The GENEPIC-3C accelerator for the GUINEVERE project

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Abstract. GUINEVERE, Generator-of-Uninterrupted-Intense-NEutrons-at-the-lead-VEnus-REactor, is a project of FP6 EUROTRANS Integrated Project devoted to Accelerator Driven System (ADS) feasibility studies. The second domain, ECATS, is dedicated to specific Experiments for Coupling an Accelerator, a Target and a Subcritical core. GUINEVERE aims to investigate on-line reactivity monitoring, sub-criticality determination and operational procedures in an ADS. For this project, a modified VENUS facility at the SCK•CEN site (Belgium) will be coupled to an upgraded GENEPI neutron source. SCK•CEN is transforming the water moderated VENUS reactor at Mol into a fast lead core facility, fuel and lead rodlets being provided by CEA. The GEnerator-of-NEutrons-Pulsed-and-Intense is an electrostatic accelerator generating 14 MeV neutrons by bombarding deuterons onto a tritium target located in the reactor core. CNRS is designing and building a new versatile accelerator, GENEPI-3C, to meet the requirements of the experimental program: it will be capable of delivering alternatively intense 1 µs long deuteron pulses with adjustable repetition rate, as well as continuous beam with programmable interruptions. This paper describes the design and commissioning of the accelerator.

1. Introduction

The GUINEVERE project (Generator of Uninterrupted Intense NEutrons at the lead VEnus REactor) is part of the EUROTRANS Integrated Project (6th EURATOM FP) which gathers feasibility and design studies of an ADS prototype 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-GENEPI system will provide a unique facility in Europe for fast sub-critical reactor physics investigations.

2. Coupling with the VENUS-F reactor

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

2.1. 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 figure out the presence of a fast system coolant, surrounded by lead plates. 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) [1]. The supporting structure of the vessel holding the core will be reinforced due to the added weight of the lead components. Every components of the new FA structure are manufactured and preassembled.

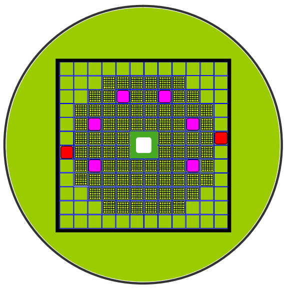

FIG. 1. Cross section of a sub-critical core configuration (SC1, 84 FA), including safety rods (pink), control rods (red) and accelerator insertion channel (central zone).

The core will be surrounded by axial and radial lead reflectors. At the center a channel is arranged with a stainless steel shaft to insert the accelerator thimble. To keep a simple geometry and allow sufficient room for the thimble (see section 3.5), this channel matches the cross section of 4 standard FA's. A small lead buffer will fill the gap between the target tube shaft and the central hole. A radial view of the reactor at mid-plane, in a sub-critical configuration (SC1, k_{eff}~0.97) is shown in Fig.1. A new shut down system is implemented for the fast neutron reactor: safety rods fall into the core by gravity upon de-energizing electro-magnets. Control rods contain an absorber part sliding in a wrapper tube. Rods are located as close as possible to the center without interfering with the vertical structure of the accelerator.

2.2. Coupling

The accelerator coupling is vertical to keep the cylindrical symmetry. Due to the small size of the reactor (160 cm in diameter), the accelerator cannot be hosted at the reactor top level. Therefore the reactor bunker was modified to implement a room GENEPI-3C at an upper level (see Fig.2). Civil engineering work at VENUS building was completed in March 2009. Electrical power equipment and ventilation system will be installed by the summer 2009.

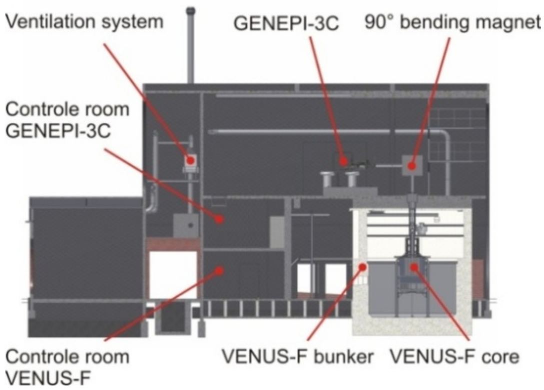

FIG. 2. Side view of the modified VENUS facility

3. The accelerator GENEPI-3C

The GEnerator of NEutrons Pulsed & Intense-3 Continuous, is the third accelerator of a series devoted to neutronic experiments [2] [3]. It is designed and built by a CNRS/IN2P3 collaboration. It is being assembled and commissioned at LPSC-Grenoble by the summer 2009 before being transferred to SCK•CEN and reassembled within the VENUS-F building.

