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The High Energy cosmic-Radiation Detection (HERD) facility: a future space instrument for cosmic-ray detection and gamma-ray astronomy

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The High Energy cosmic-Radiation Detection (HERD) facility is a future space mission, scheduled to start its operation around 2027 aboard the China's Space Station. Thanks to its novel design, based on a homogeneous, isotropic and finely-segmented 3D calorimeter, the detector will have a good particle energy resolution and a large effective geometric factor. With these specifications, the experiment is expected to extend the direct measurements of cosmic rays and gamma rays by at least one order of magnitude in energy with respect to the current limits. In such a way, the space mission aims to accomplish important and frontier goals relative to dark matter search, cosmic ray observations and gamma ray astronomy. In this contribution, a review of the current status of the experiment is presented, with particular regards to the estimated detector performances and the expected physics results.

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1. Introduction

The High Energy cosmic-Radiation Detection (HERD) facility [1] is a future experiment that will be installed aboard the China's Space Station (CSS) around 2027. Based on a novel design that exploits the benefits of a homogeneous, isotropic and finely-segmented 3D calorimeter, the space mission will extend the direct measurements of cosmic rays and gamma rays by at least one order of magnitude in energy with respect to the current limits. In this way, the experiment will be accomplish - with a single instrument - important and frontier goals in different fields of research, involving dark matter search, cosmic ray observations and gamma ray astronomy.

2. Scientific goals

Nowadays, the picture of cosmic rays is much more complex than it was a few decades ago. Most of nuclear species exhibits a clear hardening at a rigidity of around $250 - 500\ GV$ as shown by AMS-02 measurements [2]. Furthermore, the CALET and DAMPE experiments enlightened a softening in the proton flux at an energy of about $10\ TeV$ [3, 4] and in the helium flux at higher energies [5]. On the other side, the knee structure have been measured only inclusively by ground experiments and its origin remains unclear. The HERD experiment will extend the direct measurements of the fluxes of proton and helium up to a few PeV, and of the other nuclear species up to tens or hundreds of TeV/n. For example, Fig.1 top shows the expected proton and helium flux that will be measured in five years of HERD operation. As we can see, the experiment will provide the first direct measurements of the knee structure for at least proton and helium, and will improve the measurements of the spectral features of all nuclear species. These results are of fundamental importance for the understanding of acceleration and propagation mechanisms of cosmic rays.

Electrons and positrons in cosmic rays are of particular interest because of their large energy loss during propagation. Because of this reason, we expect a spectral cutoff around $1\ TeV$, above which only local sources could contribute - with characteristic structures - to the flux. The cutoff was found by the CALET and DAMPE experiments [6, 7], with no evidence of local sources either from the flux or the anisotropy. However, the two results - together with the results of other experiments - are not consistent with each other. 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. Fig.1 bottom shows the expected electron+positron flux that will be measured in five years of HERD operation. Moreover, the analysis of the spectral shape could indirectly give a hint on the origin of the positron excess, discovered by the PAMELA experiment [8] and possibly connected with dark matter.

Dark matter search is one of the main goal of the HERD experiment. This could be associated to a possible clear structure in the electron+positron flux or a possible excess in the gamma-ray emission from a source. For this purpose, the instrument is optimized for the detection of gamma-rays above $100\ MeV$, with an effective area that is about a factor ten smaller than the Fermi-LAT one [9]. The HERD experiment will extend the Fermi-LAT catalog of gamma-ray sources above $300\ GeV$, study the diffuse gamma-ray emission and look for rare gamma-ray events, like Gamma Ray Bursts. This last task will be accomplished in a multimessenger approach, exploiting the synergies with gamma-ray, gravitational-wave and neutrino observatories at ground.

