Demonstration of direct fast heating of counter-imploded core plasma by LFEX laser

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abstract

This study investigates the heating efficiency of the fast heating when the imploded core is directly illuminated with an ultraintense laser. Heating efficiency is defined as an increment of internal core energy divided by a heating laser energy on target. Six counterbeams of the GEKKO XII (GXII) green laser at the Institute of Laser Engineering (ILE), Osaka University, of which the output was 1.6 kJ, imploded a spherical CD (Deuterated polystyrene) shell target of 500 μm in diameter and formed a dense core. DD-reacted protons and the x-ray core emissions showed a core density of $2.8 \sim 2.7\,\mathrm{g/cm^3}$. DD thermal neutrons were used to estimate the core temperature determined as $650 \sim 750\,\mathrm{eV}$. The mixing of "beam-fusion" neutrons makes difficult to analyze the neutron energy spectra. The core was then directly heated by a laser for fast-ignition experiments (LFEX), which is an extremely energetic ultrashort pulse laser at the ILE either with its axis lying to the GXII bundle axis, which we call "Axial mode", or with its axis perpendicular to the GXII bundle axis, which we call "Transverse mode". η is 2% or less for Axial mode and 5% or less for Transverse mode. The efficiencies were compared to that of a uniform implosion mode, which is 3%.

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 be achieved[2].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 [3].

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. 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 ^3He (α 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.

The self-ignition fusion scheme must concentrate the centrifugal shock waves to ignite a central hot spark. For this purpose, it requires a 4π 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. We have proposed a counter illumination fusion reactor, named CANDY, whose whole and chamber images are in Figs.1(a) and (b)[4].

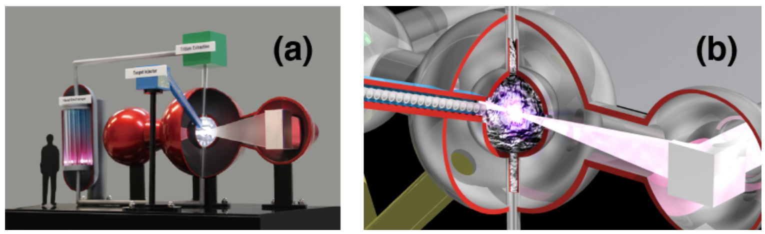

Figure 1: (a) Image of the Counter implosion fast ignition reactor CANDY. (b) Reactor chamber of CANDY[Movie:CANDY2015-English-0505-MPEG-4-1080-12000Kbps].

For the fast ignition fusion, the direct illumination of an ultraintense laser onto the imploded core is the simplest technical and economical way.

We began the fast heating studies with the Peta-Watt-Module laser (90J/0.8 ps)(2001)[5], which enhanced the thermal neutrons by a factor of 1.7 ($7\times10^5/4\pi$ sr). The subsequent Peta-Watt Laser (190J/0.7 ps)(2004)[6] further enhanced the thermal neutron yield (by a factor of 5, or 4×10^6 n/4π sr) [7].

However, 2D simulations and experiments suggested that the hot electrons diverge, thereby heating the whole core area rather than a local region [8, 9, 10]. To demonstrate the feasibility of direct core heating, we used LFEX, which directly heated a CD shell target, imploded by GXII laser. Recently we have reported the LFEX direct heating[11].

In this paper, we compare the heating efficiency between two experiments with two different illumination configurations, as shown in Figs. 2(a) and (b). Figure 2(a) mode is similar to the laser configuration in CANDY and will be the simplest one, but the cutoff point is far from the core and much plasma clouds block the hot electron and ion transports[7].(b) mode, the same configuration as published in [11, 12],may not be so simple in the scheme of power plant, but the cutoff point is close to the core and there is less cloud plasmas, blocking the transport[11, 12].

