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The light tracker based on scintillating fibers with SiPM readout of the Zirè instrument on board the NUSES space mission

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NUSES is a low Earth orbit pathfinder satellite for innovative particle detectors dedicated to the study of cosmic radiation, astrophysical neutrinos, Sun-Earth environment, space weather and magnetosphere-ionosphere-lithosphere coupling. The satellite will host two instruments: Terzina and Zirè. While Terzina will focus on space based detection of ultra high energy extensive air showers, Zirè will perform measurements of electrons, protons and light nuclei from few up to hundreds MeV, also testing new tools for the detection of cosmic MeV photons, and monitoring possible MILC signals. Zirè will consists of a scintillating fiber tracker, a stack of plastic scintillator counters and an array of LYSO crystals. An active veto system and a Low Energy Module (LEM) are also part of the payload. In this work we present the design of a novel tracker prototype based on plastic scintillating fibers coupled with SiPM linear arrays. The preliminary results obtained in a beam test with the prototype module will be discussed.

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1. Introduction

NUSES (NeUtrino and Seismic Electromagnetic Signals) is a joint project between Gran Sasso Science Institute (GSSI) and Thales Alenia Space Italy (TAS-I), in strong collaboration with the Italian National Institute of Nuclear Physics (INFN) and several international Universities. The mission is conceived as a technological pathfinder to study high and low energy radiations, using new observation methods and new technological solutions for the satellite platform. The NUSES proposal has been approved by the Italian government as a flagship initiative and, recently, by the Italian Space Agency (ASI) as a new space mission [1].

The mission scientific goals include the study of low-energy cosmic radiation through low-energy cosmic rays (CRs) and gamma rays (GRs), the study of showers induced by ultra-high energy (UHE) CRs and neutrinos via Cherenkov light emission at the top of the atmosphere, detected at the satellite orbit altitude.

NUSES will reside in a Sun-synchronous low Earth orbit (LEO) at an altitude of about 500 km, and at an inclination of 97.8°. The orbit will lie in the day-night border with the local time of the ascending node (LTAN) at 18:00:00. The scientific payloads will be hosted onboard the NIMBUS (New Italian Micro BUS) platform, developed by Thales Alenia Space. The NUSES experiment is composed of two main sub-detectors called Terzina and Zirè.

Terzina is a new concept of optical telescope for the detection of high-energy neutrinos and CRs, which combines space-based atmospheric Cherenkov light detection and SiPM (Silicon Photomultiplier) technology. Thanks to the NUSES orbit attitude, the Terzina field of view will point to the dark side of the Earth's limb, looking for Cherenkov light emissions from UHE CRs or neutrinos. For more details see [2] and ref. [3] in these proceedings.

Zirè is dedicated to the measurement of the fluxes of cosmic-ray electrons, protons and light nuclei with energies up to hundreds of MeV, but also operates as a gamma-ray telescope in the MeV energy range. Further objectives include the study of space weather and the search for possible correlations of the electron and proton fluxes with seismic activities through the magnetosphere-ionosphere-lithosphere coupling (MILC) effects [4]. For more details see ref. [5] in these proceedings. In this work we present the design of a novel tracker prototype based on thin plastic scintillating fibers for the Zirè instrument.

2. The NUSES Zirè instrument

The Zirè instrument consists of a system of several sub-detectors: a new light tracker (FTK) equipped with thin scintillating fibers; a stack of plastic scintillator bars (PST); a compact calorimeter of LYSO cubic crystals (CALOg). The line of sight of FTK, PST and CALOg is always towards the celestial horizon, with three entrance windows: one on the FTK side and the other two on the CALOg. A set of scintillator tiles (ACS) surrounds these three detectors on their five sides, except the FTK window entrance. The ACS system, together with FTK and the first PST planes, operate as anticoincidence for the gamma-ray events. In this way, the Zirè design allows to identify gamma rays in the energy range from 0.1 to 10 MeV, allowing the investigation of transient phenomena and steady gamma-ray sources as well (see ref. [5] in these proceedings). The common read-out system of these detectors is based on silicon SiPM sensors.

