The diagnostics of the energy coupling efficiency in the Fast Ignition integrated experiment

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Abstract. The energy coupling efficiency (CE) in Fast Ignition (FI) laser fusion was studied at GEKKO XII and LFEX laser facility by using newly developed targets and plasma diagnostic instruments. The gated-liquid scintillator neutron detectors had been upgraded by using neutron collimators for intense background fluxes of γ-rays and neutrons in the FI experiment. Clear fusion neutron signal was successfully recorded in the sub-kJ heating FI experiment. Up to 5 times neutron yield enhancement was observed, and the CE of the heating laser to core plasma was estimated to be 1.6 % for cone-in-shell target implosion by 9 beams and core heating by LFEX pulse 115 ps before bang time. The laser-to-electron energy conversion efficiency was separately diagnosed using a newly developed target and resulted to be 45 %. The fast electron energy spectrum was estimated to be 2.3 MeV slope temperature by hard x-ray spectroscopy. Monte Carlo simulations demonstrate the consistency of the data set.

1. Introduction
The Fast Ignition (FI) laser fusion scheme is an alternative approach to Inertial Confinement Fusion which provides a more compact laser design compared to the classic Central Hot Spot ignition scheme. The goal of the FI realization experiment (FIREX) project phase-I, conducted at Institute of Laser Engineering, Osaka University is to demonstrate the fast heating of the core plasma up to 5 keV ignition threshold temperature by using LFEX laser with the designed maximum energy of 10 kJ. In order to achieve this goal more than 10 % laser-to-core plasma energy coupling efficiency is required [1]. The deposited energy in the core plasma can be measured from the increment in the ion temperature which can be measured by fusion neutron yield or neutron spectrum Doppler broadening, and the core density profiles which can be measured by x-ray radiography. The detection of the fusion neutron in the FI experiment represented a challenging subject in the past decade due to the intense background of hard x-ray and the photo-nuclear reaction neutrons. The neutron detectors have been dramatically improved by installing Oxygen-enriched liquid scintillators, gated-PMT, and neutron collimators in the neutron TOF detection systems [2,3,4]. Another fundamental parameter is represented by the laser-to-fast electron energy conversion efficiency [5,6,7]. In most of the previous studies, a short pulse laser was used, however the fast electron transport from the cone surrounded by shell plasma is of difficult study since the sheath field at the cone-outter-surface is significantly different from the one in vacuum. Moreover the electron spectrum in the core plasma has been technically difficult to be measured by using conventional magnet-based electron spectrometer, due to the significant fast electron stopping at high densities. Hard x-ray spectroscopy is an alternative scheme to diagnose the electron spectrum [8] and a specially designed target was used in the experiment. By using this target the laser-to-fast electron energy conversion efficiency was measured from absolute K-α yield [9], the divergence angle and the energy spectrum of the electron were measured by using five stack filter high energy x-ray spectrometers and a newly developed Compton...
\(\gamma\)-ray spectrometer [10]. In this work the progress on the neutron diagnostics and the measurement of the global laser to core plasma energy coupling efficiency are presented.

2. The progress on the neutron diagnostics

In the FI experiment the hard x-ray generated by the heating laser creates a very intense background signal preceding the fusion neutron detection [2,3,4]. The rapid decaying liquid scintillator diagnostics have been developed for this aim and they were implemented in the FI experiment. The liquid scintillators consist of oxygen gas enriched p-Xylen or TMB (Tri-Methyl benzene) having higher temperature flashing point than that of p-Xylen as a solution, BBQ (4,4''-Bis[(2-butyloctyl)oxy]-1,1':4',1''':4'',1'''-quaterphenyl) as a dye, and Benzophenon as a additional quencher to have faster decay. Figure 2 shows the temporal profiles of the newly developed liquid scintillators with and without Benzophenon. The fall time was dramatically improved from 90 % to 10% by Benzophenon quenching while the afterglow (long time constant tail) was not significantly increased. Light output was reasonably decreased with the Benzophenon fraction. By implementing these scintillators at GEKKO XII-LFEX facility, the neutron TOF system has been upgraded. The experimental setup in the 2012 experimental campaign is shown in the Fig. 2(a), and the comparison of the typical neutron TOF signal before and after upgrade is shown in the Fig.2 (b). After the upgrade, it was possible to detect DD fusion neutron yields equal or greater than \(5 \times 10^5\) with 1 kJ LFEX heating shots. The detailed description of MANDALA and the liquid TOF detectors will be presented in the same conference proceedings series.

