Direct heating of a laser-imploded core using ultraintense laser LFEX

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Abstract
A CD shell was preimploded by two counter-propagating green beams from the GEKKO laser system GXII (based at the Institute of Laser Engineering, Osaka University), forming a dense core. The core was predominantly heated by energetic ions driven by the laser for fast-ignition-fusion experiment, an extremely energetic ultrashort pulse laser, that is illuminated perpendicularly to the GXII axis. Consequently, we observed the D(d,n)3 He-reacted neutrons (DD beam-fusion neutrons) at a yield of $8.5 \times 10^8$ n/4\pi sr. The beam-fusion neutrons verified that the ions directly collided with the core plasma. Whereas the hot electrons heated the whole core volume, the energetic ions deposited their energies locally in the core. As evidenced in the spectrum, the process simultaneously excited thermal neutrons with a yield of $6.1 \times 10^7$ n/4\pi sr, raising the local core temperature from 0.8 to 1.8 keV. The shell-implosion dynamics (including the beam fusion and thermal fusion initiated by fast deuterons and carbon ions) can be explained by the one-dimensional hydrocode STAR 1D. Meanwhile, the core heating due to resistive processes driven by hot electrons, and also the generation of fast ions were well-predicted by the two-dimensional collisional particle-in-cell code. Together with hot electrons, the ion contribution to fast ignition is indispensable for realizing high-gain fusion. By virtue of its core heating and ignition, the proposed scheme can potentially achieve high-gain fusion.
Keywords: fast ignition, ultraintense laser, counter-propagating beam, ion heating

(Some figures may appear in colour only in the online journal)

1. Introduction

The National Ignition Facility (NIF) is a promising candidate for the development of a safe fusion power plant [1]. However, successful core ignition is not yet achieved. A self-ignition scheme, that is, to burn the core in implosion itself has not proved as easy as expected. The fast-ignition scheme is expected to have a complimentary ability to ignite the fuel.

In the fast-ignition scheme, a preimploded DD or DT capsule is irradiated by a laser pulse for a few tens of picoseconds, a much shorter timeframe than the hydrodynamic disassembly time of the compressed core [2]. Such a short-pulse laser generates energetic electrons and ions near the cutoff region. These electrons and ions are expected to penetrate the core and form a hot spot, from which a $^4$He ($\alpha$ particle) burning wave spreads over the core. If fast heating and ignition trigger the core ignition with high gain, it will greatly assist energy production from the inertial confinement fusion.

We began the fast heating studies with the peta-watt-module laser (90 J/0.8 ps) [3], which enhanced the thermal neutrons by a factor of 1.7 ($7 \times 10^3 \mu \text{sr}$). The subsequent peta-watt laser (190 J/0.7 ps) [4] further enhanced the thermal neutron yield by a factor of 5, or $4 \times 10^9 n/4\pi \mu \text{sr}$ [5]. However, 2D simulations and experiments suggested that the hot electrons diverge, thereby heating the whole core area rather than a local region [6–12]. Much researches are done on the possibility of collimating the fast electrons by using resistive electric fields produced by density gradient [13] or [14], Weibel fields produced by counter-propagating laser pulses [15], externally generated magnetic fields [16], etc.

Hence we propose a scheme that directly heats the imploded cores by energetic ions driven by the laser for fast-ignition-fusion experiment (LFEX), an ultraintense laser, that drives both hot electrons and energetic ions around the critical density. Fractions of these driven particles are transported through the overdense plasma to the core. The hot electrons heat the whole core, whereas the energetic ions deposit most of their energy near the core periphery, locally heating it to the $^4$He ($\alpha$ particle) burning temperature. An $\alpha$ burning wave then spreads from the hot spot over the core. A spherical deuterated polystyrene (C$_8$D$_8$ or CD) shell was imploded by the two counter-propagating beams of a GEKKO XII (GXII) green laser. The LFEX is focused onto the naked core from the side, vertical to the GXII axis. By illuminating the LFEX as closely to the core as possible, we confirmed that the hot electrons and energetic ions play equal roles in core heating. In fact, DD beam-fusion neutrons are yielded at $5 \times 10^9 n/4\pi \mu \text{sr}$.

The neutron peaks of beam- and thermal-fusion neutron indicate that the laser-driven ions (deuterons and carbon$^{6+}$ ions) not only drive the beam-fusion reaction, but also contribute to the core heating. Comparing the observed and 1D-simulated spectral broadenings of the thermal neutron peak, we estimated a twofold rise in the the peripheral core temperature (from 0.8 to 1.8 keV). Combined beam fusion and thermal fusion generates neutrons in a compressed deuterated core plasma.

