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Double read-out system for the calorimeter of the HERD experiment

X. Liu,[a,b,*] O. Adriani,[c,d] X. H. Bai,[e] Y. L. Bai,[e] T. W. Bao,[a] E. Berti,[c] P. Betti,[c,d] S. Bottai,[c] W. W. Cao,[e] J. Casaus,[f] Z. Chen,[e] X. Z. Cui,[a] Y. Y. Dai,[a] R. D'Alessandro,[c,d] Y. W. Dong,[a] W. J. Duan,[a,m] V. Formato,[g] J. R. Gao,[e] F. Giovacchini,[f] J. F. Han,[h] R. Li,[e] X. Z. Liang,[e] C. L. Liao,[a,b] Y. P. Lu,[a] L. W. Lyu,[e] J. Marin,[f] G. Martinez,[f] N. Mori,[c] L. Pacini,[c] R. Pillera,[i] C. Pizzolotto,[j] J. J. Qin,[e] Z. Quan,[a] D. L. Shi,[e] O. Starodubtsev,[c] A. Tiberio,[c,d] V. Vagelli,[k,l] M. A. Velasco,[f] L. D. Venere,[i] B. Wang,[e] J. J. Wang,[a] L. Wang,[e] R. J. Wang,[a] Z. G. Wang,[a] M. Xu,[a] G. Zampa,[j] N. Zampa,[j] L. Zhang[a] and J. K. Zheng[e] on behalf of the HERD collaboration

(a complete list of authors can be found at the end of the proceedings)

[a] *Institute of High Energy Physics, Chinese Academy of Sciences, 100049, Beijing, China*
[b] *University of Chinese Academy of Sciences, 101408, Beijing, China*
[c] *INFN sezione di Firenze, I-50019 Sesto Fiorentino, Florence, Italy*
[d] *Department of Physics and Astronomy, University of Florence, I-50019 Sesto Fiorentino, Florence, Italy*
[e] *Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, 710119, Xi'an, China*
[f] *Centro de Investigaciones Energéticas, Medioambientales y Tecnoló gicas (CIEMAT), E-28040, Madrid, Spain*
[g] *INFN Sezione di Roma Tor Vergata, 00133, Roma, Italy*
[h] *Institute of Nuclear Science and Technology, Sichuan University, 610065, Chengdu, China*
[i] *INFN Sezione di Bari, 70126, Bari, Italy*
[j] *INFN Sezione di Trieste, I-34149, Trieste, Italy*
[k] *Agenzia Spaziale Italiana (ASI), I-00133, Roma, Italy*
[l] *INFN Sezione di Perugia, I-06123, Perugia, Italy*
[m] *State Key Laboratory of High Power Semiconductor Lasers, Changchun University of Science and Technology, 130022, Changchun, China*

E-mail: xliu@ihep.ac.cn

[*] Speaker

The High Energy cosmic-Radiation Detection (HERD) facility has been proposed as a space cosmic-ray and gamma-ray detector, which will be installed on the China Space Station around 2027. HERD will be able to measure proton and nuclei fluxes up to the cosmic ray knee region (about 1 PeV), electron + positron flux up to tens of TeV and gamma rays above 100 MeV. The CALO, a homogeneous and 3D segmented calorimeter, is the core detector of HERD. It consists of about 7500 LYSO cubes with 3 cm side length, corresponding to about 55 radiation lengths (X0) and 3 nuclear interaction lengths for centrally incident particles in any direction. The fluorescence light produce by each LYSO cube is read out using two independent systems. The first one uses wavelength shifting fibers to deliver the light to Intensified scientific CMOS(IsCMOS) cameras, whereas the second one makes use of photo-diode sensors. Both systems feature a dynamic range larger than 10^7. In this paper we will report the status of the CALO hardware and Monte Carlo simulation studies on its performance.

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1. Introduction

The High Energy cosmic-Radiation Detection (HERD) facility has been proposed as a space astronomy and particle physics experiment, scheduled to be installed on the China Space Station around 2027. Its primary scientific objectives are to search for dark matter signals in the energy spectra and anisotropy of high-energy electrons and gamma-rays, precisely measure the energy spectra and composition of primary cosmic rays up to the knee energy, as well as to monitor the high-energy gamma-ray sky.[1] [2][3][4],

HERD consists of a 3-D cubic imaging calorimeter (CALO)[5] surrounded by scintillating fiber trackers (FITs)[6] on the top and on the four lateral sides. The CALO and FIT are then covered by a plastic scintillator detector (PSD) [7] and a Silicon Charge Detector (SCD). A Transition Radiation Detector (TRD) [8] is located on one of the lateral side, as showed in Figure 1. The maximum size of the envelope in orbit is approximately 4.3×2.6×1.9 m^3, with a weight of around 4400 kg.