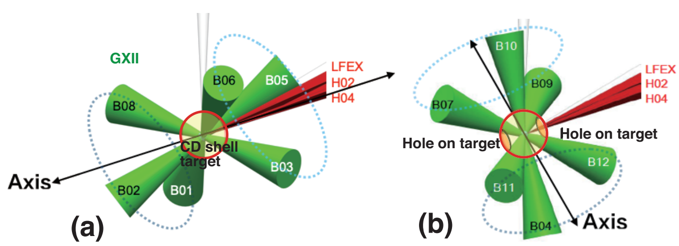

Figure 2: GXII 6beams(Green) and LFEX(Red): (a) Axial mode, where three GXII beams come from the left and the another three come for the other side and LFEX is lying to the x axis(bundle axis). Each GXII beam(F/3) makes 37° to x axis and are tangentially focused onto the target. Dotted circles show three adjacent beams groups. (b) Transverse mode, LFEX is lying perpendicular to the x axis(bundle axis). Three adjacent GXII beams are concentrated each other on a cone with the cone angle of 11°. The cone axis is on x axis.

2 Experimental setup and Core plasma

Counter 6 beams of 1.6 kJ from the GEKKO XII laser of 0.527 μm-wavelength and 1.3 ns-3rd order-super-Gaussian pulse have imploded a deuterated polystyrene (CD) spherical shell target of 500 μm in diameter and 7 μm in thickness. d/R (ratio of the shell radius R to the focal distance d) is -3. The total output energy was 1.64 ± 63 kJ, LFEX laser (wavelength 1.05 μm, pulse width 1.5 ps, out put 0.36 to 1.3 kJ) is directly focused to the core center(F/10) to heat the core. The intensity on target is $0.5 \sim 1 \times 10^{19}$ W/cm^2. CD target: diameter 500 μm, thickness 7 μm. For Transverse mode, target has two 100 μm diameter holes, of which one as a window for LFEX and another for x-ray detectors[11, 12].

The axial and transverse mode implosions form a different core shapes. A two dimensional hydro code "Star2D-Arbitrary-Lagrange-Euler hydro code (Star-2D-ALE)" was developed and simulated both the axial and transverse mode implosions without LFEX[13].Figures 3 draw (a) temporal-integrated image of self-emission x-rays using a post processor for ray-tracing for Axial mode and (b) for Transverse mode. The target used in (a) is a simple CD shell sphere and the maximum compression time is at 2.83 ns (+330 ps after the GXII peak). Electron temperature Te is ~ 800 eV, mass density ρ is ~ 2 g/cm^3 and DD neutron yield $Yn = 2.63 \times 10^5/4\pi$ sr. Target of (b) is with two holes[12]. The maximum compression is at 2.86 ns (+360 ps after the GXII peak). Te is $600 \sim 700$ eV, ρ is ~ 3 g/cm^3 and $Yn = 4.2 \times 10^5/4\pi$ sr.

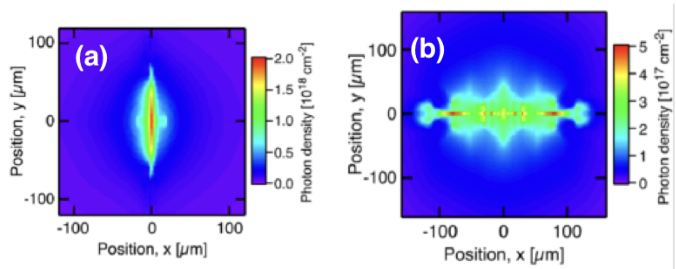

Figure 3: 2DSTAR-ALE simulation of GXII counter beams implosion at the maximum compression timing: (a) Temporal-integrated image of self-emission x-rays using a post processor for ray-tracing for Axial mode at 2.83 ns. Target is a simple CD shell. (b) Transverse mode at 2.86 ns. Target is a CD shell with two holes of 100 μm diameter. The GXII peak is at 2.50 ns.

X-ray pinhole emission in Fig. 4 (a) shows an elliptical shape, similar to 2DSTAR-ALE simulation for Axial mode (Fig. 3 (a)). For Transverse mode, the emission in Fig. 4 (b) is an ellipse, similar to the simulation of Fig. 3 (b). Figure 4 (c) shows that the GXII laser peak at 1.79 ns and x-ray emission peak at 2.0 ns, which, we think, is the maximum compression timing[13]. Protons, generated at the core center derived from DD ($d(d,n)^3He$) reaction, down shift their energy from 3.02 MeV on the way through the core. The down shift is proportional to the areal density of the proton flight path. So that to measure areal density ρr of the imploded core, we have set two CR-39 proton track detectors to x and y directions, which measured the down shifted energy spectra without LFEX illumination[14].For Axial mode, white columns in Fig. 5 shows the peak shift from 3.02 MeV to 750 keV along y-direction, which yields the core areal density of 0.016 g/cm^2. Striped columns lying to x-direction show the peak shift to 1500 keV, which yields the core areal density of 0.011 g/cm^2[15].Using the radii from Fig.4(a), $x = 37\,\mu$m and volume $V = 3.2 \times 10^{-7}$cm^3, the areal densities yield density ρ of 2.8 ± 0.4 g/cm^3 to x direction. $y = 56\,\mu$m yields 2.7 ± 0.3 g/cm^3 to y direction.

