Research on proton beam spot imaging based on pixelated gamma detector

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ABSTRACT: The secondary particles from the spallation target of the China Spallation Neutron Source are mainly gammas and neutrons, which are related to the incident proton. The reconstruction of the proton beam spot could be implemented based on the distribution of the positions of secondary gammas or neutrons. The methods of pinhole imaging and Compton imaging are developed by measuring the position distribution of gammas based on the pixelated detector. The secondary gammas could be detected by the pixelated gamma detector directly. The neutron can be identified by detecting the characteristic (478 keV) γ-rays from the $^{10}$B($n$, $\alpha$) reactions. In order to detect secondary neutrons, a layer of $^{10}$B converter is added before the pixelated gamma detector. The pixelated gamma detector is sensitive to the characteristic (478 keV) γ-rays and then the neutron imaging could be achieved based on measuring the position distribution of the characteristic (478 keV) γ-rays.

KEYWORDS: Beam-line instrumentation (beam position and profile monitors, beam-intensity monitors, bunch length monitors); Gamma detectors (scintillators, CZT, HPGe, HgI etc); Neutron detectors (cold, thermal, fast neutrons); Neutron radiography

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1 Introduction

It is crucial to monitor beam status by measuring the parameters of the beam profile. Although the Faraday cup generally is used for measuring the beam intensity, the pixelated one could measure the beam profile [1]. The wall current monitor system can provide the information of the longitudinal profile about the proton bunches [2, 3]. The two-dimensional (2-D) transverse profile of proton beam in the Linac can be measured with a multi-wire scanner (MWS) in a non-destructive way [4]. One kind of stripline-type beam position monitor (BPM) was designed and used for measuring the position and phase of the proton beam in air in a non-destructive way [5]. A proton imaging system has been also developed to measure the proton range, which is composed of a scintillator and a charge-coupled device [6].

Figure 1. Schematic diagram of the Back-n beam line at CSNS.

China Spallation Neutron Source (CSNS) has been built and commissioned successfully since August 2018, whose purpose is dedicated to the multidisciplinary research on material science [7].
It consists of an 80MeV linear proton accelerator, a 1.6GeV proton Rapid Cycling Synchrotron (RCS), a target station and the different kinds of neutron spectrometers. For example, an associated white neutron beam line was built for nuclear data measurement by exploiting the back-streaming neutrons (Back-n) [8, 9]. Figure 1 shows the schematic diagram of the Back-n beam line. The position distributions of proton beam from the rapid cycling synchrotron at CSNS are measured by the position sensitive MWS [10, 11]. However, it measures only the horizontal and vertical profiles of the proton beam separately, and can not obtain real two-dimensional (2-D) position distribution.

In this work, we can directly monitor the secondary particles to measure the 2-D position distribution of the proton beam spot from the spallation target on the Back-n beam line. This method is based on a mathematical model constructed by the relationship between the position distribution of secondary particles (gammas and neutrons) and that of the incident protons. We used Geant4 software [12] to simulate the physical process of generating neutrons and gammas by slamming protons onto a cylindrical tungsten target. The position distribution of gammas on the target surface was measured by the pixelated detector of Cadmium Zinc Telluride (CZT). The proton beam spot is reconstructed by utilizing the position distribution of gammas based on the method of the pinhole imaging. In addition, when the pixelated gamma detector could be combined with a neutron converter of $^{10}$B, the method of combining the pinhole and Compton imaging is used for neutron imaging based on measuring the characteristic (478keV) $\gamma$-rays so that we can use the position distribution of neutrons to accomplish the reconstruction of the proton beam spot.

2 The principle of Compton imaging and pinhole imaging

Compton imaging is based on reconstruction of Compton scattering events of incident gammas, which provides a promising approach for the localization of $\gamma$-ray source. The system of Compton imaging generally consists of a scattering detector and an absorbing detector. The single layer Compton camera has a huge advantage of detection efficiency compared with two detector system. The three-dimensional (3-D) position sensitive detector is able to measure the energies and the positions of scattered gamma. The scattering angle is determined by using the Compton scattering equation. The gamma source position can be limited on the surface of a cone. Therefore, the image of the gamma source could be reconstructed by recording the number of Compton scattering events. The process of Compton scattering is illustrated in figure 2 (Left).

