PROCEEDINGS OF SCIENCE

Status of the HERD trigger design

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The High Energy cosmic-Radiation Detection (HERD) facility has been proposed as one of several space astronomy payloads onboard the China Space Station (CSS). HERD will address several major problems in fundamental physics and astrophysics, including cosmic ray (CR) direct measurements up to PeV energies, dark matter searches, and a gamma-ray survey above 0.1 GeV. HERD consists of five sub-detectors, including a 3D imaging calorimeter (CALO) with two independent readout systems, based on image intensified CMOS (IsCMOS) camera and photodiodes (PD), respectively. The CALO is surrounded by a scintillating fiber tracker (FIT), a plastic scintillator detector (PSD) and a silicon charge detector (SCD). Additionally, a transition radiation detector (TRD) is placed on one of the lateral sides to provide accurate energy calibration. To accomplish the different HERD scientific goals, several trigger strategies have been defined. The baseline trigger relies on the energy deposited in different CALO regions and in the PSD. To enhance HERD science capabilities and calibration qualities, the advanced trigger strategy is designed with the information provided by the CALO PD, FIT and TRD. This will provide an efficient extension of the energy range for specific samples. The baseline and advanced trigger strategy will be presented, together with some optimization work of the calibration events selection in HE trigger channels.

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1. Introduction to HERD Detector

The High Energy cosmic-Radiation Detection (HERD) facility is a particle space borne detector, planned to be operational starting from 2027 for about 10 years onboard the China Space Station (CSS). The objectives of HERD are: (1) searching for the decay or annihilation signal from dark matter by measuring the energy spectra and anisotropy of high energy electrons and gamma-rays; (2) studying the origin, propagation and acceleration mechanism of cosmic-rays by measuring precisely and directly the energy spectra and composition of primary cosmic rays from 10 GeV up to PeV; (3) monitoring the high energy gamma-ray sky above 0.1 GeV.[1]

As shown in figure 1, HERD will be a cubic-like detector composed with 5 active faces in order to maximize utilization of its available field of view.

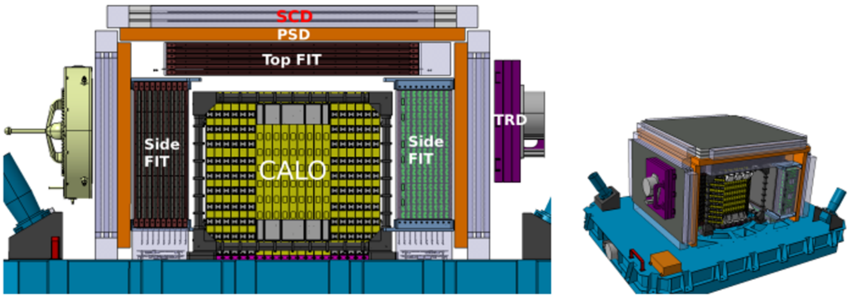

Figure 1: Transversal view of HERD sub-detectors layout.

From the outside in, particles first cross the Silicon Charge Detector (SCD). The SCD is used to measure the absolute value of the charge (|Z|) of the incoming cosmic rays. Next up is the Plastic Scintillator Detector (PSD). The PSD can also provide the charge information but it is mainly used to participate in the anti-coincidence trigger system for charged particles in the low-energy gamma-ray detection. Then, the FIber Tracker (FIT) which is the main instrument used for reconstructing the incident direction of gamma-ray. At the center of HERD, a deep (55 radiation lengths and 3 nuclear interaction lengths) 3D imaging CALOrimeter (CALO), made of about 7500 LYSO cubes with a side length of 3 cm, measures the energy of the particles entering the detector from five sides except the bottom. The CALO was designed nearly spherical to reach a higher efficient acceptance with the same number of crystals. The scintillation light of each LYSO crystal is read-out by two independent systems: the first one consists of WaveLength Shifting fibers (WLS) coupled to image Intensified scientific CMOS (IsCMOS) cameras, the second one is made of photo-diodes (PD). Finally, the Transition Radiation Detector (TRD) is on one lateral sector of the SCD to calibrate the CALO response to high energy hadronic showers.

