THE GENEPI-3C ACCELERATOR FOR THE GUINEVERE PROJECT

M.Baylac[1], H.Aït Abderrahim[2], P.Baeten[2], A.Billebaud[1], G.Bergmans[2], J.Bouvier[1], JM.De Conto[1], G.Gaudiot[5], JM.Gautier[4], G.Granget[6], D.Grondin[1], G.Heitz[5], B.Laune[3], D.Marchand[1], F.Mellier[6], Y.Merrer[4], R.Micoud[1], A.Mueller[3], E.Perbet[1], M.Planet[1], D.Reynet[3], C.Ruescas[5], B.Verboomen[2], F.Vermeersch[2], G.Vittiglio[2]

[1] *Laboratoire de Physique Subatomique et de Cosmologie, UJF/CNRS-IN2P3/INPG, 53 Avenue des Martyrs, 38026 Grenoble cedex, France; corresponding author: baylac@lpsc.in2p3.fr*
[2] *SCK-CEN, Mol, Belgium*
[3] *IPNO, CNRS-IN2P3/UPS, Orsay, France*
[4] *LPC Caen, ENSICAEN/Université de Caen/ CNRS-IN2P3, Caen, France*
[5] *IPHC-DRS/ULP/CNRS-IN2P3, Starsbourg, France*
[6] *CEA, Cadarache, France*

GENEPI is a type of electrostatic neutron generators designed for reactor physics. It consists of a deuteron, high intensity, electrostatic accelerator (250 keV, 40 mA peak intensity, 1μs pulse width, 5 kHz repetition rate) producing neutrons on a tritium target located in the reactor core. Two GENEPIs have already been built: the first accelerator was coupled to the sub-critical MASURCA reactor in Cadarache and the second machine is operating at LPSC in Grenoble for nuclear cross-section measurements. We propose to develop and build a third accelerator, GENEPI-3C, dedicated to the GUINEVERE project at SCK-CEN. This accelerator will have the characteristics of the previous machines, with new specifications (continuous beam and possibilities of micro beam interruptions for reactivity ADS monitoring) and must accommodate the topology of the SCK-CEN site. A general and technical presentation of the GENEPI machines is given. Then we present the preliminary design of the GENEPI-3C accelerator and report on progress achieved by the collaboration to date.

I. INTRODUCTION

The GENEPI (GEnérateur de Neutrons Pulsé Intense) machines are a family of electrostatic neutron generators dedicated to Accelerator Driven Systems (ADS) studies. They are motivated by the necessity to extend the validation of calculation and measurement methods already made for critical fast reactors to ADS and/or to new reactor concepts using new fuels. The first GENEPI machine was designed and built by the Laboratoire de Physique Subatomique et de Cosmologie de Grenoble (LPSC). It was a specific pulsed 250 keV deuteron accelerator (1 μs or below, sharp edges pulses, no tails, 40-50 mA peak intensity). Neutrons (2.5 or 14 MeV) were produced by the fusion (D+D) or (D+T) reactions of the incident deuterons hitting a deuterium or tritium target located in the reactor core. GENEPI-1, installed at the Cadarache MASURCA reactor, was dedicated to MUSE-4 experiments[1]. A second machine GENEPI-2, very similar, was built in LPSC where it is still under operation to measure nuclear cross sections for generation IV reactor concepts.

In the framework of FP6 "IP-EUROTRANS", the GUINEVERE project proposes to extend the MUSE-4 experimental program. GUINEVERE intends to use the VENUS reactor from SCK-CEN, serving as a lead fast critical facility, coupled to a continuous beam accelerator. In order to achieve this goal, the VENUS facility has to be adapted and a modified accelerator, GENEPI-3C, has to be designed and constructed. Unlike the two previous GENEPI machines, this new accelerator shall provide both pulsed and continuous mode operation with possible beam interruptions at the millisecond level. Besides, GENEPI-3C must accommodate the VENUS topology including a vertical coupling to the reactor.