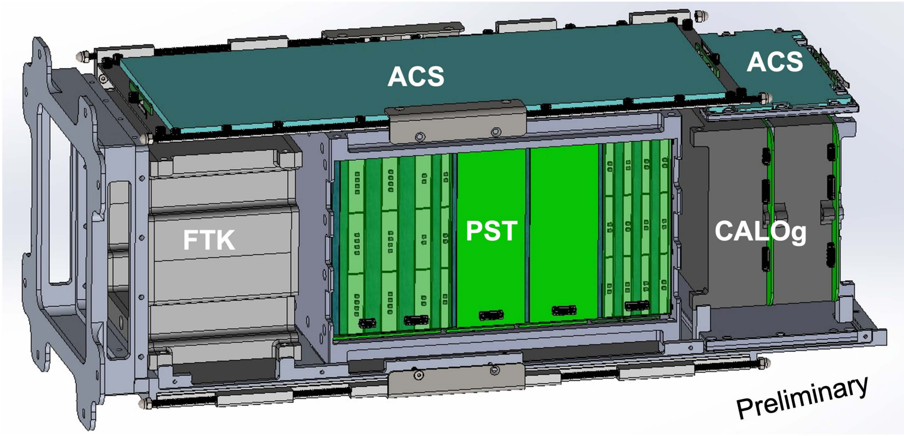

Figure 1: Preliminary mechanical design of the Zirè instrument (the LEM detector is not shown). The experiment will target charged particles entering from the FTK side and gamma-rays mainly entering from the side of the CALOg.

A compact detector, called Low Energy Module (LEM), will be also placed next to Zirè. The LEM is designed to detect electrons from hundreds keV up to 5 MeV with the center of its field of view along the zenith direction (see ref. [6] in these proceedings).

Figure 1 illustrates the current design of the Zirè instrument, which consists of:

- Fiber TracKer (FTK): three X-Y modules with a sensitive area of 9.6 cm × 9.6 cm for track reconstruction of charged particles;
- Plastic Scintillator Tower (PST): 32 layers with an active area of 12 cm × 12 cm, each one composed by three plastic scintillator bars of 4 cm × 12 cm cross section, used for particle identification. Adjacent layers consist of orthogonal bars in a hodoscopic configuration. The first six layers of the PST, namely those close to the FTK, are 1 cm thick, while the other 26 layers are 0.5 cm thick;
- CALOrimeter-gamma (CALOg): 32 optically independent LYSO (Lutetium-Yttrium oxy-orthosilicate) scintillating crystals arranged in two layers with 4 × 4 matrices of crystal cubes of 2.5 cm × 2.5 cm × 3.0 cm. The CALOg is used for energy measurements of the incoming CR induced events and for the detection of gamma-rays in the 0.1 MeV - 10 MeV energy range entering from two windows suitably placed on its sides;
- AntiCoincidence System (ACS): 9 plastic scintillator tiles, with 0.5 cm thickness, surrounding the 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 incoming charged particles.

3. The Zirè FTK

Figure 2 shows an artist view of the three FTK modules. Each one consists of two orthogonal ribbons, composed by two layers of round Kuraray SCSF-78MJ [7] fibers with 750 μm diameter in a

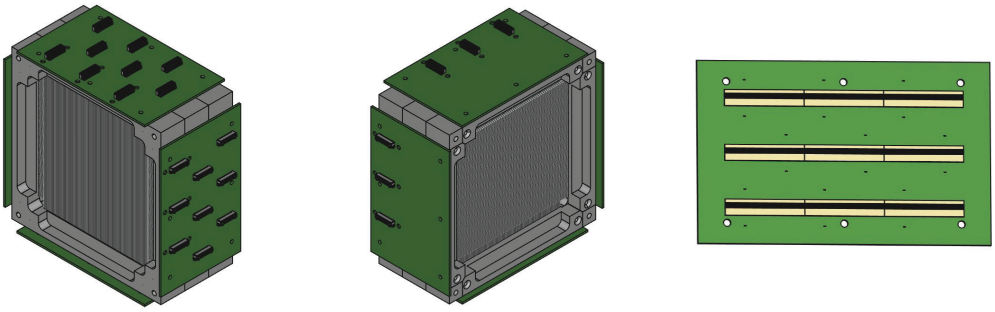

Figure 2: Artist view of the FTK detector. The fibers are oriented along two orthogonal directions. The PWBs are located on the four sides with their SiPM arrays (right panel). The first two modules are equipped with SiPM sensors on one fiber end (left panel), while the third inner FTK module is equipped with additional SiPM sensors on the opposite side (middle panel). The LSHM-120 connectors routing the SiPM analog signals to the front-end board located far away by means of high speed 50 Ohm multi-channels HLCD SAMTEC cables are also visible.

Figure 3: A FTK module without (left panel) and with (right panel) PWBs.

staggered configuration. The fibers are made of a polystyrene core with a fluorescent agent (n=1.59), surrounded by a double cladding structure; the inner cladding is made of polymethyl-methacrylate (PMMA) (n=1.49), while the outer cladding is made of a fluorinated polymer (n=1.42). The double cladding is adopted to enhance the scintillation light trapping efficiency, which is of about 5.4%, given that light propagates in the fiber via total internal reflections.