The back-projection (BP) algorithm [13] and maximum likelihood estimation (MLE) algorithm [14, 15] are used to Compton imaging. The reconstruction technique of Compton imaging in this work is based on the simple BP algorithm [16, 17]. The distance-weighted of Compton scattering angles is defined as

$$\text{Distance} = \frac{1.0}{\cos \theta(\vec{r}_1, \vec{r}_2) - \cos \theta(E_1, E_2))^2}. \quad (2.1)$$

One can determine the scattering angles by using the information of the position and deposited energy of gamma respectively. The equations are described as

$$\cos \theta(\vec{r}_1, \vec{r}_2) = \frac{\vec{r}_1 \cdot \vec{r}_2}{|\vec{r}_1| \cdot |\vec{r}_2|}. \quad (2.2)$$

$$\cos \theta(E_1, E_2) = 1 + \frac{m_e c^2}{E_1 + E_2} - \frac{m_e c^2}{E_2}. \quad (2.3)$$

\[2\]
Where $E_1$ is the deposited energy of the recoiling electron, $E_2$ is the energy of the scattering gamma, $m_e$ is the normal mass of the electron, $c$ is the speed of the light, $\vec{r}_1$ is the vector from $r_0$ to $r_1$ and $\vec{r}_2$ is the vector from $r_1$ to $r_2$, $r_0$ is the position of gamma source, $r_1$ and $r_2$ represent the 3-D position of each radiation interaction in the detector.

A Monte Carlo (MC) sample of Compton process was generated by using GEANT4 software [12]. The size of the pixelated CZT detector is 25.4 mm x 25.4 mm x 5 mm. The 478 keV gamma point-source is 50 mm away from the pixelated CZT detector. Compton imaging was reconstructed with a simple BP method. The information of 3-D position and the deposited energies obtained from the simulation is used for calculating the $\cos \theta(\vec{r}_1, \vec{r}_2)$ and $\cos \theta(E_1, E_2)$. The position of 478 keV gamma point-source could be located to the exterior surface of a cone by calculating the distance-weighted for each interaction event. Figure 2 (Right) illustrates the oval projection of cones in a rectangular coordinate system from four events.

![Figure 2](image)

Figure 2. (Left) Schematic diagram of Compton imaging for a scattering event by using a single 3-D position sensitive detector. (Right) The oval projection of the cones from four events of Compton scattering process.

Pinhole imaging relies on the principle of the rectilinear theory of light and appears upside down in the physical image space. It is a practical device of offering freedom from distortion and virtually infinite depth of field [18]. A pinhole imaging diagnostic has been implemented to measure the electron beam position and profile in the SPEAR storage ring [19]. The imaging system of variable and moving pinhole arrays based on a time multiplexing method achieves much better resolution and signal-to-noise [20]. Because the proton beam has a high intensity, pinhole imaging is suitable for measuring the proton beam spot on the target surface.

3 The feasibility of realization for Compton imaging and pinhole imaging

The gamma detector has to provide the information of the position and deposited energy of gamma according to the principle of Compton imaging. The position and energy resolution of the detector system affect the angular resolution of Compton imaging. The semiconductor detectors, such as high-purity germanium (HPGe), have higher detection efficiency and energy resolution compared to the inorganic crystals and plastic scintillators. The HPGe is the semiconductor detector with the best energy resolution. Due to the narrow band gap, the detector of HPGe only works in the liquid nitrogen.
temperature zone. The CZT has a wide band gap and can work at room temperature. Therefore, the Compton cameras have been developed based on the 3D position-sensitive semiconductor detector [21–24]. The positional resolution of the interaction points in the x and y directions was limited by the finite size of the CZT, and that in the z direction was limited by the finite resolution of drift time. The best angular resolution of the Compton camera consisting of a single Timepix3 detector with a thick 2 mm CdTe sensor reaches the order of a few degrees [25, 26]. Figure 3 shows the promising applications of the proton beam spot imaging on the target surface.

