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Development of a innovative electron-positron discrimination technique for space application: the EPSI Project

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Fifteen year later the first detection of the cosmic positron excess, the origin of this structure is still unclear. Its understanding is crucial not only for astrophysics but also for fundamental physics, since it is one of the most striking signature that could be possibly associated with dark matter origin. In order to shed some light on the nature of the positron excess, it is necessary to separately extend the measurement of electron and positron fluxes above a few hundreds of GeV. In a relatively short time scale, this can be performed by developing an innovative charge sign discrimination technique that could be mounted aboard calorimeter-based experiments. The Electron Positron Space Instrument (EPSI) project is a two year R&D aiming to study the feasibility of electron/positron separation in space by exploiting the synchrotron photons emitted as the charge particles travel in the geomagnetic field. This goal requires the development of a X-ray detector optimized to have a high detection efficiency in the low energy region, while keeping the cost low enough to make it scalable to a large area. In this contribution, the general idea of the project is presented, together with the description of the on-going laboratory activities.

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1. Introduction

The search for a direct or indirect evidence of dark matter is one of the main experimental challenges in particle physics. In the last decades, an intense effort has been dedicated to this item without reaching any conclusive result. One of the most striking signatures that could be associated with dark matter origin is the positron excess [1–3] observed for the first time by the PAMELA experiment . Unfortunately, the current measurements are not sufficient to reach a definite statement, since the effect may also be explained using ordinary astrophysical sources, such as local pulsars or supernova remnants [4]. In order to test the validity of the dark matter hypothesis, it is necessary to separately extend the measurement of electron and positron fluxes above a few hundreds of GeV. This would also have important consequences for cosmic ray physics, due to the cutoff of the electron+positron flux at around 1 TeV [5, 6]. Above 1 TeV there could be characteristic structures if local astrophysical sources are present, as the results by the CALET experiment may suggest.

The detection techniques used by present and future space experiments are not suited to extend the current measurements above a few hundreds of GeV in a relatively short time scale. Calorimeter-based experiments are excellent instruments in the high energy region thanks to their good energy resolution and large geometric factor, but they are intrinsically unable to measure the charge sign. On the other side, spectrometer-based experiments can distinguish matter from antimatter, but at high energies they suffer of poor rigidity resolution, limited charge sign identification and small geometric factor. The attempts to overcome these limitations, pioneered by the ALADInO [7] and AMS-100 [8] projects, are still technologically challenging and not feasible in the short time.

Given its excellent performances at high energies, most of current and future direct cosmic ray experiments [9–11] are based on a large calorimeter. In order to separately extend the measurement of electron and positron fluxes, it is therefore necessary to develop an innovative charge-sign discrimination technique that could be used for an auxiliary detector aboard a calorimeter-based instrument. This is the goal of the Electron Positron Space Instrument (EPSI) project, a two year R&D approved in 2023 as *Progetto di Rilevante Interesse Nazionale*, with EU recovery funds.

2. Detection method

The basic idea of the EPSI project is to discriminate electron/positron in space by exploiting the simultaneous detection of the particle and the synchrotron photons emitted as it travels within the geomagnetic field. In the relativistic case, the particle undergoes very small deflection angles and the photon emission angle is so small that its direction can be considered tangent to the particle trajectory at the emission point. Hence, if we consider a plane orthogonal to the axis of motion, synchrotron photons will always cross it on the opposite side from the curvature of the particle. As shown in Fig.1, knowing the configuration of the magnetic field, it is thus possible to distinguish

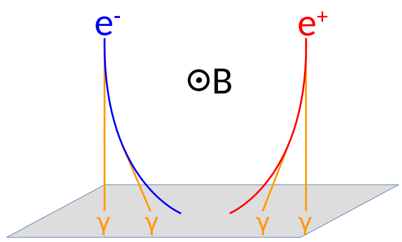

Figure 1: Principle of charge sign identification exploiting the simultaneous detection of a particle (an electron or a positron) and the synchrotron photons emitted during its motion within the magnetic field.

the charge sign of the incident particle by simply looking at its intersection with the detector, with respect to the arrival position of the synchrotron photons emitted by it.

The idea of using synchrotron radiation for cosmic ray detection in space was suggested for the first time in 1972 by the Soviet physicist Prilutskii [12] and significantly developed in [13]. It has been considered as a primary/complementary detection technique for several balloon and satellite experiments (AMS [14], SRD [15], CREST [16], Sonya [17]), and the CREST and SRD collaborations have also tested a synchrotron radiation detector prototype in space. The EPSI project differs from all the previous R&Ds in two aspects. Firstly, the previous projects aimed to use synchrotron photons as a primary technique to indirectly reconstruct the electron/positron energy, with the only exception of the AMS case where it would have been a complementary technique for a spectrometer-based instrument. Conversely, this project is intended to develop an auxiliary detector for charge sign discrimination to be mounted aboard an instrument based on a large acceptance calorimeter and therefore well suited to reach multi-TeV energies. Secondly, the technological breakthroughs achieved in recent decades allows for the development of a synchrotron radiation detector having better performances and at a lower cost than in previous R&Ds.

