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The High Energy cosmic-Radiation Detection (HERD) Facility

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The High Energy cosmic-Radiation Detection (HERD) facility, planned for launch in 2027 and is one of the scientific payloads on board of the Chiniese Space Station. HERD's primary scientific objectives covers several high energy astrophysics topics, including the search for dark matter annihilation products, precise measurements of the cosmic electron (and positron) spectrum beyond 10 TeV, analysis of cosmic ray spectra for various species up to the knee energy, and the monitoring and surveying of high-energy gamma rays. At the heart of HERD lies a 3-dimensional imaging calorimeter, surrounded by a fiber tracker, a plastic scintillator detector, and a silicon charge detector on five sides. To ensure calibration of TeV nuclei, a transition radiation detector is employed. Thanks to its design with five instrumented sides, HERD has an acceptance area an order of magnitude greater than that of existing experiments. In this work an overview of the recent progress made in the HERD project will be provided.

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1. Introduction

The High Energy cosmic-Radiation Detection (HERD) facility is an international space mission that will start its operation at the end of 2027 on board the China's Space Station (CSS) [1]. Thanks to its novel design, the HERD mission is expected to accomplish important and frontier goals relative to CR observations, dark matter (DM) search and gamma-ray astronomy. In this paper, we will provide a brief overview of the primary scientific objectives of the HERD mission and an overview of the present status of the main subdetector prototypes.

2. Scientific Objectives of the HERD Mission

The HERD mission, with its groundbreaking design is, to date, the only experiment foreseen in the next years that will offer the exclusive opportunity to explore the scientific frontier of very high energies from space. The main requirements of the HERD payload are summarized in Tab.1 [8]. Compared with the actual on orbit satellite experiments performances as AMS-02 (2011) [9], CALET (2015) [10], DAMPE (2015) [11] and Fermi-LAT(2008) [12], HERD will potentially have much better performance on direct high energy e, p, gamma ray detection.

Item	Value
Energy range (e/γ)	10 GeV - 100 TeV; >0.1 GeV(γ)
Energy range (nucleus)	30 GeV - 3 PeV
Angular resolution (e/γ)	0.1 deg.@10 GeV
Charge measurement (nucleus)	0.05 - 0.15 c.u.
Energy resolution (e)	1% @ 200 GeV
Energy resolution (p)	20% @ 100 GeV - PeV
e/p separation	$\sim 10^{-6}$
Geometric factor (e)	>3 m^2Sr @ 200 GeV
Geometric factor (p)	>2 m^2Sr @ 100 GeV

Table 1: Main requirements of the HERD payload

Study of the electrons and positrons in cosmic rays is a target of particular interest because of their large energy loss during propagation. This means that, in the observation of the electron-positron flux, we expect a spectral cutoff around 1 TeV, beyond which, only nearby sources (distinguished by characteristic structures), are likely the only ones that contribute to the flux. DAMPE experiment was able to precisely measure the electron-positron spectrum up to 10 TeV, reporting a spectral features at ~TeV [15]. but with no associated evidence of local sources from the flux. Moreover, an excess of high-energy positrons was observed in cosmic rays detected by the PAMELA [13] and later confirmed by the AMS-02 [14]. This excess has a significant rise at higher energies and suggests that there could be additional (local) sources contributing to the positron population. This observation can be consistent with expectations from both astrophysical sources such as pulsars wind nebulae (PWN) or exotic sources like DM annihilation products. The HERD experiment will not only extend the direct measurements of electron/positron flux up to a few tens of TeV, but will also improve the quality of the current measurements with a better control of systematic effects. The mission will provide important indications on the origin of the positron excess distinguish from astrophysical explanation or DM nature, thanks to precise measurement of the different spectral shape in case of additional PWN or DM production.

More in general, the picture of cosmic rays is much more complex than it was a few decades ago. Most nuclear species exhibit a clear hardening at a rigidity of around 250 – 500 GV as shown by AMS-02 measurements [9]. Furthermore, the CALET and DAMPE experiments enlightened a softening in the proton flux at an energy of about 10 TeV [16, 17] and in the helium flux at higher energies [17]. However, the knee structure has been measured only inclusively by ground experiments, and its origin remains unclear. Finally, the current B/C ratio measurements, which is the "standard probe" for propagation models, is limited to the ∼ TeV/n region due to low statistics or instrumental limits. Also in this case, HERD will provide the first direct measurement of p and He knees and it will extend the measurements of B/C ratio at higher energies, shed light on our understanding of the knee origin and acceleration and propagation mechanisms.