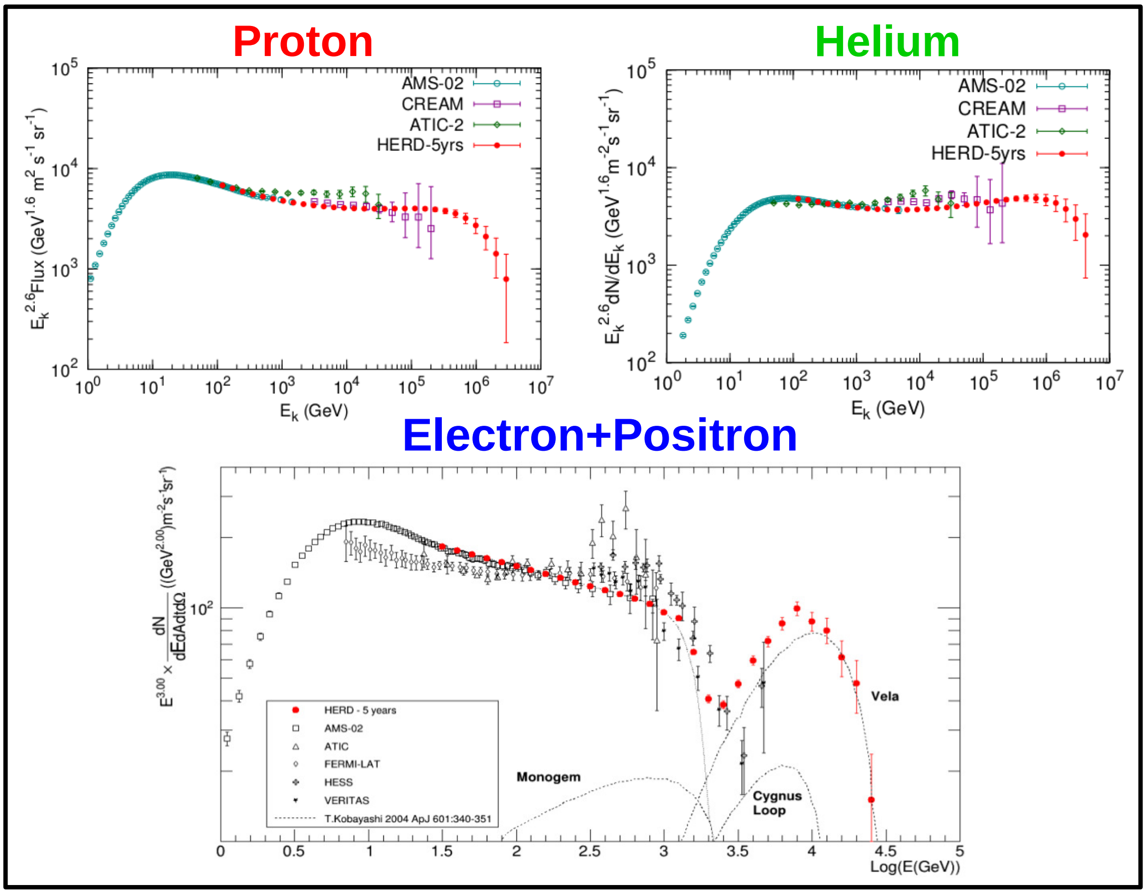

Figure 1: Expected flux in five years of HERD operation for proton, helium and electron+positron.

3. Detector design

Since the flux of cosmic rays steeply decreases as a function of energy, a large effective geometric factor G_{eff} and a good energy resolution σ_E/E are necessary to extend the current measurements to higher energies. Because of the strong mass constraints of a space apparatus, the detector must be carefully optimized to match these requirements. As summarized in Tab.1, the HERD experiment is designed to reach G_{eff} higher than 2 $m^2 sr$ for $e^- + e^+$ and 1 $m^2 sr$ for p and nuclei, and σ_E/E better than 2% for $e^- + e^+$ and 30% for p and nuclei. This is possible thanks to an innovative geometry based on a homogeneous, isotropic and finely-segmented 3D calorimeter, as demonstrated by the Calocube collaboration [10–18]. As shown in Fig.2, the calorimeter (CALO) is the main instrument of the HERD detector and is made of LYSO cubic crystals of 3 cm side arranged in an octagonal shape. The detector depth among the main directions is 21 cubes, corresponding to 55 X_0 and 3 λ_I, ensuring a good energy resolution. This geometry ensures good reconstruction performances for particles impinging not only from the top face, but also from the lateral ones, strongly increasing the geometric factor with respect to the limits of the current experiments. Finally, the fine segmentation of the calorimeter is important to reach a proton rejection factor of 10^6, necessary to extend the electron+positron flux to the high energy region.