3. Synchrotron radiation

In order to have an estimation of the relevant quantities involved, let us consider the simplified case depicted in Fig.2. Here, an electron with energy $E = 1\ TeV$ moves in the x-z plane, perpendicular to a constant geomagnetic field of intensity $B = 0.4\ G$ and directed along the y axis. Under these assumptions, the general solution leading to a helicoidal motion is reduced to a circular motion. Let us consider a detection surface in the x-y plane, with a long x side to better contain the projected bending plane. For this simplified case, we assume a x side length of $\Delta x = 2\ m$. As discussed in Sec.4, in the basic design of the space instrument, Δx represents just half of the detector length, since we require the electron to hit in the region around detector center.

Using these values we obtain a curvature radius of $R[m] = p[GeV]/0.3\ B[T] \sim 83 \times 10^3\ \ km$. Since $R \gg \Delta x$, the effective track length[1] can be approximated as $L \sim \sqrt{2\,R\,\Delta x} \sim 18.3\ km$. This quantity represents the length of the electron track along which all synchrotron photons arriving on the detector are emitted. Furthermore, considering that synchrotron radiation is emitted inside a cone having a RMS angle $< \theta_{SR}^2 >^{1/2} = 1/\gamma$, the *position dispersion* of synchrotron photons in the x-y detector plane with respect to the bending plane is of the order of $\sigma_{x-y} \sim L < \theta_{SR}^2 >^{1/2} \sim 9.3\ mm$. This means that, as sketched in Fig.2, synchrotrons photons lie almost on the same line - the intersection of the detector plane and the bending plane - and it allows for the discrimination between synchrotron radiation and astrophysical backgrounds. To fully exploit this effect, we need a detector with a segmentation of the order of $1\ cm \times 1\ cm$ and an independent information on the electron track.

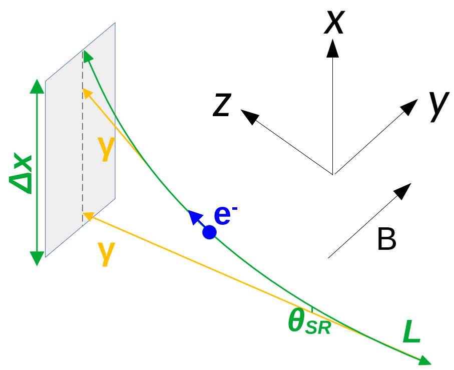

Figure 2: Simplified case of synchrotron emission to estimate the relevant quantities discussed in the text.

[1] In the generic case, we should consider the projection of the effective track length on the x-z plane.

The other key parameters that can be estimated from this simplified case are the *average number* and *characteristic energy* of synchrotron photons reaching the detector. The first one can be obtained by multiplying the average number of photons emitted per unit of track length $< dN/dl >$ for the effective track length L, whereas the second one is the *critical energy* ϵ_c, which represents 0.29 times the energy for which the synchrotron power spectrum is maximum:

$$< N > = < \frac{dN}{dl} > L = \frac{5\sqrt{3}}{6}\alpha\gamma\sqrt{\frac{2\,\Delta x}{R}} = 4.5 \quad \text{at} \quad 1\,TeV \tag{1}$$

$$\epsilon_c = \frac{3}{2}\hbar c\frac{\gamma^3}{R} = \frac{3}{2}\frac{\hbar e B}{m^3 c^4}E^2 = 26.8\,keV \quad \text{at} \quad 1\,TeV \tag{2}$$

Given the very limited number and very low energy of synchrotron photons, and considering that we need to detect at least two of them to clearly reconstruct the charge sign, it is necessary to have a high detection efficiency, of at least 80%, in the soft X-ray region, ideally $1 - 100\ keV$. This is the main instrumental challenge of this technique since it is difficult to develop a large detector array having these performances at a reasonable cost.

The above quantities scale as $< N > \propto \sqrt{E}$ and $\epsilon_c \propto E^2$. Thus, the technique works better and better as electron energy increases, but it cannot be applied below one hundred GeV because of the low values of these two parameters. Below this energy, electron/positron discrimination can be performed by using the geomagnetic east/west asymmetry method, and it would be useful to have a small overlapping energy region where the two techniques can be crosschecked.

4. Space Instrument

A possible geometry of a future experiment based on the EPSI approach is shown in Fig.3. It is designed assuming a 2 t mass for the calorimeter, a typical value for a payload in space, and requiring an effective geometric factor of at least 2 $m^2 sr$, necessary to extend measurements in the multi-TeV region. The instrument is based on a large Electromagnetic CALorimeter (ECAL) with a Synchrotron Radiation Detector (SRD) made of two single layers on opposite sides.