The CD core consists of deuteron and carbon ions, of which the ion number density n_i is 2.3×10^{23} /cm^3. Since the core temperature is high enough for full ionizing, Z_{CD} is supposed to be 3.5, leading to the electron number density $n_e = Z_{CD} n_i = 1 \times 10^{24}$ /cm^3.

A neutron scintillator array "MANDALA" counted the 2.45 MeV neutron yield Yn to be $3.47 \times 10^6/4\pi$sr, as in Fig. 6(a)[16, 17]. Thermal neutron yield Yn is given by $Yn = \left(\frac{n_i}{4}\right)^2 < \sigma v >V\tau$, where $< \sigma v >$ is

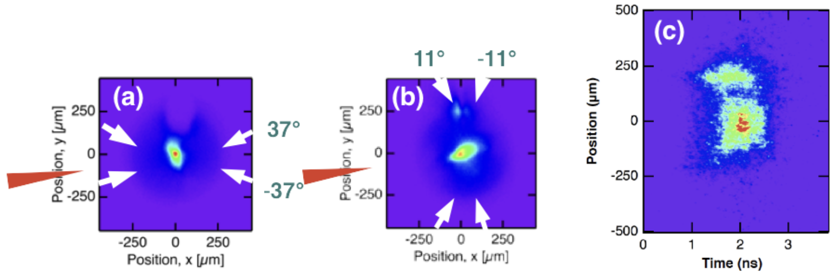

Figure 4: X-ray pinhole camera images from the imploded core: (a) Axial mode, where three GXII beams come from the left and the another three come for the other side and LFEX is lying to the x axis(bundle axis). Core size: x = 37μm and y = 56 μm. (b) Transverse mode, LFEX is lying perpendicular to the x axis(bundle axis). Core size: x = 81μm and y = 32 μm. GXII (white arrows): pulse shape 1.1 ns, 1.64 ± 63 kJ, Dotted circles show three adjacent beams groups. Each beam(F/3) makes 37° to x axis and are tangentially focused onto the target. LFEX (red arrow): wavelength 1.05 μm, pulse width 1.5 ps, 245 ± 12 J on target. F/10. The intensity on target is $0.5 \sim 1 \times 10^{19}$ W/cm^2. CD target: diameter 500 μm, thickness 7 μm. (c) X-ray streak photograph of the CD shell implosion without LFEX($\sharp 24T1\#42476$). $\sharp$ is the shot number, # is the serial number from the first light of GXII. The GXII laser peak time is 1.79 ns. Temporal resolution is 40 ps[13].

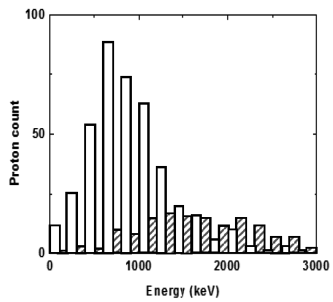

Figure 5: DD reacted-proton spectrum without LFEX from a track detector of 0.4 mm×0.6 mm-square CR-39 films, positioned 5 cm far from the target. DD reaction has two branches, one of which yields n (2.45 MeV). Here, we use the another branch, yielding p (3.02 MeV). White columns are spectra shifted from 3.02 MeV along the transverse direction and striped are shifted to the axial direction, respectively[15, 14, 15].

a thermal fusion reactivity, that is a fusion cross section-velocity product, averaged over Maxwell distribution, and τ is burning time ($\leq$ stagnation duration). The spectrum broadening in Fig.6(a) gives the ion temperature $T_0 \leq 0.8 \sim 1.0$ keV and $\tau \approx 40$ ps. The above n_i, V, and Yn values lead to $T_0 \sim 0.75$ keV. τ can be written as $R/4C_s$, which is now 44 ps, using $T_0 = 0.75$ keV. C_s is a sound velocity. Here we estimate the core internal energy $E_{int} = 3/2n(Z_{CD}+1)T_0V = 60 \pm 9$ J.