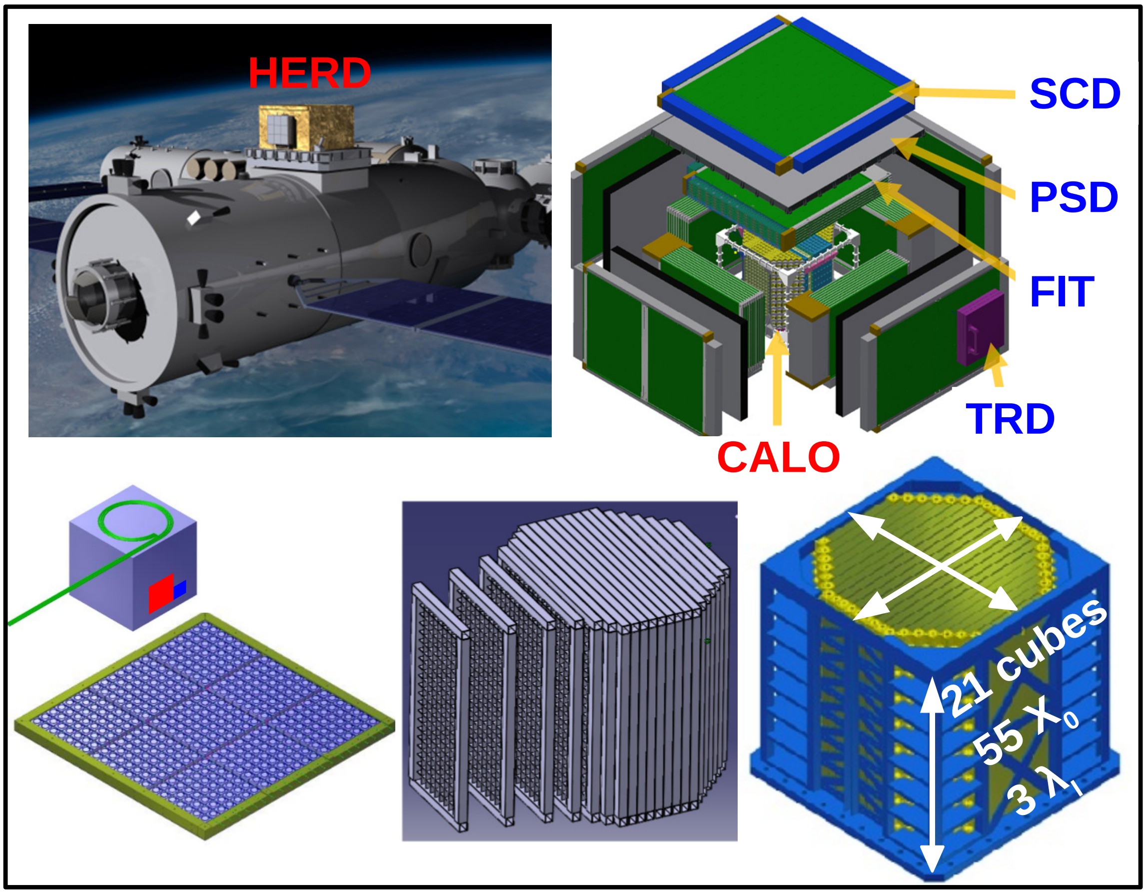

Figure 2: Outline of the HERD experiment. Top: left is an artist's impression of the facility on the CSS, right is a schematic design of the detector in the current configuration. Bottom: schematic design of the calorimeter, from the single LYSO crystal on the left to the final mechanical structure on the right.

