Hot electron spectra on advanced targets in FIREX

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Abstract. The traditional fast ignition scheme is that a compressed core created by an imploding laser is auxiliary heated and ignited by the hot electrons (produced by a short pulse laser guided through the cone and guided under-dense plasma). However sufficient heating has not be achieved because the hot electron energy is too high and dissipated in the cone, the angular divergence of the hot electron is too large, and the distance from the generation point to the core is too long. Here we clarify the problems of fast ignition by observation of the hot-electron spectra.

1. Introduction

Fast ignition (FI)$^{1,2}$ will be performed to heat an imploded core which is created by an imploding laser, by hot electrons (optimum energy of 2 MeV)$^3$. The hot electrons are produced by the interaction between a chirped ultra-short pulse laser (heating laser) and the pre-formed plasma created by the pre-pulse of the heating laser at the tip of a guiding cone. If the scale length $L$ of the plasma density is long, the effective electron temperature $T_{\text{eff}}$ (=slope of the electron spectrum) is too high and the coupling efficiency $\eta_i$ is reduced because the electron passes through the core with small energy deposition. When $T_{\text{eff}}$ is too high, the amount of the lower energy electrons is reduced because the laser energy is used for energetic electron production. At the same time, when the scale length $L$ is long, the distance between the core and the hot electron source point: $S$ is long. Therefore the distance between the core and the hot electron generation point, $S$ becomes long. It is one of the key issues that $T_{\text{eff}}$ remains low with the higher conversion efficiency from the laser to the hot electrons.

The total coupling efficiency: $\eta$ is the product of the conversion efficiency and the irradiation efficiency $\eta_i$. $\eta_i$ is determined by the conversion efficiency from the laser to the hot electrons, the transparency in cone, the irradiation efficiency $\eta_i$ to the core and the energy deposition in the core. However in the most experiments a little energy of the hot electrons can be deposited because the hot electron energy is too high against an areal density $\rho R$ of the core. It is important to decrease $T_{\text{eff}}$ in order to increase $\eta_i$. To obtain a high ion temperature $T_i$, the fuel amount should be tuned.
The hot-electron spectrum can be approximated by two or more Gaussian distributions. Although the higher energy component of the Gaussian spectrum has a small contribution to heating, the lower energy component has been thought to play a heating role. It is difficult to measure the lower component using an electron spectrometer (ESM). The heating by the lower component may not be larger than that we expect. Here we conservatively consider $\eta_c$ and $T_i$ using the spectra with one Gaussian approximation which is determined by ESM4.

2. Comparison of $T_{\text{eff}}$ in various targets

The LFEX laser (two beams, 1.053 $\mu$m) has an energy from 500 J to 1.6 kJ and the pulse width of 1.5 ps in the experiments. The energy of 82 % is focused at the focal spot size (50%) of 40 $\mu$m. Gekko XII (9-12 beams, 250 J/beam, 0.53 $\mu$m) is used for implosion of the deuterated polystyrene shell (500 $\mu$m, 7 $\mu$m-thickness). The neutron yield is measured by the MANDALA and three liquid scintillation detectors. Back ground neutrons caused by $\gamma n$ reaction are remarkably increased over the LFEX energy of 500 J. $\gamma n$ neutrons are shielded by polyethylene blocks. The LFEX laser-plasma interaction position is monitored by the X-ray streak camera.

$T_{\text{eff}}$ in plain, cone and integrated targets are compared. LFEX laser has a pre-pulse of about 1 ns with the contrast of about $10^8$. The pre-pulse creates a pre-formed plasma. According to Phukov scaling5, $T_{\text{eff}}$ is determined by $L$ as follows;

$$T_{\text{eff}} = \frac{\alpha}{3.546} \left(\frac{I}{I_{18}}\right)^{\frac{3}{2}} \left(2.465L^\frac{1}{2} - 2.223\right), \tag{1}$$

where $I/I_{18}$ is the laser intensity (W/cm$^2$) normalized by $10^{18}$, $\alpha$ is the coefficient factor of 1.5 MeV, respectively. Figure 1 shows the laser intensity dependence of $T_{\text{eff}}$. Generally $T_{\text{eff}}$ in high-Z material is small because $L$ is short due to the heavy mass. Therefore in low-Z material as a diamond-like-carbon (DLC), we use Au coating. In the conical target, higher $T_{\text{eff}}$ is observed than $T_{\text{eff}}$ in the plain. The plasmas produced by the irradiation of the inner wall of the cone, gather to the laser axis. As the result, $L$ may be extended.

