The GUINEVERE Project for Accelerator Driven System Physics

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Abstract – *The GUINEVERE project is part of the EUROTRANS Integrated Project of the 6[th] EURATOM Framework Programme. It is mainly devoted to ADS on-line reactivity monitoring validation, sub-criticality determination and operational procedures (loading, start-up, shut-down, …) as a follow-up of the MUSE experiments.*

The project consists in coupling a fast lead core, set-up in the VENUS reactor at SCK•CEN Mol (B), with a GENEPI neutron source under construction by CNRS. To accommodate the accelerator in a vertical coupling configuration, the VENUS building is being heightened. The fast core will be loaded with enriched Uranium and will be moderated and reflected with solid lead (zero power experiment). For the purpose of the experimental programme, the neutron source has to be operated not only in pulsed mode but also in continuous mode to investigate the current-to-flux reactivity indicator in representative conditions of a powerful ADS. In this latter mode it is also required to make short beam interruptions to have access to the neutron population decrease as a function of time: from this spectrum it will be possible to apply different analysis techniques such as "prompt decay" fitting techniques and "source jerk" techniques. Beam interruptions will be repeated at a programmable frequency to improve time spectra statistics. Different sub-criticality levels (k_{eff}=0.99, 0.97, 0.95, …) will be investigated in order to obtain a full set of data points for the final overall validation of the methodology.

This paper describes the status of the experimental facility assembling, and the foreseen experimental programme to be started.

I. INTRODUCTION

The GUINEVERE project (**G**enerator of **U**ninterrupted **I**ntense **NE**utrons at the lead **VE**nus **RE**actor) is part of the EUROTRANS Integrated Project (6[th] EURATOM FP) which gathers feasibility and design studies of an ADS demonstrator as well as its possible extend to an industrial transmutation installation. GUINEVERE aims at providing a zero power experimental facility to investigate reactivity on-line monitoring and absolute measurement which are major issues for ADS safety.

To do so the VENUS reactor (SCK•CEN, Mol, Belgium) will be coupled to a neutron source driven by the GENEPI-3C accelerator. This new GENEPI machine will have the particularity to be operated in both pulsed and continuous modes, this latter being more representative of a powerful system operation. The VENUS system will provide a unique facility in Europe for fast sub-critical (coupled to a flexible accelerator GENEPI) and critical reactor physics investigations.

II. THE VENUS REACTOR

The VENUS reactor (SCK•CEN, Mol, Belgium) was a zero power thermal critical mock-up up to 2007. From then on it has been dedicated to the GUINEVERE experimental programme for which it has to be changed into a lead fast reactor.

II.A. The core

The VENUS-F core will consist of Fuel Assemblies (FA) arranged in a cylindrical geometry (~80 cm in diameter, 60 cm in height), and composed of a 5x5 pattern mixture of fuel and solid lead rodlets to mimic the presence of a fast system coolant. Lead plates are added around the pattern to decrease the fuel/coolant ratio (and hence increase the core size). The outer section of a FA is 80 mm and the pattern chosen is shown in Fig.1. The fuel is 30% ^{235}U enriched metallic uranium (provided by CEA).

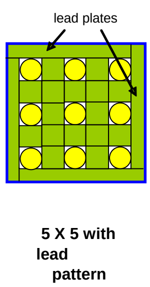

Fig. 1. Cross section of the FA pattern chosen for the VENUS-F core: fuel rodlets are cylindrical and lead ones are square.

The core will be surrounded by two 40 cm axial (top and bottom) and 30 cm radial lead reflectors. At the core centre a channel is arranged with a stainless steel shaft for the insertion of the accelerator thimble. To keep a simple geometry but leave sufficient free space to finalize the thimble cooling system design, this channel is chosen to have the cross section of 4 standard FA's. A small lead buffer is foreseen to fill the gap between the target tube shaft and the 160x160 mm^2 central hole. A radial view of the reactor (inner part of the vessel) at mid-plane, in the SC1 configuration (k_{eff}~0.97) is shown in Fig.2.
The supporting structure of the vessel itself will be reinforced to support the added weight of the lead components.
Every component of the new FA structure have been already manufactured and preassembled.

