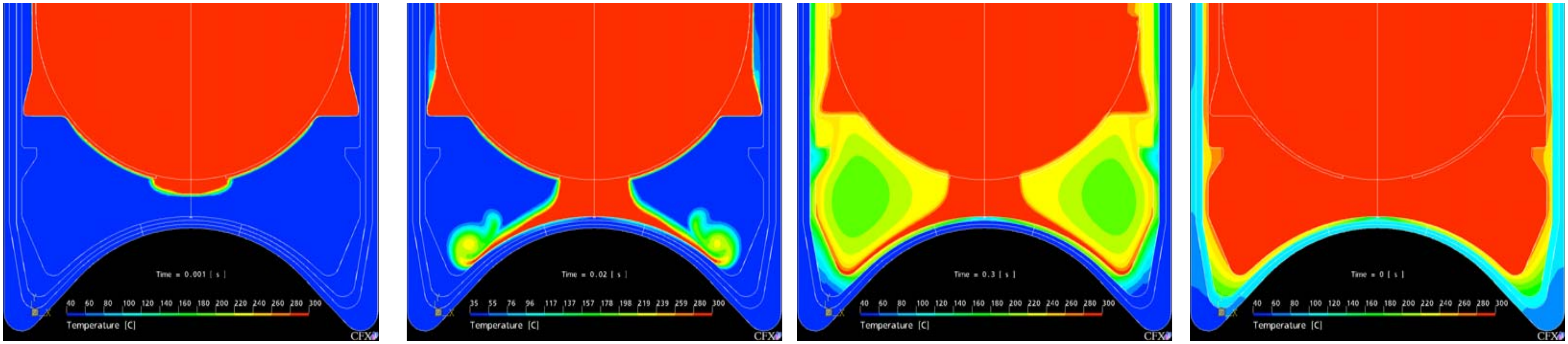


Main results :
- Lower target enclosure : able to contain LBE.
- Validation of the leak detector system :
- detection of < 0.5 liter LBE within 1 s with a very high reliability,
- 100 % detection efficiency with a very low false alarm rate,
- temperature resistant.

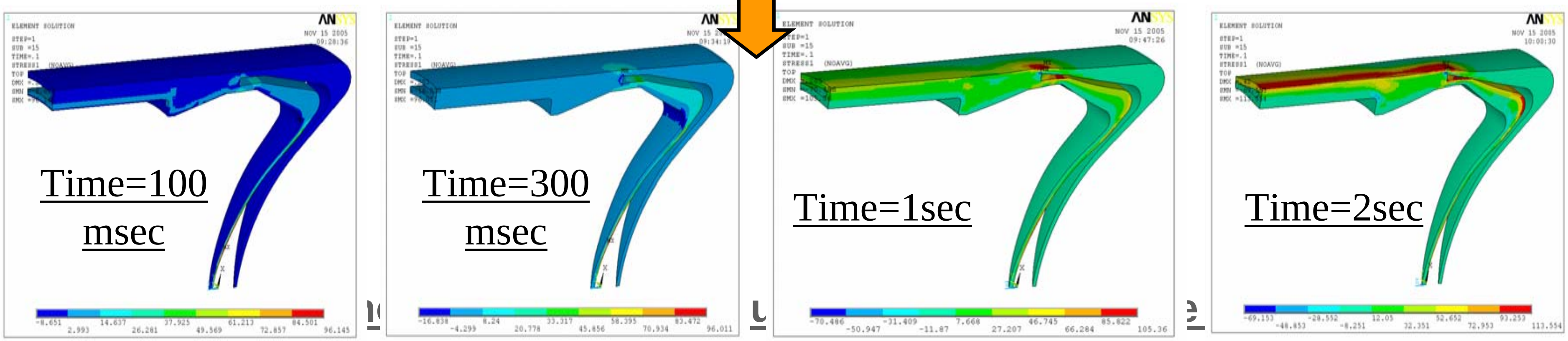


CADARACHE

Full scale leak test simulation



IN: Fluid dynamic transient of liquid metal in the containment hull



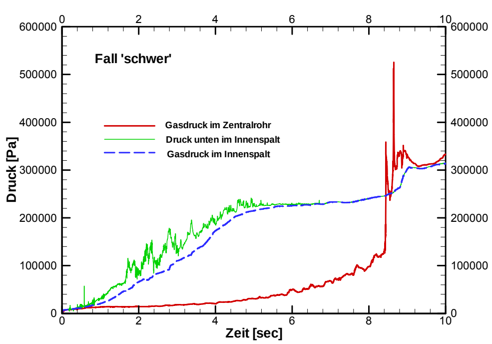
LBE-water interaction : simulation with MATTINA and SIMMER codes

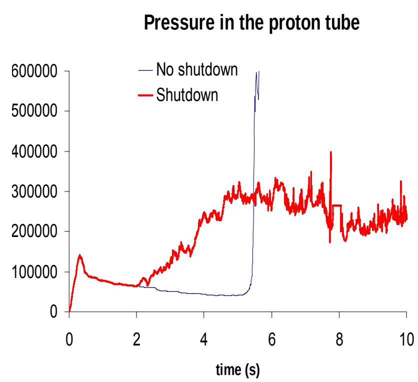
Main goals : **Analysis of the potential consequences of 3 simultaneous failures of the target shells and Lbe-water contact :**

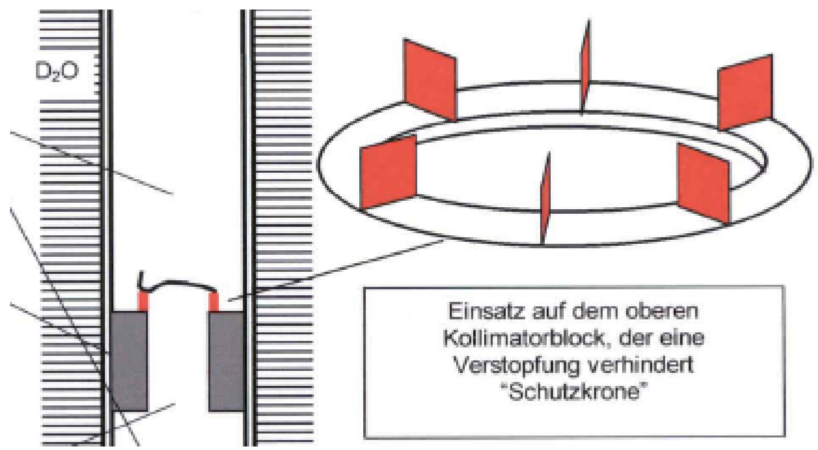
Independent investigations with MATTINA and SIMMER codes, able to model the hypothetical interaction between lead bismuth alloy and D2O, inducing water vaporisation and target pressurisation (Target can withstand P<30 bar).

Main results :

- →**evaluation of the accidental sequence,**
- →**Exclusion of the vapour explosion event**
- → **demonstration of the structure integrity (Pmax << 30 bars).**



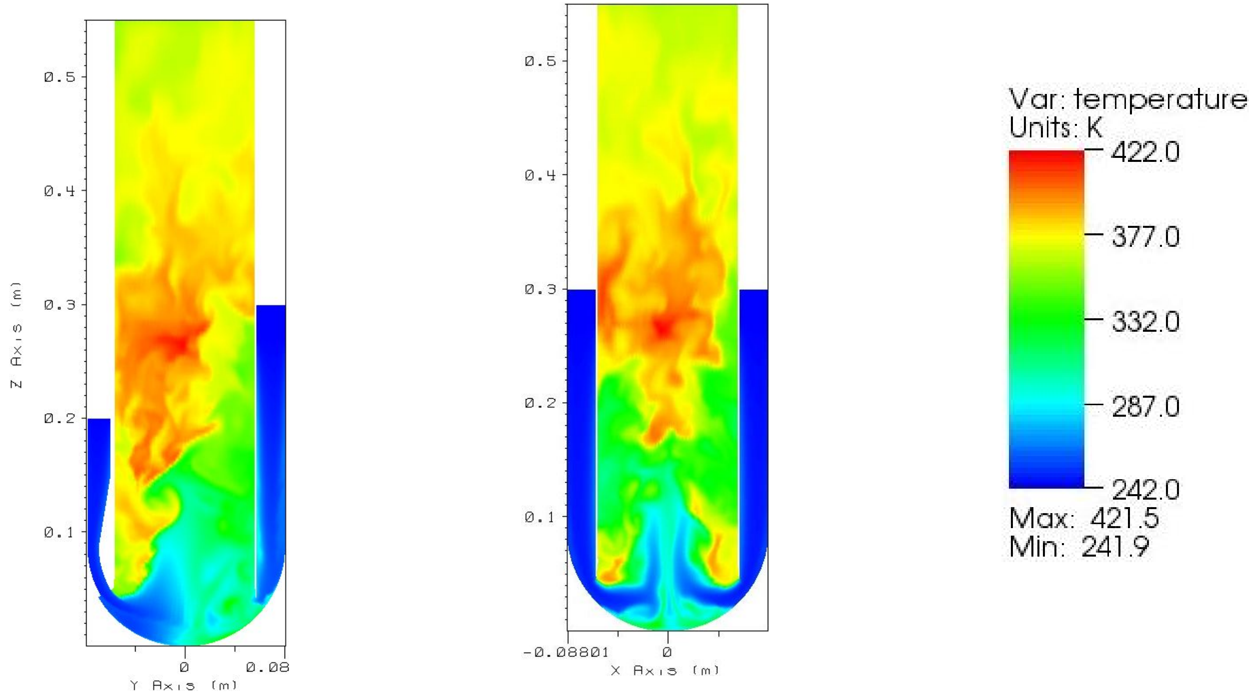




Large Eddy Scale Simulations

Main goals : <u>For the future Post Test analysis phase after irradiation:</u>

→Large Eddy Scale simulations (LES) by CEA to analyse the instability, close to the window. (CEA TRIO-U-VEF parallelized code)
→Assessment of the level of temperature and velocity fluctuations near the window, to give realistic data for thermo-mechanical studies aiming to demonstrate the integrity of the T91 window.



