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Development of Fusion Neutron Pinhole Imaging using Nuclear Emulsions for Energetic Ion Diagnostics[*]

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A compact neutron pinhole camera using nuclear emulsion has been developed as a neutrone mission profile monitor for energetic ion diagnostics in fusion plasma. We measured point-spread function of the neutron pinhole camera consists of a pinhole collimator made of tungsten alloy and stacked nuclear emulsions. Using a high-speed, automatic readout and recognition of recoiled proton tracks, point-spread function for 14 MeV neutron was clearly obtained.

Keywords: nuclear emulsion, neutron emission profile monitor, pinhole imaging

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1. Introduction

During neutral beam injection heating of magnetically confined deuterium plasma, DD fusion reaction is caused by energetic deuterium ions as follows:

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{3}\mathrm{He} + \mathrm{n}(2.5\,\mathrm{MeV}) \qquad (1)$$

$$\rightarrow \mathrm{T} + \mathrm{p}, \qquad (2)$$

in which these had each almost 50% of the total reaction rate. Because tritium is also produced asaccompanying products by the DD fusion reaction (2), DT fusion reaction occurs as secondly fusion reaction in deuterium plasma.

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}(14\,\mathrm{MeV}). \qquad (3)$$

The emission rate of 14 MeV neutron from DT reaction (DT neutron) in planned deuterium experiment at Large Helical Device (LHD) at national institute of fusion science, Japan is estimated to be two orders of magnitude less than that of DD reaction based on the measured tritium burnup ratio in JT60U [1]. The emission profile of fusion neutrons, 2.5 MeV neutron from DD reaction (DD neutron) and DT neutron, is dominated by energetic ion in fusion plasma.

Conventional neutron emission profile monitor is based on multiple channel neutron collimators with scintillation detectors [2]. Horizontal and vertical fan-shaped arrays of the collimators provide the emission profile of neutron from fusion plasma, however, the system is massive due to sufficient shielding for fast neutron. In early days of fusion neutron measurement, nuclear emulsion, which is a type of photographic film and sensitive to charged particle, was used to measure neutron emission profile in Princeton Large Tokamak [3] and ASDEX [4]. Neutrons from fusion deuterium plasma were incident to the nuclear emulsion and tracks of recoiled proton produced by elastic scattering of incident neutron with hydrogen atom were recorded in the nuclear emulsion. After development of the nuclear emulsion, these recoiled proton tracks were counted using an optical microscope. These provided shot-integrated emission profiles of neutron with a poor spatial resolution, because a number of tracks analyzed by human eyes was limited. Thus, nuclear emulsion technique was not widely used in fusion neutron measurement.

Recent progress of image processing technique allows a high-speed, automatic readout and recognition of tracks in the nuclear emulsion. One of the most advanced nuclear emulsion analyzing system, which is called S-UTS, was developed mainly for muon track analysis in the OPERA film [5, 6]. In addition, the S-UTS was applied to analyze recoiled proton tracks for neutron emission profile measurement in NSTX recently [7]. Based on state-of-the-art nuclear emulsion technique, we have proposed a compact neutron pinhole camera using the nuclear emulsion [8]. We have reported that a spatial resolution was estimated to be about 10 cm for DD neutron at 4 m far from the center of deuterium plasma by results of model calculation.

Toward an experimental demonstration of fusion neu-

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tron imaging using the neutron pinhole collimator, we investigated point-spread function of the neutron pinhole camera consists of a pinhole collimator made of tungsten alloy and stacked nuclear emulsions.

2. Neutron Pinhole Imaging using Nuclear Emulsion

Figure 1 shows the principle of the proposed neutron pinhole camera. The detailed principle of neutron imaging was described in our previous paper [8]. The camera consists of a pinhole collimator for neutron and several nuclear emulsions, which each film has two emulsion layers on both surface of a plastic plate. Incident area of neutron is confined by the pinhole collimator and the emulsion layers records a recoiled proton track due to an elastic scattering of incident neutron. Therefore, emission profile of neutron can be estimated by each incident angle of neutron using a point of elastic scattering as a starting point of the track and the position of pinhole. On the other hand, elastic scattering also occurs in the plastic plate. Most of these recoiled protons stop and other reach to the emulsion layer. Because these tracks are recorded only on the surface of the emulsion layer, it is easy to remove these tracks by analyzing the starting point of track. Probability of elastic scattering of fast neutron, *i.e.* detection efficiency, depends on atomic density of hydrogen (proton) in the emulsion layer along the neutron flight path. To obtain reasonable detection efficiency stacked nuclear emulsions was adopted. High spatial resolution for recoiled proton in the nuclear emulsion and wide viewing angle of the pinhole collimator lead to comparable spatial resolution to the conventional multi-channel profile monitor although it provide shot integrated image. In addition, it is possible to suppress events due to gamma-rays and slow neutrons scattered before reaching the emulsion by estimating the incident neutron energy derived from track analysis. Thus, the compact pinhole camera is promising as a complemental monitor for fusion neutron emission profile.

