

## Optimization of a dual-end readout bar-shaped scintillator detectors for Compton imaging

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### Abstract

Compton imaging enables high-sensitivity imaging of gamma radiation sources without collimation, making it useful for homeland security, nuclear decommissioning, and space science. This study proposes a position-sensitive bar-shaped detector used for Compton imaging. The bar-shaped scintillator detectors are arranged in a planar array, with signals read out from the dual end of the detector to reduce electronics channels. The detection system developed in this study with advantages of radiation hardness, high efficiency and low cost. A large sensitive volume of a  $5\text{mm} \times 5\text{mm} \times 100\text{mm}$  CsI(Tl) scintillator detector, with a light output of 56 000 photons/MeV, was used to verify position and energy resolution. Considering the surface roughness and reflectors, the experiment results indicate that the bar-shaped scintillators can achieve an average position resolution better than 5mm and 7.2%(FWHM) energy resolution at 662 keV. Therefore, a balance between position resolution and energy resolution can be achieved by the bar-shaped scintillators with few readout electronics. The imaging detection system of 80 cm<sup>3</sup> sensitive volume, constructed with bar-shaped scintillators, can be used for Compton imaging in an energy range of 250 keV to 3MeV.

### Full Text

#### Preamble

Optimization of Dual-End Readout Bar-Shaped Scintillator Detectors for Compton Imaging

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Compton imaging enables high-sensitivity imaging of gamma radiation sources without collimation, making it valuable for homeland security, nuclear decommissioning, and space science applications. This study proposes a position-sensitive bar-shaped detector for Compton imaging, where bar-shaped scintillator detectors are arranged in a planar array with signals read out from both ends of each detector to reduce electronic channel count. The detection system developed in this study offers advantages of radiation hardness, high efficiency, and low cost. A large sensitive volume of  $5\text{ mm} \times 5\text{ mm} \times 100\text{ mm}$  CsI(Tl) scintillator detector, with a light output of 56,000 photons/MeV, was used to verify position and energy resolution. Considering surface roughness and reflector configurations, experimental results indicate that the bar-shaped scintillators can achieve an average position resolution better than 5 mm and 7.2% energy resolution (FWHM) at 662 keV. Therefore, a balance between position resolution and energy resolution can be achieved using bar-shaped scintillators with minimal readout electronics. The imaging detection system, with  $80\text{ cm}^3$  sensitive volume constructed from bar-shaped scintillators, can be used for Compton imaging in an energy range of 250 keV to 3 MeV.

**Keywords:** Gamma-ray imaging; Position resolution; Readout electronics; Optical photon; Monte Carlo

## Introduction

Gamma cameras for radioactive imaging have been widely applied in nuclear non-proliferation [1], nuclear emergency response [2], medical imaging [3-5], environmental monitoring [6, 7], and space exploration [8-10]. Coded aperture imaging and Compton imaging represent the two primary gamma-ray imaging methods. Coded aperture imaging operates by projecting radiation from sources at various angles through an aperture array onto the detector, forming distinct patterns that are decoded to reconstruct the image [11]. This technique exhibits superior angular resolution for lower-energy incident gamma rays; for instance, the panoramic coded aperture gamma camera by Shifeng Sun achieves  $3.5^\circ$  angular resolution for a  $^{137}\text{Cs}$  source [12]. However, the coded aperture blocks a portion of gamma rays, reducing detection efficiency, and high-energy gamma rays are difficult to absorb effectively by the mask, leading to blurred projections and decreased contrast. Consequently, for medium- to high-energy gamma rays, Compton imaging is more suitable as it eliminates the need for collimators, enabling a wider field of view and higher detection efficiency [13]. Various Compton camera structures have been proposed, including monolithic detectors and multilayer detectors [14-16].

Monolithic detectors are sensitive to incident gamma rays from all directions, providing a wide field of view, but they require three-dimensional position-sensitive capability to distinguish the depth of two energy depositions. Charles University used a CdTe detector with a Timepix3 chip to image  $^{131}\text{I}$ ,  $^{137}\text{Cs}$ , and  $^{22}\text{Na}$  sources from different directions; due to the detector's thinness, filtering and deconvolution algorithms were applied to enhance image qual-

ity [17]. Tsinghua University built a Compton camera with a 3-D position-sensitive CZT detector to identify isotopes and locate  $^{137}\text{Cs}$  sources, though with slightly inadequate angular resolution [18]. In addition to semiconductor detectors, approaches using pixelated scintillators with SiPM or MPPC have also been proposed [19]. Waseda University developed a Compton camera with pixelated GAGG scintillators and MPPC arrays, achieving 7.8% energy resolution (FWHM) at 662 keV and  $8^\circ$  angular resolution for a  $^{137}\text{Cs}$  source [20]. H. Lee et al. developed a Compton camera using the same scintillators, reducing radioactive background noise and making it suitable for compact platforms like drones [21]. J. Zhang simplified pixelated scintillator manufacturing using laser engraving, with MPPC readout on both sides to enhance spatial resolution [22]. Yifan Hu developed a gamma camera with a  $4\pi$  field-of-view by interleaving GAGG(Ce) scintillator strips, eliminating collimators to improve portability and sensitivity [23]. While sophisticated electronics have been developed for monolithic detectors, their limited size means that the two interaction points of a Compton scattering event are in close proximity (relative to the detector's 3D spatial resolution), which ultimately leads to deteriorated angular resolution.

