PROCEEDINGS OF SCIENCE

A novel 3-D calorimeter for the High Energy cosmic-Radiation Detection (HERD) Facility onboard China's Future Space Station

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The High Energy cosmic-Radiation Detection (HERD) facility is a flagship and landmark scientific experiment onboard China's Space Station, planned for operation starting around 2025 for about 10 years. The main instrument of HERD is a 3-D calorimeter (CALO) sensitive to incident gamma-rays and particles from five sides. With this design, the effective geometric factor of HERD is more than one order of magnitude larger than that of previous missions. CALO is made of about 7,500 cubes of LYSO crystals, corresponding to about 55 radiation lengths and 3 nuclear interaction lengths, respectively. The crystal signals are transferred by wavelength shifting fibers and read out by ISCMOS devices. Energy deposition in each crystal is then derived by summing up about 400 CMOS pixels and with necessary correction for light saturation. Both a low range ISCMOS and a high range one are required to meet the requirement of a large dynamic range of at least 10 million. The prototype of CALO has been tested successfully in November 2015 at CERN, which leads to an improved design of CALO.

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1. Introduction

The High Energy cosmic-Radiation Detection (HERD) facility is one of several space astronomy payloads of the cosmic light house program onboard China's Space Station, which is planned for operation starting around 2025 for about 10 years[1].

The primary scientific objectives of HERD are: (1) searching for signatures of the annihilation products of dark matter particles in the energy spectra and anisotropy of high energy electrons and gamma-rays [2] from 500 MeV to 10 TeV; (2) measuring precisely and directly the energy spectra and composition of primary cosmic rays from 10 GeV up to PeV. The secondary scientific objectives of HERD include wide FOV monitoring of the high energy gamma-ray sky from 500 MeV up to 10 TeV for gamma-ray bursts, active galactic nuclei and Galactic microquasars.

The positron/electron ($e^{\pm}$) spectra obtained by AMS-02 and FERMI [3, 4] showed some anomalies around TeV, which can be interpreted as origin of dark matter or nearby sources[5, 6]. Combining the cosmic leptonic spectra and the e^{+}+e^{-} anisotropy is very powerful to probe the origin of high energy electrons. With large data accumulation in future experiments, the electron emission spectrum and even emission time can be well constrained[7].

The steepening of the primary cosmic ray (CR) spectrum around several PeV, the so-called "knee" region, is a classic but still unresolved problem in CR physics since its discovery in 1958[8]. Ground-based extensive air shower experiments have difficulties in making composition-resolved high-energy resolution measurements. Space experiments, which can measure the particle energy and charge directly, have been suffering from small geometrical factor and limited energy range to make statistically meaningful measurements of the "knee".

HERD is composed of a 3-D cubic calorimeter (CALO) surrounded by microstrip silicon trackers (STKs) from five sides except the bottom. Then the CALO and STK are covered by the plastic scintillator detector (PSD) from outside. A Transition Radiation Detector (TRD) is located on the lateral side (Fig. 1). The biggest advantage over previous missions is that HERD has an effective geometrical factor of >3 m^2sr for electrons and gamma rays and >2 m^2sr for protons and cosmic rays, which is more than one order of magnitude higher than others. The energy resolution is about 1% for electrons and gamma-rays beyond 200 GeV, and 20% for protons from 100 GeV to 1 PeV.

2. 3-D calorimeter

Previous space calorimeters were all built with x-y orthogonal scintillator bars [9, 10, 11]. The charge measurement detector, veto detector, TOF detector, and/or magnet were installed on top of the calorimeter. So the calorimeters are only sensitive to the front. To increase significantly the geometric factor of one unique high energy radiation detection experiment, a calorimeter composed of thousands of small cubic crystals is proposed instead of the traditional design of calorimeter with very long telescope "tube". Besides, better particle discrimination can be achieved by using 3-d imaging of the shower of the particle event.

