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Experimental Setups for Single Event Effect Studies

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Abstract Experimental setups are being prepared to test and to qualify electronic devices regarding their tolerance to Single Event Effect (SEE). A multiple test setup and a new beam line developed especially for SEE studies at the São Paulo 8 UD Pelletron accelerator were prepared. This accelerator produces proton beams and heavy ion beams up to ^{107}Ag. A Super conducting Linear accelerator, which is under construction, may fulfill all of the European Space Agency requirements to qualify electronic components for SEE.

Keywords: Radiation effects, electronic devices, single event effects.

1. INTRODUCTION

Ionizing cosmic radiation present in a space environment is a challenge for the proper functioning of equipment such as satellites, rockets and probes. It can interfere with the information generated by electronic components and even leave the min operative. Testing the resistance of these components to cosmic radiation is essential for space projects, since electronic circuits are strongly affected by radiation and the need for integrated circuits featuring radiation hardness to be used in environments such as space, nuclear reactors and high energy particle accelerators is growing rapidly [10,6]. The effects due to radiation on electronic components are usually divided into three main categories [2, 3, 6, 10]: Total Ionizing Dose (TID), Displacement Damage (DD), and Single Event Effects (SEE). TID is a cumulative effect that changes the response of electronic devices, for example, TID effects in Metal Oxide Semiconductor Field Effect Transistors (MOSFET) are responsible for trapping

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charges in the oxide and/or at the Si/SiO_2 interface, modifying the transistor off-current, leakage currents, and shifting the threshold voltage. DD can change the arrangement of the atoms in the lattice, modifying electrical properties of the electronic devices. SEE can be a transient effect in which free charge, directly generated into the device, may disturb the behavior of the device or cause data corruption or even may provoke a permanent device failure such as gatedi electric rupture in transistors. In this work, some experimental setups that are being prepared to test electronic devices regarding their tolerance to SEE, will be presented.

In order to measure the SEE cross section of a device under test (DUT), with distinct Linear Energy Transfer (LET), a multiple test setup at the 8 MeV Pelletron accelerator of the LaboratórioAberto de Física Nuclear of the Universidade de São Paulo (LAFN) was developed. This setup is composed basically of a multiple test chamber and can produce, using Rutherford scattering in a gold foil, a low intensity flux of particles in-vacuum and in-air protons and heavy ion beams. To have a dedicated system to perform SEE studies, a new beamline, specially designed to test electronic devices, with heavy-ion beams, has been mounted at the LAFN. Heavy-ion beams with high uniformity and large area can be produced by defocusing and using multiple scattering techniques. In the near future, a heavy-ion superconducting linear accelerator will be incorporated at the LAFN which will increase the energy of the particles and will allow fulfillment of the European Space Agency (ESA) requirements to qualify electronic components for SEE [7].

2. MULTIPLE TEST SETUP

To study Single Event Effects (SEE), it is necessary to hit directly the active region of the device with a sufficiently high-energy heavy-ion beam to create a high density of charge. Various heavy ions with different Linear Energy Transfer (LET) values are used to evaluate the electronic device sensitivity to radiation. In order to probe the device under test (DUT) with distinct LET values, a multiple test setup for SEE studies was mounted at the LAFN [1]. Ion beams of protons up to ^{107}Ag are produced by the 8 UD Pelletron accelerator, with energies up to 100 MeV available for heavier ions. In order to achieve very low particle fluxes, in the range from 10^2 to 10^5 particles.cm^{-2}s^{-1}, as recommended by the European Space Agency (ESA) for SEE tests [7], Rutherford scattering setup was prepared.

In this system, the primary beam is scattered by a thin gold foil, with thickness varying from 200 to 1000 μg.cm^2, in the center of a scattering chamber. For SEE tests inside the vacuum chamber, DUTs can be placed in several positions in order to perform tests in various electronic devices at the same time. The incident particle flux can be adjusted within a factor of 10^2, either by changing the beam current, the irradiation angle and/or the thickness of the gold foil. For instance, with 50 MeV ^{16}O beam, a current of 5 nA on the gold foil and a gold foil of 400 μg.cm^2, it is possible to obtain about 100 particles.cm^{-2}s^{-1} on the DUT.

