

Proton irradiation test on the flight model radiation monitor for LISA Pathfinder

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Abstract. The design of the Radiation Monitor in the LISA Technology Package on board LISA Pathfinder is based on two silicon PIN diodes, placed parallel to each other in a telescopic configuration. One of them will be able to record spectral information of the particle hitting the diode. A test campaign for the Flight Model Radiation Monitor is proposed to verify its performance. This paper shows the results obtained with a simulated flight model geometry using GEANT4, to be compared with the real data that will be obtained in a proton irradiation facility.

1. Introduction

LISA Pathfinder (LPF) [1] is a technological mission, whose main goal is to verify the ability to set two proof masses in purely gravitational free fall to a certain level of accuracy. This idea is reflected in the differential acceleration noise requirements between two Test Masses (TMs) for the LISA Technology Package (LTP)

$$S_{\delta a, \text{LTP}}^{1/2}(\omega) \leq 3 \times 10^{-14} \left[1 + \left(\frac{\omega/2\pi}{3 \text{ mHz}} \right)^2 \right] \text{ms}^{-2}\text{Hz}^{-1/2} \quad (1)$$

in the frequency band between 1 mHz and 30 mHz. This noise is the result of various disturbances which limit the performance of the instrumentation on-board.

LPF will be stationed in a Lissajous orbit around Lagrange point L1. There, the spacecraft will be exposed to ionising radiation coming from the Galaxy and from the Sun. Some of these charged particles will be stopped by the spacecraft structure surrounding the TMs, while others will make it to the TMs. The latter are particles having energies above a threshold of about 100 MeV/nucleon [2]. The deposition of excess charge in the TMs is of course a random process

which results in acceleration noise because the TM position sensor is capacitive [1]. The Radiation Monitor (RM) aboard LPF is intended to complement the measurement of the electrostatic charging rate of the TMs, in order to correlate the flux of energetic particles (detected by the RM) with the longer term charging rates observed in the TMs by means of the TM position sensor.

The RM is based on two silicon PIN diodes placed parallel to each other in a telescopic configuration. Both diodes can count single events, and one of them measures the primary energy of the particle, inferred from the energy deposited, when the events are detected in coincidence in both PIN diodes [4]. The expected deposited energy in the diodes (with added Gaussian noise to mimic the electronic noise) can be predicted through simulation.

A test campaign for the Flight Model (FM) RM is proposed to verify its performance. A similar test was done with a prototype of the RM, which probed its design. Test results gave the go ahead to the FM manufacturing, but the latter presents a few structural differences with respect to the prototype. The FM test is thus required, although it will be less comprehensive, in particular to prevent damage by excess radiation. The results obtained with a simulated model geometry using the GEANT4 toolkit will be compared with the real data that will be obtained in the proton irradiation facility at the Paul Scherrer Institute, in Switzerland.

2. Test and simulation

The test plan is designed to verify the performance of the FM RM. The simulation should assess whether or not:

- (i) The shield thickness is sufficient to stop soft protons with energy of less than 70 MeV.
- (ii) The dynamic range of the Front-End Electronics (FEE) + Analog-to-digital Converter (ADC) is set properly to accommodate the smallest (50 keV) and the largest (5 MeV) energy deposition in the Si PIN diodes.
- (iii) Angular acceptance for coincidence detection complies with the required value.

The initial beam for the Proton Irradiation Facility (PIF) has an energy of 254 MeV, and is guided to the experimental area passing through a set of movable energy degraders. These copper degraders can be used to select the energy of the protons finally sent to the target (from 250 MeV down to 70 MeV). The model geometry simulates the beam degrader plates, the aluminium box housing of the FM RM, the shield containing two Printed Circuit Boards (PCBs), the diodes mounted on ceramic substrates and the two PCBs where the electronic circuitry is placed. Figure 1 shows the model geometry simulated with GEANT4.

