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A low-power SiPM-based radiation monitor for LISA

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LISA, the first space-based gravitational wave observatory, will be able to survey the whole sky, providing for the first time insights on the physics of gravitational waves in the low-frequency band (0.1 mHz - 1 Hz). The three arms of the interferometer are defined by free-falling test masses (TMs). Each TM is a 46 mm Au-coated cube of Au/Pt. High-energy particles interacting with the spacecraft may induce a net charging rate in the TMs, which would result in acceleration noise. Monitoring the variations of the cosmic-ray flux and detecting the high-energy component of solar energetic particle (SEP) events will be essential to understand the charging background of the mission and to provide vetoes for fake gravitational-wave triggers. We present the design of a Radiation Monitor tailored to monitor the charging rate of the TMs. It aims at providing a high-sensitivity and low-power consumption solution for detecting protons and alpha particles at a few hundred MeVs. It will be able to observe SEP events and short-term variations of the cosmic-ray flux at 1 AU from the Sun, in an energy band that is inaccessible for most radiation monitors. It consists of a telescopic arrangement of absorbers and plastic scintillators coupled to arrays of silicon photomultipliers (SiPMs). The SiPM readout is performed with the BETA ASIC, which is capable of amplifying, shaping and digitizing up to 64 input signals with only $\sim$ 1 mW/ch. We describe the initial design of the radiation monitor and discuss its expected performance, based on Monte Carlo simulations.

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1. Introduction

LISA (Laser Interferometer Space Antenna) is an ESA mission that aims at detecting gravitational waves from space [1]. It will consist of three identical satellites in an Earth-like orbit, separated by 2.5 million km one from each other, forming a triangle. Each satellite will be equipped with an optical bench (including lasers) and two Test Masses (TMs, cubes of solid gold–platinum alloy). Having an arm length of 2.5 million km, LISA will be the largest existing inteferometer and will detect gravitational waves by sensing small variations in the distance between the TMs located in different spacecraft.

As in any space-born experiment, the impact that the background radiation can have in the instruments on-board should be well understood. In the particular case of LISA, galactic cosmic rays (CRs) and solar-energetic particles (SEPs) could interact with the different components of the experiment, producing particle showers. A net charge could be induced in the LISA Test Masses (TMs) as a result of those interactions, introducing acceleration noise [2].

It has been shown in previous studies that GCR protons with energies higher than ~100 MeV will be the main contributors to the charging of the TMs [2], although the contribution from heavier nuclei cannot be neglected [3]. The intensity of the CR flux can vary by a factor ~2 between the Solar minimum and maximum (11 yr period). Also the CR spectral shape changes with solar modulation. Faster variations with periods of a few days or less have also been reported [4]. The intensity of these variations at the orbit of the LISA Pathfinder were of ~10% in intensity, in a period of a particularly quiet solar activity, but the fluctuations could be higher during the mission.

Solar activity, i.e., coronal mass ejections and solar flares, may generate eventually SEP events. These events may show an SEP flux increase which is orders of magnitude higher than the steady CR flux lasting a few days (the high-energy component of SEP events may even increase several orders in magnitude above the background level in a short period of time, ~1 day). Particularly relevant for LISA will be the high-energy tail of these SEP events, which sometimes can reach a few hundred MeVs.

An optimized radiation monitor for LISA should then be able to detect protons and heavier nuclei above 100 MeV and have enough sensitivity to monitor rapid variations in the CR flux. This would be relevant to better understand and predict the charging process of the TMs and eventually reject fake triggers that could be raised by a SEP event. A first radiation monitor tailored for LISA [5] was installed in the LISA Pathfinder, a European Space Agency mission that opened the path for LISA by successfully demonstrating the feasibility of building a future space-based gravitational wave observatory [6]. This monitor consisted of two PIN photodiodes and was able to measure variations in the cosmic-ray flux by recording the single and coincidence rates of those diodes [7]. In this work we propose a new radiation monitor based on silicon photomultipliers (SiPMs) and plastic scintillators that employs the BETA ASIC [8] to readout the sensors with low power consumption.

