Development of Multichannel Time-of-Flight Neutron Spectrometer for the Fast Ignition Experiment[*)]

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Neutron diagnostic in the fast-ignition experiment was successfully demonstrated by the multichannel time-of-flight neutron spectrometer MANDALA at Institute of Laser Engineering (ILE) in Osaka University. A large neutron collimator dramatically suppressed the serious background noise caused by photo-neutrons, and a peak yield of 2×10^6 deuterium-deuterium (DD) fusion neutrons was clearly observed. The new MANDALA system will provide measurements of the ion temperature and the areal density of the core plasma in the next fast-ignition experimental campaign in 2013. In this paper, we will present the design of the neutron collimator and the experimental results in the Fast-ignition Campaign 2012.

Keywords: Fast-ignition laser fusion, neutron diagnostics, multichannel nTOF spectrometer, hard Bremsstrahlung x-ray, photo-neutron, neutron collimator

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1. Introduction

Neutron time-of-flight (nTOF) is an essential diagnostic to determine the neutron spectrum in Fast Ignition (FI) research at the Institute of Laser Engineering (ILE), Osaka University. Some of the most important quantities to be measured are the Doppler broadening and the secondery neutrons produced by $d(t,n)\alpha$ reactions relative to the primary neutrons produced by $d(d,n)^3He$ reactions allowing to measure the ion temperature (Ti) and the areal density (ρR) of the fuel [1, 2]. The multichannel nTOF spectrometer MANDALA [3] at ILE has been designed to have high energy resolution and sensitivity in the central hot spot (CHS) ignition experiment, however in the FI related experiments, MANDALA presents a critical issue constituted by high background noise such as hard x-ray and photo-neutrons (hereinafter referred to as γ-rays and γ-n neutrons). Hard γ-rays are produced via Bremsstrahlung emission form the fast electron beam propagating in the target material, causing the saturation of all the photomultiplier tubes (PMT) composing the diagnostic. A broad energy spectrum neutron pulse is produced by γ-rays via photo-nuclear reaction with the material surrounding the laser plasma interaction region, including optics and chamber wall. γ-n neutrons signal is much higher than the fusion-generated neutrons one, preventing their measurement. In this study, a series of γ-shields and γ-n shields are designed and installed. A large neutron collimator has been successfully tested and the primary neutrons (DD-neutrons) were successfully measured by the upgraded MANDALA system. In this paper we present the design of the neutron collimator and the experimental results obtained in 2012.

2. Upgrades of MANDALA

MANDALA is a single-hit neutron spectrometer with an array of 421 individual scintillator detectors located at 13.5 m from the target chamber center (TCC). The temporal distribution of neutrons is obtained with a leading edge discriminator and 500-ps Time-to-Digital Converter (TDC). Lead γ-shields with total thickness of 19 cm (14-cm thick lead covering MANDALA and 5-cm thick lead shield is placed outside the chamber) have been installed in previous experiments [4]. In addition, downsized scintillators with thickness of 6 cm and diameter of 6 cm were used to reduce γ-ray signal down to the 20%.

In an experimental campaign conducted in 2010, a neutron yield of $\sim 10^2$ - 10^3 γ-neutrons was observed. This is much larger than the few tens of DD neutrons measured in a typical implosion experiment. MCNP5 Monte Carlo simulations on γ-n neutron generation and transport were performed in order to design a collimator to shield γ-n neutrons. Based on experimental measurements [5], in our simulations we assumed a 5 MeV slope γ-ray energy spectrum, and a $P(\theta) = (\cos^5(0.5\theta))$ angular distribution. In Fig. 1 are represented respectively: a view of the GEKKO-XII interaction chamber (a), γ-ray flux map (b) and γ-n neutron flux map (c). Figure 1 (c) clearly shows

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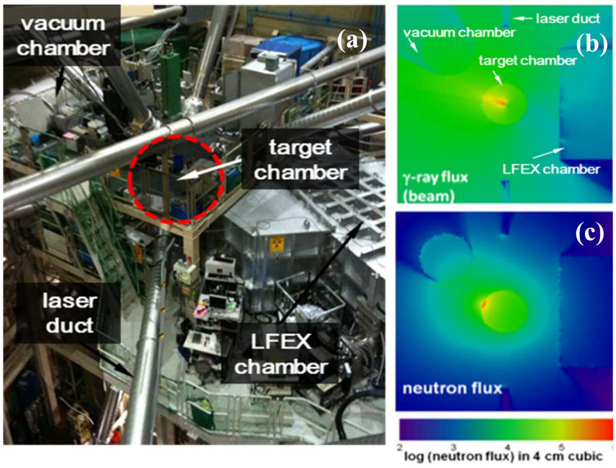

Fig. 1 (a) a view of the GEKKO-XII interaction chamber, (b) γ-ray flux map and (c) γ-n neutron flux map calculated by the Monte Carlo simulation code (MCNP5). (c) clearly shows that the target chamber is the dominant γ-n neutron origin.

