Simulation Study on Event Positioning Algorithm of Fast Neutron Imaging Detector Based on Scintillating Fiber and SiPM Array

Authors: Chen, Dr. Weikun, Zhong, Mr. Guoqiang, Dr. Bing Hong, Dr. Jian Liu, Chen, Dr. Weikun

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Abstract

The miniaturized fast neutron imaging detector based on scintillating fiber (Sci-Fi) will adopt a SiPM array as the photoelectric conversion component. The center of gravity (CoG) method, a commonly used method for neutron event positioning, exhibits poor applicability to signals in the edge region of the array. To address this issue, this paper conducts a simulation study on the distribution characteristics of light output from the Sci-Fi and light guide using Geant4. The correlation coefficients (R 2) of the photon distribution functions fitted for different regions are all above 0.99. In addition, this paper classifies the deviations generated during the application of the imaging detector into three major categories: inherent deviations, hardware deviations, and algorithmic deviations. For algorithmic deviations, scintillation photon events randomly distributed in the Sci-Fi array are simulated. The inversion method developed based on the photon distribution function adopts an iterative calculation approach to determine the event position with the best match. Compared with the CoG method, the inversion method reduces the average deviation by more than 13 %, maintains good positioning performance for events in the edge region, improves the utilization rate of the SiPM array, and is suitable for scenarios requiring higher precision and a wider field of view.

Full Text

Preamble

Simulation Study on Event Positioning Algorithm for Fast Neutron Imaging Detector Based on Scintillating Fiber and SiPM Array

Weikun Chen[1],*, Guoqiang Zhong[2],[3], Bing Hong[3], Jian Liu[1]

[1] Institute of Plasma Physics, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei 230031, China
[2] Institute of Energy, Hefei Comprehensive National Science Center (Anhui Energy Laboratory), Hefei 230031, China

*Corresponding author: 20240173@upc.edu.cn

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Abstract

Miniaturized fast neutron imaging detectors based on scintillating fiber (Sci-Fi) utilize SiPM arrays as photoelectric conversion components. The center of gravity (CoG) method, a commonly employed technique for neutron event positioning, exhibits poor performance for signals in the edge regions of the array. To address this limitation, this paper conducts a simulation study on the distribution characteristics of light output from Sci-Fi and light guides using Geant4. The correlation coefficients (R^2) of the fitted photon distribution functions for different regions all exceed 0.99. Furthermore, this study categorizes the deviations arising during detector operation into three major types: inherent deviations, hardware deviations, and algorithmic deviations. For algorithmic deviations, scintillation photon events randomly distributed throughout the Sci-Fi array are simulated. An inversion method, developed based on the photon distribution function, employs an iterative calculation approach to determine the event position with optimal matching. Compared with the CoG method, the inversion method reduces the average deviation by more than 13%, maintains good positioning performance for edge-region events, improves the utilization rate of the SiPM array, and is suitable for applications requiring higher precision and a wider field of view.

Keywords: scintillating fiber; SiPM array; fast neutron imaging detector; scintillation photon distribution; event positioning algorithm; Geant4

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1 Introduction

As a non-destructive detection technology, neutron radiography has been widely applied in scientific research, industry, medical treatment, and other fields. Fast neutron radiography (FNR) employs fast neutrons as the working medium. Compared with the relatively mature cold and thermal neutron radiography, the higher neutron energy of FNR degrades spatial resolution but provides superior penetration capability. Consequently, to meet the imaging requirements for objects with high atomic number (Z) and large thickness, FNR has become an important development direction in recent years. Typically, the fast neutron detection component of FNR uses luminescent materials to convert neutron events into scintillation photon signals, which are then converted into electrical signals by the photoelectric conversion component. Historically, the commonly used photoelectric conversion component was the CCD camera, which could provide high spatial resolution. However, its poor radiation resistance necessitated the additional use of reflectors and optical lenses to form a curved optical path, often resulting in large system volume and high cost.