The LYSO crystal, having high light yield, fast decay time, low temperature coefficient and very short nuclear interation length, is the best candidate for space high energy calorimeters. The CALO is made of about 7500 cubes of LYSO crystals, corresponding to from all directions about

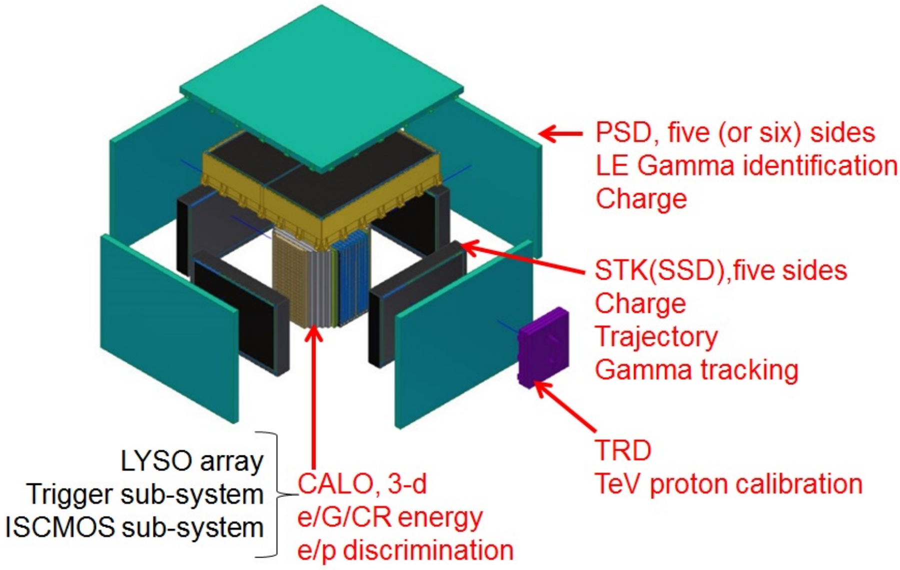

Figure 1: HERD payload configuration.

Table 1: HERD main specifications

Item	Value
Energy range (e/γ)	10 GeV - 10 TeV; 0.5-10 GeV(γ)
Energy range (nucleus)	30 GeV - 3 PeV
Angular resolution (e/γ)	0.1 deg.@10 GeV
Charge measurement (nucleus)	0.1 - 0.15 c.u.
Energy resolution (e)	1% @ 200 GeV
Energy resolution (p)	20% @ 100 GeV - PeV
e/p separation	$\sim 10^{-6}$
Geometric factor (e)	>3 m^2Sr @ 200 GeV
Geometric factor (p)	>2 m^2Sr @ 100 GeV

55 radiation lengths and 3 nuclear interaction lengths, respectively. Cosmic ray measurement up to PeV energy is then made feasible, and energy resolution of high energy particles is also guaranteed. Each LYSO crystal, with dimensions of 3cm*3cm*3cm, has a radiation length of 1.14 cm. Linearity of light output of LYSO crystal in the range from 30 MeV to 1 PeV was demonstrated at BEPC E2 by using calibrated electron bundles[12].

A novel method of reading out the LYSO signals by Wavelength Shifting Fiber (WLSF) and image intensified CMOS (ISCMOS) is applied, which can greatly reduce the complexity of onboard electronics. The reason of choosing ICCD or ISCMOS instead of EM-CCD is to slow down the scintillation photons in order to work in dedicated trigger mode and get pure events in CCD or CMOS frames. For the realization of larger dynamic range, each crystal is coupled with three WLSFs with a diameter of 0.3mm (Fig. 2). Two out of the three fibers are for high and low range

ISCMOS systems and the other one is for the trigger system. The three fibers are reshaped at the crystal end into spirals to get the largest contact area with the crystal. Nearly same number of scintillation photons are absorbed by the three fibers. MIP signal of about 100 p.e. is achieved using an XP2020 PMT, which corresponds to transmission efficiency of about 0.1%. The crystal is coated with TiO_2 reflector on all surfaces. Very good uniformity in signal output from the cube was demonstrated by a test using a high power and high energy X-ray tube. So deposited energy in the crystal is well inherited by re-scintillated photons in the fibers and no additional fluctuation is introduced. Alternative way of reading out crystal signals is using photon diodes directly coupled to the crystals[13].