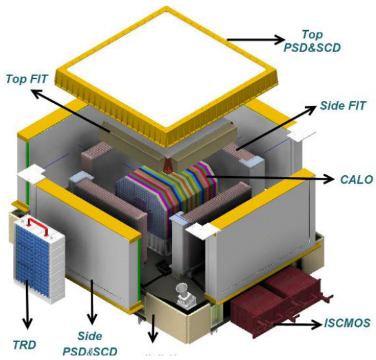


Figure 1: Explosive view of HERD payload.

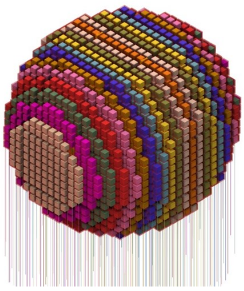
The FIT, comprising scintillating fibers read out by Silicon PhotoMultipliers (SiPM), is primarily designed for particle tracking and charge measurement. The PSD, consisting of plastic scintillators read out by SiPMs, is for trigger of low energy gamma and measures charge. The SCD comprises several layers of silicon micro-strip, will precisely measure the absolute charge of incoming particles. The TRD is composed of THick Gaseous Electron Multipliers(THGEM) and is designed for calibration of TeV nuclei. The main requirements of the HERD payload are summarized in table 1.

2. HERD calorimeter

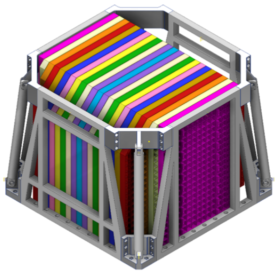
The CALO is the core detector of HERD, will detect the energy and discriminate between electrons and protons by shower morphology. It is a homogeneous, 3D segmented calorimeter composed of approximately 7500 LYSO cubes with side lengths of 3cm. The CALO external envelope is similar to a spherical shape, while the crystals are arranged in vertical layers featuring different LYSO layouts, as Figure 2 shown. The total depth of the CALO is about 55 radiation lengths(X0) and 3 nuclear interaction lengths for centrally incident particles in any direction, respectively. The effective geometrical factor of CALO is about one order of magnitude larger than previous cosmic ray calorimeters.

Table 1: Main requirements of the HERD payload

Item	Value
Energy range(e/γ)	10 GeV - 100 TeV; >0.1 GeV(γ)
Energy range(nucleus)	30 GeV - 3 PeV
Charge measurement(nucleus)	0.05 - 0.15 c.u.
Energy resolution(e)	1% @ 200 GeV
Energy resolution(p)	20% @ 100 GeV - PeV
e/p separation	$\sim 10^{-6}$
Angular resolution(e/γ)	0.1 deg.@10 GeV
Geometric factor(e)	>3 m^2Sr @ 200 GeV
Geometric factor(p)	>2 m^2Sr @ 100 GeV



(a) LYSO crystal array



(b) Structure outline

Figure 2: Images of CALO crystal array and its supporting stucture.

Each LYSO's fluorescence is read out in two independent read-out systems: the first system employs wavelength-shifting (WLS) fiber to deliver the light to Intensified scientific CMOS (IsCMOS) cameras, the second system uses photodiode (PD) sensors connected to custom front-end electronics chips[9], as shown in Figure 3. The reliability of the CALO in-orbit data acquisition can be significantly improved by cross-calibration between these double read-out systems.

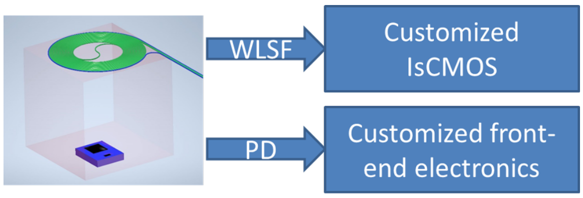


Figure 3: Scheme of double read-out systems.

2.1 WLS fiber readout

Each LYSO is equipped with two WLS fibers attached to one of its surfaces, and both ends of each fiber are used for fluorescence readout. Two fiber ends connect to a high-range IsCMOS and a low-range IsCMOS respectively, while the other two ends are linked to a trigger system. To achieve optimal amplitude in WLS fiber readout and meet mechanical environment requirements, the LYSO surface affixed to PD is roughened and the other five surfaces are polished. The WLS fiber and interior of LYSO are depicted in Figure 4 (a).