We evaluated the point spread function of the pinhole imaging system using accelerator based DT neutron point source at Fusion Neutron Source (FNS), Japan Atomic Energy Agency [9]. Figure 2 (a) shows the experimental setup at FNS. The pinhole camera was set up at 1150 mm far from a water-cooled tritium-storage target of 80 degree beam line of the “First Target Room”. 400 kV deuterium ion beam was injected into the tritium-storage target and generate DT neutron with neutron yield of 10^{11} n/s. In this experiment, we used a nuclear emulsion, OPERA film. The details of the collimator and the OPERA film are shown in Fig. 2 (b). The stacked nuclear emulsions with 10 layers were irradiated for 3 minutes behind of the pinhole collimator made of tungsten alloy. After irradiation, the emulsions were developed to make visible image of tracks.

Figure 3 shows photographs of the stacked nuclear emulsions covered by aluminum package and an irradiated nuclear emulsion after development. The tracks of recoiled proton in the nuclear emulsion were then analyzed by the S-UTS. Note that we only analyze central 4 × 4 cm region of the emulsion in this experiment. Reconstructed image at the source position was obtained by the back projection method in which the incident angle of neutron was esti-

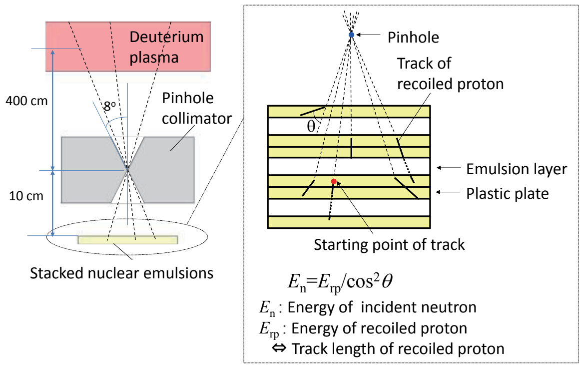

Fig. 1 Principle of neutron pinhole camera using stacked nuclear emulsions.

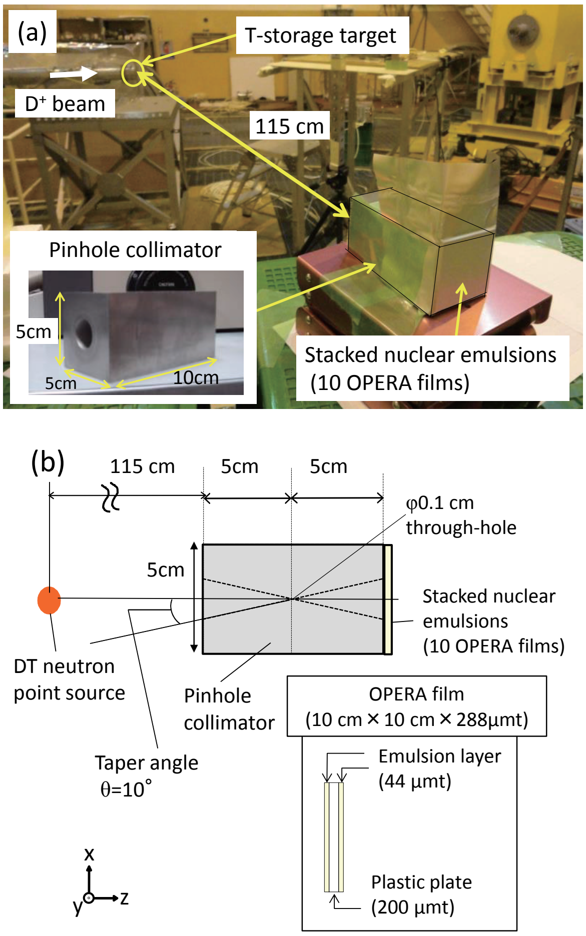

Fig. 2 Experimental setup at FNS. (a) Photograph of whole experimental setup, (b) cross-sectional view of the pinhole collimator and the stacked nuclear emulsions.