In the integrated experiment, we use three different targets, an Au cone shell, a DLC cone shell and a hole-cone shell. In the latest experiment, $T_{\text{eff}}$ of 5 keV in the DLC cone shell and 6 keV in Au cone shell can be observed. Those values correspond with $L$ of 15-30 $\mu$m according to Phukov scaling. The geometrical effect of the cone may be larger than effects caused through implosion because $T_{\text{eff}}$ in integrated targets are almost similar to $T_{\text{eff}}$ in cone targets or slightly higher.

3. Estimation of the energy deposition in the integrated experiment

The energy deposition in the core can be estimated using the hot electron spectra in the experiment. The conversion efficiency from the laser to the hot electrons (forward direction) can be estimate from the experimental results by Zhang7 and the computer simulation as a function of the laser intensity. The spectrum observed in Section 2 is used in this calculation. The interaction point between the laser and the hot electrons is assumed to be $L$ (defined in equation (1)) in front of the cone tip. The deposition of the hot electrons in the cone and the core is approximated by the energy deposition in the
cold materials of a single electron because the electron temperature of the core plasma is small enough. The classical deposition range \( R_a \) (g/cm\(^2\)) is determined by the hot electron energy \( E \) (MeV) as follows;

\[
R_a = 0.542E - 0.133, \quad (E = 0.8 - 8 \text{MeV}), \\
R_a = 0.407E^{3.38}, \quad (E = 0.13 - 0.8 \text{MeV}),
\]

(2) (3)

Actually \( R_a \) may become short due to the self-magnetic field. When the plasma temperature increases, \( RE \) may be extended. However those effects are not considered here because the calculation becomes complicated. Instead of this, we introduce the anomalous deposition factor against \( R_a \) so as to match the experimental result with the calculation.

The relaxation between the electron and the ion in the core plasma is assumed from the result of the simulation as a function of the mass density. \( \rho R \) and the core radius \( R \) are obtained to be 0.02 g/cm\(^2\) and 27 \( \mu \)m from other experimental results. \( T_i \) without auxiliary heating can be estimated to be 0.67 keV from the neutron yield. When the LFEX laser with 612 J heats the imploded core in the Au cone shell target, increasing in \( T_i \) of 0.17 keV and in \( \eta_i \) of 1.6 % can be obtained\(^6\).

We calculate \( \eta \) and \( T_i \) using the same experimental condition as the GXII-LFEX integrated experiment. If we assume the divergence angle of 62 degrees using reference [9], an anomalous deposition factor can be estimated to be 75%. The anomalous deposition may occur due to the low energy component of two Gaussian distributions of the spectrum, which is not considered here, and the high current effect and the range expansion due to the core heating as mentioned above. At that time, the conversion efficiency of 36%, the core transparency of 96.5%, \( \eta_i \) of 75% and the core deposition of 6.2% can be calculated. Lower \( \eta \) comes from \( S \). In this case, the interaction layer is shifted due to the long \( L \). \( T_i \) (0.77/0.76keV in experiment/calculation) on the DLC cone shell is smaller than \( T_i \) (0.84/0.83keV in experiment/calculation) on the Au cone shell in the experiment. \( T_i \) on the DLC cone shell in the calculation corresponds to \( T_i \) in the experimental result. By using a low-Z material, the core transparency and the core deposition are slightly improved to be 98.2% and 6.3%, respectively. However \( S \) is long because of the thicker tip in the DLC cone shell. \( \eta \) becomes worse (41%) due to the long \( S \).

