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Proceedings

A Compact Particle Detector for Space-Based Applications: Development of the Low Energy Module (LEM) for the NUSES Space Mission [†]

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Abstract: NUSES is a planned space mission aiming to test innovative observational and technological approaches related to the study of low-energy cosmic rays, gamma rays and high-energy astrophysical neutrinos. Two scientific payloads will be hosted onboard the NUSES space mission: Terzina and Zirè. Terzina will be an optical telescope readout by SiPM arrays, for the detection and study of Cerenkov light emitted by Extensive Air Showers generated by high-energy cosmic rays and neutrinos in the atmosphere. Zirè will focus on the detection of protons and electrons up to a few hundred MeV and to 0.1-10 MeV photons and will include the Low Energy Module (LEM). The LEM will be a particle spectrometer devoted to the observation of fluxes of low-energy electrons in the 0.1-7 MeV range and protons in the 3-50 MeV range along the Low Earth Orbit (LEO) followed by the hosting platform. The detection of Particle Bursts (PBs) in this Physics channel of interest could give new insight into the understanding of complex phenomena such as eventual correlations between seismic events or volcanic activity with the collective motion of particles in the plasma populating van Allen belts. With its compact sizes and limited acceptance, the LEM will allow the exploration of hostile environments such as the South Atlantic Anomaly (SAA) and the inner van Allen belt, in which are expected electron fluxes of the order of 10^{6-7} cm^{-2} sr^{-1} s^{-1}. Concerning the vast literature of space-based particle spectrometers, the innovative aspect of the LEM resides in its compactness, within 10x10x10 cm^3, and in its "active collimation" approach dealing with the problem of multiple scattering at these very low energies. In this work, the geometry of the detector, its detection concept, its operation modes and the hardware adopted will be presented. Some preliminary results from the Monte Carlo simulation (Geant4) will be shown.

Keywords: Low Energy Module; NUSES; Particle Bursts; silicon detectors; PIPS; cosmic rays; particle identification; $\Delta E - E$ telescope

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1. Introduction: The NUSES space mission

NUSES is a planned space mission aiming to test innovative observational and technological approaches related to the study of low-energy cosmic rays, gamma rays and high-energy astrophysical neutrinos. The satellite will host two payloads, named Terzina [1,2] and Zirè [3–7]. Terzina will be a pathfinder for future missions devoted to observing Ultra High Energy Cosmic Rays (UHECRs) and neutrino astronomy using space-based instruments[8–11].

Zirè is a particle detector measuring electron, proton and light nuclei fluxes from a few up to hundreds MeV, also testing new tools for the detection of γ-rays. The main purpose of the detector is to measure the counting rates of the trapped particles precipitating from the Van Allen Belts (VABs), looking for eventual anomalies occurring in the proximity of catastrophic events such as earthquakes or volcanic activities involving the lithosphere. Another essential science objective of ZIRÈ is to monitor solar activity and its periodical cycle characterised by a duration of about 11 years. In particular, it is useful to monitor the occurrence of events such as Solar Flares (SFs) or Coronal Mass Ejections (CMEs) during solar maxima[12]. The investigation of energetic particles in the magnetosphere will improve the understanding of the acceleration mechanisms involved during those events with the possibility of space weather broadcasts. The other science objective is to detect photons with energies up to tens of MeV. This allows the study of some of the most violent and energetic events in astrophysics which are the so-called Gamma Ray Bursts (GRBs) [13,14], rapid and intense pulses of gamma rays coming from very far sources.

Zirè will be equipped with an additional sub-detector: the Zirè-Low Energy Module (LEM). The LEM will be attached to the external structure of the NUSES satellite (see Figure 1). It will fit within a volume of 10x10x10cm^3 and it will be able to perform event-based Particle Identification (PID) for low-energy charged particles, such as electrons and protons.

