Hot Electron Spatial Distribution Under Presence of Laser Light Self-focusing in Over-dense Plasmas

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Abstract. In fast ignition for laser thermonuclear fusion, an ultra intense laser (UIL) pulse irradiates an imploded plasma in order to fast-heat a high-density core with hot electrons generated in laser-plasma interactions. An UIL pulse needs to make plasma channel via laser self-focusing and to propagate through the corona plasma to reach close enough to the core. Hot electrons are used for heating the core. Therefore the propagation of laser light in the high-density plasma region and spatial distribution of hot electron are important in issues in order to study the feasibility of this scheme. We measure the spatial distribution of hot electron when the laser light propagates into the high-density plasma region by self-focusing.

1. INTRODUCTION
In a fast ignition concept, when an ultra intense laser (UIL) pulse is irradiated into an imploded plasma, hot electrons are generated from laser-plasma interactions and are used to heat the fuel core. Thus the key points are the propagation of laser light and spatial distribution of the hot electrons in the over-dense plasma. The laser light must propagate close enough to the imploded plasma core in order to deliver ignition energy to the core. The laser light is stopped at the effective critical density \( \gamma n_c \) at a relativistic laser intensity. \( \gamma \) is relativistic Lorenz factor and \( \gamma = \sqrt{1 + \frac{I}{I_r}} \), where \( I \) and \( I_r \) are the incident laser and the relativistic laser intensities \( (= 1.37 \times 10^{18} \text{ W/cm}^2) \). When the self-focusing \([2,3]\) of laser pulse occurs the laser intensity becomes higher, and then the UIL pulse could propagate the over dense plasma due to relativistic increase of plasma electron mass. It is of critical importance to reveal the propagation and the hot electron generation in over dense plasmas.

We measured the spatial distribution of the hot electrons from the self-focusing laser light for the first time.

2. EXPERIMENT
The experiments are performed using the Peta Watt (PW) and the Gekko XII (GXII) laser systems at the Institute of Laser Engineering (ILE), Osaka University. The experimental set up is shown in Fig.1.
The PW laser has a high contrast (S/N=10^8) sub-picosecond UIL pulse with the wavelength 1.053 µm. The pulse duration of GXII laser is 1 ns with the wavelength 0.53 µm. Targets consist of Al (0.1 µm thickness) – CD (1 µm thickness) double-layered foils. The long pulse beams irradiate the target at first, to create a plasma with an over-dense region, and then the PW laser irradiates the plasma at a time delay.

The plasma density profile is controlled by the delay between GXII and PW irradiations. The plasma density profiles are calculated with a 1-dimensional hydrodynamic simulation (ILESTA 1D) [4] as shown in Fig.2. The plasma scale lengths \( L \) are evaluated from the approximation with the exponential function,

\[
n_e(x) = \exp(-x/L).
\]  (1)

The scale length was benchmarked between the simulation and separate experiments [9,10]. The plasma scale length is about 3 µm for the small plasma as shown in the Fig.2 (a). The plasma scale length is about 136 µm for the large plasma as show in the Fig.2 (b).

We use electron a spectrometer (ESM) [5] to measure the hot electron spectrum, x-ray pinhole camera (XPHC) for imaging of plasma self-emission and imaging plate (IP) stack for the hot electron spatial distribution. The XPHC is placed in front of the target and the ESM and the IP stack are placed behind the target. The distance from IP stack to the target is 34mm.

Figures 3 (a) and (b) show the electron energy spectra for the small plasma and the large plasma cases. The longitudinal axis represents the absolute electron numbers. The horizontal axis is the electron energy. The energy spectrum of hot electrons can be approximated with the relativistic Maxwellian distribution using the electron temperature \( T \) [6],

\[
N(E) = N_0 E^2 \exp(-E/T).
\]  (2)
The electron temperatures of small plasma and large plasma cases are 0.98 and 1.53 MeV, respectively. The incident laser intensities are about $4 \times 10^{18}$ W/cm$^2$ for both cases in this experiment. It is known that the electron temperatures have a strong relation with incident laser intensity [8]. The electron temperature of 1.53 MeV corresponds approximately to about $4 \times 10^{19}$ W/cm$^2$ from Ref. 8, which is 10 times higher than the incident laser intensity. This increase of the laser intensity could come from the laser-light self-focusing in the large plasma while the lower temperature could well result from the small plasmas without self-focusing.

Figure 4 shows the observed XPHC images. Figures 4 (a) and (b) correspond to the small plasma and the large plasma cases. The spatial scale with the arrows is 100 µm. In previous experiments [11], we observed this type of channeling shadow only when the laser light self-focusing occurs in the overdense plasma. In the Fig.4 (b), a channeling shadow is observed as the dotted line indicating a self-focusing. However, the shadow is not observed in the Fig.4 (a).

Figure 5 shows the spatial distribution of electrons. Figs. 5 (a) and (b) correspond to the small plasma and the large plasma cases. The signal intensities of these figures are normalized by the maximum signal intensity in each figure. In the small plasma case, the angle of emitted electrons from the interaction points in full width at half maximum is 66 degree. On the other hand, the angle for large plasma case is 32 degree. One can see that the peak positions are different, i.e. the large plasma case shows the peak at the laser axis whereas the small plasma case shows the peak at the target rear normal.
In a solid target with pre-plasma case, variance of the hot electron distribution and the peak position have been reported [7]. For the low laser intensity, they conclude that the electron acceleration mechanisms can be the resonant absorption and/or the vacuum heating, and the electron distribution angle becomes wide. On the other hand, for the high laser intensity case, the electrons are accelerated due to JxB force along the axis, and the electron distribution angle becomes narrow. In this experiment, the acceleration mechanism is JxB because the hot electrons propagate into the laser axis. In addition, the hot electron distribution could be narrowed. From these results, we can infer the self-focusing occurred in the large plasma case as also expected from X-ray pinhole image.

3. CONCLUSION

In conclusion, the hot electron distributions are studied with the different plasma density profiles. When the self-focusing occurred, the hot electron number increased and the spatial distribution of hot electrons became collimated ($\theta_{\text{FWHM}} = 32[$degree$]$). These hot electron distributions would provide the high efficiency core heating in FI scheme under self-focusing.

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