PROCEEDINGS OF SCIENCE

The HERD experiment: beyond the current energy limits in direct detection of cosmic rays

Pietro Betti[a,b,*] **on behalf of the HERD collaboration**

[a] *INFN sezione di Firenze,*
Via Sansone 1, Sesto fiorentino, Italy

[b] *Università degli Studi di Firenze, Dipartimento di Fisica e Astronomia,*
Via Sansone 1, Sesto fiorentino, Italy

E-mail: betti@fi.infn.it

The HERD (*High Energy cosmic-Radiation Detection facility*) experiment is a future experiment for the direct detection of high-energy cosmic rays, that will be installed on the Chinese space station in 2027. It is constituted by an innovative calorimeter made of about 7500 LYSO scintillating crystals assembled in a spheroidal shape, and it is surrounded on five faces by multiple sub-detectors, in order to detect particles entering from five sides. It will extend direct measurements of cosmic rays of more than one order of magnitude in energy, measuring proton and nuclei fluxes up to the *PeV* per nucleon energy region, performing the first direct measurement of the cosmic proton and helium *knee*. HERD will also measure the high-energy electron+positron flux and high-energy photon flux to search for possible indirect signals of dark matter and perform multi-messenger astronomy. In this paper the HERD experiment, its scientific goals and its detector design will be introduced.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

∗Speaker

PoS(ICHEP2024)682

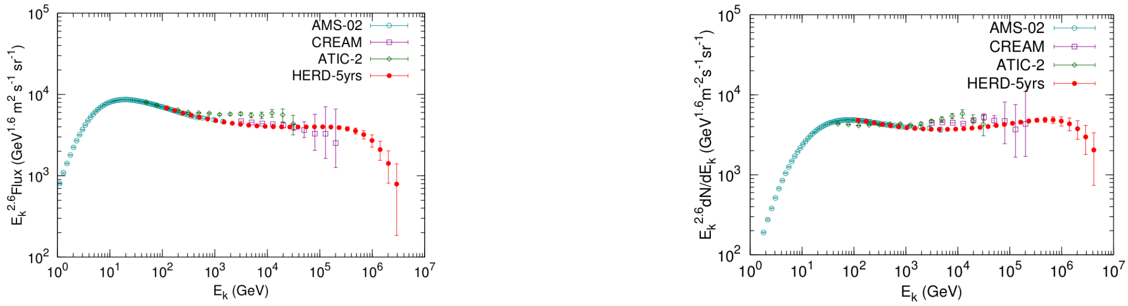
1. Introduction

The cosmic-ray differential flux depends on the energy as $E^{-\gamma}$, with the spectral index γ that varies between 2.5 and 3.3 [1]. It covers an enormous energy range from few MeV up to 10^{20} eV. Moreover, it covers also an incredibly large range of values: about 32 orders of magnitude from 10^4 $(m^2 sGeVsr)^{-1}$ to 10^{-28} $(m^2 sGeVsr)^{-1}$. Thus, the cosmic-ray detection methods are different and depends on the energy region (and so flux values) under study. Specifically, with space experiments in orbit around the Earth we can measure the cosmic rays directly up to about a hundred TeV per nucleon of energy. Space experiments usually have dimensions of m^3 and weight a few tons at the maximum, due to constraints on cost and technology for space missions. So, at higher energy where the flux is very low, they are not able to detect cosmic rays with a meaningful statistics. Some of the main currently in-orbit experiments are AMS-02 [2], CALET [3] and DAMPE [4].
Above a hundred of TeV we detect the particle showers produced by cosmic-ray interactions with the atmosphere with ground experiments that cover surface up to thousands of km^2, such as the Pierre Auger Observatory [5] and Telescope Array [6]. These experiments are called indirect experiments, since they do not detect the cosmic rays directly, on the contrary of space experiments which are called direct experiments. The interpretation of indirect measurements strongly depends on the hadronic models used to simulate these events, which are affected by significant uncertainties that limit our understanding of the measurements. For these reasons, it is very important to detect cosmic rays directly with space experiments at higher energy compared to the one of currently in-orbit experiments.
The HERD (*High Energy cosmic-Radiation Detection facility*) experiment [7, 9] is a future experiment for the direct detection of cosmic rays, that will be installed on the Chinese space station in 2027. It is a calorimetric experiment, and thanks to its innovative geometry it will extend direct measurements of cosmic rays up the PeV per nucleon energy region. HERD will measure the cosmic-ray *knee* directly for the first time. Moreover, it will measure the electron+positron flux up to tens of TeV, in order to look for possible local sources of these leptons. In addition, HERD will be a gamma-ray observatory for multi-messenger astronomy; it will look for cosmic-ray sources and for possible indirect signals of dark matter. In this paper, we briefly discuss the main scientific objectives and the detector characteristics of the HERD experiment.