In Figure 1, a schematic view of the scattering chamber is shown. Exit windows at 15º or 45º with a thin mylar foil can also be used to extract the scattered beam articles to in-air tests. Beam flux and beam energy are measured with a silicon barrier detector inside the scattering chamber. In-air beams are limited from protons up to ^{28}Si, due to the high energy loss at the exit window. More information on the setup and its characterization are reported elsewhere [1]. With this setup, it was possible to make the first SEE measurements with heavy ions in Brazil [11]. In this experiment, the SEE cross section of an off-the-shelf 3N163 CMOS transistor as a function of LET of heavy-ions from ^{12}C to ^{107}Ag was studied.

Presently the available ion beams at the LAFN are: ^{1}H, ^{6,7}Li, ^{10,11}B, ^{12,13}C, ^{16,17,18}O, ^{19}F, ^{28,29,30}Si, ^{35,37}Cl, ^{63,65}Cu and ^{107,109}Ag with LET values in silicon (surface) ranging from 0.5 to 40 MeV/mg/cm^2. In Figure 2, LET values for some of the available ion beams are plotted as a function of the range in silicon. It can be noted in this graph that for each particle beam the LET values do not vary significantly for the expected sensitive volume region, but are strongly dependent on the depth of the sensitive volume. With this multiple test setup many electronic devices, such as a pMOS transistor 3N163 [11], a Xilinx Zynq-

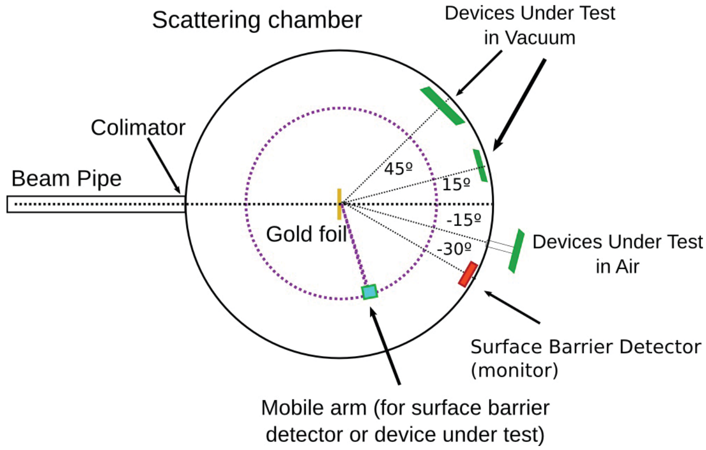

Figure 1: Schematic view of the scattering chamber for in-air and in-vacuum multiple SEE tests.

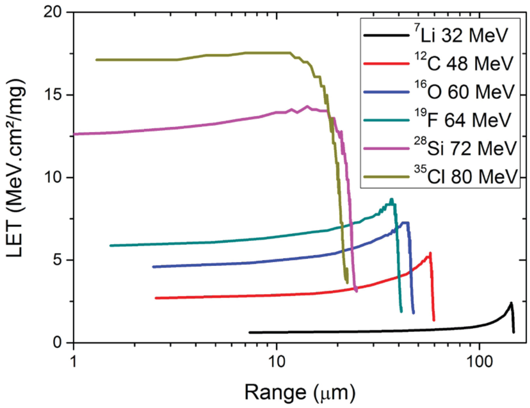

Figure 2: Linear Energy Transfer (LET) in MeV/mg/cm^2 as a function of the range in silicon for some heavy ions available at the 8 UD Pelletron accelerator.

7000 Field-Programmable Gate Arrays (FPGA) [13], a Microsemi ProASIC3 FPGA [14] and a Xilinx Spartan 3E FPGA [4], among many others, are being studied. In these experiments, asides from other studies, the SEE cross section for the FPGA as a function of the LET was studied.