MEGAPIE target in SINQ hall

Target installation in TKE

After the end of the integral tests :

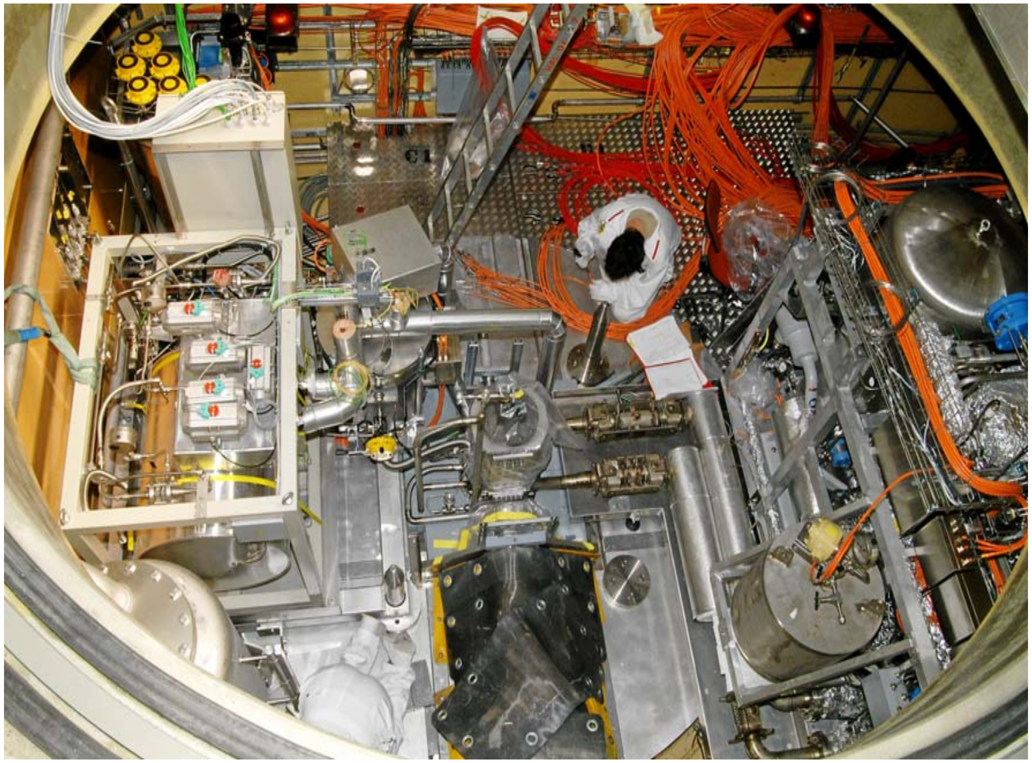
-**central rod of the target cleaned then insertion of the neutron flux detectors.**

- **electrical cabling and other connections**

- **implementation of the LBE leak detector**

-**Lower target enclosure final welding,**

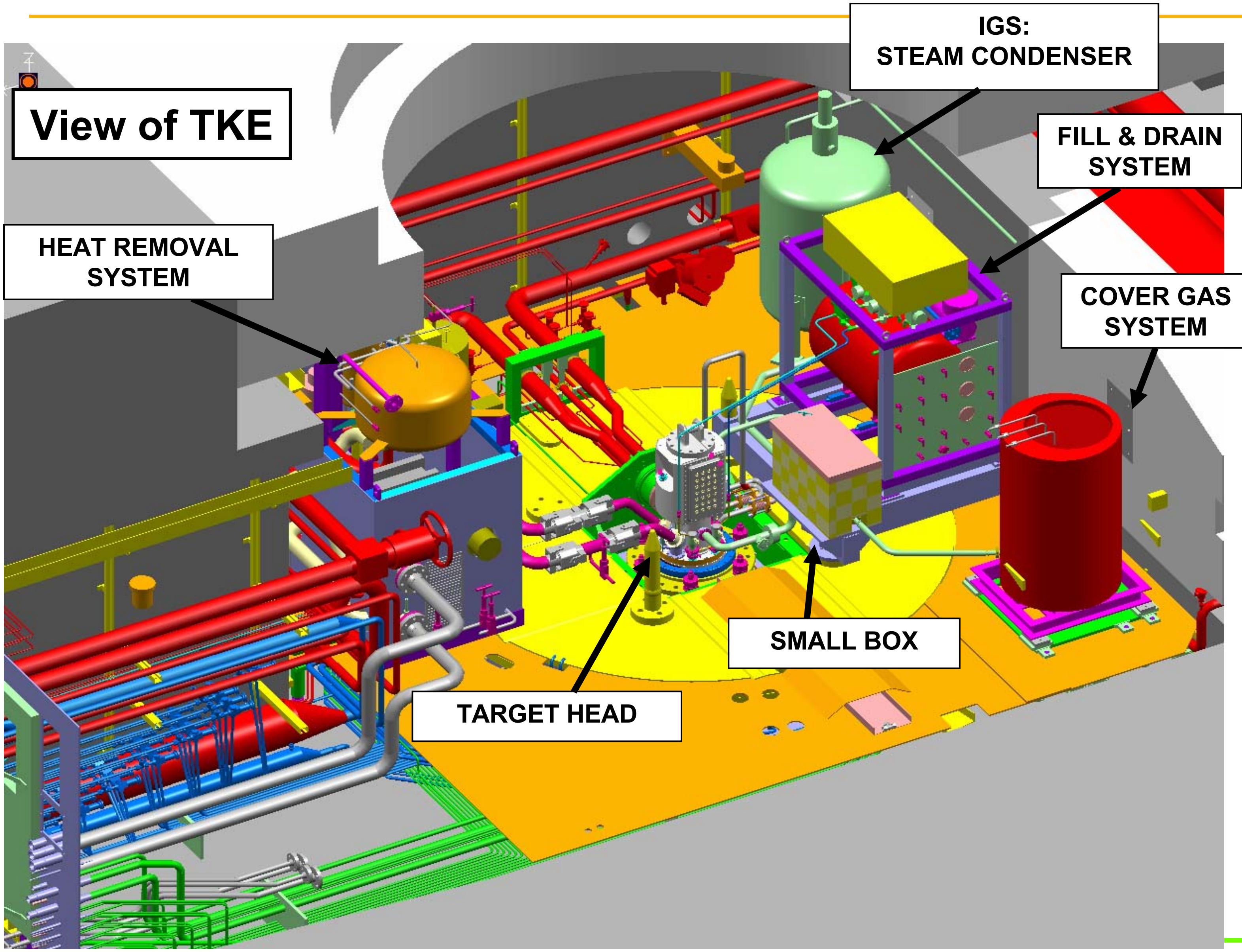
-**Checking of the LTE tightness by X-ray and pressure and leak test.**



→then target installed in SINQ, and connected to ancillary systems :

- **Fill and Drain,**
- **Heat Removal System,**
- **Cover Gas System,**
- **Isolation Gas System,..**

