Study of linearity of LYSO crystal for HERD calorimeter (Postprint)

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Date: 2017-11-10T00:00:00+00:00

Abstract

The High Energy cosmic Radiation Detection (HERD) facility is a space mission designed for detecting cosmic ray (CR) electrons, -rays up to tens of TeV and CR nuclei from proton to iron up to several PeV. The main instrument of HERD is a 3-D imaging calorimeter (CALO) composed of nearly ten thousand cubic LYSO crystals. A large dynamic range of single HERD CALO Cell (HCC) is necessary to achieve HERD' s PeV observation objectives, which means that the response of HCC should maintain a good linearity from minimum ionizing particle (MIP) calibration to PeV shower maximum. In order to study the linearity of HCC over such a large energy range, a beam test has been implemented at the E2 and E3 beam lines of BEPC. High intensity pulsed electron beam provided by E2 line are used for producing high energy density within HCC; +/proton provided by E3 line are used for HCC calibration. The results show that no saturation effect occurs and the linearity of HCC is better than 10% from 30 MeV (1 MIP) to 1.1×103 TeV (energy density is 93 TeV/cm3), which can meet the requirement mentioned above.

Full Text

Preamble

Study of linearity of LYSO crystal for HERD calorimeter

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Abstract: The High Energy cosmic Radiation Detection (HERD) facility is a space mission designed for detecting cosmic ray (CR) electrons and -rays up to tens of TeV and CR nuclei from proton to iron up to several PeV. The main instrument of HERD is a 3-D imaging calorimeter (CALO) composed of nearly ten thousand cubic LYSO crystals. A large dynamic range of single HERD CALO Cell (HCC) is necessary to achieve HERD' s PeV observation objectives, which means that the response of HCC should maintain good linearity from minimum ionizing particle (MIP) calibration to PeV shower maximum. To study the linearity of HCC over such a large energy range, a beam test has been implemented at the E2 and E3 beam lines of BEPC. High intensity pulsed electron beams provided by the E2 line are used for producing high energy density within HCC; +/proton beams provided by the E3 line are used for HCC calibration. The results show that no saturation effect occurs and the linearity of HCC is better than 10% from 30 MeV (1 MIP) to 1.1×10^3 TeV (energy density of 93 TeV/cm^3), which can meet the requirement mentioned above.

Key words: HERD, Calorimeter, LYSO, Linearity, Beam test
PACS: 29.40.Vj, 29.40.Mc

1 Introduction

HERD is one of the space astronomy payloads of the cosmic lighthouse program onboard China' s Space Station. The main scientific objectives of HERD are indirect dark matter search, precise CR spectrum and composition measurements up to the knee energy, and high energy -ray monitoring and survey [?]. To achieve these scientific objectives, a 3-D imaging and five-side active calorimeter is designed to perform high energy resolution and high statistics measurements of CR nuclei, electrons and positrons, and -rays in space. HERD CALO consists of $21 \times 21 \times 21$ cells corresponding to 55 radiation lengths (X_0) and 3 nuclear interaction lengths (λ_I) longitudinally, separately. Each HCC is made of a $3 \times 3 \times 3$ cm^3 cubic LYSO crystal and two spiral WLSFs (Saint Gobain BCF91A) as the fluorescence readout. All the WLSF signals are collected by two image intensified CCDs (ICCD) [?, ?].

LYSO (Lutetium Yttrium Orthosilicate with Cerium doping) crystal is one of the best candidates for CALO material. It has the advantages of high density, high light output, short decay time, and application of this crystal in space would be quite easier thanks to the non-hygroscopicity and small temperature coefficient. The general properties of LYSO are described in Ref. \cite{3-5}. Theoretically, the fluorescence intensity of LYSO crystal should be linear with the energy deposition induced by incident particles. However, saturation effect may occur at high ionization density of the crystal. The linearity of

LYSO crystal light output should be studied and understood before application. Results from Monte Carlo simulation show that a dynamical range of 2×10^6 is required for HCC [?]: a minimum detectable signal down to 30 MeV is required for calibration using MIP; meanwhile, the maximum energy deposition induced by PeV proton shower is up to 60 TeV (energy density is about 8 TeV/cm^3, Fig. 1).

Numerous studies of LYSO linearity have been performed using low energy -rays or electrons, with verified ranges of 511 keV-1333 keV [?], 65 MeV-145 MeV [?] and 100 MeV-1.5 GeV [?]. There are few calorimeters of space missions designed to measure PeV particles directly, thus little attention has been paid to the linearity of inorganic crystals over a large energy (or energy density) range. A study of linearity for LSO (Lutetium Orthosilicate with Cerium doping) crystal using high intensity pulsed -rays is described in Ref. [?], which demonstrates that the linear response of the crystal ranges from 5.1×10^{18} MeV/(cm$^2 \cdot$ s) to 1.9×10^{19} MeV/(cm$^2 \cdot$ s). It is reasonable to expect the same linearity of HCC which is made of similar material at that high energy density. However, the verified energy density of this study is too high and it does not cover the required range of HCC.