3 Axial mode heating

Since LFEX illumination generates a large number of hot electrons on the path through a peripheral plasma, drawing energetic ions into the core. A part of ions heat directly the core plasma, and a part of deuterons collide and react directly with core ions, yielding beam-fusion neutrons, which are shown as spectra spread from 1 MeV to 5 MeV in Figs.6(b), (c). Since as in (b), (c), the beam-fusion neutrons make it difficult to distinguish the 2.45 MeV thermal neutrons. When the LFEX output was increased to 779 J, as shown in Figs.6(e), the 2.45 MeV neutron yield was enhanced to $8 \times 10^6/4\pi$sr. We call this "High power mode".

Figure 7(a) shows the core is heated just when LFEX illumination meets the maximum compression of the core at +200 ps. While, LFEX at + 600 ps shows no apparent heating feature. The emission peak in (a) is $\geq$1.3 times as large as that of (b). Figure 7(d) is the pinhole camera image of the best core emission

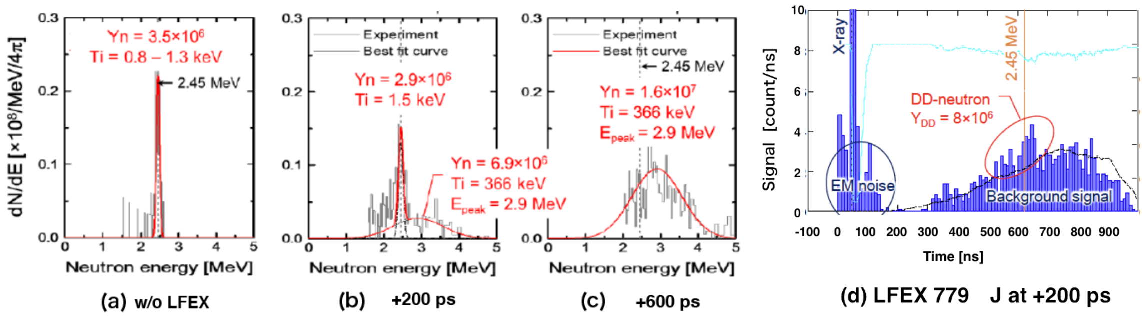

Figure 6: Neutron energy spectra from MANDALA (a) w/o LFEX ♯25T7#42488, $Yn = 3.47 \times 10^6/4\pi$sr and $T_i \leq$1 keV for GXII energy of 1.65 kJ and (b) with LFEX of 261 J at +200 ps ♯24T3#42478, (c) with LFEX of 336 J +600 ps ♯24T2#42477. (d) Neutron time-of-flight signal with LFEX of 779 J +200 ps ♯4T1#43283 (at High power mode). $Yn = 8 \times 10^6/4\pi$sr. [16, 17]