View of TKE

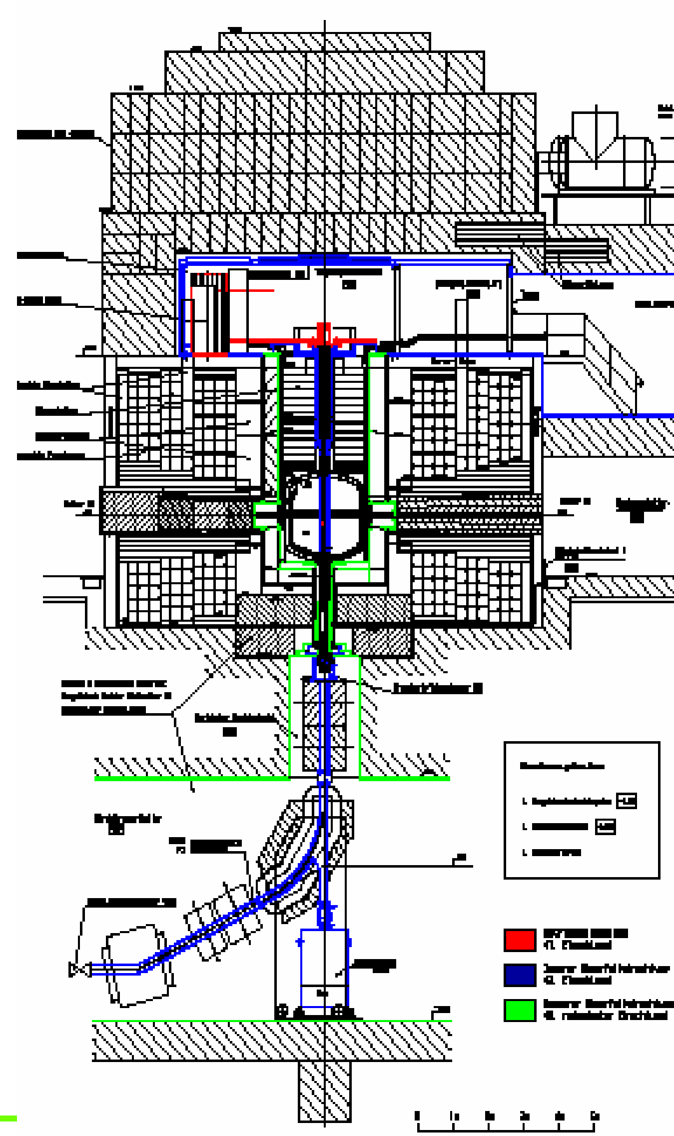


IGS:
STEAM CONDENSER
FILL & DRAIN SYSTEM
HEAT REMOVAL SYSTEM
COVER GAS SYSTEM
SMALL BOX
TARGET HEAD

Safety optimization tasks

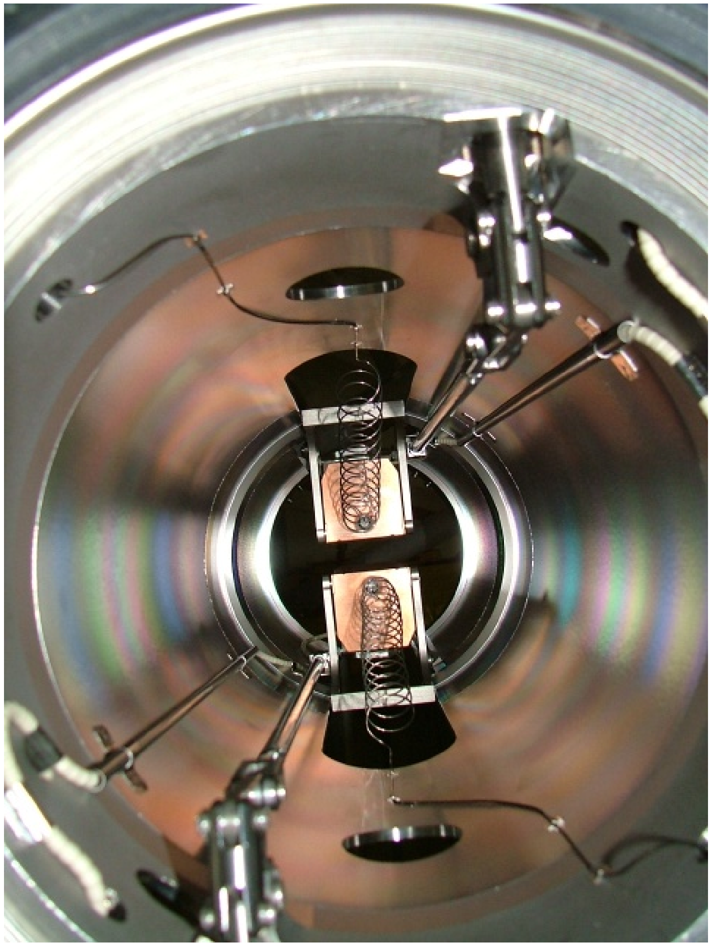
Measures for reduction of the source term in case of an incidental release of activity to reach the 1 mSv criterion for the public:

- better sealing of the TKE & STK
- O_2-Reduction system for the TKE & STK to prevent fire due to oil
- connecting the TKE with the Cooling Plant in order to reduce the possible activity concentration
- upgrade of the ventilation system (earthquake resistant stand-alone exhaust equipment) and of the filter systems (both with activated carbon and particle filters).



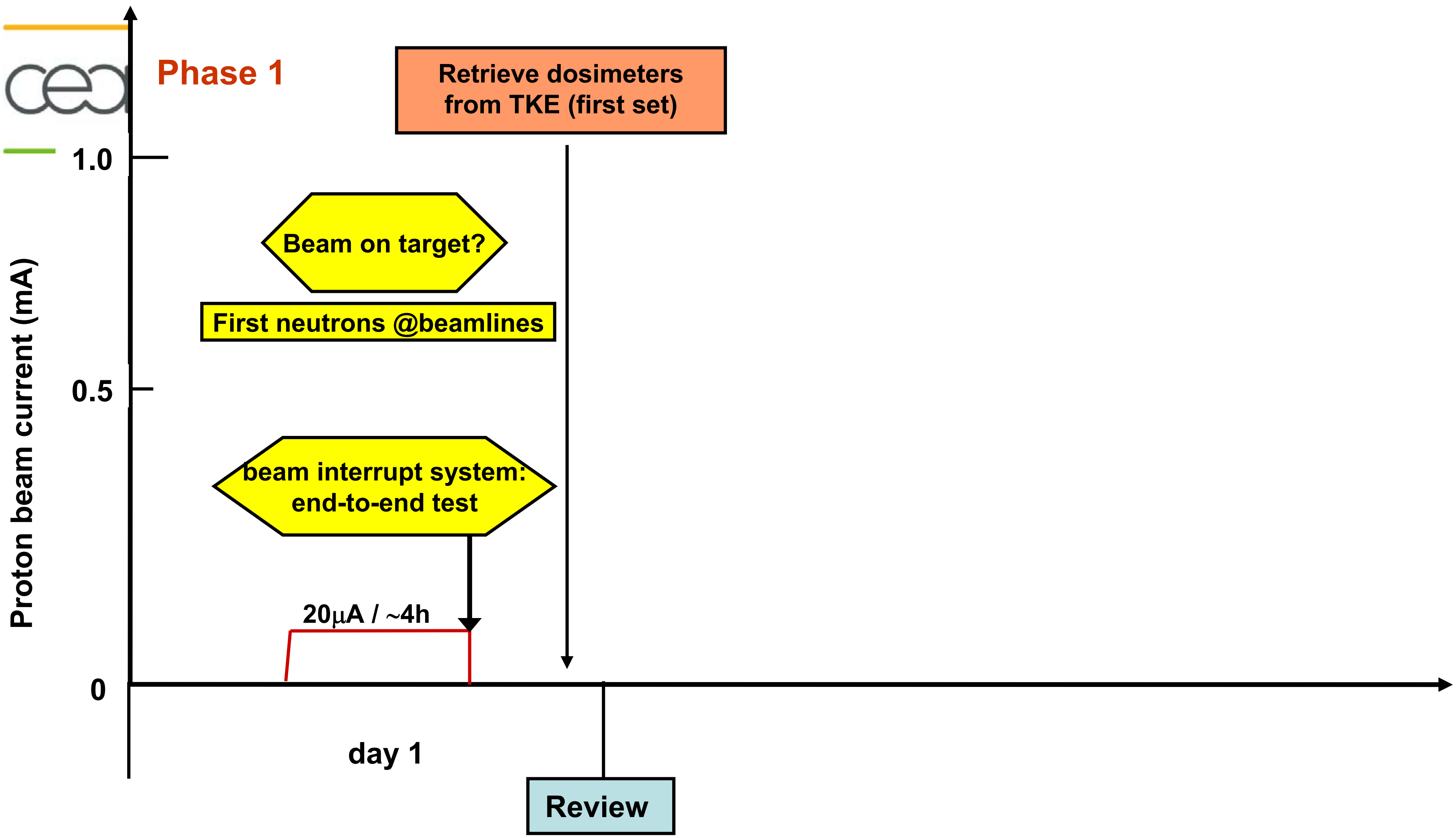
CADARACHE

Collimator slit: mounting in QHJ30 and view inside

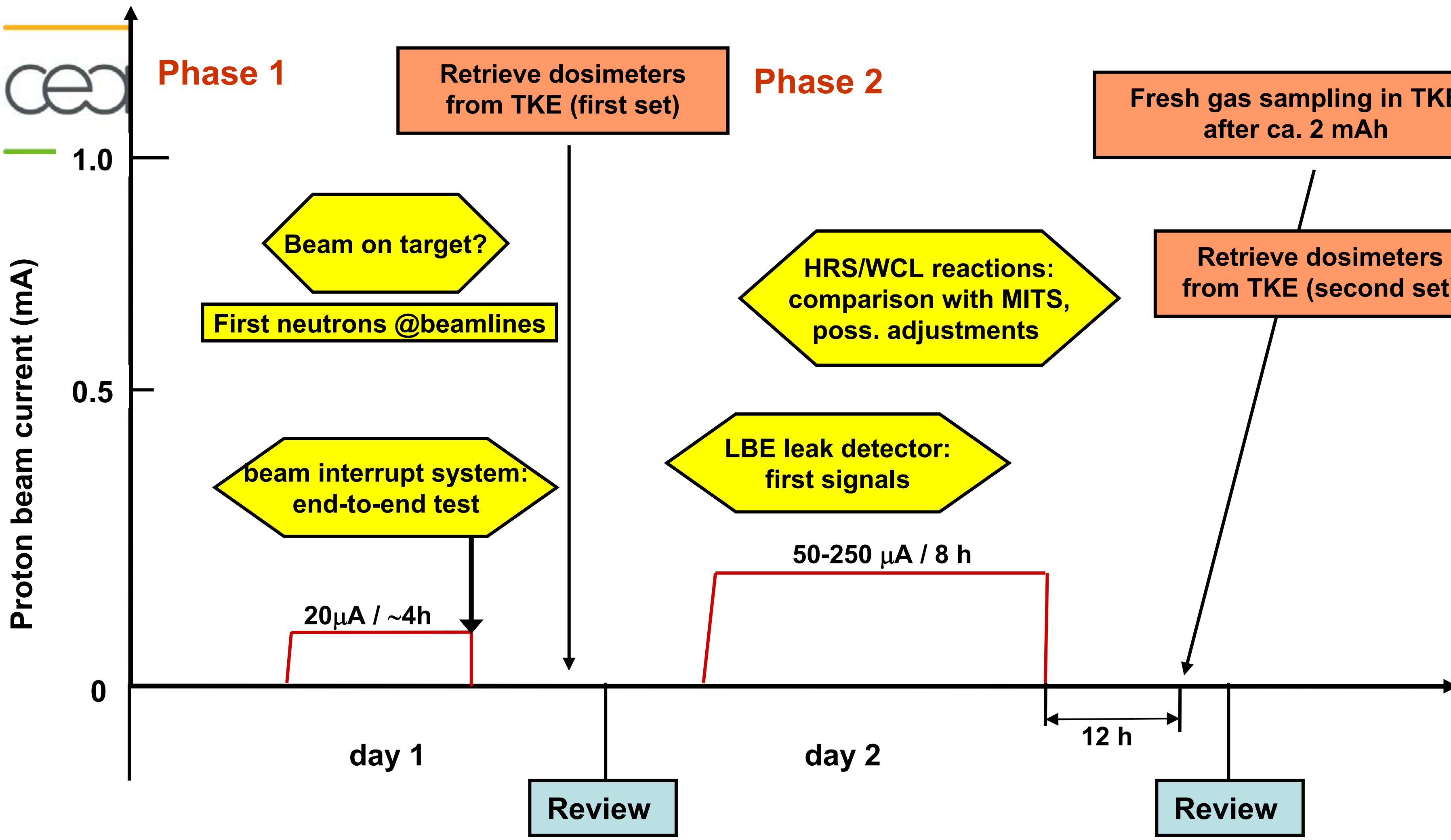


CADARACHE

MEGAPIE: proposed start-up procedure (1)