Multilayer detectors locate scattering and absorption positions in different 2-D position-sensitive detectors to increase the number of effective imaging events. Shin Watanabe designed a Compton camera using six layers of double-sided silicon strip detectors (DSSD) and three layers of CdTe pixel detectors, achieving energy resolutions of 9.1 keV for 356 keV and 14 keV for 511 keV, as well as  $3.9^\circ$  angular resolution for 511 keV gamma rays [24]. Although the multilayer structure improves imaging efficiency, it is more costly than dual-layer structures. To reduce costs, the two-layer Compton imaging structure has become mainstream. Ji-Peng Zhang built a camera using a dual-layer pixelated GAGG scintillator, achieving 7.2% energy resolution (FWHM) for 662 keV gamma rays and approximately  $8^\circ$  angular resolution [25]. To increase the camera's sensitive detection volume, Ming Hao Dong built a dual-layer Compton camera with enlarged  $\text{LaBr}_3$  detectors ( $10\text{mm}\times 10\text{mm}\times 10\text{mm}$  and  $10\text{mm}\times 10\text{mm}\times 5\text{mm}$ ), achieving  $7^\circ$  angular resolution for a  $^{137}\text{Cs}$  source [26]. To cover low-energy imaging, the High Efficiency Multimode Imager (HEMI) system from Berkeley utilizes a dual-layer array with  $1\text{cm}^3$  CZT detectors to achieve both coded aperture and Compton imaging [27].

As demand for gamma camera applications grows, various techniques have been proposed to enhance practicality, such as increasing the detector's sensitive volume [28], reducing the number of electronic channels [29], expanding the field of view, or adapting to single-direction far-field radiation imaging [30]. In addition to improvements in detector structure, numerous methods to enhance image performance have been proposed [31]. With technological development, researchers increasingly focus on improving imaging efficiency, reducing noise [32], and enhancing spatial resolution [33] and localization accuracy [34].

We propose a Compton camera design using a bar-shaped scintillator array. By analyzing signals read out from SiPMs coupled to both ends of each scintillator,

the photon interaction position along the longitudinal axis can be reconstructed. This approach replaces traditional arrays of small-volume scintillators, effectively increasing the sensitive volume of the Compton camera while reducing the number of electronics channels. The concept of using bar-shaped scintillators to determine deposition position was proposed as early as the 1970s and has been applied in high-energy astrophysics, such as the ZEBRA telescope and AGILE satellite [35–38], as well as in PET [39]. However, both the surface roughness of the scintillator and the reflective materials significantly affect energy and position resolution. To achieve better energy and position resolution while increasing the detector's sensitive volume, we conducted simulations and experiments on the surface roughness and reflective materials of a  $5 \text{ mm} \times 5 \text{ mm} \times 100 \text{ mm}$  CsI(Tl) detector, investigating the impact of different reflective materials and surface roughness on these properties. The Compton camera utilizing this approach significantly reduces the number of electronic channels compared to other Compton cameras with the same sensitive volume.

## II. Compton Imaging Detector Design

### A. Structure of Imaging Detector

Compton imaging detectors require three-dimensional (3-D) position sensitivity. As shown in Figure 1: see original paper, a typical double-layer structure was selected for this study. Generally, the first detector array layer serves as the scattering detector, while the second layer functions as the absorbing detector. Each layer comprises 16 parallel-arranged bar-shaped scintillator detectors, providing 2-D position information for interactions. The detector system with 3-D position sensitivity is formed by using two layers of 2-D position detectors. The field of view for Compton imaging can be adjusted by changing the spacing between the two detector layers.

In a two-dimensional planar array detector, position resolution is discrete due to the discrete arrangement of bar-shaped scintillator detectors. Continuous position segmentation along the bar axis results in non-uniform position resolution. Orthogonal alignment of the detectors contributes to uniformity of directional response.

