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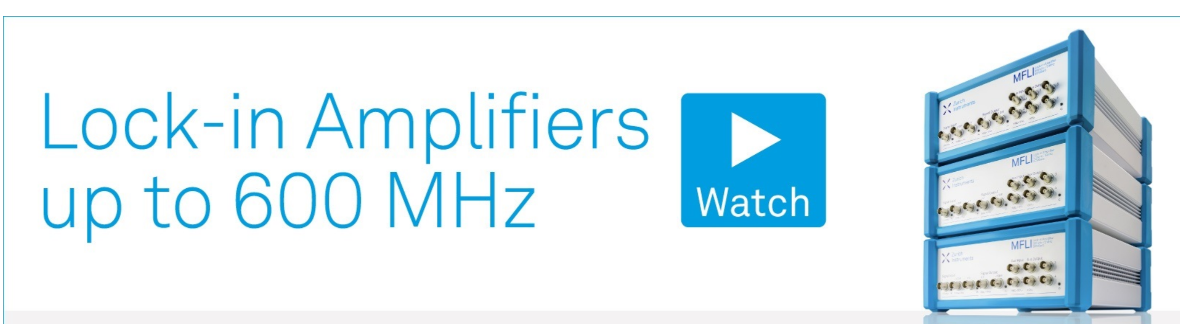

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ABSTRACT

The NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project was recently proposed with the aim to investigate the nuclear response to Double Charge Exchange reactions for all the isotopes explored by present and future studies of $0\nu\beta\beta$ decay. The expected level of radiation in the NUMEN experiment imposes severe limitations on the average lifetime of the electronic devices. During the experiments, it is expected that the electronic devices will be exposed to about 10^5 neutrons/cm^2/s according to FLUKA simulations. This paper investigates the reliability of a System On Module (SOM) under neutron radiation. The tests were performed using thermal, epithermal, and fast neutrons produced by the *Instituto de Pesquisas Energéticas e Nucleares* 4.5 MW Nuclear Research Reactor. The results show that the National Instruments SOM is robust to neutron radiation for the proposed applications in the NUMEN project.

I. INTRODUCTION

The study of the reliability of electronic devices exposed to ionizing radiation, both directly and indirectly, has intensified in recent years mainly due to the ever-growing need to use more powerful and resourceful electronic devices in harsh environments such as space, particle accelerators, nuclear power plants in which radiation effects are important. In these conditions, electronic circuits receive high radiation doses and are subject to the impact of neutrons and/or charged particles, which may affect their correct behavior.[1–3] Depending on the type and characteristics of the impinging radiation, different effects, either irreversible or (partially or totally) reversible, may arise. This is the case of the electronic modules used to monitor the experiments proposed in the NUMEN (NUclear Matrix Elements for neutrinoless double beta decay) project. The aim of this project is to investigate the nuclear response to Double Charge Exchange (DCE) reactions for all the isotopes explored by present and future studies of $0\nu\beta\beta$ decay.[4–8] Several aspects of the project require the development of innovative techniques for both experimental setup and theoretical analysis of the collected data.[4–8] A DCE reaction is a process induced by a projectile on a target in which two protons (neutrons) of the target are converted into two neutrons (protons). The experiments are being conducted at the magnetic spectrometer facility (MAGNEX) of the INFN-LNS using heavy ion beams accelerated by the K800 Super Conducting

Cyclotron. The measurements consist on identifying the nuclear species, energy, and angle of the projectile-like fragments, which arrive at the focal plane detectors through the trajectory reconstruction within the MAGNEX magnetic spectrometer. There will be an upgrade of the LNS Cyclotron in the near future in order to increase the beam current by about two orders of magnitude in view of the very small cross sections of DCE processes. Details on the project and the proposed nuclear reactions can be found in Refs. 4–8. One of the main consequences of the upgrade will be the increased radiation generated in the experimental area, to which all electronic modules and systems will be exposed. The expected level of ionizing radiation in the NUMEN experiment imposes severe limitations on the average lifetime of the devices selected for the front-end and read-out electronics of the whole MAGNEX Magnetic Spectrometer facility. The radiation to which the electronic devices will be exposed during the experiments is generated through three main mechanisms: (i) interaction between the high intense beam and the target, (ii) interaction of the beam with other components of the beam line during its transport, (iii) beam interaction with the beam stopper, and (iv) secondary radiation generated mostly by reactions of neutrons with the material present in the experimental hall.[8]

In the present work, neutron radiation tests were carried out with the core of a commercial System On Module (SOM), considered as a key component option for the electronics of the NUMEN project.

