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Design and scientific objectives of the HERD cosmic ray experiment(*)

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Summary. — The High Energy cosmic Radiation Detector (HERD) stands out as one of the most promising projects for space-based direct detection of cosmic rays. It is planned to be installed on the Chinese Space Station in 2027. The core of HERD is a 3D segmented, homogeneous, spherical calorimeter, featuring a total depth of $55X_0$. Three sub-detectors, namely the scintillating FIbres Tracker, Plastic Scintillation Detector, and Silicon Charge Detector, will enclose five out of six sides. Additionally, a Transition Radiation Detector will be installed on one face for online calibration of TeV energy events. HERD's innovative design ensures a geometrical acceptance at least 10 times larger than that of any of its predecessors. This enhanced capability will enable the measurement of cosmic ray spectra and composition up to the PeV energy scale, to conduct precision studies in γ-ray astrophysics, to monitor transient events, and indirectly search for dark matter candidates with unprecedented accuracy.

1. – Introduction

The study of the spectral shape and composition of cosmic rays (CRs) provides a unique opportunity to investigate our galaxy, delving into the most extreme astrophysical events and searching for evidences of new mechanisms beyond the established models of particle physics, cosmology and astrophysics.

While ground-based experiments allow to indirectly detect CRs up to ultra-high energies (10^{20} eV), they cannot perform precise measurements of charge and energy of the primary CR particle. Direct detection of CRs in space allows to perform percent-level measurements of the primary particle properties, thus to analyze the spectra of individual components and profile possible peculiar features. However, as consequence of the strongly depleting CR flux for increasing energies, CR direct detection with current operating detectors is effective only up to hundreds of TeV.

The High Energy cosmic Radiation Detector (HERD) has been designed to address these challenges. It combines an increased geometric factor (> 2 m^{2}sr) with advanced

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particle detectors to collect and precisely identify a significantly larger amount of CRs than its space-borne predecessors and investigate the unexplored energy frontier above 100 TeV in space.

HERD is being developed through collaboration among Chinese, Italian, Spanish, and Swiss universities and research institutes. It is scheduled to be installed in 2027 on the Chinese Space Station.

2. – Scientific objectives of the HERD mission

HERD is a multi-purpose CR detector optimized to measured CR nuclei, CR electrons and γ-rays in an energy range currently inaccessible, opening the possibility to investigate the frontiers of extreme energies and provide novel information on the mechanisms of origin, acceleration and propagation of CRs.

2·1. *CR nuclei spectra*. – The latest direct measurements of proton and light nuclei spectra in space have revealed unexpected features at higher energies which indicate the limits of our most established models [1, 2].

Although these findings still bear uncertainties due to limited statistics, HERD aims to confirm these spectral features and extend current measurements up to the PeV energy region–the region of the so-called "knee". HERD will be the pioneering experiment to directly detect CRs in this energy regime and infer the chemical contribution of different nuclei at these energies. See fig. 1a for a comparison between the expected proton spectrum observable by HERD and the latest measured spectrum.

2·2. *Electron+positron spectrum*. – While electrons and positrons constitute only about 1% of total CRs, they are a unique probe to test CR origin and propagation. Recent experiments like DAMPE and CALET have studied cosmic electrons up to a few TeV, revealing a break in the spectrum around 1 TeV and a possible new rise at a few TeV [4, 5].

The HERD design allows to accurately verify such features and to extend measurements up to a few tens of TeV, where excesses due to local sources, such as the Vela SNR, or decay/annihilation of dark matter in the galaxy halo could be revealed. See fig. 1b for a possible $e^+ + e^-$ spectrum in reach of HERD.

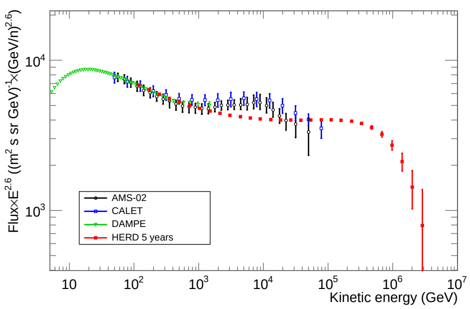
2·3. *Gamma-ray astrophysics*. – HERD will also make significant contributions to the field of γ-ray astrophysics. Capable of detecting photons with energies exceeding 100 MeV, HERD will provide a continuous scan of the γ-ray sky, serving as an extension to Fermi-LAT measurements after its end-of-life [6].

Additionally, HERD will play an important role in monitoring transient events in synergy with other space-borne and ground-based experiments.