II.B. Safety and control rods

A new shut down system had to be implemented for the fast neutron reactor. The standard philosophy of safety rods which fall in the core by gravity upon receiving the signal for de-energizing of the electro-magnets was chosen. The safety rods consist of an absorbing material (B_4C with natural boron), 60 cm long, with a fuel follower (with the same pattern as shown in Fig.1).

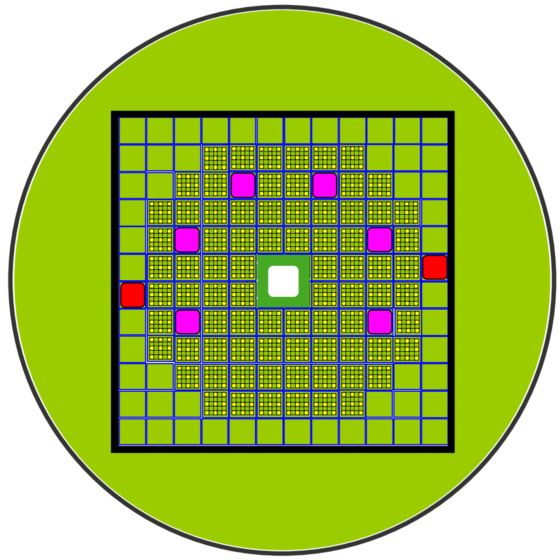

Fig. 2. Cross section (mid-plane) of the SC1 sub-critical core configuration (84 FA's).

When a safety rod is up, its fuel follower is at the same height as regular FA's in the core, thereby eliminating most of the core perturbations. This way, an anti-reactivity is inserted when a rod drops, due to replacement of the fuel by the absorber material. The control rods simply consist of an absorbing part that slides inside a wrapper tube, and their position is flexible.

In total six Safety Rods (SR) and two Control Rods (CR) are foreseen. Fig. 2 shows the final location for these rods, and their reactivity worth is given in section IV.

II.C. The coupling

The coupling with the accelerator was chosen to be vertical to keep the cylindrical symmetry. Due to the small size of the reactor (160 cm in diameter), it was not possible to host the accelerator at the reactor top level. Therefore the VENUS reactor bunker had to be modified to implement a room for the accelerator at an upper level (see Fig.3). Civil engineering work at VENUS building was started on September 1rst, 2008 and was completed in April 2009. Electrical power equipment and ventilation system will be installed before summer 2009.

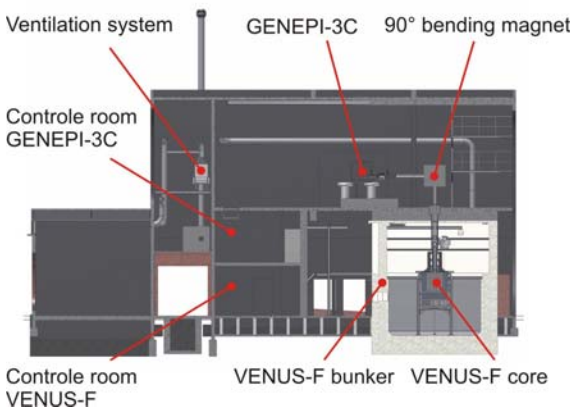

Fig. 3. Side view of the modified VENUS facility.

III. THE NEUTRON SOURCE: GENEPI-3C ACCELERATOR

III.A. The new specifications

The GENEPI-3C (**GE**nérateur de **NE**utrons **P**ulsé **I**ntense-**3C**ontinu) accelerator is the third of a series designed for neutronic experiments[1]. It is designed and built by a CNRS/IN2P3 collaboration and is being assembled at LPSC Grenoble for beam characterization measurements until the summer 2009 before its transfer to SCK•CEN in Mol and reassembling in VENUS-F reactor building.

