IL NUOVO CIMENTO **44 C** (2021) 85
DOI 10.1393/ncc/i2021-21085-6

COMMUNICATIONS: SIF Congress 2020

Design, development and realization of the calorimeter for the HERD experiment

E. BERTI([1])([2])(*) on behalf of the HERD COLLABORATION

([1]) *University of Florence - Florence, Italy*
([2]) *INFN Section of Florence - Florence, Italy*

received 14 January 2021

Summary. — The High Energy cosmic-Radiation Detection (HERD) facility is a China-led international space mission that will start its operation on board the future China's Space Station around 2025. The experiment aims to accomplish with a single instrument important scientific goals in a wide range of research fields, including cosmic-ray physics, gamma-ray astronomy and dark-matter search. These achievements will be possible thanks to its novel design, based on a 3D, homogeneous, isotropic and finely segmented calorimeter. In this paper we describe the calorimeter of the HERD experiment, from its basic idea to the optimization of the geometry, the development of the hardware, and the estimation of the expected performances.

1. – The HERD experiment

The High Energy cosmic-Radiation Detection (HERD) facility [1] is a China-led international space mission with fundamental contributions from two Italian institutes (INFN and ASI) that will start its operation on board the future China's Space Station around 2025. Based on a novel design that exploits the benefits of a 3D, homogeneous, isotropic and finely segmented calorimeter, the experiment will extend by at least one order of magnitude in energy the measurements expected by the instruments currently operating in space. In this way, it will accomplish important and frontier goals in different fields of research, involving cosmic-ray physics, gamma-ray astronomy and dark-matter search. In particular, the two main scientific goals of the HERD mission are: 1) the search for dark matter annihilation signatures both extending the electron+positron flux measurements up to a few tens of TeV [2] and looking for an unexpected excess of gamma rays from different astrophysical sources [3], and 2) the first direct measurements of proton and helium fluxes up to a few PeV, in order to test the different hypotheses on the origin of the so-called *knee* structure in this energy region.

(*) E-mail: `eugenio.berti@fi.infn.it`

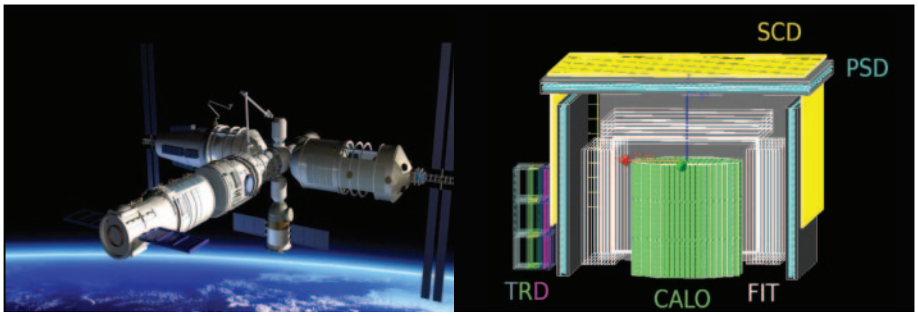

Fig. 1. – Left: artistic representation of the future China's Space Station where the HERD experiment will be installed. Right: overview of the HERD detector design, made of a central CALOrimeter (CALO), FIber Tracker (FIT), Plastic Scintillator Detector (PSD), Silicon Charge Detector (SCD) and Transition Radiation Detector (TRD).

2. – The HERD instrument

The flux of cosmic rays steeply decreases as a function of energy, following a power law with a spectral index that depends on the particle type. Thus, if we want to extend the direct cosmic ray measurements to higher energy, it is mandatory to optimize the detector design in order to have a large effective geometric factor G_{eff} and a good energy resolution σ_E/E. HERD is designed to reach G_{eff} higher than 3 m^2sr for $e^+ + e^-$ and 2 m^2sr for p and nuclei, and σ_E/E better than 2% for $e^+ + e^-$ and 30% for p and nuclei. These requirements are obtained thanks to the innovative geometry shown in fig. 1 that exploits a calorimeter as the main instrument. The CALOrimeter (CALO) is used for the reconstruction of the incident energy, for electron/proton discrimination and for the trigger of the experiment. CALO is surrounded by three subdetectors: the FIber Tracker (FIT), made of several layers of scintillating fibers; the Plastic Scintillator Detector (PSD), made of two layers of plastic scintillator bars or tiles; the Silicon Charge Detector (SCD), made of a few layers of silicon microstrip detectors. These detectors are necessary to reconstruct the incident charge (SCD, PSD, FIT) and the incident trajectory (SCD, FIT). An additional detector, the Transition Radiation Detector (TRD), is placed on a side of the instrument to calibrate the response of the calorimeter for the reconstruction of the incident energy, in order to control the absolute energy scale of the apparatus.

