Shifting scintillator prototype large pixel wavelength-shifting fiber detector for the POWGEN3 powder diffractometer

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Abstract. A prototype neutron scintillation detector has been developed, specifically aimed at the needs of the powder diffractometer POWGEN3 at the Spallation Neutron Source at Oak Ridge National Laboratory. This instrument requires a detector array with large (6mm x 40mm) pixels and an area of several square meters. The prototype uses a 2-dimensional grid of wavelength shifting fibers, with the fiber axes parallel to the scintillator screen, to collect the scintillation photons. The fiber ends for each pixel go to a specific set of 4 photomultiplier tubes, so that the position of each event can be determined by a 4-tube $^2C_n \times ^2C_n$ coded coincidence. The observed maximum light yield with a $^6$LiF/ZnS:Ag neutron scintillation screen, summed over 4 tubes, is greater than 200 photons/neutron. This is about 0.13% of the ~150000 photons/neutron produced in the scintillator. The light yield is sufficient to allow pulse discrimination between neutron signals and gamma-ray background. Further light collection gains should be achievable using double-clad fiber and green-enhanced photomultiplier tubes. Currently, the shape, structure, and specific composition of the scintillator are being investigated, on the assumption that $^6$LiF/ZnS:Ag will be the chosen scintillator material.

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1. Introduction.

The Spallation Neutron Source (SNS), under construction at Oak Ridge National Laboratory (ORNL), will have a number of neutron diffraction instruments which require large detector areas with relatively large pixel sizes, and good efficiency for energies up to about 1 eV. A scintillation detector system is being developed, specifically aimed at the requirements of the POWGEN3 powder diffractometer [1]. The POWGEN3 design requires narrow, tall pixels (6 mm wide and 40 to 100 mm tall) and good efficiency at relatively high energies (50% at 324 meV). Other SNS instruments, notably the VULCAN engineering diffractometer [2], have similar detector requirements [3].

The GEM powder diffractometer at ISIS uses end-on optical fibers to collect light and transport it to photomultiplier tubes (PMTs) for coincidence coding [4]. The small area and narrow angular acceptance of the fiber ends limit the light collection efficiency. The prospect of better light collection efficiency has driven several recent efforts in detector design for thermal neutron detection using wavelength-shifting (WLS) fibers [5-8], following the established use of this technology in high-energy physics [9]. The present work seeks to combine the advantages of the GEM coding methods, which include a relatively small number of light detector elements and an easily modified pixel size, with the geometrical advantages of WLS optical fibers.

A prototype of a shifting scintillator detector has been constructed to evaluate shifting fiber light collection and its effectiveness in coincidence counting schemes, and to provide a test bed for scintillators. The overall goal is to gain the experience to develop detector designs for POWGEN3 and VULCAN within their construction time
frame (installation is expected in 2006 – 2007), and to extend these developments to other SNS instruments in the future.

2. Estimate of light collection efficiency using fiber grid simulation.

The number of events counted for each neutron absorbed by a scintillator is a product of the light yield of the scintillator, the efficiency of the light collection and transport system, and the efficiency of the photon detector. This yield can be estimated for a system with a flat screen scintillator, an x-y wavelength-shifting (WLS) fiber array on the downstream side, and photomultiplier tubes by:

\[ N = Y_{eff} \times \Omega \times \epsilon_{shift} \times \epsilon_{reemission} \times \epsilon_{trap} \times \epsilon_{transmission} \times \epsilon_{PMT}, \]  

where \( Y_{eff} \) is the effective light yield of the scintillator, \( \Omega \) is the solid angle covered by the WLS fiber array, \( \epsilon_{shift} \) is the absorption efficiency of the WLS fiber, \( \epsilon_{reemission} \) is the probability of reemission of a photon shifted to a longer wavelength, \( \epsilon_{trap} \) is the probability that the re-emitted photon is trapped in the WLS fiber, \( \epsilon_{transmission} \) is the efficiency of transmission through the fiber from the array to the photomultiplier tube, and \( \epsilon_{PMT} \) is the quantum efficiency of the photomultiplier tube.

