

# Neutron Radiography Using Inertial Electrostatic Confinement (IEC) Fusion<sup>\*)</sup>

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(Received 28 June 2017 / Accepted 31 March 2018)

Feasibility studies on neutron radiography using an inertial electrostatic confinement (IEC) neutron source were carried out. A Monte Carlo analysis was carried out to evaluate the feasibility of neutron radiography experiment. Imaging tests using a medium-sized IEC neutron source were conducted with the indirect method using a dysprosium (Dy) foil and an imaging plate. Neutron images of objects consisting of six Cd pins and an array of B<sub>4</sub>C powder contained in a stainless-steel blade were obtained. The numerical and experimental results confirmed that the IEC neutron source can be applied to neutron radiography even with relatively low neutron flux of  $\sim 10^2$  n/s/cm<sup>2</sup>.

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Keywords: inertial electrostatic confinement (IEC) neutron source, D-D fusion, neutron radiography, indirect method

DOI: 10.1585/pfr.13.2406075

## 1. Introduction

Demand for compact and portable neutron sources has been rapidly increasing in industrial applications such as sub-criticality monitoring and neutron radiography for nondestructive inspection [1, 2]. Although radioisotope neutron sources have been demonstrated for such applications, the use of <sup>252</sup>Cf is somewhat less convenient because of relatively short half lifetime of 2.65 years, limited supply, and stressful treatment during their transportation and storage. On the other hand, conventional active neutron sources based on reactors and accelerators are not suited for field operation.

To meet recent requirements for compact active neutron sources, inertial electrostatic confinement (IEC) neutron sources have been developed because of its good controllability and long product lifetime. Although the neutron output of IEC devices are comparable to those of D-D/D-T tubes ( $\sim 10^6 - 10^9$  n/s) [3,4], they have the potential to operate with much longer maintenance cycles than D-D/D-T tubes. D-D/D-T tubes use metal targets for fusion reactions, therefore, the metal targets have to be replaced every several-thousand hours. On the other hand, since the IEC devices use deuterium gas targets, one can feed “fuel” continuously to the IEC neutron source during the operation, which makes the maintenance cycle quite long.

The IEC neutron sources generate mono-energetic

2.45-MeV neutrons by D-D nuclear fusion reactions. Figure 1 shows the operational principle of the IEC neutron source. The device consists of a vacuum chamber containing inner electrodes, a high-voltage power supply, and a gas feed control system. Positive deuterium ions are produced by glow discharge or by additional ion sources, the ions are accelerated and confined by the electrostatic potential well between the negatively charged center electrodes and grounded chamber wall. Fusion reactions generate neutrons when the ions collide with the other ions or background deuterium molecules. Most of the neutrons are emitted isotropically from the region near the electrodes in the center of the chamber.

The IEC neutron sources have been studied for the identification of fissile material for nuclear security [5] and the detection of landmines [6], but their application to neu-

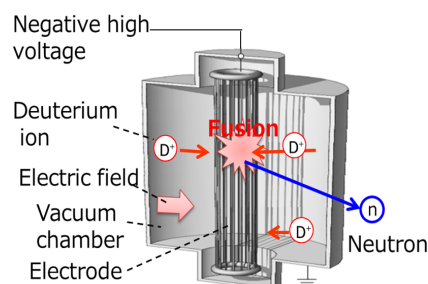


Fig. 1 Schematic image of an inertial electrostatic confinement (IEC) neutron source.

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<sup>\*)</sup> This article is based on the presentation at the Conference on Laser Energy Science / Laser and Accelerator Neutron Sources and Applications 2017.

tron radiography has not been examined. The purpose of this study is to investigate the feasibility of neutron radiography (NRG) using the IEC neutron source.

For neutron radiography, the indirect method [7] was adopted, where objects and a metal foil converter are irradiated with neutrons, the metal foil is activated by the neutrons, and the activated image is transcribed to the detector after the irradiation. The advantage of the indirect method is that it can be used under high X-ray or  $\gamma$ -ray backgrounds. We intend to use this method at nuclear power plants in the future.