The performances of such an innovative design have been investigated using Monte Carlo simulations and confirmed by prototype beam test. As shown in Fig.3 [19], the critical parameter that affects both the energy resolution and the effective acceptance is the depth of the calorimeter effectively traversed by the shower. Because the arrival direction of cosmic rays is isotropic, the longitudinal (and lateral) shower containment strongly fluctuates event-by-event. In the case of electromagnetic showers, the design values of G_{eff} and σ_E/E are matched at all energies by requiring a track length in the calorimeter that is larger than 30 cm. In the case of hadronic showers, the relevant quantity is not simply the track length, but the shower length, *i.e.* the distance between the point where the first hadronic interaction occurs and the point where the shower leaks out from the calorimeter. In both cases, it is interesting to note that the detector performances in the analysis can be varied by changing the minimum threshold on the effective length. This is an important feature at high energies -where the statistics will be very limited-, since it allows for a further increase of the effective acceptance at the price of a worsening of the energy resolution. A further improvement of the performances is expected from the on-going optimization of the final detector, which aims to smooth the edges of the calorimeter in order to increase the isotropy of the design.

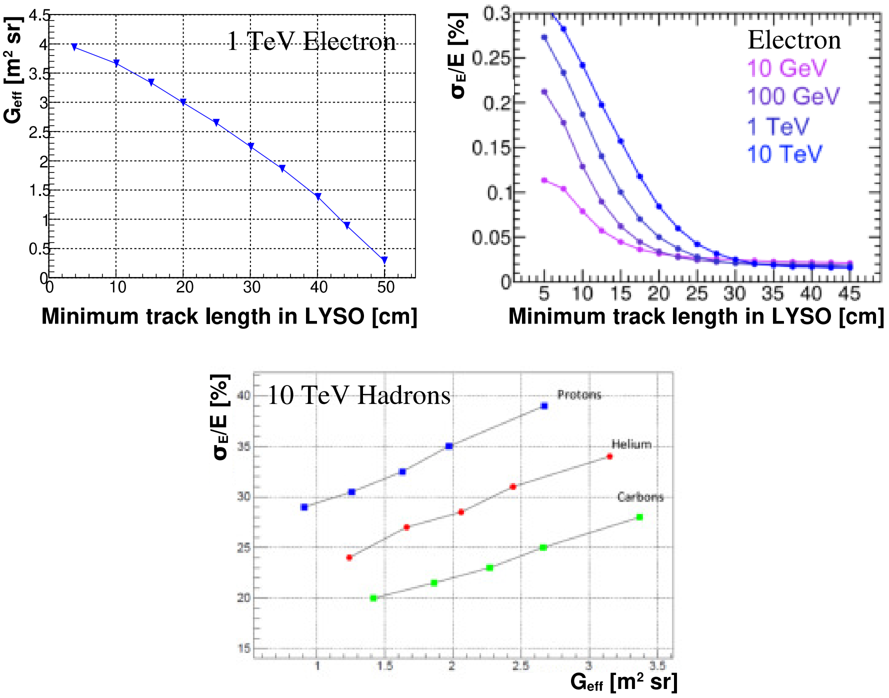

Figure 3: Expected performances of the HERD calorimeter obtained using GEANT4 simulations. Top: dependence of the G_{eff} for 1 TeV electrons (left) and of σ_E/E for 10 GeV – 10 TeV electrons (left) on the minimum track length required for the analysis. Bottom: behavior of G_{eff} versus σ_E/E for 1 TeV p, He and C nuclei (the different points corresponds to different threshold on the minimum shower length).

A critical issue of calorimetric experiments in space is the control of the absolute energy scale, due both to instrumental effects and simulation uncertainties. The HERD detector is designed to strongly reduce this systematic effect in two different ways. The first strategy is to equip each LYSO crystal with two independent readout systems, in such a way to not only increase the redundancy, but also improve the single channel cross-calibration capability. The two readout systems, shown in Fig.4, are wavelength shifting fibers coupled to Intensified scientific CMOS (IsCMOS), and photodiodes coupled to low noise electronics developed for space applications (HiDRA) [20, 21]. The second strategy is the usage of a Transition Radiation Detector (TRD), installed on a side of the instrument, to calibrate the response of the calorimeter to hadronic showers generated by $1-10$ TeV incident protons. The TRD, made of a polypropylene+air radiator and a THGEM detector, will be calibrated using $0.5-5$ GeV electrons from a test beam at ground and cosmic-rays in space.

