THE MUSE EXPERIMENTS FOR SUB-CRITICAL NEUTRONICS VALIDATION AND PROPOSAL FOR A COMPUTER BENCHMARK ON SIMULATION OF MASURCA CRITICAL AND SUB-CRITICAL EXPERIMENTS

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Abstract

Accelerator driven systems (ADS) are being explored in France in the frame of the research programme on radioactive waste management options. Besides studies aimed to clarify the motivations for ADS, a significant programme has been started to validate experimentally the main physics principles of these systems. This experimental programme was initiated at CEA-Cadarache in 1995, with the sponsorship of EdF and Framatome. Since 1997, the CNRS has joined the programme, which is now a common CEA-CNRS-EdF-Framatome programme, open to external partners, in particular since October 2000 the European Community in the frame of the 5th FW Programme.

1. Introduction

Since 1991, the Commissariat à l'Énergie Atomique (CEA) MASURCA (MAquette SURgénératrice de CAdarache) has studied the physics of hybrid systems, involving a sub-critical reactor coupled with an accelerator.

These studies are being explored in France in the frame of the research programme on radioactive waste management options.

The potential of this kind of systems is to be found in:

- The concentration of waste in a limited number of dedicated facilities.
- The sub-criticality of such a system, which is a particularly attractive argument in favour of the safety of such concepts and which, more particularly, allows for the introduction of new fuels.

Besides studies aimed to clarify the motivations for ADS, a significant programme has been started to validate experimentally the main principles of these systems, in terms of the physical understanding of the different phenomena involved and their modelling, as well as in terms of experimental validation of coupled systems, sub-critical environment/accelerator.

This validation must be achieved through mock-up studies of the sub-critical environments coupled to a well-known source of external neutrons which represents the spallation source. The experimental investigations on the physics of sub-critical external source-driven systems are performed at the CEA Cadarache MASURCA facility, in the frame of the MUSE (MUltiplication of an external Source Experiments) programme.

2. Neutronic validation of source-driven sub-critical systems

2.1 Principles

Neutronic studies of fast critical systems have been largely performed in the past and the associated calculations tools (including both recommended nuclear data and calculation tools) and bias factors developed for the predictions of such systems have been mainly based on integral experiments in critical facilities. Validated experimental techniques have also been developed, directly applied to power critical operating systems.

In order to validate the physics characteristics of a source-driven sub-critical multiplying system, the main original idea has been to separate the experimental validation of the sub-critical multiplication phenomena of the external neutron source, from the validation of the external source characteristics. This can be done using a well-known (in energy spectrum and geometrical position) external source to drive the multiplying sub-critical core.

The neutron source (e.g. a spontaneous fission source or a fixed energy neutron generator), can be surrounded by a "buffer" medium, simulating the diffusing properties of a spallation source. The leakage neutrons through the "buffer" zone are then used as an external source but with a modified energy spectrum. The source neutrons, after having travelled approximately one mean-free path in the multiplying medium, become distributed, in energy and space, as the neutrons generated by fission in the multiplying medium.

The experimental programmes allow to validate both nuclear data and calculation methods used to describe the sub-critical core, in terms of sub-critical reactivity level, spatial flux distributions, neutron spectra, spectrum indexes and source neutron worth (the φ^* parameter) [1]. If the source can be used in continuous and pulsed modes, static and dynamic reactivity measurements are possible. This point is of relevance, since the experimental investigation of the different techniques to monitor the sub-criticality level during operation of an ADS is still an open question.

2.2 The MUSE experiments

This validation experimental programme was started at CEA (with the sponsorship of EdF and Framatome) in 1995 with the short exploratory MUSE-1 experiment [1], providing some insight into the physical behaviour of the neutron population in the sub-critical system. The MUSE-2 experiment [2], (2 months in 1996) was devoted to the experimental study of diffusing materials (sodium and stainless steel) placed around the external source to modify the neutron importance of the external source.

Since 1997, the French Scientific Research Committee (the CNRS) has joined this programme, which is now a common CEA-CNRS-EdF-Framatome programme in the frame of the joint research programme GEDEON (Waste management with innovative options programme).

