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

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A world-class ultraintense laser LFEX at ILE, Osaka University directly heated a CD shell target, imploded by GEKKO XII(GXII) laser. Illuminating LFEX energy of 246 J increased the core internal energy by 23 ± 3 J, leading to the conclusion that the heating efficiency is 9 ± 0.8 %. The results encourage the fast ignition scheme fusion as a hopeful candidate of the fusion machine.

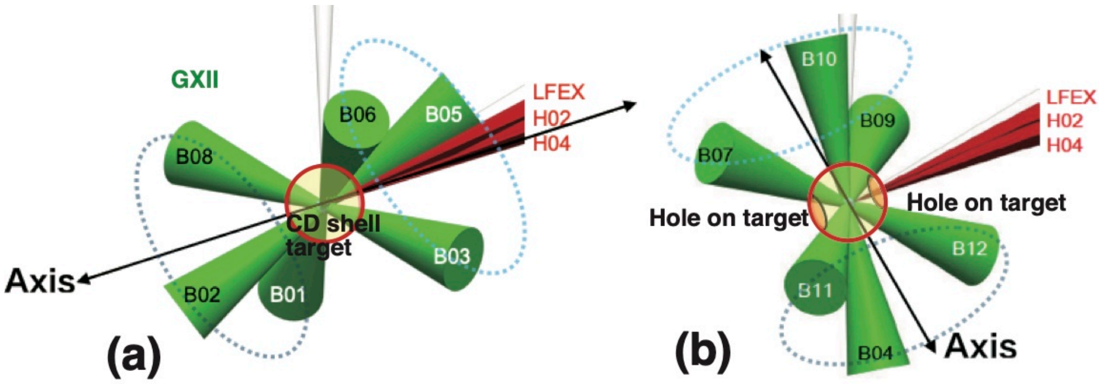

Figure 1: (a) LFEX(red) is coaxial to GXII (green) symmetric axis. Deuterated polystylene (CD) target(red circle) is without holes on shell. (b) LFEX is transverse. In (b), two 100 μm holes on shell, one for guiding LFEX and another for observing core emissions. GXII: wavelength 0.53 μm, pulse shape 1.1 ns-Gaussian, 1.7 kJ. Dotted circles show three adjacent beams groups. LFEX: wavelength 1.05μm, pulse width 1.5 ps, 360 to 780 J on target.CD target: diameter 500μm, thickness 7μm.

For the fast ignition fusion[ref1], the direct illumination of an ultraintense laser onto the core is the simplest technical and economical way. To demonstrate the feasibility of direct core heating, we have performed experiments with difficult illumination configurations, such that (a) LFEX is coaxial to the GXII bundled beams axis (Fig. 1(a)), and (b) LFEX is transverse to the axis (Fig.1(b)). (a) mode will be the simplest scheme, but the cutoff point is far from the core and much plasma clouds may block the hot electron and ion transports[ref2]. (b) mode may not be so simple to operate the power plant, but the cutoff point is close to the core and there are less cloud plasmas, which block the transport[ref3]. However, because the transverse mode results are not yet confirmed, we concentrate to the axial (a) mode. Counter illuminating 6 beams from the GXII has imploded a CD shell target. Ratio of shell radius R to focal distance d/R is -3. LFEX laser is directly focused to the core center.
The intensity on target is $0.5 \sim 1 \times 10^{19}$ W/cm^2. We have estimated the LFEX fast heating efficiency from the following procedures.