The effective light yield \( Y_{eff} \) of the scintillator is a function of the scintillator material. For the \(^6\text{LiF}/\text{ZnS}:\text{Ag}\) scintillator in the prototype, this value ranges from 150,000 photons/neutron at the surface to much lower yields from events inside the scintillator, due to the extremely poor light transmission of the ZnS material. The solid angle \( \Omega \) of light acceptance is determined by the geometry of the optical fibers. The shifting efficiency \( \epsilon_{shift} \) is a function of the absorption of the light from the scintillator in the shifting fiber. In the BCF-91A fiber [10], the mean free path, or 1/e distance, is about 400 microns for 450 nm light. The average absorption for cylindrical fiber with 1 mm diameter is about 0.85.

The product \( Y_{eff} \times \Omega \times \epsilon_{shift} \) is difficult to calculate geometrically, so we have chosen to model it using Monte Carlo simulations. We have used the geometrical
modeling capabilities of the MCNP neutron transport code to study a series of fiber grid arrangements. The goals have been to maximize light collection efficiency and balance the light collection by the front and back layers. The fiber arrangement chosen for the prototype has 1-mm-diameter fibers in the first layer (nearest the scintillator) with 2.5 mm spacing. The second layer has a series of close-packed clusters of five 1-mm-diameter fibers, with 1 mm gaps between clusters. This structure defines the 6 mm pixel width. Reflectors behind the second layer improve light collection. The simulation results are illustrated in Figure 1. Over 40% of the light emitted from a scintillator is absorbed by a fiber grid on one side of the scintillator. Figure 1(a) indicates that the light collection is quite uniform along the vertical direction. In Figure 1(b), which spans 3 pixels in the horizontal direction, the pixel edge effects in the second layer are evident, but the total light collection is still uniform.

The reemission efficiency $\epsilon_{\text{reemission}}$ is a property of the WLS dye, and is about 0.80. The trapping efficiency $\epsilon_{\text{trap}}$ is the probability that a reemitted photon will be trapped and guided along the fiber. This is determined by the difference in index of refraction between the fiber core and cladding, and by the shape of the fiber. For the round BCF-91A fiber, the trapping efficiency is about 0.034 in each direction. Double-clad fibers with higher trapping efficiency are available, and may be used in future designs.

The transmission efficiency $\epsilon_{\text{transmission}}$ is a product of the “1/e” attenuation length of the fiber and the distance from the pixel to the photomultiplier tube. For BCF-91A, the attenuation length is $\geq 3.5$ m. For the distances of $< 0.5$ m considered here, the efficiency factor should be $> 0.83$.

The quantum efficiency of the photon counter, $\epsilon_{\text{PMT}}$, is intrinsic to the device. The standard photomultiplier tubes initially installed in the prototype have an efficiency of about 0.12 for the 500 nm green photons emitted by the WLS fiber. Green-enhanced tubes with efficiencies of 0.18 to 0.22 will be tried on the prototype in the near future.
The maximum light yield expected for the prototype is about 370 neutrons/photon, with the photons distributed over four photomultiplier tubes, or .0025 of the emitted photons. If we assume that about 10 photons/photomultiplier tube are needed to reliably identify neutron events, the minimum $Y_{\text{eff}}$ needed is 16,000 photons/neutron. If the collection efficiency can be increased using double-clad fibers, green-enhanced photomultipliers, or improved fiber geometry, this number can be pushed lower.