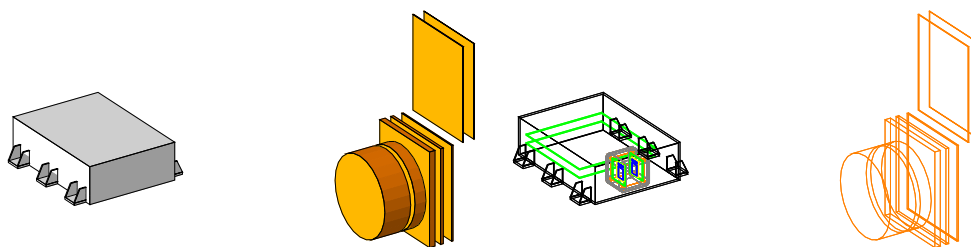


Figure 1. Beam test simulation setup in GEANT4. Left side: solid volume. Right side: clear volume showing the FM RM shield, PIN diodes and PCBs. Exchangeable degraders to select beam energies are also shown.

Several parameters of the simulation need to be tuned to improve confidence in the results. Initial theoretical values of the experimental setup are shown in brackets in the list below:

- Initial mean energy of the Beam: 255.27 MeV with an energy spread of 3.556 MeV (instead of a 254 MeV monoenergetic beam).
- Nominal thickness of the diode: 280 μm (instead of 300 μm).

3. Beam simulations

The beam is simulated as a parallel beam with a Gaussian energy profile and a flat radial profile with a diameter of 40 mm, wide enough to irradiate the diode uniformly —see figure 2. The full beam degradation was simulated in an attempt to make the calculation as representative as possible. The simulation results of the beam energy profiles after it passes through the set of movable degraders, are shown in figure 3.

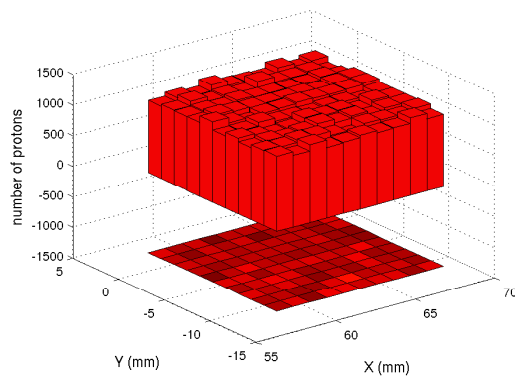


Figure 2. Uniform irradiation after exposure of the FM RM to 10^6 high energy protons.

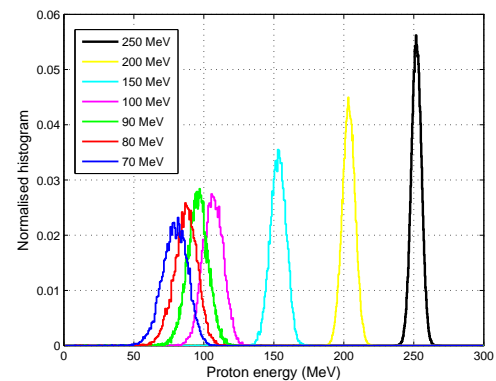


Figure 3. Simulation of the energy profiles of the final beam between 70 MeV and 250 MeV.

Based on these simulations, the properties of the energy spread of the beam (σ) for each energy setting ($\overline{E}_{\text{simulated}}$) are given in table 1, as well as the different degraders used and their thickness.

Table 1. Beam energy properties for each degrader settings used in the simulation. Ticks indicate the degraders necessary to obtain the corresponding energies.

E_{nominal} MeV	$\overline{E}_{\text{simulated}}$ MeV	σ MeV	Plate 1 0.5 mm	Plate 2 1 mm	Plate 3 2 mm	Plate 4 4 mm	Plate 5 8 mm	Plate 6 16 mm	Plate 7 38 mm
70	78.91	9.06	✓	✓	✓			✓	✓
80	86.53	8.53			✓			✓	✓
90	95.32	7.86						✓	✓
100	106.13	7.44	✓	✓		✓	✓		✓
150	152.7	6.4	✓						✓
200	203.31	4.87		✓		✓		✓	
250	251.75	3.68	✓	✓					

4. Low energy cut-off of the RM shield

The shield design is based on compromise between weight, size, and material. A good trade-off was found to be copper material. A cubic box with curved corners was the chosen shape —see figure 4. Such box is intended to stop soft-energy charged nuclei before they reach the PIN diodes in the RM. The performance of the shield will be assessed as a function of the energy of the proton beam as well as its angle of incidence on the shield.