The GENEPI machines are 250 keV 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. This new machine must fulfil the 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 short and intense bunches (1 μs, ~40 mA peak current) as described in Table I. In addition, it must also deliver continuous beam, with current up to 1 mA. Programmable beam interruptions will be implemented for the DC operation: duration and repetition rate of these beam trips must be adjustable to meet the requirements of the experimental program (Table II.). In particular, a fast transition time (~ 1 μs) is required to turn the beam on and off.

TABLE I: Specifications of GENEPI-3C in pulsed mode

Peak current	40 mA
Repetition rate	10 Hz to 5 kHz
Mean current	190 μA at 4.7 kHz
Beam energy	140-240 keV
Pulse deuteron length	~0.7 μs (FWHM)
Neutron energy	14 MeV
Beam spot diameter	20-25 mm
Max. neutron production (peak)	$\sim 5\times10^6$ n/pulse
Max. neutron production (average)	$\sim 25\times10^9$ n/s at 5 kHz
Reproducibility	1% pulse to pulse

TABLE II: 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	20-40 mm (diameter)
Max. neutron production	5×10^{10} n/s

3.1. Accelerator design

The general structure of the accelerator is typical of electrostatic machines (see fig. 3). The ion source (not represented on the figure) seats within a high voltage head held at 220 kV which is enclosed in a Faraday cage. At the source output, the accelerating tube (not represented on the figure) is followed by a horizontal beam transport section of 3 m. Beam transport is ensured with electrostatic quadrupoles. A first group of 4 quadrupoles transports and focuses the beam at the 90° dipole magnet. The dipole deflects the beam vertically downwards and ensures selection of D^+ ions. The beam is drifting over more than 1 m within a bare beam pipe in the section going through the penetration in the ceiling of the reactor bunker. Sets of quadrupoles are located around this drift as close as possible to bunker ceiling to contain the beam dimensions: a doublet is connected at the magnet output at the upper level (above the bunker) and the vertical beam line in the bunker starts with a quadrupole triplet directly under the ceiling. A final triplet located above the reactor core focuses the beam onto target. The final beam line section, the thimble, holding the target and inserted in the reactor core, contains no focusing, unlike the GENEPI-1 at MASURCA. Beam dynamics calculations show that this overall focusing scheme allows beam transport over a wide intensity range and thus should be suitable for both high current pulsed mode and lower current DC mode.