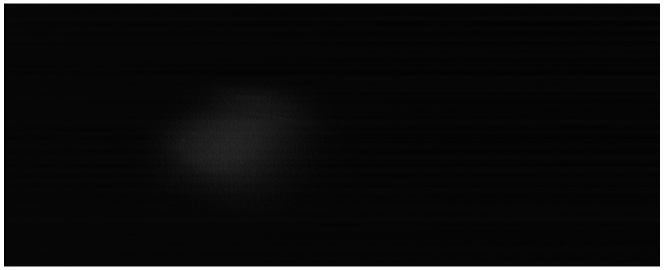
MEGAPIE: proposed start-up procedure (2)

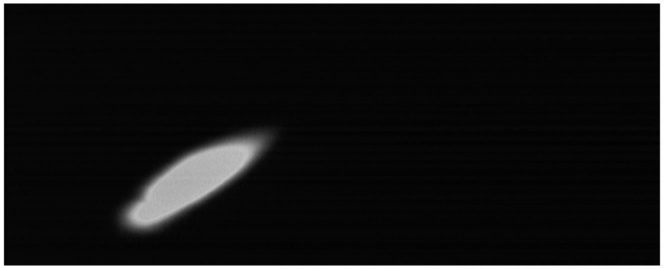


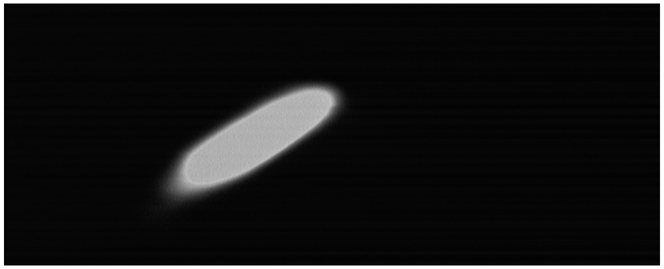
CADARACHE

Beam control systems : VIMOS

VIMOS: optical visualisation of the beam footprint in front of the SINQ beam window

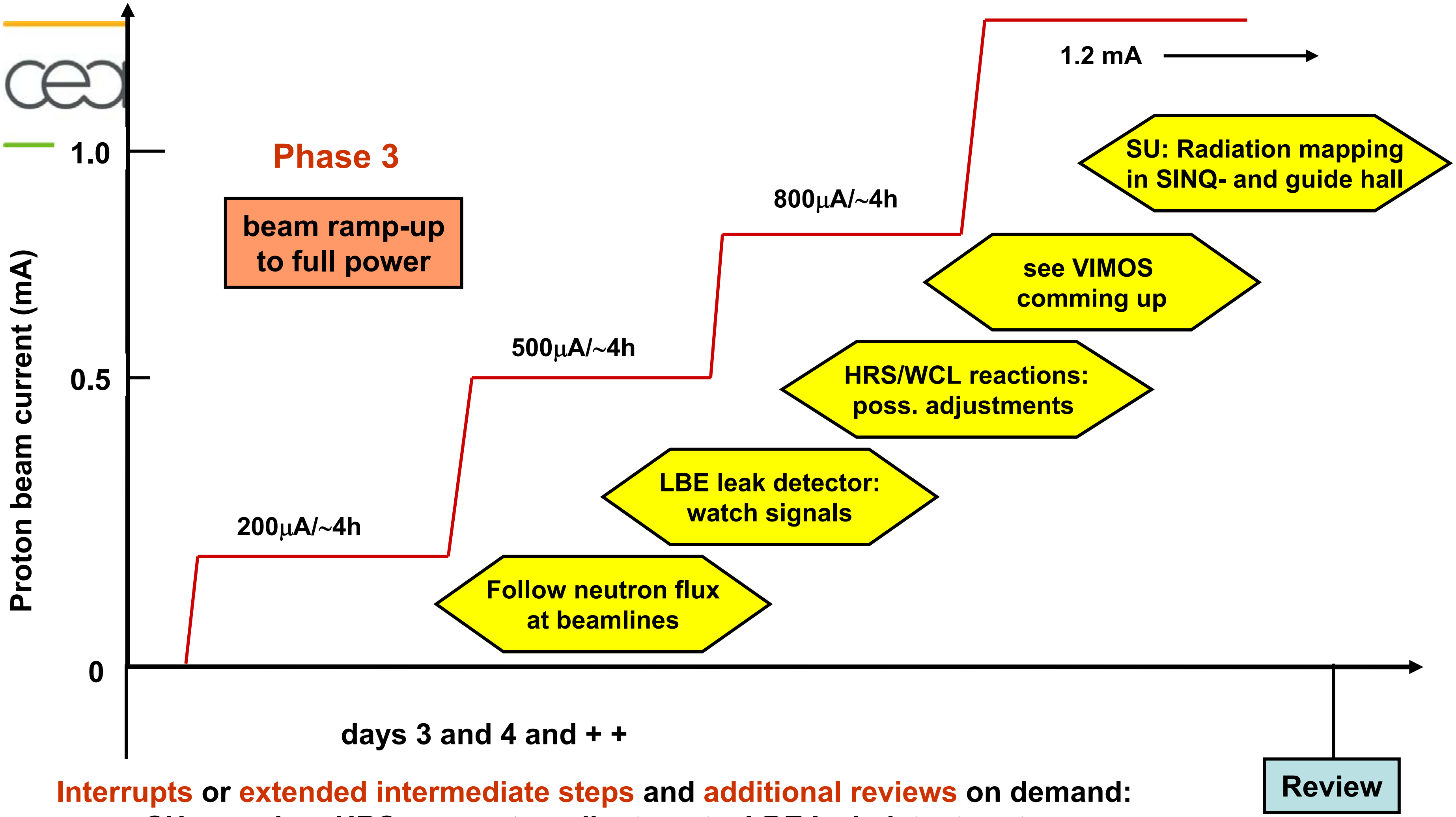






VIMOS hat in insertion tool with LED on

MEGAPIE: proposed start-up procedure (3)



Interrupts or extended intermediate steps and additional reviews on demand:
SU-mapping, HRS parameter adjustments, LBE leak detector etc.

CADARACHE

Reviews after start-up phases

Questions to be addressed:

Systems behavior as expected?

All tests done and o.k.?

Preliminary test reports available (minimum: note in logbook), are the results stored?

Parameter-/SW-adjustments necessary?

BAG requirements fullfilled?

Safe continuation possible?

Target « experimental » monitoring

During irradiation phase of MEGAPIE, numerous operating parameters are monitored :

- pressure, fluid flow-rates and temperatures.
- neutron fluxes at various positions of the facility,
- gas production; (for Monte Carlo calculations of the measured quantities)

→ goal : codes validation MCNPX and FLUKA fitted with appropriate models

Various neutron measurements :

a- Measurements at beam lines :

- with **activation foils** (Measurement of the thermal neutron flux and of the epithermal flux (at a single resonance point at 4.9 eV by wrapping the foil with a Cd layer).
- with **Bonner spheres** (Measurements performed with poly spheres of different radius surrounding 3He detectors, for sensitivity to different neutron energy range. (By Lausanne university)
- **time-of-flight measurements** performed at the SINQ ICON facility using a chopper

b- Other neutron measurements :

- neutron flux inside the target using 8 **micro-fission chambers**. (from thermal to 10 MeV)
- neutron flux with activation **Au foils** inside D2O tank (NAA/PNA stations)
- **delayed neutrons** in the upper part of the target (It is calculated that with a prompt neutron flux in the TKE of about 105 n/cm2/s, the DN flux should be one order of magnitude higher)

Target irradiation

Irradiation : **2006 August 14th to end of 2006**

Main goals :

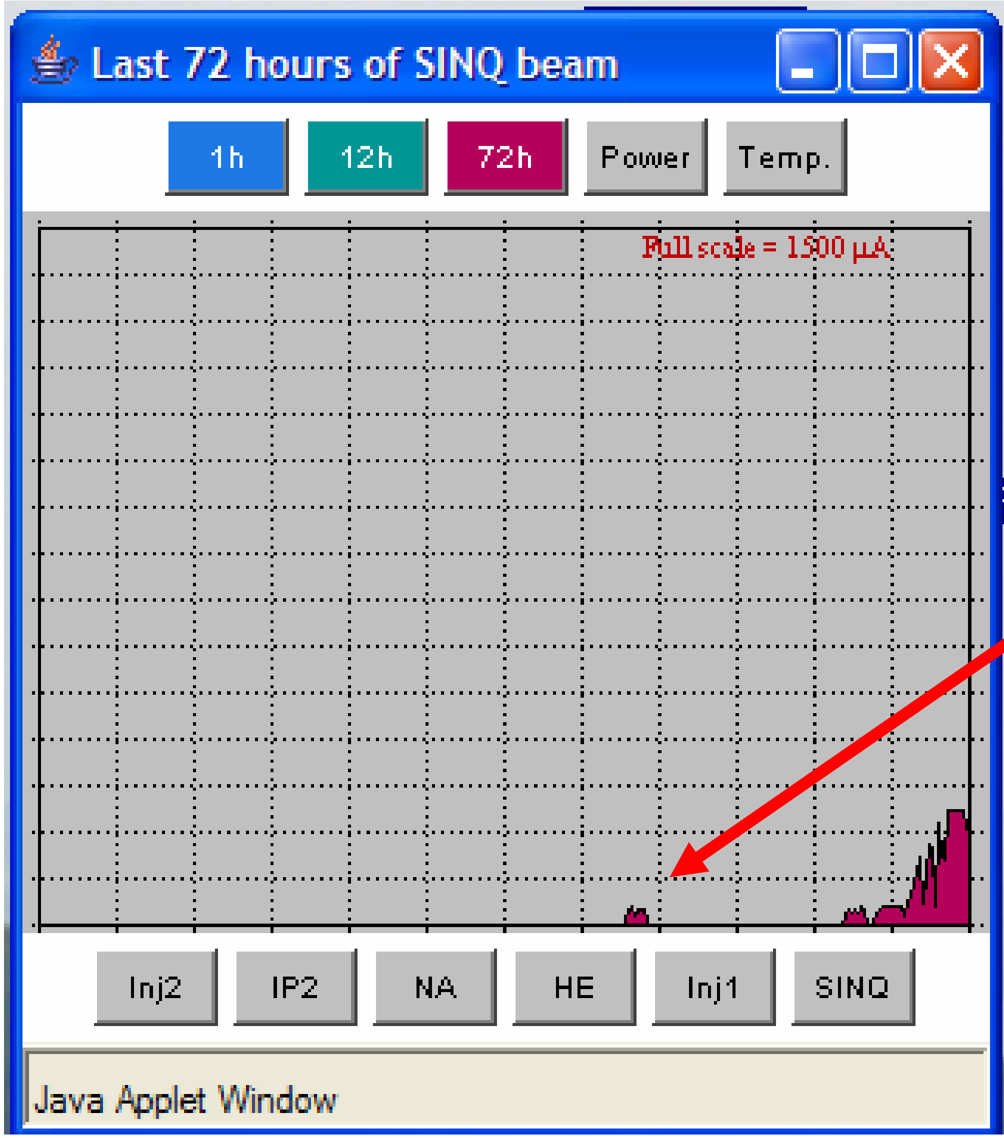
– confirm the main operating parameters,