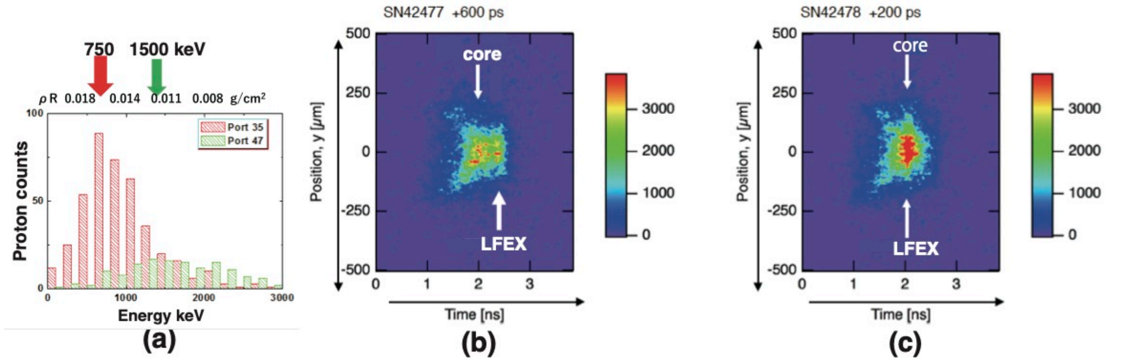

Figure 2: a) DD reacted-proton tracks without LFEX on 0.4 mm$\times$0.6 mm-square CR-39 films 5 cm far from the target[ref4]. DD reaction has two branches, one of which is D+D $\longrightarrow$ n(2.45 MeV)+ H^3(0.82 MeV)(50 %). Here, we use the another branch, D+D $\longrightarrow$ p(3.02 MeV)+ T(1.01 MeV)(50 %). Red columns and arrow are spectral shifts and their peak along the transverse direction. Green to the axial direction, respectively. (b) X-ray streak images of shell flow. y axis is space. Shell center is at 0 μm. x axis is time. GXII peak is at 1.8 ns. The core emission is +200 ps later(upper arrow),and LFEX is +600 ps(lower arrow). (c) LFEX is at +200 ps, just at the core emission timing, showing the best compression. Timing jitter is ± 100 ps.

Without LFEX illumination, Fig. 2(a) shows a DD reacted proton energy peak (3.02 MeV) shift down to 750 keV (red arrow in Fig.2 (a)) due to the core plasma, yields an areal density of 0.016 g/cm^2 along the transverse direction. Peak shift to 1500 keV (green arrow in Fig. 2 (a)) yields 0.011 g/cm^2 to the axial direction[ref4]. Considering an ellipsoidal core figure, these results lead us to the core density $\rho = 2.8 \pm 0.3$ g/cm^3 and volume $V = 3.2 \times 10^{-7}$ cm^3.

An x-ray streak camera, in Fig. 2 (b), shows both the core emissions due to the implosion +200 ps after the GXII peak and the LFEX heating +600 ps after. The intensity of core emission here is same as that without LFEX, but once LFEX is just on the compression, as in Fig. 2 (c), the core emission becomes $\sim$20 times stronger than the emissions without LFEX. The stagnation period τ, within which the maximum compression continues, ≤ 50 ps. We assume that the neutron generation period is also close to τ.