In recent years, breakthroughs in semiconductor technology have enabled the large-scale application of silicon photomultipliers (SiPMs). The realization of miniaturized fast neutron radiography by coupling flat-panel scintillators with SiPM arrays or scintillator arrays with SiPM arrays has become a research focus. For the former approach, researchers have made attempts using EJ-200 (2023) [1] and BC-400 (2024) [2] scintillators, respectively, but this method has significant drawbacks: even a slightly thicker scintillator leads to substantial degradation in spatial resolution. The latter approach has been studied through relevant simulations and experiments by scholars from the China Institute of Atomic Energy (2021) [3] and the Spallation Neutron Source Science Center (2024) [4], but it also faces problems such as differences in light yield among scintillator units and scintillation photon crosstalk. Additionally, neutron multiple scattering is an unavoidable issue in both flat-panel scintillators and scintillator arrays, which greatly reduces image contrast.

The FNR scheme based on scintillating fiber (Sci-Fi) represents an upgrade from the aforementioned methods. The fiber-type plastic scintillators it employs possess advantages of high detection efficiency, self-collimation (directionality) [5], and low cost, while also providing spatial resolution independent of length (thickness) [6]. Meanwhile, the proposed substrate component focuses on addressing the issues of neutron multiple scattering and light crosstalk [7]. Previous studies have only targeted the combination of Sci-Fis and CCDs (Fig. 1 [Figure 1: see original paper]), such as the image denoising algorithm studied by scholars from Tsinghua University (2006) [8] and the TRION system developed by scholars from Soreq NRC (2011) [9]. However, technical research on combining Sci-Fi with substrate materials and SiPMs for neutron radiography remains lacking. Therefore, research on miniaturized fast neutron imaging detectors based on Sci-Fi and SiPM arrays is of great significance.

In this type of detector, scintillation photons generated in the Sci-Fis pass through the light guide and are received by the SiPM array. Each irradiated SiPM unit outputs an electrical signal corresponding to the light intensity. Thus, the distribution of output signals from the SiPM array reflects information such as the size and position of the light spot. The commonly used center of gravity (CoG) method [10, 11] calculates the center of the light spot—which represents the coordinates of the neutron event—based on the weighted array signals. However, a deviation exists between this calculated position and the actual position where the neutron interacts in the fiber, becoming particularly large when the event position is close to the edge of the array. To address this issue, this paper first investigates the distribution characteristics of output signals from the Sci-Fi, evaluates the deviation caused by the CoG method, and subsequently develops an improved inversion-based image processing algorithm.

[Figure 1: see original paper]

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2 Photon Distribution Characteristics of Sci-Fi

The fast neutron imaging detector targeted in this study consists of the following structures: an array of fiber-type plastic scintillators serving as the sensitive volume is combined with a substrate material to form the fast neutron detection component of the imaging detector (Fig. 2 Figure 2: see original paper). Instead of the traditional CCD, a SiPM array (Fig. 2(b)) is adopted as the photoelectric conversion device. These two components are connected via a thin light guide, with a typical structure shown in Fig. 2(c). Among these components, the substrate is crucial for neutron measurement in the Sci-Fi detector. In addition to preventing light crosstalk, it also suppresses signals generated by neutrons arriving from lateral directions and inhibits secondary particles such as γ rays and β rays [12, 13]. The light guide is also indispensable in this detector. Considering that photons emitted from the end of the Sci-Fi form concentrated bright spots, a light guide of appropriate thickness can disperse these photons evenly onto multiple surrounding SiPM units, enabling improved position resolution through methods such as the CoG method. Furthermore, to avoid electrical risks (e.g., leakage current and electric field interference) that may arise from direct contact between the metal substrate and the SiPM array, as well as physical damage risks (e.g., surface scratches and pressure-induced damage), the light guide also functions as an insulator and separator.