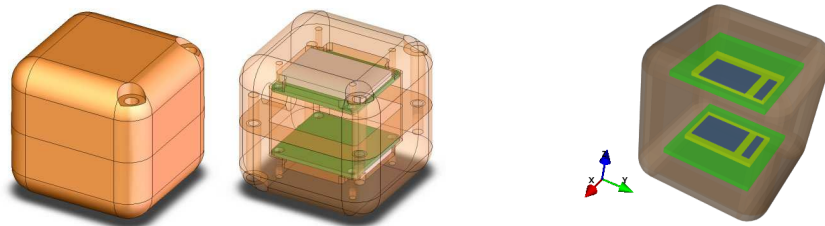


Figure 4. Design of the RM shield containing the diodes, their substrates and the PCBs. Left side: CAD model. Right side: GEANT4 model.

Simulations show that the energy cut-off below which a proton can not penetrate the RM shield is approximately 75 MeV. Normalised coincident count rates measured by the simulation as a function of the proton energy for angles between 0 and 30 degrees are shown in figure 5. Normalised count rate is obtained dividing the detection rate by the beam flux measured outside the RM shield. The energy cut-off is measured from the 50 % detection rate.

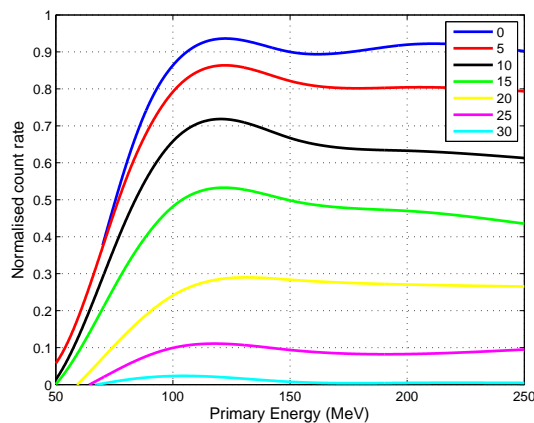


Figure 5. Low energy cut-off of the FM RM shield for different angles of incidence (from 0 to 30 degrees).

5. Angular acceptance of the FM RM

Although the Galactic Cosmic Ray (GCR) flux is isotropic, Solar Energetic Particle (SEP) events may be directional, therefore it is important to know the angular acceptance of the RM, particularly for coincidence detection, which will be used for spectral measurements. The geometrical angular acceptance of the FM RM was calculated by simulating a directional flux of protons. By

plotting the normalised rate against RM angle we can determine the efficiency of the telescopic configuration of the diodes.

The normalised count rates as functions of the FM RM orientation with respect to the beam (Z axis) is shown in figure 6. Differences between X and Y axis rotation of the FM RM in figure 7 are due to the non-symmetric active area of the detector (wider along the Y axis –see figure 4).

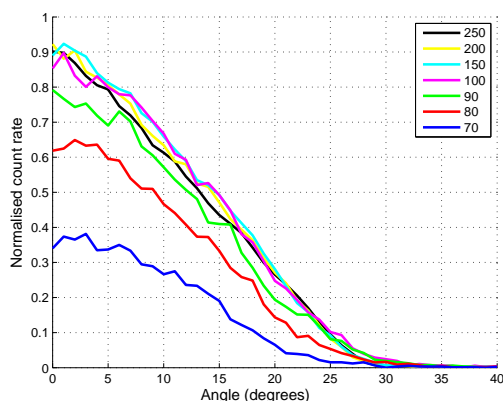


Figure 6. Acceptance angle for coincident particle detection as a function of FM RM orientation (Y axis rotation).

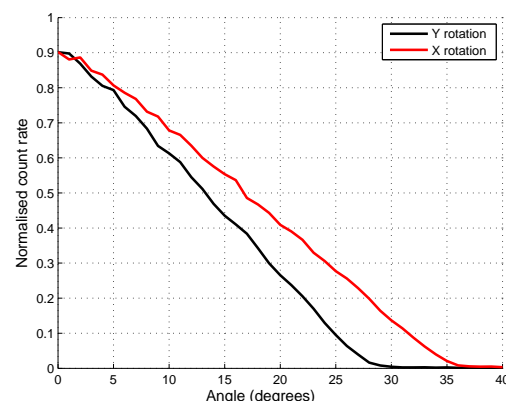


Figure 7. Comparison between X (Red) and Y (black) axis rotation of the FM RM for 250 MeV energy protons.