We developed a method of using high intensity pulsed electron beam and +/proton beam to measure the linearity of HCC. In this paper, the method and the experimental setup are presented in Section 2. Data analysis and results are presented in Section 3 and the conclusion is briefly shown in Section 4.

2.1 Test Beam

It is well known that ground accelerators can only produce primary beam particles up to several TeV, thus it is feasible to achieve an energy density up to 8 TeV/cm^3 by using a bunch of particles passing through HCC and calibrate it by using single beam particle, separately. The measurement is carried out by using the electron beam provided by BEPC E2 Line [?]. The beam properties are as follows: beam energy of 2.5 GeV, beam intensity from 10^3 to 10^{10} electrons/pulse, beam frequency of 12.5 Hz, beam size of 4×4 cm^2, and beam pulse width of 20 ps. The collimation size is 1 cm which is smaller than crystal size (3 cm) in order to reduce geometrical non-uniformities. Energy deposition of one electron with 2.5 GeV kinetic energy in HCC is about 240 MeV (Section 3.3). HCC is thick enough ($2.6X_0$) for 2.5 GeV electrons to produce showers, and the part of HCC at the shower center has the highest energy density of about 20 MeV/cm^3. Thus an adequate beam intensity up to 4×10^5 electrons/pulse (or energy deposition in HCC up to 96 TeV) is necessary to get a maximum energy density of 8 TeV/cm^3.

BEPC E3 line is a mixed beam of secondary particles including , e$^\pm$, $^\pm$, proton and μ$^\pm$. +/proton mixed beam with momentum of 600 MeV/c to 1.2 GeV/c are chosen by beam line magnets for HCC calibration.

2.2 The HCC readout

PMTs instead of ICCDs are used during the test to avoid possible non-linearity of the ICCD device. Two WLSFs coupled to a cubic LYSO crystal (from Suzhou Jtcrystal Co., Ltd.) are read out by two PMTs (XP2262) respectively. Neutral density filters (NDF) with different transmittances are attached to PMTs for detecting different energy ranges. The NDFs and the PMT are all sealed in a black plastic cylinder box with a circular aperture of 0.4 mm on top for the WLSF to plug in, as shown in Fig. 2 [Figure 2: see original paper].

2.3 Experimental setup at E2 line

Three detectors are used to calibrate the beam intensity (Fig. 3 [Figure 3: see original paper]):

- **Faraday Cup (FC):** FC is the only device which can measure the absolute beam intensity directly. However, FC is not sensitive enough, as it is designed to monitor beams with intensity $> 10^6$ electrons/pulse.
- **Ionization Chamber (IC):** designed to monitor beam intensity from 10^4 to 10^7 electrons/pulse.
- **Thin Plastic Scintillator (PS):** placed in front of the HCC and attached with 2 PMTs for readout purpose. The effective detecting range is from 10^2 to 10^5 electrons/pulse.

With cross calibration between the three detectors, a wide beam intensity from 10^2 to 10^9 electrons/pulse can then be monitored and precisely measured. A lead wall is built for shielding the detectors from contamination caused by secondaries from the interaction of beam particles with surrounding materials. Signals from FC and IC are recorded by a 12-bit peak sensing ADC (Mod. V785N), while signals from 4 PMTs are read out by a 4-channel digitizer (Mod. DT5751). Both DAQ modules share a common trigger signal from the accelerator.

2.4 Experimental setup at E3 line

In the configuration at E3 line, a time of flight system (TOF) consisting of two plastic scintillators is used for +/proton separation as shown in Fig. 4 [Figure 4: see original paper]. The trigger is the coincidence of two PMTs attached to the plastic scintillators. DT5751, which can work at a sampling rate of 1 GS/s, provides high time resolution to distinguish proton signals and + signals from TOF (Section 3.3). The NDFs are removed and the high voltages for PMTs are raised to detect the MIP signal which is much weaker than the electron signal.

3.1 Calibration of beam intensity monitoring devices

A cross-calibration between FC, IC and PS is performed as shown in Fig. 5 [Figure 5: see original paper]. Overlaps between the detecting ranges of FC, IC and PS are large enough for cross-calibration.

3.1.1 FC Calibration

Fig. 6 [Figure 6: see original paper] shows the relationship between injected electron number and FC output, demonstrating good linearity in the ADC' s counting range. The calibration factor is obtained by fitting a straight line to data points.

3.1.2 IC and PS Calibration

The IC and PS detectors are calibrated by studying the relationship between FC output and IC output (Fig. 7 [Figure 7: see original paper]), and IC output and PS output (Fig. 8 [Figure 8: see original paper]). ADC channels of IC from 200 to 750 are chosen for fitting, because when ADC(IC)$>$ 750, rare events would lead to large fluctuations, and when ADC(IC)$<$ 200, signals would be too close to the baseline. The calibration factors of IC and PS are obtained by fitting to the data.