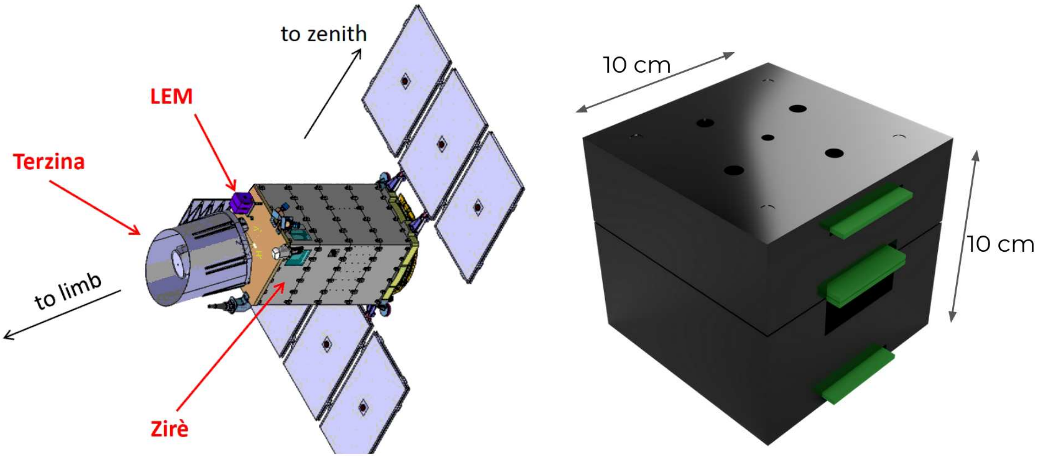

Figure 1. [Left panel] Schematic view of the NUSES mission satellite. The Terzina optical telescope will observe the night side of the Earth limb, the Zirè detector will measure charged particles and γ-rays, and the LEM spectrometer will measure low energy charged particles arriving from the zenith. [Right panel] The LEM detector inside the passive aluminium shield. The flux of charged particles crossing the five top holes is measured.

2. The need for a Low Energy Module

As mentioned before, one of the NUSES mission goals is the monitoring of particle precipitations from Van Allen Belts (VABs) investigating for possible correlations with earthquakes and validating Lithopsphere-Atmosphere-Ionosphere-Magnetosphere coupling models. Several processes can cause a precipitation of the trapped charged particles from the radiation belts. These processes are not fully understood yet, but the primary cause is thought to be electromagnetic fluctuations in the radiation belt. These electromagnetic fluctuations can be produced through solar-magnetic storms, lightning storms, man-made electromagnetic emissions and seismic activity. It is known that the measurement of the fluxes of trapped charged particles can improve the models of the coupling between the lithosphere, atmosphere, ionosphere, and magnetosphere [15]. In particular, statistical evidence of a temporal correlation between particle precipitations from Van Allen Belts and strong seismic events has been pointed out [16]. These observations, motivate the interest in further, detailed, measurements of electron fluxes in the energy window $0.1 - 7$ MeV that could be a promising channel to identify hypothetical seismic precursors.

Therefore, with the aim to extend the measurements to lower energies, a Zirè Low Energy Module (LEM), has been introduced in the design of the NUSES satellite. The Low Energy Module will be a compact spectrometer, fitting within a volume of 10x10x10cm^3 (right panel of Figure 1 for the volume envelope of the LEM), able to perform an event-based measurement of energy, direction and

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composition of low energy charged particles, in particular down to 0.1 MeV for electrons. The main goal of this detector is the monitoring of the magnetosphere and ionosphere environment. Other goals of the LEM detector will be the study of Space Weather, monitoring the flux of low energy protons, and the investigation of the particle composition within the harsh environment of the South Atlantic Anomaly (SAA), measuring the isotopic abundances of H, He and eventually the fraction of heavier nuclei.

3. Geometry and detection concept of the LEM

In a particle spectrometer (like e.g. Zirè) the measurement of the particle direction is usually performed by tracking technique; however, for low energetic particles, the standard tracking approach fails due to large multiple Coulomb scattering within the first detector layer. For the measurement of the arrival direction of low energy particles, a collimation technique must be adopted [17]. In the collimation technique, a shaped passive shield must be thick enough to stop energetic particles from “unknown”/random directions. The passive collimator allows the detection of particles arriving from the "known" directions. To avoid bulky and heavy passive shields, the technique of “active collimation” is developed for the LEM spectrometer. This technique relies on the use of shaped plastic scintillators as a veto, tagging the particles that are crossing only a relatively light passive shield. To limit the occupancy of the veto detectors in the SAA and in the lower Van Allen belt near the poles, permitting a reliable measurement of the particle composition there, a 0.8 cm thick aluminium shield is considered for the LEM. The particle identification capability of the LEM relies on the consolidated ΔE-E spectrometric technique [18–20], performed by five pairs of thin Passivated Implanted Planar Silicon (PIPS) detectors placed in a telescopic configuration. The typical resolution of the PIPS detector is $\simeq$10 keV.

