Neutron generation from Impact Fast Ignition

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Abstract. We have proposed a new ignition scheme of Fast Ignition, called “Impact Fast Ignition [1] (IFI)”, in which a compressed fuel is ignited by impact collision of a fragment of separately imploded fuel. We have started experiments that used CD colliding foils as the fundamental experiment and integrated experiment of the IFI. In the fundamental experiment, we used targets which are consists of two CD foils (thickness of 20 µm) with a 600 µm separation. We have irradiated one of the CD foils by laser beams of the energy of 2 kJ in total and accelerated. The accelerated CD foil collides with another foil, and neutrons were generated by the nuclear fusion reaction on the heated foil. In this experiment, we measured the neutron yield of 10⁶. In the integrated experiment, we used CD shell targets with a gold cone which had a hemispherical impactor (Fig.1). The shell was imploded using 9 beams and the impactor was accelerated using 3 beams of the GEKKO XII laser system. The laser energy was 350 J per beam. Observed maximum neutron yield was 2×10⁶. This yield was 80 times as large as that without impactor. We will present the experimental details and results.

1. Introduction

In our institute, the integrated experiments of Fast ignition were performed [2]. The results of these experiments have shown that substantial fraction of the incident Peta watt laser is converted to the thermal energy of the compressed core plasma. However the fast ignition approach requires the understanding of physics of hot electron generation and transport. Present physical understanding of the physics is insufficient to make a quantitative prediction of the ignition. Recently, Impact Fast ignition (IFI) was proposed as a new ignition scheme of Fast ignition that totally eliminates these complex problems while keeping the advantage of the compactness of the fast ignition. In the IFI method, we accelerated a small portion of the fuel (called “impactor”) to a super-high velocity to collide with a pre-compressed main fuel. Since the kinetic energy of the impactor is converted to the thermal energy of both ions and electrons, its velocity needs to be higher than 1000 km/s to get the
ignition temperature of 5 keV [via \( m_{DT}v_{imp}^2/2 = 2(3/2)T \), where \( m_{DT}, v_{imp}, T \) are the average mass of the DT ion, the velocity of the impactor and \( T \) is the required temperature]. The density of the impactor in flight needs to be 2-5 g/cc so that after the spherical convergence followed by the collision with the main fuel it becomes an igniter with a sufficiently high density on the order of 100 g/cc. In order to study an effectiveness of IFI method, we have started experiments that used CD colliding foils as the fundamental experiment and integrated experiment of the IFI. In these experiments, we measured neutron yields from DD thermonuclear fusion reactions to evaluate the rise of temperature on the heated impactor.

2. Fundamental experiments
In the fundamental experiment, we used two sheets of CD foil (with the thickness of 20 \( \mu \)m) with a 600 \( \mu \)m separation. One side of the CD foil is accelerated by the high power laser (1.9 kJ) from the HIPER (High Intensity Plasma Experimental Research) [3] and collides to another stationary CD foil. Fig. 1(a) shows the target arrangement of this experiment. The laser wavelength and spot size on the target surface were 0.35 \( \mu \)m and 300 \( \mu \)m respectively. The laser pulse shape was nearly flat top with the full width at half maximum (FWHM) of 2.5 ns. In order to evaluate the heating by collision, we measured the neutron yield by the DD reaction. We used two neutron detectors which consist of plastic scintillator (BC422) and photomultipliers (HAMAMATSU R2083). These detectors had been calibrated to neutron yield by measuring the DD neutron yield and DD proton yield simultaneously in a separate shot with using thin CD shell targets. The neutron yields were measured from two different directions with using these detectors. Distances from these detectors to the target were 20 cm and 25 cm. DD neutron signals were observed by digital oscilloscope (Tectronix TDS684A, bandwidth 1 GHz). In this fundamental experiment, we obtained \( 1.0 \times 10^6 \) DD neutron yield. The value of yields of two detectors were comparable each other, which means that the emission of these neutrons were isotropical.

![Figure 1(a). Design of the fundamental experiment](image1)

![Figure 1(b). Design of the reference experiment 1](image2)

![Figure 1(c). Design of the reference experiment 2](image3)

After this experiment, we conducted the two reference experiments to determine an origin of neutrons. In the first reference experiment, we measured the DD neutron yield from the corona plasma on the target surface of an impactor with used single CD plane target (Fig. 1(b)). In this reference experiment, we obtained \( 1.3 \times 10^5 \) DD neutron yield. This result means that most of the neutrons, which were obtained in the fundamental experiment with using CD colliding foil target, were produced by the collision.