II. THE ELETRONIC SYSTEM ON MODULE

The SOM to be used in the NUMEN experiments is the Xilinx Zynq-7000, a 28 nm static random-access memory (SRAM) field-programmable gate array (FPGA) read-out device developed by National Instruments (NI). The SRAM is a type of semiconductor volatile random-access memory (RAM) that exhibits data remanence, but data are eventually lost when the memory is not powered.

The SOM will be used intensively in the final apparatus for configuration and monitoring of front-end electronics as well as data acquisition and synchronization. This system was chosen due to its high performance and reliability and the possibility of interfacing to the front-end electronics through very powerful FPGAs by means of an operating system running on a real-time processor. This solution simplifies the management of standard data interfaces, such as high-band ethernet and serial communications, as well as allowing intuitive and prompt reprogramming or complete monitoring of the acquisition electronics.[9] This system encloses in a single component the most complex part of an electronic card hosting a FPGA from the management of high frequency clocks to the several power supplies needed. This device simplifies the use of the system, which needs to be plugged into an appropriate socket of a custom designed printed circuit. Therefore, the components within the SOM are widely used around the world.[10–14] Besides that, Xilinx uses ultra-low alpha emitter (ULA) packaging materials and actively monitors material suppliers to ensure compliance with ULA specifications. The ULA material is important to ensure that there will be no extra radiation effect provoked by an alpha particle emission inside the FPGA package.[9] It is known that the SRAM of this device is sensitive to thermal neutron irradiation, exhibiting, in a static test, a single-bit upset cross section of $9.2(21) \times 10^{-16}$ cm^2/bit, which represents 10–30 failures per 1 billion times of device operation per megabit.[15] This system has never been used in hard radiation environment, and this study is the first reporting of experimental data and a full-custom characterization in a dynamic test with error corrections.

III. RADIATION EFFECTS

The main effects of radiation on semiconductor electronic devices are TID (Total Ionizing Dose), SEE (Single Event Effect), and DD (Displacement Damage).[1,2] As an instance of a harsh environment, we can cite the areas surrounding particle accelerators,[16,17] where there may be a high flux of charged particles (protons, heavy ions, and electrons), high energy photons (gamma and X rays), and neutrons. The interaction of all these charged particles, neutrons, and photons with the atoms of the semiconductor devices can generate a plethora of cumulative (deterministic) and stochastic effects, which are transient or definitive. The intensities of these effects are correlated with the radiation-absorbed dose and the linear energy transfer (LET) of the particle for the materials composing the devices. In particular, incident radiation dislodges atoms from their lattice site, the resulting defects altering the electronic properties of the crystal; this is the primary mechanism of device degradation for high-energy neutron irradiation. The neutrons are non-ionizing particles that can cause DD or Non-Ionizing Energy Loss (NIEL) damage.[1,2] The neutron can collide with atoms creating displacement damage and generating secondary charged particles with enough energy to ionize the material. Moreover, neutrons can affect mainly digital components by single event effects (SEEs) triggered by secondary radiation, such as nuclear reaction products or alpha particle from the ^{10}B(n, α)^{7}Li reaction.[1,2]

IV. FLUKA SIMULATION

The FLUKA code has been used for the ambient radiation calculations and allows the simulation of scattering with nuclei.[18–20] A dedicated simulation was performed in order to evaluate the radiation spectra and fluence as a function of the topology of the detectors inside the MAGNEX experimental hall. Especially, the composition of the intense radiation field to be expected at the focal plane of the MAGNEX spectrometer is investigated. The aim of this study is the estimation of the expected neutron flux affecting the MAGNEX focal plane detector electronics foreseen in the NUMEN upgrade.

The simulation was performed using the modeled geometries of the experimental hall and main apparatus shown in Fig. 1. Four radiation sources were considered in the calculation of the ambient dose:

(a) Beam–target interaction.
(b) Leakage along the transport of beam line.
(c) Beam–beam stopper interaction.
(d) Secondary radiation induced by neutron interactions with the material inside the experimental hall, including its walls, floor, and ceiling.