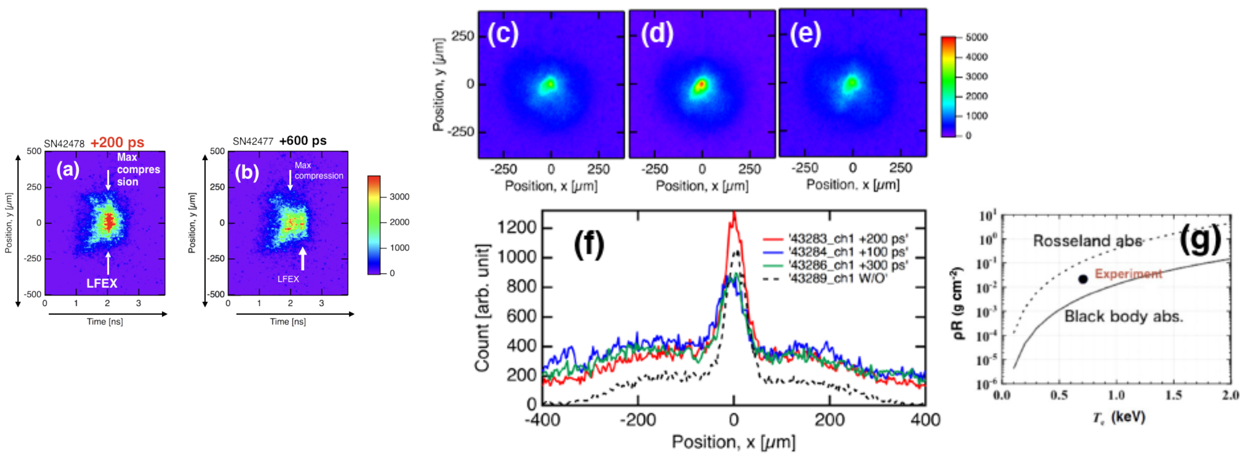

Figure 7: X-ray streak image of LFEX heated core (a) at +200 ps and (b) at +600 ps after the GXII pulse peak. Timing jitter is 100 ps. X-ray pinhole images of core (c) for LFEX 890 J at +100 ps, GXII 1.34 kJ (♯4T2#43284), (d) LFEX 779 J at +200 ps, GXII 1.42 kJ (♯4T1#43283), (e) LFEX 898 J at +300 ps, GXII 1.31 kJ (♯4T4#43286); (f) x-axis scanned data from (c), (d), and (e). The shot ♯24T1#42476 is without LFEX: dashed line from (c), red solid line from (d), and green line from (e)[13]. (g) Planck absorption and Rosseland mean-free-paths as a function of T_e. Solid point is from the experimental data, written by ρR[8, 19].

at +200 ps (at High power mode), of which the intensity is 1.1 times as larger than either(c) at +100 ps or (e) at +300 ps. (c), (d) and (e) intensities are scanned along x axis in (f). In Fig. 7(g) is plotted the core ρR-T$_e$ point, as well as Rosseland and Plank absorption mean free paths. From this figure, we supposed the core emissions in (c), (d), and (e) are in black body equilibrium[8, 19].So we assume the core temperature increment derived from LFEX heating is proportional to 1/4 power of the emission ratio, which gives us the temperature increment $\Delta T = (1.1^{1/4} - 1)T_0 = 20 \pm 5$ eV, leading to the internal energy increment $\Delta E = (1.1^{1/4} - 1)E_{int} = 1.5 \pm 0.2$ J.

We here define the heating efficiency η to be an internal energy increment divided by LFEX on-target energy, so that for Axial mode (#43283 at High power mode) yields η be 1.5/779 = 0.2 %. The neutron enhancement of 6 times (as in Fig. 6 (d)) yields $\Delta T = 200 \pm 40$ eV and $\Delta E = 15 \pm 3$ J, and $\eta = 15/779 = 1.9 \pm 0.4$ % at High power mode. At 261 J (Low power #42478), the emission enhancement was < 1.1, resulting in ΔE /LFEX $< 1.5/261 = 0.6$ %.

We put three electron spectro-meters "ESM" at 0°, 21° and 70°, respectively. ESM, consisting of a CR-39 film and a dipole magnet, detected the runaway hot electrons from the target. Figure 8(a) shows it is strongest to 0° direction. Figure 8(b) shows a slope temperature of 8.7 MeV to 0°. Core plasmas of $\rho R = 0.016\,\mathrm{g/cm^2}$ absorb hot electrons of energy less than 0.1 MeV, where electron energy range is approximated by $\rho R = 407E^{1.38}\,\mathrm{g/cm^2}$ for $E < 0.8[E$ in MeV][18].

Moreover, supposing 75% of LFEX energy on target is transported to hot electrons, an absorbed electrons will be $0.1/8.7 \times 779 \times 0.75 = 6.7$ J. Then η is 0.9 %, derived from hot electrons at High power mode.