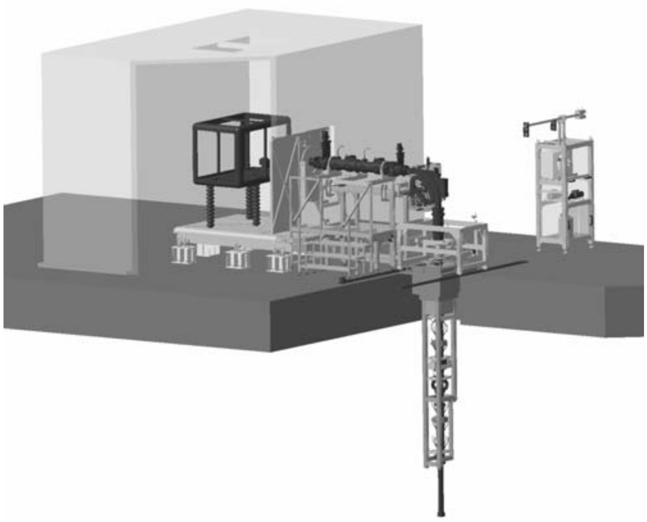

FIG. 3. Overall accelerator layout

Safety rods and measuring canes for core characterization 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. A group of 6 turbo-molecular pumps, 3 on the upper line and 3 smaller ones on the lower section, maintain a pressure along the line better than 10^{-6} mbar. Likewise, beam diagnostics above the reactor must be as compact as possible. Moreover, some interceptive diagnostics designed for the previous GENEPIs had to be reconsidered because of the high beam power generated in the continuous mode. Standard full size diagnostics measure the beam profile and current on the upper beam line section. On the lower line, a new wire scanner was developed: 2 thick tungsten wires (2 mm diameter), perpendicular to the beam direction, will be scanned through the beam using compact stepper motors mounted within the vacuum chamber. This diagnostic was designed to sustain the maximum beam power (~250 W for 1 mA DC beam). Magnetic steerers associated to diagnostics allow beam position adjustment both in the horizontal and the vertical sections. Upstream of the thimble, a set of 4 static rectangular plates, isolated from one another, are placed perpendicularly to the beam at an adjustable distance. They provide on-line monitoring of beam loss (top, bottom, left and right).

Neutron production is monitored both at the upper and lower levels by silicon detectors. A first detector, mounted in the thimble right above the reactor, collects α particles and protons produced backward during the fusion reaction while a recoil telescope, covered by an Al foil, collects protons only. Moreover the beam intensity is measured on target with a picoammeter.

3.2. Ion source

A duoplasmatron source, well adapted for short beam pulses, was chosen to drive the first 2 accelerators [4]. For simplicity of constructing and operating the third machine, decision was made to pursue one single ion source capable of meeting all beam requirements, i.e. delivering alternatively intense pulsed mode and continuous beam with programmable interruptions. Developments were thus undertaken on our duoplasmatron source. The source mainly consists of:

- An impregnated cathode (Nickel, Strontium, Barium), or hot filament, to provide an electron arc,
- An intermediate electrode of conic shape, to trigger the electron discharge,
- An anode,
- A set of 2 external coils, providing axial magnetic field, for plasma confinement.

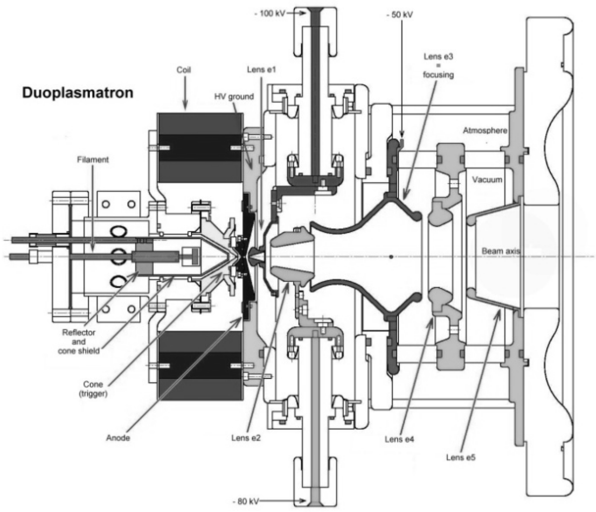

FIG. 4. Duoplasmatron source, extraction and focusing electrodes. High voltages are expressed with respect to the HV ground labelled on the figure.

In pulsed mode, the duoplasmatron is operated like a thyratron. The intermediate electrode, 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 space charge dominated and cannot be controlled by electrodes. Therefore, in order to get a short pulse, the anode is polarized by a LC delay line, determined to generate 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 mbar and the nominal magnetic field is about 0.7 T in the ionization gap. Deuterons are produced, as well as molecular ions D_2^+ and D_3^+, the ratio depending on the plasma density. Typically, the intensity ratio η, where $\eta = I(D^+)/I(\text{total})$, is about 75% when operating the source in this intense pulsed mode. The total beam current after extraction thus reaches ~70 mA peak to provide 40-50 mA of D^+ on target. The neutralization by residual gas, of time constant ~1 ms, cannot occur with the pulse time structure, so space charge must be fully handled. The beam is focused by a set of electrostatic lenses of conical shape before entering the accelerating tube. This tube was designed with a large aperture (60 mm in diameter) and to ensure a maximum focusing effect at field entrance.

