PROCEEDINGS OF SCIENCE

The NUSES space mission

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NUSES is a space mission promoted by the Gran Sasso Science Institute (GSSI) in collaboration with the Istituto Nazionale di Fisica Nucleare (INFN) and Thales Alenia Space Italy (TAS-I), devoted to the exploration of new technologies and observational approaches for space-based cosmic ray studies. The mission consists of two detectors operating onboard the NUSES satellite: TERZINA and ZIRÉ.

TERZINA is a pathfinder for Cherenkov telescope based missions for the study of Extensive Air Showers (EASs) induced by high energy Cosmic Rays and astrophysical Earth skimming neutrinos, with a focal plane made out of SiPMs. The innovative use of SiPMs will be exploited also for the ZIRÉ payload, mainly devoted to flux measurements of electrons, protons and light nuclei with kinetic energies spanning from few up to hundreds of MeVs, but also operating with a novel concept as cosmic MeV gamma ray detector. A further objective of ZIRÉ will be the study of space weather phenomena and possible correlations among seismic activity on ground and low energy electron and proton fluxes due to Magnetosphere-Ionosphere-Lithosphere Coupling (MILC). This contribution will present an overview about the scientific goals, the adopted technologies and the status of the ongoing activities for the payload development.

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1. Introduction

NUSES (NeUtrino and Seismic Electromagnetic Signals) is a space mission consisting of two experiments, ZIRÉ and TERZINA, which will independently explore different scientific fields of investigation, both exploiting innovative technologies to be developed and tested for future satellite-borne detectors. The concept of the NUSES project has been proposed by the Gran Sasso Science Institute (GSSI), collecting the interest and support from the Istituto Nazionale di Fisica Nucleare (INFN) together with many Institutes and Universities from Europe and abroad joining the activities. The NUSES Collaboration involves a strong industrial partnership with Thales Alenia Space Italy (TAS-I), engaged on the design and supply of the New Italian Micro BUS (NIMBUS), a ballistic platform for Low Earth Orbiting (LEO) microsatellites that will host the payloads, travelling at an altitude of 550 km with high inclination of 97.8° and orbiting in a Sun-Synchronous and dusk-dawn mode along the day/night boundary line.
ZIRÉ will detect low energy Cosmic Rays (CRs) [1][2], providing a precise measurement of the energy spectra for electrons, protons and light nuclei but also sheding a light upon a possible correlation between natural terrestrial phenomena and anomalies occurring in the magnetosphere and ionosphere as predicted by the MILC (Magnetospheric-Ionospheric-Lithospheric Coupling) theory [3]. Thanks to a dedicated optimization of its design, ZIRÉ will also allow the study of gamma rays in the energy range from several tens of keV up to tens of MeVs. The second module, TERZINA, will be a space-based Cherenkov telescope, testing and characterizing new strategies for the study of Ultra High Energy Cosmic Rays (UHECRs) and neutrino astronomy. In this work, a general introduction of the ZIRÉ and TERZINA purposes and preliminary design will be presented and discussed.

2. The ZIRÉ experiment

The ZIRÉ detector will be mainly devoted to flux measurements of low energy CRs with kinetic energies spanning from few up to few hundreds of MeVs. This specific study plays a role of crucial importance for several reasons. First of all, the measurement of low energy CR energy spectra is a key monitoring tool for solar activities, hence consequently for space weather phenomena caused by high intensity Solar Energy Particles (SEPs) and playing a dangerous role for orbiting objects and aviation missions [4][5]. Moreover, previous experiments on ground and with LEO satellites in the near-Earth space observed anomalies in the counting rates of low energy protons and electrons. These unexpected features in their fluxes must be better investigated in order to understand if they could reasonably entail a possible correlation with natural activities occurring on Earth, such as earthquakes or volcanic eruptions [6][7]. Furthermore, a more suitable probe of possible MILC signatures is the study of cosmic ray electrons with kinetic energies below 5 MeV, so an additional extension of the ZIRÉ instrument, the Low Energy Module (LEM), is being designed.
The design activities of the ZIRÉ payload are also addressed to its optimization for the detection of γ-rays in the energy range from 0.1 MeV to 10 MeV, allowing for the investigation of transient phenomena and steady γ-ray sources.
Together with the different scientific objectives, a technological challenge motivates the NUSES mission. In particular, both the ZIRÈ and TERZINA instruments will exploit a full Silicon Photo-