2. Radiation monitor requirements

The radiation monitor should have a maximum weight of 1.5 kg, a maximum volume of ~1 l and power consumption below 2 W. With these limitations we aim at building an instrument that:

(i) is capable of measuring the integral CR flux with a statistical error of 1% or better in ~1 hour; (ii) has some modest energy resolution at a few hundred MeVs, enough to distinguish the spectral shape of SEPs from that of CRs. The first requirement is crucial for monitoring rapid variations in the background radiation flux, while the second one aims at enhancing the accuracy of the spectrum reconstruction. The energy resolution is also important during SEP events: it will provide information on their high-energy tail, which could be useful for research in solar activity, since most monitors of solar particles operate at lower energies.

3. BETA Radiation Monitor

The BETA Radiation Monitor (BETA RadMon) aims at detecting protons and heavier ions with energies above 100 MeV with high-sensitivity and low-power consumption. Its baseline design consists of four plastic scintillators and three absorbers (see Figure 1). In this initial version the scintillators have an area of $\sim 20 \times 20$ mm^2 and a thickness of 3 mm. The absorbers are made of W and have also an area of $\sim 20 \times 20$ mm^2, with thickness of 10, 20 and 40 mm. However, the final dimensions of the scintillators and absorbers will be optimized through simulations. The scintillators can be operated in coincidence or in stand-alone mode. The single rates recorded by the outer scintillators S_1 and S_4 will provide an indirect measurement of the variations of the background flux. The coincidence rates of two or more scintillators ($S_1 - S_2$, $S_1 - S_2 - S_3$ and $S_1 - S_2 - S_3 - S4$) provide information on the spectral distribution of this flux. By measuring the energy deposited on the scintillators during coincidence events we could also extract some information of the energy of the incoming particle and eventually also of its charge.

The scintillators should be sensitive to the charged particles that go through them. They will be surrounded by a ~6 mm layer of Cu to block incident particles with energies < 70 MeV which should not affect the TMs.

The light produced in the scintillators will be collected with SiPMs. The size of the SiPMs and the number of SiPMs employed is still to be defined. The SiPMs will be readout with the BETA ASIC [8]. The ASIC, which was specifically designed for space applications, is the key component of the radiation monitor, since it allows exploiting the capabilities of SiPMs with low power consumption and with a very compact design. The current version of the BETA is capable of performing the amplification, shaping and digitization of the signal of up to 16 SiPMs with a power consumption of ~1 mW/channel. A future version of the chip will provide the same functionalities for 64 channels (see dedicated contribution in these proceedings). At least four ASICs (one per scintillator) will be employed.

An FPGA will control the trigger logic and process the digitized data provided by the ASICs. It will record the individual and coincidence trigger rates and produce histograms with the signal recorded by the SiPMs and digitized by the BETA.

4. Preliminary performance evaluation through simulations

To have a first estimation of the performance we may achieve with the proposed monitor and to optimize its design, we performed some simple simulations with Geant4. In these first simulations we only simulated the scintillators, absorbers and the Cu low-energy shielding, not the SiPMs nor

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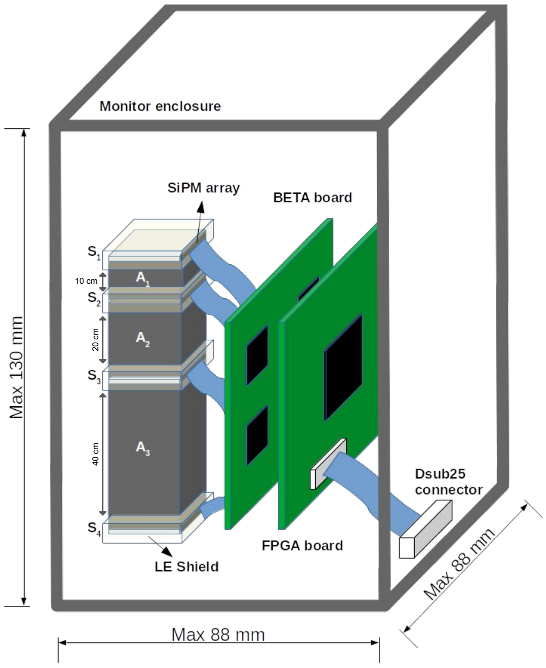

Figure 1: Scheme showing the main components of the BETA radiation monitor initial design. It employs four plastic scintillators (S_1, S_2, S_3, S_4) and three absorbers (A_1, A_2, A_3).