3. Description of the Shifting Scintillator Detector Prototype.

The shifting scintillator prototype recently constructed at SNS is shown in Figure 1(a) during fiber grid assembly. The structure of the prototype includes a frame for mounting the scintillator screen on the front. Directly behind it (about 1.5 mm away) is the “y” fiber optic array, which has eighty 1-mm-diameter WLS fiber optic strands, spaced 1.5 mm apart (2.5 mm center-to-center) and spanning the 480 mm width of the scintillator assembly. Behind this, as close as practicable, is the “x” array, which has clusters of 5 adjacent WLS fiber optic strands with 1 mm space between. There are 80 such clusters, for a total of 400 fibers in the “x” array, each of which spans 200 mm. Figure 1(b) shows a close-up of the fiber array. There are 480 fibers in the entire assembly. The fibers are mounted in slotted brackets which establish the spacing in each layer, and are held in place by soft silicone rubber gaskets.

The prototype uses 18 single photomultiplier tubes. The initial tests have been conducted using Electron Tubes 9102KB 10-stage linear focus tubes. The PMT assemblies are mounted on a frame mounted several inches behind the scintillator screen. Each socket is 40 mm in diameter and about 24 mm tall, with the circuit board for the dividers and the power supply and signal connections a few mm deeper. The PMT itself
is up to 38.7 mm in diameter and 98.5±3 mm tall, excluding the guide and pins on the plug. The individual PMTs are mounted within magnetic shields.

The entire prototype assembly is about 300 mm (12") wide and 600 mm (24") long, with enough depth to house the PMTs. The box is light tight during operation, but it is easy to change the front plate with the scintillator assembly. The back is also easily accessible for work on the fiber assembly and the PMTs.

Several coincidence-coding methods are presently in use at ISIS [11]. We use a $^2C_n$ code for each axis in the prototype (with a total of four PMTs responding to each neutron count), with each end of each wavelength-shifting fiber going to a different PMT. The end of each fiber in the first layer extends to one of four photomultiplier tubes according to a $^2C_4$ coding pattern. Each 40 mm high pixel is defined by 16 fibers with ends going to the same pair of tubes. Similarly, each fiber end from the second layer is routed according to a $^2C_{14}$ code (with 14 photomultiplier tubes), with each cluster of five fibers forming a horizontal pixel. The pixels in the prototype are sized for the POWGEN3 reference design pixels, which are $6 \times 40$ mm$^2$. The overall sensitive area of the prototype is $480 \times 200$ mm$^2$, or $80 \times 5$ pixels (400 total pixels).

The prototype has been tested at using a $^{252}$Cf neutron source with a tangentially viewed ambient polyethylene moderator, recently installed at the Californium User Facility at ORNL to support SNS detector tests. Figure 3 shows traces from a 4-tube neutron coincidence, typical of the prototype observations. The brightest traces observed have 30 to 50 peaks distinguishable using the oscilloscope. We have not yet quantitatively confirmed the number of photons counted. The data indicates that digital noise discrimination, similar to that used at ISIS, is feasible with the WLS fiber array.
4. Measurements to support scintillator selection.

Although a number of other neutron scintillator materials have been considered for neutron scattering detectors in recent years [12,13], $^6\text{LiF}/\text{ZnS}:\text{Ag}$ screens remain the most likely scintillator choice for large area scintillator screens in the immediate future. The screens commercially available at present are based on a careful optimization by Spowart for reactor-based neutron radiography [14]. These screens have a $^6\text{LiF}:\text{ZnS}$ ratio of 1:4 by weight, with a proprietary low-index binder. This mixture maximizes the number of photons produced for each neutron, but the low $^6\text{Li}$ content and the limited screen thickness (due to low ZnS light transmission) severely limits the neutron collection efficiency. With the higher energy neutrons used in scattering experiments at spallation sources, higher efficiency is needed. Some improvement can be made by installation geometries [4], but better neutron collection efficiency would be a big advantage. The data in ref. 14 indicates that the light loss in mixtures with ratios up to 1:1 is relatively small, so that it may be worthwhile to accept lower scintillator performance in exchange for higher neutron absorption.

