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Characterization of plastic scintillator detector prototypes for the HERD experiment

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Summary. — Satellite experiments employ plastic scintillators to discriminate charged from neutral particles in order to correctly identify gamma rays and to identify charged nuclei. We have assembled and tested different prototypes of plastic scintillators equipped with Silicon Photomultipliers (SiPMs) to study different designs for the SiPM-based readout system. Our studies are performed in the framework of the High-Energy Cosmic Radiation Detection (HERD) facility that will be installed onboard the future Chinese space station. The HERD experiment will provide high-quality data on charged cosmic rays up to PeV energies and gamma rays up to TeV energies.

1. – The High-Energy Cosmic Radiation Detection (HERD) facility

The High-Energy Cosmic Radiation Detection (HERD) facility is one of the cosmic-ray experiments that will be installed onboard the future Chinese Space Station (CSS) in 2026. It will provide high-quality data on charged cosmic rays and gamma rays in an energy range from a few GeV to PeV [1, 2]. The core of the detector will be a finely segmented 3-D cubic calorimeter (CALO) made of LYSO crystals. The sides of the CALO, with the exception of the bottom one, will be surrounded by Fiber Trackers (FiTs) to accurately track the impinging particles and to measure their charge. The CALO and the FiT will be covered by a Plastic Scintillator Detector (PSD), aiming to provide gamma-ray and charged particle identification. A Silicon Charge Detector (SCD) will surround the PSD, ensuring an additional level of charge measurement. A Transition Radiation Detector (TRD) is also planned to be installed on one of the lateral sides, to provide energy calibration of nuclei in the TeV region. A schematic view of HERD with its sub-detectors is given in fig. 1, where the position of HERD onboard the CSS is also shown.

2. – The HERD Plastic Scintillator Detector (PSD)

Satellite experiments employ plastic scintillators as anti-coincidence detectors for gamma rays and for the identification of charged nuclei. For this reason, the PSD must

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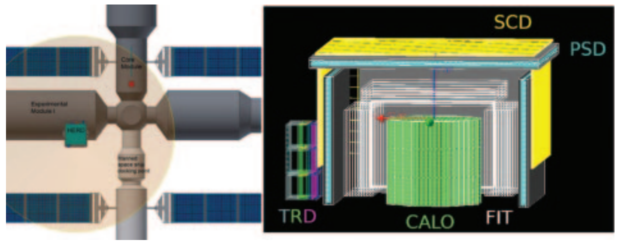

Fig. 1. – Left panel: position of the HERD facility onboard of the future Chinese Space Station (CSS). Right panel: schematic view of the HERD sub-detectors.

have a very high detection efficiency for charged cosmic rays, which represent the main source of background in the identification of gamma rays, and a very good capability in measuring the charges of cosmic-ray nuclei [3]. To read out the scintillator light, the HERD PSD will employ Silicon Photomultipliers (SiPMs), which offer the advantages of smaller sizes and lower power consumption with respect to the traditional photomultiplier tubes commonly adopted in space missions.

To reduce the back-splash effect due to secondary particles generated within the satellite, a highly segmented PSD is required, and the optimization of its geometry is crucial to maximize the detection efficiency. Currently two configurations are being studied for the HERD PSD geometry, respectively based on scintillating bars and tiles. Several tile and bar prototypes have been built by different Italian institutions involved in the PSD design within the HERD Collaboration. Ongoing tests in both configurations aim to define the optimal scintillator type and size and the best electronic readout for SiPM sensors. Both the bar and tile configurations offer advantages and disadvantages. A tile configuration allows a higher degree of segmentation than a bar configuration, and thus is more effective in suppressing possible self-vetoes due to the backsplash effect, but requires a larger number of SiPMs.

2˙1. *Characterization of scintillator prototypes*. – Figure 2 shows some of the latest prototypes actually under test in beam test campaigns and with lab measurements with radioactive sources (^{90}Sr) and cosmic rays (CRs). The pictures in the two left panels show different EJ–200 scintillator bars coupled with a different number of SiPMs per side (1, 2 or 3), built and currently under test at the Gran Sasso Science Institute (GSSI, L'Aquila) and at the INFN laboratories in Lecce. The pictures in the two right panels of fig. 2 show some BC-404 scintillator tile prototypes equipped with SiPMs that are built and are currently under test by the INFN sections of Pavia and Bari. The main ongoing lab activity is focused on the study of the response of the scintillator prototypes coupled with SiPMs in terms of uniformity of light collection.

A beam test campaign was also carried out at CERN to test two prototypes of plastic

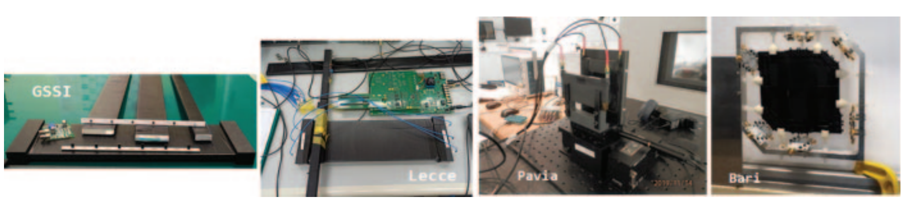

Fig. 2. – Some of the latest scintillator bar and tile prototypes built and actually under test.