In 1998, during three months the MUSE-3 experiments have been performed [3]. The external neutron source of about 1.0 E+08 n/s was produced by a commercial neutron generator based on the (d,t) reaction. This neutron generator operating in both continuous and pulsed modes allowed to complete the study of diffusing materials (sodium and pure lead) and to explore the dynamic behaviour of the multiplying medium for different sub-criticality levels (≈-0.16, -1.6, -3.2, -4.7 $ respectively). The expected dependence of monitors responses in function of the sub-criticality has been observed.

The MUSE programme is entered a new phase starting in 2000.

First of all, the installation at MASURCA of a ad-hoc deuton accelerator (the GENEPI), especially developed and built at the CNRS/IN2P3/ISN Grenoble, with improved performances (in terms of the quality of the neutron pulse and source intensity), and the use of both (d,d) and (d,t) reactions, will enable to explore different neutron spectra, different source worths and their ratios to the fission neutron worth (the φ^* parameter). Accurate dynamic measurements based on the pulsed mode operation of the GENEPI will allow new experimental reactivity determination of the sub-critical multiplying media.

Secondly, the MUSE experiments have been opened to the international collaborations via the 5th Framework Programme of the European Community and also via bilateral collaborations between CEA and Argonne National Laboratory (USA) and JAERI (Japan) respectively.

The future MUSE experiments will investigate several sub-critical configurations loaded in the MASURCA facility driven by the GENEPI external neutron sources. The foreseen configurations will have MOX fuel (with ≈25% enrichment in Pu) with sodium, gas or lead coolant. Physical presence of a spallation source will be simulated by surrounding the GENEPI neutron source with a pure lead zone (see Figure 3). Several levels of sub-criticality will be investigated (from -0.2 to -16 $). Foreseen measurements concern the sub-criticality levels by classical Source Multiplication Method but also via dynamic and noise methods, the neutron spatial distributions, the neutron spectra, the effective delayed neutron fraction and the neutron source importance parameter. Extensive cross-comparisons of codes and nuclear data are foreseen.

Experimental reactivity control techniques, related to sub-critical operation, will be developed and inter-compared. *In particular, in the field of reactivity control related to sub-critical operation, development, inter-comparison and improvement of experimental techniques will be performed.* Description of experimental conditions, techniques and associated results with uncertainties will be set up.

Complementary experiments (the SAD experiments) will be performed at Dubna (Russian Federation) in the frame of a sub-contract of the 5th FWP of the European Community, studying different spallation neutron sources (Pb, Pb-Bi, W targets) produced by the 660 MeV protons of the Dubna synchrotron. These experiments will allow the experimental characterisation of the spallation neutrons propagation into materials (target, fuel and structural materials) encountered in ADS.

The analysis of the whole experiments allows to develop a reference calculation route (including both recommended nuclear data, validated calculation tools and associated residual uncertainties) for the design of ADS and for the deep spallation neutrons transport penetration to optimise the neutron shielding, with a special attention to a “forward” direction (behind the target area).

3. The MASURCA facility

The MASURCA facility is dedicated to the neutronic studies of fast reactor lattices. The materials of the core are contained in cylinder rodlets, along with in square platelets. These rodlets or platelets are put into wrapper tubes having a square section (4 inches) and about 3 meters in height. These tubes are hanged vertically from a horizontal plate supported by a structure of concrete. The core itself can reach 6 000 litres. To build such cores the tubes are introduced from the bottom in order to avoid that the fall of a tube corresponds to a positive step in reactivity.

The reactivity control is fulfilled by absorber rods in varying number depending of core types and sizes. The control rods are composed of fuel material in their lower part, so that the homogeneity of the core is kept when the rods are withdrawn. The core is cooled by air and is surrounded by a biological shielding in heavy concrete allowing operation up to a flux level of 10^9 n/cm^2/sec. Core and biological shielding are inside a reduced pressure vessel, relative to the outside environment. The limited maximum operating power of the facility is limited to 5 kW$_{th}$.

4. The GENEPI accelerator

The GENEPI (GÉnérateur de NEutrons Pulsé Intense) accelerator has been especially formed for the MUSE experiments in the MASURCA facility for brief neutron injections with a very fast intensity decrease.