We have obtained a set of $^6\text{LiF}/\text{ZnS}:\text{Ag}$ samples with compositions having ratios of 1:5, 1:4, 1:3, 1:2, and 1:1 [15] to take another look at the optimization. Our preliminary results, obtained using a thermal spectrum from the $^{252}\text{Cf}$ source mentioned above, are summarized in Fig. 4. Figure 4(a) shows the observed count rate at a fixed position for samples, with the pulse height threshold set at 2.5%, 5%, and 10% of the maximum pulse height. There is clearly an increase in neutron counting efficiency as the ratio goes from 1:4 to 1:2; higher LiF fractions appear to offer diminishing returns. It is also clear that lower pulse height thresholds lead to higher counting rates. These counts are clearly
neutrons. When the beam was blocked with 1 mm thick Cd, the observed count rate dropped by approximately a factor of 40. When the scintillator was moved away from the source, the count rate was about 0.5 counts/second. Figure 4(b) shows pulse height spectra for the 1:5, 1:3, and 1:1 samples. The decrease in average pulse height (indicated by arrows) with increased LiF concentration is evident, as is the increase in counting rate. Further experiments are planned to study the response of these scintillators as a function of incident neutron energy.

5. Steps to operational detectors

We are continuing design work on the WLS crossed-fiber detectors, and we plan to install them as the startup detectors for the POWGEN3 and VULCAN diffractometers. The first priority is the determination of the scintillator composition. If the neutron efficiency can be improved, it might reduce the need for screen corrugation [4] or sandwich structures (scintillator plates on both sides of the fiber grid). Since the active area of the prototype is only about 50% of its structural area, redesign of the package to minimize dead area is also a high priority. The final fiber grid design is dependent on the scintillator decision (especially whether we have the option of using a sandwich or not). We will also proceed to evaluate photomultiplier tubes and confirm the advantage of double-clad WLS fiber. Finally, we will develop photon counting coincidence electronics so that we can digitally discriminate neutrons from noise.

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References:
Fig. 1. (a) The figure shows simulated light collection efficiency, calculated using MCNP, from neutron capture events within a scintillator screen as a function of vertical distance from the pixel center, for the first fiber layer (solid line), the second fiber layer (dotted line), and both layers (dashed line). (b) The figure shows light collection efficiency as a function of horizontal distance from the pixel center for three neighboring pixels, for the first fiber layer (solid lines), the second fiber layer (dotted lines), and both layers (dashed lines). (c) The figure shows a schematic of the scintillator and fibers arrangement used in the simulations. The bold lines around the second fiber layer indicate light reflectors.
Fig. 2. (a) The Shifting Scintillator Prototype is shown during fiber grid installation, illuminated by a UV lamp. The scintillator screen is to be placed on the other side of the grid. The fiber ends are routed according to the position encoding to the appropriate mounting fixtures for the photomultiplier tubes. (b) A section of the fiber grid is shown with the horizontal fibers at 2.5 mm spacing and the vertical fibers in clusters of five.
Fig. 3. Traces from a single neutron scintillation event are shown. The four traces are from 4 photomultiplier tubes, designated X1, X4, Y6, and Y8, which encode a pixel near the center of the prototype.
Fig. 4. (a) The observed neutron count rates from a series of 25.4 mm diameter $^{6}\text{LiF/ZnS:Ag}$ screens are plotted as a function of the LiF:ZnS ratio (by weight) at three different pulse height discrimination settings. The screens were at a fixed position in a thermal beam from a $^{252}\text{Cf}$ neutron source with a tangentially viewed ambient polyethylene moderator, recently installed at the Californium User Facility at ORNL to support SNS detector tests. In all cases, the count rate increases as the LiF fraction rises from 1:4 to 1:2. Significantly more neutrons are counted with lower discriminator settings. (b) Pulse height spectra for 3 screen compositions. The mean pulse height, as indicated by the arrows, decreases with increasing LiF content.