## 2. Feasibility Study on NRG with IEC Neutron Source

A Monte Carlo analysis with PHITS [8] was carried out to evaluate the feasibility of neutron radiography experiment. For the analysis, the IEC neutron device consisted of a cylindrical vacuum chamber of 394 mm in diameter and 400 mm in height. It was assumed in the simulation that 2.45-MeV neutrons were emitted isotropically from the cylindrical region of 40 mm in diameter and 320 mm in height at the center of the chamber. Polyethylene blocks of 50-mm thickness were installed in front of the IEC neutron generator to moderate MeV neutrons to the thermal level as shown in Fig. 2. Two measurement locations, A and B, were chosen, and a sheet of dysprosium (Dy) foil was set on the back side of the polyethylene moderator respectively. At the location A, objects ( $B_4C$  blocks) and the foil were closely contacted, and the Dy foil was backed by a cadmium (Cd) plate. The location B was set for the reference.

Figure 3 shows neutron flux distributions on the Dy foils at location A and B. The neutron fluxes at location A and B were around  $\sim 10^2$  n/s/cm<sup>2</sup> assuming a neutron production rate of  $10^6$  n/s at the source. Figure 4 shows the thermal neutron flux distributions on the Dy foil at location

A and B. When the neutron production rate at the source is  $10^6$  n/s, the estimated thermal neutron fluxes at location A and B were  $\sim 10$  n/s/cm<sup>2</sup>. Figure 5 shows the distribution of neutron capture reactions on the Dy foil. The total number

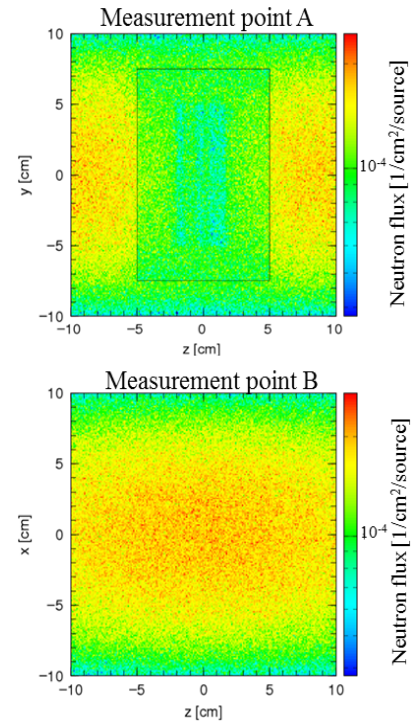


Fig. 3 Neutron flux distributions integrated from 0 MeV to 3 MeV at measurement point A and B.

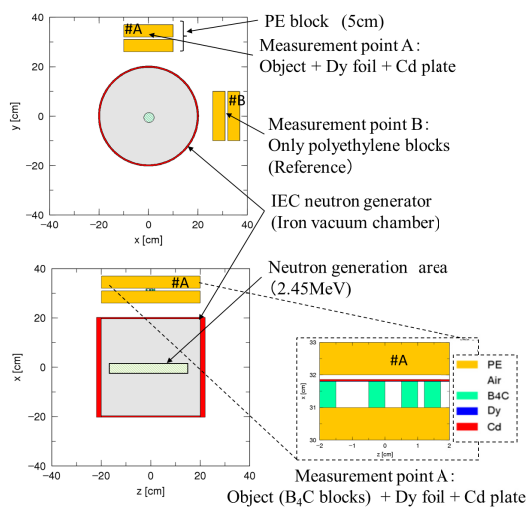


Fig. 2 Geometry of Monte Carlo analysis.

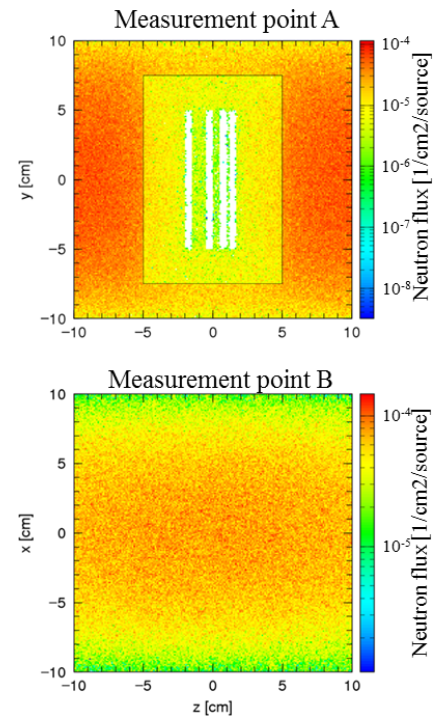


Fig. 4 Thermal neutron flux distributions at measurement point A and B.