2. Counter-propagating beam implosion of a target with side holes

The self-ignition fusion scheme must concentrate the centrifugal shock waves to ignite a central hot spark. For this purpose, it requires a 4$\pi$ laser beam illumination. In contrast, the illumination of the fast-ignition scheme needs not be fully symmetric, because the fast-ignition beam can form a hot spark in any core area.

Figure 1(a) shows the CD shell with two holes, and (b) the configuration of the target, lasers, and detectors. The target is 500 $\mu$m in diameter and 7 $\mu$m thick. The target has two 250 $\mu$m diameter holes. One hole guides the LFEX beam into the target for heating; the other ventilates the preplasmas generated by the GXII. The latter hole plays no heating role, but enables direct detection of the x-rays and charged particles emitted from the heated core. Each of the two counter-propagating beams from GXII carries $254 \pm 14$ J in a 1.3 ns-wide 3rd-order-super-Gaussian pulse at a wavelength of 0.527 $\mu$m. Each beam is focused by an aspheric lens ($F$ number 3).

By changing the focusing depth $d$ of the implosion beams, we identified the focal point that achieves the highest core density from the x-ray streak camera XSC images (see figures 1(c)–(e)). The optimum $d/R$ (where $R$ is the shell radius) is $-1.6$ (figure 1(d)). Below each flow diagram in figures 1(c)–(e) is drawn the corresponding laser configuration, where $d$ is the position of the focal point measured from the target center. The minus sign denotes that the focal point is over the target on the laser axis. Therefore, $d/R = -1.6$ means that each implosion beam is focused at 400 $\mu$m over the center. The intensity of the beam on the target is $3.1 \times 10^{14}$ W cm$^{-2}$.

Figure 1 panel (c) exhibits an exploding pusher-type feature, whereas panels (d) and (e) display implosion features. In panel (d), the DD thermal neutron yield was $1.9 \times 10^5$ and the peak density (estimated in the 1-dimensional hydrocode STAR1D [17]) was approximately 5 $\sim$ 10 $\times$ the solid density.

In panels (d) and (e), half of the shell thickness is ablated out, so the target is in quasi-exploding pusher mode. Consequently, the guiding holes might not influence the core formation. X-ray streak flow images of similar shell targets with and without side holes are compared in panels (a) and (b) of figure 2, respectively. Considering the CD shell attenuation effect in (a), the intensities of the core emissions are identical in both cases, and no apparent differences appear in the results.

3. LFEX and measurement setup

Figure 3(a) shows the hypothetical instant of LFEX illumination onto the core. The imploded areas of the shell remain.
Figure 1. (a) CD shell with two holes: one for laser (LFEX) introduction, the other for preplasma ventilation. (b) Arrangements of the target, lasers, and detectors. Radius-time flow diagrams of the shells at focal depths of (c) \( d/R = 0 \), \( I = 3.7 \times 10^{15} \) W cm\(^{-2}\), \( \pi = 5 \times 10^3/4\pi \) sr, (d) \( d/R = -1.6 \), \( I = 1.5 \times 10^{15} \) W cm\(^{-2}\), \( \pi = 1.9 \times 10^3/4\pi \) sr, and (e) \( d/R = -2.8 \), \( I = 9.7 \times 10^{14} \) W cm\(^{-2}\), \( \pi = 1 \times 10^3/4\pi \) sr. Here \( R \) is the shell radius, \( I \) is the laser intensity on the target surface, and \( \pi \) is the neutron yield. Bottom panels show the corresponding laser configurations of the flow diagrams.

Figure 2. Comparison of x-ray streak flows between (a) a simple shell target without holes and (b) a shell with side holes (as used in the present study). Horizontal axis: 1 ns/div, vertical axis: 250 \( \mu \)m/div (Hamamatsu Photonics C4575-03).
The cross-section of the LFEX beam is \((80 \times 40)\) cm\(^2\). The LFEX emits 613 J of 1.053 µm-wavelength light in 1.5 ps. With the off-axial parabolic mirror with a focal length of 4 m (F number 10), fifty-percent of this light is focused onto a 60 µm-diameter spot, producing an intensity of \(\times 11 \times 10^9\) W cm\(^{-2}\) in vacuum. The LFEX and GXII beams are electronically synchronized (jitter < 100 ps).

