Design Consideration on Compact Neutron Pinhole Camera with Nuclear Emulsion for Energetic-Ion Profile Diagnostics*)

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(Received 22 December 2010 / Accepted 3 June 2011)

For imaging of the emission profile of DD neutron produced by energetic deuterium ions, we propose a neutron pinhole camera with state-of-the-art nuclear emulsion technique. Recoiled proton due to elastic scattering of incident neutron passing though the pinhole makes a track in the nuclear emulsion. The incident neutron energy can be estimated by the energy of recoil proton and scattering angle that are derived from the track length and an angle between the track and the incident direction of neutron, respectively. DD neutron emission profile can be obtained with lower background events due to scattered neutrons and gamma-rays. We made preliminary designs on the pinhole collimator size and arrangement. The estimated spatial resolution would be better 100 mm with tungsten alloy collimator for the application to emission profile imaging of DD neutron in LHD plasma.

Keywords: nuclear emulsion, neutron profile monitor, neutron pinhole camera, DD plasma, LHD

DOI: 10.1585/pfr.6.2402148

1. Introduction

In deuterium plasmas, neutrons around energy of 2.5 MeV (DD neutron) are emitted as accompanying products of DD fusion reaction. The measurement of DD neutron emission profile plays an important role for diagnostics of energetic deuterium ion in DD plasma because the neutrons are mainly produced by beam-plasma interactions during neutral beam injection heating. Conventional neutron profile monitors installed in various magnetic confinement fusion devices such as JET in Europe [1] and JT60 in Japan [2], which were consisted of array of organic or stilbene crystal scintillators with a multi-channel collimator. In the world largest heliotron device (LHD) of National Institute for Fusion Science (NIFS) [3], the neutron profile monitor based on the scintillator is planned to be installed toward deuterium plasma experiment. Although these neutron profile monitors based on the scintillator have provided a temporal evaluation of neutron profile, more compact neutron profile monitor is required toward stable operation of DD fusion plasma in next generation reactor because of the limited space given to the monitor.

As an additional neutron profile monitor for deuterium plasma experiment planned in LHD, we propose a compact neutron pinhole camera based on state-of-the-art nuclear emulsion technique. The proposed neutron pinhole camera is designed to provide a time integrated neutron profile. In the stable deuterium plasma in the LHD, it would be possible to compare the shot integrated neutron profile obtained by the proposed neutron pinhole camera with that obtained by the neutron profile monitor based on the scintillator.

In this paper, we describe an imaging principle of the neutron pinhole camera with the nuclear emulsion and also show a preliminary design on the pinhole collimator and an expected performance of the pinhole camera based on Monte Carlo simulation of neutron transport.

2. Imaging Principle of Neutron Pinhole Camera with Nuclear Emulsion

Figure 1 shows a conceptual drawing of the proposed neutron pinhole camera. The camera consists of a pinhole collimator for fast neutron and a nuclear emulsion which is a solid state track detector with spatial resolution of a few micrometers for charged particles. After passing through the pinhole, neutron from deuterium plasma is incident into the nuclear emulsion. Incident neutron is scattered by a hydrogen atom and then a recoiled proton due to its elastic scattering of neutron make a track in the emulsion. After image development of the emulsion, the tracks of recoiled protons are acquired by an optical microscope.

The energy of the recoiled proton E_{rp} is obtained by the track length of the recoiled proton. In the case of neutron pinhole camera, incident direction of neutrons can be derived from a line extending from a starting point of the

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*) This article is based on the presentation at the 20th International Toki Conference (ITC20).

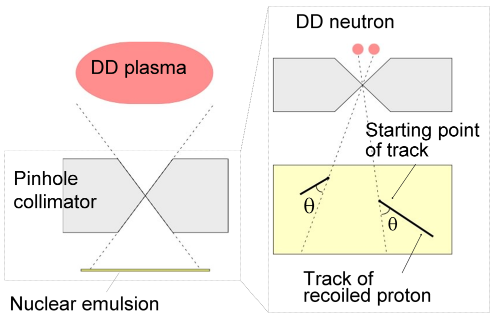

Fig. 1 Conceptual drawing of the proposed neutron pinhole camera.

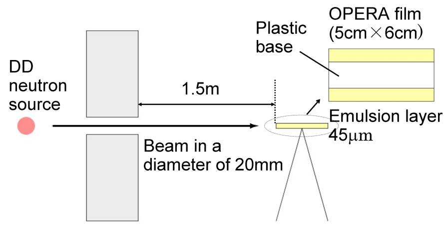

Fig. 2 Experimental setup for the mono-energetic 2.5 MeV neutron beam at FNS.

track of the recoiled proton to the center of the pinhole. Thus, the scattering angle θ would be derived from the angle between the track and the line, *i.e.* the energy of incident neutron E_n can be estimated as $E_n = E_{rp}/\cos^2\theta$. It leads to lower background events in DD neutron imaging due to gamma-rays and/or slow neutrons that are scattered at least once before reaching the emulsion. Therefore, 2D image of DD neutron could be re-constructed by the estimated incident directions of DD neutron.

