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The High-Energy cosmic-Radiation Detection (HERD) facility for direct cosmic-ray measurements

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The High Energy cosmic-Radiation Detection (HERD) facility is a future space experiment which is designed for the direct measurement of cosmic-rays (CR). The instrument will be installed aboard the China's Space Station around 2027 and is based on a homogeneous, deep, 3D segmented calorimeter. The calorimeter is surrounded by scintillating fiber trackers, anti-coincidence scintillators, silicon charge detectors, and a transition radiation detector. The HERD instrument is designed to feature a very large acceptance, thus allowing the extension of current measurements up to much higher energies. e.g. the few PeV region in the case of light nuclei, depending on their actual flux.. Fundamental progress in our understanding of propagation and acceleration of CR inside the Galaxy will be achieved by measuring the flux of protons and nuclei above hundreds of TeV per nucleon. By exploring the electron flux in the multi-TeV region, it will be possible to search for the signature of dark matter and nearby astrophysical sources. Finally, thanks to the large field of view, the experiment will also monitor the gamma-ray sky from a few hundred of MeV up to 1 TeV. In this paper a review of the current status of the experiment is presented.

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1. Introduction

The High-Energy cosmic-Radiation Detection (HERD) experiment has been conceived to constitute the next generation of space-borne, high-energy calorimetric detectors, by significantly increasing the geometric factor with respect to the current generation and by providing more accurate measurements. Its design is sketched in figure 1. A brief summary of the most important required performance figures is reported in table 1.

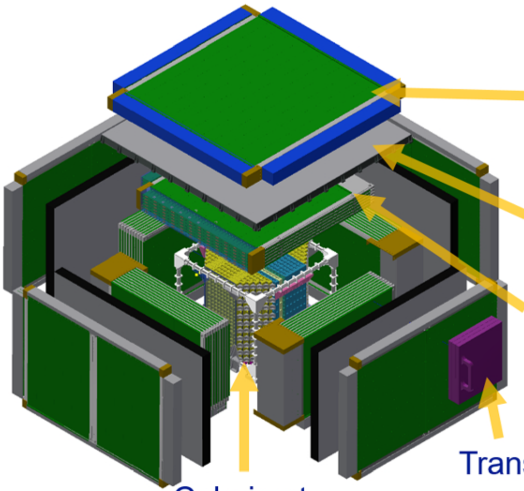

Figure 1: Design of the HERD experiment.

Particle	γ	e^+/e^-	hadrons
Energy range	> 100 MeV	10 GeV - 100 TeV	30 GeV - 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV - 1 PeV
Effective geometric factor	> 0.2 m^2sr @ 200 GeV	> 3 m^2sr @ 200 GeV	> 2 m^2sr @ 100 TeV

Table 1: HERD required performance.

The main sub-detector is a deep, homogeneous electromagnetic calorimeter made of LYSO cubes arranged in a regular 3D mesh. This peculiar design makes it able to accept particles not only from the zenith but also from the four lateral sides, the bottom one being obstructed by the device services and mechanical support. In this way the total geometric factor is roughly increased by a factor of 5 with respect to a conventional zenithal, single-face telescope at the same weight level. Each cube of the calorimeter is read out by two independent systems, to ensure a better control over systematic effects that might affect the determination of the absolute energy scale. Further help in this regard is provided by a Transition Radiation Detector (TRD) that will allow for in-orbit energy calibration with TeV proton showers. Auxiliary sub-detectors are placed on five sides of the calorimeter to fully exploit the capability of the calorimeter to accept particles from the corresponding directions. A FIber Tracker (FIT) provides tracking, while a Plastic Scintillator Detector (PSD) allows for online and offline selection of gamma-ray events. Both the FIT and the PSD have charge identification capabilities, but being this topic a potential major source of uncertainty in detecting $|Z| > 1$ hadrons due to fragmentation a dedicated Silicon Charge Detector (SCD) is placed on the outmost part of the detector. It provides multiple ionization measurements with a minimum amount of traversed material, to obtain a robust charge identification as soon as the particle enters the detector, thus minimizing the detrimental effects of fragmentation.

The HERD experiment is born out of an initiative of Chinese institutions, and is nowadays an international collaboration with a strong European component. The detector itself is currently in a design optimization and prototyping phase. It is foreseen to be installed on the future Chinese Space Station in 2027 and to take data for ten years.

2. The HERD physics

The main goal of HERD is to perform measurements of charged cosmic rays at the highest energies ever reached by direct detection experiments in space, and to monitor the gamma ray sky. The science cases covered by such measurements are described in the following.