II. STRUCTURE OF GENEPI ACCELERATORS

II.A. General structure

Figure 1 displays the overall layout of the first GENEPI accelerator, installed on the MASURCA reactor in Cadarache. Labels on the figure are explained in the following section which describes the working principle of the machine[2]. In a high voltage head (1) set within a Faraday cage, the deuterium atoms are ionized by an arc discharge using a hot filament in a duoplasmatron source (2). The ions are extracted and focused thus creating a deuteron beam. This beam is accelerated up to 250 keV (3) and deviated by a 45° electromagnet (5) to select the D^+ ions, thus removing molecular ions from the beam. The deuteron beam is transported over a 5 m long beam line and focused using mainly electrostatic quadrupoles (4, 6 and 7). Magnetic and electrostatic steerers associated to diagnostics allow beam position adjustment on the target (10). The target (T or D) sits at the end of a self-supporting thimble (8) inserted in the reactor core (9).

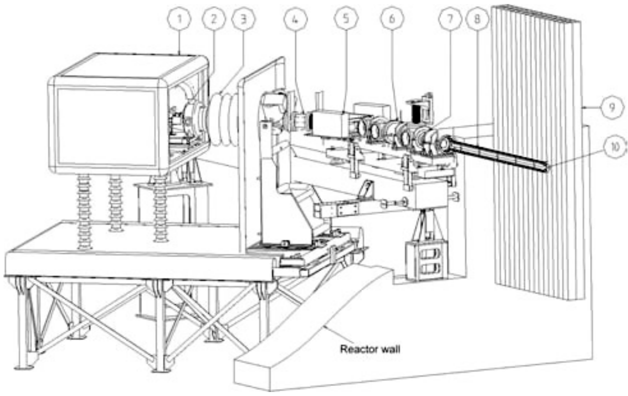

Fig.1.Layout of the GENEPI-1 accelerator on the MASURCA reactor. Labels are described in section II.A.

II.B. Ion source

The specific feature of a GENEPI accelerator is its deuteron source. A duoplasmatron source[3] is used to fulfill ion pulse requirements (short pulses, sharp edges). As displayed on figure 2, the source mainly consists of:

- An impregnated cathode (filament), to provide an electron arc,
- A first electrode of conic shape, referred to as the "cone", to trigger the electron discharge,
- An anode,
- External coils, providing axial magnetic field, for plasma confinement.

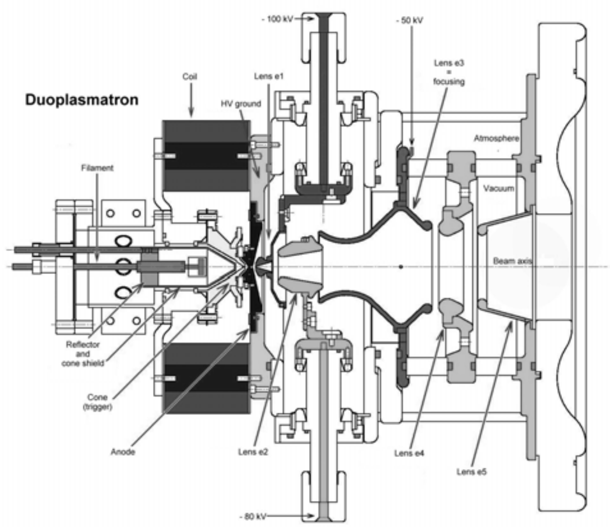

Fig.2. Duoplasmatron source, extraction and focusing electrodes. High voltages are expressed with respect to the HV ground labelled on the figure.

In pulsed mode, the duoplasmatron is operated like a thyratron. The cone, equivalent to a grid, is used as a trigger with a short positive pulse to initiate the electron discharge. Once started, the electron beam is completely dominated by space charge and cannot be controlled by electrodes. Consequently, the only way to get a short pulse is to polarize the anode by a LC delay line, whose discharge has a squared shape and the appropriate duration. After the delay line is discharged (~1 µs), the electron beam stops and the plasma vanishes. The operating deuterium pressure is 1-2 mbar and the nominal magnetic field is about 0.7 T in the cone-anode gap.