The scattering detector with 2-D position sensitivity provides the position and energy deposition,  $(x_1, y_1, z_1, e_1)$ , for the Compton scattering interaction point, while the absorbing detector obtains the interaction position and energy deposition of the scattered photon,  $(x_2, y_2, z_2, e_2)$ . Assuming electrons in the scattering process are initially at rest (i.e., their initial kinetic energy and motion are negligible), the expected energy of scattered photons can be calculated using Equation (1). This energy calculation is based on Compton scattering kinematics. Subsequently, the deflection angle of scattered photons can be derived from Equation (1), as shown in Equation (2) [40]. Due to the limited spatial resolution of bar detectors, it is not possible to know the trajectories of electrons produced in scattering, so the photon's incident directions can only

be reconstructed as a conical surface representing all directions compatible with the two photon interaction positions and their energy deposits. This conical surface is known as the Compton cone or back-projection cone. By detecting a large number of Compton scattering events, the radiation source position can be located by intersecting Compton cones [41].

$$E' = \frac{E_0}{1 + (E_0/m_{ec}^2)(1 - \cos \theta)}$$
$$\cos \theta = 1 - \frac{m_{ec}^2}{E_0} \left( \frac{E_0}{E'} - 1 \right)$$

where  $E_0$  is the energy of the incident photon,  $E'$  is the energy of the scattered photon,  $\theta$  is the Compton scattering angle,  $m_e$  is the electron rest mass, and  $c$  is the speed of light.

To increase the sensitive volume of the detector system, a large-volume bar-shaped scintillator coupled with two SiPMs on the end faces serves as the minimum detection unit, as shown in Figure 1: see original paper. When radiation interacts with the scintillator detectors, generated scintillation photons propagate toward both ends of the detector. Due to interface reflection and self-absorption in the scintillator, scintillation photons are attenuated with exponential decay. This feature facilitates position reconstruction of interactions within the detector by measuring pulse signal amplitudes from the two SiPMs along the bar's main axis. This method provides one-dimensional position resolution capability for the bar-shaped scintillator. Each SiPM is equipped with its own dedicated electronic readout channel to reduce electronic noise while improving position and energy resolution. Methods for improving spatial resolution and spectroscopy of bar-shaped scintillators applied in the ZEBRA telescope and AGILE provide valuable insights for this study [37, 38].

In experiments, to alter the surface roughness of bar-shaped scintillators, we used sandpaper with similar roughness to uniformly sand the surface, ensuring consistency. The reflective layer was applied by two methods: one involved wrapping the scintillator with Teflon tape, while the other involved placing the scintillator bar in a mold, pouring  $\text{TiO}_2$  slurry over its surface, and placing the mold in a vacuum environment to eliminate air bubbles from the slurry. After curing, the  $\text{TiO}_2$  layer was ground to a thickness of 0.5 mm. These optimizations contribute to improved signal quality and measurement accuracy. Ultimately, this imaging structure allows a single-layer array detector with 2D position sensitivity to have larger sensitive volume while using fewer electronic channels. To increase the sensitive volume of Compton detectors, consider using two or more layers of array detectors. This modular design allows flexibility in adjusting sensitive volume while reducing electronics complexity. When choosing a detector, it is critical to consider the energy resolution of the scintillator detector and available manufacturing technology.

## B. Monte Carlo Modeling

This work describes a Compton camera design employing position-sensitive bar-shaped scintillators as the minimum detection unit. However, scintillator surface parameters significantly impact optical properties. For example, two important Compton camera parameters—position reconstruction accuracy and energy resolution—are sensitive to surface roughness and reflective layer material [42]. We can optimize position resolution capabilities by adjusting scintillator surface parameters and selecting appropriate reflective materials.

To validate design feasibility, we created detailed models of the scintillator and minimum detection unit using Monte Carlo simulation software Geant4. We modeled and simulated several representative surface parameters and reflective layer materials to evaluate their effects on position and energy resolutions, providing insights for optimizing detector performance based on chosen surface characteristics.

First, based on the structure shown in Figure 1: see original paper, we constructed a simulation model of a basic unit using Geant4. Next, we employed the optical photon physics model in the Geant4 software package to simulate fluorescence photons produced in the scintillator and the internal optical characteristics of the scintillator [43]. To closely approximate real-world conditions, we adopted the Unified Model for optical simulation. This model is particularly suitable for complex optical surfaces and allows flexible adjustment of parameters such as specular spike, specular lobe, diffuse lobe, reflection, and backscattering. These parameters offer high flexibility, with the sum of Specular Spike, Specular Lobe, and Diffuse Lobe always equal to 1. By adjusting the ratios of these three parameters, we can effectively change surface roughness and simulate different optical behaviors. We selected Dielectric-Dielectric and Dielectric-Metal boundary types to represent Teflon-wrapped and  $\text{TiO}_2$ -coated surfaces, respectively. By precisely configuring these parameters, we can accurately simulate the optical behavior of various material surfaces, facilitating more in-depth research.

