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Radiation damage of electronic components in space environment ☆

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Abstract

The PAMELA apparatus is dedicated to study cosmic rays on board of a satellite mission scheduled to start at the beginning of 2004. All the electronics components of such a mission have to be chosen carefully, because no replacement is possible after launch. Irradiation tests have been performed in order to study effects of highly ionizing particles on chips and to evaluate thresholds for Single Event Upset and Latch-up. The first effect, observed in digital components, is a radiation-induced change of state in a memory cell and gives rise to loss of the stored information. The second one, present also in analog components, happens when a parasitic conduction channel opens through the chip: this can fuse the component unless a protection circuit limits the current flow. Estimates of on-orbit fluxes and results of dedicated beam tests are reported.

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1. Overview

The PAMELA experiment [1] is a satellite-borne apparatus devoted to the study of cosmic rays, with an emphasis on antiparticles and search for antinuclei. Especially, the instrument will measure the spectra of cosmic rays (protons, electrons, corresponding antiparticles and light nuclei) over an energy range and with a statistics unreachable by balloon-borne experiments. The core of the instrument is a permanent magnet spectrometer equipped with a double-sided, micro-strip Si tracker. Under the spectrometer lies a sampling electromagnetic calorimeter, composed

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of W absorber plates and single-sided, macrostrip Si detector planes. A Time-of-Flight (ToF) system made of three double-layer planes of plastic scintillator strips, and a Transition Radiation Detector (TRD) made of nine planes of proportional counters (*straw tubes*) interleaved with C-fiber radiator, are employed for particle identification at low and high energies, respectively. At the bottom, a neutron detector made of ^{3}He counters enveloped in polyethylene moderator is placed. A series of plastic scintillator counters for anticoincidence and shower tail catching complete the apparatus. The instrument will be carried as a "piggy-back" on board of the Russian Resurs-DK1 satellite for Earth observation. The launch, by means of a Russian Soyuz rocket, is scheduled for the first half of 2004 from the cosmodrome of Baykonur, in the former Soviet Republic of Kazakhstan. The satellite will fly on a quasi-polar (inclination 70.4°), elliptical orbit (altitude 300–600 km), and the expected mission length is of 3 years. During the flight, all on-board microelectronic devices will be subject to the passage of highly ionizing particles, which can degrade their performance and eventually lead to their permanent damage or loss of information. No replacement for malfunctioning components is possible once the instrument is in orbit, therefore all critical devices must be either already qualified for functionality in the space environment, or tested by us. Since normal (non-space qualified) commercially available components are cheaper, better performing and less power consuming, we have chosen the latter possibility and make our own space qualification tests. We expect that the space radiation will produce two classes of effects on our microelectronic devices:

- long-term effects, due to the prolonged exposition to radiation, as measured by the Total Ionizing Dose[1] (TID);
- events caused by the passage of a single, highly ionizing particle, the so-called Single Event Effects (SEE). Especially, we have looked for Single Event Upsets[2] (SEU) and Latch-ups[3] (SEL).

The main parameter to evaluate the latest class of effects is the Linear Energy Transfer (LET), equivalent to the ionization energy loss $-\mathrm{d}E/(\rho\,\mathrm{d}x)$ of the Bethe–Bloch formula and normally measured in MeV mg^{-1} cm^2. The Effective LET ($\mathrm{EffLET} = \mathrm{LET}/\cos\vartheta$) takes into account the angle of incidence ϑ of the particles. As for the contribution to these effects, we can take into account three main sources: protons and nuclei of galactic origin (*galactic*); trapped protons in the inner radiation belt, extending down to 500 km, in the so-called South Atlantic Anomaly (SAA) which will be crossed by the satellite in its orbit (*trapped*); protons and nuclei emitted in Solar flares and Coronal Mass Ejections, also known as Solar Energetic Particles (SEP), whose occurrence is related to the 11-year cycle of Solar activity (*solar*). In order to estimate the possible consequence of long-term exposition and the rate of occurrence of SEEs, the following steps have been undertaken:

(1) estimation of the expected flux of particles through our instrument during the 3 years of planned mission (see Section 2);
(2) measurement, through dedicated radiation hardness tests, of the cross-section for the searched effects on our devices (see Section 3);
(3) computation of the number of expected effects during the mission.

2. Flux estimation

The total dose of radiation absorbed by our apparatus has been evaluated using the CREME96 simulation software. This program, freely available online in Ref. [3], is designed to study the effect of radiation in space on microelectronic

[1] The TID is the energy released by the radiation per mass unit of the target, and is generally measured in krad.

[2] A SEU is an unplanned change of state in a memory cell of a digital electronic device. This effect, although not destructive, can lead to loss of information.