Great care must be taken for filament preparation and handling. All filaments are prepared under a hydrogen atmosphere during several hours at ~100 A for conditioning. The filament, when set on the source, is powered permanently under nominal intensity to avoid any thermal shock, even when the accelerator is shut-down.

II.C. Beam transport

After the extraction electrode (e1 on figure 2), the beam is focused by a set of electrostatic lenses of conical shape (e2 through e5) before entering inside the accelerating tube. A difficult challenge of GENEPI is the handling of high intensities. In the first part of the machine, the current is on the order of 80 mA as it also includes molecular deuterium ions. The neutralization by residual gas has a time constant of about 1 ms, and cannot occur with the GENEPI time structure, so all space charge must be managed. Therefore the accelerator tube must ensure a large enough aperture (60 mm in diameter) and a strong gradient in order to have a maximum focusing effect at field entrance. A magnetic 45° dipole removes molecular ions (D_2^+) from the beam. Beam focusing is performed with electrostatic quadrupoles with cylindrical electrodes over approximately 5 meters. The difficulty of handling high intensities is illustrated by the constant focusing required along the beam line. The GENEPI "rule of thumb" is to have a focusing element at least every 50 cm. Therefore an electrostatic focusing channel, the thimble, brought the beam onto the target in the MASURCA reactor. It is made of 6 electrostatic quadrupoles with planar electrodes. Detailed studies have shown that the non-linearities of these elements had no consequences on the beam quality. The dipole itself has 11.25 degree faces in order to have the same vergence in the two planes. Fine centering of the beam is achieved by electric and magnetic steerers.

The acceptable losses in such a machine are very high, due to the very low power of the beam. These losses will produce some deuterium implantation along the machine, leading to D+D reactions and to 2.5 MeV neutron production, but this neutron noise will remain negligible.

II.D. Target

Neutrons are generated by deuteron irradiation of tritium (or deuterium). The target consists of a 49 mm diameter and 1 mm thick copper disk exposed to a thin layer of deposition TiT (or TiD). The mass deposited over 30 mm in diameter accounts to a total activity of 12 Ci for tritium. At LPSC, regulations impose a maximum activity of 0.9 Ci. The target is mounted at the end of the thimble with the deposit facing the beam and the back side air-cooled at atmospheric pressure. Temperature is monitored and maintained well below 100° C to avoid tritium (or deuterium) desorption.

II.E. Neutron production control

The beam intensity is measured on target with a picoammeter. The neutron production is monitored on line by two backward silicon detectors located upstream of the target. Detectors were installed on the back side of the 45° magnet for GENEPI-1 and at the front end of the thimble upstream of the spectrometer for GENEPI-2. The first detector collects α particles and protons produced backward during the fusion reaction and transmitted in the beam line while the second one, covered by an Al foil, collects only the protons. An absolute calibration is performed via Ni foils irradiations.

III. GENEPI-1 AT MASURCA

The GENEPI-1 machine has been designed and built by LPSC (former ISN) from 1996 to 1999. The final implantation at the Cadarache MASURCA reactor was completed in June 2000 and dedicated to the MUSE-4 experiments. Table I summarizes the main features of the accelerator obtained with a tritium target. Details of accelerator operation, implantation, including safety studies, operation feedback and reliability aspects can be found in Ref. 2.

TABLE I. Main features of GENEPI-1 (MASURCA)

Peak current	40-50 mA
Repetition rate	10 Hz to 5 kHz
Mean current	100 μA at 4.7 kHz
Beam energy	140-240 keV
Pulse deuteron length	0.5-0.7 μs (FWHM)
Neutron energy	14 MeV
Spot diameter	20-25 mm
Target	Tritium / Titanium
Neutron production (peak)	~5×10^6 n/pulse
Neutron production (average)	~25×10^9 n/s at 5 kHz
Reproducibility	1% from pulse to pulse

The average deuteron intensity was modified by changing the repetition rate. Thanks to this intensity variation, the MUSE-4 experiment demonstrated the real possibility to control the reactor power with the accelerator[4].

The GENEPI-1 accelerator was fully dismantled and brought back to LPSC-Grenoble for the last parts in June 2007.