It is important to consider a scintillator with high light yield. To meet these requirements, a commonly used CsI(Tl) scintillator was chosen for simulation studies due to its high scintillation efficiency and low intrinsic background radiation. The fluorescence efficiency of the CsI(Tl) scintillator is about 56,000 photons/MeV, the decay time is about 1020 ns, and the average emission wavelength is 550 nm. The photon detection efficiency (PDE) of the SiPM for light at this wavelength is approximately 20%. To reduce simulation time, the SiPM's photon detection efficiency was set to 100%, simplifying simulation without compromising result accuracy.

To increase the detector's sensitive volume and enhance imaging sensitivity, we need to maximize the cross-sectional area of the bar-shaped scintillator. SiPMs with larger light-sensitive areas are selected to achieve this goal. Currently, commercially available SiPMs with large

light collection areas include the EQR20 11-6060D-S from Novel Device Laboratory, S13360-6025PE from Hamamatsu, ARRAYC-60035 from onsemi, and AFBR-S4N66P014M from Broadcom, typically around  $6\text{mm} \times 6\text{mm}$ <sup>{2}</sup>. To collect photon emitted from both ends of the bar-shaped scintillator, we selected scintillators with a cross-sectional area and a reflective material layer thickness of 0.5 mm. To ensure accurate measurement of interaction depth within the scintillator, we chose bar-shaped scintillators with dimensions of  $5\text{mm} \times 5\text{mm} \times 100\text{mm}$ <sup>{3}</sup>. We propose constructing a double-layer Compton camera using 32 bar-shaped scintillators. A larger sensitive volume can enhance imaging efficiency, meaning more events suitable for imaging can be obtained within the same period, thereby reducing imaging time.

To study the effects of different surface roughness under the same reflective layer, and the impact of various reflective layers with the same roughness on the final energy and position resolution of the bar-shaped scintillator, we used Teflon and  $\text{TiO}_2$  as reflective materials. Considering whether the scintillator surface is rough or not, we modeled and analyzed four typical characteristics, as shown in [Figure 2: see original paper]. It should be noted that when Teflon is used as a reflective material to wrap the scintillator, the reflective material and crystal surface typically do not fit tightly, usually creating small air gaps. As shown in Figure 2: see original paper and 2(b), these air gaps can affect experimental results. In contrast, when a reflective coating is applied to cover the crystal surface, the reflective material makes tight contact with the scintillator surface. As illustrated in Figure 2: see original paper and 2(d), there are no air gaps between the two surfaces. This difference is crucial in experimental design, as air gaps can alter the optical properties of the scintillator, thereby affecting detector performance. Through simulation analysis of these characteristics, we can better understand how surface roughness and reflective layer materials affect bar-shaped scintillator performance.

In the simulation process, a gamma ray source with energy of 662 keV is used. The source is positioned 40 cm away from the central axis of the scintillator, with its emission direction aligned toward the scintillator. By moving the radiation source, a uniform irradiation scenario is simulated. The G4StepAction function is employed to monitor the type of particles produced in each step and the energy deposited by radiation. In Geant4, each individual particle trajectory is assigned a unique track ID. For photons, once generated, Geant4 assigns a track ID that enables tracking of the photon's path throughout the simulation, including propagation, interactions with matter, and eventual disappearance. When combined with the G4StepAction function, it allows simulation and tracking of the total number of photons generated within the scintillator and the number detected by dual-ended SiPMs. This data provides insights into photon propagation through the scintillator and helps evaluate energy and position resolution based on varying surface and reflective layer parameters.

The Compton imaging system consists of two layers of array detectors. Each layer contains 16 detection units with center-to-center spacing of 6.2 mm. The resulting single-layer array detector approximates a square configuration, as

shown in Figure 1: see original paper. Additionally, the spacing between the two detector layers can be adjusted as required to modify the imaging field of view (FOV). The default spacing between the two array detectors is 60 mm, which allows for a larger field of view. With this configuration, the system has 32 detection units, yielding 64 electronic channels. The effective sensitive volume of the detector is 80 cm<sup>3</sup>.

### III. Signal Processing and Event Reconstruction

#### A. Event Reconstruction Method

To determine the deposition location and energy of rays in a bar-shaped scintillator, an appropriate depth of interaction (DOI) reconstruction method is required. Currently, DOI reconstruction methods used with dual-end readout scintillator detectors fall into two categories: the time-of-flight method [44] and the amplitude-ratio method [45]. The time-of-flight method uses the time difference between pulses received at the two ends of the scintillator to determine the location of radiation interaction. This method has been applied in balloon-borne Compton telescopes [46]. However, it requires high accuracy and high sampling rates from electronics and is more suitable for longer scintillators, increasing electronics complexity and cost. The amplitude-ratio method for DOI reconstruction uses the ratio of photons emitted from the two ends of the scintillator to determine interaction depth. This method eliminates the need for high time resolution and high sampling rates, effectively reducing electronics complexity and cost. Given these considerations, the proposed design uses the amplitude-ratio method for DOI reconstruction.

