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Multipurpose applications of the accelerator-based neutron source GENEPI2

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Summary. — GENEPI2 (GEnérateur de NEutrons Pulsé Intense) is an accelerator-based neutron source operating at LPSC laboratory in Grenoble (France). The neutrons are produced at 2.5 MeV or 14.2 MeV trough fusion reactions. GENEPI2 specifications allow performing efficiently accelerated irradiation tests of integrated circuits. This facility can also be operated to test and calibrate different types of detectors. This paper will describe the facility and its performances. Then, measurements of the neutron production will be presented as well as different types of experiments and irradiations. Finally, we describe upgrades undertaken to increase the neutron flux and optimize the facility for multiple applications.

1. – The GENEPI2 facility

GENEPI machines are accelerated-based neutron sources originally built for research on future nuclear reactor concepts. These machines are electrostatic accelerators of deuterons (d). After acceleration, the ions are guided towards either a tritium (T) or a deuterium (D) target. Neutrons are produced either by dT or by dD fusion reaction:

- $\mathrm{d} + \mathrm{T} \rightarrow \mathrm{n} + \alpha \quad E_n^{ave} = 14.2\,\mathrm{MeV}$,
- $\mathrm{d} + \mathrm{D} \rightarrow \mathrm{n} + {}^3\mathrm{He} \quad E_n^{ave} = 2.5\,\mathrm{MeV}$.

Since the late 90s, LPSC has developed 3 GENEPI-type generators. GENEPI2 is located in Grenoble at LPSC (Laboratoire de Physique Subatomique et de Cosmologie). This facility was built to perform nuclear cross-section measurements. In addition, this neutron source provides a facility suitable for several other applications (see sect. **3**).

To generate the deuteron beam, a duoplasmatron source produces ions in the form of short and intense bunches (FWHM $\sim 0.7\,\mu$s, peak current $\sim 50\,$mA) with a repetition rate adjustable between 100 Hz and 4 kHz. The ion source sits within a high-voltage platform held at a constant voltage of 250 kV with respect to ground, itself surrounded by a Faraday cage (fig. 1(a)). The ions are extracted and focused by a series of 5 conical high-voltage electrodes, shaping the deuteron beam. Then the beam is accelerated up to 250 keV by a 5-stage accelerating structure. After acceleration, the beam is transported


(a) (b)

Fig. 1. – GENEPI2: (a) the deuterium ion source within the high-voltage platform (250 kV), surrounded by a Faraday cage, (b) the beam line section after acceleration transporting the deuteron beam to the target.

TABLE I. – *Summary of GENEPI2 specifications.*

Deuteron energy (keV)	220–250
Peak current (mA)	$\sim$50
Repetition rate (Hz)	100 to 4000
Average current (μA)	4 to 140
Pulse FWHM (ns)	700
Pulse stability	5%
Max. total neutron production (ns^{-1})	8×10^9 in 4π
Max. neutron flux (ns^{-1}cm^{-2})	4.5×10^7
Average neutron energy (MeV)	2.5 for dD, 14.2 for dT

through a 5 m long beam line, held under vacuum ($\sim 10^{-7}$ mbar) (fig. 1(b)). At first, the beam is deviated by a 45° electromagnet performing magnetic selection. Solely deuterons are transported towards the target. High intensity handling is achieved with constant focusing along the beam line every $\sim$0.5 m by a series of electrostatic quadrupoles. Beam diagnostics placed at different locations characterize the beam intensity and profile. Magnetic steerers allow fine beam positioning on the target. The beam dimensions are tuned to match the active area of the target (25 mm in diameter) at the end of the beam line. Its intensity, up to 200 μA, is measured on target continuously. The target active area is made of a titanium layer loaded with tritium (TiT) or deuterium (TiD) deposited on a high purity copper disk. The activity of a fresh tritium target is 0.9 Ci. The target is air-cooled to limit tritium (or deuterium) desorption. Neutrons are emitted from the target in the whole experimental area. The accelerator is entirely controlled and operated remotely via a command-control system. Table I summarizes GENEPI2 specifications.

2. – Dosimetry

Neutron production is monitored continuously throughout experiments to determine the neutron dose for each irradiation. A preliminary real-time flux estimate is obtained by the monitoring of the beam current on target. To obtain a more precise estimation, different complementary measurements are performed and off-line data treatment is required. Periodically aluminum foils are irradiated at a reference position in front of GENEPI2 target area. The activity of the foils is then measured at LPSC by the low activity laboratory (LBA) with germanium detectors. The activation technique allows us to get an absolute measurement of the neutron flux and to monitor the target aging.

Furthermore, the neutron production is directly measured online by two dedicated detectors. A silicon detector sits under vacuum within the beam line, approximately 60 cm upstream of the target. This detector collects the recoil particles backscattered from the target during the fusion reactions. When operating with T target, the detector collects α particles emitted from the target. The recorded energy spectrum is analyzed to determine the total number of collected α particles taking into account event multiplicity. This number provides the total dose. Similarly, the monitoring of the 2.5 MeV neutron flux is achieved by detecting the backscattered protons produced by the reaction $\mathrm{d}+\mathrm{D} \rightarrow \mathrm{p}+\mathrm{T}$ which is almost equally probable to $\mathrm{d}+\mathrm{D} \rightarrow \mathrm{n}+{}^{3}\mathrm{He}$.