IV. GENEPI-2

The GENEPI-2 machine was built for the PEREN (Plateforme d'Etudes et de Recherche sur l'Energie Nucléaire) facility at LPSC to investigate future reactor concepts. It is dedicated to capture cross-section profile measurements between 0.1 eV to 30 keV using a lead-slowing-down-time spectrometer coupled with a pulsed neutron generator[5], GENEPI-2, as well as to scattering cross-sections by changing the material of the spectrometer[6]. This accelerator is very similar to GENEPI-1, except for the target (D or T) location. In experiments devoted to light slow-down materials, the target is surrounded either by a graphite barrel or an assembly of Teflon® plates. Another configuration where the target sits further downstream in the centre of an eight lead block assembly requires additional focusing, provided by electrostatic quadrupoles (see fig. 3). Some reduction of the pulse duration was achieved for GENEPI-2.

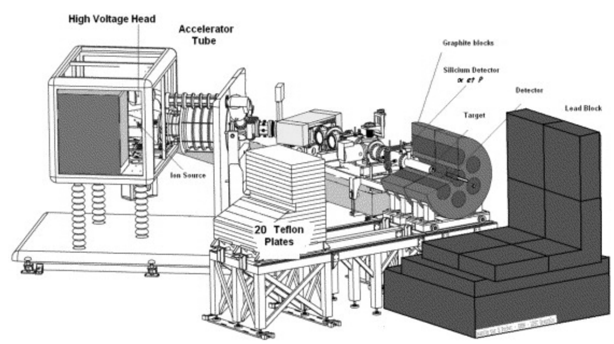

Fig.3. Layout of the GENEPI-2 accelerator at the PEREN facility (LPSC) in the short configuration where the target is inserted in the graphite barrel. The target can also be placed inside the lead block, using a longer thimble.

V. GENEPI-3C FOR GUINEVERE

The GUINEVERE program was initiated in 2006 in the framework of DM2 ECATS of the integrated activity IP-EUTROTRANS[7]. The proposed GUINEVERE project is devoted to specific experiments for the coupling an accelerator, target and sub-critical core. These experiments should provide an answer to questions of on-line reactivity monitoring, sub-criticality determination and operational procedures in an ADS. A continuous beam is required to validate the methodology for reactivity monitoring. Besides, a reactor based on a lead core will provide conditions representative of a lead-cooled ADS. The GUINEVERE program (Generator of Uninterrupted Intense NEutrons at the lead VEnus REactor) proposes to couple a GENEPI machine providing continuous beam to a modified version of SCK-CEN reactor VENUS, located in Mol, Belgium.

For the execution of the GUINEVERE project, two types of modifications must be performed: transformations connected to the installation of the GENEPI accelerator at the VENUS facility and modifications linked to the adaptation of the VENUS critical facility to host a fast lead core. Fuel and lead rodlets will be provided by CEA-Cadarache. Adaptation of the presently water-moderated VENUS reactor as well as the experimental program to be studied by GUINEVERE, are presented in Ref. 8 and will not be discussed in this paper. The GENEPI machine to be developed will have to fulfill new requirements in addition to existing specifications. The accelerator must accommodate the possibility of having a continuous deuteron beam (100 μA to 1 mA, see Ref. 8.) with some short programmable interruptions (a few ms). Moreover, unlike the coupling at MASURCA which was set in the horizontal plane, the beam line will penetrate the VENUS core vertically for core symmetry reasons and subsequent calculation and interpretation simplification.

V.A. VENUS building modifications

To implement the vertical penetration option, the accelerator has to be put on top of the VENUS bunker in a technical room to be constructed. This means that civil engineering works are necessary to build a new technical area above the existing VENUS bunker (see figure 4). This accelerator area will have a direct penetration through the ceiling of the bunker enabling the accelerator tube to enter the reactor vertically. The shielding walls in the accelerator room and the shielding of the bunker ceiling are currently under study and aim to minimize the weight of the structure. Detailed shielding calculations will determine the final choice of thicknesses and materials. A stairway gives the entrance from the lower level and allows the personnel to enter the accelerator room. Large equipment and accelerator pieces will be lifted from the floor of the VENUS reactor hall through an opening in the work floor of the accelerator room by means of a new crane installed in the accelerator room. This crane allows transporting the pieces towards the accelerator through-put where the accelerator will be assembled and installed. When the reactor is in operation, access to the accelerator room will be prohibited.

