1000$\times$ enhancement of fusion reaction in relation to fast-ion heating induced by a direct-irradiating fast-ignition scheme


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**Abstract:**

We conducted experiments that 600 J/1.5 ps ultra-intense laser pulse was directly irradiated on an imploded core that was preformed by counter irradiating 300 J/1.3 ns laser pulses. The Laser for Fast Ignition Experiment (LFEX) directly irradiated a pre-imploded core, enhancing D(d; n)$^3$He-reaction neutron (DD neutron) yields by a factor of 1000 ($5\times10^8$ n/4$\pi$ sr) from that of preimploded core. This enhancement is consistent with a model that includes beam fusion reaction induced from fast ions accelerated by collision-less shock.
1 Introduction

High-density compression and core heating are essential processes in an inertial confinement fusion. National Ignition Facility (NIF) is now on-going to accomplish above processes\[1\]. Recently, they succeed in so-called scientific break-even that fuel gain exceeding unity in the inertially confined fusion implosion. However, this self-ignition scheme, that is, to burn the core in implosion itself is not straight forward as expected and it required more elaborate schemes to control instability\[2\]. In addition to the self-ignition schemes, we should look for altanative methods to achieve more robust inertial fusion burring schemes. A potential solution for this is the fast-ignition scheme\[3, 4, 5, 6, 7, 8\], because this scheme can separate and optimize the process of fuel compression and its heating respectively. In this paper, we show an experimental result that an ultra-intense laser pulse was directly irradiation into a imploded core so as close as possible, resulting in 1000× enhancement of fusion reaction.

2 Experimental set up and results

The experimental configuration is shown in Figs. 1(a) and (b). To realize direct heating, we used two counter beams of the GEKKO XII (GXII) green laser, which imploded a 500-μm-diameter spherical deuterated polystyrene (C\(_8\)D\(_8\) or CD) shell with 250 μm holes (see Fig. 1 (b)). Each of this green laser has energy of 254 ± 14 J in a 1.3 ns wide Gaussian pulse at a wavelength of 0.527 μm. An spherical lens of f# 3 focuses each beams on the position \(d = -400 \mu \text{m}\) from the target center. Random phase plates was not installed in these experiments. The value of laser focusing distance over target radius: \(D/R\) is –1.6. The laser intensity on the target surface is \(3 \times 10^{14} \text{W/cm}^2\).

Figure 2 shows implosion dynamics taken by the X-ray streak camera installed perpendicular to the imploding beam axis as shown Fig. 1 (a). X-ray emissions induced from the target surface ablation had a duration of 1.2 ns, this was comparable to that of the imploding pulse. The diameter of imploded core was 55 ± 1 μm. At the maximum compression time, that was 0.8 ns after the peak of imploding laser pulse arrival, we focused the LFEX laser onto this area, as shown in Fig. 1 (a). Through the hole on the shell target, this LFEX laser pulse can access as close as possible to the imploded core. The LFEX has energy of 613 J in a 1.5 ns wide Gaussian pulse at a wavelength of 1.053 μm. An off-axial parabolic mirror with focal length of 3.7 m (F# is 10) focuses this beam into a spot size of 60 μm where 50% of the energy is contained, resulting in the laser intensity of \(1 \times 10^{19} \text{W/cm}^2\).

Figure 3 (a) shows the neutron time-of-flight (TOF) spectrum from the gated Liquid Scintillator that was set at 13.35 m apart from the target at –69.13° to the LFEX laser axis. The yield all over the solid angle becomes \(5.1 ± 1.6 \times 10^8\) n/4π sr. Neutrons peak at 2.45 MeV is with a fraction of 13 % or \(6.4 \times 10^7\) n/4π sr. We regard this fraction as thermal fusion because it has duplicability. Figure 3 (b) plots the neutron yield, detected from the Scintillator 1, against 4π angle, as a function of the total laser energy (LFEX + GXII). For up to 500 J, no LFEX is injected. The blue solid-squares indicate neutron
Figure 1: (a) Schematics of laser irradiation geometry and diagnostics layout. (b) 500-μm-diameter CD shell with 250 μm holes.

Figure 2: X-ray streak image of the counter-irradiated CD shell.
yield via thermal fusion around 2.45 MeV. In Fig. 3 (b), the blue dashed-line is the calculated thermal fusion yields from the imploded core. In this calculation, we simply assume that the input laser energy is proportional to the core temperature. According to STAR1D simulation with considering the imploding beam cone angle, we estimate that the imploded core radius, density and temperature is estimated 35 $\mu$m, 2.2 g/cc and 0.8 keV, respectively. This leads to thermal neutron yields of $5 \times 10^5 \text{n/4}\pi\text{sr}$, comparable to obtained in experiments as shown in Fig. 3 (b). The red dashed-line is the total neutron yields enhanced by LFEX using a beam fusion model that fast deuteron ions collide with bulk deuterons in the imploded plasma core. In this model, the fast deuteron ions are driven by the LFEX laser by collision-less shock described in the next section.

3 Fast ion generation and induced fusion reaction

To exam the beam fusion reaction obtained in the experiments, we introduce a model that fast ion generation as a result of laser-plasma interaction at the cut-off density and fusion reaction induced by these fast ions pass through the core.

