LISA PathFinder radiation monitor proton irradiation test results

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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 is able to record spectral information of the particle hitting the diode. A test campaign for the flight model Radiation Monitor was done in the Paul Scherrer Institute Proton Irradiation Facility in September 2010. Its purpose was to check correct functionality of the Radiation Monitor under real high energy proton fluxes. Here we present the results of the experiments done and their assessment by means of a simulated flight model geometry using GEANT4 toolkit. No deviation from nominal RM performance was detected, which means the instrument is fully ready for flight.

1. Introduction

LISA Pathfinder (LPF) [1] is a technologically sophisticated mission to demonstrate that two proof masses (TMs) can be put into free-fall to a certain level of accuracy. This idea is reflected in the differential acceleration noise requirements for the LTP

$$\sigma_{be,LPF}(\omega) \leq 3 \times 10^{-14} \left[ 1 + \left( \frac{\omega/2\pi}{3 \text{ mHz}} \right)^2 \right] \text{ms}^{-2} \text{Hz}^{-1/2}$$

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 for operations in a Lissajous orbit around the Earth-Sun Lagrange point L1. This is about 1.5 million kilometers from Earth, i.e. well beyond its radiation belts. There, the spacecraft will be exposed to various ionising radiations coming from the Galaxy and from the Sun, so that, solar and galactic proton and helium particles will charge the onboard test masses (TMs) generating a significant source of noise for the experiments [3] [4]. The charge management device (CMD) will be used to discharge the TMs by means of a system of ultraviolet
lamps to ensure they remain in operational modes. However, the CMD can only provide charging average information over long periods of time (several hours), which is insufficient to address TM charging noise in the LTP MBW. In order to better estimate the latter, LISA PathFinder will contain a Radiation Monitor (RM), which will allow the relationship between the incident radiation and test mass charging to be studied in an environment that will be similar to that of LISA, a space-based gravitational wave detector with the main goal of observing astrophysical and cosmological sources of low frequency gravitational waves. The experience gained during LISA Pathfinder mission will provide important keys to optimize particle detectors and TM monitoring for LISA, as well as will be of interest to both the solar physics and the cosmic-ray communities. It should be noted that the charging disturbances tend to increase with decreasing frequency and hence are more significant for LISA than for LPF. However, the aim of LPF on this topic is to investigate charging and charge management for LISA. For detailed information of the RM aims during the mission, the reader is referred to [5].

The RM is based on two silicon PIN diodes placed parallel to each other in a telescopic configuration, housed within a thick copper shield. The signal of the diodes is processed by a suitable electronics, which is able to identify single-particles and determine the energy deposition spectrum of an incoming particle flux when events are detected in coincidence in both PIN diodes [6]. The expected deposited energy in the diodes (with added Gaussian noise to mimic the electronic noise) is known by simulation.

Before it can be flown on-board LISA Pathfinder, it is necessary to test the flight model (FM) RM so as to verify its performance [7]. Here we describe the verification tests under real high energy proton fluxes that were performed in September 2010 at the Paul Scherrer Institute (PSI) in Switzerland. Along with the tests themselves, a GEANT4 simulation was also created to further understand the RM and its properties. Part of this work was carried out earlier [8], however, an update was needed due to the redesign of the proton beam facility in the PSI.

The experiments were split into three parts. The first (sections 4 and 5) involved irradiating the RM at various proton energies and at various incident angles in order to check the effectiveness of the copper shield and the angular acceptance of the diodes telescopic configuration. The second part (section 6) involved irradiating the RM at various incident proton energies in order to test that the RM was recording the deposited energy spectrum as expected, and in the third part (section 7) the RM was irradiated with a fixed proton energy but with increasing flux to determine the maximum count rate. The test was carried out to verify the performance of the FM RM, whose results should assess whether or not:

(i) The shield thickness surrounding the RM diodes is sufficient to stop soft protons with energy less than 70 MeV.
(ii) The dynamic range of the FEE+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 expected value ($\leq 10\%$ of $4\pi$ solid angle).
(iv) Each Si PIN diode, with its FEE, is able to handle 5 kHz triggers. When the two PIN diodes are triggered in coincidence, the ADC can handle a rate of 500 Hz.