In addition, thanks to its large acceptance and sensitivity, HERD will be also able to perform a full gamma-ray sky survey in the energy range > 100 MeV extend Fermi-LAT catalog [7] to higher energy (> 300 GeV) allowing the mission to make significant contributions in the search for dark matter signatures, the study of galactic and extragalactic sources, as well as the investigation of galactic and extragalactic diffuse emission. Moreover, the broad field of view, achievable with the instrumentation on all five sides, enhances the chances to detect rare gamma events, such as the identification of high-energy gamma-ray bursts. This particular objective will be accomplished through a multi-messenger approach, exploiting the synergies with gamma-ray, gravitational-wave and neutrino observatories at ground.

3. The HERD Design

The HERD design (see Fig. 1) features a 3D cubic electromagnetic calorimeter (CALO) surrounded for 5 over 6 faces of the facilities by all the other subdetector modules [2]. Starting from the innermost detector, there will placed the Fiber Tracker (FIT) [3] located immediately outside of the calorimeter. It will be used for particle tracking and as gamma-ray converter. On the outer sides of the FIT modules there will be the Plastic Scintillator Detector (PSD) [4] modules that act as an anti-coincidence shield and charge detector. The PSD and the FIT will be responsible of the dedicated trigger mode for low-energy gamma rays thanks to their fast response and the ability to reject charged particles at trigger time. On the outermost part of each side, the Silicon Charge Detector (SCD) [5] also will provide charge identification and particle tracking measurements. A Transition Radiation Detector (TRD) [6] will be also placed on one of the lateral sides, in the outermost position. It will be used for CALO calibration during dedicated runs and it will kept out of the field of view during physics runs to avoid interference with SCD charge measurements.

The CALO [19] is the main detector of HERD instrument: it is a homogeneous, isotropic, 3D segmented calorimeter which can accepts particles coming from each surface. The baseline design of the CALO consists of about 7500 LYSO cubes with edge length of 3 cm (∼ $2.6X_0$ and 1.4 Molière radius). Fig. 2 shows an example of CALO cube (Schematic on the left and prototype on the center) and a picture of the overall geometry (on the right). The total depth of the CALO for vertical particles is about 55 X_0 and 3 interaction length (λ_I) giving the CALO the capability to measure high energies with a good energy resolution. The isotropic 3D geometry and the segmentation provides a large geometric factor and a good e/p discrimination. Each cube is readout by 2 systems. The double read-out system allows for redundancy, independent trigger, and cross calibration in

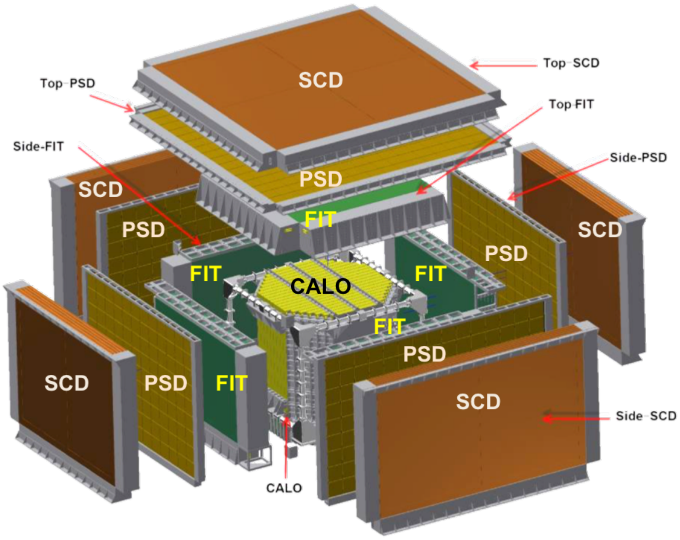

Figure 1: Exploded view of the HERD detector. The innermost subdetector is the calorimeter (CALO), surrounded on the top and the four lateral sides by the scintillating FIber Tracker (FIT), the Plastic Scintillator Detector (PSD) and the Silicon Charge Detector (SCD).

order to reduce the systematic uncertainties (especially on the absolute energy scale). The first one consists of WaveLength Shifting fibers (WLS) coupled to image Intensified scientific CMOS (IsCMOS) cameras (WLSFs), the second one is made of photo-diodes (PD) connected to custom front-end electronics (HIDRA). Furthermore, both WLS and PD systems provide independent fast trigger information which will be employed to improve the HERD trigger capabilities.