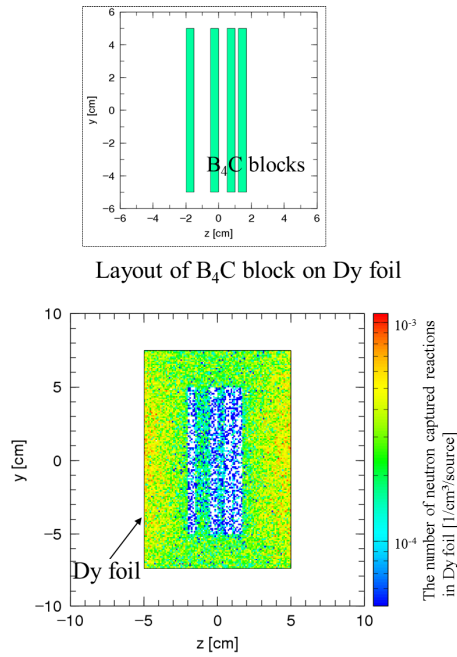


Fig. 5 The number of neutron captured reactions in Dy foil at measurement point A.

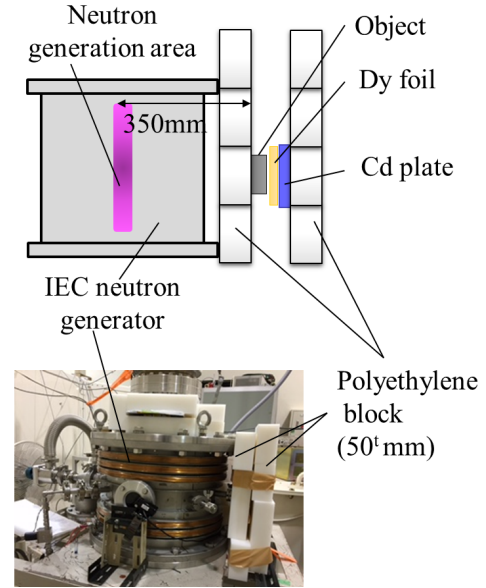
of injected neutrons in this simulation was  $2 \times 10^8$ , which was equivalent to the case of irradiation for 200 seconds with  $10^6$  n/s. A significant difference between the presence and absence of the  $B_4C$  blocks was observed since the neutrons were absorbed by the  $B_4C$  blocks.

The simulation suggested that the IEC neutron source could be applied to neutron radiography.

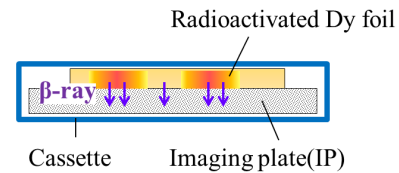
### 3. Experimental Setup of NRG

Figure 6(a) shows the experimental setup of the neutron radiography with the IEC neutron source. A conventional middle-sized IEC neutron generator [9] was used. The device consists of a cylindrical vacuum chamber of 394 mm in diameter and 340 mm in height, and a grid cathode in the center of the chamber. The typical operation voltage and current of the IEC device are  $-75$  kV and  $10$  mA, respectively. A typical neutron production rate (NPR) was  $\sim 10^6 - 10^7$  n/s. In this study, deuterium gas was fed to the chamber through a flow-control valve. The background gas pressure ( $\sim 0.8$  Pa) was stably maintained by a flow control valve, whose flow rate was precisely feedback-controlled based on the monitored gas pressure in the chamber. Thanks to this upstream feedback system, neutron imaging under a constant NPR value became possible for more than several hours.