Finally, a movable monitor [1] characterizes the forward emission of neutrons from the dT reaction. The 15 MeV neutrons hitting the detector are converted to protons by an hydrogenous layer. Then protons are detected by a 3-stage Si telescope with a triple coincidence. The intrinsic detection efficiency of the monitor is ~0.1%. From the combination of the different methods, it is possible to get a precision better than ±15% on the flux measurement.

For the dT reaction, in addition to the 14.2 MeV neutrons, it is necessary to monitor also the parasitic dD neutron source, caused by beam deuterons interacting with implanted deuterons in the tritium target. Since a fresh tritium target is mounted every year, we estimate that the parasitic source contribution is less than 3% of the total neutron flux. In order to improve its measurement, a new silicon detector monitoring at the same time backscattered α particles and protons will be installed at GENEPI2 by the end of 2015.

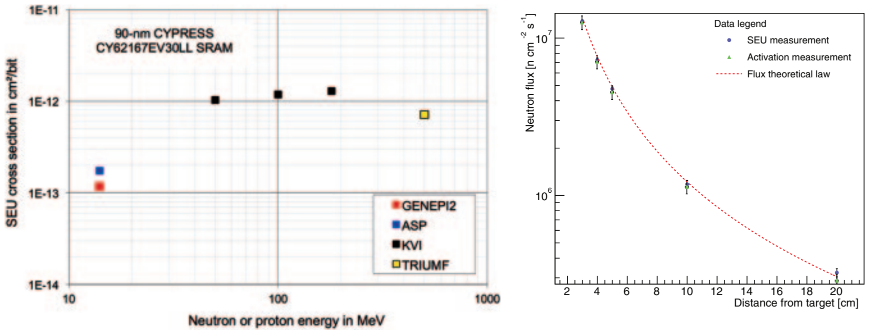
3. – GENEPI2 applications

Since late 2103, the community of GENEPI2 users was enlarged, opening to new fields of research. In this section we describe the two main applications.

3˙1. *Detector calibration.* – Several tests and calibration of detectors have been performed and are scheduled on GENEPI2. Recently, diamond detectors MONODIAM developed for hadrontherapy beam monitoring were tested. For these tests, a layer of polyethylene was used to convert 14.2 MeV neutrons into protons. Thus, it was possible to recreate the mixed (neutrons and protons) radiation field typical of the hadrontherapy environment. The experiment allows to validate the detector setup, the data acquisition system and to compare the specification of monocrystalline and polycrystalline diamonds.

By the end of 2015, detectors developed for the Neutron For Science line of the SPIRAL2 accelerator will be tested and calibrated at GENEPI2. These detectors are a ${}^{238}\mathrm{U}$ fission chamber dedicated to neutron flux monitoring, a liquid scintillator detector for energy spectrum determination and, finally, a gaseous detector specially designed to measure the ${}^{16}\mathrm{O}(\mathrm{n},\alpha){}^{13}\mathrm{C}$ process cross-section.

3˙2. *Integrated circuit irradiations.* – Neutron-induced soft errors are now identified as a major reliability issue for complex electronic systems. The interactions of neutrons with nuclei in the device create secondary ions, which may be highly ionizing and can easily induce Single Event Upsets (SEU) in integrated circuits. With the continuous evolution of scaling, the neutron energy threshold decreases, then the appropriate neutron energy range for measuring SEU risks needs to include 1–15 MeV. Figure 2(a) shows the SEU



(a) (b)

Fig. 2. – Integrated circuit irradiations: (a) neutrons and protons SEU cross-section of 90 nm CYPRESS SRAM memory (CY62167EV30LL) from [2], (b) the plot displays the comparison between two neutron flux measurements: green triangles show results from Al foil activation and bleu circles from SEU counts for the SAMSUNG KM684000 SRAM.

cross-section measurement for protons and neutrons at different energies for a 90 nm CYPRESS SRAM memory. This technology is well know and very sensitive to radiation effects. The result from GENEPI2 is compatible with the one obtained at ASP [3] which is a reference facility for 14.2 MeV neutron radiation tests. This result [2] allowed the validation of GENEPI2 as integrated circuit irradiation platform for cross-section measurements. Data obtained at GENEPI2 can be compared to simulation to improve model predictions and to extrapolate at higher energies. Since then, collaborations started with research teams and industrial partners. Tests on integrated circuits contribute to the characterization of GENEPI2. For example, fig. 2(b) displays the comparison between the neutron flux measurement performed by foil activation and the flux value obtained counting SEUs generated in a highly sensitive low power SRAM used as flux reference [4]. The values are compatible and the agreement is better than 4%.

4. – Conclusions and perspectives

GENEPI2 is a simple, robust and reliable neutron source originally dedicated to reactor physics research. The platform is now open to new communities of users from the fields of fundamental physics and microelectronics industry.

An upgrade of the facility is undergoing to improve its performances. A new ECR source for deuteron production, developed by the Ion Source Division of LPSC, will be installed by the end of 2015. This will allow the facility to be more reliable and the neutron flux to increase by a factor 3 at least. The support of local technicians, engineers and neutron physics experts and the variety of programs ensure the machine operation and the scientific production.

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