[3] In the case of a SEL, the charge deposition by the ionizing radiation can open a low-resistance conduction channel inside the device, actually connecting its power supply to ground. If no current-limiting mechanism is implemented, the device can suffer permanent damage.

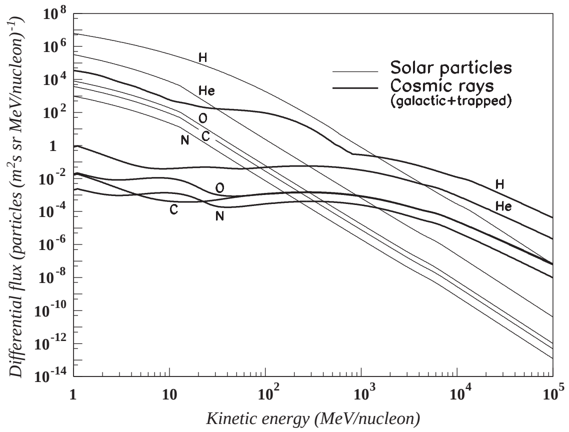

Fig. 1. Main contributions from galactic, trapped and solar cosmic rays (averaged on 200 orbits) to the differential flux of particles on the PAMELA detector.

devices taking into account the different contributions (solar, galactic and trapped). In Fig. 1 the flux of particles impinging on the PAMELA detector is showed. Our calculation has taken into account the orbital characteristics of the satellite, and the Al shield (2 mm thick) which envelopes our apparatus. The contribution of each component has been calculated in the worst-case scenario, that is to mean: the galactic and trapped contribution during the minimum of the Solar activity, and the solar one during the maximum. It must be noted that, while the galactic and trapped cosmic rays are contributing to the total flux during the whole flight of PAMELA, we foresee a maximum of 10 days of emission of SEP. Overall, the expected TID for PAMELA coming from the different sources are

$$TID_{galactic+trapped} = 4 \times 10^{-1}\ \text{krad}$$
$$TID_{solar} = 5 \times 10^{-1}\ \text{krad}$$
$$TID_{total} \approx 1\ \text{krad}.$$

3. Radiation hardness tests

3.1. Tests for TID

The first type of check has been performed in 1999 at the ENEA labs at La Casaccia, near Rome (Italy). The Devices Under Test (DUTs) were exposed to a high-intensity (3.7×10^{15} Bq) ^{60}Co source, emitting 1.25 MeV γ's. The advantage of irradiating with γ-rays (which, at this energy, interact primarily via Compton scattering) is that in this case the energy release in the devices is due to secondary electrons, therefore is more uniform in the sensitive volume. In the irradiation phase, the source is extracted from the deep well where it is usually kept for safety reasons, and placed near the objects to be exposed. Test of functionality of the chips have been performed when doses of 1, 2, 10 and 30 krad were reached. The final dose, 30 krad, is about 30 times greater than the expected for our mission. At the end, only four chips out of almost 100 showed a failure. Of course, all failing devices have been rejected for future use. A full listing of the tested chips is available online in Ref. [2].

3.2. Tests for SEE

In the period 2000–2002, two heavy-ion beam tests have been performed at the GSI in Darmstadt (Germany), and two at the JINR in Dubna (Russia). At GSI in November 2000, the devices were exposed to beams of ^{131}Xe and ^{238}U in the energy range 100–800 MeV n^{-1}. Also different incidence angles (0°, 30° and 60°) were applied, thus resulting in EffLET values between 5 and 70 MeV mg^{-1} cm^2. The main DUTs where two FPGA chips, namely QuickLogic QL12x16BL and Actel 54SX32, to be used in PAMELA control logic. These chips were mounted on a board where they could be controlled by a microprocessor (DSP). In order to check for upsets, on each FPGA two identical counters (see Fig. 2), driven by a clock signal from the DSP, have been implemented. A comparator was continuously checking the values given by the counters. If a difference was found, a signal was sent to a SEU counter implemented in the DSP. Then the counters on the FPGAs were reset. Latch-ups were detected monitoring the current in the chips. In Fig. 3, SEE cross-sections for both FPGAs are showed. Our results can thus be summarized:

- the Actel chip showed a lower cross-section: we have therefore chosen this chip family for use in our control logic;

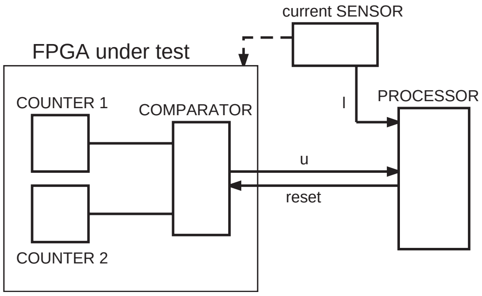

Fig. 2. Scheme of the circuit for SEU/SEL detection at GSI.