It will produce a pulsed neutron beam of about 1 μs during a maximum relative time of 5 . 10^{-3} s, that is a maximum frequency of about 5 000 Hz.

In this way, deuton impulses are created, then focalised, accelerated and guided to a deuterium or tritium target. The (D,D) or (D,T) nuclear reactions produce neutrons of about 2.67 MeV or 14.1 MeV respectively. For incident deutons of about 250 keV, the neutron yield is greater for the (D,T) reaction than for the (D,D) reaction.

This accelerator is a classical electrostatic one with a lower mean neutrons production than the same type of accelerators. The main originality of GENEPI concerns its operating mode based on high ions peak current (50 mA) and a decreasing time of the neutron impulse of some 100 μs.

The GENEPI accelerator is mainly composed of:

- A deuton source.
- The extraction and focusing electrodes.
- The 250 keV electrostatic accelerator.
- The mass separator.
- The deuterium or tritium target , as indicated in the Figure 1.

The main characteristics of the ion beam are indicated in the Table 1.

Table 1. **Deuton beam characteristics**

Beam energy	140 to 240 keV
Peak current	50 mA
Repetition rate	10 to 5000 Hz
Minimum pulse duration	700 nanoseconds
Mean beam current	(200 μA (for a duty cycle of 5 000 Hz)
Spot size	Diameter ≈20 mm
Pulses reproducibility	Fluctuations at the 1% level

The characterisation of the neutron production by both deuterium and tritium targets has been performed by the ISN Grenoble team. The characterisation of the neutron source intensity is based on the activation of a Si detector by:

- The recoiled protons produced by the (d,d) reaction on the deuterium target and in the magnet chamber due to deuterium implantation.
- The recoiled protons and alpha particles produced by the (d,t) reaction on the tritium target.

This alpha monitoring gives a neutron pulse shape very similar to this obtained by ionic current as indicated in Figure 2.

The characterisation of the neutron production spectrum is based on the activation analysis of ^{58}Ni foils. For the 2.67 MeV neutrons produced by the D(d,n)^{3}He reaction, the ^{58}Ni(n,p)^{58}Co is used. The 14 MeV neutrons spectrum produced by the T(d,n)^{4}He reaction is determined by both the ^{58}Ni(n,2n)^{57}Ni and ^{58}Ni(n,np)^{57}Co reactions representative of the neutrons with an energy higher than 13 MeV. For a natural Ni target of 20 mm diameter (corresponding to a mass of about 580 mg) irradiated during 14 hours at 2 000 Hz with a pulse width of 700 nanoseconds FWHM, the neutrons/pulse intensities, indicated in the Table 2 have been measured.

Table 2. **Neutron intensities**

Target characteristics*	Nuclear reaction	Neutrons/pulse
D in 1mg/cm^2 Ti deposit (Φ 30mm)	D(d,n)^{3}He	4.0 E+04
T (1Ci) in 0.25 mg/cm^2 Ti deposit (Φ 25mm)	D(t,n)^{4}He	1.7 E+06**
T (10 Ci) target	idem	Expected: 3.0 to 9.0 E+06

*D/Ti or T/Ti atomic ratio is close to 1.5.
**Measurement done after a 50% decrease of the tritium content of the target.

An accurate monitoring of the external neutron source in term of intensity and pulse form is of prime importance for a good and accurate understanding of the dynamic measurements. The target beam current, the proton and alpha + proton spectroscopy signals and the alpha + protons time distribution referenced to the neutron source pulse will be available for the physicists during the future MUSE experimental campaigns.

5. The MUSE-4 experiments

As the MUSE experiments are based on a parametric approach, the MUSE-4 configurations are based on the ZONA2 fuel cell (see Figure 2), representative of a Pu fast burner core (Pu enrichment of ≈25% with ≈18% content of ^{240}Pu) with sodium coolant. The fuel zone is radially and axially reflected by a stainless steel/sodium (75/25) shielding. The GENEPI deuteron guide is horizontally introduced at the core mid-plane and the deuterium or tritium target is located at the core centre (see Figure 3). To compensate the spatial effect due to the presence of the GENEPI beam guide in the north part of the loading, the south symmetric part will be loaded with pure lead. To simulate the physical presence of a spallation source, a pure square (20 cm thick) lead zone will be introduced around the GENEPI target (see Figure 3).

