# The Development of the Neutron Detector for the Fast Ignition Experiment by using LFEX and Gekko XII Facility<sup>\*)</sup>

Takahiro NAGAI, Mitsuo NAKAI, Yasunobu ARIKAWA, Yuki ABE, Sadaoki KOJIMA, Shohei SAKATA, Hiroaki INOUE, Shinsuke FUJIOKA, Hiroyuki SHIRAGA, Nobuhiko SARUKURA, Takayoshi NORIMATSU and Hiroshi AZECHI

Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 565-0871, Japan (Received 1 August 2013 / Accepted 27 November 2013)

The progress on the neutron time of flight (nTOF) detection system for Fast Ignition (FI) related experiment was presented. The novel nTOF detector consists with custom-developed liquid scintillator and gated PMT was implemented. The origin of the harsh backgrounds which had been observed in previous experiment was identified by Monte Carlo simulation. The neutron yield around  $10^6$  in the 1 kJ-heating experiment which is 10 times lower than previous lower limit was clearly diagnosed.

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# 1. Introduction

Fast ignition scheme inertial confinement fusion has been studied for more than a decade. Especially, the world largest peta-watt laser "LFEX" with energy exceeding 1 kJ and 1 ps pulse duration is currently operated at the Institute of Laser Engineering (ILE), Osaka University. At the moment, this is a unique laser system, which parameters make it particularly attractive for application to FI studies [1]. However, diagnostics of the fusion neutron in the fast ignition is extremely difficult due to intense  $\gamma$ -ray generated from the heating laser.

In the experiment, the background signals detected by the nTOF were identified to be  $\gamma$ -rays which directly come from target, scattered  $\gamma$ -ray mainly from target chamber and photo-nuclear neutrons  $((\gamma, n)$  neutron) which are mainly generated at target chamber wall as reported in our previous study [2]. A fast response, afterglow-free scintillator, is necessary to discriminate the fusion neutron signal from the various background sources. Furthermore the gain saturation or afterpulse of the photo multiplier tube (PMT) which is created by the intense  $\gamma$ -ray signal must be suppressed. Figure 1 shows the typical signal obtained, in a previous experiment [3], with conventional plastic scintillator (BC-422Q) detector. The first strong signal is produced by direct  $\gamma$ -rays, the second peak by scattered  $\gamma$ rays signal and the subsequent broad signal is produced by  $(\gamma, n)$  neutrons. Since the intensity of the  $\gamma$ -ray emission is much larger than that of fusion neutron, the diagnosis of the latter is indeed very challenging.

In this paper, the progress on the development of the nTOF detector in FI laser fusion project at GEKKO XII-



Fig. 1 Signal measured by the conventional detector in fast ignition experiment with LFEX laser energy of 540 J.

LFEX facility in ILE is presented. A scintillator having a fast decay time and a low afterglow was developed by modifying the Oxygen-quenching liquid scintillator reported in our previous work [4].

The scintillator was coupled to the gated PMT so that the strong  $\gamma$ -ray can be blocked. The neutron collimator was developed in order to shield ( $\gamma$ , n) neutrons which are mainly generated at target chamber wall. The location of the detector was carefully chosen so that scattered  $\gamma$ -rays don't interfere with fusion neutron. By using this detector we finally succeeded to detect the fusion neutron signal with relatively low neutron yield among the harsh environment.

# 2. Diagnostic Design

## 2.1 Low-afterglow liquid scintillator

The scintillation afterglow masks the small signal of fusion neutron [4–6]. Xylene-based 4,4""-Bis[(2butyloctyl)oxy]-1,1':4',1":4",1"'-quarterphenyl (BBQ) liquid scintillator enriched oxygen was developed by modifying Oxygen-quenching liquid scintillator reported

author's e-mail: nagai-t@ile.osaka-u.ac.jp

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in our previous work [4,7]. Figure 2 shows the comparison of the scintillation afterglow and the fast decay component of the BBQ scintillator and BC-422Q. Scintillation afterglow was measured by Time-Correlated Single Photon Counting method [4]. In order to measure the fast decay profile of these scintillators, a silica glass cell was filled with the mixture and then irradiated by 150-fs, frequencytripled (290 nm) Ti: sapphire laser pulses, having  $20 \,\mu$ J pulse energy and operating at 1-kHz repetition rate [7]. The scintillation afterglow of the BBQ scintillator is about 50 times smaller than that of BC-422Q 100 ns after irradiation. Fast decay time of the BBQ scintillator (0.76 ns) is as fast as that of BC-422Q (0.65 ns). This characteristic, together with a fast response and low afterglow is very preferable for FI related experiments application.