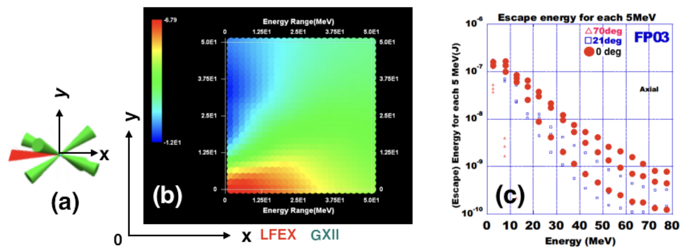

Figure 8: (a) Map direction: LFEX is on x-axis, GXIIs are up and down to y-axis (♯4T4#43286). (b) Runaway electron distribution. (c) Electron spectum:solid circle is 0°, square 21°, and triangle 70°to x-axis. LFEX 779 J +200 ps (♯4T1#43283 High power mode) and GXII 1.44 kJ,

4 Transverse mode heating

We assume the imploded core density and temperature w/o LFEX heating are as same as those of Axial mode.

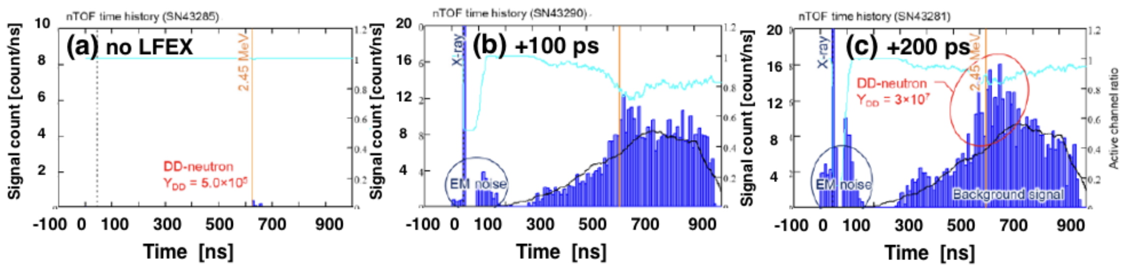

Figure 9: (a) No LFEX(♯4T3#43285) GXII 1.33 kJ, $Yn = 5.0 \times 10^5/4\pi$sr, (b) LFEX 816 J +100 ps (♯5T4#43290) GXII 1.43 kJ, $Yn = 3.7 \times 10^7/4\pi$sr, and (c) LFEX 794 J +200 ps (♯3T4#43281) GXII 1.44 kJ, $Yn = 3 \times 10^7/4\pi$sr.

Yn without LFEX for Transverse mode is $5 \times 10^5/4\pi$sr, as in Fig. 9 (a), leads to the core temperature $T_0 = 650$ eV and $E_{int} = 50$ J. From Fig. 9 (b) or (c), LFEX seems to enhance Yn to 60 times as large as that of (a), which may lead to ΔT of $(60^{1/5.5} - 1)T_0 = T_0$ and $\Delta E = 45$ J. Thus the neutron enhancement leads to $\eta = 45/832 = 5.4 \pm 0.3\,\%$ at High power mode. As seen from Figs. 9 (b) and (c), however, LFEX derives much background signals derived from beam fusion neutrons, which make difficult to estimate the thermal neutron yield.

The core x-ray emission of Fig. 10 (c) is 2 times as large as (a), which leads to $\Delta T = (2^{1/4} - 1)T_0 = 0.2T_0 = 120$ eV and $\Delta E = 10$ J. Thus the x-ray emission enhancement leads to $\eta = 10/832 = 1.2\,\%$, a fifth of that from neutron. At 342 J (-200 ps ♯25T2#42483), although the timing is 200 ps earlier than GXII peak, nevertheless emission enhancement is not zero or η not 0 %,. The above discussions seem to lead to that the efficiency of Transverse mode is higher than Axial mode at High power.

The runaway hot electrons from the target for Transverse mode is strongest to 21° direction shown in Fig. 11(a). Figure11(b) shows the electron spectrum to 21° has a slope temperature of 0.7 MeV. Core plasmas of $\rho R = 0.011\,\mathrm{g/cm^2}$ absorb hot electrons of energy less than 0.075 MeV. Moreover, supposing 75% of LFEX energy on target is transported to hot electrons, an absorbed energy will be $0.075/0.7 \times 794 \times 0.75 = 72$ J. Then η derived from hot electrons is 9.9 % at High power.

