PROCEEDINGS OF SCIENCE

The NUSES space mission

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NUSES is a new space mission project aimed at studying cosmic and gamma rays, high-energy astrophysical neutrinos, the Sun-Earth environment, space weather, and magnetosphere-ionosphere-lithosphere coupling. Additionally, the NUSES mission will serve as a technological pathfinder for the development and testing of innovative technologies and observational strategies for future missions. The satellite will host two payloads named Terzina and Zirè. Zirè will perform measurements of electrons, protons, and light nuclei from a few up to hundreds of MeV, while also testing new tools for the detection of cosmic MeV photons and monitoring of MILC signals. The Terzina telescope aims to detect ultra-high-energy cosmic rays (UHECRs) through the Cherenkov light emission from extensive air showers that they create in the Earth's atmosphere. The telescope will also monitor the light emissions from the Earth limb in the near-UV and visible ranges at the nanosecond timescale, thus testing the observational concept of detecting Earth skimming astrophysical high-energy neutrinos. Terzina will be able to study the potential for future physics missions (e.g. POEMMA) devoted to UHECR detection and UHE neutrino astronomy. In this talk, the status of the NUSES project design will be discussed along with the scientific and technological objectives of the mission.

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[*] Speaker

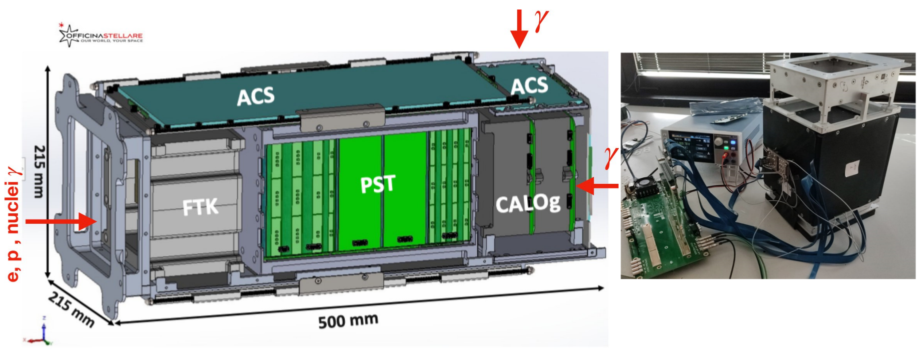

Figure 2: Left side: preliminary mechanical design of the Zirè detector. Right side: picture of the e Zirèttino prototype that has been tested/calibrated at CERN with beam-test.

The NUSES (Neutrinos and Seismic Electromagnetic Signals) space mission project aims to explore new scientific and technological pathways for future astroparticle physics space-based detectors [1]. The NUSES satellite will host two instruments: Terzina [2] and Zirè [3]. NUSES will orbit in Low Earth Orbit (LEO) at an altitude of 550 km with a high inclination of approximately 97.8°. It will follow a Sun-Synchronous orbit and operate in a dusk-dawn mode along the day/night boundary. A schematic representation of the NUSES satellite design is presented in Fig. 1, highlighting the instrument's positions and pointing directions.

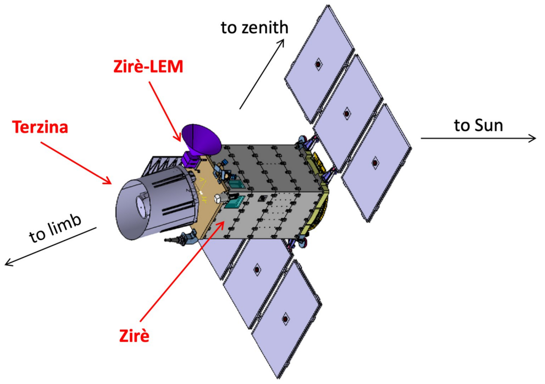

Figure 1: General scheme of the NUSES satellite design.

The **Zirè** experiment's primary objective is to study Gamma Ray Bursts (GRBs) and to detect cosmic rays (CRs) in the energy range of a few to hundreds of MeVs. It will not only investigate the spectral features of CRs but also will seek anomalies in their counting rates that could be linked to Earth's natural events like earthquakes, volcanic eruptions. Other experiments, both on the ground and in LEO, have observed unanticipated phenomena in the ionosphere, including disturbances in electromagnetic and plasma density. These observations align with the Magnetospheric-Ionospheric-Lithospheric Coupling (MILC) model [4]. Additionally, the Zirè payload focuses on detecting photons with energies from 0.1 MeV to several tens of MeVs, facilitating the study of transient events like GRBs, electromagnetic signals following gravitational wave events, supernova emissions, and steady gamma sources. The instrument aboard Zirè also opens up the possibility of investigating potential correlations between intense GRBs and their impact on local charged particles [5].The Zirè design is shown in Fig. 2. It is composed by (starting from the left):