3. – The HERD calorimeter

As demonstrated from the results of the CaloCube collaboration (led by the Florence secion of INFN) [4-8], it is possible to match the required performances exploiting a geometry based on a 3D, homogeneous, isotropic and finely segmented calorimeter. Figure 2(top) shows the design of the HERD calorimeter, made of LYSO cubic crystals of 3 cm side arranged in an octagonal shape, so that the detector depth among the main directions is 21 cubes/55 X_0/3 λ_I, therefore ensuring a good σ_E/E. Differently from the experiments currently operating in space, reconstruction performances are good for particles impinging the detector not only from the top face, but also from the lateral sides, therefore leading to a large G_{eff}. In addition, the fine segmentation of the calorimeter allows for an excellent separation of electromagnetic and hadronic showers, thus giving the 10^6 proton rejection factor required to extend the $e^+ + e^-$ flux measurement at higher energies. Figure 2(bottom) shows the largest HERD calorimeter prototype so far realized. In particular, we can see two cubes corresponding to the two different read-out schemes that have been suggested for the single channel: wavelength shifting fibers

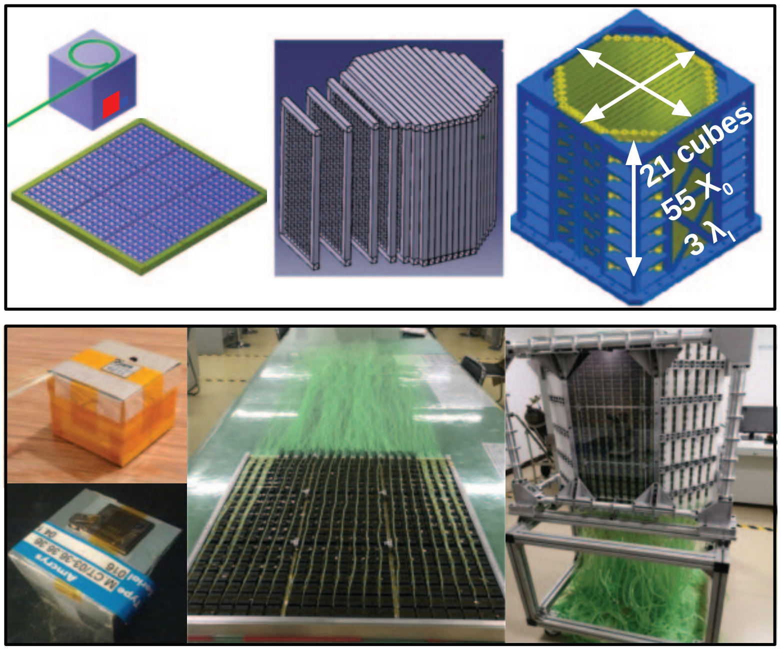

Fig. 2. – Top: HERD calorimeter schematic design: from left to right, the single crystal with the three WLSs and the two PDs, a tray of crystals, the trays assembled to form the octagonal prism and the final detector with the mechanical structure. Bottom: HERD calorimeter hardware prototypes: from left to right, two crystals equipped with three WLSs or two PDs, a full layer made of 21×21 crystals and a large-scale prototype designed for AIT verification.

(WLSs) coupled to an Intensified scientific CMOS (IsCMOS [9]) and photodiodes (PDs) coupled to a low noise electronics developed for space applications (HiDRA [10]). In both cases, more than one sensor is needed to cover the 10^7 dynamic range required to detect a deposit in the crystal from a few fraction of MIP needed for channel calibration (10 MeV) to the shower maximum of a 1 PeV proton (100 TeV). All crystals will be equipped with WLSs and a fraction or all of them will be equipped with PDs in order to increase the redundancy of the system and to allow for additional sensor cross calibration. The performances of the HERD calorimeter were investigated both using simulations and prototypes. A large contribution to these studies was given by the CaloCube Collaboration, using a slightly different design with no significant change in the conclusions. Figure 3(top) shows simulation studies relative to high energy protons: we concluded that LYSO crystal is the best candidate for our application, allowing for the best σ_E/E and largest G_{eff} among the materials tested, without a significant dependency of these parameters in the range 1 TeV–1 PeV. Figure 3(bottom) shows prototype results for the reconstruction of electromagnetic showers in the range 50 GeV–280 GeV: we can see that, combining the information in large and small PDs (corresponding to low and high energy deposit), nonlinearity and energy resolution are better than 1% and 1.5%, respectively.