2.1 Combined SEE and TID Effects

The use of Field-Programmable Gate Arrays (FPGA) has become a consensus among system designers, with numerous applications in many fields such as automotive, telecommunication, defense and aerospace. In particular, for these devices to be installed in an embedded system for satellite applications, and due to transistor miniaturization, which could increase the sensitivity to SEE, intensive radiation tests must be performed in order to verify their reliability in such environment. In order to study combined SEE and TID effects, a Xilinx Spartan 3E FPGA was studied with heavy ion beams, combined with X-ray radiation doses [4]. A decapsulated FPGA was irradiated outside the scattering chamber with^{12}C, ^{16}O, ^{28}Si and ^{35}Cl heavy-ion beams. The beams were scattered at 15^o by a 180 μg/cm^2 gold foil in order to reduce drastically the beam flux. In Figure 3, the pictures of the external beam setup and the decapsulated DUT are presented. The external beams were extract at 15^o through a 0.95 mg/cm^2 mylar foil. It was chosen to use the external beam setup in order to reduce electronic noise and minimize in-vacuum heating. A surface barrier silicon detector, placed inside the vacuum chamber at 45^o, monitored the beam current. In Figure 4, the Spartan 3E SEE configuration bitcross sectionas a function of the LET in MeV/mg/cm^2 produced by ^{12}C, ^{16}O, ^{28}Si and ^{35}Cl heavy ion beams is shown. The error bars were estimated depending the number of SEE events and the number of incident particles. The results show the same behavior of standard cross section curves, indicating lower cross section to lighter ions [11]. The FPGA was irradiated three times, after each heavy-ion beam irradiation procedures, up to 750 krad with 10-keV X-ray beams, produced in a Shimadzu XRD-7000 X-ray diffractometer of the Centro Universitário da FEI, São Bernardo do Campo. The time interval between each X-ray irradiation and heavy-ion beam irradiation was about 10 hours. In Figure 5, the SEE cross section for ^{16}O ions as a function of the

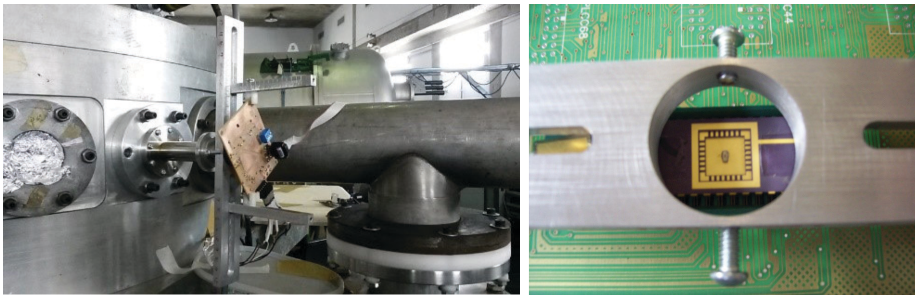

Figure 3: External beam setup (left) and an example of a decapsulated device under test (DUT).

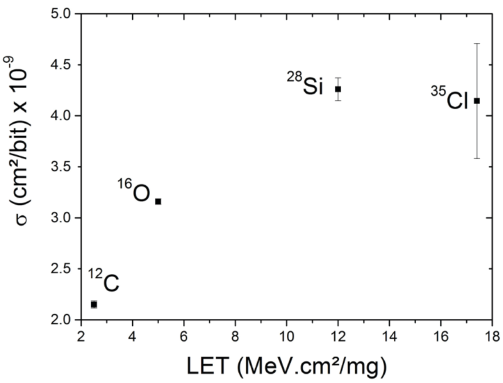

Figure 4: SEE configuration bit cross section in a Xilinx Spartan 3E FPGA as a function of the LET in MeV/mg/cm^2 produced by ^{12}C, ^{16}O, ^{28}Si and ^{35}Cl heavy ion beams.