Six different experimental configurations will be studied:

- A critical one, the GENEPI being shut off, in which all the safety and neutron flux level and spectrum measurements will be performed. In this configuration the reactivity scale will be experimentally determined by classical pilot rod shutdown measurement.
- Three sub-critical configurations (k_{eff} being successively of about 0.994: the SC1 configuration, 0.97: the SC2 configuration and 0.95: the SC3 configuration). These three configurations will be obtained by replacing radially some peripheral fuel cells by stainless steel/sodium cells. The west/east symmetry along the beam guide axis will be preserved.
- Two complementary asymmetrical sub-critical configurations, with k_{eff} of about 0.95 and 0.93, obtained from the reference critical one and from the above SC1 sub-critical respectively, by complete insertion of the same safety rod. These two last configurations will be of interest in the frame of studying the decoupling effects and the excitation of high order flux harmonics by the external source.

A very extensive experimental programme has been planned for one year, including the active participation of the different partners as indicated in the Table 3. In support to the transmutation studies of minor actinides, fission rates of ^{232}Th, ^{233}U, ^{237}Np, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am and ^{244}Cm will be measured using fission chambers. Transmutation of some long-lived fission products will be also experimentally determined using activation foils such as ^{197}Au, ^{115}In, ^{160}Dy, natural Mn, representative of the LLFP's of interest in term of capture cross-sections.

6. Benchmark on computer simulation of MASURCA critical and sub-critical experiments

The study of the neutronic of accelerator driven systems, in which an intense external neutron source maintains a stationary power level, requires the extension and validation of appropriated computational tools to solve steady-state and time–dependent problems, from the standard codes and nuclear data libraries developed for critical reactors. The MASURCA nuclear assembly used in the MUSE experiment, that has been and will be configured as a critical and sub-critical reactor, offers a unique opportunity for test and validation of the available and new computational tools. For these purposes we propose to organise in collaboration with the OCDE Nuclear Energy Agency a benchmark on computer simulation of MASURCA critical and sub-critical experiments particularly concentrated on the MUSE-4 experiments. The fact that the results can be compared with already available experimental data and data to be obtained in very short time will allow to go beyond the simple observation of the coincidence and discrepancy between codes or nuclear data libraries.

The benchmark model would be oriented to compare simulation predictions based on available codes and nuclear data libraries between themselves and with experimental data related to: TRU transmutation, criticality constants and space and time evolution of the neutronic flux following source variation, in the framework of liquid metal fast sub-critical systems.

The benchmark could be divided in three steps:

- First step will allow understanding the simulation methods of the different groups and tuning of the simulations programmes with the experimental data of one already measured critical configuration (COSMO).
- In the second step, the MUSE-4 reference configuration is proposed for simulation of the different reactor parameters (criticality constant, flux distribution...) in a nearly critical configuration, critical-2$.
- The third step is oriented to the simulation of reactor time response to the external source in the sub-critical reference configuration.

To allow the use of the widest range of simulation codes to participate in the benchmark the geometry and material compositions will be described in detail but homogenised at the tube level. The errors introduced by the homogenisation approximation have been checked by the MUSE collaboration, and they are very small, typically from less than 0.1% in k_{eff} to a maximum of 8% in the absolute flux at the worst tube (k_{eff} = 0.995). Detailed figures and tables will clarify this geometrical description of the MASURCA configurations and of the reference points for requested calculations. Special attention will be paid to insure that most of the requested calculations can be compared with directly measurable parameters.

In the case of the COSMO critical MASURCA configuration the requested calculations will include: the criticality constant, k_{eff}, ^{235}U fission rate as a function of the position at the available experimental channels (horizontal and vertical); spectral index from the reaction rates in the available detectors and activation foils and the energy dependence of the neutron spectrum in a few characteristic positions (to clarify discrepancies between codes).

For the critical-2$ MUSE-4 reference configuration calculations the requested parameters should include: the criticality constant, k_{eff}, ^{235}U fission rate as a function of the position at the available experimental channels (horizontal and vertical); spectral index from the reaction rates in the available detectors and activation foils and the energy dependence of the neutron spectrum in a few characteristic positions; the ^{235}U fission rate in the available experimental positions as a function of the time after the deuteron-tritium source pulse and the neutron mean lifetime.