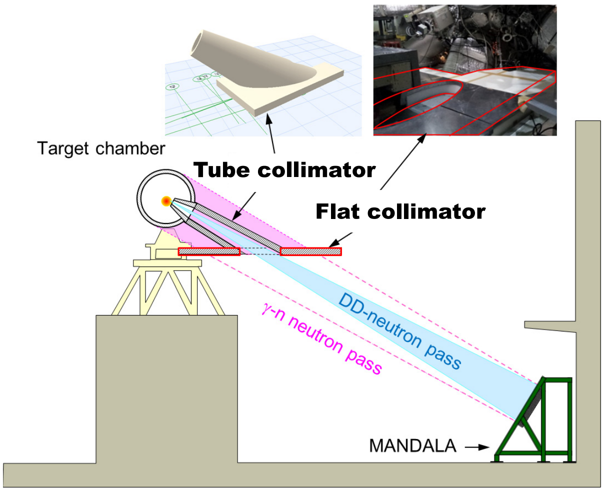

Fig. 2 The schematic view of the neutron collimator.

that the target chamber which is made of stainless steel is the dominant cause of γ-n neutron production amongst any other component around the target. The neutron collimator is a very effective method to shield γ-n neutrons. The collimator consists of two parts and is designed as schematically represented in Fig. 2. The first collimator is a polyethylene-board (hereinafter referred to as the flat collimator) having 2.4×10^4 cm^2 surface area and 10-cm thick having a neutron path line of sight thickness of ~16.2 - 26.7 cm . The second collimator is a polyethylene-made tube (hereinafter referred to as the tube collimator), 1.7 m long and 10 cm thick. By using only the flat collimator the 72% background suppression was estimated, rising up to the 99% suppression by adding the tube collimator. Figure 3 shows the relation between the lower limit neutron yield that can be measured by MANDALA and the γ-n neutron generation versus the heating energy. In this estimation, the Bremsstrahlung x-rays generated by the fast electrons from an Au-cone target were simulated. The 20% of energy coupling efficiency from laser to hot electrons [6] and typical divergence angle [5] were assumed. Finally, the electron spectrum adopted in the simulations was calculated form the $\boldsymbol{J} \times \boldsymbol{B}$ ponderomotive scaling law [7]. The lower limit of the measurable neutron yield for the cases with no-collimator, flat collimator only and flat and tube collimator are reported in black, blue and red line respectively. 100-count DD-neutrons, equivalent to the yield of 1×10^7 is required for the determination of Ti and ρR. The flat collimator provides enough shielding for 1-kJ short pulse energy (as in the present experiment). Adding to this the tube collimator, the shielding will provide sufficient shielding for 2-kJ short pulse energy, as planned for an experimental campaign to be conducted in 2013. The flat collimator has been installed and tested in a FI related experiment in 2012. The tube collimator is under construction and will be completed in 2013.

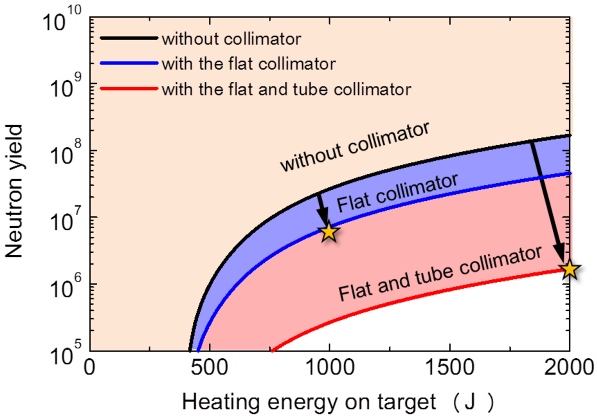

Fig. 3 The region of the neutron yield that can be measured with the signal-to-noise ratio of > 1 for the cases with no-collimator (orange), with the flat collimator only (blue) and with the flat and tube collimator (red).