The fast ion acceleration is combination with a Sheath acceleration by electrostatic field behind the electron density pileup and piston acceleration by collision less shock. From the pressure balance equation including a electron pressure, we have

$$ (1 + \eta) \frac{I_L}{c} = n_e T_e + 2Mn_i u^2 \quad (1) $$

where, $\eta$ is the laser reflectively, $I_L$ is the laser intensity, $c$ is the speed of light, $n_e$ is the electron density, $T_e$ is the electron temperature, $M$ is the ion mass, $n_i$ is the ion density, and $u$ is the ion velocity. Here, we take into account the electron pressure in the piston model commonly used. We assume the electron temperature at the interaction as $T_e \sim m_e c^2 (\gamma_{os} - 1)$ by the ponderomotive potential of the laser field.
The laser propagation is stopped, $u = 0$, at $n_e = \gamma_{os} n_c$ where the laser photon pressure balances the electron temperature. Therefore, we can rewrite the laser intensity like $(1 + \eta) I_L / c = \gamma_{os} n_c m_e c^2 (\gamma_{os}' - 1)$, where $\gamma_{os}$ is a relativistic gamma factor of the standing wave, $\gamma_{os} = \sqrt{1 + (1 + \eta) a_L^2 / 2}$, and $a_L$ is a vector potential of laser light. Then the piston velocity $u = v_f$ is obtained by

$$v_f^2/c^2 = \frac{Z(\gamma_{os}' - 1)m_e n_c}{2M n_c} (\gamma_{os} - n_e / n_c).$$

(2)

From Eq. (3), only when $\gamma_{os} > n_e / n_c$, the laser pulse can propagate by sweeping plasmas from its own path or it can bore a hole. Where $Z$ and $M$ denotes the charge state and ion mass of bulk plasma, respectively. For free ionized CD plasma, we concerned here, $M/Z = 2$ for deuteron and carbon. For ion density at cut-off; $n_i \sim n_e / Z$, the value of $v_f / c$ is reduced to

$$v_f / c = \sqrt{\frac{Z m_e}{2M} (\gamma_{os}' - 1)}.$$

(3)

Ions accelerate by this collision-less piston has a velocity of $2v_f$. The energy of accelerated ions $E_i$ is given by

$$E_{ion} = \frac{1}{2} M (2v_f)^2 = Z m_e c^2 (\gamma_{os}' - 1)^2.$$

(4)

The amount of fast ion flux $\Gamma_{ion}$ is evaluated by assuming that (i) ions at the cut-off density $n_e / Z$ get acceleration to the velocity of $u = 2v_f$ by collision-less shock front moving $v_f$ during the laser duration of $\tau_L$, and (ii) the number of these ions is proportional to the laser absorption; $(1 - \eta)$. This leads to

$$\Gamma_{ion} = (1 - \eta) (n_e / Z) \tau_L v_f.$$

(5)

The fast ion energy flux is given by $\Gamma_{ion} E_{ion}$. Therefore, an energy conversion efficiency from laser to fast ions is given by

$$f_i = \frac{\Gamma_{ion} E_{ion}}{E_L} = \frac{(1 - \eta) n_e (\gamma_{os}' - 1)^3 m_e c^2}{(I_L / c)} \sqrt{\frac{Z m_e}{2M}}.$$

(6)

Figure 4 shows laser intensity dependence of (a) accelerated deuteron energy and (b) conversion efficiency for variable laser reflectivity. From the previous particle-in-cell (PIC) simulation results, we apply $\eta = 0.16$. At the laser intensity of $1 \times 10^{19}$ W/cm$^2$, the value of our experiments, the deuteron energy is 1 MeV, and conversion efficiency is 0.15 %. In CD plasma, these fast ions include both deuteron and carbon. The beam fusion reaction is induced by fast deuterons moving into the imploded core. In particular, these fast deuterons lose its energy as they pass through the core. However, note that a range of fast ions in hot plasma is much longer than that of cold solid target. For example, the range of deuteron with energy of 1 MeV is 0.04 cm in the CD plasma with solid density and temperature of 1 keV. This is one order longer than that in a cold CD sold;
0.0025 cm. In our experiments, the imploded core with density of a few times of solid has a diameter of around 50 μm. This diameter is 10 times shorter than the range of deuterons. Therefore, the deuteron can penetrate the core without tremendous energy loss. The beam fusion yields are more active in hot plasma than that of in solid target. The beam fusion reaction is given by

\[ \frac{dY_n}{dn_D} = \Gamma_D \int_0^L \sigma(E_D(x)) dx, \]

\[ E_D(x) = E_D(x=0) - \int_0^x \frac{dE_D}{dx} dx \]

where, \( x \) is the traveling distance of fast deuterons, \( n_D \) is the deuteron ion density in the core with diameter of \( L \), \( \sigma(E) \) is the cross section of D(d; n)3He-reaction\(^1\). \( dE/dx \) is the stopping power of deuterons in the plasma. Figure 4 (c) shows beam fusion neutron yields as a function of laser intensity for parameters of experiments. The yields shows saturation over intensities of \( 10^{19} \) W/cm\(^2\). This is because D-D beam fusion reaction has maximum cross section at energies around a few MeV and a weak energy dependence for over 10 MeV. The red curve in Fig. 3 (b) is evaluated from Fig. 4 (c). The beam fusion model presented here is consistent with observed neutron yields in experiments.

4 Conclusions

We conducted experiments that 600 J/1.5 ps ultra-intense laser pulse was directly irradiated on an imploded core that was preformed by counter irradiating 300 J/1.3 ns laser pulses. The neutron yield has increased as high as 1,000 time \( (5 \times 10^8 \ n/4\pi \ sr) \) than that achieved without ultra-intense laser irradiation. The beam fusion model induced by fast ions driven by collision-less shock explain this enhancement.
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