The ^{20}Ne beam interaction with a ^{76}Ge target with ^{12}C backing was simulated and the analysis of the distribution of secondary particles was made in order to derive the dose, energy spectra, and

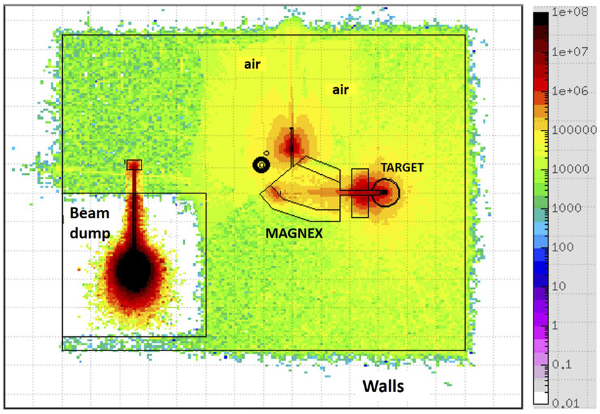

FIG. 1. FLUKA simulations of the neutron flux in MAGNEX experimental hall. The target chamber is placed just before the MAGNEX quadrupole. The region where the focal plane detector is located is denoted with an open black circle.

the flux of neutrons in the experimental hall. A fully stripped ^{20}Ne beam with an energy of 60 MeV/A and a current of 85 eμA was considered. In Fig. 1, the results of the FLUKA simulation of the neutron flux in the MAGNEX experimental hall are shown. The beam dump is inside a concrete bunker. The highest value for the neutron flux inside the experimental hall is expected to be close to the focal plane detector region, where a loss of 10 W for the beam transport was considered. The estimated neutron flux close to the focal plane detector is 1.3×10^4 thermal neutrons/cm^2/s ($E_n < 0.1$ eV), 1.7×10^4 epithermal neutrons/cm^2/s (0.1 eV $< E_n <$ 100 keV), and 9.0×10^4 fast neutrons/cm^2/s ($E_n >$ 100 keV), which totalize at most 1.2×10^5 neutrons/cm^2/s, without considering any shielding material (e.g., polyethylene). In Fig. 2, a simulated neutron energy spectrum at the region of the MAGNEX focal plane detector is shown.

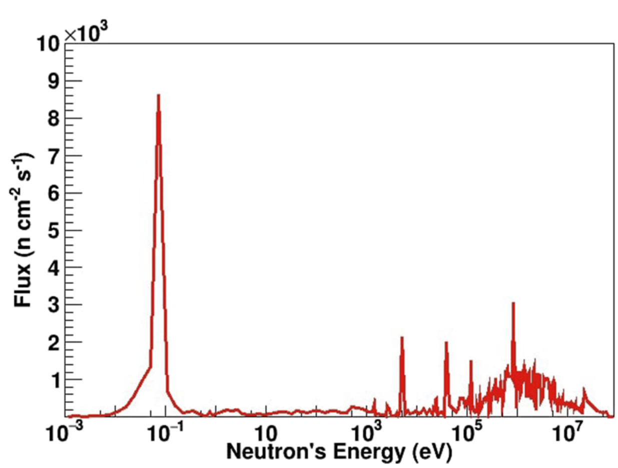

FIG. 2. Neutron energy spectrum obtained via FLUKA simulations for the region where the MAGNEX focal plane detector is located (see also Fig. 1).

V. METHODOLOGY

A. Test strategy

In this test, a Block Random Access Memory (BRAM) of 65 k × 32 bit (the maximum size configurable in the FPGA) is written with a fixed and known *a priori* pattern and read-out continuously by the real-time processor, which reports if any change in the pattern is found. This read-out-and-compare cycle is repeated and tagged in time, in order to count the observed SEU (Single Event Upset) FIT (Failures In Time).

A four-word FIFO (First-in First-out) memory buffer composed of three 1023 × 64 bits and one 1023 × 8 bits is used to perform Direct Memory Access (DMA) transfer from the FPGA to the real-time processor. In parallel, a continuous check of the digital-input–output (DIO) write and read is performed to investigate the effects of the neutron radiation. In Fig. 3, the test block diagram is shown.

The software was developed and tested at the Laboratori Nazionali del Sud—Istituto Nazionale di Fisica Nucleare (LNS-INFN), Catania, Italy, with the SOM in a normal environment in order to test the software itself and to identify also problems of intrinsic stability of the SOM in a standalone test.