The laser intensity dependences of \( T_i \) and \( \eta \) have been performed in three different spectra, the average spectrum of the experiment (Standard), the minimum spectrum of the experiment (Improved) and Wilks scaling (Wilks)\(^9\). If we can suppress \( T_{\text{eff}} \) to the \( T_{\text{eff}} \) determined by Wilks scaling, four times or more \( T_i \) and \( \eta_i \) can be achieved as shown in Figure 2. To achieve Wilks scaling, \( L \) should be minimize by the pre-pulse suppression. Therefore \( \eta_i \) can be also improved when \( T_{\text{eff}} \) can be reduced. We survey \( T_i \) and \( \eta_i \) using realistic spectra obtained in the experiments when \( \rho R \) is scanned under the same conditions. There are two ways to scan \( \rho R \), variable density with fixed \( R \) and variable \( R \) with fixed fuel amount as shown in figure 3. When \( R \) is fixed, \( \eta_i \) determined by \( R \) and by \( S \), is not changed. If \( \rho R \) increases, the fuel amount also increases. Therefore \( T_i \) does not increase although \( \eta_i \) increases because the deposited energy per one deuteron is not so changed. When the fuel amount is fixed, \( R \) should be smaller by increasing \( \rho R \). \( \eta_i \) does not increase because \( \eta_i \) decreases.

In the latest experiment, \( \rho R \) is smaller than the most suitable value (0.05 g/cm\(^2\)) as shown in Figure 3. Therefore if we can achieve higher \( \rho R \) by improvement of the implosion, slightly higher \( T_i \) can be expected to be 0.86 keV. Indeed higher neutron yield (\( T_i \)) can be obtained at a higher impoding laser energy, which leads to better implosion. \( \eta_i \) is determined by the product of conversion, \( \eta_i \) and deposition efficiencies. It is most important to decrease \( T_{\text{eff}} \) up to Wilks scaling because \( T_{\text{eff}} \) is related to both \( \eta_i \) and the deposition efficiencies. For example, the LFEX laser energy of 3.2 kJ (0.02 g/cm\(^2\), 4.4x10\(^{18}\)W/cm\(^2\)) is required if \( T_{\text{eff}} \) can be reduced down to Wilks scaling in order to achieve \( T_i \geq 5 \) keV, which is a goal of FIREX although 16 kJ is necessary in current experimental scaling.

4. Proposal of hole cone hole shell target
The most suitable target for FI can be sought by comparison of the spectra between varied targets using ESM. We compare $T_{\text{eff}}$ in the cone irradiated by the LFEX laser with $T_{\text{eff}}$ in the plate. Direct heating of the imploded core has been performed by using the hole-cone shell target. $T_{\text{eff}}$ does not become high and high neutron yield can be obtained. This means the hole-cone shell target is another candidate of FI. At earlier LFEX injection timing, for example, before the imploding shell is filled by the pre-formed plasma, more effective $\eta_c$ may be expected. At that time, the electron deposition is decreased because the density is still low. However almost the hot electrons can irradiate the core from inside as a cavity even if the beam divergence is large. The relaxation between the electron and the ion is enough although the density is over several g/cm$^3$.

If another hole is drilled in the opposite side of the cone (hole-cone hole shell target), $T_{\text{eff}}$ may be strongly reduced. The pre-formed plasma cannot be created because the pre-pulse goes through the hole during the imploding phase. If the LFEX laser is injected when the pre-cursor fills the cavity, lower $T_{\text{eff}}$ and short interaction distance and higher $\eta_i$ can be expected.

5. Summary
The results in the latest experiment can be explained by the results in a simple calculation using realistic spectra obtained in the experiments. We survey $T_i$ and $\eta_i$ with regard to the LFEX laser intensity and $\rho R$. Higher $T_i$ can be expected by strong implosion. However it is necessary to increase $T_i$ and $\eta_i$ drastically such that $T_{\text{eff}}$ should be also decreased drastically. One of the candidates to reduce $T_{\text{eff}}$ is the hole-cone-hole shell which does not create the pre-formed plasma until the arrival of the main pulse.

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6. References
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