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Development of Transition Radiation Detector for the High Energy cosmic-Radiation Detection Facility

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The Transition Radiation Detector (TRD) plays a vital role as an integral component of the High Energy cosmic-Radiation Detection (HERD) facility, a scientific payload designed for measuring cosmic rays. HERD is scheduled to be installed on the China Space Station in 2027 and comprises five sub-detectors. One of these sub-detectors is the TRD, which will facilitate energy cross-calibration with the calorimeter in the TeV energy range. During the development and evaluation of the TRD, two prototypes were created and assessed using electron beams sourced from CERN and DESY. The measurement of transition radiation photon yields was conducted using various regular radiators, revealing a noteworthy signal of transition radiation for Lorentz factor γ greater than 2000. Leveraging the beam test data, we constructed a Monte Carlo (MC) simulator to optimize the TRD design. This presentation will delve into the TRD design, laboratory and beam tests, simulations, and the corresponding results obtained from our research.

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1. Introduction

The High Energy cosmic-Radiation Detection (HERD) facility [1] is an astrophysics payload that focuses on measuring high energy cosmic rays to detect the signal of Dark Matter and study the contribution of nearby sources to the cosmic-ray flux. It will be installed on board the China Space Station in 2027 and will operate for over 10 years. The facility includes five sub-detectors: a calorimeter (CALO), a fiber tracker, a plastic scintillator (PSD), a silicon charge detector, and a transition radiation detector (TRD). The calorimeter's calibration can be performed using accelerator beam particles with a known energy, but it is limited to a few hundred GeV. The TRD can extend the calibration range for higher energies. To date, only the CREAM experiment has used TRD cross-calibration with a calorimeter [2].

HERD-TRD primarily serves the purpose of calibrating the calorimeter within the TeV energy range by utilizing cosmic-ray protons during in-orbit operations. To achieve this objective, we have introduced a novel TRD structure, called the side-on TRD, which differs from the conventional straw tube TRD and multi-wire proportional chamber (MWPC) TRD designs. The side-on TRD is a time projection chamber (TPC) based on the thick-gas electron multiplier (THGEM) technology. We have successfully developed a prototype of the side-on TRD and conducted thorough testing using accelerator beams [3, 4]. The experimental results align remarkably well with the expectations set by our Monte Carlo simulations [5]. This outcome confirms the viability and effectiveness of the proposed side-on TRD design.

Regarding the side-on TRD prototype, its working gas implemented a circulation system. However, this operational mode resulted in unstable gain and consumed a significant amount of resources during in-orbit operations. In response to these challenges, the HERD-TRD was designed as a fully sealed chamber, eliminating the need for gas circulation. A new TRD prototype, based on this full-sealed chamber design, has been successfully developed and subjected to rigorous testing using an electron beam. This paper provides a comprehensive description of the prototype's design and presents the corresponding experimental results. Additionally, a comparison between the experimental findings and the results obtained from Monte Carlo simulations is provided.

2. Detector description

The "side-on" refers to the installation of the transition radiator on the lateral face of the detector chamber, where the particle's trajectory aligns parallel to the anode plane and perpendicular to the electric field within the drift region. The new side-on TRD prototype utilizes a full-metal chamber to seal the working gas. A 3D view of the prototype is depicted in Fig. 1, while its profile can be observed in Fig. 2(a), as presented in this paper. The prototype consists of several components, including a regular radiator, an X-ray gas detector chamber, and a readout system.

Transition radiation (TR) refers to an electromagnetic wave generated by relativistic charged particles as they move between two different media. Regular radiators typically exhibit a higher TR yield compared to irregular ones of the same thickness. Five key parameters determine the TR yield: foil material, foil thickness, gap material, gap thickness, and layer number. In order to achieve a higher TR yield, we have optimized the radiator parameters based on literature [5] research. Specifically, we have replaced the original polypropylene (PP) film with polyimide (PI) as

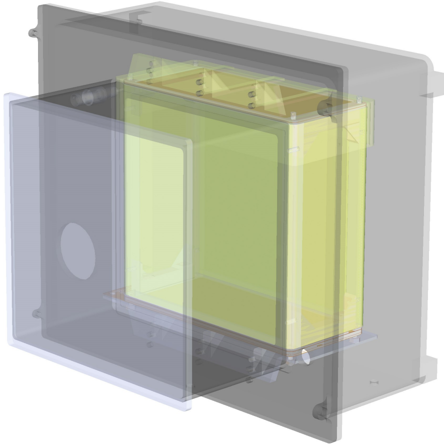

Figure 1: 3D view of new side-on TRD prototype.

the foil material due to its low out-gassing rate. To accommodate the size constraints of the TRD, the number of foil layers has been reduced to 170, resulting in a total radiator thickness of 10 cm. The new regular radiator configuration consists of 170 layers of PI foil, each with a thickness of 23 μm. The gap material used is Argon, with a gap thickness of 574 μm. These optimized parameters are illustrated in Fig. 2(b).