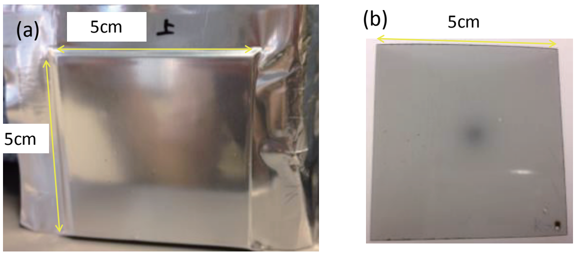

Fig. 3 (a) Photographs of the stacked nuclear emulsions covered by aluminum package, (b) an irradiated nuclear emulsion after development.

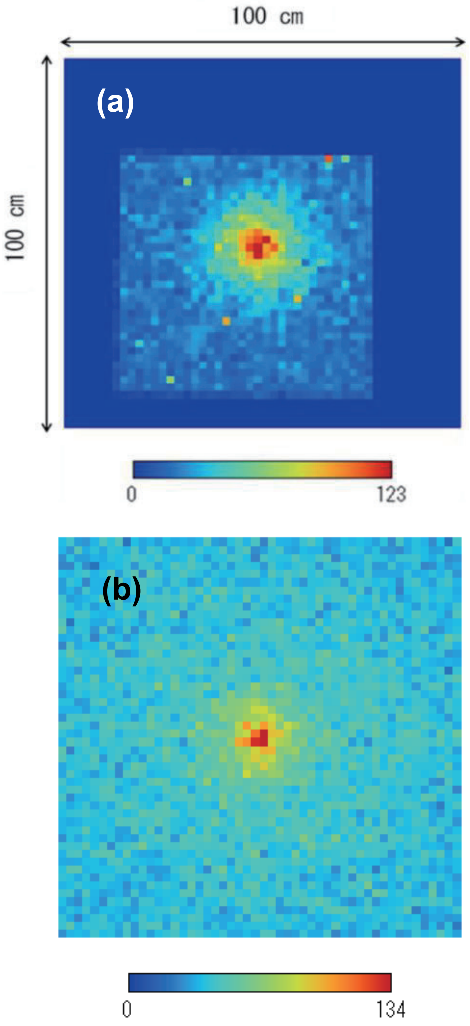

Fig. 4 Reconstructed image of DT neutron at the source position, (a) experiment, (b) calculation.

mated by the starting point of the tracks of recoiled proton in the nuclear emulsion and the center of the pinhole. Figure 4 (a) shows the reconstructed image of DT neutron at the source position. Point-spread function for DT neutron was calculated by Monte-Carlo simulation of neutron and recoil proton transport based on PHITS (Particle and Heavy Ion Transport code System) [10]. The geometry of the pinhole camera for the simulation was same as the experimental setup. Here, volume of the DT neutron source was negligible compared with its spatial resolution. We considered the uncertainly in track recognition as 0.5 μm for x, y axis and 0.12 μm for z axis in the simulation, in which xyz axes are defined in Fig. 2 (b). Figure 4 (b) shows the reconstructed image of point DT neutron source at its position by model calculation. Figure 5 shows the normalized line profile at $x = 50$ cm. The FWHM in the profile as a spatial resolution was estimated to be 17 cm and 15 cm for experimental and calculated results, respectively. The experimental value of the spatial resolution agreed with the calculated value. The effective pinhole size for DT neutron d_e was evaluate to be $17 \times 5/(5+115) = 7.0$ mm, which was by a factor three larger than that for DD neutron.

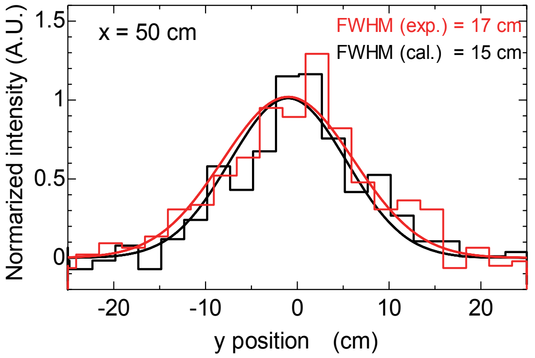

Fig. 5 Normalized line profile of reconstructed image at x = 50 cm.

3. Conclusion

We made a pinhole collimator made of tungsten alloy-for neutron imaging and adapt stacked nuclear emulsions for the fusion neutron pinhole camera. We evaluated the point spread function of the neutron pinhole camera using the accelerator based DT neutron point source at Fusion Neutron Source (FNS). Point-spread function was clearly obtained using the S-UTS and its FWHM was good agreement with the calculated value. Using the pinhole camera, we intend to demonstrate the DD neutron imaging using the accelerator based DD neutron point source at FNS to investigate its applicability for planned deuterium experiment at LHD and also DD neutron measurement at Korea Superconducting Tokamak Advanced Research (KSTAR) at national fusion research institute, republic of Korea.

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