EPSI R&D: development of a X-ray space detector for observing the synchrotorn radiation from electron and positrons in the geomagnetic field

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Summary. —
Directly measuring the antimatter component in cosmic rays provides crucial information on the mechanisms responsible for their acceleration/propagation and represents a powerful tool for indirect dark matter searches. Charge sign discrimination in cosmic ray experiments has been performed, to date, by the use of magnetic spectrometers, which are not suited to extend the measurements above a few hundreds of GeV in relatively short time scales. It would be therefore important to develop a an alternative charge sign discrimination technique that can be integrated with present and future calorimetric experiments. This is the objective of the Electron Positron Space Instrument (EPSI) project, a two year R&D focused on studying the feasibility of electron/positron separation in space based on the simultaneous detection of the lepton with an electromagnetic calorimeter and its synchrotron emission in the geomagnetic field with a X-ray detector. This requires to develop a X-ray detector optimized to have high detection efficiency in the low energy region, large active area and low cost. In this contribution, after a short introduction to the project's motivations, we describe the experimental activities regarding the optimization of the single cell of the X-ray detector.

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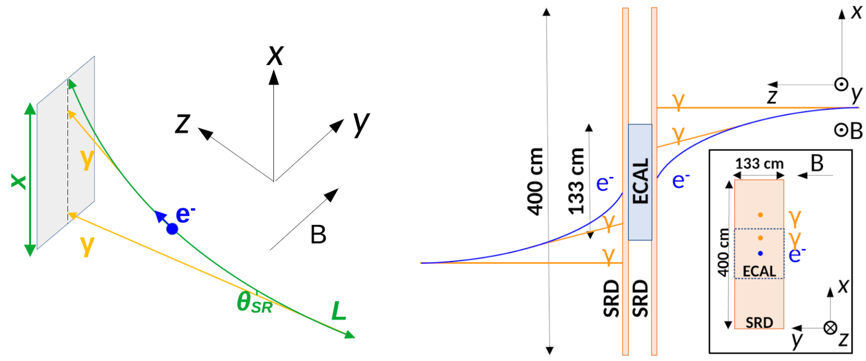

Fig. 1. – EPSI particle identification principle (*left*) and a possible ECAL+SRD detector implementation (*right*).

1. – Introduction

The search for direct or indirect evidence of dark matter is one of the major experimental challenges in particle physics. Significant efforts have been made to address the issue over the last decades but at present no conclusive result has been obtained. A promising candidate signature was discovered in the positron excess measured first by PAMELA [1] and later confirmed by other space experiments [2, 3]. Current measurements are, however, still insufficient to make a conclusive statement about the origin of the observed effect, which could be explained by ordinary astrophysical sources, such as local pulsars or supernova remnants [4]. To distinguish between the possible origins and test the dark matter hypothesis, it is essential to extend the measurement of the electron and positron fluxes above several hundred GeV. As an example, the astrophysical contribution to the electron+positron spectrum is expected to show a cutoff at energies around 1 TeV, above which only particles injected by young, local sources are present, as suggested by the CALET measurements [5]: studying features in the spectra could provide a hint on the origin of the positron excess.

Currently available detectors are not capable of performing charge sign discrimination at such high energies. The maximum detectable rigidity in space experiments is determined by technological limitations that cannot be overcome in the short term. On the other hand, calorimeter-based instruments, on which most near future space experiments are based, are intrinsically unable to measure the charge sign. In this experimental landscape, a detector able to perform charge sign discrimination and that can be paired with calorimeter-based instruments could provide crucial measurements, currently inaccessible by other means. The development of such detector is the goal of the Electron Positron Space Instrument (EPSI) project, a two year R&D initiative approved in 2023 as a *Progetto di Rilevante Interesse Nazionale* and funded by the EU recovery program.

2. – Detection principle

The core principle behind the EPSI project is the simultaneous detection of the primary lepton (electron or positron) and the synchrotron radiation it emits while travelling in the geomagnetic field, with sufficient spatial resolution to perform charge sign discrimination. Relativistic electrons and positrons in the geomagnetic field will be deflected in different directions and emit synchrotron photons tangentially to their trajectories. Measuring the relative position of the charged particles and the photons is sufficient to discriminate between the two leptons on an event-by-event basis, as illustrated on the left in Figure 1.

The first published work on the detection of synchrotron radiation from charged particles in the geomagnetic field is [6] and practical implementation of the principle with recent instruments has been first suggested by [7]. A notable contribution has been provided by the CREST experiment, that flew a high-altitude balloon in Antarctica for 10 days starting December 25, 2011, and aimed to identify the synchrotron radiation signature by reconstructing the events' topology with precise timing and position measurements. This experimental campaign demonstrated the difficulties of detecting the synchrotron radiation with only a X-ray detector due to the astrophysical background [8].