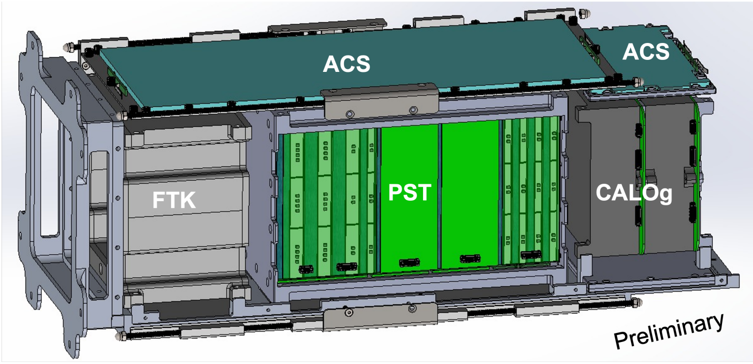

Figure 1: Preliminary mechanical design of the ZIRÉ payload. The experiment will target charged particles entering from the top of the FTK and gamma-rays entering from the side of the CALOg.

Multiplier (SiPM) technology for the readout system using sensors with different characteristics.

A preliminary design of the ZIRÈ module, shown in Fig. 1, is currently under optimization and it consists of:

- **Fiber TracKer (FTK)**: three X-Y modules with 9.6 cm × 9.6 cm of sensitive surface for track reconstruction of charged particles. Each module is composed by two orthogonal layers of scintillating fibers with 750 μm of diameter and a double-layer structure. Each fiber is made by a polystyrene core (inner side) with a fluorescent agent (n=1.59), an inner cladding of Polymethylmethacrylate (PMMA) (n=1.49) and an outer cladding of fluorinated polymer (n=1.42).

- **Plastic Scintillator Tower (PST)**: 32 layers, each one consisting of three Plastic Scintillator (PS) bars, used for particle identification. The first six layers of the PST, namely the ones below the FTK, are of 12 cm × 12 cm × 1 cm, while the other 26 layers have dimensions of 12 cm × 12 cm × 0.5 cm. In order to enhance the track reconstruction, adjacent layers have orthogonal bars following the X-Y coordinate scheme.

- **CALOrimeter-gamma (CALOg)**: 32 optically independent LYSO (Lutetium-yttrium oxy-orthosilicate) scintillating crystals arranged in two layers with 4x4 matrices of LYSO boxes with dimension 2.5 cm × 2.5 cm × 3.0 cm. The CALOg is used for energy measurements of the incoming CR induced events but also for the detection of γ-rays in the 0.1 MeV - 10 MeV energy range entering from two windows suitably placed on the side of the CALOg.

- **AntiCoincidence System (ACS)**: 9 plastic scintillator tiles with 0.5 cm of thickness surrounding the lateral sides of the instrument and the bottom side of the CALOg. The main purpose of the ACS is to provide a veto system for side or not fully contained events of incoming charged particles.

