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A scintillator-based detector with sub-100-μm spatial resolution comprising a fibre-optic taper with wavelength-shifting fibre readout for time-of-flight neutron imaging

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ABSTRACT

A scintillator-based neutron-counting imaging detector with a sub-100-μm spatial resolution was developed for energy-selective neutron imaging. The detector head of the detector comprised a thin ZnS/^{6}LiF scintillator screen, a fibre-optic taper and crossed wavelength-shifting (WLS) fibre arrays. A high spatial resolution was achieved by constructing the scintillator with a thickness of 100 μm and placing it in contact with the fibre-optic taper at a magnification ratio of 3.1:1. WLS fibres with a diameter of 100 ± 5 μm (mean ± SD) were specially made, and their dye content was optimized for use in crossed WLS-fibre arrays. The developed detector had a pixel size of 34 μm × 34 μm, and exhibited spatial FWHM resolutions of 80 ± 7 μm and 61 ± 6 μm in the x and y directions, respectively. A small prototype detector demonstrated the capability of neutron imaging using Bragg edges of a Cu/Fe sample when using the pulsed-neutron source in the Materials and Life Science Experimental Facility at the Japan Proton Accelerator Research Complex.

1. Introduction

Neutron radiography and neutron tomography are powerful non-destructive techniques for visualizing an object that is not visible when using other types of radiation, such as x-rays. The applications range across various fields, including engineering, archaeology, material science, and magnetic visualization [1,2]. In particular, imaging techniques using neutron-energy information open up a wide variety of applications thanks to the utilization of Bragg edges and the neutron resonance of materials. However, the specifications required for neutron imaging present challenges; generally these include small pixels, a spatial resolution of less than 100 μm, a timing resolution of a few microseconds and a count rate capability of more than 10^5 cps.

Many imaging detectors have been developed for energy-selective neutron imaging [3]. Lehman et al. performed pioneering work on a high-resolution neutron camera system [4], and Kockelmann et al. applied a gated CCD camera to energy-selective neutron-transmission measurements at a pulsed-neutron source [5]. There are many types of neutron-counting detectors, such as a position-sensitive photomultiplier tube (PMT) coupled with a neutron-sensitive screen [6], a pixelated semiconductor detector [7], a pixelated ^{6}Li glass scintillator detector [8] and neutron-sensitive multichannel plate detector [9]. We have also previously proposed a scintillator/wavelength-shifting (WLS) fibre detector incorporating a fibre-optic taper (FOT) [10] that can produce neutron images with small pixels and less contamination by gamma rays at a moderate count rate.

In this paper we present a prototype detector that exhibited a spatial resolution of less than 100 μm for energy-selective neutron imaging at a pulsed-neutron source.

2. Scintillator/FOT/WLS-fibre detector

Fig. 1a and b show schematic views of the neutron-detecting head of the scintillator/FOT/WLS-fibre detector. The detector comprises a single scintillator screen, an FOT, crossed WLS-fibre arrays, amplifier and signal processing/encoder electronics (the amplifier and signal processing/encoder electronics are not shown in the figure). The detector has the potential to exhibit a high spatial resolution down to the sub-100-μm level with a low

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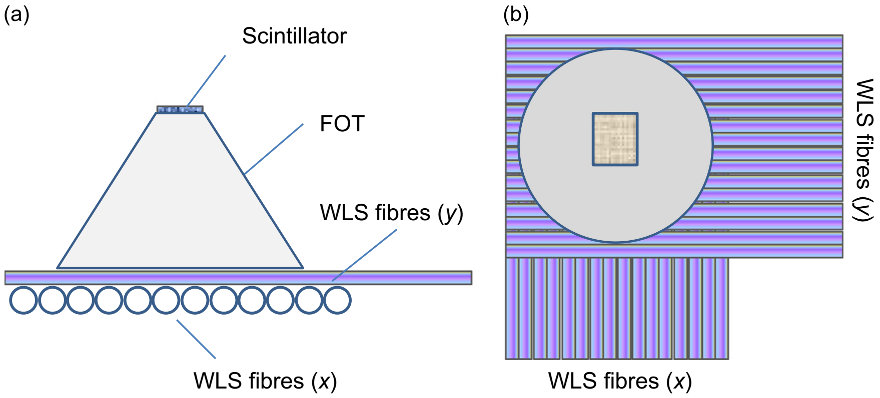

Fig. 1. Schematic (a) side and (b) top views of the neutron-detecting head of the scintillator/FOT/WLS-fibre detector.

gamma-ray sensitivity of less than 10^{-6} at ~1 MeV. Since this is a neutron-counting-type detector, the neutron image can be reprocessed using event data with access to the whole range of measured neutron energies.