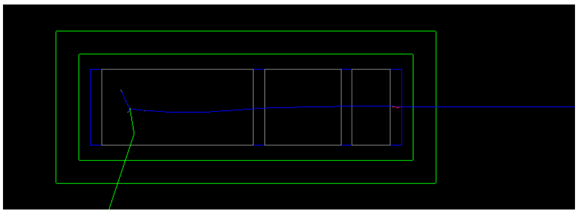

Figure 2: Example of a Geant4 simualtion of an incident 400 MeV proton (in blue) entering the radiation monitor and being absorbed before reaching S_4.

the electronics (see Figure 2). The scintillators were made of polystirene, which is often used in particle detectors. We simulated linear beams and isotropic sources of protons and He nuclei with energies from 70 MeV to 20 GeV and recorded the energy deposited in all scintillators.

The initial simulated system is still far from optimal, but still useful to have a first estimation of the performance we may achieve. In the future we also plan to include the SiPMs and simulate and track the scintillation photons. Since this will have a significant impact in the performance of the system, the results presented here should be considered as very preliminary.

4.1 Energy resolution

The energy resolution of the radiation monitor relies on coincidence events in two ways. On one hand, and as it will be shown in section 4.2, the different coincidence channels will have different energy thresholds. Then by monitoring the fluctuations of the rates detected by each coincidence channel it should be possible to identify variations in the spectral shape of the background radiation, at least at a few hundred MeVs. On the other hand, some energy resolution could be achieved by measuring the energy deposited in the scintillators, which depends on the charge (see section 4.4) and the kinetic energy of the incoming particle.

Figure 3 presents the sum of the energy deposited in S_1 and S_2, S_1, S_2 and S_3 and all four scintillators for coincidence events $S_1 - S_2$, $S_1 - S_2 - S_3$, $S_1 - S_2 - S_3 - S_4$, respectively, when the monitor is irradiated with monoenergetic protons. It shows the results for two different cases: a linear beam normally incident towards S_1 and an isotropic flux. In the case of the isotropic flux, a sphere encompassing the entire monitor was simulated and the flux was weighted by $cos(\theta)$, with θ the angle between the particle momentum and the local normal to the sphere surface. If we consider the beam scenario, by looking at the energy deposited in $S_1 + S_2$ we should be able to achieve some energy resolution at 200–300 MeV in the $S_1 - S_2$ channel. Energy resolution at 300–400 and 400–500 MeV could be achieved with $S_1 - S_2 - S_3$ and $S_1 - S_2 - S_3 - S_4$, respectively. This energy resolution clearly worsens in the more realistic case of an isotropic flux. As expected, the energy resolution is better for $S_1 - S_2 - S_3 - S_4$, which is the channel with the lowest acceptance angle. Anyway, as it will be shown in section 4.3, this limited energy resolution should be enough to distinguish the spectral shape of SEP events from that of CRs.