B. Neutron radiation tests

During the tests performed with the SOM, the effects in Xilinx FPGA Zynq 7000 series were investigated. The ionization generated by irradiation in this Device Under Test (DUT) causes charge deposition that can be interpreted as a transient pulse (Single Event Transient—SET) or a signal (Single Event Upset—SEU) in the circuit.[1,2] Since Zynq-7000 is composed of a variety of embedded memories, such as the cache memories of the hard-core processor, SRAM memory, block RAM memories of the programmable matrix, and all the configuration memory bits responsible to configure the programmable matrix, the radiation effects may represent a serious problem.[21] The SOM was monitored as a function of the radiation

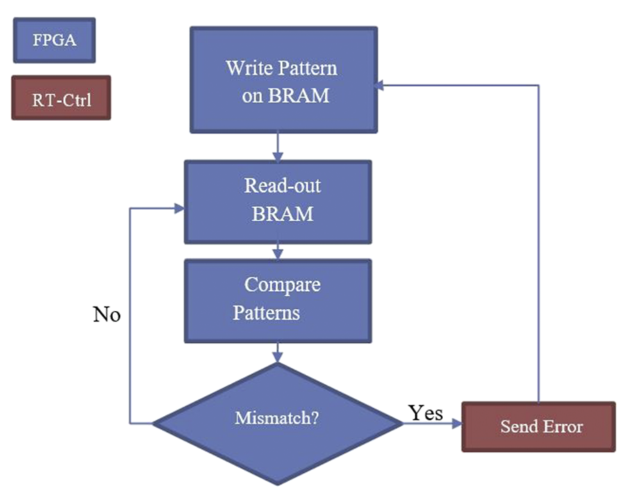

FIG. 3. Block diagram of the test strategy to verify the SOM neutron radiation tolerance.

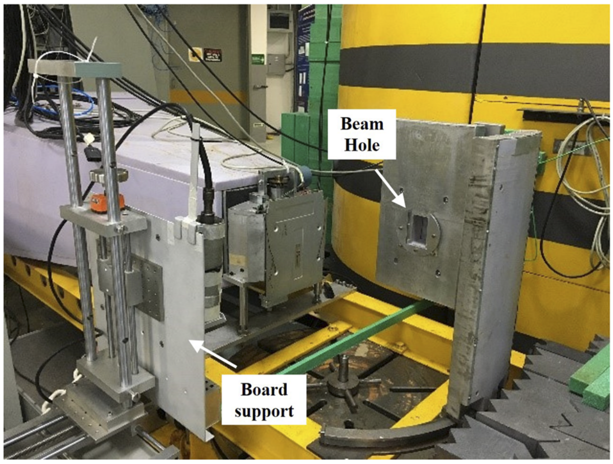

FIG. 4. Experimental setup to neutron radiation tests.

exposure to different neutron fluxes due to single event upset and multiple event upset. The neutron beam was produced by the São Paulo Nuclear Research Reactor IEA-R1 of the *Instituto de Pesquisa Energéticas e Nucleares* (IPEN/CNEN-SP) operating at 4.5 MW.

In the first stage, the board containing the DUT was positioned perpendicularly to the neutron beam, ensuring homogeneity of the radiation field in the device area. In Fig. 4, the experimental setup is shown. The beam consisted of 6.2(2) × 10^4 thermal neutrons/cm^2/s flux at 41.8 meV energy.

In a second stage of the test, the device was submitted to a beam composed of mixed thermal, epithermal, and fast neutrons. The irradiation was performed at a neutron device formerly used for BNCT (Boron Neutron Capture Therapy) experiments.[22] The thermal neutron flux was measured at one irradiation position using the method of gold foil activation with and without a cadmium cover. According to this method, thermal neutrons are considered as those of energies of less than 0.5 eV, which is the cadmium cut-off energy, and epithermal + fast neutrons, those of energies above this value. The ratio of thermal to epithermal + fast neutrons as well as the thermal neutron flux at other positions were calculated by interpolation from results of previous measurements and Monte Carlo simulations.[22,23] The spectrum shape should be roughly similar to the one of Ref. 23, which presents a peak around the thermal energy, a low level epithermal continuum and a peak structure of fast neutrons in the 0.1 MeV–10 MeV range. The device was irradiated at three positions with increasing neutron fluxes, as described in Table I. The first irradiation was performed in a neutron flux of about 1 × 10^6 thermal mixed with 2 × 10^5 epithermal + fast neutrons/cm^2/s. In this condition, the SOM presents a low number of errors. The device was then moved toward the beam outlet, exposed to a flux of 5 × 10^6 thermal neutrons/cm^2/s and 1 × 10^6 epithermal + fast neutrons/cm^2/s. In this new condition, the SOM still presents a low number of errors. The device was then moved again toward the beam outlet, exposed to a flux of 1 × 10^8 thermal neutrons/cm^2/s mixed with 2 × 10^7 epithermal + fast neutrons/cm^2/s.