3.2 NDF Calibration

A measurement of transmittance of NDFs was performed before the beam test. We used an optical fiber irradiated by an LED as the light source and a PMT for readout. The NDF was installed on a linear stage which could provide high precision linear movement. The original signal and attenuated signal could be obtained by moving the NDF to the position between the light source and the PMT. Fig. 9 [Figure 9: see original paper] shows the calibration result of one NDF with 0.6 optical density (O.D., Transmittance = $10^{-O.D.}$). The total transmittance of attached NDFs are 2.8×10^{-3} and 8.3×10^{-5} (Table 1) for the two PMTs (defined as PMT L, PMT H). Thus the intensity of light reaching the windows of PMT L is about 34 times higher than that reaching PMT H. The dynamic range of the HCC readout system is then extended naturally by combining the two PMTs.

3.3 HCC Calibration using E3 beam

Most of the E3 beam particles are protons and $+$. TOF data, which clearly illustrates the difference between them in Fig. 10 [Figure 10: see original paper], is needed to separate $+$ from protons to obtain a clean spectrum as shown in Fig. 11 [Figure 11: see original paper]. Energy deposition in HCC for different particles is then calculated by Monte Carlo simulation using Geant 4.9.6 [**?**]. The simulation environment is built based on the experimental setup, with results shown in Fig. 12 [Figure 12: see original paper] and Table 2 . Energy deposition is nearly constant for $+$ in the case of normal incidence when its momentum $>$ 400 MeV/c; for 2.5 GeV electrons, energy deposition is much higher because electromagnetic showers are initiated inside the crystal.

3.4 Results and Discussions

The results of linearity at different beam intensities as well as correlation between output of PMT L and PMT H are illustrated in Fig. 13 [Figure 13: see original paper]. To calculate the equivalent HCC output for protons and +, the NDFs' attenuation effect and the change of high voltage for PMTs should be taken into account:

$$HCC_{\pi^+,proton} = A_{HV} \cdot A_F \cdot S_{\pi^+,proton}$$

where A_{HV} represents the high voltage correction factor defined as the ratio of two gains of PMTs used by E2 test and E3 test; A_F represents the total transmittance of NDFs used in E2 test; and $S_{\pi^+,proton}$ represents the PMT output given by E3 test (Table 2). Fig. 14 [Figure 14: see original paper] shows the profile histogram which combines all the results for different intensity ranges as well as + and protons. The maximum deviation is defined as the linearity of HCC. Fig. 14 shows the linearity is better than 10% when energy deposition (energy density) in HCC ranges from 205 GeV (17 GeV/cm^3) to 1.1×10^3 TeV (93 TeV/cm^3), which covers the requirement. The + and proton signals agree well with the fitting function.

There are several factors that may affect the measurement result of linearity:

a) Non-linearity of PMTs: Non-linearity of the two PMTs was studied before the beam test, with details described in [**?**]. The result shows the non-linearity of PMT is less than 2% when the output signal is not higher than 2 V. NDFs with high attenuation are used in the beam test to ensure the output signals are lower than 2 V.

b) Stability of PMTs: Before data acquisition, the high voltage of PMTs is usually switched on at least two hours in advance, during which the response of PMTs gradually becomes stable. Temperature variation may also cause drift. To minimize such effects, one full data acquisition is completed within 3 hours and the data acquisition is repeated several times. The temperature variation during the beam test is smaller than 2℃. Therefore, this residual influence is negligible compared to the calibration error.

c) Backgrounds at E2 line: The backgrounds are secondary particles from the interaction of beam electrons with shielding material, mostly X-rays and -rays. One part of them is absorbed by the LYSO crystal, but the signal-to-background ratio is lower than 2% (Fig. 15 [Figure 15: see original paper]), which does not have significant impacts on the measurement. Both beam signal and background have a linear relationship with beam intensity, with the signal-to-background ratio being about 1.7%.

d) Calibration Error: Because the FC has a large size, perfect shielding is nearly impossible. Primary electrons may hit the FC directly and lead to overestimation of beam intensity. The large fluctuation of FC response can also influence the accuracy of IC and PS calibration.

4 Conclusion

In this paper, the linearity of LYSO crystal for HCC is studied by measuring the relationship between HCC output and electron beam intensity given by Faraday cup, ionization chamber, and plastic scintillator. The linearity is better than 10% from 205 GeV to 1.1×10^3 TeV (or from 17 GeV/cm^3 to 93 TeV/cm^3), which meets the requirement of PeV hadron detection. The linear range can be extrapolated to + (MIP, 30 MeV) and protons. No obvious saturation effect of HCC is observed in this range. The uncertainty of linearity measurement is mainly dominated by the measurement system and beam monitoring system.

From this work, we obtain a preliminary conclusion that LYSO has good linearity and can be used in HERD CALO for detecting high energy particles. A beam test at CERN SPS, which can supply electrons and protons with energies up to 300 GeV, is planned to verify the main performances of HERD CALO.

Acknowledgement
We are thankful to Jianchao Sun, Xuan Zhang, Xiaofeng Zhang, and Zhe Ning for their support.

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