![Diagram of gamma and neutron imaging](image)

**Figure 3.** Scheme of the experimental setup of the proton beam spot based on the distribution of the secondary particles. (Left) Secondary gamma imaging using the pinhole technique. (Right) Secondary neutron imaging of combining the pinhole with Compton techniques. In order to detect secondary neutrons, $^{10}$B converter is added before the pixelated gamma detector.

## 4 Reconstruction of the proton beam spot

### 4.1 Algorithm model

The 2-D position distribution of the proton beam spot is reconstructed based on the relationship between the incident protons and the secondary particles on the target surface. The mathematical model is described by a linear equation, which is defined as

$$\tilde{G} = \tilde{A} \times \tilde{P},$$

where $\tilde{G} = [g_1, g_2, \ldots, g_M]$ is vector rearranged by the 2-D position distribution of secondary gammas or neutrons on the target surface, which is replaced by the measured image obtained by the imaging system at a distance from the target. $\tilde{P} = [p_1, p_2, \ldots, p_N]$ represents vector rearranged by the 2-D distribution of the incident proton beam spot, $\tilde{A} = (a_{ij})_{M \times N}$ is the response matrix, $a_{ij}$ stands for the contribution of the $j^{th}$ pixel of $\tilde{P}$ with respect to the $i^{th}$ pixel of $\tilde{G}$, which is 2-D integral of the point response function (PRF). PRF denotes the distribution of diffusion of the secondary particles generated by a point proton beam bombarding the tungsten target, which could be estimated based on the MC simulation. The inverse linear problem described in eq. (4.1) could be solved by algebraic reconstruction technique (ART) [27].
4.2 Gamma imaging

Due to the high intensity of secondary gammas, we use only the pinhole imaging system to measure the 2-D position distribution of gammas with the pixelated CZT detector, as shown in figure 3 (Left). According to the relationship between the position distribution of incident protons and the position distribution of back-streaming secondary gamma, we can reconstruct the 2-D position distribution of the proton beam spot on the target surface.

The physics list of QBBC from GEANT4 was used to simulate the interaction of 1.6 GeV proton beam on a cylindrical tungsten target with a radius of 10 cm and a height of 30 cm. The incident proton beam is uniformly square distribution with the length of a side is 10 cm. The secondary particles were emitted in the backward direction. The vertex position distribution of secondary gammas could be found in figure 4 (Left). Figure 4 (Right) shows the 2-D position distribution of secondary gammas on the target surface.

![Figure 4](image)

Figure 4. (Left) Vertex position distribution of secondary gammas. (Right) The 2-D position distribution of gammas on the target surface.

Figure 5 (Left) is the 2-D position distribution of gammas detected on the target surface from the proton point-source. In order to calculate the response matrix, the position distribution of gammas is described by 2-D double Gaussian function. The 2-D distribution of the response matrix is drawn in figure 5 (Right). Figure 6 (Left) shows the 2-D position distribution of gammas on the target surface from the rectangular proton beam (10 cm × 10 cm). The position distribution of gammas consists of 1024 pixels (32 × 32). The linear equation could be solved by algebraic reconstruction technique (ART) to reconstruct 2-D position distribution of the proton beam spot, as shown in figure 6 (Right). The reconstructed 2-D position distribution of the proton beam spot has a clear circle, which is the boundary of the cylindrical target.

The size of a pixelated CZT detector is 25.4 mm × 25.4 mm × 5 mm, and the number of anode readout pixels is 256 (16 × 16). Taking into account the different assembly combinations of the pixelated CZT detector, 4 pieces of the same CZT detectors consist of 32 × 32 pixels and 9 pieces have 48 × 48 pixels. In order to obtain the best resolution of reconstructed position distribution of the proton beam spot, we have performed different bins of 2-D position distribution of gammas and protons. The reconstructed 2-D position distributions of the proton beam spot are shown in figure 7. Its columns are the number of bins for reconstructing image of the proton beam spot. The first-row reconstructed position distributions of the proton beam spot result from the measuring position.
Figure 5. (Left) 2-D position distribution of gammas from target surface generated by incident proton beam of point source. (Right) The 2-D distribution of the response matrix.