– obtain neutronic performances, in order to validate the neutronic codes and spallation models

– to confirm material performances evaluated during design support phase,

– more generally demonstrate the ability to operate a liquid metal target in ADS relevant conditions

On Monday, August 14 at 15:30, the target received the first protons !!!.



ca. 2:30 pm first protons hit the target and produce first neutrons

Protonenbeam current 40µA
~ 25 kW

Test duration ca. 3.5 h

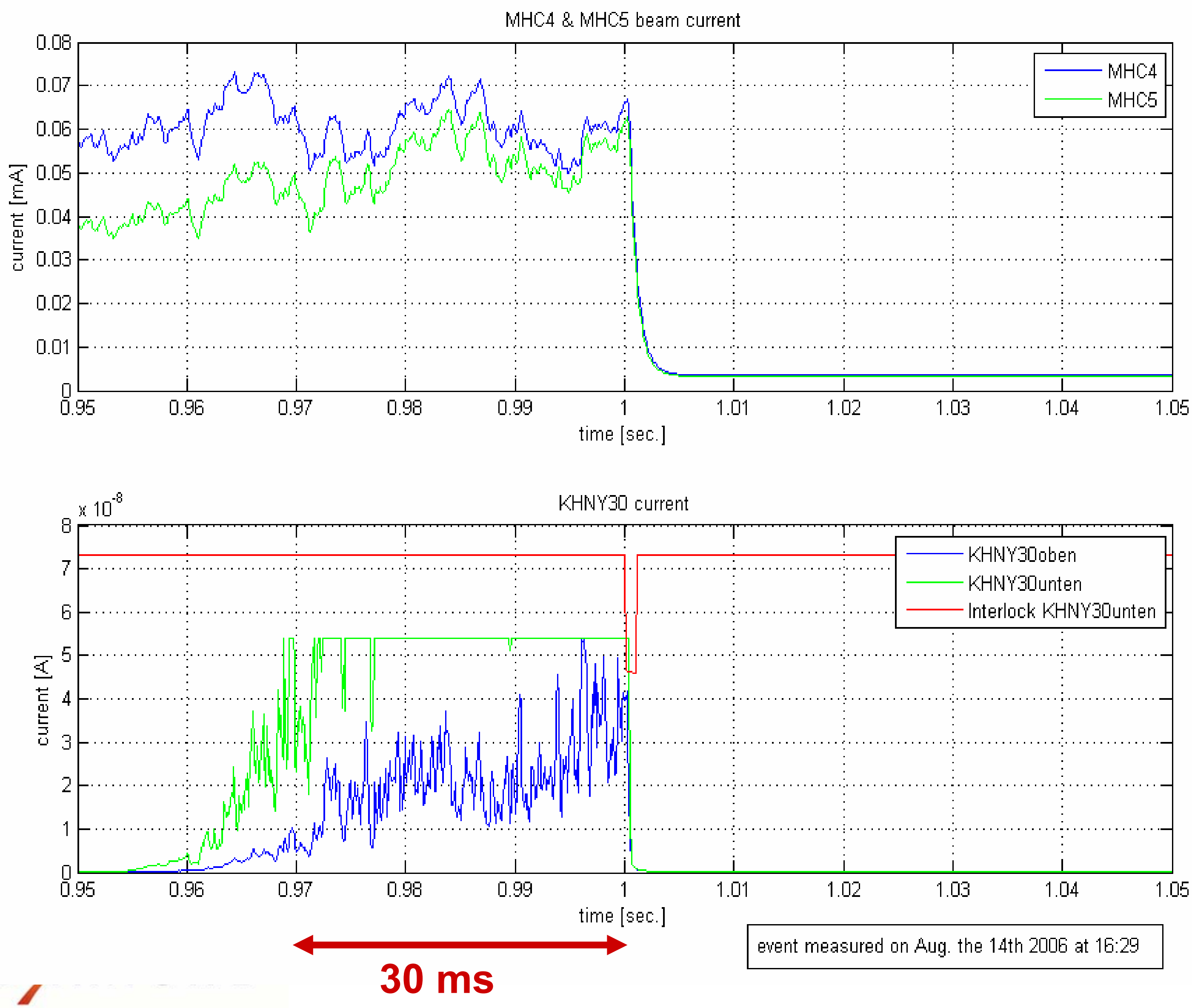
Stable beam for ca. 90 min

ca. 60 µAh total charge received

(sufficient for TKE dosimetry)

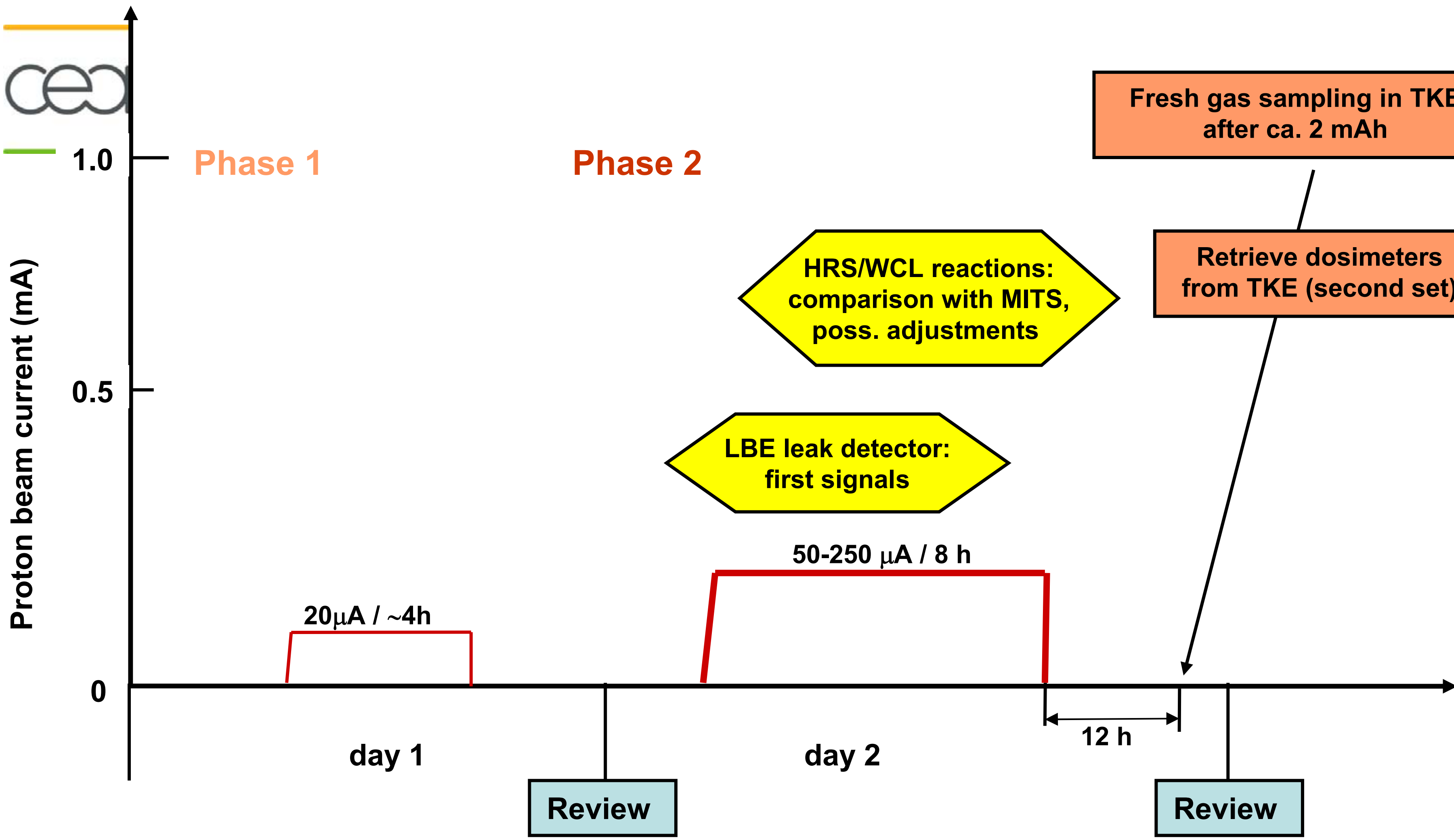
CADARACHE

End-to-end Test @ 40 µA: response time < 40 ms



Proof of Functionality and Sensitivity at very low signal level

MEGAPIE: proposed start-up procedure (phase 2)



MEGAPIE start-up : phase 2

On Tuesday, the beam current was ramped up in steps to 250 mA and the target was on-beam for almost 8 hours.

During a scheduled shutdown of the accelerator on Wednesday :

- cover gas samples extracted
- dosimeters were retrieved.