In Figure 2 an exploded view of the detector shows the components and a preliminary assembly of the detector. On the other hand, in Figure 3, a schematic representation of the instruments explains its adopted detection scheme. Coming from the zenith, a particle can enter inside the LEM through the holes drilled in the top shield avoiding being tagged by the drilled top veto. Depending on the particle direction, the nature of the charged particle is identified by one of the five ΔE-E spectrometers. Each spectrometer is composed of a 100μm thin silicon detector superimposed to a 300μm thick silicon detector. To extend the energy range capability for the LEM particle identification, a lower calorimeter is placed below the PIPS. A lower calorimeter made by a 2 cm thick plastic scintillator allows a flux measurement of up to 10 MeV for electrons, thus a reasonable overlap is expected with the Zirè flux measurements [21]. Finally, a bottom veto is identifying particles of relatively large energy, that are not contained by the lower calorimeter. A good particle identification capability is expected for contained particles that are crossing one of the 100μm top PIPS.

Assuming a low energy non-relativistic charged particle passing through the thin PIPS detector, both the energy deposited, $\Delta E \propto \frac{Z^2}{\beta^2}$, and the total kinetic energy, $E_k \approx \frac{1}{2}m(\beta c)^2$, are velocity dependent. Combining these quantities, a particle classifier can be defined: PID = $\log_{10}\left(\Delta E \cdot E_k\right) \approx \log_{10}\left(Z^2 m\right) + const.$, that is mainly dependent on the particle mass, m, and charge, Z, but is almost energy independent.