TABLE I. Neutron beam characteristics, number of SEU events, and SEU cross sections during the second stage tests.

Neutron beam characteristics (neutrons/cm^2/s)	Acquisition time (s)	Number of SEU events	σ (cm^2/bit)
1 × 10^6 thermal mixed with 2 × 10^5 epithermal + fast	1576	11	1.5(7) × 10^{-15}
5 × 10^6 thermal mixed with 1 × 10^6 epithermal + fast	1582	14	3.9(16) × 10^{-16}
1 × 10^8 thermal mixed with 2 × 10^7 epithermal + fast	626	24	8.4(30) × 10^{-17}

VI. RESULTS

In the first stage, with an average flux of about 6.2(2) × 10^4 thermal neutrons/cm^2/s during about 1 h, the few errors detected were corrected by the software, and therefore, the electronics proved to be robust to the effects of SEU in this test condition.

In the second stage, the increase in the neutron flux was accomplished by progressively moving the DUT toward the neutron beam hole (BH) until it stopped functioning. In Table I, the SEUs observed during all the tests and the corresponding neutron beam characteristics are described. When the device was exposed to a neutron flux of about 1 × 10^8 thermal neutrons/cm^2/s mixed with 2 × 10^7 epithermal + fast neutrons/cm^2/s, the SEU number increased, causing the device to stop operating.

VII. DISCUSSION

The results obtained in the first test stage with an average flux of about 6.2(2) × 10^4 thermal neutrons/cm^2/s during about 1 h, together with the relatively small error rate at more than an order of magnitude higher flux intensity of mixed energies of the second test stage, indicate that the SOM will be able to operate satisfactorily with the expected neutron fluxes predicted by the simulations. In case the actual flux turns out to be larger than expected, a reduction of a factor of 10 or more can be obtained by introducing some shielding around the electronics, such as paraffin moderators and cadmium absorbers. The results in Table I, summarizing the second stage measurements, present compatible order of magnitude for neutron SEU cross section compared to another study on 0.13 μm–0.22 μm Complementary Metal Oxide Semiconductor (CMOS)-based SRAMs, with thermal and fast neutrons below 6 MeV.[24] The results in this reference show that the SEU cross sections vary considerably with neutron energy, supply voltage, and component model in the range of 10^{-16} to 10^{-13} neutrons/cm^2/bit for thermal neutrons at nominal voltage.[24]

Other studies, on the sensitivity characterization of 28 nm SRAM-based FPGA using higher energy neutrons, were performed in recent years.[10–14] Soft neutron upsets in Xilinx Virtex-4 and Virtex-5 FPGA devices were measured at the 88-in. cyclotron of the Lawrence Berkeley National Laboratory with neutrons mostly in the 3 MeV–30 MeV range.[10] Fast neutrons from the Los Alamos

Neutron Science Center spallation neutron source were used for tests of other Xilinx models such as Kintex 7,[11] Zynq-7000,[12] and with a 20-nmTaiga RISC-V soft processor.[13] The Xilinx Artix-7 was studied with 14.2 MeV neutrons from the "Genérateur à Neutrons Pulsés Intenses" neutron source at the Laboratory of Subatomic Physics and Cosmology.[14] All these reported results, performed with high energy neutrons, indicate that the 28-nm SRAM-based FPGA are reliable to be used in harsh neutron environment, especially if mitigation techniques are applied. The results obtained in this work are to be considered a use case, extending the reliability of the SOM, based on a Xilinx Zynq-7000 FPGA, closely linked to the NUMEN experiment for what regards the irradiation conditions during the tests, but of general interest for different electronic systems used in other applications.

VIII. CONCLUSION

In this work, the results of neutron tolerance tests of a National Instrument SOM composed by a Xilinx Zync-7000 FPGA are presented. This device will be used in the data acquisition system of the NUMEN DCE experiments, where it will be exposed to high fluxes of thermal, epithermal, and fast neutrons, which can cause damage to its electronic components.

In order to reproduce the expected conditions to which the SOM will be submitted during the experiments, different fluxes of irradiating neutrons were used. The results indicate the electronic devices are tolerant to SEUs up to a flux of about 10^5 neutrons/cm^2/s. Only with fluxes higher than 10^7 neutrons/cm^2/s did the system present problems interrupting its functionality. Although the results obtained in this work are directly related to the NUMEN experiment, they are of general interest for different apparatus used in various applications.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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