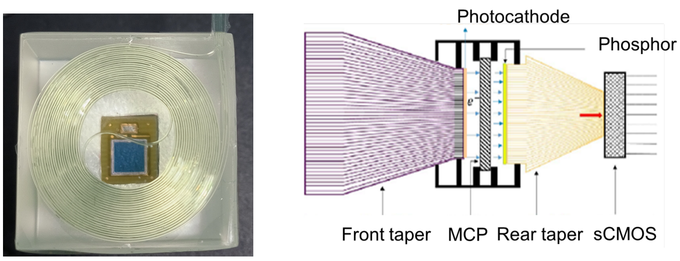
Each IsCMOS includes an Image Intensifier (II) and a scientific CMOS camera, providing a dynamic range of 5000. The light emitted from the WLS fiber is converted into electrons on the photocathode through a front taper in II, then multiplied on a microchannel plate (MCP), reconverted to photons via phosphor, and finally focused on the CMOS camera by a rear taper.[5]. A schematic of IsCMOS is shown in Figure 4 (b).

The two IsCMOS have different electron multipliers in their MCPs, with one IsCMOS featuring relatively high magnification for low-range imaging and the other serving as the high-range option. By selecting specific MCP gain values, the two IsCMOS combined can achieve a dynamic range of over 10^7 times . The phosphor's decay time is approximately $200us$, and the CMOS has a high frame rate (>800 frames per second) and low readout noise (<1.5 electrons)[5].

To optimize the amplitude distribution of the four WLS fiber ends, two 0.3 mm diameter WLS fibers are wound in different loops. The inner fiber (Kuraray Y-11(200)MS) is wound 11 loops, while the outer fiber (Kuraray Y-11(100)MS) makes a single loop around the inner one(Figure 4 (a)). The minimum length of the fiber outside LYSO is 2.4 meters, ensuring connectivity to the fiber at the farthest position relative to IsCMOS and consistent light output across all fibers within their respective ranges. The inner fiber end has a larger contact area with LYSO, resulting in a higher light output compared to the outer one. The ratio of light output between the inner and outer fiber ends is approximately 15:1.

In order to achieve a good signal-to-noise (S/N) ratio, one end of the inner fiber is chosen as the low-range output. An outer fiber end is connected to high-range IsCMOS as the high-range output, because the high-range IsCMOS is designed to operate in lower light levels than the low-range IsCMOS to prevent saturation. The remaining two fiber ends are directed to the trigger system. The fibers' winding section is coated with silicone elastomer (DOW CORNING Sylgard 184) and then molded into a 0.8 mm thick mat to optimize the coupling efficiency with the LYSO surface(Figure 4 (a)).

The fibers dedicated to the trigger systems are grouped to couple with several Photo Multiplier Tubes(PMT) that provide fast trigger information regarding energy deposition in specific regions. The read out of both fiber ends can backup each other within the trigger system.



(a) Photo of WLS fiber mat attached to LYSO

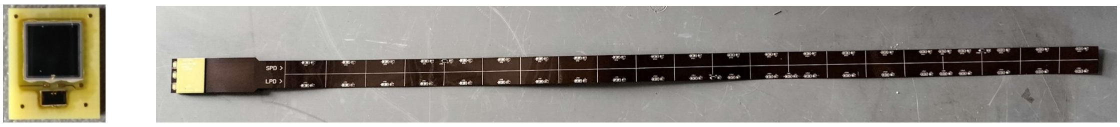
(b) IsCMOS

Figure 4: WLS fiber readout.

2.2 PD readout

The configuration of the HERD PD read-out system benefits from the CaloCube project experience[10]. A monolithic package comprising a Large PD (LPD) and a small PD(SPD) is affixed to the opposite face with respect the one attached with WLS fibers mat[9], as illustrated in Figure 4 (a). The active area of LPD and SPD are 25 mm^2 and 1.6 mm^2, respectively, as shown in Figure 5 (a). An optical filter with a transmittance of about 1.5% will be applied to the active area of the SPD, the final LPD-to-SPD signal ratio is approximately 1500:1.

The main component of the front-end electronics is called HiDRA2, based on the CASIS ASIC developed by INFN for space experiments[11]. It features low noise (about 2500 electrons), low power consumption (2.8 mW/channel), and large dynamic range (from few fC to 52.6 pC). The gain is automatically selected on an event-by-event basis for each channel, enabling a high dynamic range of the FEE without increasing the number of channels. The ratio between high-gain and low-gain is about 20. PDs are connected to the FEE via specifically designed Kapton cables, as shown in Figure 5 (b). Every cable can simultaneously connect up to 21 pairs of PDs of 21 crystals and is approximately 80 cm in length. The expected saturation level for the SPD is about 250 TeV per channel, which provides sufficient capability to accurately measure hadronic showers in the PeV energy range.