Figure 6. (Left) 2-D position distribution of gammas with $32 \times 32$ pixels from the target surface. (Right) The reconstructed 2-D position distribution of the proton beam spot with $32 \times 32$ pixels obtained by solving linear equation based on the ART method.

distribution of gammas with $16 \times 16$ pixels. The second-row reconstructed position distributions of the proton beam spot result from the measured position distribution of gammas with $32 \times 32$ pixels. The third-row reconstructed position distributions of the proton beam spot result from the measured position distribution of gammas with $48 \times 48$ pixels. With the increase of pixels, the reconstructed 2-D position distribution of the proton beam spot has a much higher resolution. Although a single CZT detector was used for pinhole imaging, the 2-D position distribution of the proton beam spot on the target surface has been also reconstructed clearly.

4.3 Neutron imaging

In order to perform the neutron imaging, figure 3 (Right) shows a compound detection system constructed by combining the pinhole with Compton techniques. This system includes a mechanical collimator for the pinhole imaging and a Compton camera. The 3-D position information and energy information of incident gammas are recorded by the pixelated gamma detector and used for Compton imaging.
Figure 7. Reconstructed position distributions of the proton beam spot based on measured position distributions of gammas with different combinations of the pixelated CZT detector. The column stands for the number of bins for reconstructed 2-D position distribution of the proton beam spot (First column $[16, 16]$, second column $[32, 32]$, third column $[48, 48]$). The first-row reconstructed position distributions of the proton beam spot result from measured position distribution of gammas with $16 \times 16$ pixels, the second row reconstructed position distributions of the proton beam spot result from measured position distribution of gammas with $32 \times 32$ pixels, the third row reconstructed position distributions of the proton beam spot result from measured position distribution of gammas with $48 \times 48$ pixels.

Comparing with measuring the position distribution of the secondary gammas, a converter of $^{10}B$ is required for the secondary neutron detection. $^{10}B$ has a high cross section for thermal neutron absorption. The probability of emitting 478 keV $\gamma$-rays is about $94\%$ in the $^{10}B(n, \alpha)$ reactions. The neutrons are identified by detecting the characteristic (478 keV) $\gamma$-rays from the $^{10}B(n, \alpha)$ reactions\[28\]. However, the gamma backgrounds have a great influence on the detection of the characteristic $\gamma$-rays. These gamma backgrounds are mainly from two processes. One is from the prompt $\gamma$-rays (gamma flash) that come from the spallation process and very intense. We could remove them and select low-energy neutrons by utilizing the information of time of flight (TOF). The other comes from the decays of the activated nuclei. In order to distinguish the characteristic $\gamma$-rays from gamma backgrounds, the pixelated gamma detector should be well shielded in the experiment.

The 2-D position distribution of neutrons could be reconstructed with Compton imaging method by measuring the position distribution of the characteristic gamma from the $^{10}B(n, \alpha)$ reactions. The CZT detector is sensitive to the emitting characteristic gamma of 478 keV. The pixelated CZT detector combined with the neutron converter can be used for neutron imaging. Making use of the advantage of the characteristic (478 keV) gamma to set the energy range could suppress the backgrounds of gamma and improve the quality of Compton imaging.

Taking the conversion efficiency of neutrons into account, we performed the optimization to the thickness of the pure $^{10}B$ membrane corresponding to the thermal neutron. The neutron moderator has
not been considered in the MC simulation. Figure 8 (Left) shows the energy distribution of gammas from $^{10}\text{B}(n, \alpha)$ reactions. The conversion efficiency is calculated by requiring the energy of gammas to be larger than 0.47 MeV. The curve of the conversion efficiency of is drawn in figure 8 (Right). The uncertainty of conversion efficiency is determined according to the following formula

$$\sigma_\epsilon = \sqrt{\frac{\epsilon(1 - \epsilon)}{n}},$$

(4.2)

where $\epsilon$ is the conversion efficiency of the thermal neutrons, $n$ denotes the number of the incident thermal neutrons in the MC simulation, $\sigma_\epsilon$ presents the uncertainty of the conversion efficiency.