The all-particle spectrum features a departure from the single power law behavior predicted by conventional acceleration and propagation mechanisms at around 1 PeV. In this region, called the *knee region* a spectral softening hints for a change of acceleration and/or propagation mechanisms, for example a possible transition from galactic to extragalactic origin of the cosmic rays, that is still to be understood. An important contribution in understanding this feature may come from measuring the spectra of the various hadronic components, starting from the most abundant ones, at these energies. Thanks to its large geometric factor allowing for detecting particles at very low flux values, HERD will provide the first-ever direct measurements at these energies. Recent measurements of the proton and helium spectra (the most abundant species in cosmic rays) have uncovered several unexpected departures from the single power law behavior predicted by conventional acceleration and propagation mechanisms. A hardening in both spectra at around 200-400 GeV/n [1, 2] followed by a softening in the multi-TeV region [3–5] are hints for significant physical processes contributing to acceleration and/or propagation in addition to standard ones. Similar spectral features have been discovered also in heavier nuclear species, with different behaviors between primary and secondary species [6] that suggest possible new features in propagation across the galaxy. Regarding this aspect, the detection of a flattening in the B/C and B/O ratios above 1 TeV [7] is also of great significance. Heavier nuclei up to iron [8–10] are also subjects of recent measurements. In this rich and evolving scenario, the HERD contribution will be valuable in confirming and extending the current understanding, and possibly in discovering new, unexpected features thanks to its large acceptance and accuracy.

Measurements of electron and positron spectra have implications both for fundamental physics and for astrophysics. In particular, rare spectral components such as antimatter are considered suitable for Dark Matter searches, but lacking a magnetic spectrometer HERD won't be able to directly probe them. It will however provide accurate, high-statistics complementary measurements of inclusive particle+antiparticle fluxes like the e^{+}+e^{-} at higher energies than those accessible to spectrometers [11], that will possibly help in better understanding the spectrometric measurements. The e^{+}+e^{-} spectrum can also provide evidence of leptonic acceleration mechanisms occurring in nearby astrophysical objects. A spectral feature is predicted in this case above few TeV; being current measurements [12, 13] limited by statistics at these energies, HERD is expected to bring a significant advancement over current knowledge about this topic. Also, thanks to its improved control over systematics, HERD measurements will help in better understanding the discrepancies (e.g in the absolute normalization of the spectrum) seen in the currently available data from different running experiments.

HERD is expected to observe gamma rays in a broad energy range, from sub-GeV regions (leveraging the pair production process in the FIT support materials) to hundreds GeV (thanks to its deep calorimeter). Its innovative design will allow for observing a large portion of the visible sky for detecting gamma rays, to extend the Fermi-LAT catalogue above 300 GeV and to investigate several physics cases (dark matter signatures, galactic and extragalactic sources and background, high-energy gamma-ray bursts) by exploiting the better energy and angular resolutions compared to previous space telescopes. HERD will also monitor transients as electromagnetic follow-ups of gravitational wave or neutrino events, a key ingredient of multimessenger astronomy, with possible synergies with other gamma-ray, neutrino and gravitational waves detectors.

3. The HERD instrument

The HERD calorimeter features two independent readout systems. The first one is based on wavelength-shifting fibers read out by intensified scientific CMOS cameras [14], while the second on photodiodes directly attached to the LYSO cubes [18]. The two systems have been extensively prototyped and tested, both with Monte Carlo simulations and with particle beams [15–17]

The FIT [19] will be the main tracking device. It is currently made of 7 double layers of scintillating fibers on each of the 5 sides of the calorimeter, read by silicon photomultipliers (SiPMs). It will also be capable of measuring the absolute charge |Z| of the impinging particle by means of multiple ionization measurements. Furthermore, the passive material supporting the fibers will act as a converter for gamma rays, providing a sufficient conversion efficiency for detecting and tracking gamma rays at sub-GeV energies.

The main aim of the PSD [20] is to provide a veto (both online and offline) to identify gamma rays. The current design is made of rectangular tiles read out by SiPMs, and is currently being optimized for hermeticity. As for the FIT, also the PSD will provide charge identification capabilities.

The SCD is the main charge identification system for HERD, covering the full |Z| range from single charge up to iron and beyond. It is currently made of eight layers of silicon microstrip detectors on each of the five sides, with sensors optimized for charge measurement. The spacing between layers is of the order of cm, to preserve the overall geometric factor and limit the extension of the planes. Engineering studies are ongoing to minimize the amount of passive material, to lower the nuclei fragmentation probability as much as possible. The SCD will also act as a secondary tracking device.

The TRD [21] will be used for on flight calibration with TeV proton showers. Being sensitive to the Lorentz factor γ, its response will be calibrated on ground with GeV electrons, and then used in flight to select TeV protons, whose showers will in turn be used to calibrate the calorimeter response.