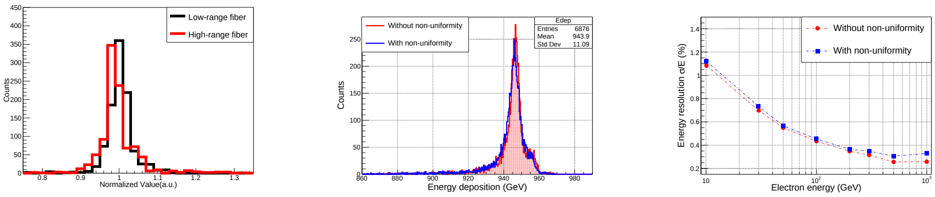
(a) PD (b) Kapton cable

Figure 5: Photos of a monolithic package of PDs and a Kapton cable.

3. Impact of WLS fiber amplitude non-uniformity on energy resolution.

A Monte Carlo simulation is conducted to investigate the energy resolution, as there is non-uniformity in signal amplitude within the crystal due to structural read-out asymmetry. The X-ray measurement data on surface position non-uniformity are used to generate a positional correlation factor matrix for the entire LYSO cube. In detail, the cube is divided into 3 mm cubic units, and all normalized measurement data obtained from surface measurement by X-ray tube are utilized as the response weight for the outermost layer of the cube. Duplicate position data are excluded and replaced with their average values. The internal response of the cube is determined by averaging the projected data onto its four lateral faces. Based on the WLS fiber read-out configuration, the corresponding distributions of the low-range and high-range fiber are showed in Figure 6 (a).

Energy deposition in HERD CALO is simulated with the data of positional correlation factor matrix. A crystal array geometry model consisting of 21×21×21 LYSO cubes is built in Geant4.10.7.2, and an isotropic electron particle gun with energies ranging from 10 to 1000 GeV is set up. For deposition energies below 150 GeV in a single cube, the low-range fiber output is applied, whereas for higher energies, the high-range fiber is employed to simulate the practical high/low



(a) Derived distribution of low-range and high-range fiber

(b) Reconstructed energy spectra of 1000 GeV electrons

(c) Electron energy resolution

Figure 6: Derived distribution of amplitude non-uniformity and simulation result. (a): Derived distribution of low-range and high-range fiber signal amplitude within the entire cube, each data is normalized by the average of all data in respective range. (b) The comparison of reconstructed electron energy spectra with and without position response non-uniformity within the cube at 1000 GeV. (c) The comparison of electron energy resolution with energies ranging from 10 to 1000 GeV.

range read-out configurations. To emphasize the impact of signal amplitude non-uniformity and exclude other factors, dead layer and crystal light yield are not incorporated in the simulation.

The reconstructed electron energy spectra at 1000 GeV and electron energy resolution with energies ranging from 10 to 1000 GeV are showed in Figure 6 (b) and (c), wherein the corresponding results without non-uniformity are add for comparison. Considering the non-uniformity within the cube, there is a maximum energy resolution variation of approximately 0.07‰ at an energy level of 1000 GeV. This value represents a small fraction effect on the performance of CALO's energy resolution. Currently, extrapolated data on non-uniformity is obtained from X-ray with an upper energy limit of 50keV. To obtain results that are closer to actual response, it will be necessary to test for amplitude non-uniformity using minimum ionized particles.

4. Summary

HERD has been proposed as a space astronomy and particle physics experiment that will be installed on the China Space Station around 2027. The CALO, serving as the core detector, is a homogeneous, 3D segmented calorimeter composed of about 7500 LYSO cubes. The fluorescence emitted by each cube is read out using two independent systems. The first system employs WLS fiber to deliver the light to IsCMOS cameras, the second system uses PD sensors connected to custom front-end electronics chips. A Monte Carlo simulation is conducted to investigate the energy resolution by taking account to the non-uniformity in signal amplitude within the crystal and showed a small fraction effect on the performance of CALO's energy resolution. A new prototype of CALO, consisting of 1029(7×7×21) LYSO cubes equipped with WLS fibers and PDs for readout, is currently under construction. It is scheduled to be tested at the CERN PS and SPD beamline in 2023.

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