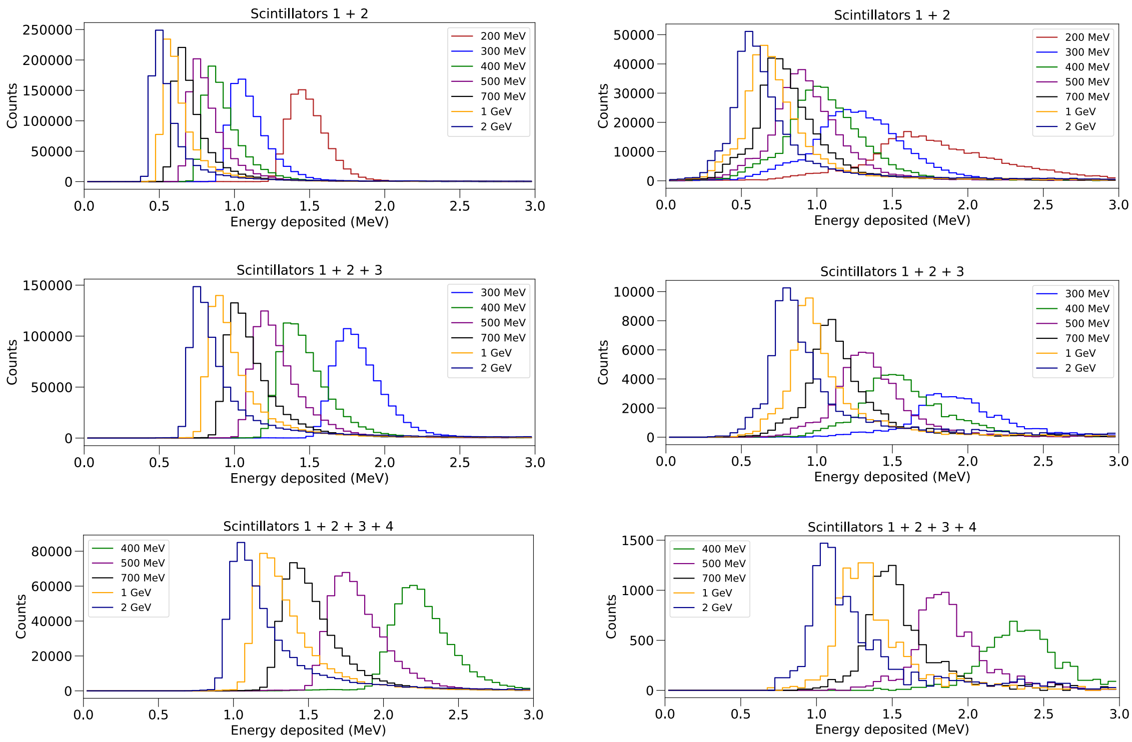

Figure 3: Deposited energy in $S_1 + S_2$ (top), $S_1 + S_2 + S_3$ (middle) and $S_1 + S_2 + S_3 + S_4$ (bottom) by linear monoenergetic beams of protons (left) and by an isotropic flux of protons (right).

4.2 Effective area

With the simulated isotropic fluxes of protons we calculated the effective area of the single and coincidence channels, which are shown in Figure 4. The effective area A_{eff} can be understood as the area that would have a 100% efficient detector and was computed as:

$$A_{eff} = A_{sim}\frac{N_{det}}{N_{sim}} \tag{1}$$

where A_{sim} is the area of the simulated source, N_{sim} is the number of simulated primary protons and N_{det} is the number of detections. A detection threshold in a single scintillator was set to 300 keV.

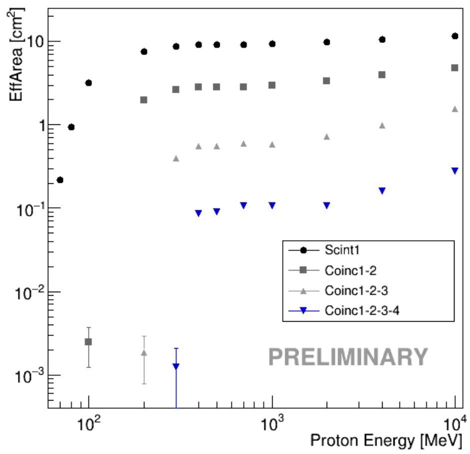

Figure 4: Simulated effective area for an isotropic flux of protons, for single rates in S_1 (Scint1), and the coincidence channels $S_1 - S_2$ (Coinc1-2), $S_1 - S_2 - S_3$ (Coinc1-2-3) and $S_1 - S_2 - S_3 - S_4$ (Coinc1-2-3-4).

The different energy thresholds of the single channels can be easily identified in Figure 4. The probability of having a detection in one of the scintillators falls quickly below 100 MeV. The preliminary energy thresholds found in channels $S_1 - S_2$, $S_1 - S_2 - S_3$ and $S_1 - S_2 - S_3 - S_4$ were ~150, 250 and 350 MeV, respectively.

With the effective areas we can compute the expected rates for any incident isotropic flux. In the particular case of cosmic rays we estimated detection rates of ~37, 12, 2.6 and 0.4 counts/s during the solar minimum in the channels S_1, $S_1 - S_2$, $S_1 - S_2 - S_3$ and $S_1 - S_2 - S_3 - S_4$, respectively. During the solar maximum the rates decrease by a factor ~2. Please note that the simulations are still in an early phase and that they have not been validated with experimental data, meaning that the results should be considered as very preliminary. The results obtained are still useful to understand the order of magnitude of the rates we may expect in the different channels.