2. Test Setup
The initial proton beam for proton irradiation facility (PIF) is delivered from the PROSCAN accelerator (590 MeV). The beam passes through a set of exchangeable copper-graphite blocks (primary degrader), which allows to set the initial beam energy to 250 MeV and an approximately Gaussian energy profile. The beam is subsequently guided to the experimental area where the PIF is located. Figures 1 and 2 show different parts of the setup configuration in the facility. The PIF experimental set-up consists of the local energy degrader, beam collimating and monitoring.
devices. The FM RM was placed in the target area, mounted on a rotary table used to set the orientation relative to the beam. After the RM had been positioned and carefully aligned the testing room was sealed and the beam settings and rotary table were controlled remotely from a separate control room.

![Figure 1. Beam test setup.](image)

**Figure 1.** Beam test setup.

![Figure 2. PIF view with ionization chamber, energy degrader and wire chamber (Left). FM RM placed on the rotary table (Right).](image)

**Figure 2.** PIF view with ionization chamber, energy degrader and wire chamber (Left). FM RM placed on the rotary table (Right).

### 3. Simulations

The RM and beam line were simulated using the GEANT4 toolkit. The model geometry simulates the beam degrader plates, wire and ionisation chambers, collimator, the aluminium box housing of the FM RM, the shield, a detailed model of the two silicon diodes, the two PCBs where the electronic circuitry is placed and the base plate of the rotary table. Figures 3 and 4 show the model geometry simulated with GEANT4.
The diodes were modeled in greater detail than the rest of the simulation geometry in order to achieve as accurate results as possible — see figure 3. The full package is modeled including silicon regions, aluminium light shields, silicone resin windows and ceramic package. For the PIN diodes geometry, it was noticed during the data analysis that the sensitive silicon regions do not lie exactly at the centre of the ceramic substrate and are in fact offset by 0.5 mm [9]. As it is the ceramic substrates that are aligned inside the copper shield, and both diodes face each other, the problem is enhanced so that the sensitive regions are actually offset by 1.0 mm with respect to each other. Considering the sensitive regions are only 10.5 mm by 14.0 mm this leads to a subtle but measurable effect, which was included in the simulation.

Several values of the experimental setup considered in the simulation are shown in the list below:

- Initial mean energy of the Beam: 250 MeV with an energy spread of 0.25 MeV.
- Thickness of the diode: 320 µm [9].
- Nominal area of the PIN Diode: 147 mm\(^2\)
- A FWHM Gaussian profile of 40 keV to mimic the effect of the electronic noise.

3.1. Beam simulation

The beam is simulated as a parallel beam with a Gaussian energy profile and a flat radial profile with a diameter of 42 mm (wide enough to irradiate the diode uniformly).

The simulation results of the beam energy profiles after it passes through the set of movable degraders, are shown in figure 5, whose degradation was simulated in an attempt to make the calculation as representative as possible. Based on these simulations, the properties of the energy spread of the beam for each energy setting (\(E_{\text{simulated}}\)) are given in table 1, as well as the different degraders used and their thickness. The maximum error between the measured value of the beam and its simulated value is \(\simeq 2\%\).

![Simulation of the degrader energy of the beam](image)

**Figure 5.** Simulation of the energy profiles of the final beam between 70 MeV and 250 MeV.

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

| \(E_{\text{nominal}}\) MeV | \(E_{\text{simulated}}\) MeV | \(\sigma\) MeV | Plate 1 | Plate 2 | Plate 3 | Plate 4 | Plate 5 | Plate 6 | Plate 7 |
|-----------------------------|-----------------------------|----------------|--------|--------|--------|--------|--------|--------|--------|
| 70                          | 72.38                       | 4.04           | ✓      | ✓      | ✓      | ✓      | ✓      |        |        |
| 80                          | 82.54                       | 3.54           | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |        |
| 90                          | 92.07                       | 3.25           | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      | ✓      |
| 100                         | 100.8                       | 2.81           | ✓      | ✓      | ✓      | ✓      | ✓      |        |        |
| 150                         | 144.5                       | 2.1            |        |        |        |        |        |        | ✓      |
| 200                         | 198.8                       | 1.39           | ✓      | ✓      | ✓      |        |        |        | ✓      |
| 250                         | 247                         | 0.38           |        |        |        |        |        |        |        |
4. Low energy cut-off of the RM shield

The shield design is intended to stop soft-energy charged nuclei before they reach the PIN diodes in the RM. The performance of the shield is assessed as a function of the energy of the proton beam as well as its angle of incidence on the shield.

Results considering the ratio obtained from the number of coincident detections over the total number of detections recorded in the RM show that, as expected, the energy cutoff below which protons cannot penetrate the RM shield is approximately 70 MeV. The Count ratios measured by the RM as a function of the proton energy for angles sweeping from 0 to 40 degrees are shown in figure 6. The simulated results show good agreement with the measured data, particularly around 90 MeV and higher energies.