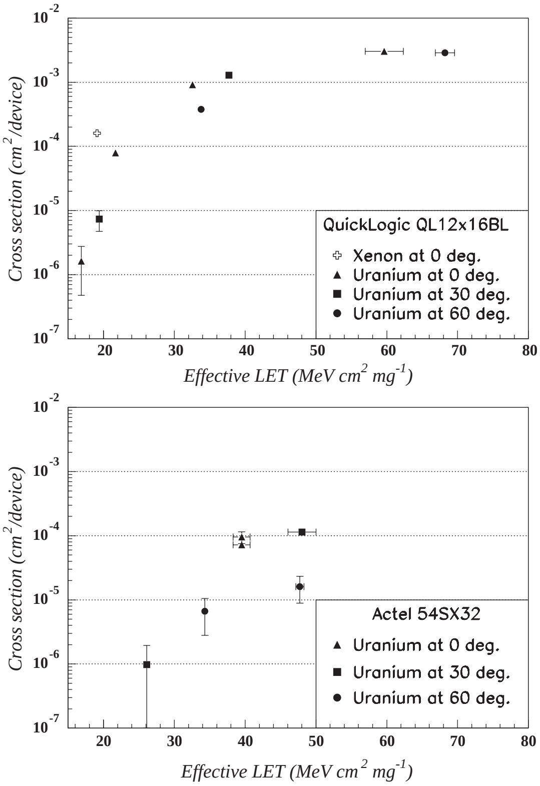

Fig. 3. SEE cross-sections measured at GSI for two FPGA chips.

- the Actel FPGA, unlike the QuickLogic, showed no latch-up, which is the most dangerous effect.

The measured cross-sections for the Actel chip have been used as an input for the CREME96 program. Taking into account the number of such devices in our instrument, and simulating fluxes of protons and high-Z nuclei, the following rates of SEE can be obtained:

galactic + trapped	0.8×10^{-5} SEU day^{-1}
solar	3×10^{-3} SEU day^{-1}

The first contribution has to be multiplied for all the days (~ 1000) of the mission to obtain the total rate, while the second contribution only for the 10 days of expected SEP emission. Thus they become of the same order of magnitude, i.e. 10^{-2} SEU for these chips during the whole mission lifetime. Some variations to these values have to be taken into account, because the SEU rates depend on the number of bits employed in the FPGA. In this and following tests at GSI, other components have been checked in similar manner. Again, the full listing is available online in Ref. [2]. In December 2001, at the Nuclotron facility of the JINR, a beam of ^{24}Mg with an energy of 150 MeV n^{-1} was available, corresponding to a LET of about 1 MeV mg^{-1} cm^2 on the sensitive part of the chips. The main DUT was a 1 Mbit flash memory chip (mod. M25P10 manufactured by ST Microelectronics). For SEU test, the memory has been filled with a sequence of '1', and continuously checked for '0' appearance. In case, a SEU counter was updated and bulk erase performed. Again, latch-ups were checked monitoring the current in the chip. No SEE was recorded, therefore we can only establish an upper limit for the SEE cross-section, of the order of 10^{-7} cm^2 device^{-1}. The other tested components were mounted on two DC/DC converter boards, mod. S9004 and S9006, manufactured by CAEN as power supplies for PAMELA. Both boards have an input voltage in the range 15–20 V, while their output voltage is 5.6 and 3.4 V, respectively. The DUTs were tested for SEL only, checking the output voltage of the boards in the irradiation phase. A power MOSFET (see Ref. [2]) was subject to a latch-up on the S9006 board. Since no current-limiting circuit is possible for these components, the chip was permanently damaged, and functionality of the board could not be restored. As a consequence of this failure, a second beam test was performed in Dubna during March 2002. A lower energy available for the Mg beam (100 MeV n^{-1}) ensured a bigger

LET value on the chips. Several power MOSFETs were placed on different DC/DC converter boards, still of the S900X series, and checked for SEL. All these MOSFETs (listed in Ref. [2]) survived the test.

4. Conclusions

For all tested components, we can be confident that no failure can occur during the mission, both for total dose and for latch-up. Also results from SEU tests are encouraging, since the threshold for this process corresponds to high LET values. In fact, by simulating a LET spectrum in orbit we found that the fraction of the spectrum above SEU threshold is very small. In addition, protection circuits for latch-up have been introduced whenever possible, and redundancies foreseen to avoid loss of information due to upsets.

References

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[2] http://hep.fi.infn.it/PAMELA.
[3] http://crsp3.nrl.navy.mil/creme96.