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Uniformity measurements and new positioning algorithms for wavelength-shifting fiber neutron detectors

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ABSTRACT

Wavelength-shifting (WLS) fiber scintillator detectors were successfully installed at two neutron powder diffractometers at the Spallation Neutron Source (SNS). However, they have the following second-order disadvantages: (i) they cannot have both high efficiency and images free of ghosting (position misassignment) concurrently; (ii) the apparent detection efficiency and spatial resolution are not uniform. These issues are related to the diffusion of scintillation photons and the fluctuation in the number of photons (quantum noise) collected by photo-multiplier tubes (PMTs). To mitigate these two issues, we developed two statistics-based positioning algorithms, i.e., a centroid algorithm (CEA) and a correlation algorithm (CA). Compared with the generally used maximum-photon algorithm (MPA), the CEA eliminates the ghosting with only about a 10% loss in detection efficiency, and provides better uniformity in detection efficiency and intrinsic background and lower gamma-ray sensitivity. The CA can effectively eliminate ghosting too, but the loss of efficiency at the group boundaries of PMTs is large. The results indicate that both algorithms can reduce the influence of quantum noise on the neutron positioning.

1. Introduction

The neutron scattering community is actively searching for alternative position-sensitive detector (PSD) technologies for thermal and cold neutron scattering and imaging due to the scarcity of ^{3}He gas [1]. The wavelength-shifting (WLS) fiber scintillator detector is one of the most promising alternative technologies [2] since it provides large area coverage, high efficiency, low intrinsic background, low gamma-ray sensitivity, and reasonable spatial resolution and time-of-flight (TOF) capabilities [3,4]. Furthermore, WLS-fiber (WLSF) detectors developed at the Oak Ridge National Laboratory (ORNL) can also provide images free from position misassignment (ghosting) [5] and a local count rate capability higher than ^{3}He linear position-sensitive detectors (PSDs) [3,4]. The WLS fiber detectors used at the Spallation Neutron Sources (SNS), with 5 mm × 5 cm pixel-size and 0.3-m^2 detector coverage per module, utilize fiber multiplexing methods [3,5] and the single-photon counting capability of PMTs [6] to determine neutron positions.

The WLS fiber detectors deployed at the two SNS powder diffractometers (POWGEN and VULCAN) have two second-order disadvantages. First, previous detector tests showed that ghosting exists, although it can be eliminated while sacrificing the detection efficiency by ~30–70% [5]. Second, there are non-uniformities in spatial resolution and effective pixel widths resulting in apparent non-uniformity in detection efficiency. The non-uniform detection efficiency appeared as the fluctuation in the intensity of diamond (111) peak vs. *x*-pixel in the TOF contour plot in Fig. 5(a and b) in Ref. [5]. These second-order effects typically have a minor influence on the performance of powder diffractometers under normal operating conditions. However, they may prevent WLSF detectors from being used for inelastic neutron scattering instruments that utilize much weaker scattered intensities. Generally, non-uniformities in spatial resolution, efficiency, and intrinsic background of a TOF n-PSD reduce the signal-to-noise ratio (SNR) or detectability.

In this work, we report the non-uniformities in detection spatial resolution and apparent efficiency. We conclude that the fluctuation of photon numbers (quantum noise or shot noise) of the PMTs and diffusive nature of the light response function (LRF) of the system [7] are the origins of the non-uniformities. Based on these results, we developed two new algorithms, one of which mitigates ghosting and reduces gamma-ray sensitivity while sacrificing little detection efficiency. The second is our first endeavor for the direct use of the LRF in determining the neutron position. Our results suggest ways to further improve the performance of WLSF neutron detectors.

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2. Experiments

Detector uniformity was characterized at the CG1A ($\lambda=4.22$ Å) and CG1B ($\lambda=2.35$ Å) beam line at the ORNL High Flux Isotope Reactor (HFIR) [8], and VULCAN beam line at SNS. The types of fiber mapping, scintillator, fiber-scintillator configuration, PMT, and the average operation voltage for PMTs on the test modules are listed in Table 1. The 0.5-mm thick neutron scintillators, purchased from Eljen Technology (Sweetwater, Texas, USA) and Applied Scintillation Technologies (AST, Harlow, UK), are composed of ZnS:Ag and ^{6}LiF micro-particles mixed in proprietary polymer matrices. Two types of PMTs (9124B, R6094) were purchased from Electronic Tube Ltd. and Hamamatsu Corp., respectively. The operation voltages for the PMTs were balanced so that the gains of the PMTs were close to each other within the same groups of X, Y, and G PMTs, respectively [5]. Two fiber mapping methods (V2 and V3) were described previously, and their schematic plots are shown in [5]. In the V2 fiber mapping method, the 154 x-pixels are encoded by 14 grouping PMTs (denoted as G_n, $n=1$–14) recording photons from the ends of fibers on the upper side of the detector and 11 X PMTs (X_n, $n=$ 1–11) recording photons from the ends of fibers on the lower side of the detector. For the V3 fiber encoding, 11 adjacent fiber pairs on the upper side of the scheme are connected to the same G PMT. On the lower side of the scheme, two fiber pairs at the group (G) boundary are connected to the same X PMT.