For DC operation, the delay line is removed: once the plasma is ignited with the intermediate electrode trigger, similarly to pulsed mode operation, continuous ionization is sustained. The main difficulty resides in the poor D^+ ionization efficiency of the source when operated continuously. A dedicated test bench was set up to study and optimize the DC operation of the source: it consists of a duoplasmatron, held at a limited voltage of 40 kV, a dipole magnet, a beam profiler and a Faraday cup which can be mounted either directly after source extraction or after magnetic selection. Tests were performed on major source parameters, such as electron intensity, gas pressure, magnetic confinement, electrodes polarization and filament temperature to optimize the plasma density. A large electron intensity, i.e. arc current, is required for a good mono-atomic deuterium rate: starting from η~5 % measured for an arc current ~100 mA, the deuteron ratio reaches ~35% for 1 A of current in the arc. The second driving parameter was found to be the gas pressure in the ionization chamber. When optimized, the duoplasmatron delivers continuous beam containing about 40% of deuterons, the remaining fraction of the beam will have to be removed from the beam before the target via magnetic separation. Measurements with a pepper-pot directly at the source extraction confirmed that the beam emittance in DC mode remains well below the emittance measured in the intense pulsed mode. Pulsed operation, characterized on previous machines, thus imposes the beam transport scheme.

Once the source is operating continuously, interruptions are generated by driving the electron intensity. First the plasma is ignited via a trigger on the intermediate electrode. The arc current is stopped after a given time referenced to the trigger signal, which can be adjusted: the beam is turned off. Ionization is restarted after an adjustable time: the beam is turned back on. Tests and optimization of this scheme are still underway. Preliminary results on beam measurements show that interruptions, on the order of 50 μs long can be generated up to 100 Hz. This indicates that the requirements of the experimental program on beam trip duration and rate seem within reach. Transitions times were also measured on the beam. While the drop time is very short (a couple of μs), the time required to re-ignite the plasma is a bit longer (5 μs) and requires some additional optimization. Beam current instabilities measured on DC beam when regularly interrupted remain under investigation.

3.3. Dipole magnet

At the end of the horizontal line, the beam is deflected downwards by a dipole magnet. This 90° bend magnet, of “C” design, with a 0.5 m bending radius and 30° faces generates a magnetic field of 0.2 T. The magnet chamber accommodates the proton recoil telescope on a port above the chamber in direct sight of the target. Moreover, it is equipped with an ion collector mounted on a side port. Molecular deuterium ions generated by the source (see section 3.2) impinge a large and thick dumping plate. The plate is air cooled as it must handle a large beam power due to the modest source efficiency in DC mode (~ 350 W lost in the collector for 1 mA D^+ on target).

The dipole itself is cooled by several water loops. As it is positioned directly above the reactor, a leakage would generate insertion of moderating liquid into the reactor core with possible consequences on reactivity. Therefore stringent precautions must be taken to prevent leakage into the core. The heat exchanger and the cooling tank are located ~2 m away from the magnet to keep most of the fluid volume far from the penetration in the bunker. The coolant (water and glycol) is brought to the waterproof coil via watertight rubber tubing. Water connections as well as the support structure of the dipole are embedded in waterproof casings equipped with leak detectors. Position sensors ensure that casings are properly positioned. Pressure, flow and temperature of the coolant loops are also monitored continuously. The dipole is supported by a mobile frame translating it away from the penetration to allow the vertical beam to be retracted.

3.4. Vertical beam line section

During machine operation, the 5 m long vertical beam line penetrates the reactor core within the 160x160 mm^2 insertion channel (see fig. 1) such that the target mounted at the thimble's end lies at the core center. For core assembly operations and GENEPI-3C target changes, the vertical line must be entirely removed from the reactor bunker. Unlike GENEPI-1, horizontally coupled to MASURCA, which was easily removed by retracting the HV platform and sliding back the beam line atop a girder, the vertical line of GENEPI-3C must be lifted above the reactor to the upper level. The beam line, as well as borated polyethylene shielding, are embedded in a support structure to be hoisted by a crane (fig 5). Frames at the upper and lower levels will guide the motions of the line. During storage or maintenance, the vertical beam line will be hosted by a dedicated deck currently under construction.