The GENEPI machines are 250 kV deuteron accelerators ended by copper targets with titanium-tritium (TiT) or titanium-deuterium (TiD) deposits, providing 14 MeV or 2.5 MeV neutrons via $T(d,n)^4He$ or $D(d,n)^3He$ reactions.

The new GENEPI-3C machine cumulates specifications of the first GENEPI accelerator, designed for the MUSE experimental programme at MASURCA reactor (CEA Cadarache, France, 2000-2004), i.e. pulsed mode operation with very sharp and intense beam pulses (1 μs, 50 mA peak current), with new continuous mode specifications summed up in Table I. In this new DC mode, it will be also possible to operate beam interruptions (so-called "beam trip") with a programmable duration and a low repetition rate for the needs of the foreseen experiments (see section V).

TABLE I

Specifications of GENEPI-3C in DC mode

Mean current	160 μs to 1 mA
Beam trip rate	0.1 to 100 Hz
Beam trip duration	~20 μs to 10 ms
Transition time (on/off)	1 μs
Beam spot size	20 to 40 mm in diameter
Max. neutron production	5×10^{10} n/s

Due to the vertical coupling conditions, the GENEPI-3C machine requires a special design allowing the entire removal of the vertical line partly inserted in the reactor: this is necessary for target changes as well as for reactor or accelerator maintenance. To do so, the vertical line has to be embedded in a supporting structure that can be hoisted along guiding structures by means of a crane, and then lifted above the reactor bunker ceiling to be stored on a stand surrounded by working platforms. To allow this structure to move, the 90° bending magnet has to be removable too and is supported by a mobile cart that can be moved along two rail tracks. A general layout of the machine with its structures is shown in Fig. 4.

III.B. The accelerator design

The accelerator itself consists of an ion source sited in the 250 kV high voltage head, followed by a horizontal beam transport line section of 3 m at the exit of the accelerator tube. Beam transport is ensured with electrostatic quadrupoles. A first group of 4 quadrupoles transports and focuses the beam at the 90° dipole magnet

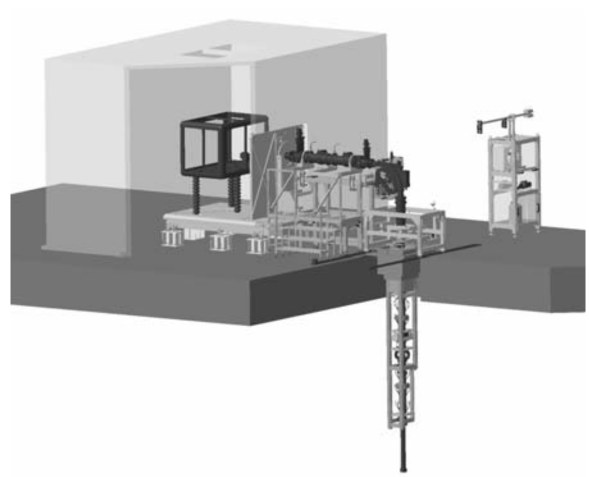

Fig.4. General layout of the GENEPI-3C machine with its supporting structures, Faraday cage and magnet cooling unit.

which deflects the beam downwards. A quadrupole doublet is located at the exit of the magnet chamber and no optical element is foreseen in the thickness of the VENUS bunker ceiling (~80 cm). Two quadrupole triplets located on the vertical beam line above the reactor core focus the beam onto the target. It is located at the end of a short optic free thimble inserted into the reactor core. The total vertical line length is about 6.5 m. Fig.5 sums up the different elements of the machine.