The above-described design of the ZIRÉ module has been adopted for preliminary Monte Carlo (MC) simulations carried out with the help of the GEANT4 toolkit [8] in order to assess the instrument performances. The left side of Fig. 2 shows the current GEANT4 geometry of

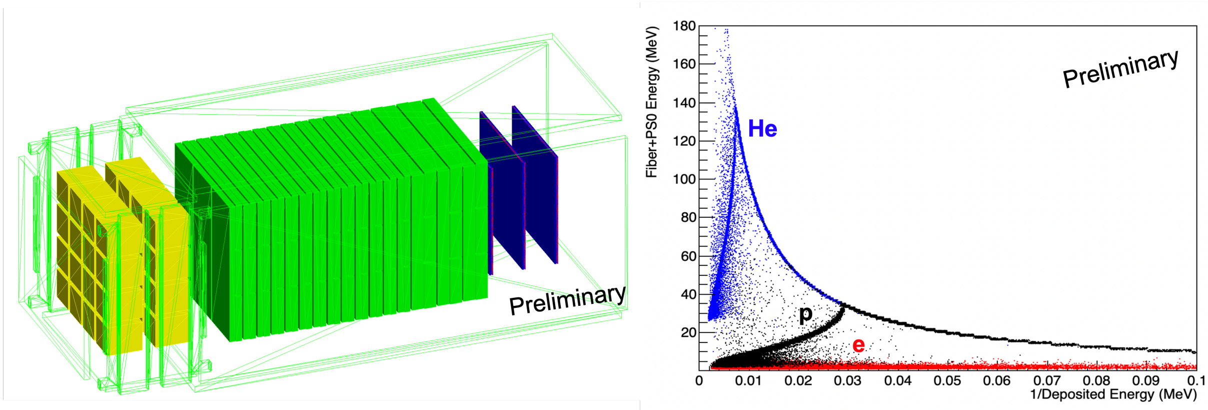

Figure 2: (Left) Preliminary GEANT4 design of the ZIRÈ geometry. (Right) Total energy deposit inside the FTK and the first layer of the PST (PS0) as a function of the inverse of the full energy deposited inside the whole detector for contained simulated events of electrons (in red), protons (in black) and helium nuclei (in blue).

ZIRÉ, where the FTK is depicted in blue, the PST in green, the CALOg in yellow and the ACS layers are represented only by their green edges. Monte Carlo simulations of primary electron, proton and helium events have been generated from 2 MeV up to 500 MeV of kinetic energy. A preliminary estimation of the particle discrimination capability, shown on the right side of Fig. 2, with the current design of the module has been obtained by applying a trigger activation requirement consisting of an energy deposit greater than 0.1 MeV and 0.3 MeV in the FTK and the first PST layer respectively, together with a full containment request for the simulated events. Further MC simulation activities are currently on-going for the study of different geometries and particle generation features, fundamental for the optimization of the detector design together with its geometrical acceptance, mechanical structure, weight and power consumption. Moreover, the digitization procedure is currently being implemented in the simulation software in order to take into account the details of the electronic read-out system (dynamic range, energy thresholds, etc...).

3. The TERZINA experiment

The TERZINA module is meant for testing challenging observational approaches and innovative technologies paving the path for future satellite-borne detectors devoted to the study of Ultra High Energy Cosmic Rays (UHECRs), namely with energies above 100 PeV, and cosmogenic tau neutrinos. A measurement of the energy spectrum of high energy astrophysical neutrinos has been provided by the IceCube experiment [9] in the energy range from 25 TeV up to few PeVs, while for higher energies the neutrino flux and so the detection power of ground-based experiments become pretty low. Hence, a possible way to gain access to this mostly unexplored domain is the use of detectors in space. One of the main projects born to reach this goal is the POEMMA [10] space mission, a Cherenkov Telescope in space looking for Cherenkov light emission signals produced by upward-going tau neutrino decays and a full-sky explorer for UHECRs, significantly improving the effective area (hence the statistics) at the highest energies.
In this framework, the key role of TERZINA is to operate as a pathfinder for next generation exper-

