PROCEEDINGS OF SCIENCE

PoS(ICRC2023)087

The Silicon Charge Detector of the High Energy Cosmic Radiation Detection facility

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The High Energy cosmic-Radiation Detection facility is a large field-of-view, high-energy cosmic ray experiment planned to be installed on the China Space Station in 2027. The Silicon Charge Detector is a specialized HERD sub-detector aimed at accurately measuring the cosmic ray absolute charge magnitude Z, thus separating chemical species in cosmic rays from hydrogen ($Z = 1$) to iron ($Z = 26$) and beyond. The SCD design is based on multiple layers of single-sided micro-strip sensors that measure the energy deposited and the impact position of the traversing particle. The status of the SCD design and results of prototypes tested on the test beam will be discussed.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

ICRC2023
38th International Cosmic Ray Conference
The Astroparticle Physics Conference

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1. Introduction

The High Energy cosmic-Radiation Detection (HERD) facility is a China-led space mission that will be installed on board the Chinese Space Station in 2027. Its purpose is to directly measure cosmic rays (CRs) up to the knee (a spectral feature present at about 10^{15} eV) separating all CR elements, make γ-ray astronomy and transient studies, and indirectly search for dark matter. The HERD mission is based on a novel design of a highly segmented, homogeneous LYSO calorimeter of 55 X_0 (CALO). The CALO segmentation in 3 cm side cubes allows for the reconstruction of 3D showers from all incoming directions. The CALO is complemented by a series of detectors for particle identification installed on five sides (top, and four sides), enclosing it in a box. From the innermost to the outermost volume, there are a Fiber Tracker (FIT), a Plastic Scintillator Detector (PSD), and a Silicon Charge Detector (SCD). Eventually, a Transition Radiation Detector is installed on one side and will be used for the energy scale calibration of the CALO. Globally, HERD will detect particles in a large field of view of about 2π, resulting in a large CRs statistical collection power. For details, see [1], and the proceedings of this conference [2].

2. The Silicon Charge Detector

The SCD is a specialized detector for the measurement of the particle's absolute charge magnitude Z. The SCD is designed to measure Z for a large fraction of particles passing through the CALO field-of-view, with enough resolution to separate chemical elements from hydrogen (Z = 1) to iron (Z = 26) and beyond. The SCD is the outermost detector in the HERD system. This choice allows for the minimization of the amount of cosmic ray nuclei misidentified due to fragmentation processes happening in material placed above the SCD volume.

The use of micro-strip Silicon sensors for measuring cosmic ray charge magnitude Z follows the tradition of the successful Silicon micro-strip tracking device used also for charge measurement in space-borne experiments such as AMS-01 [3], PAMELA [4], AMS-02 [5] and DAMPE [6].

Other important design guidelines for the SCD are: a) minimization of materials inside the SCD volume, to reduce inelastic interaction that could decrease charge measurement accuracy; and b) having enough segmentation to cope with the large backsplash coming from particles interacting in the CALO.

Additionally, the SCD segmentation will allow for additional 3D tracking and will be used together with the FIT for the HERD particle track reconstruction. The additional capabilities of the SCD improve the redundancy between different sub-detectors and allow for cross-calibrations.

Additionally, all other HERD detectors (PSD, FIT, and CALO) are able to measure the particle's absolute charge magnitude, giving measurement redundancy and the possibility of detecting fragmentation interactions inside the detector volume.

3. The SCD Design

The SCD is composed of 5 thin detector units: one square-shaped unit placed on the top of the instrument (SCD-Top) with a surface of 1.8×1.8 m^2, and 4 identical rectangular-shaped units (SCD-Side) with dimensions of 1.6×1.1 m^2 placed on the other 4 sides.