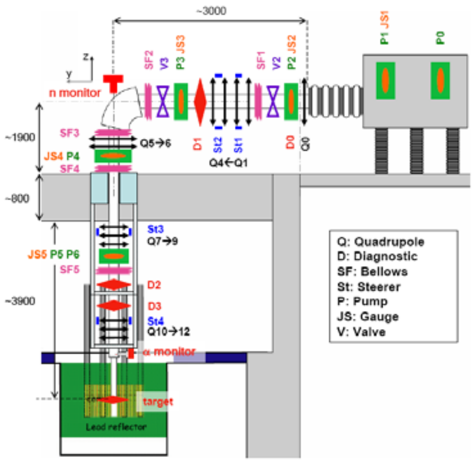

Fig. 5. Layout of the GENEPI-3C beam line components.

III.C. Safety

Due to the coupling with VENUS-F reactor, several precautions have been taken regarding to the safety aspects. The two main points concern the target cooling, and protections against dipole coolant leakage: as the dipole magnet is positioned directly above the reactor, a leakage would lead to insertion of moderating liquid into the reactor core with possible consequences on reactivity. Also a general interlock module is collecting in series all signals (relay switches) related to safety information: a defect ("false" logical input) of one of them leads to an emergency stop of the accelerator (switch off of the accelerator Very High Voltage).

Temperature aspects on the target are of prime importance: when operating the accelerator in the continuous mode, a maximum of 1 mA deuteron current on the Tritium target can be reached. Particle maximum energy being 250 keV, a maximum power of 250 W on the target has to be considered. Despite the fact that a high temperature on the target would cause Tritium desorption (and therefore a decrease of the neutron production -a drawback only for experiments), it can rapidly lead to the melting of the target support (copper) which would create a major vacuum accident in the accelerator beam line, but above all a Tritium contamination of the reactor vessel and room (targets to be used are 12 Ci T loaded). To prevent such accidents, particular attention is paid to the target cooling and temperature monitoring on the support. To avoid hydrogenous liquid into the core, the cooling system consists of 4 compressed air pipes feeding a diffuser drilled with 16 small holes producing as many air jets on the target support backing. This support backing is designed with 2.4x2.4 mm^2 pin fins, 7 mm long, to increase heat exchange with cooling air. To avoid condensation and frost hole blockage, the compressed air is dried (therefore cooled), and heated before inlet pipes. Two thermocouples inserted into the backside allow target temperature monitoring. Three other measurements, temperature, humidity and pressure of the cooling air at the heater exit, guaranty proper operation of the air drying system. A defect on any of these 5 measurements triggers off the interlock module, thus inhibiting beam production.

The dipole cooling system is shifted away from the magnet (more than 3 meters) so that the heat exchanger and the coolant tank are as far as possible from the penetration hole into the reactor bunker. The coolant (water and glycol) is brought to the dipole via 2 watertight rubber tubings hold up by a stand. Under the dipole support itself and around connexions, waterproof casings are installed, with humidity detectors. Pressure, flow and temperature of the coolant loops are also monitored to detect any possible leakage. Several position sensors ensure that casings are well positioned.

At last, an interlock module collects 12 signals related to people safety (accelerator room and Faraday cage doors), beam line vacuum, target cooling, dipole cooling, and tritium release. A defect on any of these signals breaks open the safety loop, thus shutting down the accelerator high voltage: neutron production is instantaneously stopped and the accelerator turns into a "safe" state.

III.D. GENEPI-3C beams

One of the main challenges of the new GENEPI machine is to operate the duoplasmatron source, particularly well suited for pulsed mode, in continuous mode and with short and repetitive beam interruptions. The continuous operation of the ion source was investigated on a test bench purpose-built for the GUINEVERE project at LPSC (Grenoble). The source was easily operated up to 3 mA total direct deuteron DC current. The fraction of the beam efficient for neutron production on the target is the D^+ atomic ions bent by the 90° magnet. Work was achieved to optimize the D^+ fraction with respect to D_2^+ and D_3^+ (removed by the dipole): a maximum ratio of 35-40% was reached for a total current of 2.6 mA, leading to about 1 mA of D^+ as required by the specifications. Work has been focused from then on beam trip mode operation. Possibility to turn off a stable DC beam with a transition time of the order of 1 μs was established. Making the interruption duration programmable in the range required for experiments (see Table I) is in progress.