In the second reference experiment, we checked the effect of beam fusion event. We considered neutrons from two types of beam fusion events. One is the neutrons from direct interaction of the deuterons in the CD impactor with those in another stationary CD foil. Predicted neutron yield on this process is too low to account for the observed yield. Another is the neutrons from a high energy deuteron beam with energy on the order of MeV generated by laser-plasma interactions. Second reference experiment was performed to check the effect of these processes. We used CD impactor and
stationary CH plane target (Fig. 1(c)) to remove the high energy deuteron beam fusion event. In this second reference experiment, we observed $8.3 \times 10^5$ DD neutron yield. This yield is comparable to the one observed in the fundamental experiment. These results of the reference experiments mean the neutrons obtained in the fundamental experiment were mainly produced by thermonuclear fusion reaction on the collided impactor.

3. Integrated experiment

In the integrated experiment, we used a CD shell target and a hemispherical CD impactor attached on an Au cone. Figure 2 shows the target design of this experiment. A CD hemispherical impactor was accelerated by the high power laser and collides to a compressed CD shell. The shell was imploded using 9 beams and the impactor was accelerated using 3 beams of the GEKKO XII laser system. The laser energy was 350 J per beam and the laser wavelength was 0.53 μm. The laser pulse shape was gaussian with FWHM of 1.3 ns. We used four current mode neutron detectors and one multi channel neutron spectrometer (MANDALA [4]). Experimental set up is shown in Fig. 3. We measured neutron yields from five different directions by using these detectors.

![Figure 2. The target design of the integrated experiment](image)

Figure 2. The target design of the integrated experiment

![Figure 3. Schematic view of the set up of the integrated experiment](image)

Figure 3. Schematic view of the set up of the integrated experiment

We measured neutron yields varying the time lag between the incidence time of laser for impactor and laser for main fuel to research the timing dependence of neutron yields (Fig. 4). The horizontal axis of Fig.4 means the incidence time of laser for the impactor acceleration relative to that of laser for the main fuel implosion. For example, +1 means that the laser for the impactor irradiated 1 ns after the laser for the implosion. The observed values of neutron yields of five detectors were comparable to each other and the significant energy shift of the neutron spectrum was not observed, so the neutrons observed in this experiment were concluded to be generated by the thermonuclear fusion reactions. It
was shown that the generated neutron yields depended on the timing for the impactor to collide with the imploed main fuel. In these shots, the density and mass of the impactor just before the collision were essentially the same because the target specification and the laser condition were identical in every shot. The difference of generated neutron yields came from only the difference of density of the main fuel to collide. The temperature of collided impactor increases as the density of compressed main fuel increases. The dramatic increase of the neutron yield in about 100 psec demonstrates a sharp increase of the fuel density by stagnation. When the laser for the impactor irradiated before 1 ns from the laser for the implosion, neutron yield was the maximum value ($2 \times 10^6$). On this timing, a density of a main fuel was considered to be the highest in this experiment as was reproduced by a computer simulation.

Figure 4. Experimental results of the integrated experiment

Figure 5. DD neutron TOF spectrum observed by MANDALA and fitting line.

Figure 5 shows the neutron time-of-flight (TOF) spectrum observed by MANDALA at the shot when we observed maximum neutron yield. Ion temperature of heated plasma was obtained from the Doppler broadening of this neutron spectrum by a first-hit method [5] as $1.59^{+0.29}_{-0.20}$ keV.

Additionally, we also imploded the target without an impactor in a reference experiment. As is shown by the broken line in the Fig. 4, we observed $3 \times 10^4$ neutrons in this reference experiment. This result means that the neutron yield had increased by a factor of 70 at the maximum by impact heating.

4. Conclusion
In the fundamental experiment with using CD colliding foil target, $1.0 \times 10^6$ DD neutrons observed. Most of these neutrons were generated from CD impactor heated by collision.

We found that the generated neutron yields depend on the timing for the impactor to collide with the imploed main fuel. It means that the generated neutron yields depend on the density on pre-compressed main fuel. $2.0 \times 10^6$ neutrons were observed at the maximum value. In this shot, the impactor was heated to 1.6 keV by the collision. And the impact heating increased the neutron yield by a factor of 70.

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