Radiation damage of electronic components in space environment

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Outline

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The PAMELA experiment: an overview

The PAMELA experiment is a satellite-borne space mission, developed by an international collaboration, devoted to the study of cosmic-rays (CRs), with emphasis on the antimatter component (antiproton, positrons, eventually antinuclei).

The PAMELA Collaboration

Università and INFN, Bari
Università and INFN, Napoli
Università and INFN, Trieste
Laboratori Nazionali INFN, Frascati
Kungl Tekniska Högskolan, Stockholm
Universität-GH, Siegen
NASA-GSFC, Greenbelt (MD)
INCOS-MEPhi, Moskva
Ioffe Physico-Technical Institute, St. Petersburg
TATA Institute of Fundamental Research, Mumbai

Università and INFN, Firenze
Università and INFN, Roma 2
IFAC-CNR, Firenze
PAL-NMSU, Las Cruces (NM)
P.N. Lebedev Physical Institute, Moskva
The instrument

**Magnetic Spectrometer:**
- 5 Nd-Fe-B permanent magnet modules
- 6 Si double-sided µstrip tracker planes

**ToF:**
- 3 double-layer planes of plastic scintillator strips

**TRD:**
- 9 planes of proportional counters interleaved with C fiber radiators

**CAS+CAT:**
- 5 plastic scintillator counters

**S4:**
- 1 plastic scintillator counter

**ND:**
- 36 $^3$He counters + polyethylene moderators

**Electromagnetic calorimeter:**
- 44 Si single-sided detector planes
- 22 W absorber plates
The instrument will fly as a “piggy-back” on the Russian Resurs-DK1 Earth Observation satellite, scheduled to be launched in the first half of 2003 from the Baykonur cosmodrome in Kazakhstan by a Russian Soyuz TM rocket.
Orbital characteristics

- quasi-polar (70.4°)
- elliptical (350–600 km)
- 3-years-long mission

SAA
in a space mission as that of PAMELA, on-board electronics are continuously exposed to highly ionizing particles which can degrade their performance and/or permanently damage them. Radiation hardness tests of critical components must be performed because no replacement is possible once the instrument is in orbit. In order to use normal commercial components, cheaper, more performing and less power-consuming, we've decided to make our own space-qualification tests.
We look after two classes of effects:

- *long-period effects due to prolonged exposition to radiations*, related to the **Total Ionizing Dose (TID)**
- *Single Event Effects (SEEs)* caused by the passage of a single energetic particle through a microelectronic device, and especially **Single Event Upsets (SEUs)** and **Single Event Latch-ups (SELs)**
Main parameter is the Linear Energy Transfer (LET)

\[ \text{LET} = -\frac{dE}{\rho dx} \]

The Effective LET takes into account the angle of incidence \( \theta \)

\[ \text{EffLET} = \frac{\text{LET}}{\cos \theta} \]
Main contributions

- protons and nuclei of \textit{Galactic origin}

- trapped protons in the inner radiation belt, extending down to 500 km, in the so-called South Atlantic Anomaly (\textit{SAA}) which will be crossed by the satellite in its orbit

- protons and nuclei emitted by \textit{Solar flares and Coronal Mass Ejections}, also known as \textit{Solar Energetic Particles (SEPs)}
Flux estimation

The expected fluxes have been evaluated using the CREME96 simulation package. Calculation has taken into account the orbital characteristics of the satellite and the metallic shield surrounding the detector (2 mm of Al). Contributions have been evaluated in the worst-case scenario (for Solar, during the worst week of the Solar Maximum phase, for Galactic and Trapped, during the Solar Minimum phase).
Galactic, trapped and solar CRs
Flux estimation: results

\[ TID_{\text{galactic+trapped}} = 4 \cdot 10^{-1} \text{ krad} \]

\[ TID_{\text{solar}} = 5 \cdot 10^{-1} \text{ krad} \]

\[ TID_{\text{all}} \approx 1 \text{ krad} \]