	γ	$e^- + e^+$	p, nuclei
Energy Range	$> 100\ MeV$	$10\ GeV - 30\ TeV$	$30\ GeV - 3\ PeV$
σ_E/E	$< 2\%$ @ $200\ GeV$	$< 2\%$ @ $200\ GeV$	$< 30\%$ @ $100\ TeV$
G_{eff}	$> 0.2\ m^2$ @ $200\ GeV$	$> 2\ m^2 sr$ @ $200\ GeV$	$> 1\ m^2 sr$ @ $100\ TeV$

Table 1: Main specifications of the HERD experiment: for each particle we report the range, the energy resolution and the effective geometric factor (effective area in the case of gamma-rays).

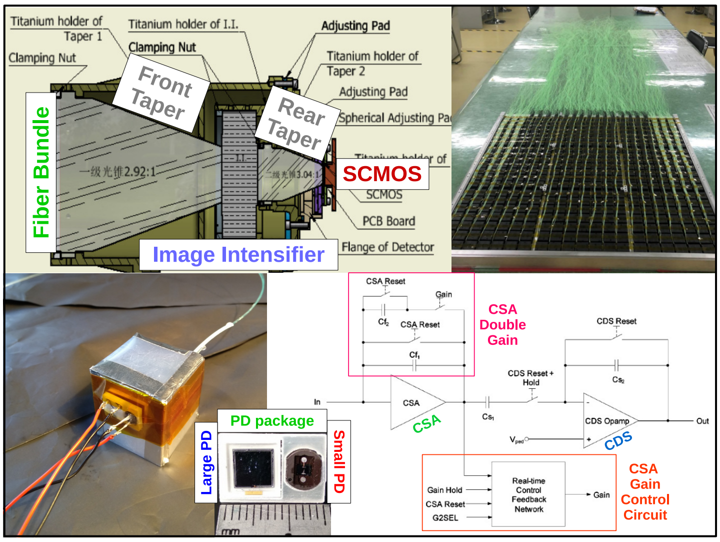

Figure 4: Read-out system of the HERD calorimeter. From top to bottom and left to right: schematic illustration of the IsCMOS sensor; a layer fully equipped with cubes readout by wavelength shifting fibers; a cube instrumented with both wavelength shifting fiber and photodiode readout systems; a prototypal study for the monolithic package used for the photodiode readout; and HiDRA schematic design.

The CALO is surrounded on five sides by the FIber Tracker (FIT) [22], the Plastic Scintillator Detector (PSD) [23] and the Silicon Charge Detector (SCD). For each of the five sides, the FIT is composed of 7 x-y layers of scintillating fiber mats coupled to SiPM arrays, the PSD consists in 2 layers of plastic scintillator tiles readout by SiPM, and the SCD is made of 4 x-y layers of silicon microstrip detectors. The main purpose of the FIT is track reconstruction, which is accomplished with a resolution of about 0.1° for 10 GeV gamma-rays. The PSD is dedicated to gamma-ray identification, with a rejection efficiency higher than 99.98% for charged particles. The main purpose of the SCD is charge reconstruction, which is accomplished with a resolution of about $0.05 - 0.15$ charge unit (using also the information from PSD and FIT). The three subdetectors are designed in order to improve charge reconstruction by decreasing the effect of two serious problems that affect the current experiments: calorimeter backscattering and nuclear fragmentation. Backscattering, which is very significant at high energies, is reduced adopting a fine segmentation of the detector. Fragmentation, which spoils the identification of heavy nuclei, is reduced by placing the main charge detector (SCD) in the outermost position.

4. Conclusions

The HERD experiment is scheduled to start its operation around 2027 aboard the CSS. The detector exploits an innovative design based on a homogeneous, isotropic and finely-segmented 3D calorimeter, leading to good energy resolution and large geometric factor. These features allow the experiment to extend the direct measurements of cosmic rays and gamma rays by at least one order of magnitude in energy with respect to the current limits. In the field of cosmic rays, it will achieve fundamental results necessary to improve our understanding of acceleration and propagation mechanisms, in particular with the first direct measurement of the knee structure for at least the proton and the helium fluxes. In the field of gamma-rays, it will search for rare events in a multimessenger approach and will extend the Fermi-LAT catalog to higher energies. With such a large number of observation channels available to a single instrument, the experiment will search for an indirect evidence of dark matter, possibly associated to a clear structure in the electron+positron flux or an excess in the gamma-ray emission from a source.

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