4. Summary

The HERD instrument represents the next generation of calorimetric cosmic-ray detection experiments in space, featuring innovative design solutions like a double-readout calorimeter with 3D structure providing an accurate energy measurement and a large geometric factor, a charge detector with minimal amount of traversed material, and a detector for calibration with TeV proton showers. HERD will provide valuable data for studying a wide range of fundamental physics and astrophysics topics, significantly extending the energy range covered by direct measurements up to the PeV region and allowing the understanding the nature of the all-particle knee and quantifying the maximum energy reached by galactic accelerators.

References

[1] M. Aguilar *et al.*, *Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station*, Phys. Rev. Lett. 114 (2015) 17, 171103

[2] M. Aguilar *et al.*, *Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station*, Phys. Rev. Lett. 115 (2015) 21, 211101

[3] O. Adriani *et al.*, *Observation of Spectral Structures in the Flux of Cosmic-Ray Protons from 50 GeV to 60 TeV with the Calorimetric Electron Telescope on the International Space Station*, Phys. Rev. Lett. 129 (2022) 10, 101102

[4] Q. An *et al.*, *Measurement of the cosmic-ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite*, Sci. Adv. 5 (2019) no.9, eaax3793

[5] F. Alemanno *et al.*, *Measurement of the cosmic-ray helium energy spectrum from 70 GeV to 80 TeV with the DAMPE space mission*, Phys. Rev. Lett. 126 (2021) 20, 201102

[6] M. Aguilar *et al.*, *Observation of New Properties of Secondary Cosmic Rays Lithium, Beryllium, and Boron by the Alpha Magnetic Spectrometer on the International Space Station*, Phys. Rev. Lett. 120 (2018) 2, 021101

[7] DAMPE Collaboration, *Detection of spectral hardenings in cosmic-ray boron-to-carbon and boron-to-oxygen flux ratios with DAMPE*, Science Bulletin, 2022, in press

[8] O. Adriani et al., *Direct Measurement of the Cosmic-Ray Carbon and Oxygen Spectra from* 10 GeV$/n$ *to* 2.2 TeV$/n$ *with the Calorimetric Electron Telescope on the International Space Station*, Phys. Rev. Lett. 125 (2020) 25, 251102

[9] O. Adriani et al., *Measurement of the Iron Spectrum in Cosmic Rays from* 10 GeV$/n$ *to* 2.0 TeV$/n$ *with the Calorimetric Electron Telescope on the International Space Station*, Phys. Rev. Lett. 126 (2021) 24, 241101

[10] O. Adriani et al., *Direct Measurement of the Nickel Spectrum in Cosmic Rays in the Energy Range from 8.8 GeV/n to 240 GeV/n with CALET on the International Space Station*, Phys. Rev. Lett. 128 (2022) 13, 241101

[11] L. Accardo *et al.*, *High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station*, Phys. Rev. Lett. 113 (2014) 121101

[12] O. Adriani et al., *Extended Measurement of the Cosmic-Ray Electron and Positron Spectrum from 11 GeV to 4.8 TeV with the Calorimetric Electron Telescope on the International Space Station*, Phys. Rev. Lett. 120 (2018) 261102

[13] G. Ambrosi et al., *Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons*, Nature 552 (2017) 63-66

[14] F. Gargano et al., *The High Energy cosmic-Radiation Detection (HERD) facility on board the Chinese Space Station: hunting for high-energy cosmic rays* Proc. of Sc. (ICRC2021) (2021) 026

[15] O. Adriani *et al.*, *The CALOCUBE project for a space based cosmic ray experiment: design, construction, and first performance of a high granularity calorimeter prototype*, Journ. of Instr. 14 (2019) 11, P11004

[16] O. Adriani *et al.*, *CaloCube: An isotropic spaceborne calorimeter for high-energy cosmic rays. Optimization of the detector performance for protons and nuclei*, Astropart. Phys. 96 (2017) 11-17

[17] O. Adriani *et al.*, *The CaloCube calorimeter for high-energy cosmic-ray measurements in space: performance of a large-scale prototype*, Journ. of Instr 16 (2021) 10, P10024

[18] O. Adriani *et al.*, *Development of the photo-diode subsystem for the HERD calorimeter double-readout*, Journ. of Instr 19 (2022) 09, P09002

[19] C. Perrina *et al.*, *FIT: the scintillating fiber tracker of the HERD space mission*, Proc. of Sc. (ICRC2021) (2021) 067

[20] D. Kyratzis *et al.*, *The Plastic Scintillator Detector of the HERD space mission*, Proc. of Sc. (ICRC2021) (2021) 651

[21] B. Huang *et al.*, *Side-On transition radiation detector: A detector prototype for TeV energy scale calibration of calorimeters in space* Nucl. Inst. and Meth. in Phys. Res. A 962 (2020) 163723