[Figure 2: see original paper]

This study employs the Monte Carlo simulation method [15, 16] using Geant4 [17] (version 11.3) as the simulation software. The Geant4 toolkit has been widely applied in simulating Sci-Fis for radiation and optical applications [18-20], with simulation results showing good consistency [21] with those from the professional optical software Zemax [22-24]. Prior to this study, simple verification confirmed that the light transmission and end-face distribution characteristics simulated by Geant4 are consistent with Zemax calculation results. The physics list QGSP_{{{BIC}}{{HP}}} [25] was selected according to the energy range of incident particles. This physics list defines the physical laws governing all interactions within the model, including processes such as radiation, electromagnetism, and attenuation. To ensure that all scintillation photons can be correctly generated, reflected, attenuated, and absorbed, the optical portion of the original physics list was replaced with G4EmStandardPhysics{option4} [26], thereby incorporating optical physics into the simulation process.

The single-fiber model used in this section’ s simulation mainly includes components such as the Sci-Fi, substrate, light guide, outer shell, and reflective layer. The counting surface was set as the rear end-face of the light guide, which also serves as the photon-receiving plane of the SiPM array. The Sci-Fi model was constructed with reference to the Kuraray SCSF-78M [27], a multi-clad fiber with a diameter of 1 mm. Its optical parameters were determined based on the product manual and relevant literature [28]. This fiber type has been used in the D-T neutron detection system of the EAST fusion experimental device, achieving favorable performance [13]. Considering that the neutron source commonly used in application scenarios is a D-D neutron generator producing fast neutrons with energy around 2.5 MeV, the fiber length and substrate thickness were set to 10 mm. At this dimension, the energy of recoil protons generated by neutrons in the fiber can be well deposited while considering the efficiency of fiber transmission of scintillation photons. It should be noted that although longer Sci-Fi increases the sensitive volume, the attenuation of scintillation photons during transmission also increases, so the Sci-Fi length is not necessarily "the longer, the better." Additionally, the substrate material was set to pure aluminum, which has been verified to be insensitive to both incident neutrons and γ rays [29], meeting the requirements of the imaging detector. The contact surfaces between the core and cladding of the Sci-Fi, between the fiber and substrate, and between the fiber and light guide were all configured with corresponding optical boundary layers according to the materials used to improve the accuracy of the optical process simulation.

The position resolution of imaging detectors for neutron events is affected by multiple factors. In addition to the Sci-Fi and SiPM array themselves, the light guide is also a key factor. The study of output photon distribution characteristics from the Sci-Fi array must consider light guide thickness, as it directly determines the degree of conical diffusion of photons emitted from the rear end-face of the fiber. A light guide that is too thin lacks the ability to disperse scintillation photons emitted by the fiber, while an excessively thick light guide leads to an overly large photon diffusion range. Both scenarios directly impact the detector' s position resolution. Typically, light guide thickness is selected within the range of 0.5–3 mm. In this study, four types of polymethyl methacrylate (PMMA) light guides with different thicknesses were chosen to investigate the radial distribution law of light spots formed by a single fiber on the SiPM plane.

Considering the extremely small reaction cross-section between fast neutrons and Sci-Fis and that the main reaction process is elastic collision, recoil protons with an energy of 2.5 MeV were directly used as source particles in the simulation. Their emission positions and directions were set randomly within the core layer of the Sci-Fi, with 10^7 source particles in each simulation. It should be noted that in actual experimental environments, neutrons only incident from the front end-face of the detector in a direction close to the axial direction, so the emission direction of recoil protons is restricted. The purpose of using random emission directions in this simulation is to obtain more general laws.

The simulation results are shown in Fig. 3 [Figure 3: see original paper]. The typical light spot formed by a single fiber is a uniform circle with obvious count attenuation along the radial direction. In the double logarithmic coordinate system, the curve showing the relationship between counts and radial distance exhibits an approximately linear trend in the middle and rear sections, and this characteristic exists for light guides of different thicknesses.