Incident charged particles release an ionization energy deposit in the fiber, which is converted to optical photons (the light yield is about 8000 photons/MeV or more), which are transported by internal reflections to the light sensors located at the end of the fibers. We have used the Hamamatsu 128 channels SiPM arrays S13552 [8] developed for the LHCb SciFi tracker [9], consisting of two 64-channels SiPMs separated by 0.22 mm. Individual cells have a size of 57.5 μm $\times$ 62.5 μm, and are arranged in columns of 4 $\times$ 26 pixels, resulting in a channel area of 0.23 mm $\times$ 1.62 mm and a pitch of 0.25 mm. The SiPM array is soldered on one side of a printed wiring board (PWB), and all channels are routed to four LSHM-120 Samtec multi-channel connectors [10] assembled on the other side of the PWB. To reduce the number of electronic channels, an equivalent read-out pitch of 1 mm can be obtained by OR-ing groups of 4 adjacent SiPM strips. In this way each

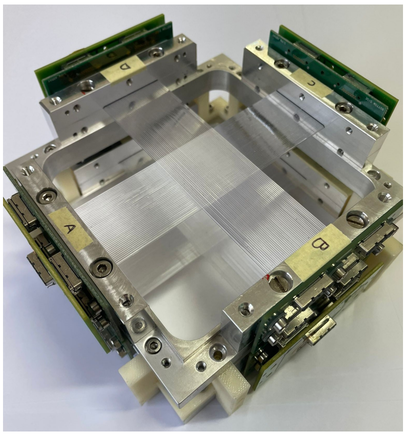

Figure 4: Two X-Y modules tracker prototype: the upper module is equipped with 500 μm fiber diameter, while the lower module is equipped with 750 μm fiber diameters.

of the LSHM-120 connectors can read-out one 128-channel S13552 sensor, routing the 32 SiPM analog signals to the front-end board (FEB) located far away by means of high speed 50 Ohm multi-channels HLCD SAMTEC cables [11]. The FTK PWB will also host temperature sensors to monitor the SiPM status.

The first two FTK modules are equipped with the SiPM sensors just on one fiber end view, while the third inner FTK module (the one close to the PST) is equipped with additional SiPM sensors on the opposite side for each view. In this way, it is possible to enable a trigger configuration in which the coincidences between 2 corresponding adjacent left/right channels are requested.

The FTK read-out board will consist of four FEBs, each hosting six CITIROC 1A front-end ASICs [12], an anolog-to-digital chip and a FPGA for local CPU processing. The boards will be connected with a motherboard with a proper FPGA to manage the data acquisition system.

4. The fiber tracker prototype

The design of the Zirè FTK detector is based on detailed studies performed on a reduced scale X-Y module [13, 14]. Each module is equipped with two planes (views) of fibers oriented along two orthogonal directions (X-view and Y-view). Each view consists of two staggered layers (ribbons) of round scintillating fibers, coupled with a Hamamatsu S13552 SiPM arrays placed at their ends. The width of each layer is about 3.25 cm, to match the size of the SiPM array. We have used fibers of different diameters, i.e. 500 μm and 750 μm, and we have implemented configurations with different read-out pitches for the SiPM strips. A picture of the 2-modules prototype is shown in Fig. 4.

The SiPM array is soldered on one side of a PWB, and all channels are routed to four LSHM-120 Samtec multi-channel connectors assembled on the other side of the PWB. Even and odd SiPM strip channels are routed to different connectors, i.e. two bottom (top) connectors for the 64 even (odd) channels.

To implement configurations with different read-out pitches, we have designed PWB interfaces with four LSHM-120 Samtec connectors on one side, to match those on the back side of the SiPM array PWB, and two (or one) LSHM-120 Samtec connectors on the other side. In this way we are able to group sets of two or four adjacent SiPM strips. We have tested configurations corresponding to the original pitch of 250 μm and to larger pitches of 500 μm and 1 mm. Hereafter we will refer to these configurations as OR-1, OR-2 and OR-4, respectively.

A custom FEB has been used for the prototype. The FEB hosts four PETIROC 2A ASICs [15], a CAEN A7585D SiPM voltage module [16] and a Kintex-7 FPGA mounted on a Mercury+ KX2 module [17] to configure the ASICs, the trigger and the data acquisition (DAQ). The FEB is connected to a PC with a TCP interface. The DAQ is based on a custom C++ software code [18]. Different NIM logic I/O signals are used on the FEB to route the ASIC output or to accept external signals, as for example an external trigger. The programmable trigger logic allows the user to choose among different trigger configurations: random trigger for pedestal measurements; single channel trigger; coincidence of two or four ASICs; coincidence of any two consecutive SiPM channels; external trigger.