3. The energy coupling efficiency of the laser to the core plasma

The FI integrated experiment (implosion and heating joint shots) was conducted at GEKKO XII – LFEX facility. A typical FI target with a gold cone attached deuterated-polystyrene shell was irradiated by GEKKO XII and LFEX. The LFEX pulse width was 1.2 ps FWHM. The shell used was 7 \(\mu\)m thick and 500 \(\mu\)m diameter. The increment of the neutron yield by LFEX heating was clearly observed, rising from \((5.7\pm1)\times10^5\) without LFEX pulse, to \((2.2\pm1)\times10^6\) for a 612 J heating shot. Unfortunately, the LFEX timing was not optimized in this shot, and it was estimated to be 115 ps before the maximum compression time by x-ray streak camera. The core density and the areal density at this time were separately measured to be respectively about 7 g/cm\(^3\) and 20 mg/cm\(^2\), by using a monochromatic x-ray framing backlighting image with 100-ps time resolution. The size of the core plasma was measured to be 54 \(\mu\)m in diameter by x-ray streak image. The ion temperature was estimated using following simple formula:

\[
Y_n = \frac{n^2}{2} \langle \sigma v \rangle V \tau
\]

where \(n\) is the number density of the deuterium, \(\langle \sigma v \rangle\) is the Maxwell averaged fusion cross section, \(V\) is the volume of the core plasma, \(\tau\) is the temperature dependent confinement time. The ion temperature (Ti) without LFEX heating shot was estimated to be 0.67±0.02 keV and 0.84±0.05 keV.
for 612 J heating shot. A slight Doppler broadening in the neutron spectrum was observed by MANDALA, and Ti resulted to be less than 1 keV, in agreement with the estimated value. A multi-images x-ray streak camera observed the time resolved electron temperature (Te) image around the fast heating time. At the heating time, a significant emission from the core-tip and a small emission from the core plasma were found. Te at the core plasma resulted to be 1 keV, in agreement with the Ti estimated from neutrons while the Te at the cone-tip was around 2 keV. With these information we conclude that the DD neutrons were produced in the core plasma, and finally we conclude that the core ion temperature increase was 0.17 \pm 0.05 keV, and the deposited energy was 9.8 J. The CE of the laser to the core plasma resulted to be 1.6 \pm 0.4 %. If the heating time had been at maximum compression the electron stopping efficiency would much better. As shown in the next section the reason of the low CE is due to the density of the core plasma was too low and Te of the fast electron was too high.

4. The laser-to-electrons energy conversion efficiency
To better understand the energy transfer from the laser to the core plasma, fast electron generation must be separately studied. The electron spectrum, the divergence angle, and the laser-to-electron conversion efficiency were studied by using a newly designed target with a cone attached hemispherical shell coupled with a layered metal block [8]. A standard gold cone target was adopted, and the electrons spectrum was measured to be 2.3 MeV slope temperature and a 60 degree full angle angular distribution was measured by using Bremsstrahlung x-ray spectrometers. The laser-to-electron conversion efficiency was estimated to be 45 % by the absolute K\alpha yield spectroscopy. The detailed description of the experiment and the target will be presented in the same conference proceeding series. The electron stopping efficiency was estimated by using Monte-Carlo simulation code PHITS [11].

Figure 2 (a) The experimental setups of the neutron TOF detectors in the FI experiment in 2012. (b) The comparison of the signal of neutron TOF detectors between 2009 and 2012.
assuming using a uniform CH solid core plasma with 7 g/cm$^3$ density, 54 μm core size, electron beam injection 50 μm far from the core center, beam divergence of 60 degree full angle, and 2.3 MeV slope temperature. Figure 3 shows the electron trajectories and the deposited energy map. The energy deposition efficiency on the core resulted to be 2.5 %. Since the laser-to-core energy transfer is considered to be originated from the core heating. The laser-to-electron conversion efficiency can be improved by better imploding of the core. This study represents a step forward in the understanding of the Fast Ignition heating process.

Conclusion
The laser to the core plasma CE in FI was studied by using advanced neutron detectors, x-ray spectrometers, and a new target. The laser to the core CE was measured to be 1.6 ± 4 %. The incremental ion temperature measured by the neutron diagnostics is in agreement with the electron temperature measured by streaked x-ray image, and therefore the neutrons were considered to be originated from the core heating. The laser-to-electron conversion efficiency and the electron spectrum were separately studied by using new cone-shell-block target, and resulted respectively to be 45 %, and 2.3 MeV. The electron stopping efficiency was estimated by Monte Carlo simulations, and these values were confirmed to be well consistent with the CE of the laser to the core plasma determined by neutron diagnostics. This analysis indicates the CE can be improved by better implanting of the core plasma and the reducing Te of fast electron. This study represents a step forward in the understanding of the Fast Ignition heating process.

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