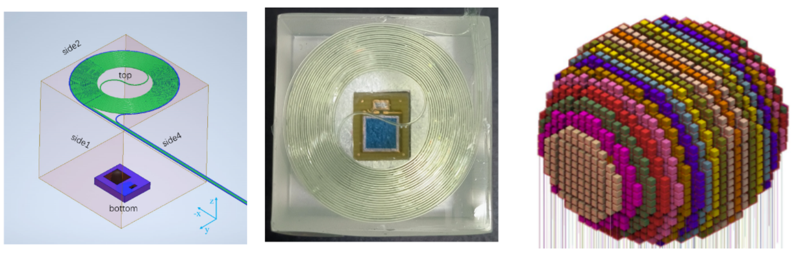

Figure 2: Schematic illustration (*on the left*) and picture (*on the center*) of a LYSO cube with WLSFs and PDs. *On the right* illustration of the displacement of LYSO cubes inside the CALO.

In the current design, HERD scintillating FIber Tracker (FIT) [3] consists of 5 tracking sectors (Fig.3), made of 7 tracking planes, for 7 independent measurements of the position of a traversing charged particle. Each tracking plane consists of two layers of FIT modules measuring the two orthogonal spatial coordinates. The tracking planes of the top sector are made of 10 FIT modules on both the x layers and y layers, while the tracking planes of the side sectors are made of 6 FIT modules on the x layers and 10 FIT modules on the y layers. A module includes one scintillating fiber mat defined by 6 layers of round fibers with a diameter of fibers 250 μm that are read-out by a SiPM array.

The Plastic Scintillator Detector will be used as anti-coincidence systems for gamma-ray

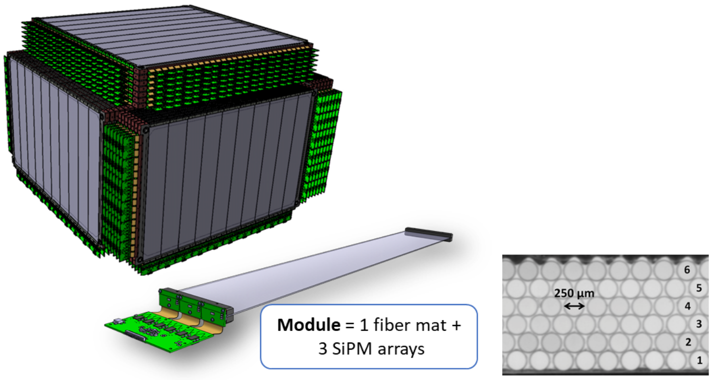

Figure 3: Schematic illustration of the 5-side FIT detector, a module and a Fiber mat.

detection (VETO of charged particles) and for the identification of charged cosmic-ray nuclei (energy loss $\propto Z^2$) [4, 20–22]. The configuration proposed for the HERD PSD consists of trapezoidal scintillator tiles coupled to Silicon Photomultipliers (SiPMs). The segmented geometry is necessary to reduce the possible self-veto due to the backsplash effect [23], while the trapezoidal shape is chosen to ensure the best packaging of the whole detector. Each trapezoidal tile (of a dimension of 40 cm long and 5/4 cm wide) will be equipped with SiPMs placed in different positions along the tiles. The sensor positioning is optimized using dedicated Monte Carlo simulations [24, 25] to ensure uniform light collection. Two different sensor sizes will be utilized to cover a wide dynamic range and achieve good energy resolution for identifying signals from Minimum Ionizing Particles (MIPs) to high-Z nuclei energy releases. In Fig. 4 an illustration of the PSD geometry. The gap between the tiles is increased for visualization reasons.

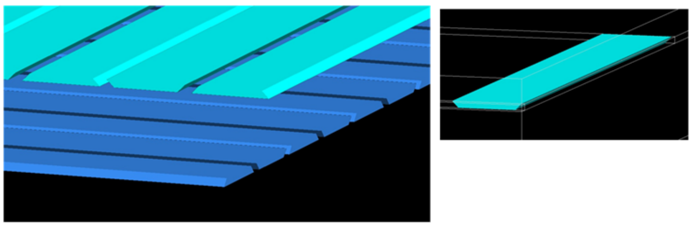

Figure 4: Schematic illustration of the PSD geometry. The gap between the tiles is increased for visualization reasons.