2. Scientific Objectives

2.1 Proton and nuclei

HERD will measure cosmic rays up to the PeV per nucleon energy region for the first time directly. Thus, it will extend the flux direct measurement of more than one order of magnitude in energy compared to past and currently in-orbit experiments. Moreover, HERD will measure the cosmic-ray *knee* directly for the first time, in order to understand better the origin of this feature of the cosmic-ray flux. In Figure 1a and 1b we plot the predicted proton and Helium flux measurements of HERD.
HERD will measure heavier nuclei too, up to Iron and beyond. Indeed, it will look for possible hardening and softening in the nuclei spectra, since these structures have been already observed



(a) **(b)**

Figure 1: Projection of HERD five years measurement of proton flux (a) and Helium flux (b) [8].

in proton and Helium fluxes [1]. Moreover, it will measure the ratios between different species in order to study the cosmic-ray propagation in the galaxy, such as the Boron-Carbon ratio.

2.2 Electrons and positrons

HERD will extend the direct measurement of the electron+positron flux up to tens of TeV, more than one order of magnitude higher in energy compared to currently in-orbit experiments. It will look for possible local sources of high energy electrons and/or positrons. Indeed, if these high-energy leptons exist, they should be accelerated within few kpc from the Earth, otherwise due to continuous energy loss processes in their path through the galaxy we could not detect them with such high energies. Moreover, if local sources exist, we expect to observe some characteristic structures in the high-energy electron+positron flux. For example, in Figure 2 we report a projection of the HERD high-energy electron+positron flux measurement considering the Supernova Remnant Cygnus Loop as source. We plot two different lines, because we consider two different energy

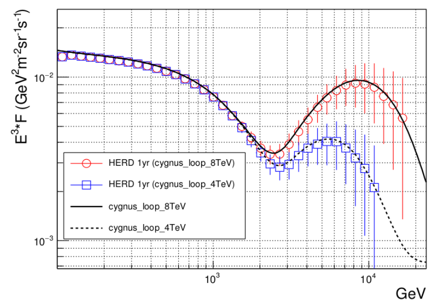


Figure 2: Projection of the HERD electron+positron flux measurement if the SNR Cygnus loop can accelerate high-energy electrons and positrons. Two lines are present, since two different energy cut-offs in the source are considered.[8]

cut-offs in the source. We observe that HERD will be capable to detect structures in the flux related to the presence of this kind of sources.

2.3 Gamma-rays

HERD will also be a gamma-ray observatory. Indeed, it could be used for multi-messenger astronomy, to study the diffuse gamma-ray emission and to look for cosmic-ray acceleration sites.

In addition, it will look for possible indirect signals of dark matter. Indeed, if particle-antiparticle couples of dark matter annihilate in gamma-ray couples, we expect to see a signature in the high-energy gamma-ray spectrum.

3. The detector

The HERD detector is based on a calorimeter with an innovative geometry. Indeed, the calorimeter is constituted by about 7500 LYSO cubic scintillating crystals of side 3 *cm* (equivalent to about 2.6 *radiation length*) assembled in a spheroidal shape. The calorimeter is homogeneous, 3D segmented, finely segmented, isotropic and deep about 55 *radiation length* and about 3 *hadronic interaction length*. In this way the calorimeter is able to detect and reconstruct particle showers coming from every direction with similar performance. This innovative geometry has been studied and designed for the first time by the CaloCube collaboration [10, 11], which has demonstrated the very large geometric acceptance that we can reach with this geometry, with only a small increasing in weight and power consumption compared to currently in-orbit calorimetric experiments, which detect particles entering only from the top face. Moreover, the calorimeter is surrounded by multiple sub-detectors from five sides, all except for the side connected to the space station, as shown in Figure 3. So, the detector can properly detect particles entering from five sides, and it has a

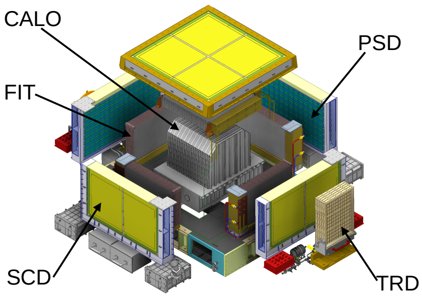


Figure 3: Picture of the HERD detector [12].

geometric factor (geometric acceptance multiplied for detection efficiency) of more than one order of magnitude larger compared to that of currently in-orbit experiments: about 2.4 $m^2 sr$ for electrons and about 1 $m^2 sr$ for protons.

The scintillation light emitted by LYSO crystals is detected through a double read-out [12], in order to have two independent triggers, redundancy and a strong control on the energy scale, one of the main issues for calorimetric space experiments. The first read-out system is based on the use of *WaveLength Shifting Fibers* coupled to *Intensified Scientific* CMOS [13]. The second read-out system, that possibly will be installed, is based on the use of two Photdiodes with different active areas [14, 16]. Both read-out systems are characterized by a low power consumption and an incredibly high dynamic range: larger than 10^7.