The amplitude-ratio reconstruction method proceeds as follows. When the bar-shaped scintillator has the same cross-sectional area shape (rectangular or cylindrical) and no light guide exists between the scintillator and photodetector, and when the scintillator surface exhibits uniform roughness, scintillation photons produced within the scintillator are transmitted to both ends with approximate exponential attenuation. The attenuation distance  $l_0$  is related to scintillator size, surface roughness, and reflector. This exponential decay behavior is critical for determining DOI within the scintillator by comparing relative pulse amplitudes from both ends.

Assuming the interaction position and energy deposition position are at the middle of the bar-shaped scintillator, the DOI value  $Z_{DOI}$  is 0, and the scintillator length is  $L$ . If an incident particle deposits energy at position  $Z_{DOI}$  within the scintillator and generates  $N$  photons, the number of photons collected at the left and right ends can be calculated as:

$$N_{left} = 0.5\epsilon N e^{-(L/2+Z_{DOI})/l_0}$$

$$N_{right} = 0.5\epsilon N e^{-(L/2-Z_{DOI})/l_0}$$

where  $\varepsilon$  is the photodetector detection efficiency, defined as the ratio of photons detected to photons incident on the detector, and  $l_0$  is the exponential attenuation length for photons within the scintillator.

To evaluate positioning accuracy, we define parameter  $F$  as the ratio of photons emitted from one end to the total photons emitted from both ends:

$$F = \frac{N_{right}}{N_{right} + N_{left}}$$

By substituting formulas (3) and (4) into formula (5), we obtain:

$$Z_{DOI} = -\frac{l_0}{2} \ln \left( \frac{1-F}{F} \right)$$

Using the error propagation formula, the positioning accuracy can be obtained by measuring fluctuations in parameter  $F$ :

$$\sigma_{DOI} = \frac{\partial Z_{DOI}}{\partial F} \sigma_F = \frac{l_0}{2F(1-F)} \sigma_F$$

Since  $N_{left}$  and  $N_{right}$  are random variables obeying Poisson distribution, their variances are:

$$Var(N_{right}) = N_{right}, \quad Var(N_{left}) = N_{left}$$

Based on the variance formula for ratios:

$$\sigma_F^2 = \frac{N_{right}N_{left}}{(N_{left} + N_{right})^4} (N_{left} + N_{right}) = \frac{N_{right}N_{left}}{(N_{left} + N_{right})^3}$$

Therefore:

$$\sigma_{DOI} = \frac{l_0}{2F(1-F)} \sqrt{\frac{N_{right}N_{left}}{(N_{left} + N_{right})^3}} = \frac{l_0}{2} \sqrt{\frac{1}{N_{left}} + \frac{1}{N_{right}}}$$

According to formulas (3) and (4), the geometric mean of the read signal at both ends is proportional to the total number of photons generated and is independent of interaction depth. Thus, energy resolution can be measured:

$$\sqrt{N_{left}N_{right}} = 0.5\varepsilon N e^{-L/2l_0} \propto N \propto E_{deposition}$$

Each minimum detection unit is equipped with its own signal readout circuit. The method described above can reconstruct position by analyzing signal amplitude, and the signal amplitude can determine the energy deposited by radiation in the bar-shaped scintillator, enabling energy measurement.

## B. Simulation Results and Experimental Parameter Selection

After building the simulation model for the minimum detection unit in Geant4, we performed simulation and comparative analysis on the four typical scenarios shown in [Figure 2: see original paper] to identify characteristics suitable for position and energy reconstruction in bar-shaped scintillators, which will be validated experimentally.

The simulation recorded the incident position of gamma rays and the number of photons emitted from both ends of the scintillator. The photon counts from both ends in the four simulations are plotted as scatter plots, as shown in [Figure 3: see original paper]. The plot in [Figure 4: see original paper] shows parameter  $F$  versus the reconstructed interaction position along the bar's main axis.

Simulation results indicate that under the conditions shown in Figure 3: see original paper, photon attenuation within the scintillator is minimal, resulting in no significant difference in photon counts emitted from both ends. This leads to poor position resolution for the strip-shaped scintillator. In contrast, results in Figure 3: see original paper show high photon attenuation within the scintillator, making it difficult for photons generated in the middle to exit from both ends, which deteriorates energy resolution. Meanwhile, results shown in Figure 3: see original paper and (c) reveal a good balance between energy and position resolution.