The SCD is the outermost detector to avoid early charge-change interactions in the PSD and to reduce the systematic uncertainty on the reconstructed charge due to fragmentation. It is a silicon micro-strip detector that will measure with precision the impinging particle charge. In the current design the SCD is constituted by 5 thin detector units, one squared-shaped with dimensions of $1.6\times1.6\,\mathrm{m}^2$ placed on the top on the instrument, and 4 with dimensions of $1.4\times0.9\,\mathrm{m}^2$ placed on the other 4 sides. Each detection unit contains 8 layers of 300 μm microstrip silicon detectors mounted with alternating orthogonal direction strip directions onto low-density aluminum honeycombs. Globally the active area is about $60\,\mathrm{m}^2$. Design choices for the SCD, as the strip pitch and the distance between SCD and PSD, will also be studied in order to minimize the effect of pile-up in charge measurement due back-splash particle emerging from interactions in the calorimeter. Additionally, SCD is capable of 3D tracking and will be used together with the FIT for the HERD particle track reconstruction. The advanced functionalities of the SCD will contribute to increased redundancy among various sub-detectors, facilitating cross-calibrations

Conclusion

The High Energy cosmic-Radiation Detection facility is an international space mission that will start its operation at the end of 2027 on board the China's Space Station (CSS). Thanks to its novel design based on a 3D, homogeneous, isotropic and finely-segmented calorimeter, HERD mission will be able to measure the cosmic ray flux up to the knee region and it is expected to accomplish important and unreached frontier goals in the field of CR observations, DM search and gamma-ray astronomy.

References

[1] Zhang, S. N., et al. (HERD Collaboration), Proc. SPIE 91440X (2014)

[2] Adriani, O., et al., JINST 17 (2022) P09002.

[3] Perrina, C. et al., (HERD Collaboration) Proc. of Sc.(ICRC2021) (2021) 067

[4] Gargano, F., et al., (HERD Collaboration) Nucl.Instrum. Meth.A 983 (2020) 164476.

[5] Oliva, A. et. al., (HERD Collaboration) Proc. of Sc.(ICRC2023) (2023) 087

[6] Huang, B. et al., Nucl. Inst. and Meth. in Phys. Res. A 962 (2020) 163723

[7] Abdollahi, S., et al., ApJS 247 (2020) 33

[8] Gargano, F., et al., (HERD Collaboration) Proc. of Sc.(ICRC2021) (2021) 026

[9] Aguilar, M. et. al. (AMS-02 Collaboration) Phys. Rep. 894, 1 (2021)

[10] Torii, S., et al. (CALET Collaboration) Nuclear Physics B-Proc. Sup. 166 (2007): 43-49

[11] Chang, J., et al., (DAMPE Collaboration) Astroparticle Physics 95 (2017) 6-24

[12] Ackermann, M., et al. (FERMI Collaboration), Phys. Rev. Lett. 108 (2012) 011103

[13] Adriani, O., et al. (PAMELA Collaboration) Nature 458 (2009) 607-609

[14] M. Aguilar, et al., (AMS Collaboration) PRL 122 041102 (2019)

[15] G. Ambrosi, et al., (DAMPE Collaboration) Nature, 552 (2017) 63–66

[16] Adriani, O., et al. (CALET Collaboration), Phys. Rev. Lett. 129 (2022) 101102

[17] Alemanno, F., et al. (DAMPE Collaboration), Science advances 5.9 (2019) eaax3793

[18] Alemanno, F., et al. (DAMPE Collaboration), Phys. Rev. Lett. 126.20 (2021) 201102

[19] Pacini, L., et al., (HERD Collaboration), Proc. of Sc.(ICRC2021) (2021) 066

[20] Serini, D.,et al. (HERD Collaboration) Il nuovo cimento C 43.2-3 (2020): 1-2

[21] Serini D., et al. (HERD Collaboration) (IWASI), 2023, pp. 184-189

[22] Serini D., et al. (HERD Collaboration) Proc. of Sc.(ICRC2023) (2023) 112

[23] Peng, H., et al. (HERD Collaboration), Radiation Detection Technology and Methods (2021) 1-7

[24] Altomare C., Serini D., et al., Nucl.Instrum.Meth.A 982 (2020) 164479

[25] Altomare, C., Serini D., et al., Journal of Physics: Conference Series. IOP Pub., (2022) p. 012050

[26] Sanmukh, A., et al. IEEE (NSS/MIC), (2021), pp. 1-3.

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