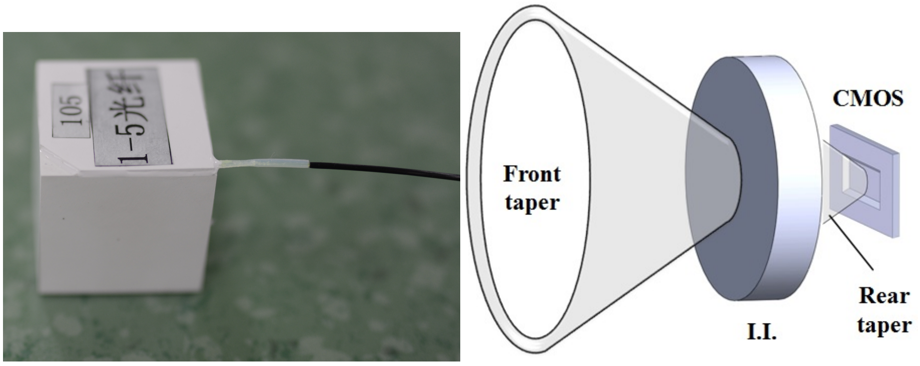

Figure 2: Left: Encapsulation of HERD crystals. All sides are covered by TiO_2 reflection layers.Three WLSFs are routed out. Right:schematic design of ISCMOS system.

Each ICMOS system is composed of a front taper, an image intensifier, a rear taper and a CMOS chip. A P20 phosphor screen with a decay time of 1 ms is integrated in the image intensifier. The maximum frame rate of the CMOS is 500 fps. When a trigger comes, the image intensifier is shutdown, and the electronic shutter is turned "OPEN" for 1 ms to collect the fluorescence photons. When the charges in pixels are all shifted out, the image intensifier is re-open and waits for the next trigger. About 20 by 20 CMOS pixels are assigned to one fiber. The sum of charges in these pixels is expected to be linear to the energy deposition in the corresponding crystal. Crosstalk coefficient between faculae has to be measured for accurate energy reconstruction. The high range ISCMOS system and the low range one are distinguished by different gain settings of the image intensifiers. Energy information can be derived from the high range ISCMOS when saturation occurs in the low range ISCMOS.

A beam test on a HERD prototype, composed of an array of 5*5*10 LYSO crystals and two ICCD systems, was implemented at CERN SPS in 2015. The main specifications and the reading out scheme of WLSF+ICCD were successfully verified[14].

All the trigger fibers are routed to the PMT in the trigger system. The trigger system is dedicated to providing common trigger signals to all the other payloads. In normal working mode (Fig. 3), events with >10 GeV energy deposition are triggered. Events with >0.5 GeV energy deposition and no response from PSD are identified as low energy gamma rays and are also triggered. In calibration working mode, only MIP events are triggered by the PMT system. Coarse energy measurement by using the trigger PMT could possibly be realized. A beam test on the HERD prototype with the PMT system was implemented at BEPC E2. The response of the PMT system remains linear within the range of number of 2.5 GeV electrons from 2e4 to 1e7.

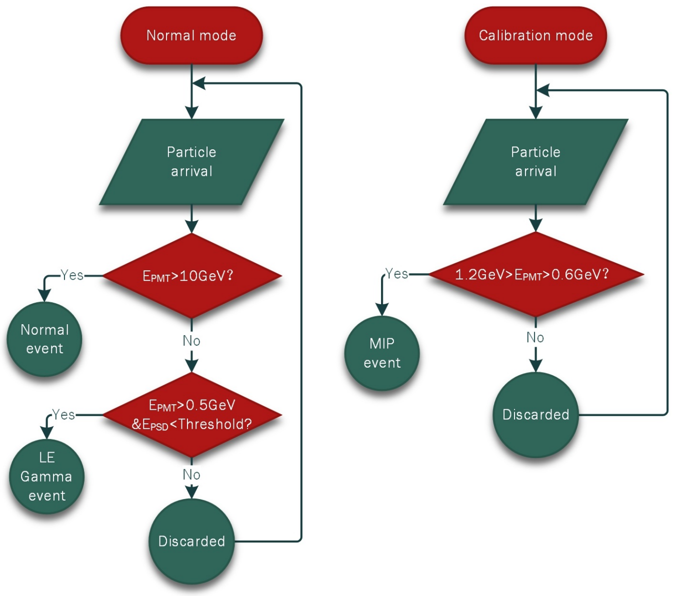

Figure 3: Trigger logic of HERD. Left:normal mode; Right: calibration mode.