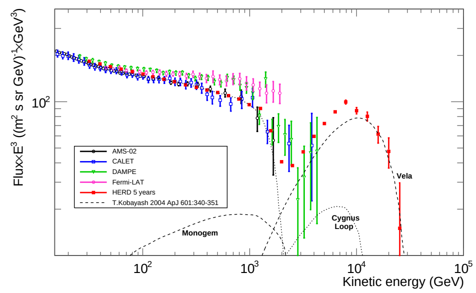
3. – The HERD facility

The HERD payload is based on a design that maximizes the detector acceptance while maintaining a contained volume and weight budget to be installed onboard the Chinese Space Station. This is achieved by exploiting a highly isotropic calorimeter, surrounded by a sequence of additional sub-detectors on each face, except that facing Earth.

The exploded structure of HERD is illustrated in fig. 2 together with a summary of the experimental performances that the facility will achieve.



(a)



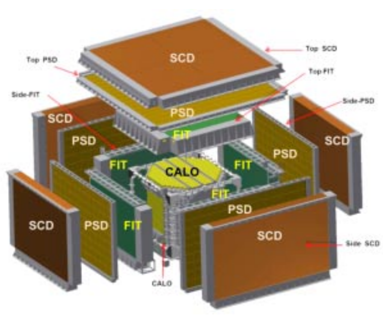
(b)

Fig. 1.: Protons (a) and $e^+ + e^-$ (b) spectra measured in 5 years of HERD operations (red) [3]. Protons predictions has been calculated before the publication of the latest measurement, thus the inconsistency between spectral shapes.

3˙1. *CALO.* – CALOrimeter is the core detector of the facility. It is a homogeneous, spherical calorimeter made of 7500 $3 \times 3 \times 3$ cm^3 LYSO cubes, for a total depth of 55 X_0, corresponding to 3 λ_I. The design provides a fine 3D segmentation and allows for the reconstruction of the longitudinal and transversal development of showers generated by particles from any direction. The ability to profile shower shapes enhances the electron/proton discrimination power, required for precision CR electron measurements.

The scintillation light of LYSO crystals is measured by a dual read-out system: Wavelength Shifting Fibers coupled to image-intensified scientific CMOS cameras, and photodiodes connected to custom front-end electronic chips. This redundant acquisition ensures continuous cross-calibration to reduce systematic errors in the energy measurement [7].

3˙2. *FIT.* – The Fiber Tracker (FIT) serves as the inner tracker of the facility, positioned just outside the calorimeter. Each of 5 sectors is formed by seven tracking modules equipped with layers of scintillating fibers. FIT is also designed to induce the conversion



(a)

Energy range (γ)	> 0.1 GeV
Energy range (e)	10 GeV $\div$ 100 TeV
Energy range (nuclei)	30 GeV $\div$ 3 PeV
Energy resolution (e/γ)	1% @ 200 GeV
Energy resolution (nuclei)	20% @ 100 GeV $\div$ 100 TeV
Angular resolution	0.1° @ 10 GeV
Charge resolution	0.05 $\div$ 0.15 c.u. @ $Z = 1 \div 26$
Geometric factor (e)	> 3 m^2 sr @ 200 GeV
Geometric factor (nuclei)	> 2 m^2 sr @ 100 TeV
e/p separation	$> 3 \times 10^5$ (90% eff. @ 100 GeV)

(b)

Fig. 2.: Exploded model of the HERD payload (a) and summary of the experimental performances expected(b). Reproduced with permission from [8]. CC BY-NC-ND 4.0

of low-energy γ photons into $e^+ - e^-$ pairs that can be easily detected.

The estimated spatial resolution is 45 μm, while the single-hit efficiency is expected to be around 99.6% [9].

3˙3. *PSD*. – The Plastic Scintillator Detector (PSD) is employed both as veto in γ-ray detection and for measuring the nuclear charge up to $Z = 26$. It uses organic scintillators read out by Silicon PhotoMultipliers to acquire fast signals, employing low-density materials and minimal energy consumption.

The PSD utilizes scintillator bars measuring 30 and 40 cm in length, arranged in a hodoscopic configuration. To improve hermeticity, these bars feature a trapezoidal cross-section, enabling a slight overlap between them [10].

3˙4. *SCD*. – The Silicon Charge Detector (SCD), positioned as the outermost detector, is designed to measure both the charge, up to $Z = 23$ and beyond, and the trajectory of incident particles before any interaction with passive materials occurs.

Each of the five sectors of SCD is made of eight layers of single-sided silicon micro-strip detectors, with each layer being 300 μm thick and featuring a strip pitch of 150 μm [11].

3˙5. *TRD*. – Since ground laboratories can only provide particle beams up to a few hundred GeV limiting the possibility to calibrate the calorimeter energy scale at the TeV scale, HERD incorporates a Transition Radiation Detector (TRD) on one side. This device, sensitive to protons in the energy range of 1÷10 TeV, is essential for calibrating the CALO response at higher energies and therefore ensuring accurate measurements.

4. – Conclusions

The HERD experiment, leveraging on its innovative design and on the collaboration between European and Chinese institutes, will provide breakthroughs in our understanding of the origin, acceleration and propagation of CRs, of the most extreme Universe events and on the origin of mechanisms that could not be described by the Standard Model of particles.

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