To investigate the impact of scintillator surface parameters on energy resolution in these four scenarios, we used the method described in Section 3.1 to calculate energy resolution based on photon counts from each end. The results are shown in .

Energy resolution of four simulation results

Condition	FWHM
Polished + Teflon	7.77%
Rough + Teflon	10.49%
Polished + TiO <sub>2</sub>	7.90%
Rough + TiO <sub>2</sub>	44.14%

Based on these simulation results, we can draw the following conclusions:

1. According to results shown in Figure 4: see original paper, when the scintillator surface is polished and wrapped with Teflon reflective material, parameter  $F$  remains relatively constant as DOI varies. This may be due

to high probability of total internal reflection at the medium's surface, resulting in no discernible difference in photon counts from both ends—unfavorable for position reconstruction. However, as illustrated in Figure 4: see original paper, when the scintillator surface is rough,  $F$  varies monotonically and noticeably with DOI, beneficial for position resolution. Meanwhile, comparing Figure 3: see original paper and 3(b), when surface roughness increases, energy resolution deteriorates to some extent.

2. According to results shown in Figure 4: see original paper, when the scintillator surface is polished and coated with  $\text{TiO}_2$ , the coating tightly adheres to the scintillator surface. Parameter  $F$  exhibits clear, monotonic variation with DOI, indicating good position and energy resolution capabilities, possibly because the  $\text{TiO}_2$  coating has certain granularity that increases the probability of diffuse reflection. However, as shown in Figure 4: see original paper, when the scintillator surface becomes rougher, diffuse reflection increases, resulting in a broader range of  $F$  values that no longer follow a monotonic trend. As shown in Figure 3: see original paper, this affects both position reconstruction and energy resolution. Increased surface roughness may reduce energy resolution due to additional scattering and reflections, complicating position and energy determination.
3. According to results shown in Figure 3: see original paper and 3(c), the scintillator exhibits both position and energy resolution when the surface is polished and coated with  $\text{TiO}_2$  or when the surface is rough and wrapped with Teflon. However, under the conditions shown in Figure 3: see original paper, the number of photons emitted from both ends is significantly higher than under conditions in Figure 3: see original paper, which is more favorable for reconstructing energy and position information.

To achieve the conditions described in Figure 3: see original paper, the bar-shaped scintillator requires surface roughening and wrapping with reflective material. In this process, ensuring uniform contact between scintillator surfaces and Teflon is challenging. The above simulations only validated trend-based changes caused by varying surface parameters and reflective layer materials. Additionally, changes in factors like scintillator surface roughness, refractive index, and reflection efficiency can influence photon counts from both ends and further affect SiPM output pulse amplitude. Therefore, the simulation model must be adjusted based on experimental results.

## IV. Experimental Results and Discussion

### A. Hardware System Verification

To experimentally validate the simulation results, we established a corresponding electronic hardware system that must meet multi-channel, high-precision data acquisition requirements. The system includes a preamplifier readout circuit whose scheme is shown in Figure 5: see original paper, a fixed framework and circuit module in the blue box on the left whose scheme is shown in Figure

5: see original paper, and a four-channel high-speed waveform data acquisition card (DAQ) shown in Figure 5: see original paper. These components together form a comprehensive system for capturing and analyzing signal data. The fixed frame is designed to hold three CsI(Tl) scintillators simultaneously. In actual experiments, to minimize electronic measurement errors, a consistent set of electronic devices was utilized, and repeated measurements were performed with different scintillator bars. This approach effectively mitigates experimental deviations caused by electronic errors, thereby improving the reliability and accuracy of collected data.

The circuit shown in Figure 5: see original paper ensures stability of SiPM output signals and reduces distortion. The SiPM anode is directly coupled to the charge-sensitive preamplifier input, ensuring all charge output from the SiPM is collected. However, this design can be affected by SiPM dark current, which may impact output signal precision. In actual measurements, it is necessary to adjust RC parameters for different scintillators to achieve better energy resolution. This approach helps maintain signal integrity while optimizing SiPM-based detection system performance. shows the value ranges of some SiPM features.

#### SiPM features

Feature	Value
Effective Pitch	$6.24 \times 6.24 \text{ mm}^2$
Terminal Capacitance	397 pF
Breakdown Voltage ( $V_B$ )	$27.2 \text{ V} \pm 1 \text{ V}$
Maximum operation voltage ( $V_m$ )	$34.7 \pm 1.6 \text{ V}$
Recommended Operation Voltage	$V_B + 5 \text{ V}$
Temperature Coefficient for $V_B$	$24.8 \text{ mV}/^\circ\text{C}$
Peak PDE @ 420nm	47.8%
Dark Count Rate (DCR)	$8.0 \times 10^5$ (Typical) 150 kHz/mm <sup>2</sup> , 450 kHz/mm <sup>2</sup> (maximum)

To ensure photons emitted from both ends of the scintillator are collected as effectively as possible by SiPMs, we selected unique Epitaxial Quenching Resistor (EQR) SiPMs from Novel Device Laboratory (NDL). These SiPMs offer several advantages, including compact structure, high-density microcells, wide dynamic range, high detection efficiency, fast response time, excellent time resolution, insensitivity to ambient temperature, and radiation resistance [47].