First section of the accelerator (exit of the accelerator tube) was completed in November 2008, with deuteron beam production in pulsed mode in December 2008.

IV. PRELIMINARY CALCULATIONS

Considering the limited amount of fuel (about 1200 kg) and the lattice chosen to have a regular mixture of lead and uranium rodlets (cf. section II), a critical "reference" core (called CR0) will be initially built without buffer and central hole, to assess the reactivity scale by the rod drop and multiplication method through the entire programme. It will consist of 88 FA's (when the SR are up). The CR0 core is shown in Fig. 6 and 7. Main parameters of this core have been calculated with MCNPX 2.5.0 code[2], and with the ZZ ALEPH-LIB-JEFF3.1 nuclear data library, a continuous energy multi-temperature library created at SCK•CEN[3,4,5]. Results are summed-up in Table II[6].

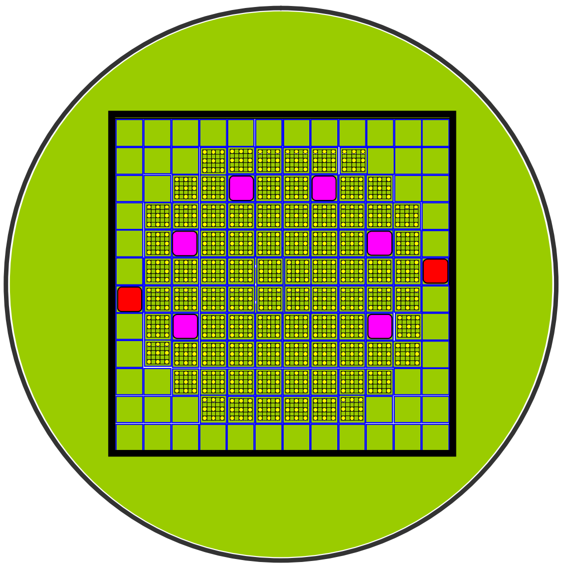

Fig. 6. Critical (CR0) configuration (88 FA's when SR up): safety (pink) and control (red) rod locations are shown.

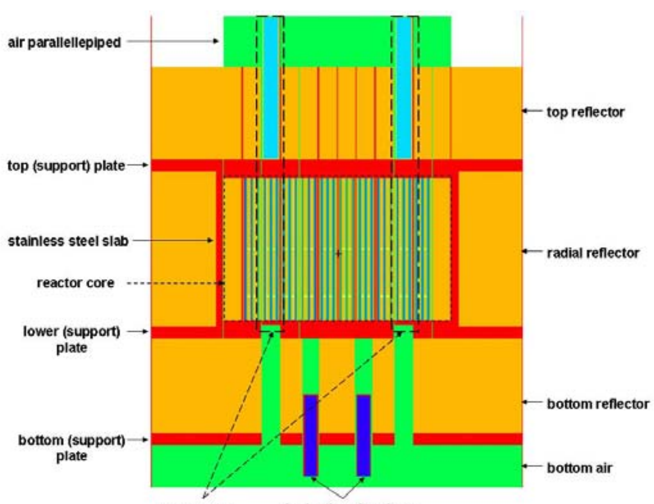

Fig.7. Critical (CR0) configuration vertical cut: all the rods up (legend: orange=lead, red=stainless steel, light blue=B_4C, blue=ionization chambers, green=air, central orange/blue stripes=fuel).

Compared calculations performed with the same code but different data libraries (ENDFB-VI.6, JEFF3.1), the results for k_{eff} values remain in agreement within 500 pcm.

In Table II are also shown calculation results for the SC1 configuration but in a special case: for licensing purpose it was asked to estimate how many FA's have to be added to the SC1 configuration (with the 4 central FA's removed, i.e. with 84 FA's) to make it "critical": 16 peripheral FA's (84 ➔ 100) are needed (cf. Fig. 8).