2. Trigger Strategy

Three WLSs are used to read the scintillation light from each LYSO crystal, two of which are routed to the IsCMOS and the other one is used for trigger. Based on the coordinate position of the crystal, the CALO is divided into 11 trigger regions as shown in figure 2. The scintillation light from the trigger WLSs in the 11 trigger regions are read out with 11 independent photo-multiplier tubes (PMTs). Based on the signals from the 11 PMTs which represent the energy deposition in different trigger regions, the trigger strategy is designed.

To accomplish the different HERD scientific goals, several trigger strategies have been defined. The baseline trigger relies on the energy deposited in different CALO regions and in the PSD. To enhance HERD science capabilities and calibration qualities, the advanced trigger is further introduced with the information provided by the PD, FIT and TRD.

2.1 Baseline Trigger Strategy

To fulfill the operating requirements and scientific goals of HERD detector, several baseline trigger channels are defined based on the logical combination of the signals obtained from the CALO trigger regions with different discriminator thresholds. The baseline trigger strategy is divide to science mode and calibration mode. The science mode includes the High Energy trigger (HE), Low Energy Gamma trigger (LEG), Low Energy Electron trigger (LEE), Unbiased trigger (UNB) and the calibration mode includes a standalone calibration trigger (CALIB). The detailed description of these baseline trigger channels can be found in Ref. [2].

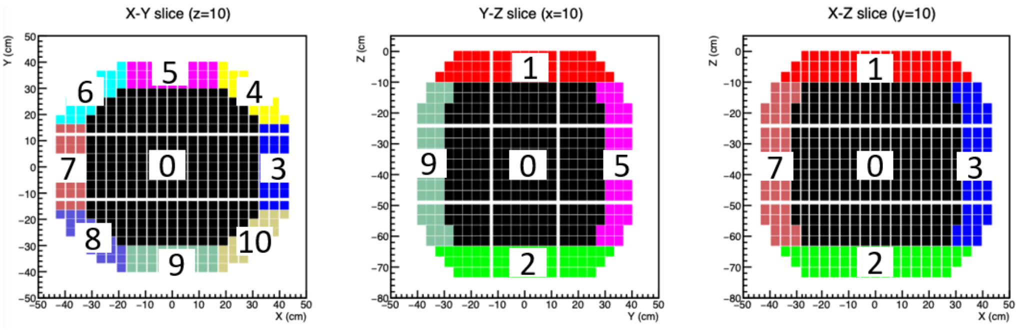

Figure 2: The trigger regions definition for the nearly spherical CALO.

2.2 Advanced Trigger Strategy

CALO plays a central role in trigger design since it provides a direct measurement of the energy deposition. The CALO is read out with the IsCMOS camera. Compared to the traditional photoelectric devices, the sequential logic of the IsCMOS camera is quite unique. The IsCMOS camera is composed of a front taper, an Image Intensifier (I.I.), and a sCMOS chip. The baseline trigger signal must arrive as fast as possible for an efficient light collection by the sCMOS. Given the fast time constant of the fluorescence decay process more than 85% of the photons are kept if the trigger delay less than 200 ns. A fast signal, within 200 ns, is required in order to avoid light losses in the CALO IsCMOS camera. This constraint strongly compromises the potential contribution of other subsystems, such as CALO PD, TRD or FIT.

In order to avoid massive light losses in the IsCMOS camera, the trigger delay time is required to be less than 200 ns, which limits the sub-detector types that can participate in the baseline trigger (L1) logic.

To enhance the HERD science capabilities while maintaining the overall detection efficiency of the system, the multilevel trigger design is introduced. In the multilevel design, the second level

(L2) trigger with a higher latency (1 μs) is added to reset the IsCMOS and further select the events. Therefore, the criteria of L1 can be relaxed to extend the detection energy range and a further selection is done in L2 with more information from other sub-detectors such as the CALO PD, TRD and FIT. The total trigger rate is thus kept under control and the overall detection efficiency for HERD is maintained.

Several new possibilities of advanced trigger strategy includes:

1. CALO PD Topological Trigger. Based on the event topology obtained with the CALO PD readout, it becomes possible to design dedicated triggers for specific particle species and energy ranges, serving various purposes. The detailed advanced strategy based on PD topology can be seen in Ref. [2].

2. High Z Trigger. A reduction of the HE threshold to 2 GeV and inclusion of a $Z > 2$ trigger based on a high threshold discriminator on the PSD signals makes it possible to record light and intermediate mass nuclei ($3\leqslant Z\leqslant 26$) from 2 GeV to 15 GeV.