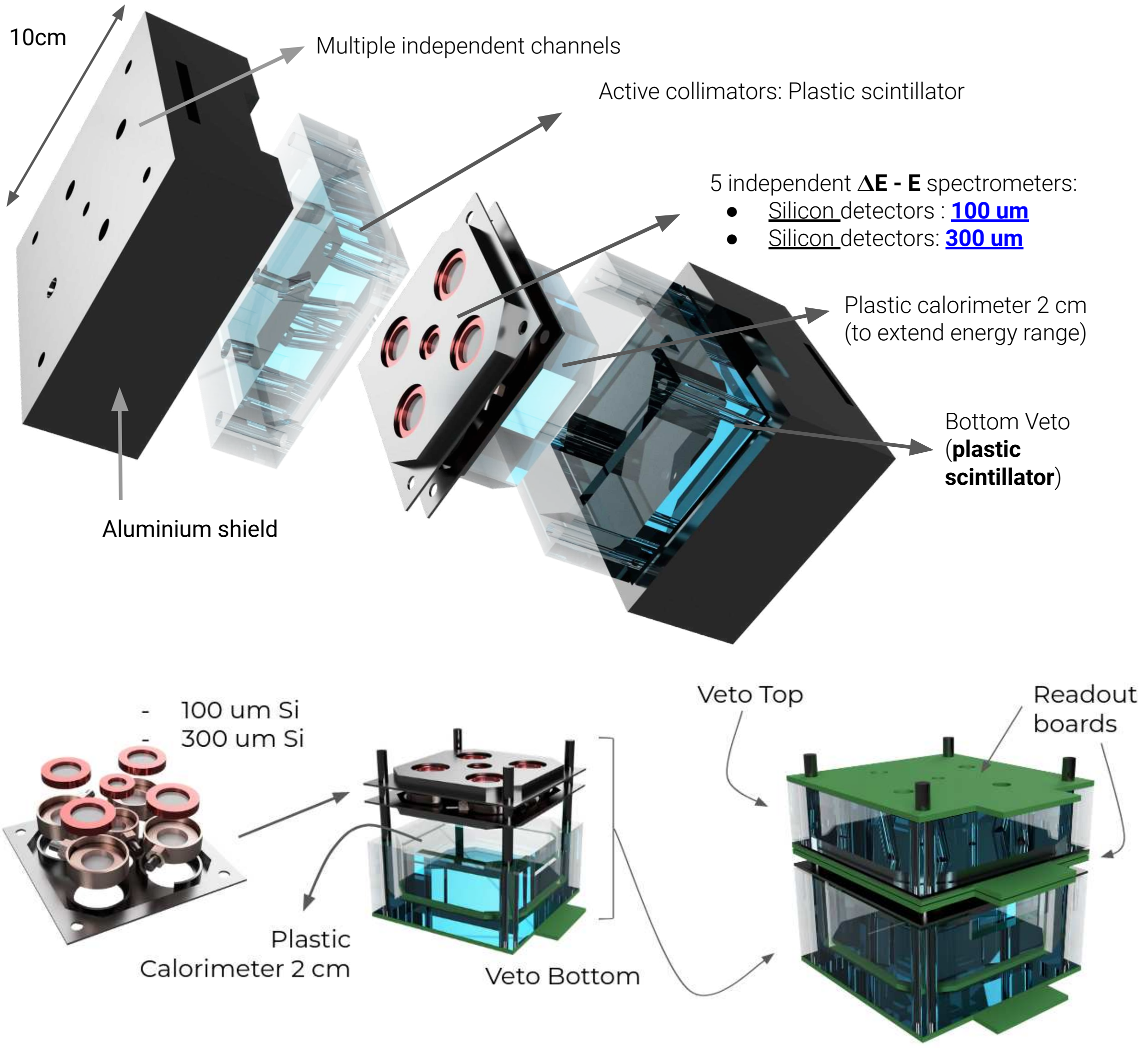

Figure 2. (Upper Panel) Exploded view of the LEM detector. (Lower Panel) These images describe the assembling and the geometry of the Low Energy Module (LEM) detector.

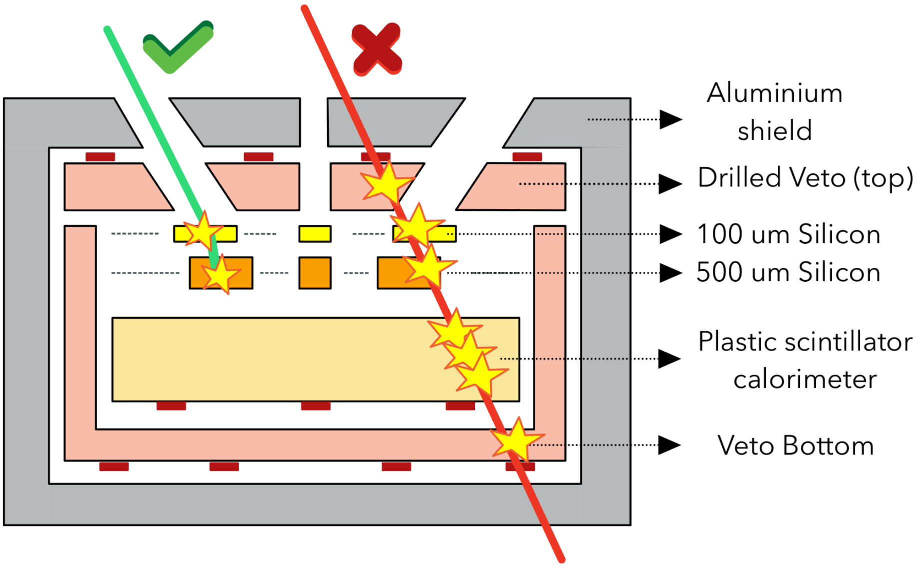

Figure 3. Schematics of the LEM detection approach; the green line is an example of accepted events, and the red line represents an example of an event to be rejected.

For the characterisation of the detector's performances, a GEANT4 Monte Carlo simulation [22] was appositely developed. For the simulation of the geometry reported in Figure 2, developed with a parametric computer-aided design (CAD) software, we adopted the Geometry Description Markup Language (GDML) [23]. We generated the GDML file (compatible with the GEANT4 toolkit) using the GDML Workbench [24] for *FreeCAD 0.20*.