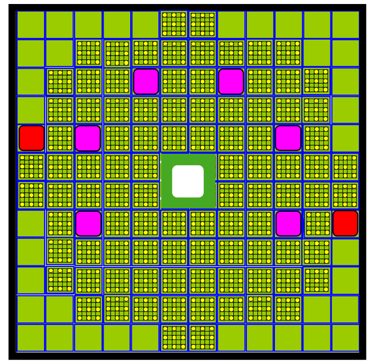

Fig. 8. SC1 core modified to be critical (100 FA's when SR up).

According to the reactivity worth of such a FA (cf. Table II), the 84 FA's SC1 configuration k_{eff} value is found around 0.97. At this stage the reactivity of the SC1 configuration cannot be assessed with a good accuracy as it adds the effect of the 4 central FA's removal (negative), the effect of the GENEPI-3C thimble insertion (slightly positive), and is depending on the initial number of FA's to reach the criticality and the as-built dimensions of tube shaft and lead buffer. However, the reactivity effect associated with these modifications of the initial CR0 critical core is expected to be about 3000 pcm.

TABLE II

Neutronic characteristics of core configurations with standard FA's

Configuration:	**CR0**	**"SC1"**
Number of Fuel Assemblies	88	100
Number of fuel rodlets	2376	2700
k_{eff}	1.01031±0.00029	1.00674±0.00025
β_{eff} (pcm)	748±17	720±28
Λ (μs)	0.390±0.025	0.42±0.06
Peripheral FA (Pb/U) reactivity worth (pcm)	-232±42	-196±38
Peripheral FA (with air instead of lead) reactivity worth (pcm)	-542±42	-365±42
Control Rods reactivity worth (pcm)	-794±40	-886±37
Safety Rods reactivity worth (pcm)	-10270±40	-11227±37

V. EXPERIMENTAL PROGRAMME

The GUINEVERE experimental programme aims at providing answers to the questions of on-line reactivity monitoring, sub-criticality determination and operational procedures for an ADS. The MUSE experiments[7] concluded that these objectives cannot be reached by a unique method but thanks to a methodology based on several techniques. It is the main objective of GUINEVERE to validate this procedure.

The experimental programme foreseen in the scope of the GUINEVERE activity within the EUROTRANS project (i.e. till the end of March 2010) will concern the CR0 and SC1 configurations. Two more sub-critical configurations (k_{eff}=0.95, 0.99) are expected to be investigated beyond this period as well as a deep sub-critical as low as 0.85 to mimic a loading situation. We limit here the description to experiments planned in the former configurations.

V.A. CR0 critical configuration

In the CR0 phase the experiments will be limited to measurements allowing core characterization and providing necessary information for validating sub-criticality measurement techniques. Radial and axial traverses will be executed by foil activation and with fission chambers (FC) respectively and a limited number of spectral indices will be performed in the core center. Control rod worth will be calibrated by means of the stable period measurement and rod-drop measurements will be used to determine the sub-critical reactivity scale and allow the implementation of a reference technique for validation of sub-critical reactivity measurements. Measurements of β_{eff} are also planned by Cross Power Spectral Density (CPSD) and Rossi-α techniques.

V.B. SC1 sub- critical configuration

The SC1 configuration (k_{eff}~0.97) is supposed to be representative of the nominal operation mode for a powerful ADS. Several steps are foreseen.

A first one will consist in absolute reactivity calibration of the SC1 level by applying the Area method in Pulsed Neutron Source (PNS) conditions, i.e. by operating the GENEPI-3C accelerator source in the pulsed mode. The PNS conditions will be the same as for the MUSE experiment, given that both GENEPI-1 and -3C accelerators have the same pulsed mode specifications. The Area method will be applied to time measurements performed with standard ^{235}U fission chambers but also with fast neutron threshold detectors such as ^{237}Np and ^{238}U FC in the core region as well as in the reflector region. The PNS time spectra will also be analyzed with the fitting techniques to be applied at beam interruptions in the continuous mode in order to characterize the impact of the source mode on the reactivity level values they provide. At last, control rods, as for the CR0 core, will have to be calibrated for the SC1 by the PNS Area method.

