Nuclear Instruments and Methods in Physics Research A 605 (2009) 73–76

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Development of a converter made of scintillator and wavelength-shifting fibers for fast neutron radiography

Yubin Zou *, Li'an Guo, Zhiyu Guo, Guoyou Tang, Guohui Zhang

State Key Laboratory of Nuclear Physics and Technology & School of Physics, Peking University, Beijing 100871, China

A R T I C L E I N F O

Available online 4 February 2009

Keywords:
Converter
Scintillator
Wavelength-shifting fiber
Fast neutron radiography

A B S T R A C T

Wavelength-shifting fiber (WSF) converter is a novel converter for fast neutron (FN) radiography, which has high light output, high detection efficiency and low gamma sensitivity. In order to improve the performance of WSF converter, we optimized the WSF converter design with a simple model and manufactured it with a new method, which can increase the scintillation material concentration. The light output and gamma sensitivity of WSF converters were measured on accelerator-based fast neutron sources, and gamma sensitivity was measured with an activated indium gamma source. FN radiographs were taken with WSF converter and some other traditional converters for comparison. We found that the light output of the new WSF converter is more than 5 times that of a 2 mm polypropylene (PP) converter for 5.8 MeV neutron beam, while its relative gamma sensitivity is still low.

1. Introduction

Fast neutron can penetrate massive objects, which shows the promise to use fast neutron as a nondestructive testing technique for large industry products. But the excellent penetration character also makes fast neutron hard to be detected. The neutrons are usually detected with a converter–charge-coupled-device (CCD) system. The converter should have high detection efficiency of fast neutrons, while its gamma ray sensitivity should be low, especially in fast neutron resonance radiography [1].

Plastic scintillators are often used as fast neutron converters. They are transparent to its own radiation photons, which makes it possible to use thick converters for higher neutron detection efficiency [2]. Also, plastic scintillator fibers can be used to improve spatial resolution [3]. But plastic scintillator is sensitive to gamma ray and its photon emission efficiency is low.

ZnS(Ag)-based scintillator is another option for fast neutron detection. It has higher light output, and the sensitivity to gamma ray is lower than plastic scintillators. Lots of work have been carried out to improve the performance of this kind of converter. Different hydrogenous materials and fluorescence materials were tested and the mixture ratio and the particle size of fluorescence powder were optimized [4–6]. However, the effective thicknesses of those optimized converters are no more than 2 mm only, so their detection efficiency is limited.

Matsubayashi et al. [7] have proposed a new kind of scintillator screen called wavelength-shifting fiber (WSF) converter, which was piled up with 0.1-mm thick polypropylene (PP) scintillator sheets and the sheets of WSF with diameter of 0.5 mm alternatively. They got nearly triple light output as 2 mm PP converter for a 15-mm thick WSF converter, and kept the gamma sensitivity low. But the scintillation sheet is rather thin and there are many voids among the scintillation sheets and WSF sheets. Thus the volume ratio of the scintillation, where the neutrons are detected, is rather small.

In this work, a simple model was built to optimize the main geometry parameters of the SWF converter. And a new technique was attempted to make the WSF converter. And they were compared with some other traditional converters on an accelerator-based neutron source.

2. WSF converter

In a WSF converter, the processes of neutron detection and light transmission are separated. The WSF provides an efficient channel to guide the light emitted in the scintillator to the surface [7], and then the image on the surface is recorded by a CCD camera.

The WSFs are arranged along the neutron traveling direction in a 2D matrix, and the gaps among them are filled with scintillator, as shown in Fig. 1. Photons emitted from the scintillator near the fiber can be absorbed and transmitted to secondary photons of longer wavelength. Some of the secondary photons were guided to the surface where the CCD can record them.

Fast neutrons are mainly detected in the part filled with scintillator [7], while the light output is from the WSF. The

* Corresponding author. Tel.: +86 10 62767895; fax: +86 10 62751875.
E-mail address: zouyubin@pku.edu.cn (Y. Zou).

0168-9002/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2009.01.130

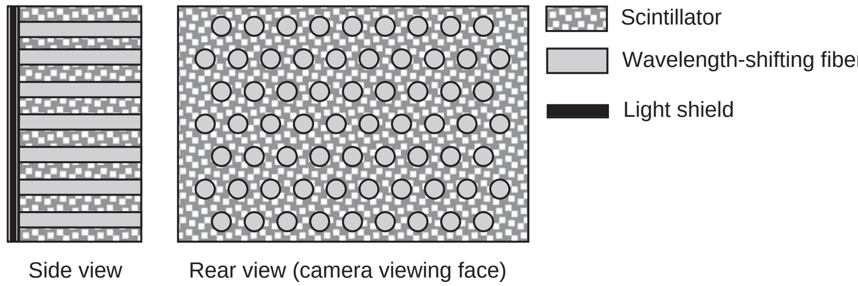

Fig. 1. Sketch map of the WSF converter.