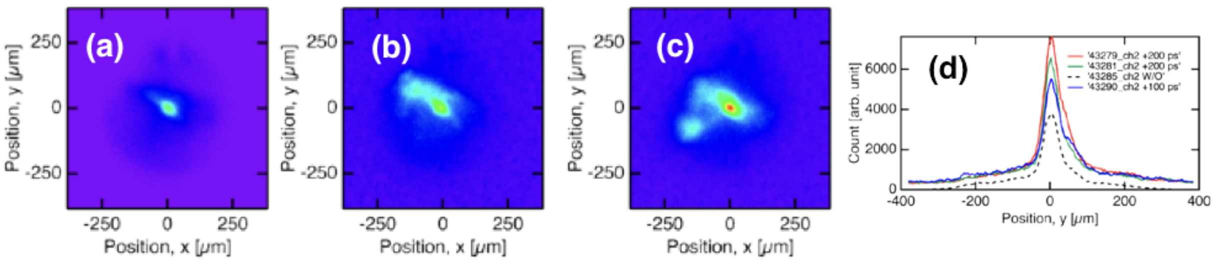

Figure 10: X-ray pinhole images of core (a)w/o LFEX, GXII 1.33 kJ (♯4T3#43285), (b) LFEX 816 J at +100 ps, GXII 1.44 kJ (♯5T4#43290), (c) LFEX 887 J at +200 ps, GXII 1.37 kJ (♯3T2#43279); (d) x-axis scanned (a) dashed line, (b) blue line, and (c) red line.

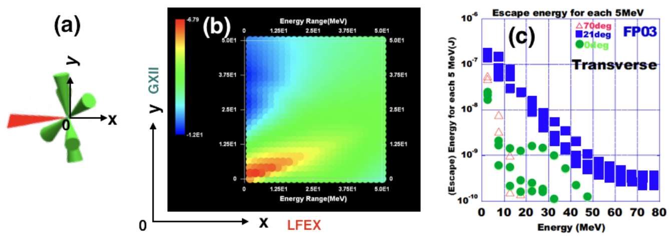

Figure 11: (a) Map direction: LFEX is on x-axis, GXIIs are up and down to y-axis(♯5T4#43290). (b) Runaway electron distribution. (c) Electron spectrum: square is 21°, solid point 21°, and triangle 70° to x-axis, respectively. LFEX 794 J +200 ps (♯3T4#43281 at High power) and GXII 1.44 kJ,

5 Uniformly heating mode and discussions

We have applied the same procedure to get η to the previous uniform implosion experiment using 12 beams from GXII and PW heating laser in 2005 [7]. PW laser is another ultra-intense laser of 190 J/ 0.6 ps pulse. The paper shows that $Yn = 1 \times 10^6/4\pi$ sr at GXII of1.8 kJ, which gives T_0 of 700 eV. PW laser of 190 J enhanced the core emission to 4 times as large as that without PW, leading to temperature enhancement to1.4 times. The core internal energy was as well increased from 19 J to 27 J, resulting in $\eta = 3.9\,\%$. Thermal neutron enhancement was also 4 times, which leads to 1.3 times temperature enhancement. and $\eta = 3.0\,\%$.

Table 1 summarizes η's, obtained from x-ray core emissions, thermal neutrons, and runaway hot electrons. Take note to the following points: So far since both the data show a similar feature, we conclude that η is larger than 1 %, but less than 10 %[20, 21].Since laser-plasma interactions are same both for Axial and uniform modes, we can include the uniform mode to Axial mode. Then, Table 1 seems to say that η for Axial mode decreases as increasing LFEX output. η for Transverse mode is larger than Axial mode and increases as increasing LFEX output.

Table 1: η from x-ray, neutron, and hot electron, respectively.

Mode	shot number	GXII	LFEX	η from x-ray	neutron	hot electron
Uniform	[7]	1870 J	190 J	3.9 %	3.0 %	-
Axial	♯24T3#42478	1657 J	261 J	< 0.6 %	-	2.1 %
Axial	♯4T1#43283 High power	1428 J	779 J	0.2 %	1.9 %	0.9 %
Transverse	♯25T2#42483	1740 J	342 J	> 0 %	-	6.4 %
Transverse	♯3T2#43279 High power	1378 J	887 J	1.2 %	5.4 %	9.9 %

(♯ is the shot number, and # is the serial number from the first light of GXII.)

6 Conclusion

The heating efficiency η of the fast heating was investigated, when the imploded core is directly illuminated with an ultraintense laser. η is 2% or less for Axial mode and 5% or less for Transverse mode. η is large for Transverse at high LFEX power.

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