Figure 3(b) shows the x-ray streak camera image XSC of the core emission without LFEX illumination. The bottom is emission trajectory. The target configuration is that of figure 1(b). Reprinted figure with permission from [23] Copyright 2015 by the American Physical Society.

4. X-ray pinhole images of LFEX-heated cores

The LFEX-heated core in 2–3 keV energy range was observed from two directions by a pair of pinhole cameras (PH01 and PH02; see figure 4(a)). Panel (b) of figure 4 displays the x-ray pinhole images without the LFEX. PH01 viewed the initial shells and the implored cores, whereas PH02 viewed the shell emissions overlapping the core. Panel (c) presents similar images to panel (b), but with illumination by the LFEX. The emission size along the GXII and LFEX axes were 360 µm FWHM and 230 µm, respectively; therefore, the LFEX absorption point is 0.6 times closer to the core than expected in a uniform implosion. On the other hand, the time-resolved core diameter was 55 ± 1 µm FWHM at maximum compression (figure 3(b)). Assuming that the imploding beams converge two \((200 \times 200 \times 7)\) µm\(^3\) shell volumes into a 55 µm-wide and 230 µm-long ellipsoidal core, we estimated that the material was compressed to at least twice its solid density (2 g cm\(^{-3}\)). However, in STAR 1D predictions, the core is compressed to 5–10 g cm\(^{-3}\), the discrepancy is attributed to the narrow width of the GXII-beam cone angle (19°), which realizes only twice the solid density under 2D expansion. STAR 1D also estimated a core radius and temperature of 35 µm and \(\sim 0.8\) keV, respectively, at the maximum compression. The pinhole images of PH02 and PH02 are replotted in panels (d) and (e) of figures 4, respectively. Here, the vertical axis (colored axis) denotes the x-ray intensity. The LFEX illumination is focused on the point indicated by the arrow in (e). Note that the peak core emission appears brighter without the LFEX ((b) or (d)) than that of with the LFEX ((c) or (e)), respectively. Why the laser illumination reduces the emissions from the heated core into the camera is not yet resolved. To investigate this phenomenon, we must observe x-ray emissions over a wider energy range.
5. Neutrons

The neutron time-of-flight (TOF) signals were detected by two gated oxygen-enriched liquid scintillators [18]. Liquid scintillator LS1 was set 13.35 m from the target at 69.13° (right-forward) to the LFEX incidence (in the horizontal direction), and liquid scintillator LS2 was set 2.5 m from the target perpendicular to the LFEX axis. To prevent γ noises, we electronically gated the photomultiplier dynode prior to the arrival of the neutron signals. Before illuminating with the LFEX, we confirmed that the neutrons were generated from the core and not from the shell. Without the LFEX, the yield was $10^5$–$10^6$ n/4π sr/shot; a yield of $7 \times 10^5$ (No. 35739) was detected by LS2. Figure 5(a) shows the TOF signals from LS1 without the LFEX, and panels (b) and (c) show the TOF signal and its energy spectrum, respectively, with the LFEX illumination. Illumination by both the GXII and LFEX produces high DD neutron yields. The solid angle and sensitivity of LS1 are 1.4 × 10⁻⁴ sr and 1 count/5.6 neutrons, respectively.

The neutron signals in (c) were fitted by a two-peak Gaussian curve:

$$\frac{dN}{dE} = 1 \times 10^7 + 9.8 \times 10^6 \exp \left(-\left[\sqrt{E} - \sqrt{3.5}\right]^2/0.01\right) + 4.9 \times 10^6 \exp \left(-\left[\sqrt{E} - \sqrt{2.5}\right]^2/0.0025\right),$$

where the energy unit is MeV. The second term on the right-hand side describes the main peak in (c), which is upshifted from 2.45 to 3.3 MeV. Although LS1 was angled at −69.13° (right-forward) from the LFEX axis, we infer that the peak at 3.3 MeV arises from beam fusion (its width $\Delta E_B$ is 0.01 MeV × ln 2 = 0.69 keV at HWHM). The third term describes the 2.5 MeV peak (with width $\Delta E_T$ of 0.0025 MeV × ln 2 = 1.7 keV at HWHM). This peak is inferred as the core temperature. Thermal neutrons were generated within a very short period before the flow started moving, or at the instant of flow movement [5]. Therefore, the core was presumed static with no residual velocity during the stagnating period. Integrating the curve from 2 to 6 MeV and normalizing by 4π sr, the yield is obtained as $(5.1 \pm 1.6) \times 10^9$ n/4π sr. The peak at 2.5 MeV corresponds to $6.4 \times 10^7$ n/4π sr (13% of the total yield), indicating the thermal neutron yields were enhanced 100-fold from $5 \times 10^5$ n/4π sr and that the core temperature has roughly doubled from 0.8 to 1.8 keV. Assuming that the core is in thermodynamic equilibrium; that is, the emission temperature is 2.8 × the plasma temperature, the x-ray pinhole emission of 2–5 keV infers a core temperature of 0.8–2 keV [19]. The total yield normalizes to $3.8 \times 10^7$ n/4π sr, of the same order of magnitude as the 2.45 MeV peak yield in the LS1 signal (figure 5(c)).