In order to further improve the trigger capabilities and to have a better energy calibration, the possibility to equip a subsample of the LYSO cubes with photodiodes is under evaluation[15].

3. Silicon tracker

The STK of HERD is similiar to AMS-02 and DAMPE in design. Multiple x-y layers of silicon strips are allocated on the top side and four lateral sides of the calorimeter, for the charge and trajectory measurement of cosmic rays. Longer strips maintaining same noise level are needed because of large size of the HERD calorimeter. Technologies of bended silicon ladder and flex bonding are under consideration to increase the coverage of inner calorimeter. A gamma converter in the outer region of the STK is necessary for the gamma conversion to precisely identify the arrival direction. An active gamma converter made of thin crystals, having an advantage over tungsten plate in better energy resolution of low energy gamma rays, is under evaluation.

4. Plastic scintillator

The priority task of the HERD PSD is real-time identification of low energy gamma rays. One layer of one-dimentional long plastic scintillator bars, both ends of which are coupled with multiple SiPMs, are arranged on each of the six surfaces. In the current trigger strategy, the event will be marked as a non "LE gamma" when either SiPM having a signal above threshold. The coverage ratio and detection efficiency should be large enough, in case too many low energy charged particles are recorded. Information of the SiPMs from both ends could also help on charge measurement, as complementary to the STK. Better particle discrimination is foreseen by using the bottom PSD to help on neutron detection[16].

5. Transition radiation detector

Ground calibration of space calorimeters can only go to 400 GeV at maximum by using CERN SPS beam. For TeV protons, only few particles have showers all contained in the calorimeter and only visible deposited energy is recorded by detectors. Energy of primary proton is then derived by data extrapolation of low energy protons, which is not reliable. A transition radiation detector could be used to calibrate the incident particle with a dedicated energy at which transition radiation is generated but not saturated. As a reference, the AMS-02 TRD is built for mainly particle discrimination[17] and also expansion of CR energy range[18]. HERD TRD will perform in-orbit calibration of TeV protons and other nuclei in a short time scale thanks to its large detection efficiency(Fig. 4). Technical solutions of the TRD detector are straw tube scheme[19] and MWPC scheme[20]. The MWPC prototype is under construction by the Tsinghua team.

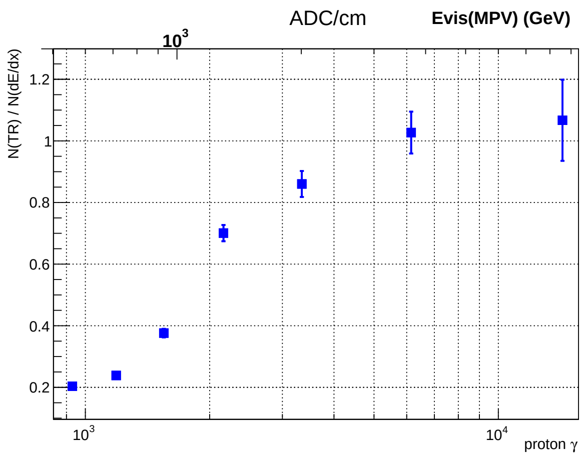

Figure 4: Simulated 2-months spectrum of a TRD with an area of 6300cm^2. TeV proton can easily be calibrated by ratio of transition radiation to ionizing radiation. Energy resolution of 15% for TRD is considered in the simulation.

6. Summary

HERD, with the largest geometric factor and unique capabilities in PeV CR measurement, LE gamma identification & measurement, is a flagship and landmark scientific experiment onboard China's Space Station. Several novel design features are utilized in the HERD payload:

1) A 3-d crystal array to allow large geometric factor and better particle discrimination.

2) A WLSF+ISCMOS read-out system to simply electronics.

3) An active converter to improve energy resolution of LE gamma.

4) One-dimensional long PS bars to identify LE gamma in real time and to complementarily measure the charge of particles.

5) A Transition Radiation Detector to calibrate TeV protons and other nuclei in orbit.

A beam test on upgraded HERD prototype will be arranged at CERN SPS in October, 2017. Key performances of the CALO, PSD functions and dynamic range of STK electronics will be verified.

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