[Figure 3: see original paper]

Taking the model with a 1.0 mm-thick light guide as an example for detailed analysis, the radial distribution diagram of photon counts on the SiPM plane can be divided into three regions, as shown in Fig. 4 [Figure 4: see original paper]. The red region (Region 1) accounts for the largest number of counts, with its corresponding maximum radial distance close to the radius of the Sci-Fi; the relationship between counts and radial distance in this region follows a Gaussian distribution. The maximum distance corresponding to the blue region (Region 2) may be related to the maximum allowable photon exit angle of the Sci-Fi and the thickness of the light guide, which requires further research; the fitting line of counts in this region can be expressed by an exponential function. The yellow region (Region 3) has the largest range and covers the most SiPM units, with the relationship between counts and radial distance approximately following a power function distribution. The functions and parameter values corresponding to the three regions are presented in Table 1 . Similarly, in other simulations using light guides of different thicknesses, the relationship between photon counts and radial distance can also be represented by the same type of functions, though the parameters differ. It should be noted that the parameters of different functions are independent of each other; identical parameter names are used only for space-saving purposes.

[Figure 4: see original paper]

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3 Positioning Method of Neutron Events and Discussion

In current SiPM array applications, "deviation" is inevitable regardless of the positioning algorithm used. Here, deviation refers to the distance between the calculated event position (x_1, y_1) and the projected position (x_0, y_0) of the actual event position (x_0, y_0, z_0) on the SiPM array plane. The main sources of deviation can be divided into three categories:

3.1 Inherent Deviation

The event center calculated by various algorithms essentially corresponds to the center of the position where scintillation photons are generated in the fiber, rather than the position where the incident neutron undergoes elastic scattering. A deviation exists between these two positions, which is smaller than the range of the recoil proton. Typically, this deviation is extremely small—on the order of tens of micrometers for incident neutrons with energy of 2.5 MeV. The inherent deviation is minimized when the emission direction of the recoil proton is close to the axial direction.

3.2 Hardware Deviation

Deviations arise due to hardware non-ideality, primarily from gaps and inhomogeneities. For example, in the SiPM array, gaps exist between individual units; the sensitive area of each unit that can detect optical signals does not fully cover the unit surface, with a portion of ineffective area at the edges; physical gaps also exist between pixels within the sensitive area. All these dead zones can lead to loss of optical signals. Inhomogeneities include misalignment between scintillating fibers and SiPM array units, as well as parameter inhomogeneities in the SiPM array—such as sensitivity, gain, and dark count rate—which also introduce deviations. Furthermore, noise in the electronic system affects the counting of optical signals, indirectly causing deviations.

3.3 Algorithmic Deviation

Deviations are introduced by algorithms used to calculate the center position of events. For example, the CoG method generates deviations at edge positions, while the inversion method in this study introduces deviations due to inaccurate photon distribution functions or different iteration termination conditions. These deviations can be mitigated by improving the algorithm but are difficult to avoid completely.

In addition to these major deviation sources, factors with higher randomness also exist. These include statistical deviations caused by random fluctuations in the number and emission direction of scintillation photons, as well as deviations induced by external environmental factors such as temperature and electromagnetic interference. These factors are usually difficult to predict and control, so they are not the focus of main studies in this field. This paper carries out follow-up studies targeting algorithmic deviations, with the verification dataset also generated via Geant4 simulation. The Sci-Fi array model employed consists of 2304 Sci-Fis with a length of 10 mm embedded in an aluminum substrate, corresponding to a 16$×$16 square SiPM array.

Fiber spacing must consider the degree of matching with the SiPM array; ideally, the number of fibers corresponding to each SiPM unit should be consistent. However, unavoidable gaps exist between each unit, as shown in Fig. 5 [Figure 5: see original paper]. Therefore, the final fiber axis spacing is set to 1.12 mm, enabling uniform matching between the fiber array and the SiPM array. Considering that the inherent deviation generated when the recoil proton energy is 2.5 MeV is very small, the process from proton energy deposition to scintillation photon generation is simplified in the simulation to improve computational efficiency. Optical photons emitted isotropically are directly set as source particles, with their emission positions randomly distributed within the Sci-Fi array, thus covering particle events at both center and edge positions of the array.