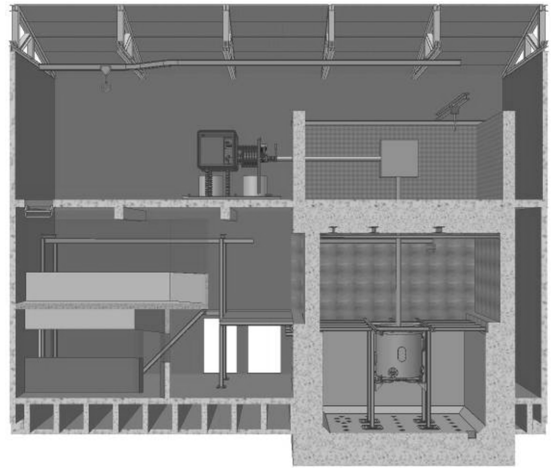

Fig.4. Cross-section of a preliminary layout of the VENUS building with the additional level to be built to accommodate the GENEPI-3C accelerator (courtesy of SCK-CEN).

V.B. GENEPI-3C

The new accelerator, referred to as GENEPI-3C (3rd of its kind, continuous mode) is developed by the French CNRS/IN2P3 teams of:

- Institut de Physique Hubert Curien (Starsbourg)
- Institut de Physique Nucléaire (Orsay)
- Laboratoire de Physique Corpusculaire de Caen

with and under the coordination of LPSC. We will now present the state of the art of the GENEPI-3C machine design to date (July 2007) and detail some key components of this accelerator, which differ from the previous machines.

V.B.1.General structure

Figure 5 displays the general and preliminary structure of GENEPI-3C. The ion source seats in the high voltage head lying above the reactor bunker, followed by a horizontal beam transport section of ~ 3.5 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 which deflects the beam downwards. A quadrupole doublet is located at the exit of the magnet, no optical element is foreseen in the thickness of the bunker ceiling. Two quadrupole triplets located on the vertical beam line above the reactor core focus the beam onto target. Unlike the GENEPI-1 at MASURCA, no beam focusing is envisioned in the thimble within the reactor. Beam dynamics calculations show that this focusing scheme allows deuteron beam to be transported over a wide intensity range and thus should be suitable for both high current pulsed mode and lower current continuous mode.

Control rods and measuring canes strongly limit the space available for the accelerator above the reactor. This generates stringent transverse dimensional constraints on machine components located on the vertical beam line, in particular vacuum pumps and beam diagnostics. The vacuum system is being optimized in terms of pump sizes, numbers and locations, while maintaining a pressure on the order of 10^{-6} mbar at the end of the thimble. Likewise, beam diagnostics above the reactor must be as compact as possible. Moreover, interceptive diagnostics designed for the previous GENEPIs must be reconsidered because of the high beam power generated in the continuous mode. Some components from GENEPI-1, such as the high voltage head and platform, the ion source and the accelerator tube will be re-used for constructing the new GENEPI-3C.

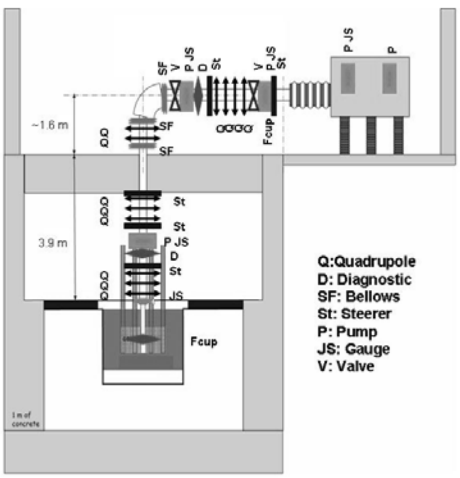

Fig.5. Preliminary layout of the GENEPI-3C structure.