Finally for the sub-critical MUSE-4 reference configuration calculations the requested parameters should include: the ^{235}U fission rate as a function of the position at the available experimental channels (horizontal and vertical); spectral index from the reaction rates in the available detectors and activation foils and the energy dependence of the neutron spectrum in a few characteristic positions; the ^{235}U fission rate in the available experimental positions as a function of the time after the deuteron-tritium source pulse; the neutron mean lifetime; the change in neutron multiplication from the critical-2$ to the sub-critical configuration and the difference between k_{eff} and k_{source} for the sub-critical configuration.

The probable situation that some of the calculations will be made before the experiments are performed is the best warranty for making blind simulations and to understand the potentialities and accuracy of the different computational tools.

7. Conclusions

From the year 2000, the MUSE experiments begin an international test stand for the inter-comparison and development of specific experimental techniques and for the validation of a reference calculation route, including recommended nuclear data, validated calculation tools and associated residual uncertainties related to the neutronics specificities of the accelerator driven systems. During the MUSE-4 experiments in year 2001, the coupling between the GENEPI accelerator and a MOX fuel with sodium coolant will be studied. During the two following years, the GENEPI accelerator will be coupled with a MOX fuel with gas coolant representative of Fast Gas Cooled sub-critical system. A small MOX fuel zone with lead coolant will be also investigated.

A first important conclusion of the European collaboration during the definition of the MUSE-4 critical and sub-critical configurations concerns the important discrepancy observed between deterministic code and stochastic codes using *a priori* the same nuclear libraries. The understanding of this discrepancy should be obtained via an international calculation benchmark based, in a first step on very simplified experimental configurations, in terms of geometrical description and material compositions. In a second step, real critical and sub-critical configurations studied during the MUSE-4 experiments will be proposed.

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Figure 1: Schematic view of the GENEPI-MASURCA coupling

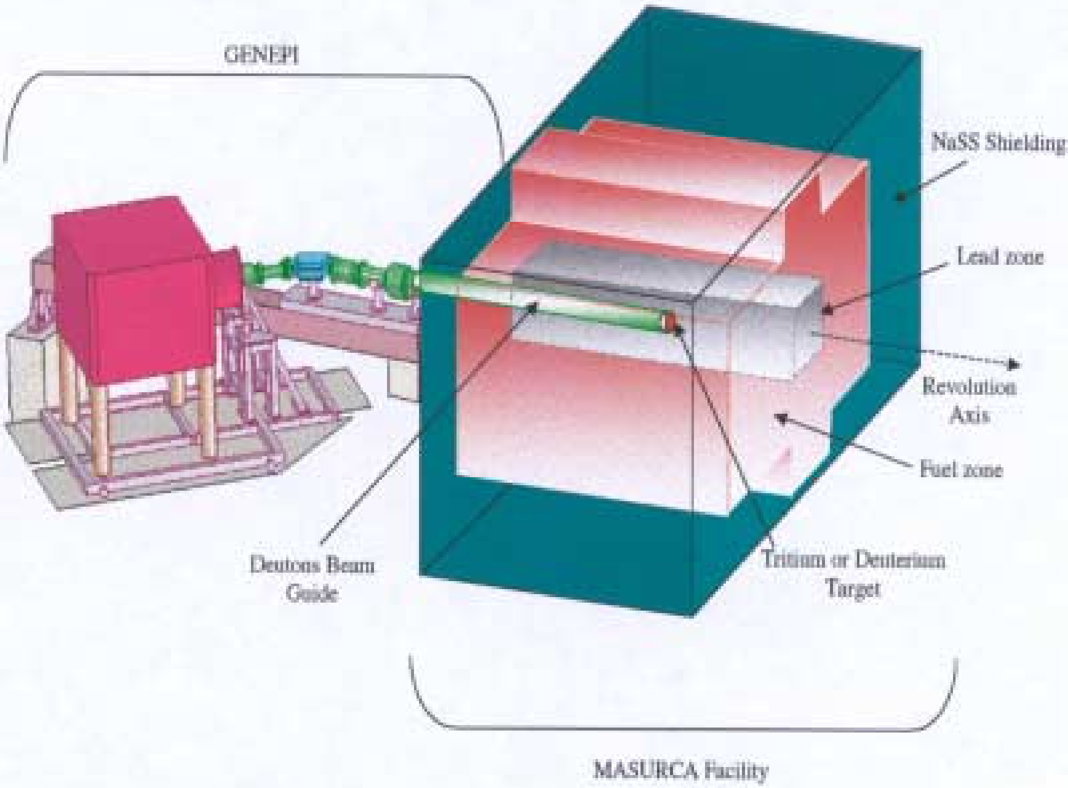
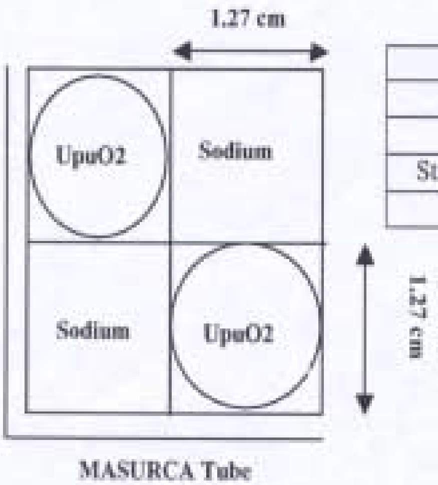