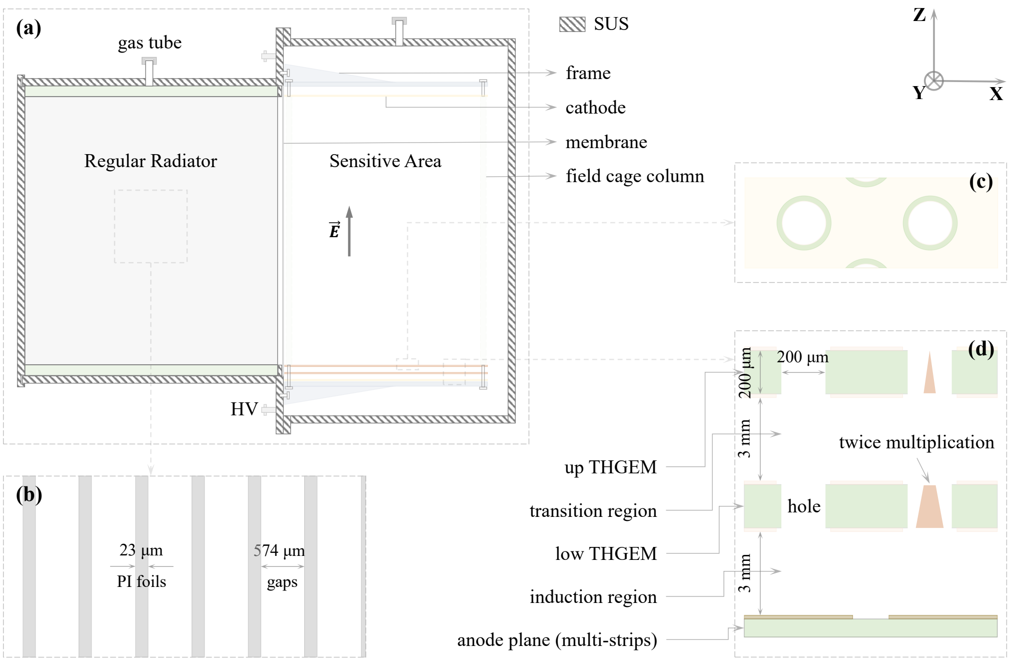

Figure 2: (a) Profile of transition radiation detector; (b) structure of the regular radiator; (c) a front view of THGEM; (d) THGEM parameters and the multiplication of electron in the THGEM hole.

The X-ray gas detector consists of several components, including the cathode, field cage, THGEMs, anode, and frame. The field cage is designed with 75 wire pieces plated on a polyimide

(PI) film, reducing the margin effect from 10 mm in the old prototype to 3 mm in the new prototype. The distance between the entrance window and the field cage film has also been reduced from the original 20 mm to 3 mm. These first two optimizations are crucial for improving the TR strength by minimizing photon attenuation in the material. The X-ray gas detector incorporates two THGEMs, as depicted in Fig. 2(c), with their respective parameters labeled in Fig. 2(d). The anode is designed with 55 readout strips, spaced at 1.28 mm intervals, resulting in a total sensitive thickness of 70.4 mm. To ensure structural stability, a frame made of polyetheretherketone (PEEK) is selected for securely fixing all the components within the chamber. PEEK offers excellent mechanical strength and has a low out-gassing rate. The chamber itself is constructed from stainless steel and is sealed using laser welding techniques, resulting in a gas leakage rate of $3.6 \times 10^{-11}\mathrm{Pa} \cdot \mathrm{m}^3 \cdot \mathrm{s}^{-1}$. This ensures the gas detector's operational stability for over 5 years without the need for a gas circulation system during in-orbit operations.

The readout system [6] utilizes an optical fiber-based multi-channel configuration, consisting of four front-end cards (FEC) and a data collection module (DCM). The FEC serves the purpose of conditioning and digitizing the analog signals received from the detector. It comprises the AGET chip, which is an application-specific integrated circuit designed for generic TPC readout, along with the associated circuitry. The FEC is designed with specific configurations, including a charge-sensitive amplifier with four selectable gains ranging from 120 fC to 10 pC. It also incorporates a switched capacitor array structure with 512-sample analog memory. The sampling frequency can be adjusted within a range of 1 to 100 MHz, providing flexibility for signal processing requirements. On the other hand, the DCM acts as an interface between the FECs and the data collection system. It facilitates the transfer of data from the FECs to the data collecting unit, while also providing external trigger functionality for synchronization purposes.