The uniformities in spatial resolution and apparent efficiency for module A were characterized using slit images. A 1-mm wide, 25-mm long slit was placed in the front of the detector. 1–5 mm thick boron-aluminum alloy plates were used to shield the detector. The detector was installed in the CG1A beam line, 50 cm away from a 1-in.-thick polyethylene plate in the beam line. Within 11 x-pixels ($x=33$–43) covered by one group-PMT (G-PMT), slit images were collected when the slit was moved horizontally at a step of one pixel each time. After integrating the obtained aperture image along the vertical direction, the net count rate versus the x-pixel numbers, $c(x)$, was calculated by subtracting the two profiles obtained when the slit was open or closed. The obtained slit profiles were fitted with a Gaussian. The full-width-at-half-maximum (FWHM) and the relative total area of the Gaussian were used as the spatial resolution and relative detection efficiency. To eliminate the ghosting effect in the slit image, we only show results of strong neutron events [5]. Here we define a strong neutron event as one with a photon (or photoelectron pulse) number $n_p \geq 10$ at one X, Y, or G-PMT at least. The profiles that used all neutron events, which contain ghosting artifacts due to much lower photon thresholds ($n_p \geq 2$ or 3), gave a slightly worse uniformity variance.

The apparent efficiency uniformity across the whole detector was characterized by the incoherent scattering profile of a vanadium rod, collected from module B positioned at $2\theta \approx 90^\circ$ at the CG1B ($\lambda=2.53$ Å). Bragg peaks of several standard powder samples (Ni, stainless steel, and ZnO) were collected at the same geometry for calibrating the 2θ position of each x-pixel. For the vanadium intensity profile vs. 2θ (or x-pixel), was corrected by $1/\sin(2\theta)$, account for the difference in solid angle subtended by each x-pixel.

The apparent efficiency uniformity of module C and its light response function (LRF), also known as a light cone, were measured using a vanadium rod, placed on the VULCAN beam line (BL7) set at the central wavelength of 2.0 Å. The LRF, $R(x, X)$, is defined as the photon-number histogram vs. X-PMT position when neutrons hit the x-pixel of the detector. The detector center was positioned at $2\theta=51^\circ$, and the sample-detector distance was 2.0 m. After integrating the scattered intensity over the incident wavelength spectrum using the neutron time-of-flight (TOF) and correcting with a factor of $1/\sin(2\theta)$ for each x-pixel, the relative intensity $c(x)$ was obtained to characterize the efficiency uniformity vs. x-pixel. We did not consider the wavelength-dependent $c(x)$ profile. The list-mode data from the detector contains the photon numbers recorded by 32-PMTs corresponding to each neutron event. We summed the photon counts at 11 X-PMTs for the neutron events incident at x positions, regardless of neutron wavelength. Normalizing by the highest photon number in the histogram, the LRF, $R(x, X)$, was obtained, where X is the order of an X-PMT in the group defined by one G-PMT. We did not observe a variation of the LRF with the depth-of-interaction (DOI) (or wavelength) of neutrons in the scintillator.

TOF powder diffraction data were also collected from a diamond powder using module C at the VULCAN beam-line. The list-mode data of both diamond and vanadium at the same detector position were used for algorithm development. Several background data sets were also collected at the VULCAN beam-line for the characterization of intrinsic background uniformity.

3. Neutron positioning algorithms

A thermal neutron typically generates photons that spread across multiple fibers covering several x-pixels in a WLS fiber detector (see Fig. 4). A maximum-photon algorithm (MPA) has been used in the present detector communication program (dcomserver v5.1) for neutron positioning, e.g., the neutron position is determined by the location of the PMT with the maximum-photon number. As described below, we developed two new algorithms, whose results were compared to those from a new version of MPA with fewer number of event rejection criteria compared with the original MPA.

3.1. Centroid algorithm (CEA)

In analogy to the weighted centroid method developed by Joung, et al. [9], the X position of a neutron event in a group is the weighted average position of 11 X-PMTs

$$X=\frac{\sum_i X_i(n_i-b)}{\sum_i(n_i-b)}, \quad i=1, 2\ldots, 11, \tag{1}$$

where n_i is the photon number recorded by the ith X-PMT positioned at X_i within a group, b is the background or the average

Table 1
Test detector modules.

Module	Fiber-mapping	Scintillator	Front[a]	Back[b]	PMT	$<V_{PMT}>$ (V)
A	V2	Single grooved AST	X		9124B for y R6094 for x	1394
B	V2	Single flat Eljen	X		9124B for y R6094 for x	1394
C	V3	Double flat Eljen	X	X	9124B	1469

[a] Front: a scintillator is in the front side of the cross-fiber array.
[b] Back: a scintillator is in the back side of the cross-fiber array.