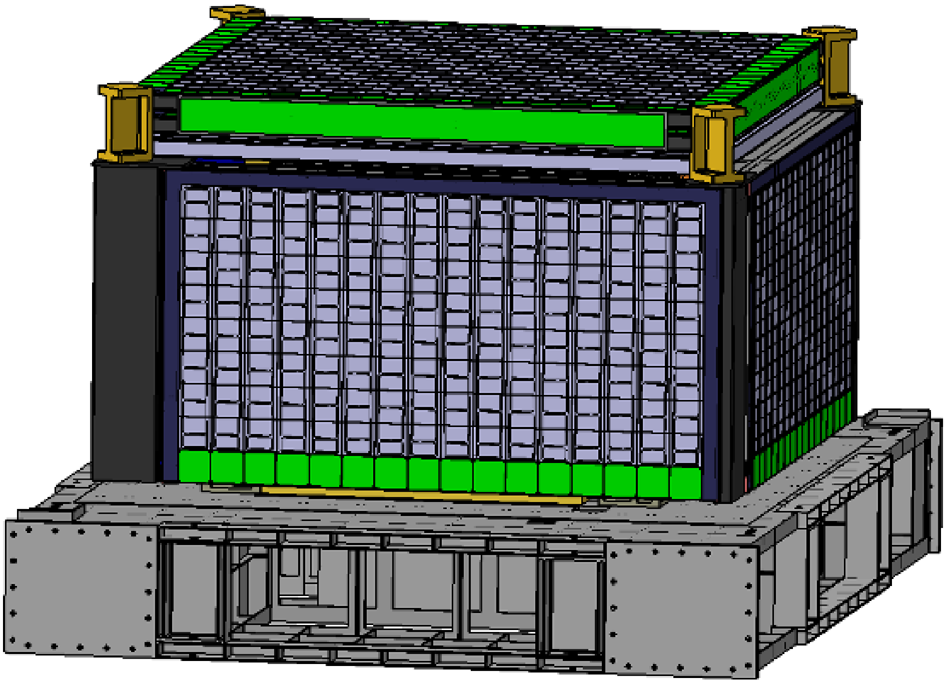

Figure 1: The overall design of the HERD experiment. The instrumented part is approximately a box with dimensions of about $2 \times 2 \times 1.3$ m^3. The external cover has been removed to expose the first layers of the SCD detector. Silicon sensors are colored gray, while front-end electronics are green.

Each detection unit contains 8 layers of single-sided Silicon Strip Detectors (SSDs) of about 300 µm thickness mounted over 2 supporting frames in alternating orthogonal directions. In Fig. 2, the design of a single tray is presented. The tray is constituted by a supporting plane with 2 layers of Silicon mounted on each of the two sides. On one side, a first Silicon layer is directly glued over the supporting structure, while the second layer is glued over an Airex structure mounted directly on top of the first Silicon layer, see 2 b).

The choice of 8 layers is enough for the targeted charge measurement, as verified with Monte Carlo simulation. Multiple layers also allow for: a) verifying that no charge interaction is happening inside the active volume; b) the development of single-layer charge calibration procedures using the SCD alone; c) enabling tracking; and d) the direct evaluation of the SCD detection efficiencies.

In the current design, the SSDs have dimensions of 95×95 mm^2. On SCD-Top, there are 256 sensors in each layer, while on the SCD-Side, there are 128 sensors arranged over an 8 by 16 matrix. Strips are oriented in the same direction on a single layer and in the orthogonal direction on consecutive layers. Strips of several sensors are connected together and routed to the readout electronics installed on one side, forming a unique readout unit, called ladder, see Fig. 2 a).

SCD-Top ladders are made by a series of sensors daisy-chained along the strip direction, connected on one side to the front-end electronics. On the SCD-Top, each ladder sensor row is divided into two 8-sensor long ladders, for a total of 32 ladders per layer. Front-end boards are located on different sides of the SCD-Top for alternating layers.