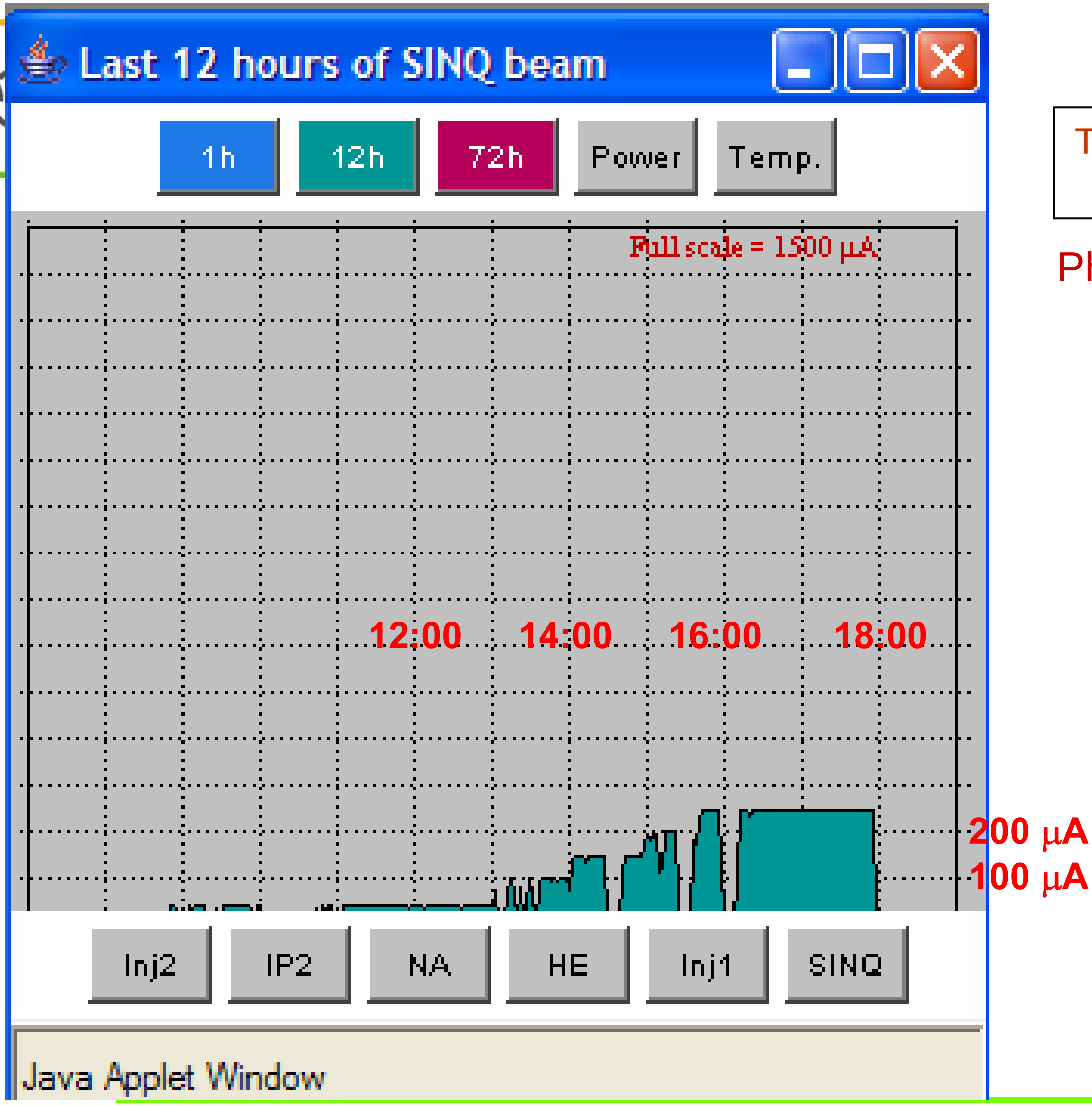
→second review : OK to go on

On Thursday operation continued by ramping up to “full power” (about 1200 mA) (700 kW). The target continued to work as expected.

Measurement of neutron flux in the target and delayed neutrons in TKE : successful.

→Calibration of the LBE flow measurements carried out : OK.

→Calibration of the LBE leak detectors carried out : OK



Tu, Aug 15, 2006

Phase 2

250 mA ~150 kW

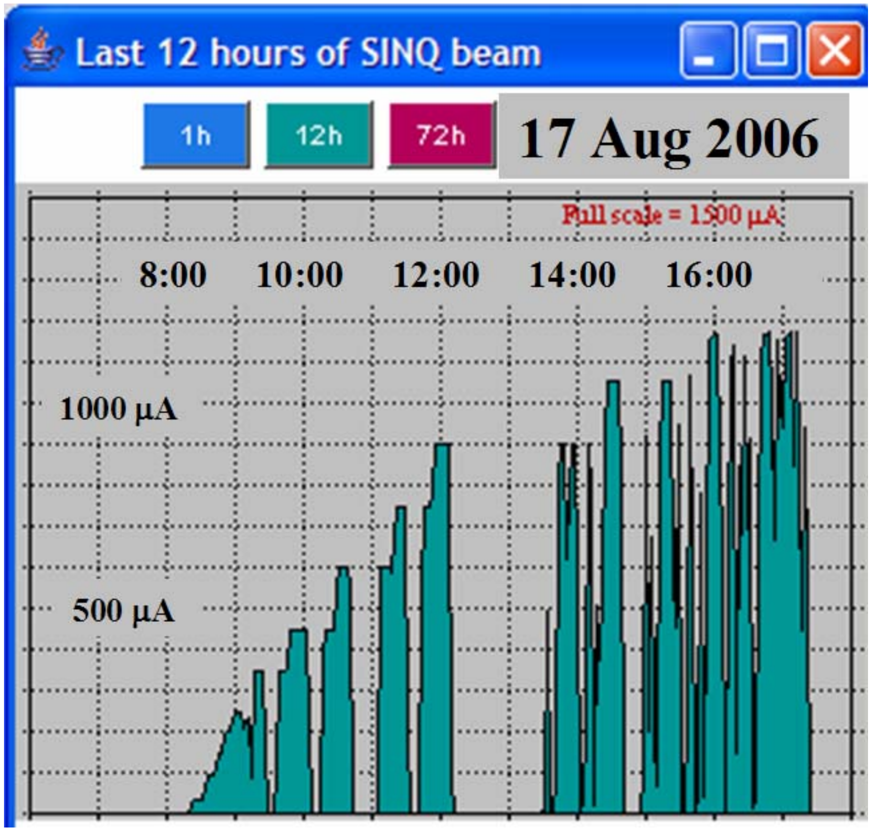
MEGAPIE start-up : phase 3

On Thursday operation continued by ramping up to “full power” (about 1200 mA). The target continued to work as expected.

Measurement of neutron flux in the target and delayed neutrons in TKE : successful.

→Calibration of the LBE flow measurements carried out : OK.

→Calibration of the LBE leak detectors carried out : OK



VIMOS triggered correctly @ 900 µA

Thu Aug 17 13:56:33 2006

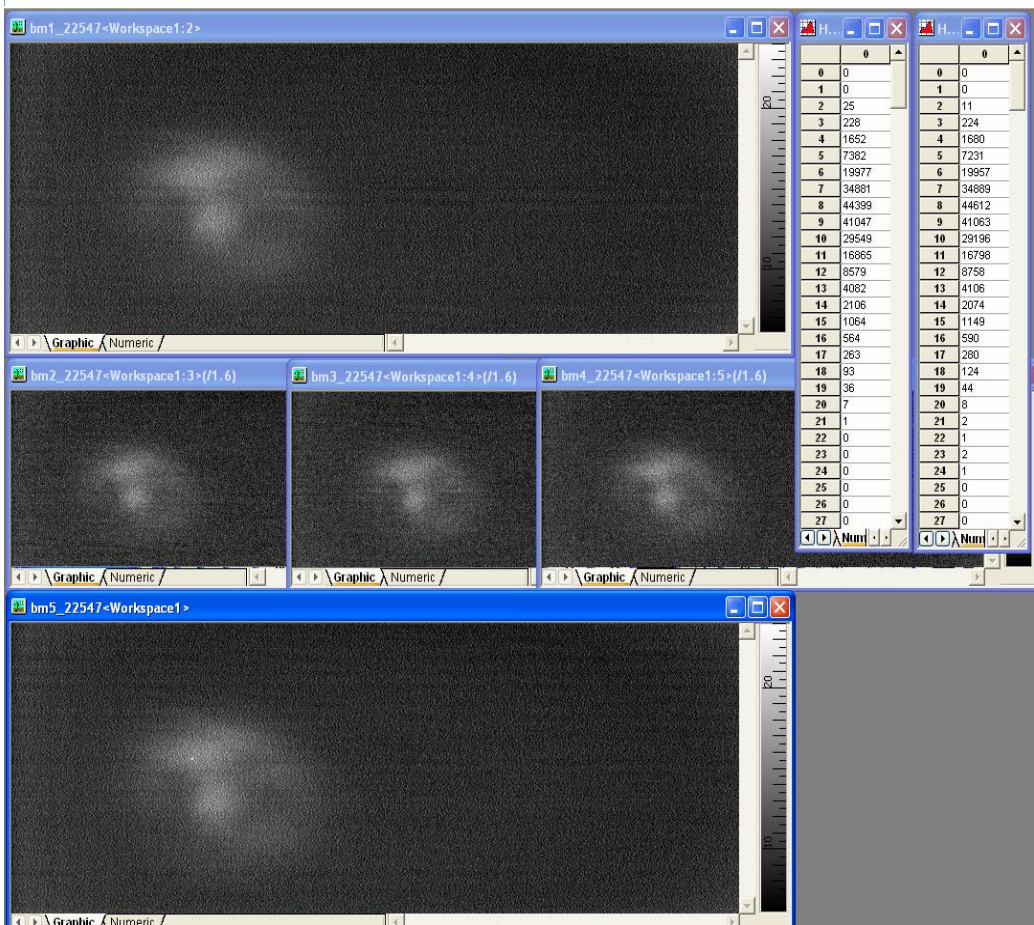
Lost frames: 0
bm1_22547: Mean1:12.440595, Mean2:9.807785, Ratio:1.268441,X-Center of ROI1:227, Y-Center of ROI1:162,X-Center of ROI2 and ROI1 :230, Y-Center of ROI2 and ROI1 :154