3. Experimental Result in the Fast-Ignition

The flat collimator was installed and tested in FI related experiments. A typical fast ignition target constituted by an Au-cone attached to a deuterated polystyrene (CD) shell was imploded using nine beams of the GEKKO-XII laser system operated at a wavelength of 0.53 μm and with a total energy of 2.3 kJ. The imploded core plasma was heated by a LFEX pulse, having the pulse width of 1.2 ps and energy ranging from 0.6 to 1.0 kJ on target. γ-n neutron signal was successfully suppressed by the collimator. Reducing it to the 28.5% overall and more specifically to the 27.2% at the temporal window of DD-neutron arrival time (620 - 720 ns) with a good agreement with the sim-

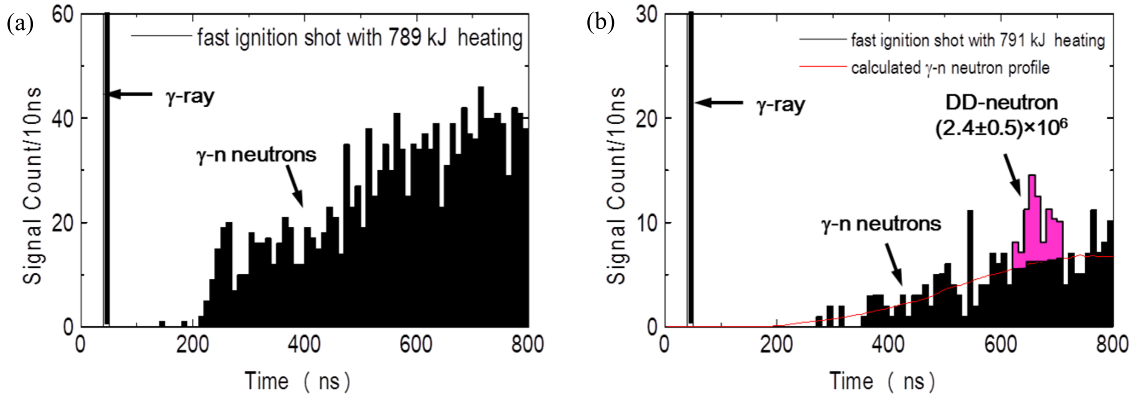

Fig. 4 The typical signals observed by MANDALA (a) without the collimator in 2010 and (b) with collimator in 2012. DD-neutron signals are clearly seen in 620 - 720 ns in 2012. The DD-neutron yield was evaluated to be (2.4 ± 0.5) × 10^6.

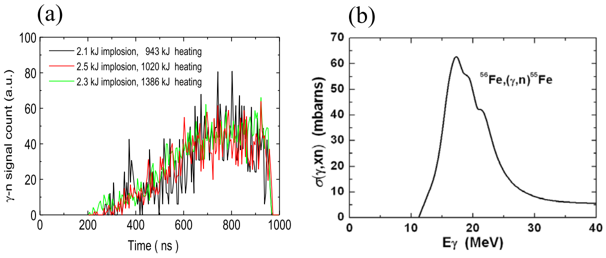

Fig. 5 (a) Comparison of the time profile of γ-n neutrons and (b) (γ,n) cross section of ^{56}Fe quoted from Japanese-evaluated nuclear data library (JENDL). γ-n spectrum does not be affected significantly by γ-ray spectrum because (γ,n) cross section shape is monochromatic.

ulation. A typical signal from MANDALA is represented in Fig. 4 for two cases, (a) without collimator in 2010 and (b) with collimator in 2012. Very small shot-to-shot variation is observed for the temporal profiles the γ-n neutrons (a). This is mainly because the cross section of the photo-nuclear reaction has a resonant window as shown in Fig. 5 (b) and thus γ-n neutron energy spectrum is not significantly affected by the γ-ray spectrum. The time profiles of the γ-n neutrons at DD-neutron arrival time was evaluated by using the simulated profile represented by the red line in Fig. 3 (b), and finally a signal count of DD-neutron of 28±5, which is equivalent to the neutron yield of (2.4±0.5)×10^6 was confirmed. On the other hand, the DD-neutron yield in absence of the intense LFEX pulse were less than 5 × 10^5, and thus we concluded that 4 ∼ 5 times enhancement of DD-neutron yield by the fast-heating was successfully obtained.

4. Conclusion

MANDALA diagnostic was improved by suppressing the background noise caused by γ-n neutrons in FI related experiment. A neutron collimator, designed on the basis of a series of calculations using the Monte Carlo code MCNP5 was tested and a suppression ratio of 72% was achieved in agreement with the simulations. A 2 × 10^6 DD-neutron yield was successfully measured in the present experimental condition. After completion of the tube collimator, the neutron yield, the ion temperature and the areal density will be measured in an upcoming experiment using a 2 kJ intense pulse for heating.

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