![Measured energy cut-off (RM ratio with corrected dead-time)](image)

![Simulated energy cut-off (RM ratio)](image)

**Figure 6.** Measured (left) and simulated (right) low energy cut-off of the RM shield for different angles of incidence. A dead time of \( \tau = 35 \, \mu s \) is considered for the FM RM (non-paralyzable dead time). Note that the red curve (5 degrees) slightly overshoots the blue one (perpendicular incidence) at 150 MeV, it is caused by the small effect due to the linear offset of the PIN diodes, as previously mentioned in section 3.

5. Angular acceptance of the RM

Simulations show that the charging rate of the TMs depends on whether the primary particles are galactic cosmic rays (GCR) or correspond to flares in the Sun (SEP events, solar energetic particles). These two types of flux have different energy spectra, and the way to distinguish between them is therefore to do spectroscopy [2]. Although GCR fluxes are isotropic, 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 a directional flux of protons. By plotting the count rate against RM angle we can determine the efficiency of the telescopic configuration of the diodes.

From purely geometrical considerations, the angular cut-off for the diodes telescopic configuration should be \( \theta_{CE} = \arctan \frac{10.5}{20} = 27.7 \) degrees. Figure 7 shows good agreement between measured and simulated data, particularly at higher energies, considering the ratio obtained from the number of coincident detections over the total number of detections recorded in the RM. The measured results suggest an angular acceptance of \( \approx 30^\circ \).
6. Measured energy deposited in PIN diodes

In order to ensure the FM RM measures the deposited energy spectra correctly, different runs were performed with nominal beam energies between 70 MeV and 250 MeV at perpendicular incidence. Using the parameters described in section 3, good agreement between the measured data and simulation was found, as can be seen in figure 8.

Experimental measurements show 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. 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 8. Comparison between simulation and real data in the FM RM for all incident energies (left) and a more detailed plot for incident protons with 100 MeV (right).

Figure 7. Measured and simulated angle acceptance for coincident to total counts ratio as a function of FM RM orientation (Y axis rotation) considering the FM RM dead time.
7. Count Rate
In order to verify the maximum count rate at which the RM can operate, a series of measurements at a nominal energy of 100 MeV and with perpendicular incident beam were taken while increasing the beam flux from \( \simeq 500 \text{ protons/s/cm}^2 \) to \( \simeq 5700 \text{ protons/s/cm}^2 \) (according to the plastic scintillator data). By plotting the count rates measured by the RM against the flux measured by the plastic scintillator, we can set an upper limit for the maximum count rate based on when the linear relationship between the two breaks down. Figure 9 shows this relationship and suggests a good linear agreement above 5000 protons/s/cm\(^2\) in the plastic scintillator equating to around 6300 protons/s total counts in the RM. In space, even the most violent SEP events are expected to produce count rates less that \( \simeq 2000 \text{ protons/s/cm}^2 \) in the RM while the GCR background less than \( \simeq 20 \text{ protons/s/cm}^2 \).

Figure 9. Demonstrates the linear relationship between the PIF scintillator flux measurements and the RM count rate at fluxes less than about 5000 protons/s/cm\(^2\). Above this, dead time caused by the RM electronics begins to have a significant effect. Right figure shows the corrected count rates if one assumes a non-paralyzable dead time \( \tau = 35 \mu \text{s} \). By correcting for this effect the count rate continues to be linear up to 6000 protons/s/cm\(^2\) and above.

A possible systematic error in the beam flux measurements by the plastic scintillator could also introduce a discrepancy between results.

8. Conclusions
The test results of the FM RM can be summarised as follows:

- Simulations and experimental data from the FM RM are in good agreement across all incident energies and angles.
- The shield surrounding the PIN diodes prevents the detection of particles with energy below \( \sim 70 \text{ MeV} \), complying with the requirement.
- According to expectations, the acceptance angle of the coincident mode of the FM RM is \( \sim 30 \text{ degrees} \) of the rotary table for the diodes telescopic configuration.
- The ADC dynamic range of the deposited energy measurements (0 to 5 MeV) is sufficient to capture the entire spectra for incident protons down to 70 MeV.
- The maximum count rate before dead time in the electronics becomes significant is found to be \( \simeq 6300 \text{ protons/s total counts in the RM} \).
- Measurements under real high energy proton fluxes have confirmed the correct functionality of the FM RM.
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