In a second step, the "current-to-flux" proportionality relation with the reactivity

$$\rho = C\frac{I}{P_{th}} = C'\frac{I}{\phi} \qquad (1)$$

(where I stands for the beam intensity, P_{th} for the thermal power, ϕ for the neutron flux, and where C, C' are constants) will be investigated. To do so the accelerator will be operated in the continuous beam mode. The proportionality constant will be determined in advance by means of calculation tool and by independent measurement techniques. Two different types of experiments are planned: static and kinetic measurements. For static measurements, the parameters to be measured to have a reactivity indicator are the neutron flux level in the core, the beam current on the target but also the neutron production in the target S (neutrons/second). This last parameter is of prime importance in such experiments performed with a T(d,n)^{4}He neutron source because the value of the beam current on the target is not sufficient to monitor the neutron source as the beam may impact off target tritium deposit, and also because of the target aging (which can occur rather quickly in the continuous beam mode). Two special detectors will then be devoted to neutron production monitoring: one will monitor directly the 14-MeV neutrons at 180° from the target thanks to a recoil proton telescope[8] located above the 90° dipole ("n monitor" in Fig. 5), and the other will detect the alpha-particle associated to the neutron production reactions in the backward direction, just at the entrance of the thimble ("α monitor" in Fig. 5). The experiment will consist of so called "current-to-flux" measurements with neutron flux detectors of different types and at different locations and for several beam current values. Since this type of procedure will be repeated for several slightly modified sub-criticality levels obtained by moving the control rods, a global picture of the accuracy of the current-to-flux indicator will be obtained. Besides these static measurements, where the proportionality relationship can be investigated in discrete static conditions to get a high precision on the results, continuous variations (referred to as "kinetic measurements") of reactivity with current will be investigated:

$$\rho(t) = C'\frac{I(t)}{\phi(t)} = C''\frac{S(t)}{\phi(t)}. \qquad (2)$$

Different specific time evolutions of the beam current are foreseen to be imposed. The kinetic behavior of the current-to-flux indicator with these changes will be recorded by continuous measurements of the parameters seen above (*I(t), S(t),* $\phi(t)$). An analysis will then be performed to determine to which extent this reactivity indicator is sensitive to the beam current changes. Otherwise, continuous reactivity changes are also planned to be imposed by piloting a specific time evolution of the insertion of the CR, hence the need for their calibration. At last, one will consider a mixed variation of both parameters, beam current (neutron source) and core reactivity, to check the robustness of the current-to-flux technique.

As a last step, interim reactivity cross checking techniques applied at continuous beam interruptions will be investigated. This kind of measurements is planned to be applied at dedicated accelerator "beam trips" dimensioned for not disturbing the ADS operation. During these beam interruptions the time spectra of the neutron population decrease are recorded, then analyzed with different techniques. To get more statistics, the beam trips will be repeated with a fixed programmable frequency (*F*). This will allow a regular cross checking of the proportionality constant of relation (1) in order to have a continuous access to an absolute reactivity monitoring. Two types of independent technique are planned to be applied (on separate time spectra): prompt decay fitting techniques, and prompt jump techniques. The formers consist in fitting the prompt neutron population decay (with exponential combination) or its decrease rate ("k_p method"[9,10]), both giving access to the prompt multiplication factor (Fig. 9). To be relevant, the fitted function, and therefore the interpretation model, has to be the most representative of the sub-critical core physics as possible. A beam interruption duration of the order of 4-5 times the prompt decay period *T* is sufficient for the analysis (i.e. about 200 μs). The following continuous beam duration before the next interruption has to be at least 10x*T*.