The PID classifier is shown in the left plot of Figure 4. The non-relativistic approximation is not valid for electrons, however they are identified thanks to the very low mass. The poor energy resolution expected by the plastic scintillator calorimeter is responsible for the PID performance degradation at relatively large energy where the particles are crossing the thick PIPS stopping in the plastic calorimeter.

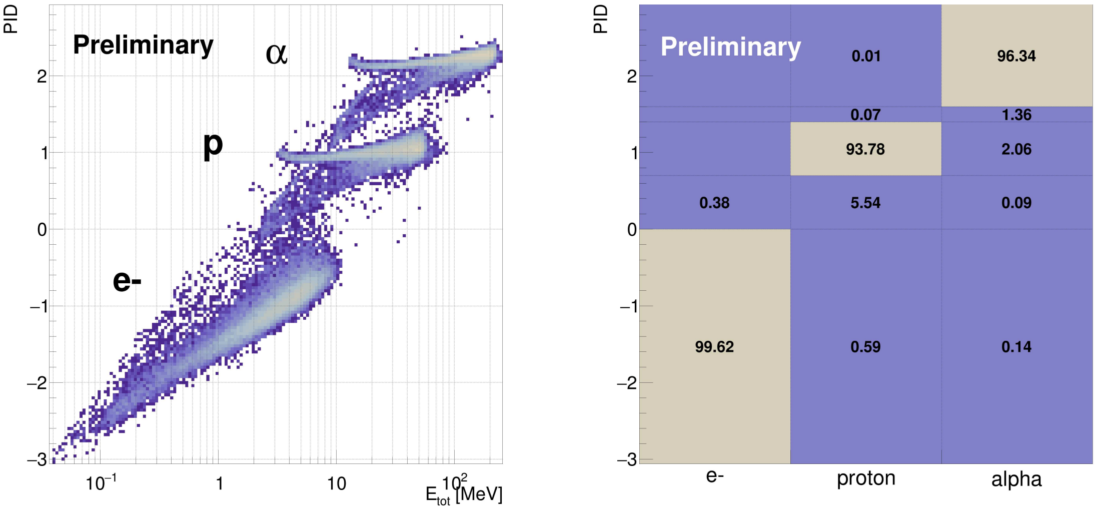

Figure 4. (Left panel) Particle identification capability for events crossing the top 100μm PIPS and contained in the LEM. (Right panel) Particle tagging efficiency for the three families of particles: electrons, protons, and alpha particles. For each particle family (Monte Carlo truth) reported on the horizontal axis, the tagging efficiency is reported on each bin of the histogram.

To estimate the particle identification efficiency, it is possible to define some specific intervals for the PID for each particle: [-3, 0] for electrons, [0.7, 1.4] for protons, and [1.6, 2.5] for alpha particles. In the right panel of Figure 4, the particle identification tagging efficiencies, for the three families of particle, is higher than 90 % in the three respective PID proxy intervals. In particular, we observed that for accepted electrons, protons, and alpha particles, respectively the 99%, 94%, and 96% were correctly tagged.

In Figure 5, the characterisation of the LEM Field of View (FoV) and angular resolution for protons and electrons is shown. The scatter plot shows the incoming direction of the particle (at the Monte Carlo truth level) projected on the plane. Here, the zenith direction is assumed to be encoded by the origin of the plot. The colour identifies which ΔE-E channel has been triggered. The overall LEM FoV is $\approx 45°$. The obtained angular RMS is $\approx 6°$ for proton and α particles while a worse resolution ($\approx 12°$) is expected for electrons due to interactions with the inner fringes of the LEM aperture.

