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 Thales Alenia Space and the Italian National Institute for Nuclear Physics (INFN). NUSES will be a technological pathfinder for the development and test of innovative technologies and observational strategies for future missions aiming at investigating cosmic radiation, astrophysical neutrinos, the Sun-Earth environment, space weather and magnetosphere-ionosphere-lithosphere coupling (MILC).

The NUSES satellite will host two payloads, TERZINA and ZIRÉ. The first one, TERZINA, consists of a compact optical instrument equipped with a Cherenkov telescope based on the use of state-of-art of Silicon Photomultipliers (SiPMs). TERZINA will characterize the Cherenkov signature of high energy proton-induced background and therefore it will be instrumental for future missions for the detection of astrophysical earth-skimming neutrinos. The second payload, ZIRÉ, will be tailored to provide high precision measurements of the flux intensity of electrons, protons and light Cosmic Ray nuclei up to hundreds of MeV and of gamma-rays in the 0.1 MeV - 10 MeV energy range. ZIRÉ will be also capable of pinpointing possible MILC events by measuring the charged particle flux.

In this paper we report the overall description of the instruments onboard the NUSES satellite along with the scientific and technological objectives of the mission.

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1. Introduction

The NeUtrino and Seismic Electromagnetic Signals (NUSES) satellite will operate on a polar Sun-Synchronous Low Earth Orbit (LEO) at an altitude of 550 km, 97.8° inclination, along the day/night boundary line. The mission has the main purpose of developing new technological and observation strategies for the measurement of the low energy cosmic ray component [1, 2], together with the characterization of the Sun-Earth system [3], the investigation of the magnetosphere-ionosphere-lithosphere coupling (MILC)[4] and the characterization of high energy proton-induced background critical for the detection of astrophysical neutrinos [5] by future missions.

The satellite will host two payloads: ZIRÉ and TERZINA. ZIRÉ is a particle detector that will be sensitive to electrons, protons and light cosmic ray nuclei at few MeV up to hundreds of MeV of kinetic energy. It will also perform the detection of MeV photons and the measurement of MILC signals by studying charged particle flux variations. TERZINA is a Cherenkov telescope that will characterize the high energy proton-induced background by measuring the light emissions from the Earth limb in the near UV and visible ranges at nanosecond time scale, thus testing the observational concept of detecting Earth-skimming astrophysical high energy neutrinos [6].

The light detection in NUSES has been conceived to be solely performed by means of Silicon Photo Multiplier (SiPM) and thus NUSES is expected to set the benchmark for space-borne particle detectors based on the SiPM technology.

In the following sections, the detection concept of both payloads will be discussed along with the current mechanical configuration of the instruments. Preliminary studies based on GEANT4 simulations will be also presented and the expected payload performances discussed.

2. The ZIRÉ payload of the NUSES mission

The main task of ZIRÉ is to provide a measurement of the energy spectra of Cosmic Rays (CRs) with kinetic energies up to hundreds of MeVs. This specific investigation goal is deeply connected to the observations provided by previous experiments onboard satellite operating at Low Earth Orbits (LEO): pinpointing anomalies in the counting rates of low energy electrons and protons precipitating from the lower boundary of the inner Van Allen Belts (VABs) as linked to geophysical phenomena, such as earthquakes or volcanic eruptions [7][8].

The properties of low energy CRs are affected by the solar activity: the measurement of such low energy component could be the key probe for monitoring the high intensity Solar Energy Particles (SEPs). Hence, space weather observatories would profit from the capability of monitoring the intensity of SEPs and their spatial distribution, minimizing the irradiation risks to manned (or even unmanned) space missions [9][10].

ZIRÉ will also test innovative detection techniques for γ-rays in the energy range 0.1 MeV - 10 MeV, allowing for the investigation of transient phenomena and steady astrophysical γ-sources.

The ZIRÉ experiment comprises five main sub-detectors:

- **Fiber TracKer (FTK)**. The FTK is composed of three modules, each one made out of two orthogonal layers containing 256 scintillating fibers, 9.6 cm long and of 750 μm of diameter, and organized in two staggered rows (128 scintillating fibres each). In such configuration, each FTK module has a sensitive area of about 9.6 cm × 9.6 cm. The FTK main task is to finely reconstruct the track of crossing charged particles in the X-Y coordinates.

- **Plastic Scintillator Tower (PST)**. The PST is made out of 32 layers, each one containing three plastic scintillator bars. The first six layers are of 12 cm × 12 cm × 1 cm dimensions, while the others are 12 cm × 12 cm × 0.5 cm). A layer is composed of three plastic scintillator bars. In order to provide with the X-Y coordinates, adjacent layers have orthogonal plastic scintillator bars. The PST is instrumental to the particle identification in Z (Atomic Number).