3. Laboratory test and beam setup

The choice of working gas in the detector has a significant impact on its performance. There are three factors that can affect the stability of the working gas: gas leakage, out-gassing of internal materials, and gas permeability in the entrance window membrane. While an Argon-based gas is utilized as the working gas in the new prototype, the selection of a quenched gas must consider its permeability. In this case, we have chosen iso-butane as the quenched gas due to its larger molecular radius compared to carbon dioxide and its lower permeability in thin plastic.

We conducted laboratory tests to measure the gains of several gas mixtures at various multiplication voltages using a ^{55}Fe source, as illustrated in Fig. 3. The results indicate that the mixed gas containing 3% and 5% iso-butane achieved gains of 10^4 at THGEM voltages of 460 V and 500 V, respectively. These values are higher compared to the mixed CO_2, which only reached a maximum gain of 2,000 at a THGEM voltage of 680 V.

The typical ^{55}Fe spectrum obtained from the new prototype as shown in Fig. 4. The spectrum is fitted using three Gaussian functions, each corresponding to specific features: the escape peak, the full-energy peak at 5.9 keV, and a branch at 6.4 keV associated with ^{55}Fe. The detector demonstrates performance characteristics such as a gain of approximately 2000 and an energy resolution of 35% at 5.9 keV.

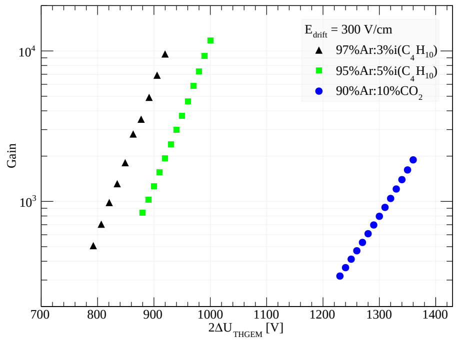

Figure 3: The gain curve of three mixture gases. Geometric configuration of double THGEM as shown in Fig. 2(d), and the field intensity of drift region set to 300 V/cm.

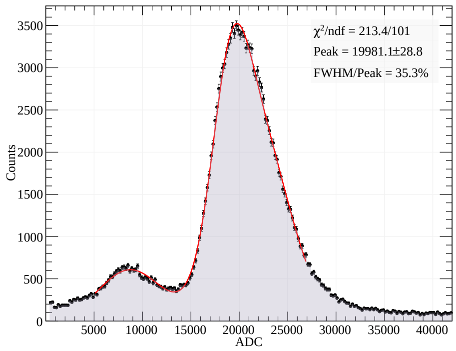

Figure 4: The ^{55}Fe test result in laboratory. Working gas is Argon/iso-butane mixture with a ratio of 97:3 and pressure of 1 bar. Other configurations are $2\Delta U_{THGEM}$ of 850 V and E_{drift} of 330 V/cm.

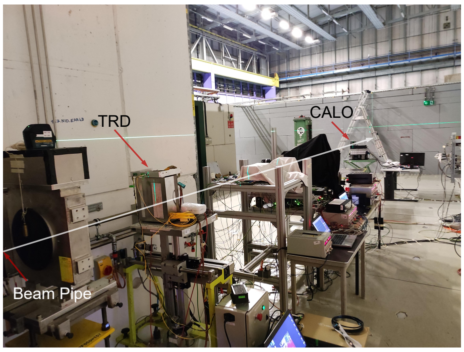

Figure 5: The transition radiation detector installed on the beam-line.

The new side-on TRD prototype underwent testing using an electron beam provided by CERN PS in 2022. During this test, the working gas used was a mixture of Ar:i(C_4H_{10}) in a ratio of 97:3, with a pressure of 1 bar. The single THGEM multiplication voltage was set to 425 V, while the electric field intensity in the drift region was maintained at 330 V/cm. Fig. 5 depicts the prototype installed on the beam-line for testing. The PSD and CALO are aligned downstream of the TRD along the beam. The PSD serves as the trigger, which is then distributed by the HERD integrated electronics system. The triggered area for the beam is $1 \times 1\text{cm}^2$, and the energy divergence of the beam is 2%.

4. Simulation and results

An MC simulator was developed using GEANT4.10.03 [7] to accurately describe the energy deposition of particles within the detector. The simulator includes a comprehensive representation of the materials, physical processes, and digitization effects. Along the beam direction, the MC simulation constructs various components such as the stainless steel chamber, radiator, entrance window membrane, field cage, copper wire, and sensitive volume. To faithfully reproduce the response of the TRD, specific models were employed within the MC simulator. The Photo Absorption Ionization model (G4PAImodel) [8] accurately describes the energy loss of relativistic charged particles in thin gas. The TR model G4TransparentRegXTRadiator [9] captures the transition radiation process within the radiator. Additionally, the G4VAtomDeexcitation model is utilized to accurately reproduce the Auger electron emission and characteristic X-ray processes associated with atomic deexcitation. All beam parameters within the MC simulation are set to correspond with the actual configuration described above.