- a Fiber TracKer (FTK): three X-Y modules with a total sensitive area 9.6×9.6 cm^2 for track reconstruction of charged particles. Each module is composed by two orthogonal layers of scintillating fibers read out by linear arrays of Silicon Photon Multipliers (SiPMs);
- a Plastic Scintillator Tower (PST): 32 layers X-Y modules made of scintillating tiles read out by two sets of SiPMs of different sensitive area used for particle identification;

- a calorimeter (CALOGs): a 4×4×2 matrix made by 2.5 cm × 2.5 cm × 3.0 cm Lutetiumyttrium oxyorthosilicate (LYSO) crystals read out by three sets of SiPMs of different sensitive area used for energy measurements of the incoming CR induced events and for the detection of low energy gamma-rays entering from two windows suitably placed on its sides;
- an ACS (Anti-Coincidence System): a VETO for a charged particle induced events made of plastic scintillator tiles and read out by SiPMs.

The line of sight of FTK, PST and CALOG will always be pointing towards the celestial horizon, with three entrance windows: one on the FTK side and the other two on the CALOG (one towards the horizon and the other towards the zenith, called H and V respectively). Preliminary Monte Carlo (MC) simulations of incoming electron and proton events have been done by using the Geant4 toolkit [6] to predict the detector performance. In the upper side of Fig. 3, a preliminary estimate of the effective acceptance for both protons and electrons are shown, obtained by selecting those events satisfying a trigger activation requirement based on the energy deposit together with the full containment request. Further MC simulations have been performed to generate 100k events of electrons, protons and helium nuclei with continuous energy spectrum from 2 MeV up to 500 MeV in order to study the particle identification capability of the Zirè module that is shown in the lower side of Fig. 3 by plotting the energy deposit inside the FTK+PS0 as a function of the inverse of the total energy deposition inside the whole detector; the sample separation is clearly observable.

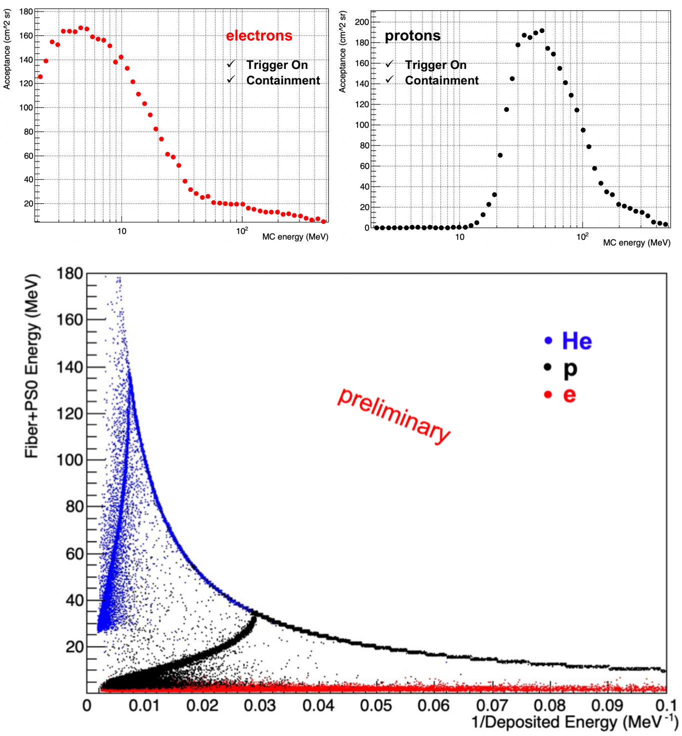

Figure 3: Upper panel: preliminary effective acceptance for protons (right) and electrons (left). Lower panel: total energy deposition inside the Fiber tracker and the first layer of the PST (PS0) as a function of the inverse of the energy deposited inside the full instrument.