V.B.2. Ion source

One of the main challenges of the GENEPI-3C machine is to operate both in pulsed and continuous mode. In the continuous current mode, brief interruptions of the beam will be required to study neutron decay from different origins, as explained in Ref. 8. Table II summarizes the operating conditions required for the continuous mode operation.

The duoplasmatron source driving the first two accelerators is particularly well suited for pulsed mode operation[3]. Developments were undertaken at LPSC to determine whether a duoplasmatron can be used as a continuous source able to produce short and repetitive beam interruptions. Generating the appropriate time structure of the beam directly at the source would indeed greatly simplify the accelerator design.

TABLE II. Specifications of GENEPI-3C in DC mode

Mean current	160 μA 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
Maximum neutron production	5×10^{10} n/s
Reproducibility	1% from pulse to pulse

The continuous operation of the ion source was investigated on a test bench purpose-built for the GUINEVERE program at LPSC. It consists of a duoplasmatron source similar to that of the previous GENEPIs, held at 40 kV, followed by a pepper-pot profiler system. A collimator, equipped with 1.5 mm diameter holes spaced by 6.5 mm along the vertical axis, is centered on the beam axis. A Faraday cup with a 0.1 mm slit is located 52 mm downstream of the collimator and translates behind it to measure the intercepted beam current[9].

First, usual pulsed operation was set in order to characterize the beam on this test bench. Then the duoplasmatron was run up to 1.2 mA of total deuteron DC current without major difficulty. This corresponds to a deposited power of 48 W on the Faraday cup and about 20 W on the cone. Preliminary measurements of the RMS emittance gave a non-normalized value on the order of 20π mm.mrad at 40 keV. The size of the beam spot is about 20 mm in diameter, which is about a factor of 2 smaller than the spot measured in the intense pulsed mode. Tests were run in order to estimate the heating of the source components while depositing substantial beam power within the non-cooled duoplasmatron. Temperature measured at several locations outside of the duoplasmatron showed a temperature elevation less than 20° after 8 hours of high current DC operation. Beam interruptions are also under investigation. Preliminary tests seem to indicate the possibility to turn off an established DC beam with a transition time on the order of 1 μs.

In the duoplasmatron, atomic deuterons are produced, as well as molecular ions D_2^+, the ratio depending on the plasma density. Typically, in pulsed mode, the ratio is about 25% molecular ions, which have to be removed from the D^+ beam by the magnetic dipole. The molecular ion contribution must be characterized while running the duoplasmatron continuously to determine what fraction of the total beam measured on the test bench will be efficient for neutron production. The contribution of the D_2^+ ions must also be considered in the magnet design: molecular ions will be dumped on the magnet chamber and may generate substantial heating.

The test bench is currently being upgraded with a 45° dipole magnet to isolate the atomic deuterium ion beam. Based on the full characterization of the beam in the range of continuous to pulsed intensities (~100 µA up to 40 mA), transport calculations will be refined and focusing will be determined.

V.B.3. Dipole magnet

The 90° bend magnet, of “C” design, has a 0.6 m bending radius, 30° faces and a magnetic field of 0.2 T. The magnet chamber must accommodate a proton recoil telescope to monitor neutron rates. The dipole is cooled by several water loops and the heat exchange unit is distant from the magnet to keep most of the cooling fluid away from the hole above the reactor. Great precautions must be taken to prevent leakage in the reactor core as it would drive it critical. The magnet coil and its cooling system are waterproof thanks to fiber glass ribbon and epoxy resin body. Water and electrical connections are also embedded in a waterproof casing with humidity detectors. Pressure in the water circuit is controlled permanently. The dipole will be supported by a mobile frame translating it away from the hole in the bunker ceiling to allow the vertical beam to be retracted.

V.B.4. Vertical beam line handling

During core assembly operations and GENEPI-3C target changes, the vertical beam line must be entirely removed from the reactor. Unlike GENEPI-1 at the MASURCA, which was easily removed by disconnecting the HV platform, retracting it and by sliding back the beam line on top of the girder, the vertical line of GENEPI-3C must be lifted above the reactor to the accelerator level. The vertical line will be embedded in a supporting structure which will be hoisted along guiding structures by mean of a crane (see figure 6). A structure dedicated to the vertical beam line storage is currently under design.