The sub-detector nearest to the calorimeter is the *FIber Tracker* (FIT) [17]. It is composed by plastic scintillating fibers read-out by SiPMs, and it is used for particle tracking and low-energy gamma-ray detection. Going outside there is the *Plastic Scintillator Detector* (PSD) [18], constituted by plastic scintillator tails. It measures the particle charges, and it is an anticoincidence system for gamma-ray detection too. The outermost detector is the *Silicon Charge Detector* (SCD) [19], for charge measurement and particle tracking. It is constituted by silicon micro-strip detectors of 300 μm thickness. Moreover, on one face of the detector we have also the *Transitrion Radiation Detector* (TRD) [20]. It will be used in space to tag TeV protons and check the calorimeter calibration at these energies. This innovative system is another valuable tool to check the calorimeter energy scale calibration together with the double read-out system.

4. Conclusion

The HERD experiment is an innovative experiment for the direct detection of cosmic rays, that will be installed on the Chinese space station in 2027. Thanks to its innovative geometry it will have a geometric factor more than one order of magnitude larger compared to that of currently in-orbit experiments. Thanks to its large geometric acceptance, it will extend direct measurements of more than order of magnitude in energy. Indeed, HERD will measure the proton and Helium cosmci-ray *knee* directly for the first time, and it will extend the electron+positron flux measurement up to tens of TeV, looking for possible sources of these high-energy leptons. In addition, HERD will be a gamma-ray observatory for multi-messenger astronomy, and it will look for possible indirect signals of dark matter. We look forward to flight in 2027.

Acknowledgments

The HERD mission is supported by the Italian Space Agency through the ASI - INFN agreement n. 2023-8-HH.0.

References

[1] Adriani O. et Pacini L., Results from high energy direct measurements and future prospects, EPJ Web of Conferences 283, 02001 (2023).

[2] M. Aguilar et al., The Alpha Magnetic Spectrometer (AMS) on the international space station: Part II - Results from the first seven years, Elsevier, Physics Reports 894, 1-116 (2021).

[3] O. Adriani et al., The CALorimetric Electron Telescope (CALET) for high- energy astroparticle physics on the International Space Station, Journal of Physics: Conference Series 632, 012023 (2015).

[4] J. Chang et al., The Dark Matter Particle Explorer mission, Elsevier Astroparticle Physics 95, 6-24 (2017).

[5] The Pierre Auger Collaboration, The Pierre Auger Cosmic Ray Observatory, Nuclear Instruments and Methods in Physics Research A 798, 172-213 (2015).

[6] H. Kaway et al., Telescope Array Experiment, Nuclear Physics B 175-176, 221-226 (2008).

[7] L. Pacini et al., Design and expected performances of the large acceptance calorimeter for the HERD space mission. In Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021), Berlin, Germany, 12-23 July 2021.

[8] P. W. Cattaneo, The space station based detector HERD: precise high energy cosmic rays physics and multimessenger astronomy, Nuclear and Particle Physics Proceedings 306–308 (2019) 85–91.

[9] P. Betti, The HERD experiment: new frontiers in detection of high energy cosmic rays, In Proceedings of XVIII International Conference on Topics in Astroparticle and Underground Physics — PoS(TAUP2023)142, Vienna, Austria, 28 August - 1 September 2023.

[10] E. Vannuccini et al., CaloCube: A new-concept calorimeter for the detection of high-energy cosmic rays in space. Nuclear Instruments and Methods in Physics Research A 845 (2017) 421–424.

[11] O. Adriani et al., The CaloCube calorimeter for high-energy cosmic-ray measurements in space: Response of a large-scale prototype to protons. Nuclear Instruments and Methods in Physics Research A 1061 (2024) 169079.

[12] X. Liu et al., Double read-out system for the calorimeter of the HERD experiment. In Proceedings of 38th International Cosmic Ray Conference — PoS(ICRC2023), Nagoya, Japan, 26 July - 3 August 2023.

[13] X. Liu et al., Optimization of WLS fiber readout for the HERD calorimeter, JINST 18 P09002 (2023).

[14] O. Adriani et al., Development of the photo-diode subsystem for the HERD calorimeter double-readout, JINST 2022, 17, P09002.

[15] P. Betti et al., Photodiode Read-Out System for the Calorimeter of the Herd Experiment. Instruments 2022, 6 33.

[16] P. Betti et al., Double Photodiode Readout System for the Calorimeter of the HERD Experiment: Challenges and New Horizons in Technology for the Direct Detection of High-Energy Cosmic Rays. Instruments 2024, 8 5.

[17] C. Perrina et al., FIT: the scintillating fiber tracker of the HERD space mission. In Proceedings of 37th International Cosmic Ray Conference — PoS(ICRC2021), Berlin, Germany, 12-23 July 2021.

[18] D. Kyratzis et al., The Plastic Scintillator Detector of the HERD space mission. In Proceedings of 38th International Cosmic Ray Conference — PoS(ICRC2023), Nagoya, Japan, 26 July - 3 August 2023.

[19] C. Altomare et al., The Silicon Charge Detector of the High Energy Cosmic Radiation Detection facility. In Proceedings of 38th International Cosmic Ray Conference — PoS(ICRC2023), Nagoya, Japan, 26 July - 3 August 2023.

[20] B. Huang et al., Side-On transition radiation detector: A detector prototype for TeV energy scale calibration of calorimeters in space, Nuclear Inst. and Methods in Physics Research, A 962 (2020) 163723.

PoS(ICHEP2024)682