3. TRD Trigger. In the baseline LEE definition, a fraction of the triggered events can not be used for TRD calibration because they do not have a valid track in TRD. The L2 trigger makes it possible to add the TRD signal in the trigger logic which will greatly improve the trigger efficiency.

4. Ultra Low Energy Gamma-ray Trigger. Determined by the minimum detectable energy for the CALO PMT system, the energy threshold of LEG is about 350 MeV. The ULEG trigger aims to lower energy threshold of gamma detection, based on a L1 trigger provided by the combination of the FIT trigger signal and the PSD veto, further filtered down by a slower L2 trigger using the energy deposition read by the CALO PD system. [3]

3. Update Study

In this section, the update design and performance for HE trigger channel is given. The Monte Carlo productions in this work are generated and analyzed using the HERDOS software, where the whole HERD geometry is constructed and simulated.

An alternative to the standalone calibration channel is designed by selecting the partially penetrating protons in HE channel. Total 10^8 protons with energies from 18 GeV to 200 GeV are produced for analysis.

3.1 HE Trigger Channel

Proton events can be categorized into three types based on the starting point of the hadronic shower within the CALO: pure penetrating events, partially penetrating events and events with complete showers, as shown in figure 3.

Pure penetrating protons provide efficient MIP hits for all crystals along the path traversed. However, it is hard to reconstruct the energy for pure MIP protons. Considering the energy-dependent nature of proton ionization energy loss, the MIP peak information provided by these pure penetrating protons will be shifted due to the low-energy protons. Therefore, the events recorded in HE channel whose energy deposition is larger than 15 GeV will enable a more accurate calibration.

The partially penetrating protons can be energy-reconstructed and can provide efficient MIP events for CALO unit before the shower starting point. Moreover, the energy threshold of 15 GeV for HE trigger channel will naturally reject the low-energy protons and avoid the peak shift. Therefore,

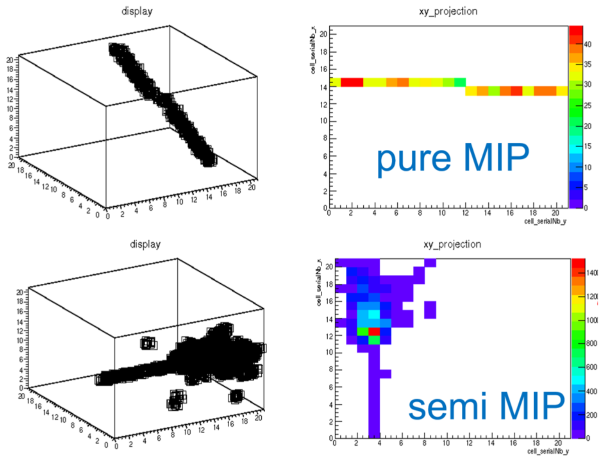

Figure 3: Schematic diagram of pure penetrating events (Up) and partially penetrating events (Down).

with appropriate shower starting point judging algorithm, the CALO calibration samples can be selected from the proton events recorded by HE trigger channel. If the rate of the selected efficient calibration events is enough for the CALO unit calibration, the standalone calibration trigger mode can be cancelled and thus the complexity of on-orbit operation is reduced.

3.2 MIP Selection Algorithm

The development of partially penetrating proton inside the CALO can be divided to two parts: the minimum ionization energy loss before the shower starting point and the shower energy loss after the starting point. Due to the significant increase in energy deposition within the crystal units after the starting point, we can determine the position of the starting point by comparing the energy loss through unit length.

The primary proton passes through a series of crystal units in the CALO. To determine whether the judged crystal unit is the shower starting point, we define a set of variables:

$$ratio_a[n] = \frac{(dE/dx)[n]}{(dE/dx)[-1]}(n = 0, 1, 2)$$

where dE represents the energy loss; dx represents the track length traversed in the crystal and $[n]$ represents the n-th unit before (-) and after (+) of the judged crystal.

However, if the shower start point is the first crystal or outside the CALO, the $ratio_a$ is not available here because we do not have the value of $(dE/dx)[-1]$. Therefore, a set of similar variables are defied based on a predefined MIP_MPV:

$$ratio_b[n] = \frac{(dE/dx)[n]}{MIP\_MPV}(n = 0, 1, 2)$$

where the MIP_MPV represents the most probable value of the distribution of the deposited energy by MIPs, which is set as 9.5 MeV/cm here. The threshold of these six parameters are determined by finding the position of the first crystal with first π^0 over threshold.