4. – Conclusions and prospects

Thanks to its novel design, based on a 3D, homogeneous, isotropic and finely segmented calorimeter, the High Energy cosmic-Radiation Detection (HERD) experiment

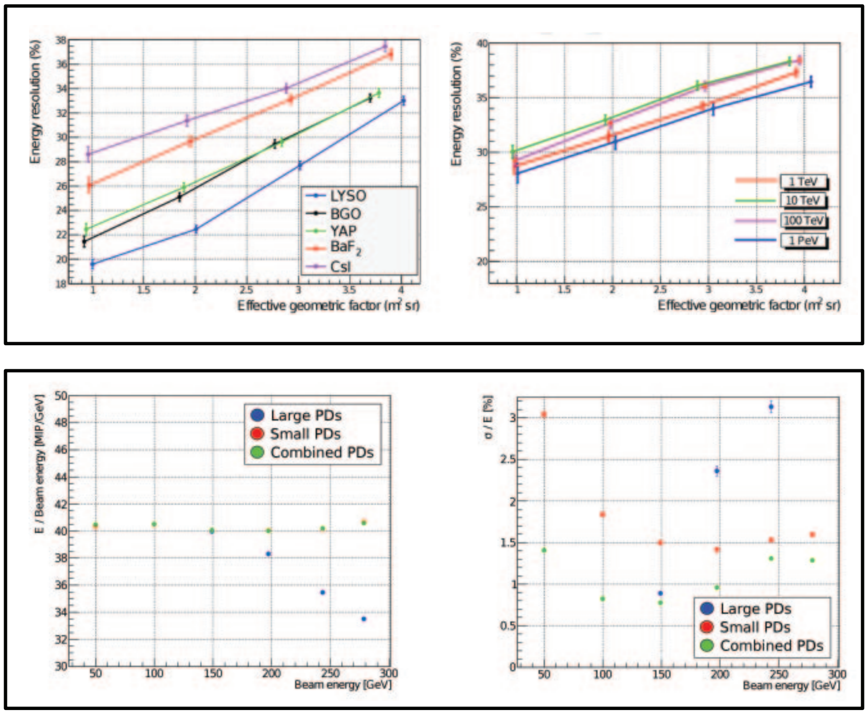

Fig. 3. – Top: performances expected from simulations for high energy protons: dependence on the scintillator crystal used to build the calorimeter for 1 TeV energy (left) and on the proton incident energy in the range 1 TeV–1 PeV (right) [11]. Bottom: Performances obtained from the prototype for incident electrons in the energy range 50 GeV–280 GeV: average deposit/beam energy (left) and energy resolution (right) [12]. Note that energy is reconstructed using large PDs only (blue), small PDs only (red) or combining the two information (green).

will accomplish important scientific goals in a wide range of research fields, including cosmic-ray physics, gamma-ray astronomy and dark-matter search. While the design of the calorimeter have been mostly defined, in the next year we plan to use simulations to investigate the performances of the whole HERD instrument, and to build a large HERD prototype where we will also test the double read-out scheme of the calorimeter for the first time.

REFERENCES

[1] Zhang S. N. *et al.*, *Proc. SPIE*, **91440X** (2014).
[2] Fang K. *et al.*, arXiv:1706.03745 (2017).
[3] Huang X. *et al.*, arXiv:1509.02672 (2016).
[4] Vannuccini E. *et al.*, *Nucl. Instrum. Methods A*, **845** (2017) 421.
[5] Adriani O. *et al.*, *Nucl. Instrum. Methods A*, **824** (2016) 609.
[6] Bongi M. *et al.*, *J. Phys.: Conf. Ser.*, **587** (2015) 012029.
[7] Pacini L. *et al.*, *J. Phys.: Conf. Ser.*, **298** (2017) 012013.
[8] Adriani O. *et al.*, *JINST*, **14** (2019) P11004.
[9] Dong Y. *et al.*, *Proc. Sci.*, **2017** (2017) 253.
[10] Bonvicini V. *et al.*, *IEEE Trans. Nucl. Sci.*, **57** (2010) 2963.
[11] Adriani O. *et al.*, *Astropart. Phys.*, **96** (2017) 1117.
[12] Berti E. *et al.*, *J. Phys.: Conf. Ser.*, **1162** (2019) 012042.