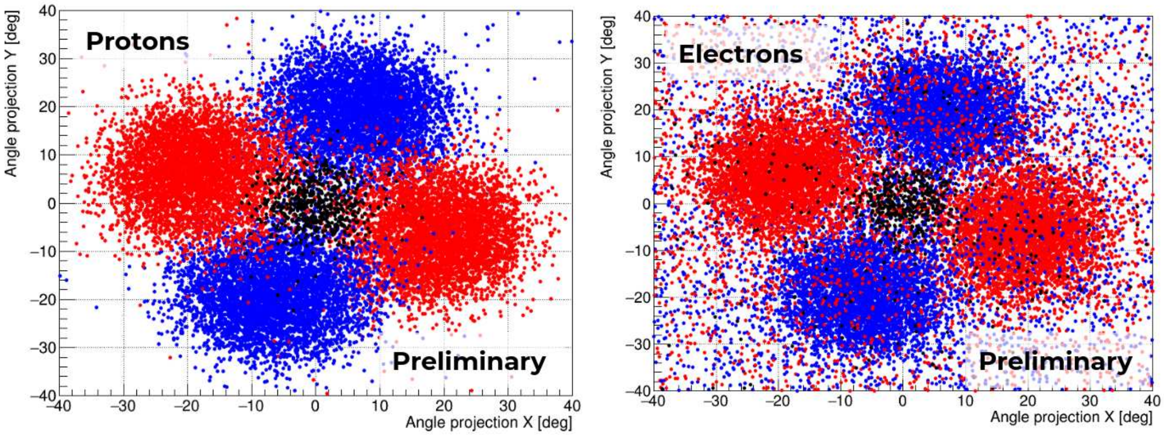

Figure 5. Field of view and angular resolution of the LEM detector for protons (left panel) and electrons (right panel), the different colours are encoding which pair in the ΔE-E spectrometer detects the particle.

The overall LEM geometrical factor[1] is ≈ 0.2-0.3 cm^{2}sr. It is approximately constant for electrons in the range 0.2-5 MeV, for protons in the range 3-50 MeV and for α particles in the range 20-200 MeV. In Figure 6, the geometric factor estimated for electrons, protons, and alpha particles is shown.

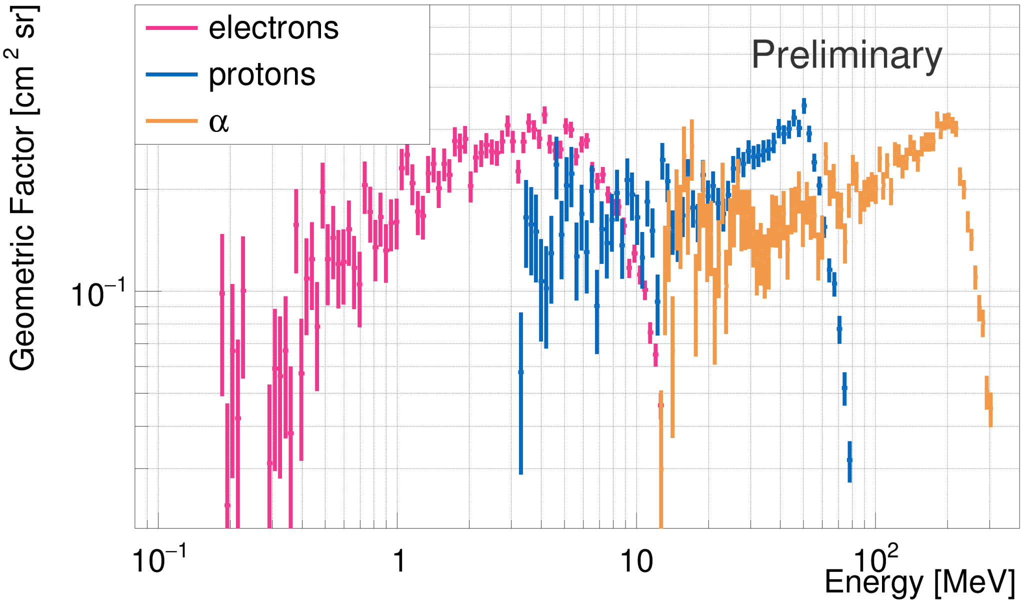

Figure 6. Geometric factor estimation for the LEM.

Knowing the orbit parameters of the NUSES mission (Sun-synchronous, 97 degrees, LEO 550km), a preliminary map of the expected rates of the LEM can be evaluated using the model *International Radiation Environment Near Earth AE9/AP9* (IRENE-AE9/AP9) [26]. In the LEO environment, the most impacting populations of charged particles are trapped protons and electrons. With IRENE-AE9/AP9 we could estimate the differential omnidirectional/isotropic fluxes of those particles.

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[1] The estimation of the geometric factor was carried out assuming the definitions and methods described in [25].