The ZnS/^{6}LiF scintillator absorbs neutrons in a nuclear reaction of ^{6}Li(n,α)T, and the secondary alpha and triton particles deposit their kinetic energy onto the ZnS scintillator. The scintillator emits scintillation light whose peak wavelength is about 430 nm. The neutron-induced scintillation light propagates through the FOT while magnifying the light image onto the WLS-fibre arrays. The scintillation image is magnified, in our case by a factor 3.1; in other words the effective pixel size of the detector becomes about one-third of the fibre diameter. The limited aperture of the FOT decreases the light divergence generated in the scintillator, which ensures a high spatial resolution. The diameter of the WLS fibre is chosen according to the required spatial resolution. The WLS fibre reemits a shifted green light that is transmitted to the PMTs. In each fibre the propagated light is detected and digitized at the single-photon level. The incident position of a neutron is calculated by the signal processing and encoder electronics according to the excitation pattern of the PMTs.

The detector components should have the following characteristics in order to achieve the required spatial resolution:

1. A scintillator screen with a thickness of less than 100 μm.
2. An FOT that can perform image magnification with good light transmission.
3. Crossed WLS-fibre arrays that have reasonable light propagation and small pixels.

The basic principles of the scintillator and FOT have been reported previously [10,11]. The selection of the WLS fibres and the optimization of the dye content in the fibres are described in Section 3.

3. Optimization of crossed WLS-fibre arrays

3.1. Dye content in the fibres

3.1.1. Light-transmission characteristics

The diameter of each WLS fibre should be as small as possible in order to achieve a high spatial resolution and small pixels. However, in general the light output from a smaller-diameter fibre is lower due to it accepting less light from the scintillator. Moreover, light propagating in the fibre is attenuated by self-absorption in the fibre core. Therefore, the light attenuation was evaluated for WLS fibres with diameters ranging from 100 to 1000 μm.

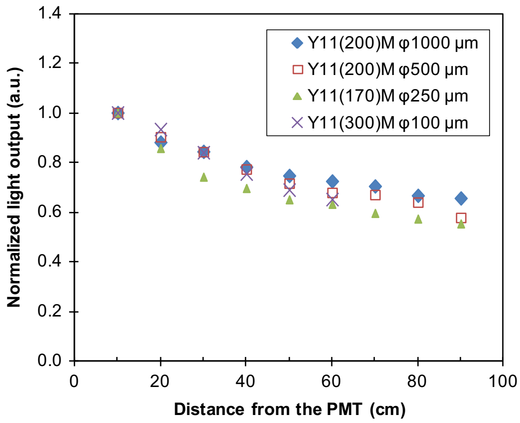

Fig. 2. Measured light transmission for Y11 Kuraray fibres with diameters of 100, 250, 500 and 1000 μm. The corresponding dye contents in the fibres were 300, 170, 200 and 200 ppm, respectively (the numbers within parentheses indicate the dye content in parts per million).

Fig. 2 shows the light transmission measured for fibres with diameters of 100, 250, 500 and 1000 μm (the diameter of the fibre is a nominal value, and can vary by 5–10%). The dye contents, corresponding to the amount of wavelength shifter in the fibre core, were selected to be similar in all of the fibres in order to facilitate the comparison; they were 300, 170, 200 and 200 ppm, respectively. One end of each fibre was connected to a PMT (model 9102S, ET Enterprises) to measure the light yield, while the other end was simply cut and left free in the air. The total length of the WLS fibre was 1000 mm, and a blue LED illuminated the fibre from the side of it while varying the distance from the PMT to the LED (the illumination area was 3 mm × the diameter of the fibre). The light output for all fibres decreased as the illumination point moved further from the PMT with a similar attenuation rate, which was 0.5–0.7%/cm in average. The transmitted light is attenuated by several factors, including (1) self-absorption of the light re-emitted in the fibre core, (2) Rayleigh scattering of the light re-emitted by defects in the fibre core and (3) imperfect light reflection at the core/cladding interfaces. In our practical application the fibre length in the assembled detector was less than 200 mm, so factor 3 would be negligible.

Fig. 3 shows the light yield in a unit illumination fibre volume for a fibre length of 200 mm. The figure includes results for the BCF92A fibre manufactured by Saint-Gobain. This indicates that the light yield was larger for Y11 fibres (manufactured by Kuraray) than for BCF92A fibres, and hence Y11 fibres were chosen for our detector. A two-dimensional neutron detector constructed using