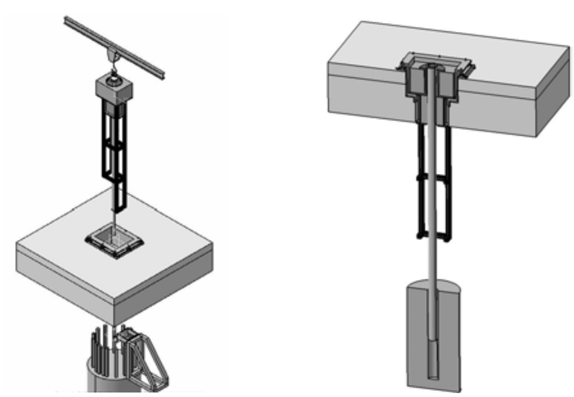

Fig.6. Vertical beam line removed from the reactor (left) and inserted in the core (right).

V.B.5. Thimble

The thimble, a 900 mm long section, ends the vertical beam line and supports the neutron production target. As this section is inserted in the reactor among fuel assemblies, its transverse dimensions must be minimized. This led to the choice of an optics free thimble, validated by beam dynamics calculations. The size of the target, conditioned by the maximum beam size, is currently set to 40 mm in diameter. In this first design, the external diameter of the thimble is on the order of 90 mm, which is suitable for the insertion in the VENUS reactor. The target module ending the thimble is very similar to that of the previous GENEPIs. It is designed to be easily removed from the thimble to allow target changes. To minimize tritium contamination, handling and mounting operations of the targets will be performed in a glove box located in the accelerator room at the upper level. An uncontrolled heating of the target would lead to a fast tritium release and thus to a premature target change. The target cooling system is one of the challenges of GENEPI-3C: the operation in continuous mode assuming a 1 mA beam will bring 250 W on the target to be evacuated without water and in a non-cooled environment (reactor core) reaching 45º C at the envisioned reactor power of 50 W. The target cooling system is proposed as two compressed air pipes dispatching air on the back side of the target via a series of nozzles. Optimization of this design is in progress and the efficiency under realistic conditions will have to be validated. Temperature and beam current will also be measured at the back of the target.

V.B.6. Commissioning

The accelerator will be assembled and tested at LPSC (France) before being shipped to SCK-CEN (Belgium). Infrastructure at LPSC is currently under preparation to provide a mock-up of the VENUS site. Following the GENEPI-1 experience, the accelerator is expected to be fully designed, assembled and commissioned in Grenoble for the first quarter 2009. This first commissioning will be progressive and will require an easy access to the beam line, which is not possible at SCK-CEN.

After commissioning of the beam line, the deuteron beam will be fully characterized (profile, intensity, emittance measurements, beam position and steering calibration). Motions and storage of the different beam line sections will also be validated at that stage. This should minimize the commissioning time required at the VENUS facility.

VI. CONCLUSIONS

The GUINEVERE project in the framework of FP6 "IP-EUROTRANS" aims at defining the design of a demonstration facility for the Accelerator Driven System concept and solving the main R&D issues related to the operation of such a facility. To investigate this topic a fast lead reactor coupled to a flexible neutron generator is needed. In this paper, we presented a proposed design for a GENEPI accelerator bringing the external neutron source to the modified VENUS reactor of SCK-CEN in Mol. Unlike previously developed GENEPIs, this new machine is intended to provide both pulsed and continuous beam current with short and repetitive interruptions. This GENEPI-3C accelerator must accommodate the VENUS topology including a vertical coupling to the reactor and a high beam power generated by continuous mode operation. Work is in progress regarding the use of a duoplasmatron as a versatile ion source able to fulfill the demanding requirements on the beam properties in terms of intensity and time structure. The accelerator is expected to be fully designed, assembled and operational at VENUS by the summer 2009.

ACKNOWLEDGMENTS

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