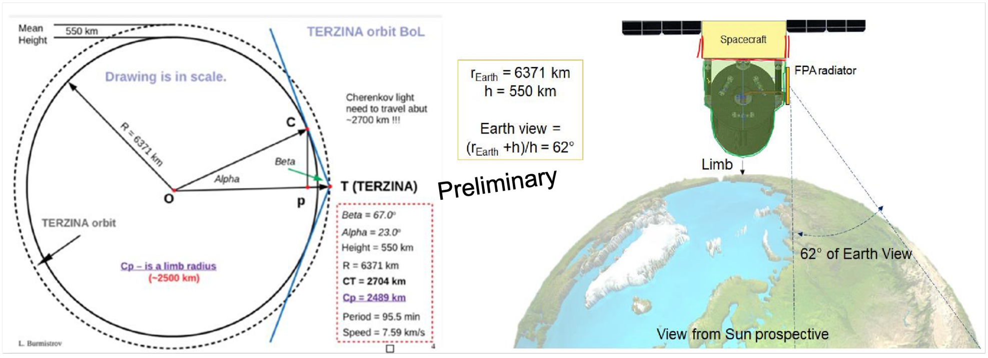

Figure 3: (Left) Detector principle of Terzina. (Right) Position of the Terzina detector on-board the NUSES satellite in space looking towards the limb.

iments, such as POEMMA. In particular, TERZINA will be a Cherenkov telescope in space and it will provide a full characterization of the background conditions above the limb for the detection of UHECRs and Earth skimming events but also a first detection in space of showers generated by UHECRs with energies greater than 100 PeV and resulting in Cherenkov light emission [11][12]. At the same time, TERZINA will also perform a technological test and validation of a full SiPM-based technology in space. The detector principle of Terzina is illustrated in Fig. 3.

A preliminary optical design of the TERZINA telescope is shown in Fig. 4, consisting of:

- **Primary mirror**: oblate spheroidal geometry characterized by a diameter of 0.39 m and a radius of curvature (RoC) of ∼ 0.8 m:
- **Secondary mirror**: oblate spheroidal geometry with a 0.14 m diameter and ∼ 0.36 m of RoC ;
- **Focal surface**: SiPM multi-pixel detector;
- **Corrector**: a PMMA made planar surface correcting incident photon angles.

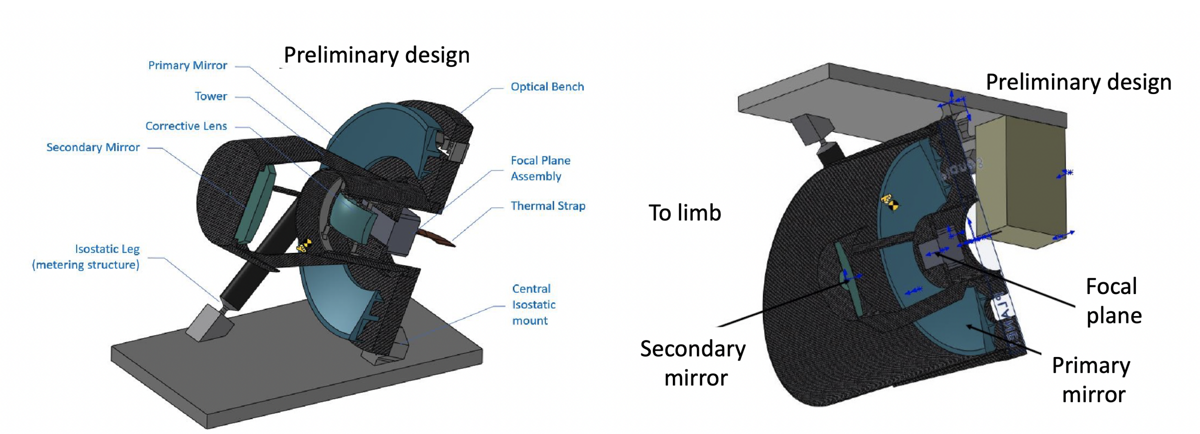

Figure 4: Preliminary optical design of the TERZINA telescope.