Figure 5(d) plots the 4π sr neutron yield from LS1 and LS2 as functions of the total laser energy $E$ (LFEX + GXII). No LFEX is illuminated up to 500 J. The solid (from LS1) and open (from LS2) circles indicate the neutron yields yielded by thermal fusion at around 2.45 MeV. The dashed line in (d) is the best fit to the experimental data, and is proportional to $E^3$.

The neutron yields were confirmed by STAR 1D. In this simulation, 50% of the laser energy is assumed to be absorbed by hot electrons with a 4 MeV-slope temperature and 1.3% were converted to carbon and deuterons ions under a laser intensity of $1 \times 10^{19} \text{W cm}^{-2}$. The temperature of the ions and...
bulk electrons is 1.8 keV near the surface and 1.0 keV far from the surface. Figure 5(e) plots the STAR 1D lines as functions of the LFEX intensity. Deuterons and carbons are related to the beam fusion and thermal fusion lines, respectively. The diamonds, solid and open circles are the experimental points in figure 5(d).

The data of two LFEX shots and one no-LFEX shot are listed in table 1.

6. Ion and electron emissions from the core

We positioned two CR-39 ion-track detectors, one at 20.9° (Detector (a)) and the other at 109° (Detector (b)) relative to the LFEX incidence. The signals detected at (a) traveled straight throughout the core and are shown in figure 6(a); the side signals detected at (b) are shown in figure 6(b). Both detectors were located 10 cm from the target. The counting area of each detector was 0.0227 mm², implying a detection solid angle of 2.3 × 10⁻⁶ sr. Before the LFEX arrives at the target, the GXII illumination ablates and removes the surface hydrocontamination layers. Therefore, the LFEX heats pure CD plasma, producing only hot electrons, energetic carbons and deuterons. Under the ponderomotive force of the short-pulse laser, hot electrons are driven at their critical density, dragging the ions away. The energy gain G of the ions is given by $G = (1 + a_0^2/2)^{1/2}m_eV^2$, where $a_0 = eE_L/\omega mc$ for the electron mass $m_e$ and the laser field $E_L$ of the frequency $\omega$. Deuterons below 1 MeV are rarely observed in figure 6(a), but are common in figure 6(b). Both signals detected at (a) (71 counts in figure 6(a)) and the other at 109° (Detector (b)) relative to the LFEX incidence. The signals detected at (a) and (b) (71 counts in figure 6(a) versus 231 counts in figure 6(b)). An electron detector with LS1 scintillator.

| Shot# | GXII (J) | LFEX (J) | Thermal neutrons/4π | Beam neutrons/4π |
|-------|----------|----------|---------------------|------------------|
| 35732 | 515      | 613      | 6.4 ± 1.9 × 10⁷    | 5.1 ± 1.6 × 10⁸  |
| 35737 | 501      | 410      | 4 ± 1.2 × 10⁶      | 1.6 ± 0.5 × 10⁸  |
| 35739 | 498      | 0        | 7 ± 2 × 10⁵        |                  |

*Detected with LS1 scintillator.

7. Particle-in-cell (PIC) simulations of energetic electrons and ions

Particle-in-cell (PIC) simulations predict that hot electrons spread over ~60°. In the present setup, the path to the core area is so short (100 μm), that more than a third (33%) of the hot electrons strike the core plasma and deposit their energy therein [5].