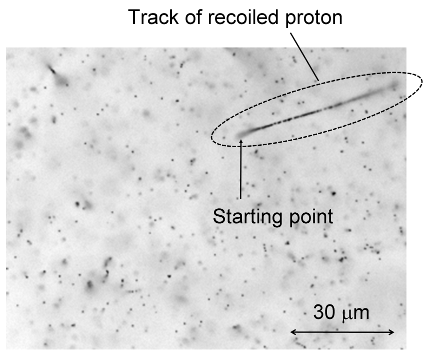

Fig. 3 Typical image of the nuclear emulsion irradiated by DD neutron.

3. Track Readout and Estimation of Incident Energy of Neutron

We evaluated the energy resolution of the proposed method by using the mono-energetic 2.5 MeV neutron beam at Fusion Neutron Source (FNS), Japan Atomic Energy Agency. Figure 2 shows the experimental setup. Nuclear emulsion called "OPERA film", which was originally developed for OPERA (Oscillation Project with Emulsion tRacking Apparatus) experiment [4], was placed at 1.5 m from the front surface of a collimator and irradiated by the DD neutron beam in a diameter of 20 mm. After irradiation, the emulsion was developed and then analyzed the tracks of the recoiled proton by a prototype system for automatic track readout. The automatic readout system consisted of a microscope with a xy- stage, an objective lens driven by piezo actuator, a CCD camera and standard PC.

Three-dimensional information of tracks was obtained by taking multi-images at different focal (z) positions, at each xy position. Figure 3 shows a typical image of the nuclear emulsion irradiated by DD neutron. The image field was an area of 110 μm × 140 μm. The tracks of the recoiled proton, an example was shown in Fig. 3, were analyzed as follows: At first, an obtained image was binarized. The black pixel was a part of recoiled proton track or noise. Here, a size is defined as number of pixels that were adjoined to each other and were consisted of an "object" If the size was above a threshold, these objects were extracted as a part of recoiled proton track. Then, a series of pixels of one object were fitted to straight line by least square method. Multi-images in depth direction were processed similarly, and if several objects had similar slopes

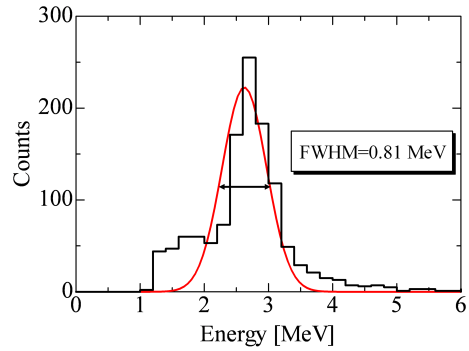

Fig. 4 Energy spectrum of mono-energetic 2.5 MeV neutron beam measured by the nuclear emulsion.

and positions, they were recognized a part of track of same recoiled proton. Finally, the energy of incident neutron was estimated by the length corresponding to E_{rp} and angle of readout track θ.

Figure 4 shows the energy spectrum of mono-energetic 2.5 MeV neutron beam measured by the nuclear emulsion. The incident neutron energy was estimated to be 2.5 MeV with FWHM of 0.9 MeV. The energy resolution of the estimated spectrum was rather poor because of lack of the track length at the edge of the image field of microscope or the emulsion layer, however it was enough to pick out the tracks of recoiled proton caused by neutrons directly incident into the emulsion.

4. Design Considerations of the Neutron Pinhole Camera

We considered a design of the neutron pinhole camera based on Monte-Carlo simulation of neutron and recoil proton transport, by PHITS (Particle and Heavy Ion Transport code System) [5]. Figure 5 shows geometry of the neutron pinhole camera. The collimator had two conical holes with taper angle ϕ shown in Fig. 5. Here, the intensity of neutrons I after passing through the collimator at a distance to the central axis r was given by

$$I(r) = I(0)\exp\left(-\frac{2r\Sigma}{\tan\varphi}\right),$$

where Σ was a macroscopic cross-section of the collimator material for DD neutron. Assuming that an effective diameter of the pinhole for DD neutron d_e was defined as full width at half maximum (FWHM), the d_e was given by

$$d_e = (\ln 2/\Sigma)\tan\varphi.$$

Thus, the spatial resolution of pinhole imaging X was given by

$$X = \frac{B}{A}\sqrt{R_D^2 + \left(\frac{A+B}{B}\right)^2 d_e^2}, \quad (1)$$

where R_D was the spatial resolution of nuclear emulsion, *i.e.* 2 μm for OPERA film, A was the distance from a point neutron source to the center of the pinhole, and B was the distance from the center of the pinhole to the nuclear emulsion. Since larger macroscopic cross-section for DD neutron is more suitable for the collimator material, we adopted Tungsten alloy (W : Ni : Cu = 94 wt% : 4 wt% : 2 wt%) with Σ of 0.43 cm^{-1}, which is better than polyethylene with Σ of 0.27 cm^{-1}.