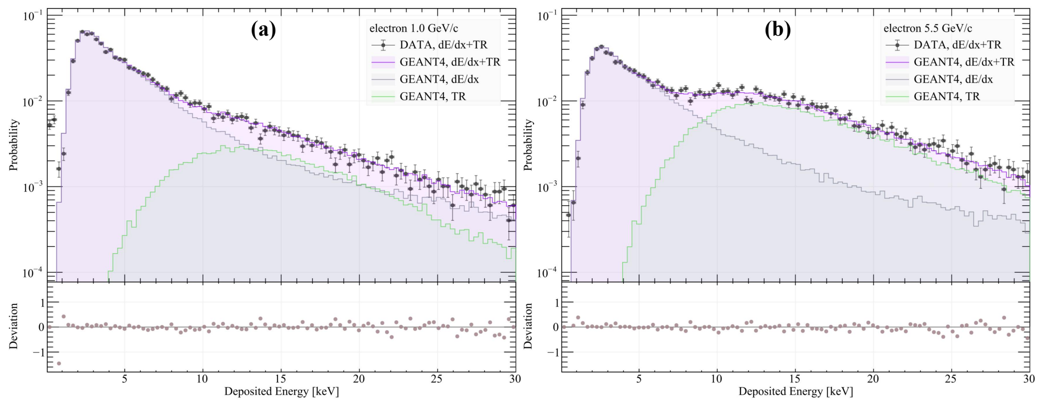

Figure 6: Transition radiation and ionization spectra of simulation and test beam results: (a) 1.0 GeV/c; (b) 5.5 GeV/c. The bottom two panels show the associated deviation between data and GEANT4.

The digitization process takes into account three main factors: electron transverse diffusion, gain and energy broadening of the THGEM, and electronic noise. In the literature [5], the transverse diffusion of electrons in the side-on TRD has been discussed. For this particular TRD configuration, the electron dispersion only needs to be considered along the beam direction. The dispersion of ionization electrons can be described by a Gaussian distribution with a standard deviation of σ_x along the beam direction. The value of σ_x is correlated to the drift length L and follows the relationship $\sigma_x = D_T \cdot \sqrt{L}$, where D_T is the transverse diffusion coefficient. The value of D_T is obtained through Garfield++ [10] calculations, and in the case of an electric field intensity of 330 V/cm, it is determined to be $579.5 \pm 19.8\ \mu m/\sqrt{cm}$. The gain and energy resolution are determined based on the corresponding measured values from the ^{55}Fe source, as shown in Fig. 4. These values are used to accurately represent the gain and energy broadening effects of the THGEM in the digitization process. Lastly, the baseline noise of the electronics is described by a Gaussian distribution. The mean and sigma values of the Gaussian distribution are obtained from test data, ensuring that the electronic noise is realistically simulated in the digitization process.

The comparison between the MC simulation and the actual data can be evaluated by analyzing the energy spectra. Fig. 6 displays the measured and simulated TR spectra for two different electron momenta. In the bottom panel of the figure, the deviation between the MC simulation and the data is shown within each energy bin. It is evident from the figure that there is a remarkable agreement between the data and the MC simulation. The energy spectra of the TR radiation obtained from both sources exhibit similar patterns and trends. This consistency suggests that the MC simulation accurately reproduces the behavior and characteristics of the TR radiation as observed in the experimental data. The good agreement between the data and MC results further validates the reliability and effectiveness of the MC simulation in describing the performance of the side-on TRD prototype.

5. Conclusions

The new side-on TRD prototype has undergone design, development, and testing using both ^{55}Fe and accelerator beams. The key feature of this prototype is its innovative chamber structure, which utilizes a full-metal construction and laser welding for complete sealing. This design choice enhances the stability and performance of the TRD prototype, eliminating the need for a gas circulation system.

The main purpose of developing the side-on TRD is to facilitate the calibration with the HERD calorimeter. To achieve a high significance in the detection of TR, a Xenon-based gas is preferred as the detection medium. Currently, efforts are underway to test and optimize the Xenon pressure, quenching gas, and mixing ratio in the TRD system. Furthermore, ongoing research is being conducted on various aspects of the side-on TRD. This includes studying the three-dimensional uniformity of the detector's response, assessing its long-term stability, investigating potential systematic errors, and conducting in-orbit simulations. These endeavors aim to ensure the optimal performance and reliability of the side-on TRD when integrated into the overall HERD facility.

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