Therefore, the MIP selection algorithm is divided to three parts:

1. For the first crystal hit by the original proton, conduct $ratio_b$ selection. If the selection condition of $ratio_b$ is met, these events are considered as a full shower event. If the selection condition is not met, enter the second step and start searching shower starting point. The $ratio_b$ selection is:

$$ratio_b[0] > 2.93 \;\&\; ratio_b[1] > 5.57 \;\&\; ratio_b[2] > 7.23$$

2. For the crystal unit on the track of the primary proton, the $ratio_b$ selection is conducted one by one according to the CALO unit hit order. If the selection condition of $ratio_b$ is met, the current crystal is seen as the starting point of the shower and all hits before the current crystal are valid MIP hits. The $ratio_a$ selection is:

$$ratio_a[0] > 5.1 \;\&\; ratio_a[1] > 13.9 \;\&\; ratio_a[2] > 18.3$$

3. The last two passed CALO units are directly seen as shower event due to the energy loss threshold of 15 GeV for the HE channel.

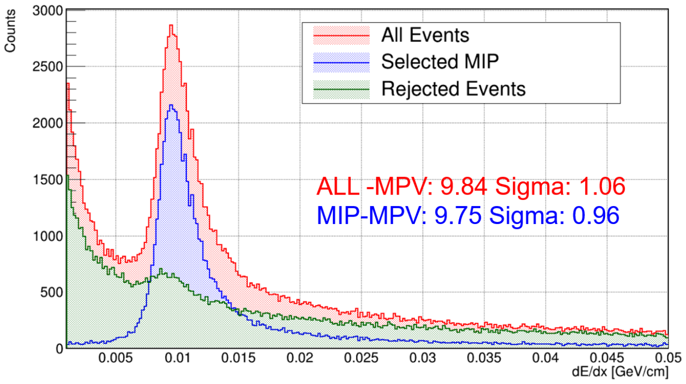

Figure 4: dE/dx distribution for CALO crystal unit on primary proton track before and after selection

As shown in figure 4, the MIP selection algorithm can reject the shower hits and reconstruct the dE/dx distribution, showing a good performance. But a small peak around the MIP position can be found in the dE/dx distribution for the rejected events. This is because the threshold for both $ratio_a$ and $ratio_b$ is a little too strict and they should be carefully adjusted to ensure a good separation of MIP and shower hits.

3.3 Selected MIP Rate in HE

The selected MIP rate for each CALO unit when on-orbit is calculated after considering a smearing on the energy and track length. The mean MIP counts per day for each crystal is 1864.

However, as shown in figure 5, compared with other layers, the bottom layer of crystals have few MIP counts. This is because the HERD detector is five-sided sensitive and HE channel does not contain pure MIP events. Therefore, it is needed to specifically design other logic to select MIP hits for bottom crystals.

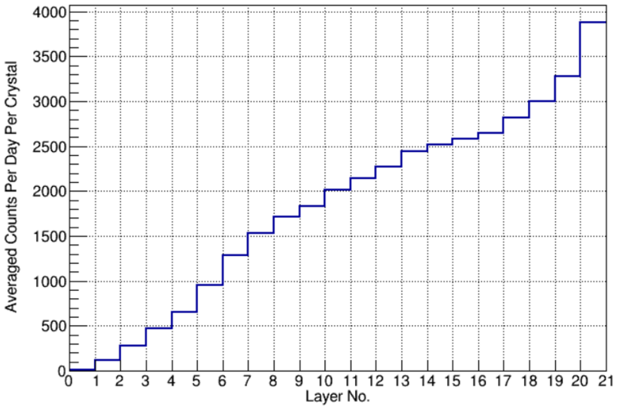

Figure 5: Averaged MIP Counts Per Crystal for different CALO Layer

4. Conclusion

The HERD detector onboard the CSS is planed to be operational starting from 2027 for about 10 years, expecting to accurately measure the charged cosmic rays and gamma-rays from few GeV to PeV energies owing to its high effective geometrical factor.

The optimization on baseline and advanced trigger are undergoing. Concerning the HE channel, the results presented prove the possibility to cancel the standalone calibration trigger mode and select the semi-MIP calibration events in the HE channel. But more studies are to be done to increase the efficient MIP counts for the bottom crystals.

5. Acknowledgement

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