**note:** Solar contribution assumed 10 days of maximum Solar activity over the 3-years mission
Radiation hardness tests

**TID:**
- **ENEA (La Casaccia)** - 1999
  - [www.casaccia.enea.it](http://www.casaccia.enea.it)

**SEU and SEL:**
- **GSI (Darmstadt)** - 2000
  - [www.gsi.de](http://www.gsi.de)
- **JINR (Dubna)** - 2001, 2002
  - [www.jinr.ru](http://www.jinr.ru)
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ENEA 1999

high intensity \((3.7 \times 10^{15} \text{ Bq})\) \(^{60}\text{Co}\) \(\gamma\) source (1.25 MeV)

\(\text{TID} = 30 \text{ krad} \) (~30 times greater than the expected for the PAMELA mission)

only 4 devices (out of almost 100) failed

complete listing available on the Web!
GSI 2000

$^{131}\text{Xe}$ and $^{238}\text{U}$ beams@ 100÷800 MeV/n @ 0°÷60°

EffLET = 5÷70 MeV/(mg/cm$^2$)

main Devices Under Tests (DUTs) were 2 FPGAs:
- Actel A54SX32 (A54SX)
- QuickLogic QL12x16BL (pASIC1)

SEU/SEL detection circuit
Cross sections

Given the number of occurred SEEs ($N_{\text{SEE}}$) at a given value of the LET, and the integrated and renormalized(*) flux $\Phi$ we can calculate the cross section

$$\sigma = \frac{N_{\text{SEE}}}{\Phi}$$

(*) with respect of the relative beam and chip sections, and with respect of the incident beam angle.
Actel FPGA has lower cross-section for SEEs
Actel showed no Latchups, unlike QuickLogic
using the Actel FPGA cross-section in CREME96, we can estimate the number of expected SEUs

\[ \frac{dN}{dt}_{g+t} = 0.8 \cdot 10^{-5} \text{ SEU/day} \times 1000 \text{ days} \Rightarrow N_{g+t} \approx 10^{-2} \text{ SEU} \]

\[ \frac{dN}{dt}_s = 3 \cdot 10^{-3} \text{ SEU/day} \times 10 \text{ days} \Rightarrow N_s \approx 10^{-2} \text{ SEU} \]
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Dubna 2001

$^{24}\text{Mg}$ beam @ 150 MeV/n @ 0°
LET = 0.73 MeV/(mg/cm$^2$)

DUTs were:

- **1 Mbit flash memory (ST M25P10)**
  - SEU: memory filled with a known pattern of '1' and '0', continuously checked. No SEU recorded
  - SEL: continuous monitor of output voltage. No SEL recorded

- (SEL test only) several chips on 2 DC/DC converter boards (CAEN S9004 and S9006)
  - continuous monitor of output voltage. Only one MOSFET failed (GATE rupture - DUT not recoverable)
$^{24}\text{Mg}$ beam @ 100 MeV/n @ 0°

LET = 1.0 MeV/(mg/cm$^2$)

DUTs were:
- (SEL test only) several MOSFETs on some DC/DC converter boards (CAEN S900X series)
- continuous monitor of output voltage. No SEL recorded

complete listing available on the Web!
Summary

the PAMELA apparatus, devoted to the study of cosmic rays, is scheduled to be launched in the first half of 2003 for a three-years-long mission in space.

the expected particle rates during the mission have been calculated using the CREME96 simulation package taking into account the worst-case scenario.

test both for TID and SEE have been performed in these years (and more to come!)
Conclusions

- No failure due to TID is expected during the flight.
- No failure due to SELs is expected during the flight. Also, results for SEUs are encouraging, because threshold is for very high LET.
- Protection circuits for latch-ups have been introduced where possible and redundancies foreseen to avoid loss of information due to upsets.
Bibliography and references

- visit the official Web Page of the PAMELA experiment
  
  http://wizard.roma2.infn.it/pamela

- all tests reports and full list of DUTs
  
  http://HEP.fi.infn.it/pamela
  http://pamela.physik.uni-siegen.de/pamela

- the CREME96 program is available online
  
  http://crsp3.nrl.navy.mil/crete96
Enjoy your evening in Firenze!
Appendix 1 - the PAMELA experiment

The PAMELA experiment is the last of a series of cosmic-ray apparata flown by the WiZard collaboration, for purposes ranging from Medical physics to Solar physics to antimatter search.

