Development of the High Energy Bremsstrahlung X-Ray Spectrometer by Using (γ, n) Reaction*)

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A (γ,n) reaction based hard X-ray spectrometer with energy range from 4 MeV to 30 MeV has been developed for Fast Ignition related experiments. The hard X-ray spectrum is indirectly measured by counting neutrons generated via photo-nuclear reaction from various materials. The performance was evaluated by using a linear accelerator facility, and the obtained results are in good agreement with Monte-Carlo simulation.

Keywords: high energy X-ray, (γ,n) reaction, bubble detector

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1. Introduction

In the Fast Ignition (FI) [1] approach to Inertial Confinement Fusion (ICF), the compressed Deuterium-Tritium (DT) fuel is heated by means of an ultra-high intensity generated fast electron beam, transporting the laser energy from the critical surface up to the compressed core. The knowledge of the fast electron energy spectrum is of fundamental importance for the achievement of FI [2]. However, its measurement represents a difficult challenge due to the fast electron energy loss in the target material and space charge sheath fields at the target surface, which dose not allow direct measurements via classic electron spectrometer. Bremsstrahlung X-ray emission produced by fast electron transport in the taregt material is an attractive alternative-diagnostic to measure the fast electron energy spectrum [3]. Bremsstrahlung X-rays generated by fast electrons present a very wide range of energies from few keV to tens of MeV. In this work, we focus our attention on X-ray in the tens of MeV energy range. Furthermore, high energy X-ray spectroscopy is expected to be developed at National Ignition Facility [4] for fusion science research or nuclear science with ultra-intense laser [5]. In this study, a (γ, n) reaction based hard X-ray spectrometer, with energy range from 4 MeV to 30 MeV has been developed for FI related experiments. The performance was evaluated by using a Liner Accelerator (LINAC) at the Institute of Scientific and Industrial Research (ISIR), Osaka University [6], and the signal obtained in the experiment is in good agreement with the Monte-Carlo simulation.

2. Principle of Measurement

Bremsstrahlung X-rays spectrum generated by fast electron transport in FI related experiments, exceeds the threshold for photo-nuclear reaction. Figure 1 shows normalized photo-nuclear cross-sections for various materials. The X-ray spectrum within the energy range 4 - 30 MeV can be measured by counting neutrons generated via photo-nuclear reaction from various materials. Figure 2 shows a schematic of the developed diagnosis.

Bubble detector spectrometer (BDS series) [8] was chosen as a neutron detector being only sensitive to neutrons. When neutrons enter bubble detector, small visible bubbles appear instantly showing the path of the neutron emission. γ-ray insensitivity of the bubble detector was confirmed by irradiating it with 1 MeV γ-ray from ^{60}Co with the radioactivity of 8 TBq at ISIR, Osaka University.

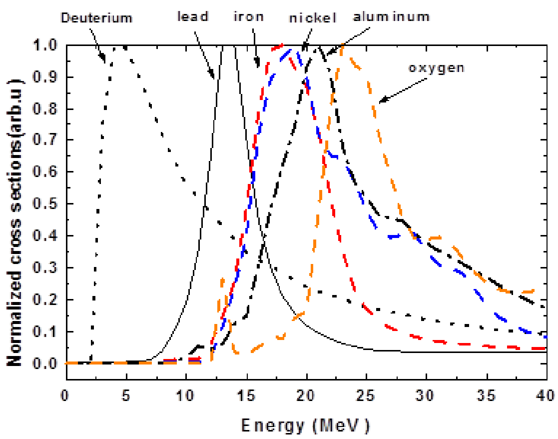

Fig. 1 (γ, n) reaction cross-sections from JENDLE photo- nuclear data 2004 [7].

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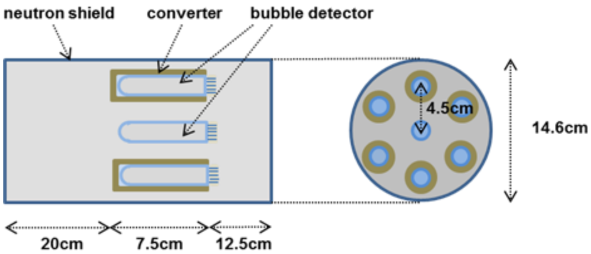

Fig. 2 The structural drawing of the X-ray spectrometer.

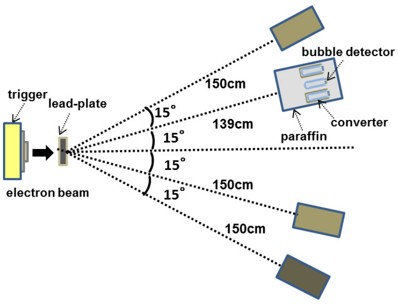

Fig. 3 Experimental configuration of evaluating performance.

Deuterium water, lead, iron, nickel, aluminium and hydrogen water were chosen as converter. These materials present a variety of (γ, n) reaction resonance peaks, from 4 MeV to 22 MeV. A 5-mm thick cylindrical converter was designed to obtain a large neutron count in our experimental conditions.

The bubble detectors are covered with paraffin for shielding the background neutrons. Background is constituted by photo-nuclear neutron from the experimental structure, DD fusion neutron and the photo-nuclear neutron from the target itself. Since DD reaction neutrons give the largest contribution to the background, a 20-cm thick paraffin was placed in front of the bubble detector, suppressing the DD neutrons at 2.45 MeV to 1%. A bubble detector without converter is also equipped in the center of the shield for measuring background neutrons.