Figure 2: Fuel basic cell for the MUSE-4 experiments



	Volumetric composition %
UpuO2 fuel	≈ 34
Sodium coolant	≈ 43
Structural materials (SS)	≈ 12
Void	≈ 11

Figure 3. **XY loading (at the core mid-plane)**
of the MUSE-4 reference critical configuration (provisional)

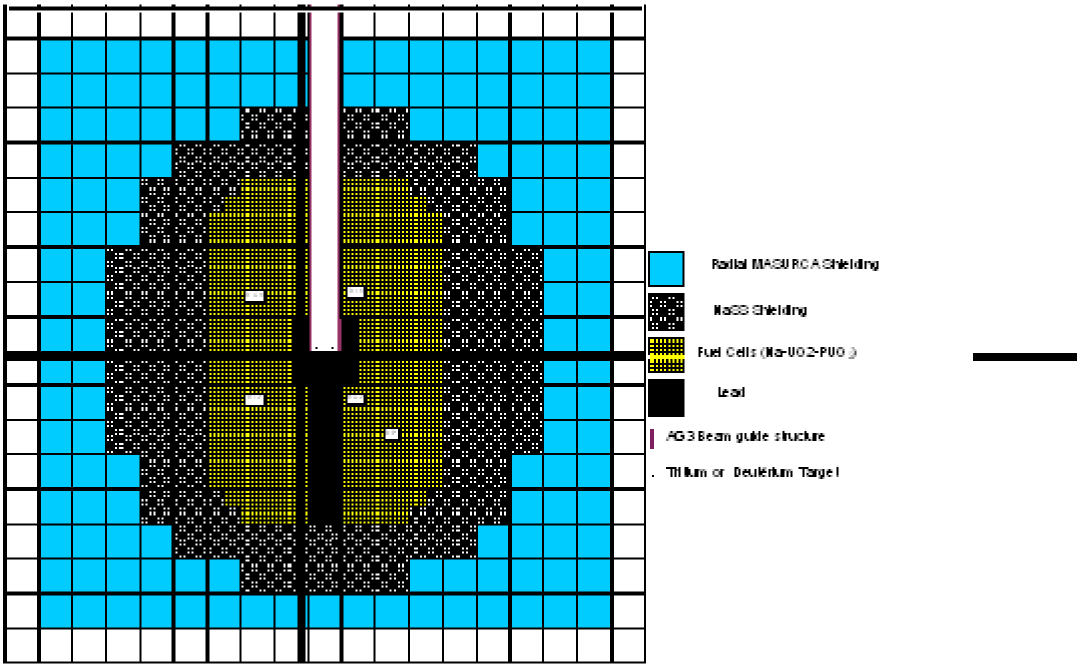


Figure 4. **Neutron pulse time spectrum**

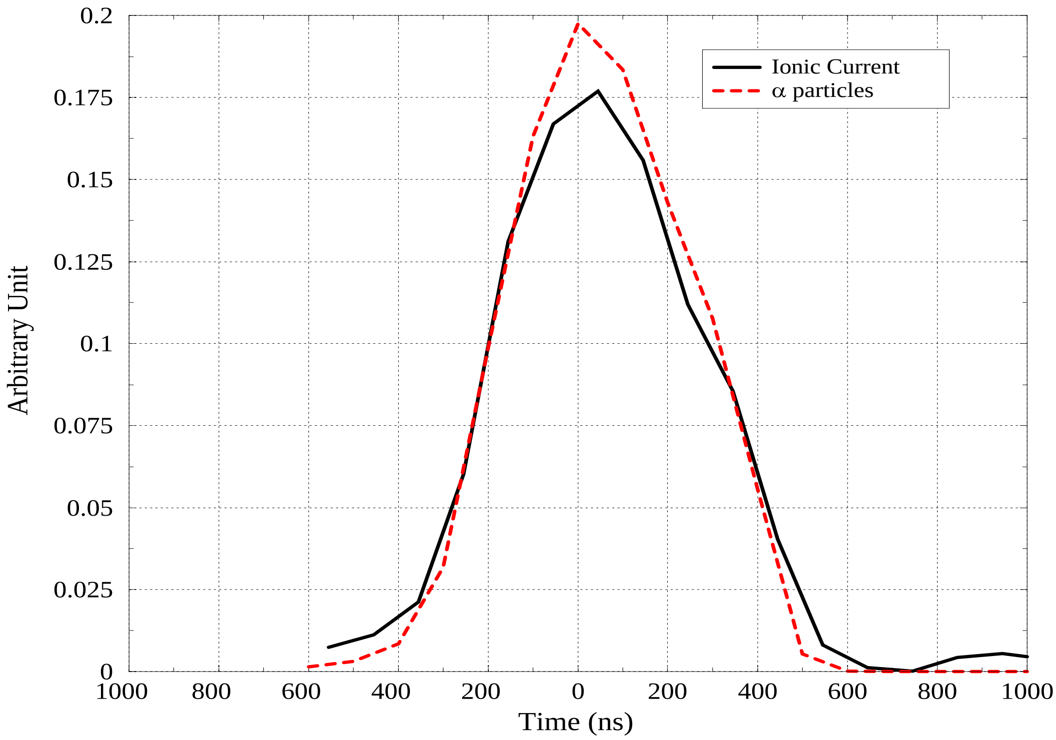


Table 3. **Planned experimental programme during the MUSE-4 experiments**

	REF	**SC1**					**SC2**				**SC3**		**SC3**	**SC2**
		OFF		(d,d)	(d,t)		OFF		(d,t)		OFF	(d,t)	(d,d)	(d,d)
		SYM	ASY		SYM	ASY	SYM	ASY	SYM	ASY				
Operating														
Rod worth	X	X					X				X			X
Monitor calibration	X	X					X				X			X
Reactor calibration	X	X					X				X			X
Chamber inter-calibration	X													
GENEPI monitoring				X	X									
Target control study				X	X				X			X	X	X
Statics														
Source multiplication	X	X					X				X			
Radial traverses	X			X	X	X			X	X		X	X	X
Axial traverses	X			X	X	X			X	X		X	X	X
Spectrum indices	X								X					X
Foil activation	X			X	X				X			X	X	
^{3}He spectrum				X	X				X			X	X	X
^{252}Cf source importance		X	X					X			X			
GENEPI source importance				X	X	X			X	X		X	X	X
Dynamics														
Reactor noise	X	X												
Transfer function				X	X				X			X	X	X
Frequency modulation				X	X				X			X	X	X
Pulsed source methods				X	X	X			X	X		X	X	X
Rossi- & Feyman-α methods	X	X		X	X		X		X		X	X	X	X

- For each sub-critical configuration (SC1, SC2 and SC3) the GENEPI will be shut OFF/ON with deuterium target and ON with tritium target.
- SYM configurations correspond to “clean” configurations.
- ASYM configurations correspond to the above “clean” configurations, but with BC2 safety rod completely inserted.