- **Gamma calorimeter (CALOg)**. The CALOg consists of 32 optically independent LYSO scintillating crystals (GAGG(Ce) as possible alternative is under consideration) arranged in two detection matrices. Each scintillating unit has a volume of 2.5 cm × 2.5 cm × 3.0 cm. The CALOg is used to measure the energy released by a fully contained charged particle induced event and to detect γ-rays in the 0.1 MeV - 10 MeV energy range.

- **AntiCoincidence System (ACS)**. The ACS consists of 9 plastic scintillator tiles (0.5 cm thick) surrounding on five sides the assembly composed by the FTK, PST and CALOg (the FTK requires one unobstructed view to be operated). The ACS is used to suppress charged particles induced background and to remove partially contained events from the sample.

- **Low Energy Module (LEM)**. The LEM consists of a core of 32 PIPS (Passivated Implanted Planar Silicon) detectors organised in two matrices and surrounded by a aluminum mask containing a scintillating collimator to resolve the direction of the impinging particle. The LEM, that will be installed on one ACS layer, has dimensions of 10 cm × 10 cm × 5 cm. The LEM main task is to track and detect low energy electrons (down to few hundreds of keV) in order to enhance the discover capability of MILC signatures.

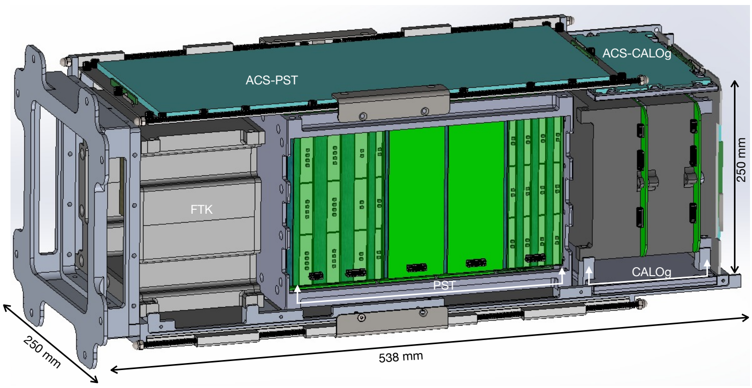

Figure 1: The mechanical layout and dimensions of the ZIRÉ payload with the different subsystems labelled in the picture. The experiment will target charged particles entering from the unobstructed view of the FTK (left side) and gamma-rays entering the CALOg (right side).

The present geometry of the detector has been tailored around the physics requirements by means of simulations carried out with GEANT4 toolkit [11]. Samples with different primary particles (protons, electrons, gamma-rays, low-Z nuclei), with different primary kinetic energies,

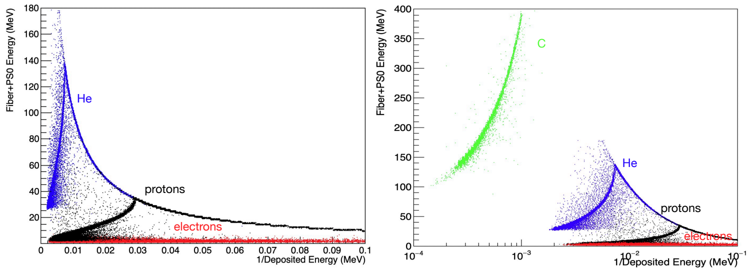

Figure 2: (Left) Total energy deposit inside the FTK and the first layer of the PST (PS0) as a function of the inverse of the full energy deposited inside the whole detector for contained simulated events of electrons (in red), protons (in black) and helium (in blue). (Right) A carbon sample (in green) has been simulated in order to check the eventual discrimination power of the ZIRÉ detector for heavier nuclei.

have been generated and analysed. In particular, primary electron, proton and helium events have been generated from 2 MeV up to 500 MeV of primary energy, while the range 1 GeV – 100 GeV has been chosen for carbon. After applying a trigger activation requirement (energy deposit in the full FTK and in the first layer of the PST larger than 0.1 MeV and 0.3 MeV respectively) together with a strict containment request for the simulated events (energy deposit in the ACS must be less than 1 MeV), a preliminary study of the particle identification power has been obtained. In Fig. 2, it is apparent that all the different samples appear clearly separated. Simulations are currently on-going to help finalizing the ZIRÉ design optimizing its geometrical acceptance and performance within the mechanical, mass and power consumption constraints. The digitization procedure with the details of the electronic read-out system (dynamic range, energy thresholds, etc...) is currently being implemented in the simulation framework.

3. The TERZINA payload of the NUSES mission

Neutrinos can travel almost undisturbed bringing information about their original production sources therefore providing useful insights for High Energy Astroparticle observations. When neutrinos are jointly detected with other probes such as γ-ray or Gravitational Wave (GW) signals, a multi-messenger approach is enabled [12] .