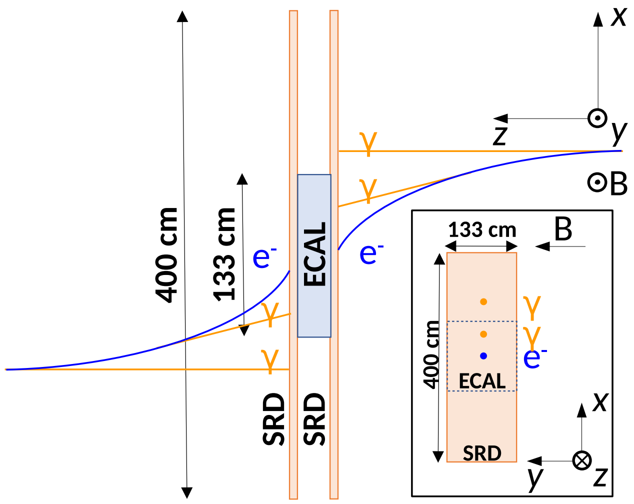

Figure 3: A possible implementation of the EPSI space instrument: also shown are two electrons from opposite directions, orthogonal both to magnetic field and detector surface.

The ECAL is intended to reconstruct the energy and the trajectory of the incident electron/positron, suppress the proton background and generate the main trigger of the instrument. Exploiting the results of the Calocube collaboration [18–23], it can be made of CsI:Tl cubic crystals readout by photodiodes. Considering a 2 t ECAL made of CsI:Tl crystals, a reasonable size is obtained assuming a depth of 25 cm (13.44 X_0), which is enough for energy reconstruction by fitting the longitudinal profile, and square surfaces of 1.33 $m \times$ 1.33 m, in order to maximize the geometric factor. The granularity must be carefully studied in terms of incident track and shower profile reconstruction performances, respectively for charge-sign identification and energy reconstruction.

The SRD is intended to detect the synchrotron photons emitted by the incident particle to allow for electron/positron discrimination. The two single layers are placed on opposite faces of the ECAL in order to double the acceptance of the instrument by detecting particles coming from both sides. The main features directly follow from the discussion of the detector requirements in Sec.3. A surface of $4\ m \times 1.33\ m$ is assumed in order to maximize the number of incident photons, which lie on the bending plane. A segmentation of the order of $1\ cm \times 1\ cm$ is enough to discriminate synchrotron photons from astrophysical backgrounds. The X-ray detection efficiency must be at least 80% for incident energies of $2.5 - 100\ keV$ or, even better, of $1 - 100\ keV$.

5. R&D activity

The main activity of the EPSI project is the development of the single detection cell for the SRD. Given the large area needed, the high detection efficiency in the soft X-ray region cannot be obtained with semiconductor devices, which are generally expensive and inefficient above a few tens of keV. The best solution is to exploit a thin scintillator layer wrapped with a reflective coating and coupled to a SiPM. To have an idea, the typical size of the cell could be $2\ cm \times 2\ cm \times 0.25\ cm$ and high light yield scintillators like CsI:Tl and GAGG are good candidates for the active medium. The main challenge is the coating which must be reflective to optical scintillation photons, but transparent to the incident soft X-rays.

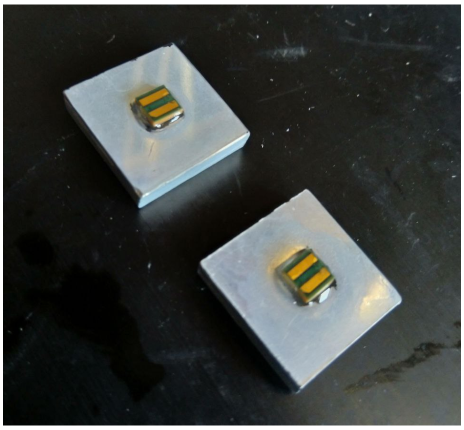

Figure 4: Example of 300 *nm* thick Al deposited on CsI:Tl crystals coupled to SiPMs.

In order to optimize light yield collection efficiency, different materials and geometries are being tested both using optical simulations and laboratory measurements. Commercial reflective layers like Enhanced Specular Reflectors (ESR) have a large X-ray absorption probability below $10\ keV$. It is therefore necessary to choose a different coating at least for the entrance surface. Thin reflective entrance windows can be realized by a few hundreds *nm* thick Al or Ag layers, deposited on the crystal thanks to a sputtering machine. Different solutions are under study, with Al deposition on the entrance face and the remaining faces covered with Al deposition, Ag deposition or ESR instead. As an example, Fig.4 shows two crystals with 300 *nm* thick Al deposition on all faces.

6. Summary

The Electron Positron Space Instrument (EPSI) project is a two year R&D approved in 2023 as *Progetto di Rilevante Interesse Nazionale*, with EU recovery funds. Its goal is to develop an innovative charge-sign discrimination technique that could be used for an auxiliary detector aboard a calorimeter-based instrument. We are currently working on the development of the single detection cell for synchrotron radiation. Once the cell is completely defined, we will focus on the space instrument design, with special attention to reconstruction performances and background rejection.

7. Acknowledgments

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