Because a field of view $B\tan\phi$ should exceed the poloidal diameter of LHD plasma of 1 m, we considered two types of the geometry, *i.e.* B of 5.72 m with ϕ of 5 degrees (type 1) and B of 4 m with ϕ of 8 degrees (type 2). Figure 6 shows the dependence of spatial resolution of pinhole imaging on A. The spatial resolution of 10 cm was achieved by using A of about 100 mm.

The quality of image depended on a thickness of the collimator. Figure 7 shows reconstruction images of neutron point source on a project plane for the type 2 collimator with the collimator thickness of (a) 2 cm, (b) 10 cm, and (c) 20 cm. We defined S/N as follows:

$$S/N = \frac{N_{center} - N_{bg}}{N_{bg}},$$

where N_{center} was the track density of recoiled protons inside central area, and N_{bg} was the track density of recoiled protons outside the central area. Figure 8 shows S/N versus the collimator thickness with type 1 and type 2 collimators. To obtain the better quality of image, the collimator thickness of more than 20 cm is required. In this case, the expected absolute detection efficiencies for point source of DD neutron were 2×10^{-12} tracks/neutron and 1×10^{-11} tracks/neutron with type 1 and type 2 collimator, respectively. If neutron emission profile with spatial resolution of 10 cm is measured in LHD, total neutron yield of each cell is evaluated to be 3×10^{13} for time integrated over a single plasma discharge. The improvement of the

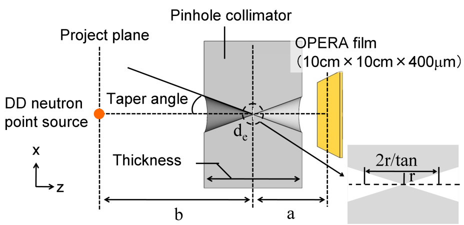

Fig. 5 Geometry of the neutron pinhole camera. The pinhole camera consists of a collimator and a nuclear emulsion.

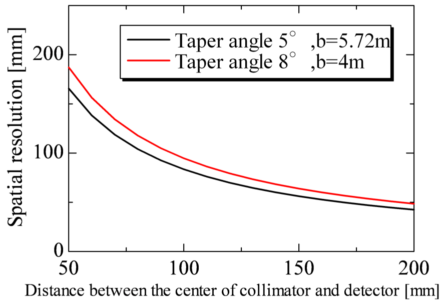

Fig. 6 Dependence of spatial resolution of pinhole imaging on A.

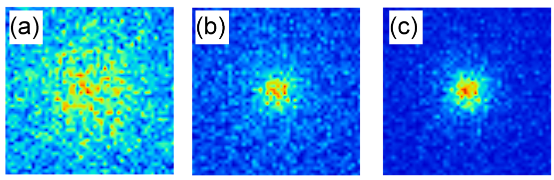

Fig. 7 Reconstruction images of neutron point source on project plane for the type 2 collimator with the collimator thickness of (a) 2 cm, (b) 10 cm, and (c) 20 cm.

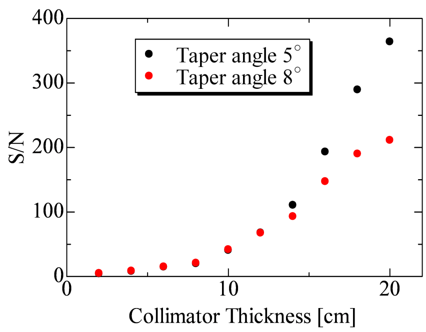

Fig. 8 S/N versus collimator thickness with type 1 and type 2 collimators.

efficiency at least one order of magnitude than the present collimator by using multi-pinhole collimator would lead to reduced statistical uncertainly of neutron imaging by the proposed neutron camera.

5. Conclusion

We proposed neutron pinhole camera with nuclear emulsion for measurement of DD neutron emission profile, and made preliminary designs on the pinhole collimator size and arrangement, which made of Tungsten alloy with two conical holes. With analysis based on model calculation, the spatial resolution of 100 mm might be achievable, whereas the S/N of reconstruction image should be improved by increasing efficiency (*e.g.* by using multi-pinhole collimator) for the application to emission profile imaging of DD neutron in LHD plasma. We will demonstrate DD neutron imaging using the prototype of the proposed neutron pinhole camera.

Acknowledgments

This work is performed with the support and under the auspices of the NIFS Collaboration Research program (NIFS08KOBH001).

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