Terzina is a telescope specifically designed for the detection of Cherenkov light emitted by extensive-air shower (EAS) induced by ultra high-energy CRs (UHECRs) and neutrinos in the Earth's atmosphere. At sufficiently high energy ($E > 1$ PeV), tau neutrinos and muon neutrinos passing through the Earth can produce τ and μ leptons, which can emerge by decaying or interacting in the atmosphere (Earth skimming events). As a result, Earth skimming neutrinos generate EAS moving in the atmosphere from bottom to top, similar to the EAS produced by charged particles (CR) impinging the atmosphere from above the Earth limb [7, 8]. The Cherenkov emission from these EAS can be detected by space-based instruments with high exposures [9, 10]. The telescope will operate inclined by 67.5° with respect to nadir, with the optical axis pointing towards the dark

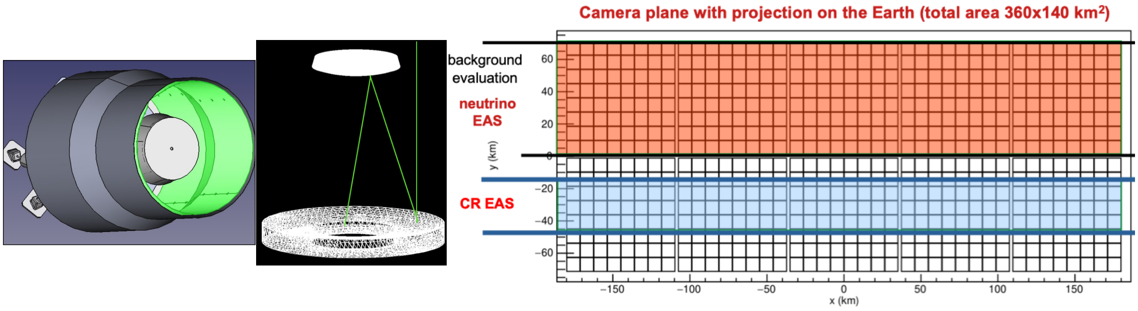

Figure 4: Left side: Terzina telescope with its outer baffle to protect from light and radiation and secondary mirror holder. Middle: detail of the two mirrors. Right side: the focal plane with two ros of 5 SiPM arrays of 8×8 pixels. The upper arrays ill be sensitive to the Earth and UHE neutrinos and the lower to the UHECRs produced in the Earth's atmosphere.

side of the Earth's limb, the expected duty cycle will be around 40%. The Terzina detector is composed by a near-UV-optical telescope, with a Schmidt-Cassegrain optics, and the Focal Plane Assembly (FPA) (see Fig. 4). The FPA, designed to detect photons from both below and above the limb, is composed of 10 SiPMs arrays of 8×8 pixels of 3×3 mm^2 each (640 pixels overall, see Fig. 4 right panel) with sensitive area of 2.73×2.34 mm^2. The upper row of 5 SiPM arrays [11] will observe events coming from below the Earth's limb (read area in right panel of Fig. 4), this part will perform a clear characterisation of the background and is unlikely to observe neutrino-induced EAS. On the other hand, the lower row of 5 SiPM arrays will observe events coming from EAS generate by CR from above the limb (blue area in the right panel of Fig. 4). To understand the telescope performance a dedicated simulation pipeline has been constructed. The Cherenkov emission as observed from a space based telescope in the case of above-the-limb EAS has been estimated by the EASCherSim computational framework. Given the geometry of the observation from the Terzina altitude and the characteristics of the atmosphere, Cherenkov emission can be observed from a tiny layer of the atmosphere with an angular size less than 1° (altitude above the limb from 20 km up to 50 km). Dedicated MC simulation of photon propagation to the telescope have been produced by implementing the design in Geant4 toolkit. The expected background for Terzina is composed by the Night Glow Background (NGB) of visible light and the background radiation of charged particles in the 100 keV -100 MeV energy range. The rate per pixel due to the NGB has been estimated using the formula: $R_{\text{pix}}^{\text{NGB}} = \eta \times \Delta\Omega \times \phi_{\text{NGB}} \times S \times PDE_{eff}$ where $S = 0.1$ m^2 is the collecting area of the telescope; $\Delta\Omega$ is the pixel viewing solid angle; PDE_{eff} is the total optical efficiency calculated from the convolution of the SiPM PDE and the NGB spectrum; ϕ_{NGB} is the total integrated NGB flux in the wavelengths range $\lambda = [300 - 1000]$ nm; $\eta = 6$ is a conservative safety factor considering the possible largest variation of the NGB flux. Moreover, the in-orbit background radiation produces a progressive sensor damage with an increasing Dark Current Rate (DCR) during the mission. For the camera the NUV-HD-MT SiPM produced by FBK [12, 13] with a DCR= 40 kHz/mm^2, after-pulsing AP= 5% and optical cross-talk CT~ 5% will be used. Given the SiPM choice we have simulated the background rate due to the NGB and DCR and we have produced the expected detector's aperture [2].

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