4.3 Energy deposited by CRs and SEPs

Figure 5 depicts the energy deposited in S_2 during $S_1 - S_2$ coincidence events for CR protons during solar maximum and for SEP protons. The SEP protons were simulated assuming the model used in [2] to describe a dim SEP event like the one of 20 May, 2001. The plot shows that the proposed system has the capability to distinguish, within a few minutes, the spectral shape of SEP events from the characteristic one of CRs.

4.4 Charge identification

Since the energy deposited by hadrons is proportional to z^2 (with z the atomic charge), the proposed system has also the potential to perform charge identification. This can be seen in Figure 6,

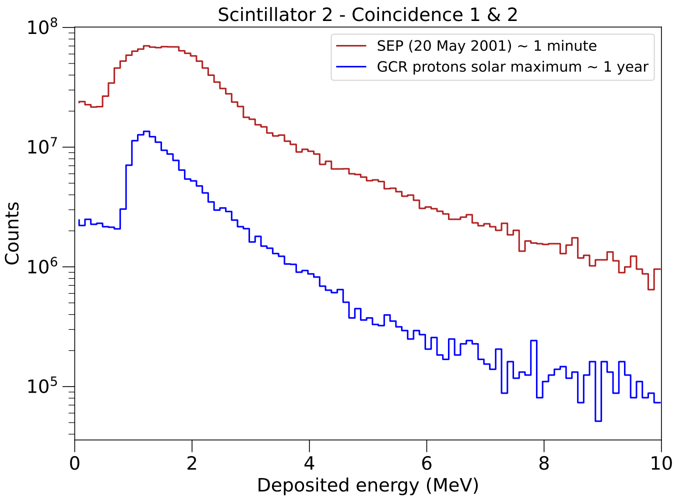

Figure 5: Energy deposited in S_2 for coincidence events in $S_1 - S_2$ after ~1 minute for SEP particles and ~1 year for CR protons during solar maximum conditions.

which shows the energy deposited in S_2 vs the energy deposited in S_1 during $S_1 - S_2$ events, for CR protons (red) and CR ^{4}He nuclei. While the bulk of the protons will deposit less than 1 MeV in each scintillator, the ^{4}He nuclei would typically deposit more than 2 MeV. To exploit this functionality the detector (scintillator + SiPMs + readout) will need to have a dynamic range going from ~ 400 keV to at least ~5 MeV.

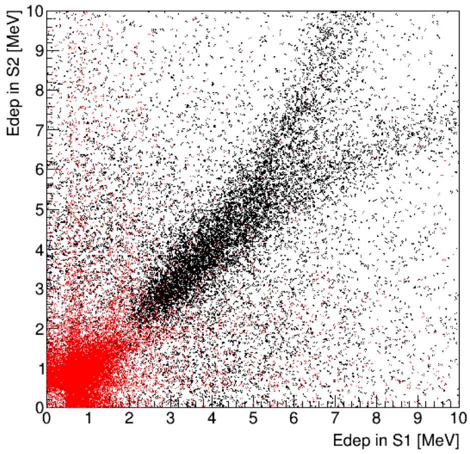

Figure 6: Energy deposited in S_1 and S_2 for $S_1 - S_2$ events during solar minimum and after one day. Protons in red, ^{4}He nuclei in black.

5. Conclusions

In this work we proposed a radiation monitor dedicated for the LISA mission. It is focused on detecting the fluctuations of the background radiation flux in the energy range that affects the TMs.

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This detector is based on plastic scintillation detectors and SiPMs readout with the BETA, an ASIC developed for processing and digitizing SiPM data in space applications.

We described the proposed system for the first time and presented its initial design. We estimated the performance it could achieve through Geant4 simulations, showing some preliminary expected rates and its potential to perform charge identification and to distinguish the spectra of CRs and SEPs with its limited energy resolution. The design is expected to be optimized in the next few months and we expect to develop and validate our first prototype in the incoming years.

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