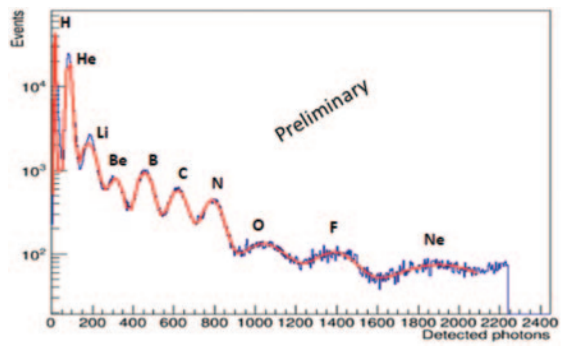

Fig. 3. – Spectrum of detected photons. The peaks corresponding to different ions have been identified performing a multi-Gaussian fit of the spectrum. These results have been obtained at the CERN SPS H4 beam line by irradiating the tile prototype in the central position [3].

scintillator tiles equipped with a set of SiPMs. The first prototype was tested at the CERN PS T10 beam line with a beam of electrons and pions to study the dependence of the collected light on the impact point of the beam particles. The results obtained show that the response of our prototype is almost uniform in all scanned positions and the detection efficiency achieved is comparable with the typical values required for anti-coincidence detectors in satellite experiments (>99.9%) [4].

The other tile prototype was tested at the CERN SPS H4 beam line with a beam of selected 330 GeV/Z momentum, coming from a primary beam of lead, with 150 GeV/A momentum, impinging onto a beryllium target. The tile was irradiated in the central position by a beam of 1 cm diameter to test the capability of the PSD to discriminate the ion charges. According to Bethe's formula, the energy released by charged particles is proportional to the square of the charge Z of the particle [5]. The spectra of scintillation photons produced inside the material are then expected to exhibit multiple peaks, whose positions are proportional to the squared charges of the nuclei. The plot in fig. 3 shows the spectrum of detected photons by SiPMs obtained by irradiating the tile in the central position. The prototype can clearly identify ions at least up to $Z = 9$ (fluorine) [3].

For low-energy depositions, the number of scintillation photons increases linearly with the energy deposited by the primary particles. For higher-energy losses a saturation effect is observed, which is described by Birks' law [6]. This effect has been taken in account to study the scintillator prototypes performances in terms of charge identification. This is one of the main goals of a beam test campaign that is ongoing at the CNAO (*Centro Nazionale di Adroterapia Oncologica*) in Pavia, that is a facility for hadron therapy for treating solid tumors using beams of proton and carbon ions. Some tile prototypes coupled with different Hamamatsu SiPMs were tested at the CNAO beam line with protons with kinetic energies from 60 to 250 MeV and carbon ions with kinetic energies from 120 to 400 MeV/nucleon [7]. Since the energy loss in the scintillator (and the subsequent production of scintillation photons) is proportional to $(Z\beta)^2$ [5], the average loss due to relativistic ions equals that due to lighter ions with $\beta \ll 1$ [7]. For this reason, the high-energy ion interaction with the scintillator can be mimicked by slower velocity ($\beta < 1$) ions, as illustrated in fig. 4. Scanning the response of the tile with different beam particle energies (acting on the β of the particles) allows to study Birks saturation of light yield in the presence of large local energy release.

Finally, together with the prototypes assembly and tests activities, a full customizable

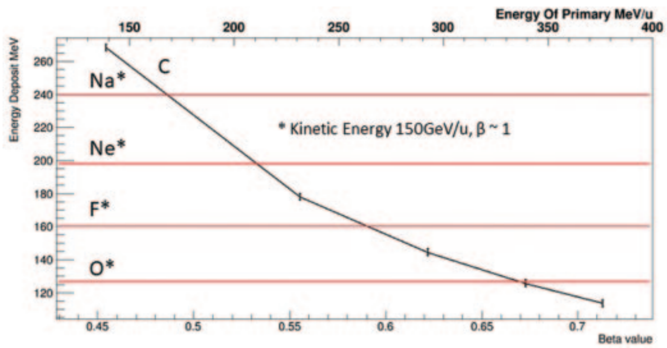

Fig. 4. – Simulation results in which the energy released by carbon ions with different β factors is compared with the energy released by different ions with $\beta = 1$.

simulation tool based on GEANT4 has been also developed by the HERD-PSD Italian Collaboration [8]. The purpose of the simulation is to study the scintillator optical properties and the coupling with SiPMs in order to be able to choose the best geometry of the scintillator and the best design for the SiPM-based readout system.

3. – Conclusion

The High-Energy Cosmic Radiation Detection (HERD) facility will start its operation around 2026 aboard the future Chinese Space Station. One of the main sub-detector of the HERD satellite is the Plastic Scintillator Detector (PSD), that needs to have a very high detection efficiency for charged cosmic rays, which represent the main background for the identification of gamma rays, and a very good capability in identifying charged nuclei. The choice of the proper PSD geometry and of its readout system are critical aspects to reach the best particle identification performances. A strong effort in the realization and test of new prototypes is ongoing in Italy through beam test campaigns, lab measurements and with the realization of a dedicated simulation tool to define the best geometry end the best SiPM-based readout system design for the HERD PSD.

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