6. Measured energy deposited in PIN diodes

The energy deposited in the PIN diodes was simulated for orientations between 0 and 40 degrees (Y axis rotation) with nominal beam energies between 70 MeV and 250 MeV.

Figure 8 shows the energy deposited by the proton beam in the PIN diodes: low energy protons deposit higher energies than high energy protons, while the latter have a smaller spread in deposited energy. At 60 MeV almost no protons penetrate the copper shield and hence do not reach the diodes. Additionally (not shown in the figure), for angles of 30 degrees and above, the number of coincident events is largely suppressed by the geometric acceptance of the diode arrangement. Also, oblique beam incidence on the FM RM causes the distribution peaks to shift towards higher energies, as this increases the path-length of the protons inside the PIN diodes.

Figure 9 gives a comparison between experimental data from the prototype RM beam test and GEANT4 simulations for the prototype [3] and for the FM RM, with 100 MeV protons, showing good agreement between them. The main discrepancies between the FM and the prototype RM design are shown below:

- A silver layer surrounds the copper shielding in the FM RM, needed to avoid copper oxidation.
- Structural differences in the aluminium box housing of the FM RM.
- Data management by means of a Field Programmable Gate Array (FPGA) is added in the electronic circuitry for the FM RM.

All these details have been taken into consideration in the GEANT4 model of the FM RM.

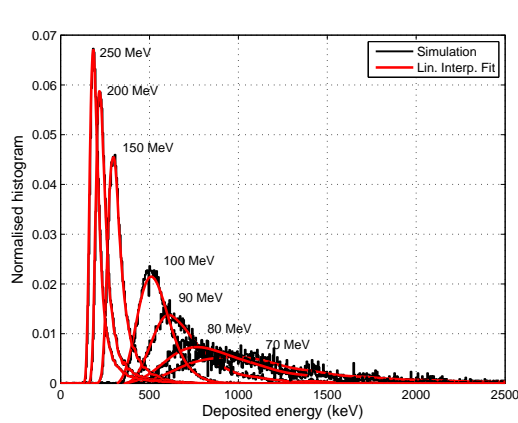


Figure 8. Simulations of the energy distribution deposited in the diode at 0 degree incidence. Labels on curves indicate the mean energy of the incident beam.

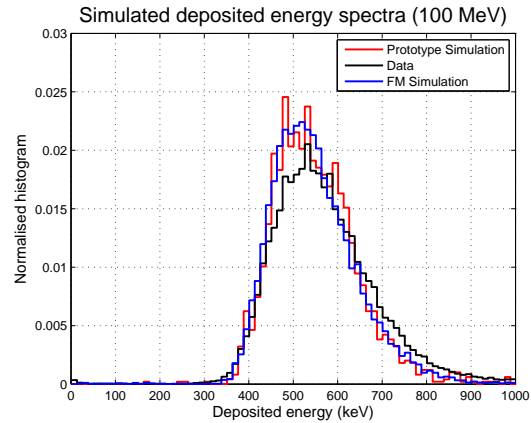


Figure 9. Comparison between real data in the prototype RM and GEANT4 simulations results for the prototype and for the FM RM.

7. Conclusions

The results of the simulation of the RM can be summarised as follows:

- The shield surrounding the PIN diodes prevents the detection of particles with energy less than ~ 75 MeV.
- The acceptance angle of the coincident mode of the FM RM is ~ 25 degree (worst case: Y rotation).
- The ADC dynamic range of the deposited energy measurements (0-5 MeV) is sufficient to record the energy deposited by all protons at 70 MeV.
- Simulations and experimental data from the prototype RM are in good agreement.
- The FM RM test should confirm that all the above is actually verified in the real device.

There are the basic facts which the FM RM test will have to validate.

Acknowledgments

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