The initial density and temperature at maximum compression were determined by STAR 1D (see figures 7(a) and (b)). Next, the energetic particle generation and heating by the LFEX were verified in a 2D collisional PIC simulation (PICLS) [22], revealing the mechanism by which the bulk electrons are heated and the heat is transported to the core (figure 7(a)). At 2 ps, the bulk electron temperature in the core exceeds 1 keV. The fast-electron Ohmic current heats the deuterons to a few hundred eV at the core periphery (~1 g cm⁻³ at $x = 160 \mu m$); see figure 7(b). The collision-less shock accompanying the MeV-energy deuterons arrives at the core after the 2-ps simulation time. At 2 ps, the shock front appears approximately $x = 100 \mu m$ (figure 7(b)). The high-energy deuterons will reach the core region a few picoseconds later and deposit additional energy. Panels (c) and (d) of figure 7 show the 2D profiles of the electron energy density at 1 ps and the deuteron energy density at 2 ps, respectively. The resistive processes driven by the hot electrons and fast-ion generation might additionally heat the core on arrival.

8. Conclusion

The preimploded core of a CD shell target was heated by the direct LFEX illumination, yielding $5 \times 10^8$ DD neutrons by deuteron-beam fusion. This result verifies local heating of the core by ions. Thermonuclear neutrons are driven by energetic ions such as carbon⁶⁺. The STAR 1D results reasonably agreed with the experiments. The LFEX increased the peripheral core temperature from 0.8 to 1.8 keV. By coupling PICLS to STAR 1D, we evaluated the bulk heating and heat transport mechanism by the LFEX-driven electrons and ions. Our polar implosion scheme enhances ion heating by placing the ignition laser closer to the core than in spherical implosion schemes.

Whereas the hot electrons heat the whole core volume, the energetic ions locally deposit their heat into ignition spots. However, as the core density is limited to 2 g cm⁻³, the deuterons will be stopped by the core plasma.
in the current experiment, neither hot electrons nor fast ions can efficiently deposit their energy, so the neutron yield remains low. At higher core densities (>10 g cm⁻³), hot electrons could contribute more to the core heating by drag heating. Additionally, a higher power laser (e.g. 10²⁰ W cm⁻²) would increase the energy carried by the fast ions, largely increasing the ion contribution. Part of this manuscript is published in [23].

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References

[1] Lindl J.D. 1998 *Inertial Confinement Fusion, The Quest for Ignition, Energy Gain Using Indirect Drive* (New York: Springer)

[2] Tabak M. et al 1994 *Phys. Plasmas* **1** 1626

[3] Kitagawa Y. 2001 43rd APS DPP meeting (Long Beach, California) invited QI2.006

[4] Kitagawa Y. et al 2004 *IEEE J. Quantum Electron.* **40** 281

[5] Kitagawa Y. et al 2005 *Phys. Rev. E* **71** 016403

[6] Atzeni S., Meyer-ter-Vehn J. 2004 *The Physics for Inertial Fusion, Beam Plasma Interaction, Hydrodynamics, Hot Dense Matter* (New York: Oxford Science Publications)

[7] Sentoku Y. et al 2004 *Phys. Plasmas* **11** 3083

[8] Jung R. et al 2005 *Phys. Rev. Lett.* **94** 195001

[9] Lei A.L. et al 2006 *Phys. Rev. Lett.* **96** 255006

[10] Naumova N. et al 2009 *Phys. Rev. Lett.* **102** 025002

[11] Kitagawa Y. et al 2012 *Phys. Rev. Lett.* **108** 155001

[12] Norreys P. et al 2014 *Nucl. Fusion* **54** 054004

[13] Robinson A.P.L. et al 2015 *Plasma Phys. Control. Fusion* **57** 064004

[14] Sentoku Y. et al 2011 *Phys. Rev. Lett.* **107** 135005

[15] Mori Y. et al 2016 *Phys. Rev. Lett.* **117** 055001

[16] Strozzi D.J. et al 2012 *Phys. Plasmas* **19** 072711

[17] Sunahara A. et al 2008 *Plasma Fusion Res.* **3** 043

[18] Arikawa Y. et al 2012 *Rev. Sci. Instrum.* **83** 10D909

[19] Zel’dovich Y.B. and Raizer Y.P. 1967 *Physics of Shock Waves and High-temperature Hydrodynamic Phenomena* vol I (New York: Academic) p 116

[20] Sentoku Y. et al 2002 *Appl. Phys. B* **74** 207

[21] Wilks S.C. and Kruer W.L. 1997 *IEEE J. Quantum Electron.* **33** 1964

[22] Sentoku Y. and Kemp A.J. 2008 *J. Comput. Phys.* **227** 6846

[23] Kitagawa Y. et al 2015 *Phys. Rev. Lett.* **114** 195002