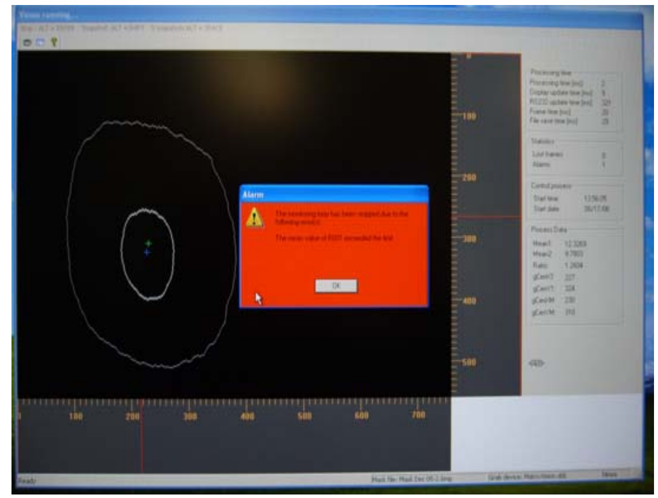
bm2_22547: Mean1:12.471129, Mean2:9.817343, Ratio:1.270316,X-Center of ROI1:227, Y-Center of ROI1:162,X-Center of ROI2 and ROI1 :230, Y-Center of ROI2 and ROI1 :154

bm3_22547: Mean1:12.461930, Mean2:9.817775, Ratio:1.269323,X-Center of ROI1:227, Y-Center of ROI1:162,X-Center of ROI2 and ROI1 :230, Y-Center of ROI2 and ROI1 :154

bm4_22547: Mean1:12.533764, Mean2:9.835573, Ratio:1.274330,X-Center of ROI1:227, Y-Center of ROI1:162,X-Center of ROI2 and ROI1 :230, Y-Center of ROI2 and ROI1 :154

bm5_22547: Mean1:12.569779, Mean2:9.853515, Ratio:1.275664,X-Center of ROI1:227, Y-Center of ROI1:162,X-Center of ROI2 and ROI1 :230, Y-Center of ROI2 and ROI1 :154

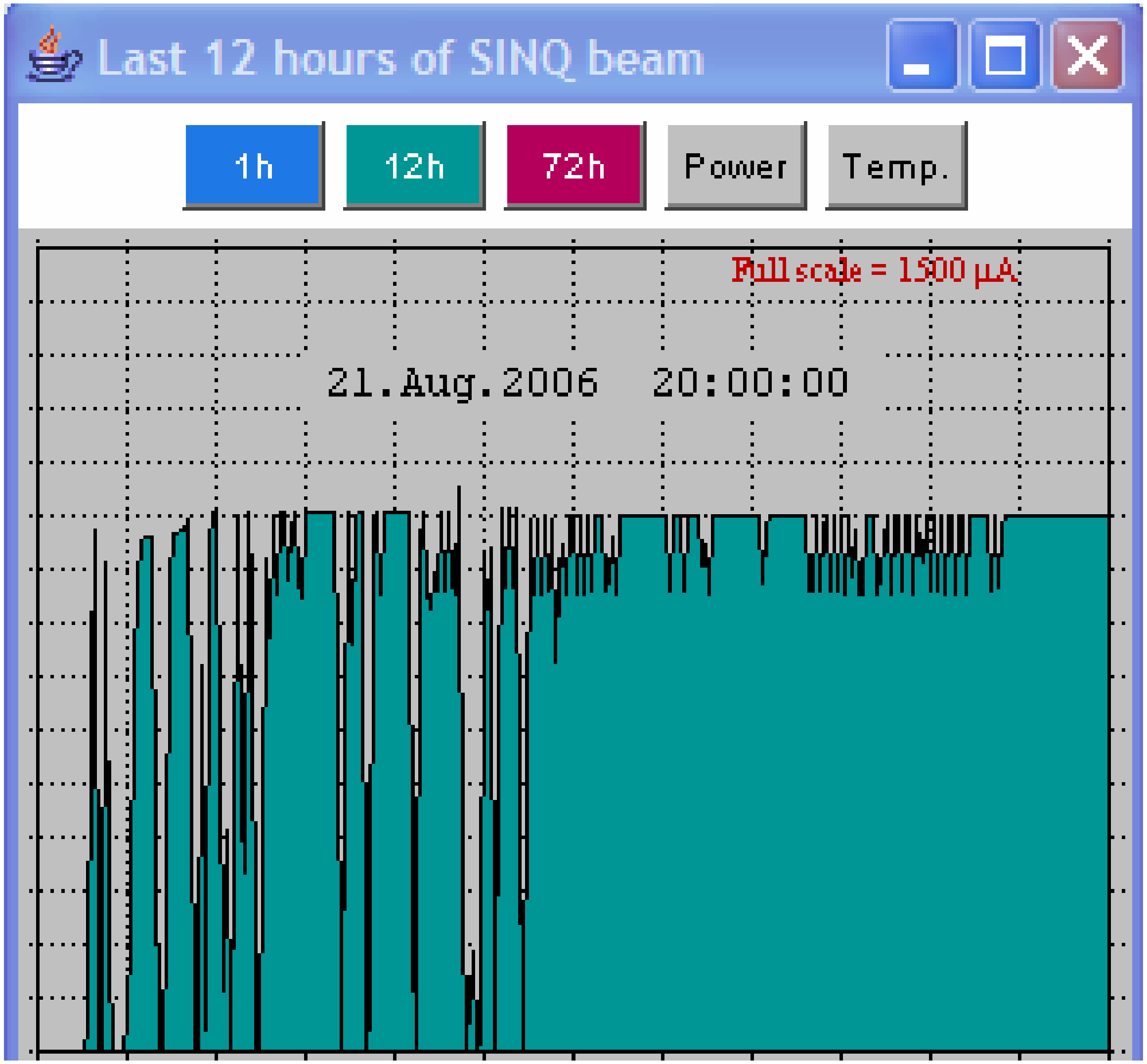




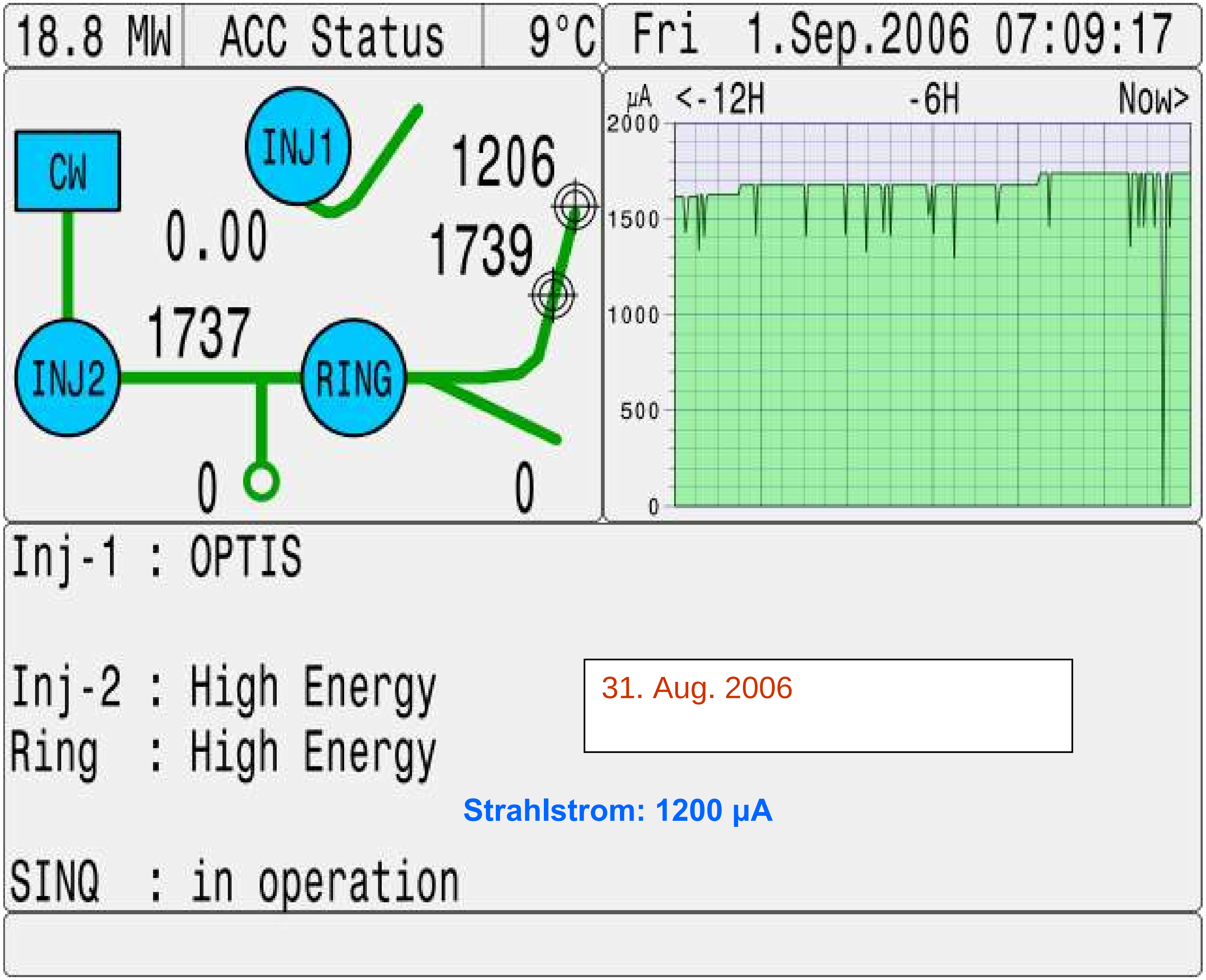
Proof of Functionality and Sensitivity at Very Low Signal Level

(frames enhanced)