proportion of the effective light output area on the CCD viewing face can be described as

$$K_L = \frac{\pi r^2}{(2r+d)^2} \quad (1)$$

where r is the radius of the WSF and d is the distance between two fibers. The light intensity at the fiber side surface I_S is approximately given by

$$I_S \approx \frac{I_0}{r}\int_r^{r+d} r' \exp(-\alpha r')dr'. \quad (2)$$

In this equation, I_0 is the generated intensity and α is the light attenuation coefficient in the ZnS(Ag) scintillator. If d is less than several times of r, the expression can be further approximated to an empirical form:

$$I_S \approx C(1-\exp(-\alpha' d)) \quad (3)$$

where the C and α' are coefficients related to I_0, r and α. If the WSF can absorb most incident photons, the transmitted light by a single fiber dI in the thickness of dh can be expressed as

$$dI = \frac{2\pi r \nu I_S}{\pi r^2} dh \quad (4)$$

where ν is the transmit coefficient of the fiber. Therefore the mean light output over the cross-section is

$$dL = \frac{2\pi r \nu I_S}{\pi r^2} K_L dh. \quad (5)$$

For given radius of the WSF, d can be decided as follows:

$$2r = \frac{2\exp(\alpha' d) - 2}{\alpha'} - d. \quad (6)$$

In this work, α is about 1 mm^{-1}. The diameter of the fiber is 0.8 mm. Thus α' is 0.44 mm^{-1}. The optimal distance between fibers is 1.0 mm, but 0.8 mm was actually chosen for the convenience of manufacturing.

For cost saving, decoration grade fibers were used in these testing converters. The fibers were cut into short pieces and fixed in a pattern, which can keep the fibers evenly distributed and paralleling to each other. There is a sealed chamber in the pattern. The WSF cannot resist heat or high pressure, so the epoxy resin is chosen instead of PP to provide recoil protons in order to avoid these heating processes. However, the light output of the epoxy resin scintillator is lower than PP converters. The ZnS(Ag) powder was mixed up with the epoxy resin at the weight ratio of 1:1. Then the mushy mixture was filled into the chamber with all the fibers fixed. After the resin solidified, the pattern was removed and the front and rear surfaces of the converter were smoothed. Two pieces of converter were made. A small piece was cut into steps, of which the thicknesses varied from 10 to 45 mm, so that the light output of different thickness can be investigated. A large one with field-of-view of $150 \times 200\,mm^2$ and thickness of 30 mm was made for testing imaging.

3. Tests and discussions

The WSF converters were tested on the Peking University 4.5 MV Van de Graaff accelerator with a CCD-based system, as shown in Fig. 2. In total, 3 MeV deuterons were employed to bombard thick beryllium or deuterium gas target to produce neutrons. The neutrons from a thick target D–Be reaction have a broad spectrum with mean energy of 1.5 MeV [9] and accompanied with gamma rays. The deuterium gas target is 3 cm long and 1 atm pressure. The target chamber was sealed with a 5-μm thick Mo film and connected to the beam line tube. The energy of neutrons from 3 MeV deuterons bombarding this target is 5.8 MeV. A Princeton Instruments PIXIS 1024B camera was used to record the light output of the converters. The CCD chip was cooled to $-50\,^{\circ}C$, and the images acquired were all corrected of the dark frame. The converters are coupled to the camera with two mirrors and an f1.2 lens. No shield was placed around the target, but the CCD was protected from the radiation with paraffin wax and lead.

Two ZnS(Ag)-based scintillators of 2 mm thickness were made for comparing imaging. These converters were made of silicon polymer and ZnS(Ag). The Si polymer converter has about 0.6 times light output as PP converter and is much easier to manufacture [8]. One has a larger field-of-view of $20 \times 20\,cm^2$ for imaging, while another is a small piece for parameter measurement.

3.1. *Light output vs. WSF converter thickness*

The step-shaped converter was imaged in flat fields of neutrons generated by both D–Be reaction and D–D reaction. The average intensities recorded by the CCD camera were used to evaluate the light output. The relative light output of converters of different thicknesses is shown in Fig. 3. The intensity was normalized to the light output of the 2 mm Si polymer converter in the same condition.

As the thickness of the WSF converter increases, the light output increases and approach a saturation level. The data were fitted with the equation

$$L = L_{max}(1-\exp(-\mu h)) \quad (7)$$

where the L is the total light output, L_{max} is the possible maximum light output and μ is the neutron attenuation coefficient in the converter. In this equation the light attenuation in the fiber is neglected.

If the thickness of $2/\mu$, in which 86% light was produced, is assumed to be effective thickness of the converter, the effective thickness for detecting D–D reaction neutrons is 26 mm, and for D–Be reaction neutrons is 34 mm.

The light output of SWF converter is much higher than the 2 mm Si polymer converter. For a 15 mm SWF converter with D–D