The energy spectrum of high energy astrophysical neutrinos has been measured by the IceCube experiment [13] in the 25 TeV up to few PeVs energy range, revealing to be consistent with a power-law. At higher energies (larger than 10 PeV), the neutrino flux intensity becomes pretty much undetectable by current ground-based observatories.

In order to overcame this limitation, an innovative and challenging approach consists on the use of telescopes in space. One of the main projects is POEMMA [14], a space mission that will host a Cherenkov Telescope pointing at the dark side of the Earth's limb and looking for the Cherenkov signature produced by Upgoing Air Showers (UASs) generated by the interaction of high-energy Earth-skimming neutrinos with the terrestrial crust. POEMMA will be sensitive to neutrinos with energies up to few tens of EeV, therefore opening up for new and unprecedented measurements.

The TERZINA experiment onboard the NUSES space mission is therefore the first explorer in this research domain and the technological pathfinder for the development of new observational

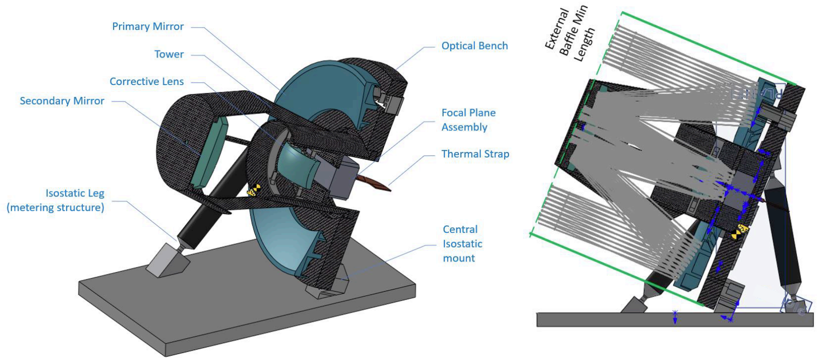

Figure 3: (*Left*) Schematic view of the preliminary design for the TERZINA optics. (*Right*) The optical detection concept of the TERZINA instrument.

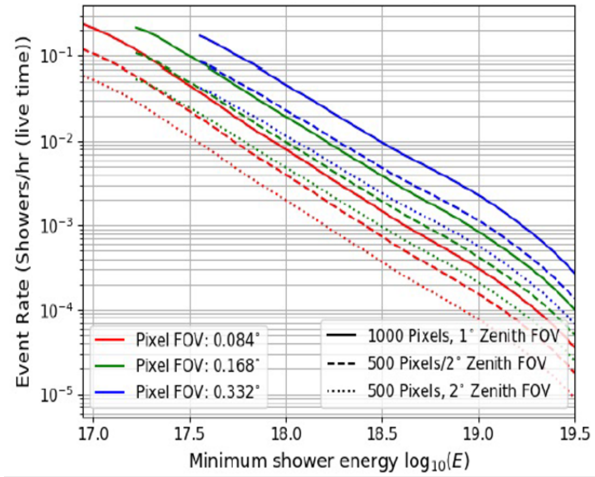

Figure 4: Estimated event rate per hour of live time of above-the-limb UHECR induced events as a function of threshold energy for a TERZINA mirror optics with 0.1 m^2 of surface and for different pixel field of views and configurations (adopted orbit altitude of 525 km).

strategies. The main scientific target of TERZINA, the first space-born Cherenkov Telescope designed for Space, is to characterize the background that affects the observation of astrophysical neutrinos by means of a Cherenkov telescope, at energies higher than 100 PeV.

The optical axis of the TERZINA telescope will point to the Earth's limb, where Ultra High Energy Cosmic Rays (UHECRs) can produce Extensive Air Showers (EAS) into the atmosphere, so that it will be possible to test the detection technique of τ neutrinos which, as discussed above, produce UAS resulting in Cherenkov light emission. A preliminary optical design is shown in Fig. 3. A simulation of this geometry, although without the Corrector lenses, has been performed by exploiting the GEANT4 toolkit [11], and it is shown on the right side of Fig. 3. Fig. 4 shows the estimated event rate per hour of live time of above-the-limb UHECR simulated events as a function of energy, resulting by adopting the mirror optics with a surface of 0.1 m^2.

The TERZINA innovative feature is the SiPM-based technology used for the projection plane. Compactness, low power consumption, together with the excellent single photon detection capability made the SiPM technology the ideal candidate for the instrumentation of the TERZINA Cherenkov telescope. 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 NUSES project will be the test bench of breaking through technologies for space applications. An innovative full SiPM technology using sensors with different characteristics, will be operated in space (both in ZIRÉ and TERZINA). New observational approaches for future space missions such as MILC signal hunters or observatories for high energy astrophysical neutrino signals will be tested.

5. Acknowledgments

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