In the present study, a sheet of Dy foil ( $160$  mm  $\times$   $110$  mm  $\times$   $0.1$  mm) was activated, and later transcribed to an imaging plate (IP) as shown in Fig. 6(b). Polyethylene blocks of  $50$ -mm thickness were installed on the side of the IEC device, and both the imaging objects and the Dy foil were located on the back side of the polyethylene moderator. The objects and the foil were closely contacted. The

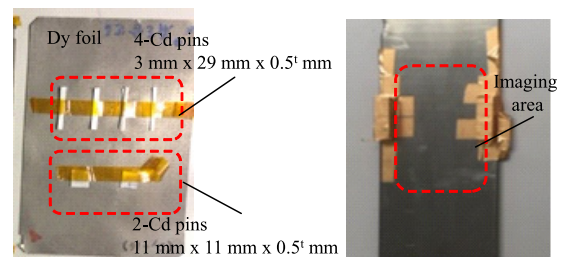


(a) Setup of neutron radiography.



(b) Setup of transcription to imaging plate after neutron irradiation.

Fig. 6 Experimental setup of neutron radiography with IEC neutron source.



(a) Object #1: Cd pins.

(b) Object #2:  
A SUS blade containing  
 $B_4C$  powder.

Fig. 7 Photos of two objects.

Dy foil was backed by a cadmium (Cd) plate of  $0.5$ -mm thickness to remove backscattered thermal-neutrons and to maximize the image contrast.

### 4. Results and Discussion

Two objects were prepared for the present study: six Cd pins were placed on the Dy foil as shown in Fig. 7(a); a stainless-steel blade containing  $B_4C$  powder as shown in

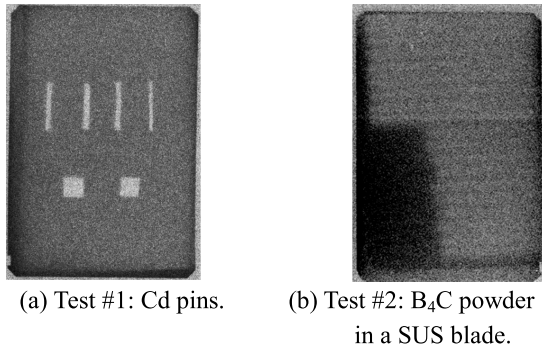


Fig. 8 Results of neutron radiography tests.

Fig. 7 (b). In the test #1 using Cd pins, the neutron production rate of the device was  $\sim 10^6$  n/s and the Dy foil was continuously irradiated with neutrons for 3 hours. After the irradiation, the activated Dy foil was transcribed to an imaging plate (IP) for 12 hours in a cassette. The image on the IP was read with an IP scanner and the result is shown in Fig. 8 (a). The objects (Cd pins) were clearly imaged as white areas on the imaging plate. The edges of the images are sharp enough to recognize the shape of the objects. The result showed that the total dose of thermal neutrons satisfied the minimum requirement for the neutron radiography.

In the test #2, the stainless-steel blade containing  $B_4C$  powder was irradiated with neutrons for 3 hours with neutron production rates over  $10^6$  n/s. After the irradiation, the activated Dy foil was transcribed to the IP for 14 hours. In Fig. 8 (b), the horizontal columns in the blade containing  $B_4C$  powder are separately imaged as horizontal white line patterns in the image. Some of the columns are not fully filled with  $B_4C$  powder. This non-uniform distribution of

$B_4C$  powder in the blade was successfully imaged.

The experimental results confirmed that the IEC neutron source could be applied to neutron radiography. The neutron images were successfully obtained even with a low neutron flux of  $\sim 10^2$  n/s/cm<sup>2</sup>.

## 5. Conclusions

An IEC neutron source was used to demonstrate neutron radiography for nondestructive inspection. Imaging tests using a medium-sized IEC neutron source was conducted by the indirect method using a Dy foil and an imaging plate. Objects consisting of six Cd pins and an array of  $B_4C$  powder contained in a stainless-steel blade were used for the demonstration, and the images of these objects were successfully obtained. The experimental and numerical results showed that the IEC neutron source with  $10^6 - 10^7$  n/s can be applied to neutron radiography.

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