Figure 8. (Left) Energy distribution of gamma from $^{10}\text{B}(n, \alpha)$ reactions. (Right) Optimization of the conversion efficiency versus the thickness of $^{10}\text{B}$ based on the characteristic gamma.

The neutron imaging is also reconstructed by using a similar method of solving the linear equation (4.1). The response matrix was also calculated based on the 2-D position distribution of Compton imaging from the 478 keV gamma point-source. The 2-D position distribution and 1-D position projections of Compton imaging are shown in figure 9. The position distribution of the secondary neutrons from pinhole imaging corresponds to the vertex position distribution of characteristic (478 keV) $\gamma$-rays from $^{10}\text{B}(n, \alpha)$ reactions. We used the physical list of QGSP-BIC-HP to simulate a square source with the side length of 10 mm emitting the isotropic $\gamma$-rays based on GEANT4. The energy of characteristic $\gamma$-rays is equal to be 478 keV. The reconstruction of the vertex position distribution of initial gammas was implemented based on Compton imaging. Figure 10 (Left) and (Right) shows the comparison between the raw and the reconstructed square distribution of characteristic (478 keV) $\gamma$-rays.

5 Conclusion

The pixelated detector is suitable for measuring the 2-D position distribution of gammas based on the principle of pinhole imaging and Compton imaging. Pinhole imaging has a good application prospect for the measurement of high intensity proton beam spot. Compton imaging method used for the measurement of the neutron position distribution is proposed for the first time in this work. A 3-D position-sensitive CZT detector can work at room temperature, which has high detection efficiency and
**Figure 9.** (Left) Result of Compton imaging from the gamma point-source. (Middle) X-axis projection of Compton imaging. (Right) Y-axis projection of Compton imaging.

**Figure 10.** (Left) Original square distribution of the characteristic (478 keV) γ-rays. (Middle) The result of Compton imaging for the square distribution of the characteristic (478 keV) γ-rays. (Right) The reconstruction of the vertex position distribution of the characteristic (478 keV) γ-rays.

energy resolution for gamma. Based on the pixelated CZT gamma detector, the system of the pinhole imaging and Compton imaging will be applied to measure the proton beam spot at CSNS in the future.

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**References**

[1] A. Papa, S. Bertschi, L. Künzi and G. Signorelli, *A pixelated faraday cup for proton beam diagnostics*, *Nucl. Instrum. Meth. A* **936** (2019) 25.

[2] T. Suwada, K. Tamiya, T. Urano, H. Kobayashi and A. Asami, *New analysis and performance of a wall current monitor*, *Nucl. Instrum. Meth. A* **396** (1997) 1.

[3] P.R. Cameron et al., *The RHIC wall current monitor system*, in *Proceedings of the 1999 Particle Accelerator Conference*, New York, NY, U.S.A., 29 March–2 April 1999, pp. 2146–2148 [https://accelconf.web.cern.ch/p99/PAPERS/WEA116.PDF].

[4] Q.Z. Xing, L. Du, X.L. Guan, C.X. Tang, M.W. Wang, X.W. Wang et al., *Transverse profile tomography of a high current proton beam with a multi-wire scanner*, *Phys. Rev. Accel. Beams* **21** (2018) 072801.

[5] P.K. Roy, J.W. Lewellen, L.P. Neukirch and H.A. Watkins, *Proton beam position measurement in air using a BPM*, *AIP Adv.* **10** (2020) 095023.
[6] C.D. Darne, F. Alsanea, D.G. Robertson, F. Guan, T. Pan, D. Grosshans et al., A proton imaging system using a volumetric liquid scintillator: a preliminary study, Biomed. Phys. Eng. Express 5 (2019) 045032.

[7] H. Chen and X.-L. Wang, China’s first pulsed neutron source, Nat. Mater. 15 (2016) 689.