The circuit shown in Figure 5: see original paper was fabricated as a minimum basic detection circuit module depicted in the blue box on the left of Figure 5: see original paper. The preamplifier and SiPM are mounted on the same PCB to reduce signal transmission distance and maintain signal quality. These components are coupled to the two end faces of the bar-shaped scintillator shown

in Figure 5: see original paper, with signal output through coaxial cables. Pulse signals from SiPMs at both ends of the scintillator are captured using the 4-channel high-speed waveform acquisition card shown in Figure 5: see original paper. This acquisition card has excellent signal processing capabilities. The ADC on the card has 16-bit resolution and 80 MHz sampling rate, ensuring signal fidelity during sampling. After high-speed ADC sampling, data including channel number, timestamp, and raw waveform are processed and packaged within an FPGA, then sent to a computer for processing and display through an Ethernet interface. The hardware gain, DC offset, and trigger threshold of the acquisition card can be adjusted through the host computer, allowing flexible selection of optimal parameters to achieve the best signal-to-noise ratio.

Original pulse data is transmitted to the host computer via network interface. Because captured pulse signals have a typical exponential decay pattern, digital filtering with the trapezoidal shaping algorithm is used to improve pulse amplitude measurement accuracy. This method not only filters out high-frequency noise but also allows precise amplitude extraction, useful for subsequent analysis. The device shown in Figure 5: see original paper was placed in a fully light-tight metal shield box. In the experiment, the energy resolution of the bar-shaped scintillator was first tested using an uncollimated  $^{137}\text{Cs}$  source. Subsequently, the source was collimated to measure position resolution at different points. This controlled environment helps ensure accurate measurements while reducing interference from external factors.

According to simulation results in Section 3.2, we selected four CsI(Tl) scintillators with dimensions of  $5 \times 5 \times 100 \text{ mm}^3$  for experimental verification, applying the following four experimental conditions: (a) Polished scintillator wrapped with Teflon; (b) Polished scintillator coated with  $\text{TiO}_2$ ; (c) Scintillator surface with 800-mesh roughness, wrapped with Teflon; (d) Scintillator surface with 800-mesh roughness, coated with  $\text{TiO}_2$ .

We conducted preliminary tests on the four selected scintillators. The scintillators were fixed using the frame shown in Figure 5: see original paper and uniformly irradiated with a  $^{137}\text{Cs}$  radiation source at 40 cm distance. Signal amplitudes read by SiPMs at both ends were recorded and plotted as scatter plots, as shown in [Figure 6: see original paper]. Based on preliminary test results, signal amplitude scatter plots from SiPMs at both ends of the four selected scintillators closely match simulation results.

## B. Performance Measurement

To evaluate scintillator position resolution, a collimated radioactive source was used to measure multiple points on the scintillator, as shown in Figure 7: see original paper. To ensure collimation measurement accuracy, the midpoint of the bar-shaped scintillator was taken as the reference point ( $Z_{DOI} = 0$ ). Five measurement points were evenly spaced on both sides, resulting in 11 total measurement points for collimated measurements. The experimental setup, shown

in Figure 6: see original paper, includes two lead bricks spaced 3 mm apart to collimate the  $^{137}\text{Cs}$  source, with a guide rail employed to slide the source, ensuring measurement accuracy.

The scatter plot of collimation measurements is summarized, and data corresponding to the full-energy peak are selected to calculate position resolution. Taking the bar-shaped scintillator under experimental condition (b) as an example, the scatter plot of the eleven measurement points is shown in Figure 8: see original paper. The fitted diagram of parameter  $F$  values for the remaining points is shown in Figure 8: see original paper.

Following the same approach, measurement data from the other three bar-shaped scintillators were processed, and parameters  $F$  and  $Z_{DOI}$  from the four measurements were fitted using Equation 6, as shown in [Figure 9: see original paper].

Results shown in [Figure 9: see original paper] indicate that under experimental condition (a), bar-shaped scintillator position resolution is relatively poor. Under condition (b), the distribution of parameters  $F$  and  $Z_{DOI}$  exhibits an approximately linear relationship, and position resolution demonstrates good consistency. Under condition (c), position resolution near the two ends of the scintillator slightly decreases, but overall performance remains within an acceptable range. In contrast, under condition (d), the distribution of parameters  $F$  and  $Z_{DOI}$  shows a nonlinear relationship, and position resolution error is larger near the two ends of the scintillator, leading to uneven overall position resolution.