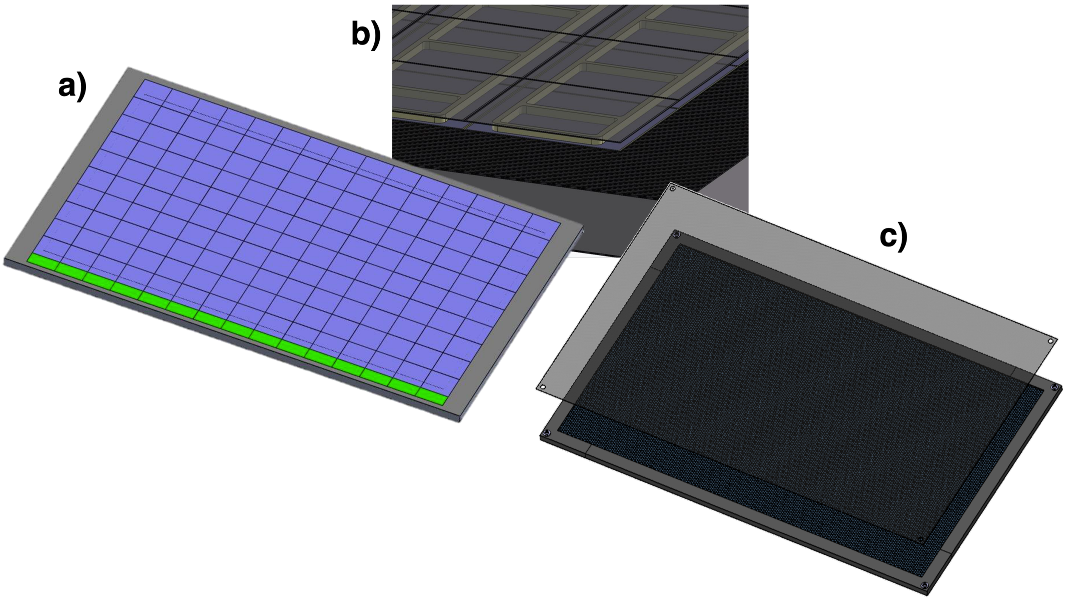

Figure 2: The design of the SCD tray: a) sensors (in blue) connected by strip bonding along the coordinate measurement are arranged over the supporting plane, and readout on the side (green); b) a detail of a possible integration strategy, one Silicon layer is directly glued on the supporting structure while a second one is glued over an Airex foam structure installed over the first layer; and c) exploded view of a solution for the supporting structure, here made by an aluminum honeycomb with a carbon fiber skin and carbon fiber frame.

In the case of SCD-Side ladders, the front-end boards are designed to always sit on the bottom part of the detector, and all ladders are 8 sensors long and placed along the z-axis. While ladders that measure the horizontal coordinate, on the Side-h (horizontal) layers, are similar to the ones on the SCD-Top, the ladders that measure the z coordinate, on the Side-v (vertical) layers, have a different arrangement. The SCD v-ladders are arranged vertically with horizontally oriented strips, and the channels of each sensor are connected through a Kapton foil running on the back of the sensor to the channels of the sensor below up to the readout electronics. Therefore, the signal observed on the v-ladders will only allow the measurement of z-coordinates with a multiplicity pitch of 95 mm. This will result in the reconstruction of parallel tracks along z-coordinates, which will be solved by the combined use of the CALO and the FIT in the reconstruction.

Globally, the HERD SCD will have a sensitive area of about 60 m^2.

4. The SCD SSD Prototypes

During the last few years, several SCD prototypes have been produced both by the Italian and Chinese (IHEP and PMO) SCD groups. The different designs involve different sensor thicknesses, different implantation pitches, strip widths, different numbers of floating strips, and different decoupling capacitances in the readout chain. These SSDs have been tested in the laboratory, and under ion test beams, and compared to simulations to understand how to achieve the best charge measurement performance.

In this work, we will focus on the preliminary results obtained with the SSD prototypes tested in November 2022 on the ion beam at the H4 experimental area of the CERN North Area. The ion

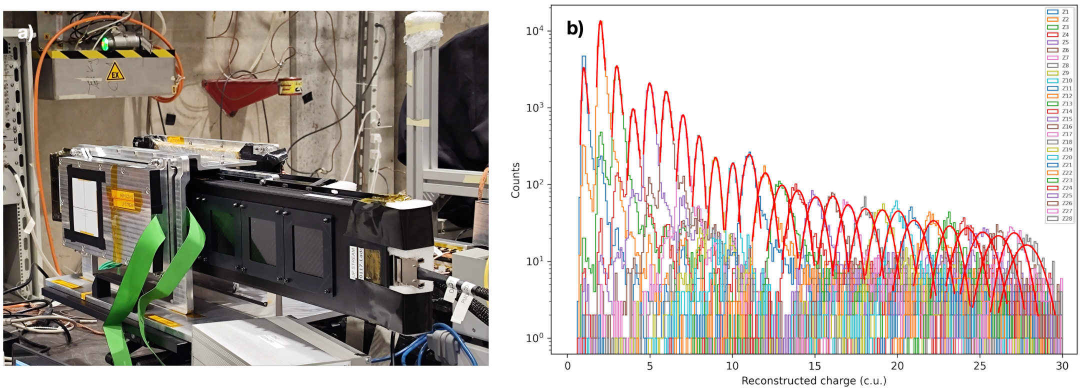

Figure 3: a) the SCD prototypes developed in China from IHEP (front) and PMO (back) on the beam area, and b) the achieved resolution for a single IHEP sensor, after the calibration procedure, obtained for the portion of the sensor with 60 µm strip width and 20 pF decoupling capacitance.