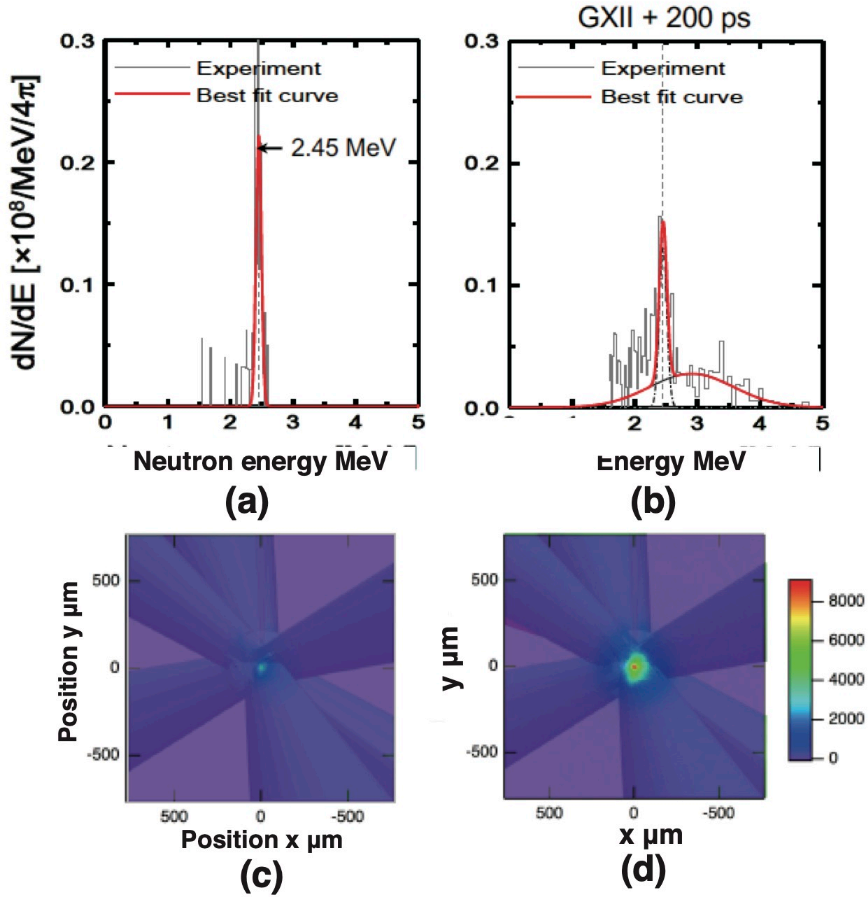

Figure 3: (a) Neutron TOF signals from MANDALA (Multichannel single-hit neutron scintillation detector array[ref2]) without LFEX: $N_y = 3.5 \times 10^6/4\pi$, and (b) signals with LFEX of 246 J: Total Ny = $9.8 \times 10^6/4\pi$; Red curves are the best fitted spectra. (c) X-ray core emission from a pinhole camera corresponding to (a). (d) X-ray core emission corresponding to (b). Emission peak(d) is 4 times larger than (c).

3.5×10^6 neutron yields(Ny) without LFEX illumination in Fig.3 (a) gives us the ion temperature T_i to be 700 eV, if we assume $Ny = n_i^2/4 < \sigma v >_{Ti} V\tau$. While, with LFEX at +200 ps, Ny of Fig.3 (b), 9.8×10^6 gives T_i ~1.0 keV. The ion temperature increment ΔT_i is 0.3 ~ 0.4 T_i, or ~300 eV.Supposing $T_i \sim T_e$ in equilibrium, then $\Delta T_e \sim \Delta T_i \sim 300$ eV with LFEX. The intensity of x-ray emission of the core (Fig.3(d)) is 4 times larger than the Fig.3 (c), leading to the electron temperature increment ΔT_e is ($4^{1/4}$-1)$T_e = 0.4 T_e$, if the core is yet in equilibrium. The increment of core energy is given by $\Delta E = \Delta E_e + \Delta E_i = 3/2(n_e \Delta T_e + n_i \Delta T_i)V$, where ΔE_e and ΔE_i are the electron and ion contributions, respectively. Assuming the core plasma is fully ionized, then $n_e = Z_{CD} n_i$, where Z_{CD} is total charges of a CD ion and also using $\Delta T_e \sim \Delta T_i$, we could estimate ΔE= $3/2 V \Delta T_i n_i (Z_{CD} + 1)$= 23 ± 3 J. Since the LFEX energy is 246 J, we expect the heating efficiency to be 9 ± 0.8 % for the axial mode. Without LFEX, the implosion efficiency, defined as a core internal energy divided by an implosion laser energy (now GXII), is $53 \pm 7\text{J}/1.7\text{kJ} = 3.1 \pm 7$ %. With LFEX, we can estimate that the total implosion efficiency is improved to 85 J/1946 J = 4.4 %.

We will discuss the transverse mode later on.

[References]

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