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In Figure 7 it is shown that the LEM will experience a high acquisition rate (≈ 50 kHz) in the SAA, thus a twofold data transmission approach is in preparation ("event-based" for rates below 1kHz and "histogram based" for larger rates) to fulfil the data bandwidth assigned to LEM in the NUSES mission.

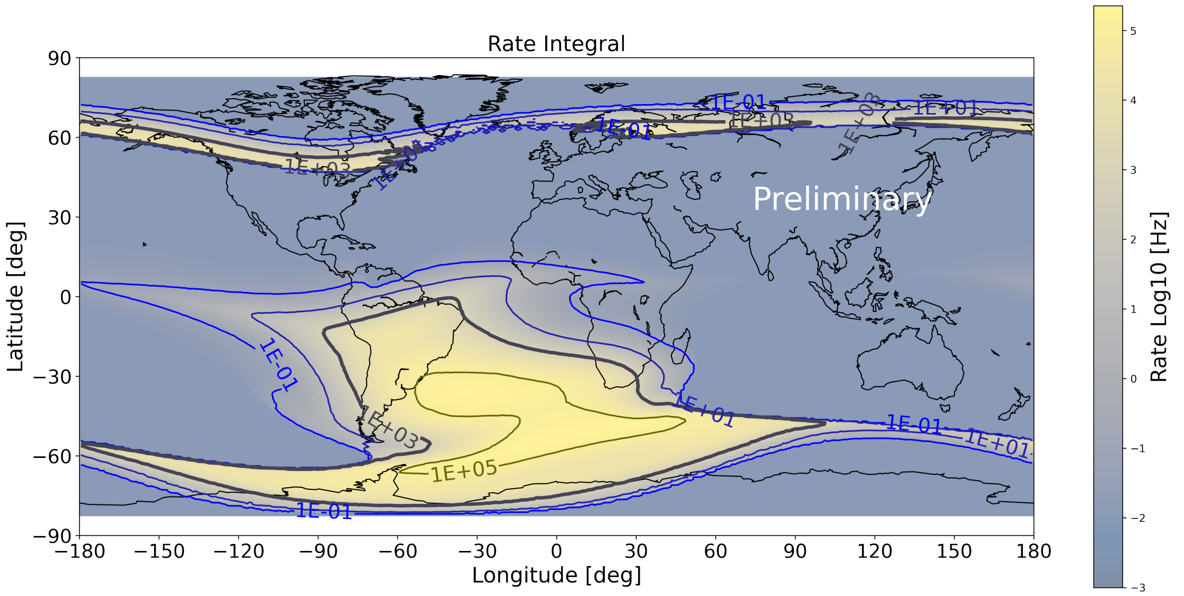

Figure 7. Expected rate map considering the satellite polar orbit and the ≃ 0.2 cm^2sr acceptance. The thicker contour in the map represents the region inside of which the LEM will operate in the histogram-based mode.

4. Preliminary test on PIPS sensors.

The heart of the LEM detector is composed of the PIPS spectrometer. The spectrometer will use four circular PIPS with an area of 150mm^2 surrounding a central one with an area of 55mm^2 (see Figure 8). The central PIPS diameter is smaller to equalize the geometrical acceptance among the five channels. The five top sensors, with thickness 100μm, will be the R-series (ruggedized) PIPS manufactured by ORTEC/AMETEK [27].