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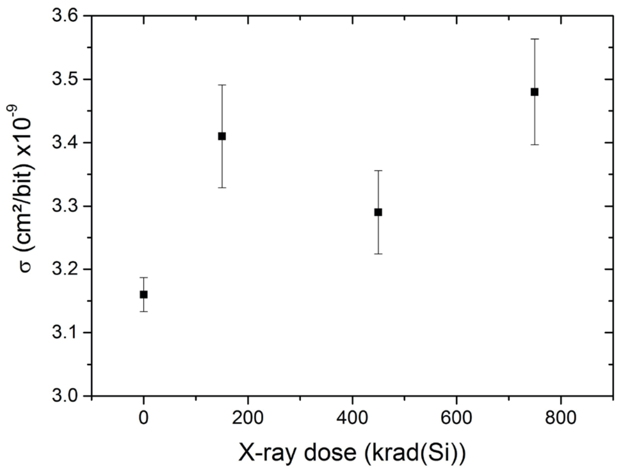

Figure 5: SEE configuration bit cross section in a Spartan 3E FPGA for ^{16}O heavy-ion beam, as a function of the dose produced by a 10-keV diffractometer X-ray source.

absorbed dose in Si is shown. The results indicate a slight increase of the cross section after the X-ray irradiation.

3. DEDICATED SEE TEST SETUP

To have a dedicated test setup to qualify radiation tolerant electronic devices, via Single Event Effect studies, and to achieve the requirements of the European Space Agency [5], such as large beam diameter (~cm), low particle flux (10^2 to 10^5 part/s) and high uniformity, a new beamline has been constructed at the 8 UD Pelletron accelerator at LAFN. Initially, to design the whole system, the trajectories of heavy ion beams scattered in two gold targets were studied via Monte Carlo simulation in order to obtain a low-intensity high-uniformity heavy-ion beam. Monte Carlo simulations of the beam trajectories, considering 10^6 particles of ^{12}C, ^{16}O and ^{63}Cu, using the ROOT software [8] were performed. SRIM [9] calculations were also done considering the stopping power and angular straggling of the ion beam in gold targets placed in scattering chambers, with thicknesses ranging between 0.4 mm to 1.8 mm. With these calculations, it was possible to construct a three-dimensional profile of the beams. The results suggest that with several combinations of gold targets it is possible to produce heavy-ion beams with high uniformity and very low intensity. In order to have good uniformity and beam enlargement, the new beamline consists of two scattering chambers and another larger scattering chamber for the tests. Data reading for in-line testing of integrated circuits and FPGAs will be done with computers, oscilloscopes, NI-PXI acquisition system and LabView tools.

This experimental setup, named SAFIIRA (SistemA de FeixesIônicos para Irradiações e Aplicações) has been designed to produce low-flux, high uniformity and large area heavy-ion beams up to ^{28}Si by defocusing and multiple scattering techniques [5] and from ^{28}Si to ^{107}Ag by a defocusing technique. The system was designed to operate for irradiation in-vacuum or in-air using a thin mylar window. A multi-axis motorized equipment is used to manipulate samples in a low-noise environment. An orbitron pump and two turbo-molecular pumps of 90 l/s and 260 l/s, respectively, compose the high-vacuum system, allowing operation at about 2×10^{-6} Torr. The vacuum system is controlled through a dedicated electronic system designed to provide a safe operation of the accelerator even in the case of a window break. A quadrupole magnet, a pair of trimmers, motorized slits, an electrically suppressed Faraday cup and a beam scanner compose the beam focusing system. A beam monitoring system with photodiodes is under development. In Figure 6, a schematic drawing of the complete new beamline is shown. The new experimental setup is being tested and the particle beam characteristics will be presented in a forthcoming paper.