Differently from CREST, EPSI's detection technique is based on the pairing of a large collecting area Synchrotron Radiation Detector (SRD) with a Electromagnetic CALorimeter (ECAL), which will provide the trigger for the SRD. A possible detector configuration is shown on the right in Figure 1. Recent technological advancements also make it possible for such a detector to be built with sufficient effective area and low enough mass and cost.

3. – Instrument requirements

The SRD should be able to detect at least two spatially separated synchrotron photons in order to independently reconstruct the electron/positron bending plane.

A preliminary assessment of the SRD requirements can be obtained by the order-of-magnitude estimates shown in Table I. These are evaluated for a 1 TeV $e^{\pm}$ travelling orthogonally to the geomagnetic field, for which an average intensity of $\langle B \rangle \sim 0.4$ G is assumed. The SRD size in the bending plane direction is assumed to be 4 m. The value of the synchrotron radiation emission angle $\Theta_{SR} \sim 0.5 \times 10^{-6}$ indicates that the emission region is confined to a narrow beam around the tangent to the electron's trajectory. The synchrotron critical energy and peak emission energy, $\epsilon_c \sim 27$ keV and $\epsilon_{peak} \sim 8$ keV, respectively, show that most of the power is radiated in the soft X-ray range, which requires the SRD entrance window to have a low Z composition in order to maximize transmission efficiency. The average number of photons that reach the detector, $\langle N \rangle \sim 4$, is also shown in the Table. Since the detection of at least two photons is required to reconstruct the bending plane using the SRD alone, developing a detector with high light collection efficiency is of crucial importance.

The granularity of the SRD will be defined by the optimal combination of light collection efficiency, spatial sensitivity, background rejection and number of channels. Finally, in order to minimize the detector's cost, its materials will have to be properly selected and its mass will have to be kept as low as possible.

Estimated parameters for a 1 TeV $e^{\pm}$	
Θ_{SR}	0.5×10^{-6}
ϵ_c	27 keV
ϵ_{peak}	8 keV
$\langle N \rangle$	4

TABLE I. – *Relevant quantities for a 1 TeV $e^{\pm}$ travelling in the geomagnetic field, orthogonally to its field lines. These are the synchrotron emission angle Θ_{SR}, the synchrotron critical energy ϵ_c, the synchrotron peak emission energy ϵ_{peak} and the average number of photons expected to reach the detector $\langle N \rangle$.*

4. – Detector implementation

A possible implementation of the detector is shown on the right in Figure 1, based on the requirements described above.

The design considers a 2000 kg mass for the ECAL, which is intended to identify the lepton's interaction point and arrival direction, reconstruct the its energy and provide the main trigger. It is made of CsI:Tl cubic crystals read out by photodiodes, based on the results from the CaloCube collaboration [9]. In order to have sufficient radiation lengths X_0 for energy reconstruction a depth of 25 cm ($13.44X_0$) is assumed, and square surfaces of 1.33×1.33 m^2 are chosen to maximize the geometric factor.

The SRD should be able to detect synchrotron photons and provide an independent assessment of the bending plane in the geomagnetic field. It is made of two separate layers, on opposite sides of the ECAL, with the same width of the calorimeter ($L = 1.33m$) and extending beyond its edges in the direction orthogonal to the geomagnetic field ($L' = 4m$). Given the limited depth, its mass is negligible when compared to the ECAL.

5. – R&D activity

The main focus of the EPSI R&D activity has been the development of the single detection cell of the SRD. Given the requirements of large collecting area, low costs and high detection efficiency for soft X-rays, semiconductor devices cannot be employed.

The solution under study is therefore based on a scintillator crystal wrapped in reflective coating and optically paired with a SiPM.

The two crystals selected for the study are CsI:Tl and GAGG:Ce, which are both high light yield scintillators with nominal yield values of LY(CsI:Tl) $\sim$ 54 photons/keV and LY(GAGG:Ce) $\sim$ 60 photons/keV and different decay time constants, that are, respectively, 900 ns and 150 ns.

Simulations were used to estimate the optimal cell geometry a cell with a 20×20 mm^2 surface area and a 2.5 mm depth has been chosen.

The scintillator crystal is optically coupled to a Silicon PhotoMultiplier (SiPM) centred on the face opposite to the entrance window. Different SiPM options have been tested and the Hamamatsu MPPC S13360-6075PE has been selected as it has a large collecting area (6×6 mm^2 with a 82% fill factor), a high photon detection efficiency near the CsI:Tl and GAGG:Ce peak emission wavelengths ($PDE \sim 40\%$) and a low dark count rate ($DCR \sim 2$ MHz).