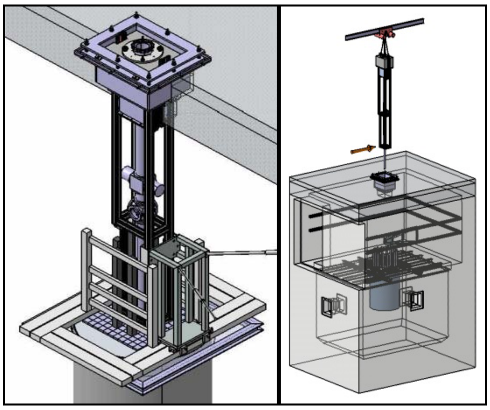

FIG. 5. Vertical beam line inserted into the reactor (left) and retracted to the upper level (right).

3.5. Target

The self-supporting thimble, a 1 m long section, ends the vertical beam line and supports the target. The neutron production target consists of a thin layer of TiT (12 Ci) deposited on a support provided by a high purity copper disk. The beam size on target matches the 40 mm diameter of the active layer. Beam current is measured at the back of the target. The target module ending the thimble 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 at the upper level.

In DC mode, a power of 250 W is dissipated by the beam on target, so particular attention is paid to the target cooling and temperature monitoring. A high temperature (> 100°) on the target would cause significant Tritium desorption and therefore a decrease of the neutron production and premature target change, but it could also rapidly lead to the melting of the target support which would create a major vacuum accident in the beam line. The target cooling system is one of the challenges of GENEPI-3C: hydrogenous liquid are not be brought into the non-cooled environment of the reactor core and the space available within the insertion channel is extremely limited. The cooling system was designed with compressed air: it consists of 4 air pipes feeding a diffuser with 16 nozzles facing the back of the target support. The back of the support is itself designed with 52 pin fins 7 mm long, to increase the heat exchange surface. To avoid condensation, the compressed air is dried and its temperature optimized before inlet pipes. For redundancy, two thermocouples monitor the temperature on the back of the target. Proper operation of the air drying system is ensured by monitoring of the temperature, humidity and pressure of the cooling air.

4. Accelerator commissioning

The accelerator will be fully assembled and tested with dummy targets at LPSC (France) before being shipped to Belgium. Indeed, the commissioning progresses along with machine construction and requires an easy access to the machine, which would not be possible at SCK•CEN. Infrastructure at LPSC was set up to provide a mock-up of the VENUS site.

The machine commissioning is organized in 3 stages. The initial configuration, consisting of the ion source and the HV platform, was validated in pulsed mode in December 2008. In April 2009, about half of the machine was constructed and successfully tested, as it ended right before the vertical beam line. Eventually, the accelerator is expected to be fully assembled and commissioned at LPSC by the summer 2009. After validation of all beam line equipments, beam will be characterized down to the target location: profile, intensity, emittance measurements, beam position and steering calibration. The target cooling system will be tested with a mock-up of VENUS-F insertion channel. Beam line motions will also be validated, in particular insertion and retraction of the vertical beam line with the guiding frames. This should minimize the commissioning time required at SCK•CEN.

The machine will then be transferred to SCK•CEN so that it can be re-assembled and tested by October 2009. After the licensing procedure is completed, the VENUS-F core could be loaded such that the experimental would start in December 2009.

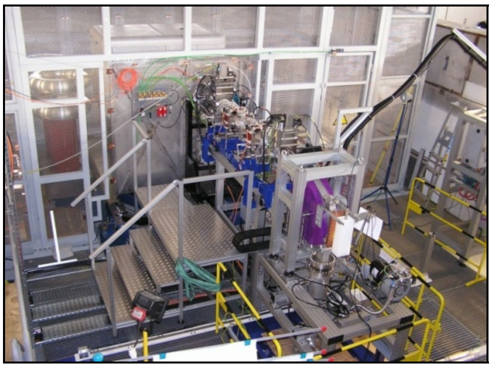

FIG. 6. Partial assembly of GENEPI-3C (LPSC, April 2009)

Acknowledgements

This work was partially supported by the 5th Framework Program of the European Commission through the MUSE contract # FIKW-CT-2000-00063, and by the 6th FP through the EUROTRANS Integrated Project contract # FI6W-CT-2005-516520.

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