According to measurement results in [Figure 9: see original paper], when the bar-shaped scintillator is under condition (b) with a polished surface and coated with  $\text{TiO}_2$  reflective coating, the scintillator achieves position resolution better than 5 mm. Therefore, energy resolution at different test points of this scintillator was further analyzed. Figure 10: see original paper shows energy spectra for half of the eleven measurement points. It can be observed that when measurement points are near the scintillator edge, energy spectra widen significantly. Figure 10: see original paper shows energy resolution at each point, revealing that energy resolution decreases at both ends of the scintillator bar, but the average energy resolution remains 7.2%.

### C. Analysis and Discussion

The estimated energy resolution and position resolution for the four bar-shaped scintillators, along with fitting functions between parameter  $F$  and interaction position, are presented in .

Comparison of energy resolution, position resolution, and  $F$  with respect to interaction position for four surface types

Surface type	Reflector	Energy resolution	Position resolution	$F$ as a Function of $Z_{DOI}$
Polished	Teflon	10.18%	No clear photopeak	$Z_{DOI} = -72.58 \ln\left(\frac{1-F}{F}\right)$
Polished	TiO <sub>2</sub>	7.21%	<5 mm	$Z_{DOI} = -26.87 \ln\left(\frac{1-F}{F}\right)$
Roughness 800 mesh	Teflon	20.67%	<5 mm	$Z_{DOI} = -18.08 \ln\left(\frac{1-F}{F}\right)$
Roughness 800 mesh	TiO <sub>2</sub>	No clear photopeak	>10 mm	$Z_{DOI} = -10.47 \ln\left(\frac{1-F}{F}\right)$

Based on experimental results, we can draw the following conclusions:

1. According to Figure 6: see original paper, when the scintillator has a smooth surface and is wrapped in Teflon reflective material, its position resolution is reduced, consistent with simulation results. Comparing Figure 6: see original paper and 6(c), where both use Teflon reflective material, the scintillator exhibits some position resolution when its surface is rough. This shows that position and energy resolution of bar-shaped scintillators can be improved by selecting suitable surface roughness when wrapped with Teflon.
2. According to Figure 6: see original paper, when the scintillator has a smooth surface and is coated with TiO<sub>2</sub>, it exhibits good energy resolution and some position resolution. However, as surface roughness increases, energy resolution decreases, consistent with simulation results. Comparing Figure 6: see original paper and 6(c), while both scenarios exhibit some energy and position resolution, pulse amplitude at both ends of the scintillator is significantly smaller under the conditions shown in Figure 6: see original paper.

In summary, to achieve good energy and position resolution for bar-shaped scintillators, two typical surface characteristics can be selected: a polished surface covered with TiO<sub>2</sub> reflective coating, or a rough surface wrapped with Teflon reflective material. When the scintillator surface is wrapped with reflective material, changes in surface roughness can significantly impact both position and energy resolution. Considering the difficulty of ensuring consistency among multiple detectors when reflective material is wrapped around the scintillator surface, it is recommended to fully polish the surface and use TiO<sub>2</sub> coating as the reflective material.

compares key advantages of the detection system proposed in this paper with data reported in the literature, highlighting unique characteristics of different Compton camera designs.

## V. Conclusions

This study describes a structure for constructing a Compton camera using a position-sensitive bar-shaped scintillator array, which utilizes pulse amplitude read out from both ends of the scintillator to reconstruct the energy and position of gamma rays deposited within the scintillator. This method offers several advantages over traditional Compton cameras built with small-volume scintillator arrays, including larger sensitive volume and fewer electronic channels. Geant4 simulation software was used for modeling and simulation to optimize bar scintillator surface parameters for better energy and position resolution of the minimum detection unit. Results showed that the best position and energy resolution was achieved when the strip CsI(Tl) scintillator surface was smooth and coated with a  $\text{TiO}_2$  reflective layer. According to simulation results, the CsI(Tl) scintillator achieved an average energy resolution of 7.2% at 662 keV and position resolution better than 5 mm. Most importantly, this study demonstrates that constructing a Compton camera using position-sensitive strip scintillators is feasible.

## VI. Authorship Contribution Statement

Cheng-Shuai Tian: Data curation, methodology, validation, Writing - original draft. Jian Yang: Conceptualization, funding acquisition, Supervision, Writing - review & editing. Guo-Qiang Zeng: Project administration, Supervision. Xin-Yu Yang: Investigation, Visualization. Hao-Wen Deng: Formal analysis, Validation. Chuan-Hao Hu: Supervision, Writing - review & editing. Chun-Di Fan: Validation, Formal analysis.

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