[Figure 5: see original paper]

3.1 CoG Method The CoG method is the most common technique for determining the position of particle events. Its principle is to calculate the weighted center of the incident photon distribution based on the position of each SiPM unit and the amplitude of the output signal. The positioning formula is as follows:

$$x_{\text{cog}} = \frac{\sum_i x_i A_i}{\sum_i A_i}, \quad y_{\text{cog}} = \frac{\sum_i y_i A_i}{\sum_i A_i}$$

where x_{cog} and y_{cog} are the x and y coordinates of the event center calculated by the CoG method, respectively; N_x and N_y are the number of SiPM units in the x and y directions, respectively; x_i and y_i represent the x and y coordinates of the i-th SiPM unit, respectively; and A_i are the output pulse amplitudes of the i-th SiPM unit, which were replaced by photon counts received by the unit in this study.

The CoG method demonstrates good positioning capability for events occurring in the central region of the SiPM array but produces large deviations when calculating positions of events in the edge region, mainly due to incomplete photon counting caused by some photons reaching areas outside the SiPM array. Simulation results from three model groups with light guide thicknesses of 0.6 mm, 1.0 mm, and 1.8 mm were selected for discussion, with deviation distributions calculated using the CoG method shown in Fig. 6 [Figure 6: see original paper]. A clear jump in deviation values can be observed in the edge region, while deviation distribution in non-edge regions is relatively uniform. When the light guide thickness is 1 mm, the average deviation across the entire region is minimized, reaching 0.54 mm. A thinner light guide has insufficient photon dispersion capability, while a thicker light guide leads to an increased edge region area. For light guides with thickness not exceeding 4 mm in general cases, the edge region with large CoG method calculation deviation is within the side length of one SiPM unit (3.36 mm). Therefore, when processing data acquired by the SiPM array, average deviation can be significantly reduced by discarding data from 1-2 layers of units at the array edge. However, this approach wastes SiPM units, particularly since these “discarded” units still generate data during detector operation and occupy bandwidth of the data acquisition (DAQ) system.

[Figure 6: see original paper]

3.2 Inversion Method Based on Photon Distribution Characteristics Combined with the distribution law when scintillation photons generated by a single Sci-Fi are transmitted to the SiPM plane through a light guide, an inversion method can be developed to localize particle events, thereby significantly reducing positioning deviation in the edge region of the array. Its principle is as follows: a random search algorithm is used to find the optimal position where the photon counts of surrounding SiPM units well conform to the photon count distribution law, allowing the center position of the light spot to be inverted from the counts of each SiPM unit. Commonly used random search algorithms include pure random search (PRS), random walk (RW), particle swarm optimization (PSO), and ant colony optimization (ACO) algorithms. In this study, the PSO algorithm [30] was used for calculation, with the correlation coefficient (R^2) between the photon count matrix around the calculated position and the theoretical distribution function taken as the fitness value. Other algorithms can also serve the same purpose, though they may differ in iteration count and computation time.

When the number of scintillation photons generated by the Sci-Fi is sufficient, the inversion method uses only the photon distribution function corresponding to the yellow region in Fig. 4, as this region covers the largest area in the SiPM array, providing the maximum number of SiPM units available for calculation. To facilitate comparison among the three simulation groups, the lower threshold of the radial distance corresponding to this region is uniformly set to 4 mm. Taking the model with a 1.0 mm-thick light guide as an example again, Fig. 7 Figure 7: see original paper shows the distribution of positions calculated by the CoG method, positions calculated by the inversion method, and actual event positions for a typical particle event.

Figs. 7(b) and 7(c) respectively show the curves of R^2 and the deviation between the calculated position and actual position during the iteration process. It should be noted that the deviation value and iteration R^2 do not exhibit a strictly negative correlation, indicating that the deviation when R^2 is maximum may not be minimum. This may be caused by multiple factors such as gaps between photosensitive regions of the SiPM array, errors in the photon distribution function, and statistical errors. However, overall assessment shows that when R^2 reaches above 0.95, the deviation has converged to a relatively low level, and the number of iterations is usually within 50. Therefore, the upper limit of iterations set for the inversion method in subsequent studies is 50, significantly saving algorithm running time. Certainly, R^2 can also be directly set as the iteration termination condition, or a dual criterion combining iteration count and R^2 may be adopted. The specific approach can be selected based on practical requirements.