#### 2.2 Gated photo multiplier tube

A gated PMT (Hamamatsu R2256-02, C1392) was used in this system [8]. Reversed bias voltage is applied



Fig. 2 Scintillation decay for oxygen-enriched BBQ scintillator and BC-422Q. (a) Afterglow for the two scintillator detectors (b) Decay time for the two detectors.

to some dynodes. This scheme can prevent the gated PMT from gate-breakthrough produced by the intense initial  $\gamma$ -ray pulse directly irradiating the PMT dynodes, which cannot be blocked by the widely used gating system implemented on the photo cathode [5]. The experimental demonstration of the PMT gating was conducted by using short pulsed x-ray generated from a Linear Accelerator (LINAC) energetic electrons colliding on a lead plate target. Figure 3 shows the signal obtained with and without gating. The signals for the gated cases show the scintillation decay curves even though non-gating signal was saturated. Applied voltage of the PMT was carefully chosen to separate the time of afterpulse from the fusion neutron arrival time.

#### 2.3 Detector design

2 types of detection systems were developed as shown in Fig. 4. One of the systems is constituted by a detector located on the flight path behind the concrete wall at 13.35 m from the target chamber center (TCC). Large vol-







Fig. 4 The setup for the fast ignition experiment.



Fig. 5 Comparison of the  $(\gamma, n)$  neutron count with-or-without the collimator, calculated via Monte Carlo simulation code. (a)  $(\gamma, n)$  neutron count detected at 13.35 m distance. Green line shows DD neutron (2.45 MeV) arrival time of 618 ns. (b)  $(\gamma, n)$  neutron count detected at 8 m under the chamber. Green line shows DD neutron arrival time of 370 ns.

ume (2.51) of BBQ liquid scintillator attached to an acrylic light guide and the PMT was designed by calculating the neutron detection efficiency and the scintillation collection efficiency. Detection efficiency of this system is set to  $8 \times 10^{-6}$ .

Another system is constituted by a multi-channel detector located in the concrete wall at 8 m from TCC. The multichannel is composed by seven BBQ liquid scintillator channels, having a volume of 180 mm $\phi \times 20$  mm thick volume which have detection efficiency of  $4 \times 10^{-5}$ . Light output of each scintillator were adjusted by using a neutral density filter and Benzophenone (1 wt%) in order to obtaining high dynamic range.

#### 2.4 Neutron collimator

The 10 polyacetal neutron collimators are set up to reducing the  $\gamma$ -ray background noises in the flight path. Comparing the results with and without the multistep collimators, the reduction rate of the ( $\gamma$ , n) neutron detected at 13.35 m distance by the collimators at the Deuterium-Deuterium (DD) neutron arrival time was estimated to be the 84% by using the Monte Carlo simulation code MCNP5 as shown in Fig. 5 (a).

The polyacetal and water neutron collimator are set up in order to reduce the background noise for the multichannel detectors. The reduction rate of the ( $\gamma$ , n) neutron detected at 8 m by the collimators at the DD neutron arrival time is estimated to be the 89% by MCNP5 as shown in Fig. 5 (b).

# **3.** Neutron Diagnostics for Integrated Experiments

Fast ignition integrated experiment was conducted in 2012. The Au cone attached with deuterated polystyrene shell target was used in the experiment. Heating laser up to 1.6 kJ was focused onto the target. The low neutron yield down to  $1 \times 10^6$ , almost at neutron counting condition, was



Fig. 6 Experimental data. LFEX pulse energy was 555 J on the target. (a) and (b): the signal measured by the detector in the flight path, (c) and (d): the signals measured by the 7-channel detector. Blue and green vertical lines are  $\gamma$ -ray and DD neutron arrival time respectively.

successfully detected with a small enough background by the two detectors simultaneously. Figure 6 shows the obtained signal from integrated shot with LFEX energy of 555 J on the target. Figures 6(a) and (b) show the signal of the detector set on the flight path, (c) and (d) shows 7channel detector. The DD fusion neutron signal can be seen in the obtained clearly at 625 ns by the detector on the flight path with well suppressed  $\gamma$ -ray scintillation by the PMT gating as shown in Figs. 6(a), (b). The neutron yield measured by this detector was  $(3.8 \pm 0.7) \times 10^6$ , where the error is statistical error of the number of detected DD neutrons. The DD fusion neutron signal was barely obtained between two afterpulses of the PMT by 7 channel detector as shown in Figs. 6 (c) and (d), because scintillation decay of the  $\gamma$ -ray pulse remained after the gate opening. The neutron yield diagnosed by this detector was  $(1.3 \pm 0.9) \times 10^6$ , where the error was calculated from dispersion of the values measured by each channels. This yield value agreed well with that of the detector in the flight path.

# 4. Conclusion

The intense  $\gamma$ -ray background noises make the neutron measurement difficult in FI related experiments. By using the oxygen-enriched BBQ liquid scintillator, the PMT gaiting, and the collimators for the  $\gamma$ -ray background noises, is possible to clearly detect the D-D neutron signal.

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