Steady state operation Mo, Aug 21 2006



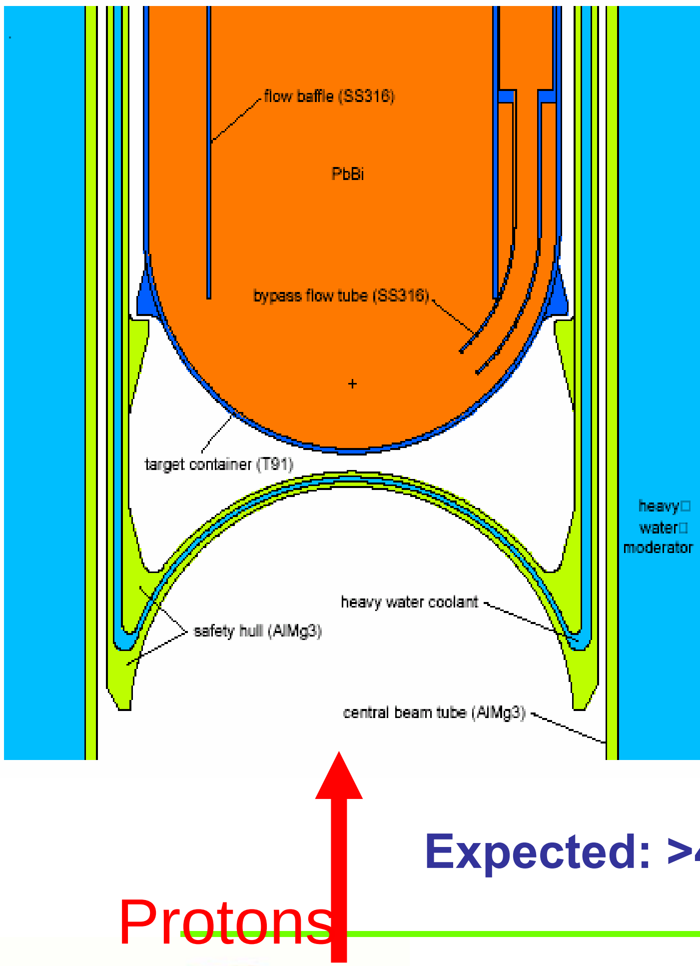
CADARACHE

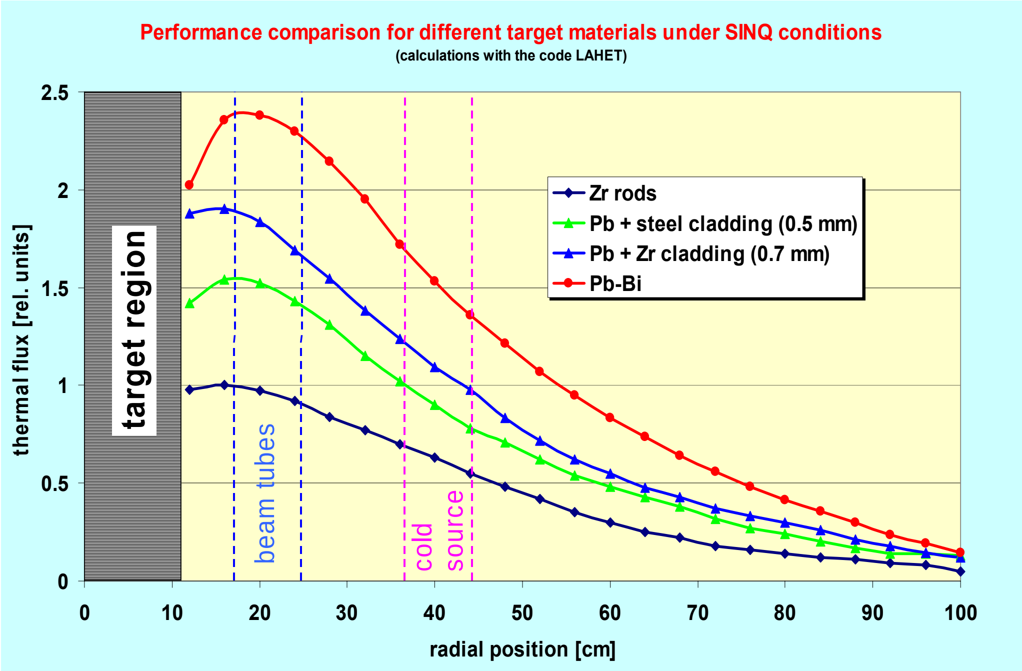


31. Aug. 2006

Strahlstrom: 1200 µA

MEGAPIE: calculated neutron flux gain





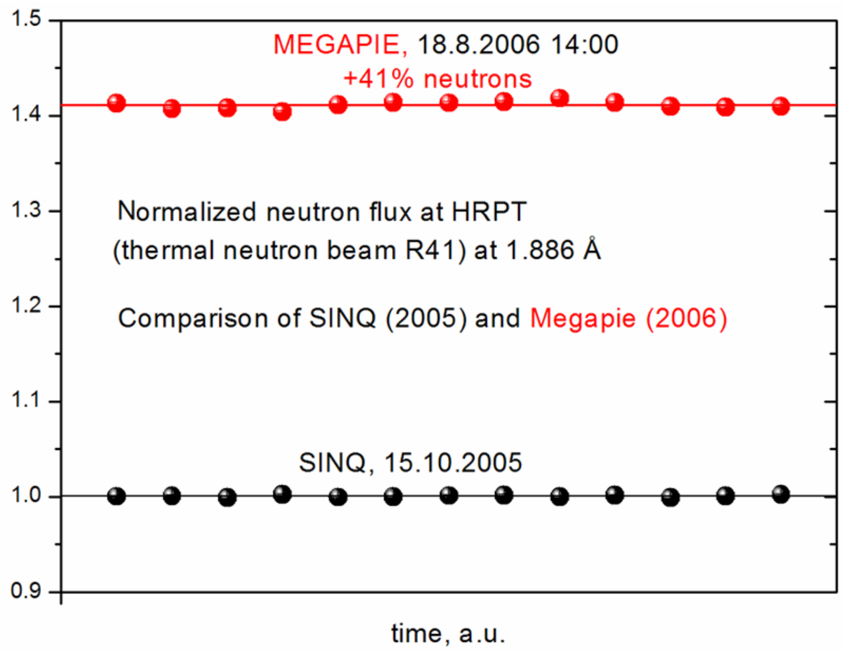
LAHET calculations A. Dementjev, E. Lehmann

Expected: >40% higher neutron flux as with solid lead target

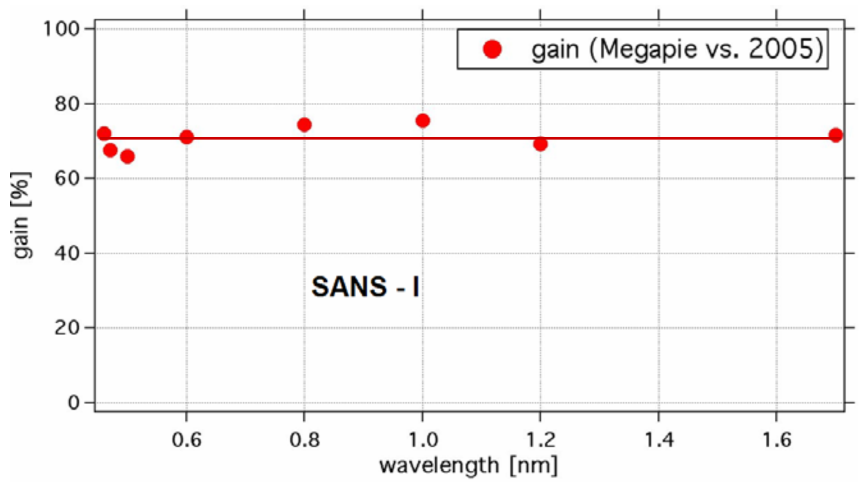
CADARACHE

MEGAPIE : neutronic flux

Thermischer Fluss (HRPT): 41%



Kalter Neutronenfluss (SANS I): ca. 70%



CADARACHE

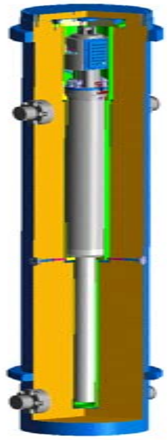
NEXt STEPS

Post Test Analysis: **2006 & 2007**

Target transfer and cutting : **2008**

PIE: **2009 & 2010**

Band saw (Behringer),



Container for transportation

Several steps :

- **cooling circuits and gas volumes emptied rinsed and dried,**
- **target disconnected and sealed up with blind flanges,**
- **target stored for several months.**
- **transfer to SWILAG hot laboratories, using a steel container.**
- **target cut with band saw (provided by Behringer), in 19 slices.**
- **pieces of target transported to the Hotlab at PSI (8 (weight) %)**
- **extraction of samples material for Post Irradiation examinations.**
- **Remaining target pieces (92%) conditioned in steel cylinder in a KC-T12 concrete container.**

Conclusions

The Scientific Design Support of this international project was an example of collaboration between design and research teams.

The target and ancillaries systems have been designed, manufactured, and integrated very efficiently.

Integral tests was a very useful step for the definition of the operationg conditions, control system parameters, and training of the PSI operating team.

PSI team has shown an impressive efficiency in order to reach this status.

The Megapie –test European project is a very important support and tool with regards to the integration of the results for the design of ADS demonstrator.

Thank You for your attention

TARGET OPERATION : 3 operational modes

The target can be operated following three main operational modes :

1. Isolation case :

The target is "disconnected" from the Heat Removal System by closed isolation valves in oil loop; the two electromagnetic pumps are running (possibly at reduced power) and the target temperature is controlled by the central rod heater

2. Hot standby case :

The target is "connected" to the Heat Removal System; all pumps (lead-bismuth, oil and water) are running in nominal conditions and the target temperature is controlled by the three way valve in oil loop. Then the system is ready to accept beam operation.

3. Beam operation case :

The target is operated as in the hot standby case but with beam operation. If during the beam operation status, an anomaly in the signals is detected, the beam is switched off and the target will go into "hot standby case" or into "isolation case" if a critical problem is detected. If during the "hot standby"case, it is not possible to maintain the selected operational conditions, the target will go into "isolation case"