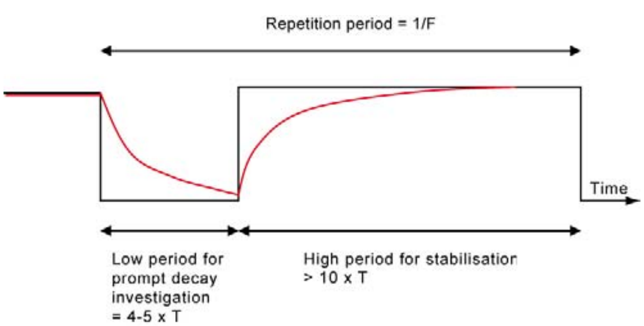

Fig. 9. Prompt decay fitting technique principle (black: beam current, red: neutron flux).

The prompt jump techniques are similar to source jerk technique. They have to be applied in a longer beam interruption as it is necessary to wait for the end of the prompt decay to have access to the right parameters. The reactivity in dollars is accessible thanks to the relation:

$$-\rho(\$) = \frac{P_H - P_C}{P_C - P_L}, \qquad (3)$$

where P_H, P_C and P_L correspond to the neutron population levels before the beam interruption, after the prompt decay, and after the delayed neutron precursor decay respectively (see Fig. 10). The delicate part of this method lies in the determination of the P_C level, intersection point between the prompt neutron and precursor decays. The beam interruption duration necessary is estimated around 100 times *T* (a few ms), but its impact on the result accuracy will be investigated.

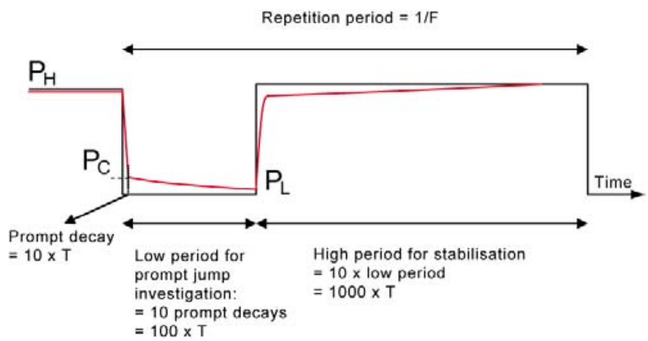

Fig. 10. Prompt jump technique principle (black: beam current, red: neutron flux).

VI. CONCLUSIONS

In the framework of the GUINEVERE project, a zero-power lead fast sub-critical facility is under construction at the SCK•CEN site in Mol (Belgium) thanks to the modification of the VENUS reactor and the construction of a new GENEPI neutron source to be coupled to the reactor by the end of 2009. Main transformations of the reactor building to host the GENEPI-3C accelerator are completed as well as the new VENUS-F core equipments. The GENEPI-3C machine, with the new requirements for the GUINEVERE experimental programme, is manufactured and under assembling at LPSC site in Grenoble (France), and the first pulsed deuteron beams were delivered at the accelerator tube exit in December 2008. Beam commissioning at the exit of the 90° dipole has been performed at the beginning of April 2009. This ADS mock-up, with pulsed or continuous neutron source options, will provide an adapted tool for continuation of investigations for a powerful ADS reactivity monitoring procedure. In particular, thanks to the DC mode operation and the possible beam trip mode, it will give the possibility to test the whole procedure outlined at the end of the MUSE experiment. The impact of the detector type or location will be investigated, with the possible extent to a powerful system studied.

Beyond the end of the EUROTRANS project this facility will also allow the study of additional sub-critical levels (0.95, 0.99) to test reactivity determination over a large range, and deep sub-critical level as low as 0.85 to mimic a core loading situation. The reliability of investigated techniques, i.e. interpretation model validity, will then be tested. The foreseen experiments aim at validating a methodology as well as at providing beam interruption characteristics and detector type and location recommendations for a demonstration ADS operation.

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