A similar diagnostic using nuclear activation-based method was presented in [9]. In this work γ-ray generated from activation of target material are used, measuring X-rays with energies above 7 MeV.

3. Testing

The developed detector was tested using the LINAC. The experimental configuration is shown in Fig. 3. The bremsstrahlung X-rays were generated by irradiating a 5-mm thick lead target with a total number of 1.15×10^{13} 26-MeV electrons. The X-ray spectrometer was set at 139 cm from the target with the angle of 15 degrees from target normal. Other X-ray spectrometers were also used for comparison.

The neutron signal counts with and without converter were compared as shown in Table 1.

Table 1 Result of experimental data at LINAC facility. (a) shows back-ground bubble counts. (b) shows bubble counts with converter, including back-ground counts.

Channel	(a) Without converter	(b) With converter	(c) Net counts
Deuterium	343(±19)	349(±17)	6 (±26)
Lead	346(±19)	493(±22)	147 (±29)
Iron	323(±18)	367(±19)	44 (±26)
Nickel	317(±18)	366(±19)	49 (±26)
Aluminum	294(±17)	317(±17)	23 (±25)
Light water	380(±19)	363(±19)	-17 (±27)
Center	309(±18)	402(±17)	93 (±23)

Spatial distribution of the background was found, due to asymmetric geometry in the experimental construction, such as Faraday cup and the other X-ray spectrometer covered with lead block. The neutron signal collected by each channel without converter was used as background signal for the converter case. Cross-talk between two neighbors channel was estimated by Monte Carlo simulation with code PHITS to be ~ 7%.

The cross-talk observed in the experiment was about four times higher than the simulated one. The reason might be related to large count errors due to the intense background. A possible solution to this problem is the increase of the neutron shielding thickness.

The number of photo-nuclear neutron $N_n(E)$ can be written in the following equation,

$$N_n(E) = Nl \int_{S_\gamma}^{\infty} N_\gamma(E)\sigma(E)dE. \tag{1}$$

Where, N is number density of converter, l is thickness of converter, S_γ is the photo-nuclear reaction threshold, $N_\gamma(E)$ is the bremsstrahlung energy spectrum and $\sigma(E)$ is photo-nuclear cross-sections. Equation (1) can be approximated as follows,

$$\langle N_n(E)\rangle = N_\gamma(E)Nl\langle\sigma(E)\rangle. \tag{2}$$

$\langle\sigma(E)\rangle$ is averaged photo-nuclear reactions cross-sections having width correspondent to the full-width half-maximum of the original curve.

On the other hand, the number of neutron detected by the bubble detector $N_b(E)$ can be written using equation,

$$N_b(E) = \eta_\Omega \int_0^{\infty} N_n(E)\eta(E)dE. \tag{3}$$

η_Ω is the incident efficiency from converter to bubble detector, $\eta(E)$ is conversion efficiency from photo-nuclear neutrons to bubbles dependent on photo-nuclear neutron energy. Equation (3) can be approximated as follow,

$$\langle N_b(E)\rangle = \eta_\Omega\langle N_n(E)\rangle\langle\eta(E)\rangle. \tag{4}$$

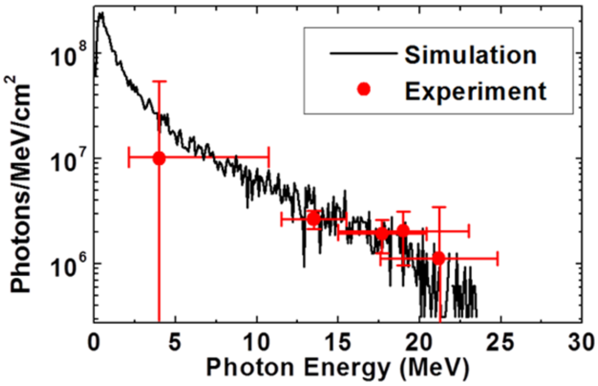

Fig. 4 Result of measurement of X-ray spectrum. Black point shows X-ray spectrum calculated by using PHITS-code [10] (black point). Red point shows experimental data. Cross-talk and full width at half maximum of photo-nuclear reaction cross-section are accounted in the error bars.

Finally, we can find a relation between the X-ray photons and the total neutron count from the bubble detector.

$$\langle N_b(E)\rangle = N_\gamma(E) Nl \langle\sigma(E)\rangle \eta_\Omega \langle\eta(E)\rangle. \quad (5)$$

Where, $\langle\eta(E)\rangle$ is the normalized conversion efficiency from photo-nuclear neutrons to bubbles per neutron energy. X-ray energy spectrum is constructed by Eq. (5).

Figure 4 shows calculated spectrum represented by a black solid line and the experimental values obtained from equation (5) and represented with red dots. These are in good agreement with simulations. The detection of the high energy X-ray was successfully demonstrated in this experiment. The background level will be reduced in future experiments.

4. Conclusions

The high energy X-ray spectrometer using (γ, n) reaction was developed and tested using bremsstrahlung radiation produced by electrons accelerated by the LINAC. Testing results show good agreement with Monte Carlo simulations despite the quite large error bars due to the large background recorded. This spectrometer can measure X-rays having energies ranging from 4 up to 30 MeV.

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