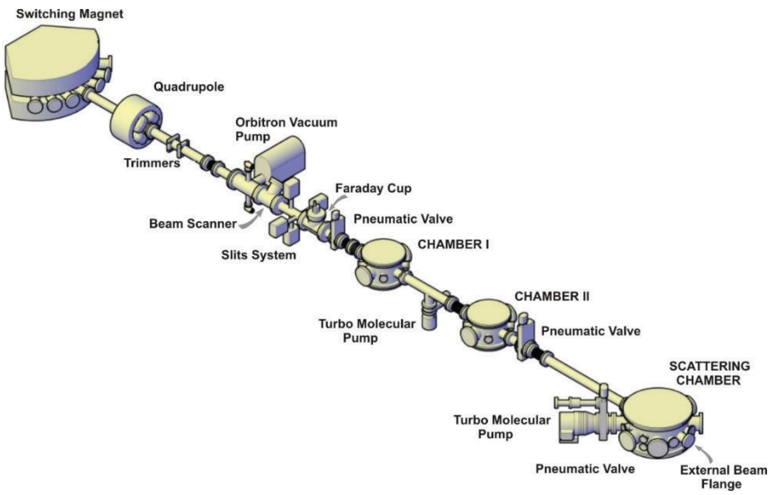

Figure 6: Schematic drawing of the dedicated beamline for SEE studies. A quadrupole magnet, beam scanner, Faraday cup, slits system, and trimmers are used for beam focusing. Vacuum pumps, pneumatic valves, three scattering chambers and the external beam flange are also shown.

4. SUPERCONDUCTING LINEAR ACCELERATOR

The São Paulo Superconducting Linear Accelerator (LINAC) is based on resonant structures to generate an oscillating electric field of the particle acceleration process [12]. These resonators were acquired through a contract with the Argonne National Laboratory (USA), which developed the project. The resonator unit, split-ring type, made of copper and niobium, is designed to operate at liquid helium temperature ($\sim$4 K). At this low temperature, the niobium presents superconductive properties, and minimizes the amount of power required for generating the electric field. As, in operation, the quality factor of such structures is of the order of 10^7, powers of a few tens of Watts are sufficient to generate high electric fields with values about 3 to 4 MV/m. The 8 UD Pelletron is used as a pre-accelerator for the LINAC. The principle of operation of the superconducting cavities requires the particles of the continuous beamfrom the Pelletron accelerator to be bunched in nanosecond duration beam pulses, in order to obtain the appropriate longitudinal emittance for efficient acceleration. To produce a pulsed beam of fixed 12 MHz frequency, the beam is adjusted with a pre-buncher, a chopper, and a super-buncher. These systems together with a phase detector ensure the acceleration of the particle beam, synchronizing the pulsed beam with the phase of the electric field within each resonator. In addition, the accelerator also uses different electromagnetic elements to transport the beam to the new experimental area. In order to be injected into the LINAC accelerator, the particle beams are produced in a Source of Negative Ions by Cesium Sputtering (SNICS), accelerated by the 8 UD Pelletron accelerator, and handled by the pulsed beam system. In Figure 7, a schematic view of the Pelletron-LINAC accelerator system is shown. The resonators are placed inside cryostats to allow their cooling and maintenance of low temperature, using liquid nitrogen and liquid helium. Nitrogen is liquefied from the air using two Linde Cryogenics plants, which produce about 45 l/h each, and is used in the cooling of the external structures, used as interfaces with the structures cooled by liquid helium. The liquid helium used in the conductive layers of resonators is produced by a Consultant Cryogenics Inc. plant, which can produce up to 150 l/h or alternatively producing about 300 W to cooldown the resonators. The LINAC accelerator may accelerate with high efficiency heavy-ion beams from ^{10,11}B to ^{107}Ag with an energy up to 10 MeV/nucleon. In Figure 8, an example of a ^{16}O pulsed beam time profile spectrum, with a repetition cycle of about 82.5ns and 1.3 ns time resolution, is shown. With this new accelerator, the ion beams will reach energies up to 10 MeV/nucleon, increasing considerably the penetration depth in the decapsulated electronic devices. Particles that are more energeticwill guarantee a range higher than 30 μm, as required from the ESA [7]. In Figure 9, LET values for some of the particle beams to be accelerated by the LINAC are plotted as a function of the range in silicon.