[8] H. Jing, J. Tang, H. Tang, H. Xia, T. Liang, Z. Zhou et al., Studies of back-streaming white neutrons at CSNS, Nucl. Instrum. Meth. A 621 (2010) 91.

[9] Y. Chen et al., Neutron energy spectrum measurement of the Back-n white neutron source at CSNS, Eur. Phys. J. A 55 (2019) 115 [Erratum ibid. 55 (2019) 145]

[10] R. Yu-Fang, H. Lu-Xiang, L. Hua-Chang, Z. Hua-Shun, X. Tao-Guang and F. Shi-Nian, Design and simulation of a wire scanner for the CSNS linac, Chin. Phys. C 34 (2010) 1655.

[11] T. Yang et al., Thermal analysis for wire scanners in the CSNS Linac, Nucl. Instrum. Meth. A 760 (2014) 10.

[12] GEANT4 collaboration, GEANT4—a simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250.

[13] L. Parra, Reconstruction of cone-beam projections from compton scattered data, IEEE Trans. Nucl. Sci. 47 (2000) 1543.

[14] T. Hebert, R. Leahy and M. Singh, Three-dimensional maximum-likelihood reconstruction for an electronically collimated single-photon-emission imaging system, J. Opt. Soc. Am. A 7 (1990) 1305.

[15] H.H. Barrett, T. White and L.C. Parra, List-mode likelihood, J. Opt. Soc. Am. A 14 (1997) 2914.

[16] Y.-L. Liu, J.-Q. Fu, Y.-L. Li, Y.-J. Li, X.-M. Ma and L. Zhang, Preliminary results of a compton camera based on a single 3d position-sensitive CZT detector, Nucl. Sci. Tech. 29 (2018).

[17] D. Xu et al., 4-pi Compton imaging with single 3D position sensitive CdZnTe detector, Proc. SPIE 5540 (2004) 144.

[18] M. Young, Pinhole optics, Appl. Opt. 10 (1971) 2763.

[19] T. Troxel, G. Brown, J. Cerino and H. Wiedemann, Measurement of electron beam profile and position using pinhole optics on SPEAR beam line II-3, Nucl. Instrum. Meth. A 266 (1988) 182.

[20] A. Schwarz, A. Shemer and Z. Zalevsky, Light intensity and SNR improvement for high-resolution optical imaging via time multiplexed pinhole arrays, Appl. Opt. 53 (2014) 4483.

[21] Z. He, W. Li, G. Knoll, D. Wehe, J. Berry and C. Stahle, 3-d position sensitive CdZnTe gamma-ray spectrometers, Nucl. Instrum. Meth. A 422 (1999) 173.

[22] D. Goodman, J. Xia, J. Sanders and Z. He, FRAM v5.2 estimation of plutonium and uranium isotopics using digitized 3-d position-sensitive CdZnTe detectors, Nucl. Instrum. Meth. A 954 (2020) 161339.

[23] Y. Kim, T. Lee and W. Lee, Radiation measurement and imaging using 3d position sensitive pixelated CZT detector, Nucl. Eng. Technol. 51 (2019) 1417.

[24] C.G. Wahl, W.R. Kaye, W. Wang, F. Zhang, J.M. Jaworski, A. King et al., The polaris-h imaging spectrometer, Nucl. Instrum. Meth. A 784 (2015) 377.

[25] D. Turecek et al., Compton camera based on Timepix3 technology, 2018 JINST 13 C11022.

[26] D. Turecek et al., Single layer Compton camera based on Timepix3 technology, 2020 JINST 15 C01014.

[27] R. Gordon, R. Bender and G.T. Herman, Algebraic reconstruction techniques (ART) for three-dimensional electron microscopy and x-ray photography, J. Theor. Biol. 29 (1970) 471.

[28] Y.K. Sun, H. Zhang, X.K. Zhao, M. Shao, Z.B. Tang and C. Li, Identifying thermal neutrons, fast neutrons, and gamma rays by using a scintillator-based time-of-flight method, Nucl. Instrum. Meth. 940 (2019) 129.