[Figure 7: see original paper]

Simulation results from three model groups with light guide thicknesses of 0.6 mm, 1.0 mm, and 1.8 mm are selected for discussion and compared with the average deviation between CoG method calculation results and actual positions, as shown in Fig. 8 [Figure 8: see original paper]. Under the condition that the R^2 of iterative calculation results is not less than 0.95, the obvious advantage of the inversion method can be observed, with average deviation reduced by more than 13%.

It should be noted that for a higher R^2 standard, although deviation will continue to decrease, iteration time becomes longer and the requirement for count rate increases. Fig. 9 [Figure 9: see original paper] intuitively shows the deviation value distributions calculated by the inversion method ($R^2 > 0.95$) and inversion method ($R^2 > 0.97$) when using the 1.0 mm-thick light guide, which demonstrates the best performance. Compared with the CoG method, the inversion method can significantly reduce calculation position deviation in the edge region of the SiPM array, meaning more SiPM units can be utilized and directly increasing the imaging detector' s field of view. Additionally, when a higher R^2 standard is used, the uniformity of deviation distribution is improved.

[Figure 8: see original paper]

[Figure 9: see original paper]

3.3 Discussion and Analysis Based on comparison between the calculation results of the two aforementioned positioning methods and actual event positions, their advantages, disadvantages, and applicable scopes can be analyzed, as shown in Table 2 . For scenarios requiring high real-time performance, the CoG method has significant advantages. The currently developed inversion method has slower calculation speed but can ensure smaller event positioning deviation and higher utilization rate of the SiPM array, expanding the imaging field of view. Additionally, it can realize uncertainty quantification. Future studies will focus on further optimizing the iterative algorithm to shorten iteration time and reduce deviation values.

Furthermore, it is worth noting that if the number of scintillation photons generated by the Sci-Fi is insufficient, the light signals reaching the SiPM array will be weak. Low sensitivity of SiPM units will also result in low-intensity output signals from the SiPM array. Both situations inevitably increase position deviation calculated by the CoG method and the inversion method. Therefore, this type of fast neutron imaging detector has high requirements for the light yield of the Sci-Fi used and the sensitivity of the SiPM unit. For this scenario, the average R^2 obtained by iterative calculation using only the photon distribution function of Region 3 in Fig. 4 is relatively low ($R^2 < 0.90$), and the deviation value increases significantly. In such cases, the photon distribution functions of all three regions in Fig. 4 can be used simultaneously. Although this increases calculation load and iteration time, the average R^2 can be restored to above 0.99.

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4 Conclusion

The FNR scheme based on Sci-Fi is expected to use plastic Sci-Fis and a SiPM array to form an imaging detector. The CoG method, commonly used for positioning neutron event centers based on signals from each SiPM unit, exhibits poor applicability to signals in the edge region of the array. To address this issue, this study first conducted a simulation investigation on the distribution characteristics of scintillation photons generated by recoil protons in the Sci-Fi and emitted through the light guide. The light spots irradiating the SiPM detection plane are divided into three regions, fitted using a Gaussian function, an exponential function, and a power function, respectively. The correlation coefficients (R^2) of the corresponding photon distribution functions all exceed 0.99.

Additionally, this study classifies deviations generated during detector operation into three major categories: inherent deviations, hardware deviations, and algorithmic deviations. For algorithmic deviations, scintillation photon events randomly distributed within the Sci-Fi array are simulated. Evaluation of the CoG method shows that for a properly thick 1 mm light guide, the average deviation is 0.54 mm, but a significant jump in deviation occurs in the edge region of the array. Based on these studies, the improved and developed "inversion method" adopts an iterative calculation approach, comparing calculated values of the photon distribution function with measured signal intensities output by each SiPM unit to determine the event position with optimal matching. Compared with the CoG method, the inversion method reduces average deviation by more than 13%, achieves good positioning performance for edge-region events, improves the utilization rate of the SiPM array, and is suitable for applications requiring higher precision and a larger field of view.

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Note: Figure translations are in progress. See original paper for figures.