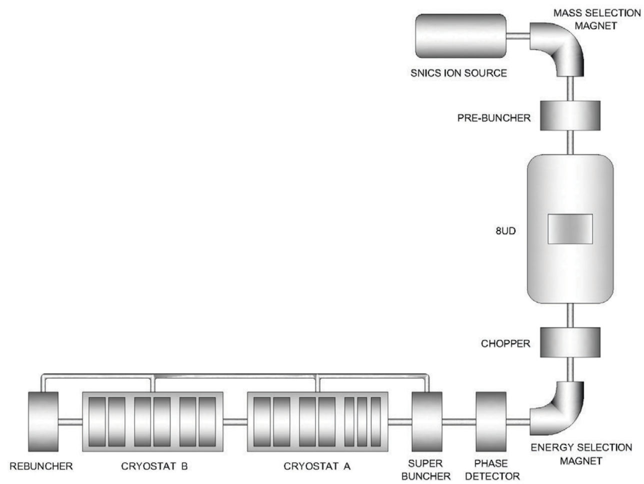

Figure 7: Schematic view of the Pelletron-LINAC accelerator system.

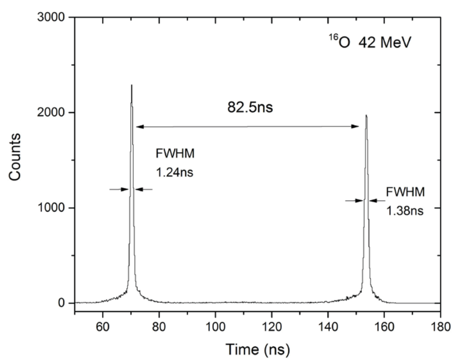

Figure 8: ^{16}O pulsed beam profile time spectrum. The Pelletron continuous beam is treated with a chopper and a pre-buncher to produce 1.0 ns pulsed beam with a duty cycle of 82.5 ns.

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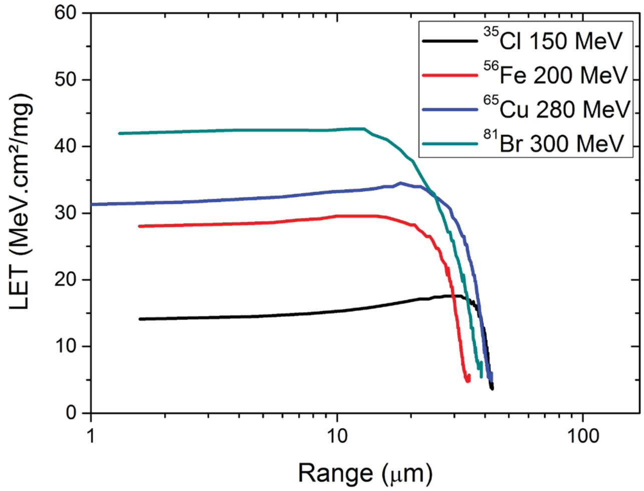

Figure 9: Linear Energy Transfer (LET) in MeV/mg/cm^2 as a function of the range in silicon for some heavy ions accelerated by the system Pelletron-LINAC.

5. CONCLUSION

In this work, some experimental setups intended to study SEE due to ion beam interactions in electronic devices were presented. A multiple test setup and a new beamline at the 8 MV tandem Pelletron accelerator were developed. To test the multiple test setup for low flux heavy ions, a pMOS transistor 3N163 was irradiated with scattered ion beams from ^{12}C to ^{107}Ag. The SEE measurement of a Xilinx Spartan 3E FPGA with ^{12}C, ^{16}O, ^{28}Si and ^{35}Cl heavy ion beams and the combined TID effect irradiating with a 10-keV X-ray beam to a dose up to 750 krad was presented. In order to better comply with the ESA requirements, a new beam line was developed for low-flux, high-uniformity ion beams for in-air and in-vacuum irradiations at the 8 UD tandem Pelletron accelerator. Higher LETs will be available in the near future after finishing the construction of the new Superconducting Linear Accelerator expected to boost the heavy ion beams produced by the 8 MV Pelletron accelerator.

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