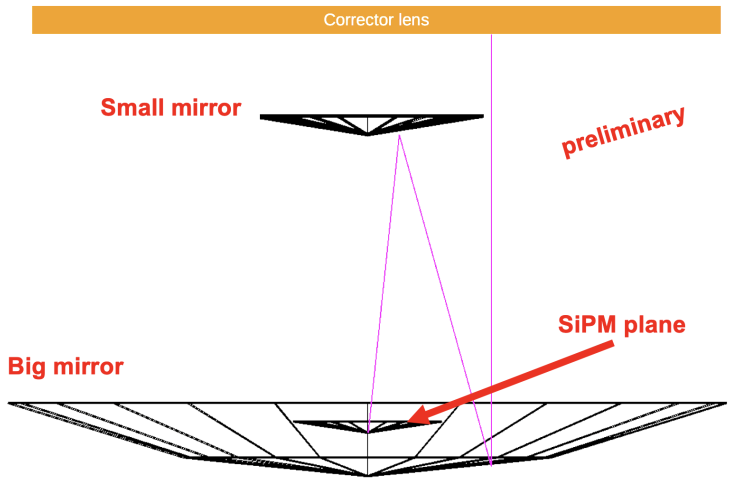

Figure 5: Preliminary simulation of TERZINA optics performed with the GEANT4 toolkit.

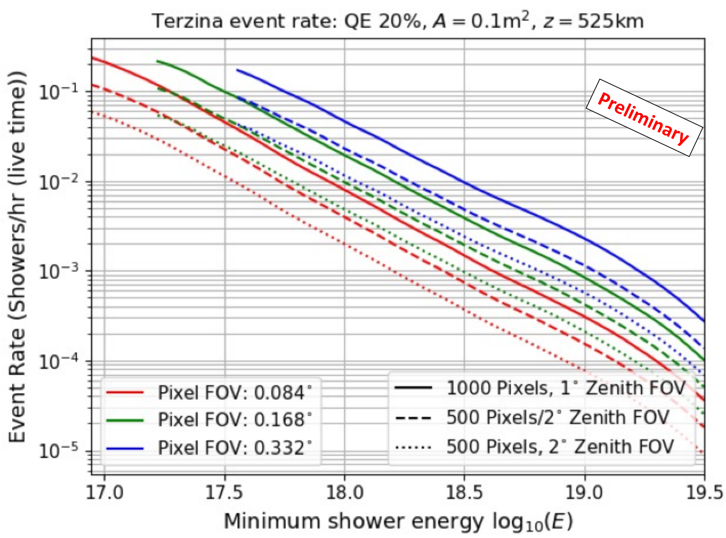

Figure 6: Preliminary estimate of the event rate per hour of live time for above-the-limb UHECR induced events as a function of threshold energy for a TERZINA telescope at the orbit altitude of 525 km with a mirror surface of 0.1 m^2 and by considering several pixel field of views and configurations.

Fig. 5 shows the preliminary geometry adopted for GEANT4 simulations performed in order to obtain a first estimate of the expected event rate per hour of live time as a function of energy for above-the-limb UHECR simulated events, shown in Fig. 6. This has been obtained by considering a 0.1 m^2 mirror optics and an orbit altitude of 525 km. Many activities are presently in progress for the full optimization of the final optical design and a more precise estimation of the energy threshold and event rate for UHECRs. As previously mentioned, the adopted technology for the projection plane of TERZINA is fully SiPM-based, exploiting the best features of this choice, such as high performances for single photon detection capability, small dimensions and low power consumption. Further technological developments include a low-power 64-channel ASIC for the readout of a matrix of SiPMs. The chip is designed in 65 nm cmOS technology with a power supply of 1.2 V and 200 MHz clock frequency.

4. Conclusions and Outlooks

The main mission goal of the NUSES project is to give an important contribution in the development and qualification of new technologies and in the validation of innovative observational strategies for experiments in space. The two modules onboard the satellite, ZIRÉ and TERZINA, will operate looking for different scientific targets, both testing a full and innovative SiPM-based technology also using sensors with different characteristics. The activities for the final optimization of the payload design are currently ongoing.

5. Acknowledgments

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