Several missions carried on balloons (MASS89, MASS91, TS93, CAPRICE94 and CAPRICE98), on Space Stations (SilEye 1, 2 and 3) and on satellites (NINA 1 and 2), from 1989 to present.
Appendix 2 - Mission goals

Study of cosmic rays with emphasis on the antiparticle component:
- antiproton spectrum from 80 MeV to 190 GeV
- positron spectrum from 50 MeV to 270 GeV
- search for antinuclei with a sensitivity better than $10^{-8}$ in the antiHe/He ratio
- proton spectrum from 80 MeV to 700 GeV
- electron spectrum from 50 MeV to 400 GeV
- light nuclei (up to O) spectra up to 200 GeV/n
Appendix 3 - antiprotons

Secondary production (upper and lower limits)
Simon et al.

Primary production from $\chi\chi$ annihilation ($m(\chi) = 964$ GeV)

Secondary production CAPRICE94-based
Bergström et al.
Fluxes can be used to test models of cosmic ray propagation in our galaxy.

At present, fluxes can be explained via (secondary) $p_{CR} + p_{ISM}$ interactions.
Appendix 5 - antinuclei search
Appendix 6 - The instrument

The PAMELA apparatus is made of several sub-detectors:

- **a Magnetic Spectrometer**, composed of a permanent magnet and a Si microstrip tracker
- **an (electromagnetic) Imaging Calorimeter** consisting in Si strip detectors and W absorbers
- **a Transition Radiation Detector (TRD)**, composed of proportional chambers (straw tubes filled with a Xe/CO₂ gas mixture) and C fiber radiators
- **a Time-of-Flight (ToF) counter**, made of plastic scintillators strips
- **several plastic scintillator counters**, for anticoincidence (CAS and CAT) and shower tail catching (S4)
- **a Neutron Detector (ND)** made of ³He counters and a polyethylene moderator
Appendix 7 - Particle identification

The identification of the charged particles traversing the telescope is obtained from the measure of:

- the momentum and the sign of charge, through the deflection in the spectrometer;
- the absolute value of charge, from the energy loss in the Si sensors and the ToF scintillators;
- the velocity (for non-relativistic particles) by the ToF system, or (for relativistic particles), a lower limit on velocity by the TRD.

The calorimeter and the TRD provide also a way to discriminate between particles of the same charge but with different mass (for example, p from e^+). The ND and S4 increase the capabilities of the calorimeter in identifying high-energy (up to 1 TeV) electrons.
The Total Ionizing Dose (TID) is the energy released by the radiation per mass unit of the target

\[ [\text{TID}] = \text{krad}, \ 1 \text{ krad} = 10 \text{ Gy} = 10 \text{ J/kg} \]

Irradiating a generic CMOS device, we can observe a variation of the performance of the device as a function of the TID, which eventually can lead to its loss of functionality.
A Single Event Upset occurs when a highly ionizing particle passing through a digital electronic device causes an unplanned change in its logic state. Afterward, the device may be re-written into the intended state.
In the case of a Single Event Latch-up, the charge deposition by the ionizing radiation can open a low-resistance conducting path between a power line and ground is opened by a sudden ionization. A very high current will flow through this path. If the current is externally limited, no permanent damage occurs and the operability of the device can be recovered by cycling the power.
Appendix 11 - LET threshold