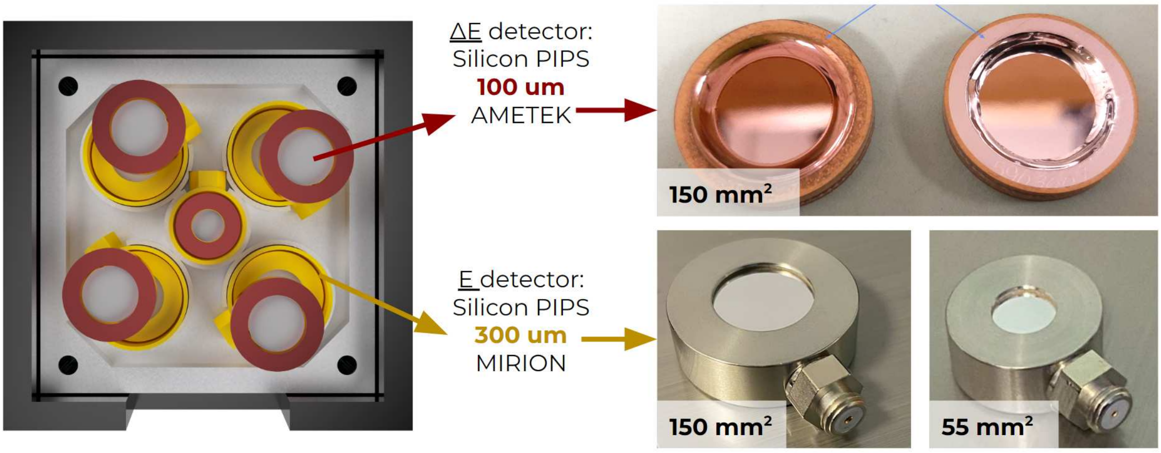

Figure 8. (Left panel) Mounting arrangement of the PIPS in the LEM spectrometer. (Right panel) A picture of the 100μm thin PIPS manufactured by ORTEC/AMETEK.

The two sides of the 100μm PIPS are covered by an aluminium and a gold layer with a thickness of ≈50μg/cm^2 and ≈40μg/cm^2, respectively. These layers ensure that the PIPS detectors are light-tight and "ruggedized". The five bottom sensors, with thickness 300μm, will be manufactured by

Canberra/MIRION [28]. The two sides of the 300μm PIPS are covered by aluminium with a thickness of $\approx$70μg/cm^2 and $\approx$250μg/cm^2, respectively, to ensure the detector is light tight.

A preliminary set-up for the measurement of the performances of a PIPS detector was tested in the INFN-TIFPA laboratory. The depletion voltage of the PIPS sensor was 60V and the preliminary measurement of the power budget of the used charge amplifier is below 100mW/ch. The sensor was tested acquiring atmospheric muons in telescopic configuration, γ-rays from ^{176}Lu source and α-particles and γ-rays from ^{241}Am source. Excellent linearity of the energy scale was obtained. Moreover, the PIPS response to particles with very different specific ionization (muons, recoiling electrons and α) has been found to be compatible within a few per cent, as expected.

Two key requirements for the LEM project are guaranteeing a low energy threshold and a relatively fast response. The acquired measures verify the feasibility of the 40 keV energy threshold adopted in the LEM simulations as well as the 10 keV energy resolution.

Another important factor for the LEM is the measurement of the signal decay time; this is related to the detector occupancy which could be an issue in the harsh environment of the SAA. The $\approx$ 200 ns measured signal decay time prevents the possible pile-up of overlapping signals from different particles in the SAA.

5. Conclusion

The project of a compact (10x10x10cm^3) particle spectrometer, the Low Energy Module (LEM) as part of the Zirè instrument on board the NUSES space mission is in the construction and testing phase. Prototypes of PIPS detector readout have been tested in the INFN-TIFPA laboratory, confirming $\approx$ 10 keV energy resolution and $\approx$ 100 ns signal decay time. The LEM will be able to perform measurements of energy, direction, and composition of low-energy charged particles down to 0.1 MeV kinetic energy, studying the coupling between the lithosphere and magnetosphere, measuring the particle fluxes in the SAA and monitoring the Space Weather.

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Abbreviations

The following abbreviations are used in this manuscript:

ACD	Anti-coincidence detector
CSA	Charge sensitive amplifier
FOV	Field Of View
GDML	Geometry Description Markup Language
GEANT	Geometrty and tracking
GRB	Gamma-ray burst
IRENE	International Radiation Environment Near Earth
LAIM	Lithosphere atmosphere ionosphere magnetosphere
LEM	Low-energy module
LEO	Low earth orbit
LYSO	Lutetium–yttrium oxyorthoSilicate
MILC	Magnetosphere ionosphere lithosphere coupling
MIP	Minimum ionising particle
MPV	Most probable value
PID	Particle identification
PIPS	Passivated implanted planar silicon
SAA	South Atlantic Anomaly
TGF	Terrestrial gamma-ray flash
VAB	Van Allen Belt

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