The PETIROC 2A ASIC combines a very fast and low-jitter trigger with accurate charge and time measurements. Energy and time are digitized internally to the ASIC with a 10-bit ADC and 40 ps-bin TDC. The PETIROC 2A chip also includes a 8-bit DAC for each channel to trim the high voltage applied to each input SiPM. The DAC is controlled through the configuration changing the bias voltage from 1 V (DAC code = 0) to 2 V (DAC code = 255). Thanks to the timing capabilities of PETIROC 2A, we are able to measure the the arrival time of scintillating photons.

We used a low-activity ^{90}Sr source, emitting electrons with energies up to 2.2 MeV to test the tracker prototype in our laboratory and characterize its response with different readout strip pitches. The source was placed on a 2 mm diameter collimator, located on the top of a fiber tracker module. The S13552 SiPM arrays exhibit a breakdown voltage of about 51.5 V at 25°C. In the present work they have been operated at room temperature, with an overvoltage starting from 4.5 V up to 5.0 V.

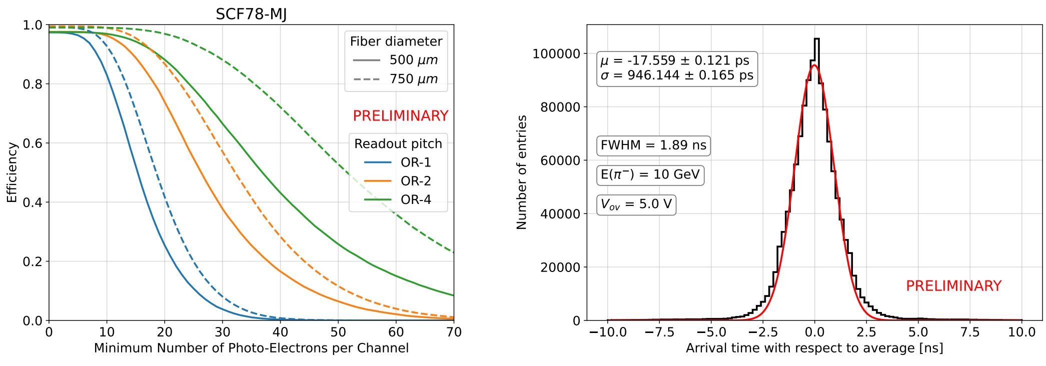

Figure 5: Left panel: Efficiencies as a function of the minimum number of photoelectrons per read-out channel. Right panel: distribution of the arrival times with respect to the average value obtained in a 10 GeV pion beam test.

To evaluate the efficiency of the prototype we read out the signals from both ends. The strips at one end, readout with OR-1 mask, are used for the trigger configuration by requiring the coincidence of two adjacent channels. We have then studied the response of the strips at the other end to evaluate the performance of the prototype [19]. The left panel of Fig. 5 shows the efficiency as a function of the minimum number of photo-electrons collected per read-out channel. Comparing the different fibers, we see that the 750 μm diameter fibers allow to collect a larger number of photo-electrons than the 500 μm diameter ones, as expected. We also see that the efficiency increases when grouping 2 or even 4 strips in the readout. Similar results have been obtained in a beam test with a 10 GeV/c pion beam. In addition, we have also measured the arrival time distribution of photo-electrons. The right-panel of Fig. 5 shows the distribution of the arrival times with respect to the average value obtained in the beam test. The arrival times are within a few ns consistent with the scintillator decay time of 2.8 ns.

5. Conclusions

The light fiber tracker (FTK) detector to be installed on the NUSES satellite mission is in construction and testing phase. It consists of three X-Y modules with an energy threshold of about few MeV. Several prototypes have been assembled and tested in the INFN-Bari laboratories and with particle beams at the CERN-PS.

The number of photo-electrons per channel collected with the 750 μm fibers is about 50 for a charged particle crossing the module perpendicularly to the fiber planes. The arrival distribution of the scintillating photons is within 1.89 ns FWHM, thus allowing to set a narrow coincidence window for the trigger coincidence to reduce the dark noise false coincidences even at the level of a single FTK view.

Following the results obtained with the single detector prototypes, a reduced scale prototype of Zirè has been designed. A full 10 × 10 cm FTK plane with 750 μm fibers and 1 mm readout pitch is fully equipped and a beam test campaign is planned this fall at the CERN PS and SPS facilities.

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