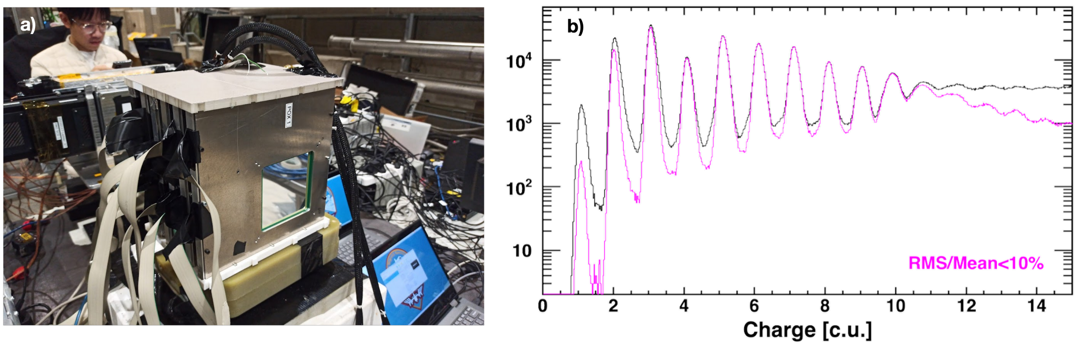

Figure 4: a) The SCD prototype was developed in Italy, placed on the beam area, and; b) the charge distribution was obtained by averaging the 8 sensors on the beam. In magenta the obtained resolution restricting to measurements with a limited spread.

beam was produced by a Lead primary beam of 150 GeV/n extracted from CERN Super Proton Synchrotron colliding on a 4 cm Beryllium target. The emerging secondary fragment beam was selected in rigidity with magnetic optics, which allowed for the selection of beam A/Z. A large variety of elements with Z spanning from 1 to 82 were present in the beam. Eventually, the ion beam reached the experimental area where the SSDs prototypes were installed, see Fig. 3 a) and Fig. 4 a). Prototypes of PSD, the FIT, and the CALO were also installed on the beamline acquired along SCD prototypes with a common trigger to allow for combined data analysis.

The SSD prototype prepared by IHEP had a thickness 300 µm, an implantation pitch of 80 µm, and 1 floating strip. On the sensor, different implantation widths were present (25 and 60 µm) and several groups of strips were readout through different readout capacitances (20, 47, 68, 100 pF). The different regions were all illuminated during the beam test. The preliminary data analysis consisted of the characterization of the signal of each strip signal as a function of the charge seen in an independent scintillating counter system. Performances for different regions were obtained and compared. In Fig. 3 b) is presented the charge distribution obtained after the preliminary data analysis for the part of the SSD with 60 µm strip width and 20 pF decoupling capacitance. The obtained performance allows separation of charge up to at least 28.

The Italian SCD prototype was composed of 8 SSDs with a thickness of 150 µm, 50 µm implantation pitch, and 2 floating strips. The 8 SSDs were arranged in orthogonal directions, to allow for 3D track reconstruction, in a similar fashion to the flight SCD. A reconstruction software program has been developed to create clusters of signals from neighboring strips with large signals and to associate them into a 3D track with a combinatorial approach. An alignment has been applied using an iterative procedure based on the minimization of track residuals. Signals from different sensors were corrected for gain differences between VAs, corrections depending on the impact position were introduced, as well as an overall conversion between the ADC and the charge unit scale. The outcome of this analysis is shown in Fig. 4 b). The device allows one to clearly distinguish charges up to at least $Z = 10$. The resolutions achieved in this range are compatible with the Monte Carlo simulations.

The comparison of these results with other prototypes, and with simulations, in an extended Z range, will be discussed in more detail in a future publication.

5. Conclusions

The HERD experiment is a space-borne, large field-of-view space experiment that will be installed on the Chinese Space Station in 2027. The Silicon Charge Detector is the outermost detector of the HERD detector and is designed to identify cosmic ray charges between $Z = 1$ to $Z = 26$ and beyond. The design of the device is in an advanced stage. Prototypes of the micro-strip Silicon detectors have been produced and tested on several test-beam campaigns. A preliminary analysis of the prototype produced in Italy shows a charge resolution in agreement with the expectations coming from Monte Carlo simulations up to $Z = 10$.

Acknowledgments

The Italian institutions acknowledge INFN and ASI under ASI-INFN Agreements No. 2023-8-HH.0.

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