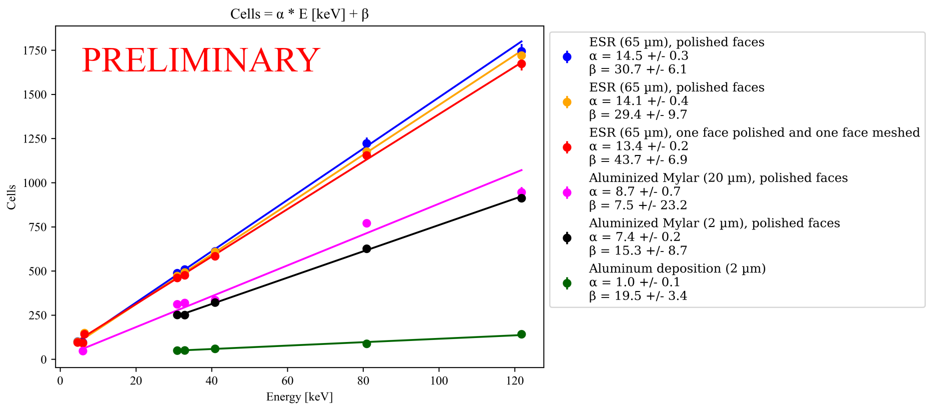

Fig. 2. – Linear fit to reference source emission lines of identified peaks in the source spectra measured with different configurations of the CsI:Tl crystal single detection unit. The entrance window material and surface polish are shown in the legend. All the other faces of the crystal are wrapped in ESR (65 μm).

In order to maximize light collection efficiency, highly reflective wrapping or coating is needed: crystals are wrapped in 65 μm thick Enhanced Specular Reflector (ESR) foil with nominal reflectivity of $\sim 98\%$. Since such material could absorb a non-negligible amount of soft X-rays at energies around 1 keV, different entrance windows are currently being studied to maximize efficiency, among which a $300 - 2000$ nm aluminium layer deposited by sputtering and aluminized Mylar foils.

The experimental setup is as follows. The signal from the SiPM is pre-amplified and digitalized by a CAEN DT2790 Digitizer. The low dark count is fundamental for the system's characterization as measuring the ADC distribution of the dark current peaks is used to extract the SiPM's gain in the specific acquisition conditions (temperature and supplied voltage). This allows us to estimate the number of photocells activated on the detector and therefore, accounting for the cross-talk probability, the number of photons collected.

Radioactive sources with clearly identifiable peaks in the 1-150 keV region are used for detector characterization. Acquired source spectra are calibrated in number of SiPM cells activated and a Gaussian fit is used to extract their mean and standard deviation. A linear fit of these values to reference tabulated values for the radioactive sources is then performed. The linear coefficient obtained by the fit is straightforwardly connected to the light collection efficiency of the system $PDE(\lambda_{peak}) \cdot \epsilon$, where ϵ accounts for the crystal's optical and geometric efficiency. This can be understood in a simplified model where the crystal emits all its scintillation light at the peak wavelength λ_{peak}. If we neglect SiPM crosstalk, the number of activated SiPM cells after a single interaction of an X-ray of energy E in the crystal is $N_{cells} = E \cdot LY \cdot \epsilon \cdot PDE(\lambda_{peak}) + DCR \cdot t$, where t is the signal's integration time.

The preliminary results comparing the light collection efficiency of different configurations are shown in Figure 2.

A study on the non-uniformity of the detector's response to irradiation by soft X-rays in different spots of the entrance window has been performed using a 5 cm thick Al collimator. Edge effects are shown to have a significant impact on light collection efficiency, which is reduced down to 80% of the central efficiency. This has a noticeable effect on the detector's energy resolution, which shows a non-uniformity constant term of $\sim 10\%$.

6. – Conclusions and prospects

Developing detectors that exploit charge sign discrimination techniques alternative to magnetic spectrometry can provide crucial contributions to the field of high energy astroparticle physics. The EPSI project builds on previous theoretical work and R&D efforts to attempt to provide new solutions to the issue. At present, the EPSI R&D activities have included the maximization of the light collection efficiency with regards to different single unit configurations of crystal geometry, surface roughness and entrance window. Future work includes testing of the single detection unit at the LABEC (Laboratorio di tecniche nucleari per l'Ambiente e i BEni Culturali) facility at INFN-FI where monochromatic proton beams at the energy of 1 MeV scattering on a fixed target will be used to produce X-rays at the relevant energies and study the detector's efficiency in the range of a few keV.

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