Isochoric heating of low-Z, reduced-mass targets with high intensity laser pulse

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Abstract. Energy deposition by hot electrons in ultra-short, high intensity laser produced dense plasma was investigated by X-ray spectroscopy. Kα lines from partially ionized chlorine embedded in a triple layered, reduced mass target was observed to derive electron temperatures. Fast electrons generated by intense laser were confined in the smaller mass target, showing efficient increase of temperature. Heating efficiency by electron refluxing was one percent of laser energy and surface heating is significant at the laser intensity of ~ 1×10¹⁸ W/cm².

1. Introduction

Recent advances of ultra-short, high intensity laser have expanded widely in various applications after the technique of chirped pulse amplification was discovered. The extremely intense field realized by the laser causes many interesting phenomena, such as generation of X-ray, γ-ray and energetic particles. Fusion in the fast ignition scheme is one of the most important applications, where a large energy, high intensity laser pulse heats and ignites hot core plasma compressed by multiple laser beams[1-3]. In this scheme and in other applications, understanding hot electron transport and laser energy deposition are one of essential issues.

Upon a classical model, laser-generated electrons penetrate into a material of solid density and dissipate their energy [4-9]. The conversion efficiency from laser to the electrons is typically 10-40%, depending on laser intensities [3,10,11]. Initially, return current of bulk electrons, needed for charge neutrality, heat the target in the penetration process. Then, the fast electrons start to recirculate after reaching rear surface in the case of a target with a finite size in the longitudinal direction because they are trapped and rebounded in plasma sheath created both on the front and the rear surfaces [12,13]. The process is called as “electron refluxing”, and a simple calculation shows that 99% electrons reflux in target with the range of laser intensity from 10¹⁸-10²⁰ W/cm²[14].
In this experiment, we aimed to realize isochoric heating of a matter using a mass-reduced target. If the target is substantially smaller than the attenuation length of hot electrons, the electrons can recirculate many times in the target and can heat it uniformly. Such an uniformly heated plasma can allow us to evaluate the temperature using spectroscopic diagnostics without considering temperature and density gradient, and enable us to investigate the physics of the hot dense matter. Several experimental researches have been done using a monolithic or multi layered target consisting of metallic materials [14-19]. However, it is well known that there exists a steep gradient appearing particularly at the target front side, this may result in difficulty in temperature derivation by X-ray spectroscopic method.

In this work, we made an experiment to assess energy transport and deposition to target using triple layered, all plastic, mass reduced target. X-ray spectroscopic measurement of K shell lines was employed in this study [20,21].

2. Experimental Setup

The Experiments was performed using Gekko MII (GMII) laser system. The energy delivered from the system was $E_L \sim 10 \text{ J}$ per pulse of typically 500 fs in duration, and the wavelength was 1 μm. The laser was focused to target surface with a spot size of ~20-35 μm at the incidence angle of 20 degrees with respect to the target normal. Typical laser intensity was $\sim 5 \times 10^{17} - 1.5 \times 10^{18} \text{ W/cm}^2$.

Four targets having different sizes were employed. All the targets consisted of 5-μm-thick $\text{C}_8\text{H}_8$ (Parylene-N)/5-m-thick $\text{C}_2\text{H}_3\text{Cl}$ (Polyvinyl chloride)/5-μm-thick $\text{C}_8\text{H}_8$, as shown in Fig. 1(a). The chlorine embedded in the middle layer was a tracer and its K-shell lines were investigated as a function of target total mass. The outer shape of the target was square and the lengths of each side, L, were 50, 100, 300 and 1000 μm. They are called type A, B, C and D. These conditions provide mass per incident energy of $4.6 \times 10^{-9} - 1.6 \times 10^{-5} \text{ g/J}$, which are comparable to those of past feasibility experiment ($2.8 \times 10^{-9} - 2.6 \times 10^{-8} \text{ g/J}$)[2]. In addition, a polyvinyl chloride film of 5-μm thick and 300×300 μm in lateral size without overcoating was used to measure their target surface temperature.

An X-ray Spectrometer used in this experiment, consisted of a conically bent crystal ($\alpha$-quartz (10-11)) and a back illuminated CCD camera (Princeton instruments inc.). This spectrometer covered spectral range from Cl-Kα (2.62 keV) to Heα (2.79 keV).

3. Results and Discussion

X-ray spectra for type A, B, C and D targets are shown in Fig. 1(b). The most intense line is Cl-Kα emissions around energy of 2.62 keV for all the targets. Besides, energy shifted Kα lines emitted from partially ionized Cl ions were observed around 2.64 and 2.66 keV particularly for type A and B targets.

Blue shift in the peak position and in overall shape of near-neutral Kα lines are obtained, as shown in Fig. 2(a) of expanded view around 2.62 keV. From comparison of spectra between these for type A and D, energy of the Kα line is shifted.
about 5 eV owing to the change of ion population to highly ionized stage.

Figure 2(b) shows radiative decay rates of Kα lines from each ionization states of Cl ions predicted with a multi configuration Dirac-Fock atomic code GRASP 92 [22] and RATIP [23]. Here, we considered Kα transitions for Cl$^{8+}$-Cl$^{10+}$, assuming their outermost bound electrons are not excited, namely, Cl$^{n\sigma\omega}$: 1s2s2p$^4$3p$^6$3d$^{n\sigma\omega}$ -> Cl$^{m\pi}$:1s2s2p$^4$3p$^6$3d$^{m\pi}$ (N=1-6). In the calculation result, line emissions from Cl$^+$ to Cl$^{10+}$ overlap each other and the energy shift caused by ionization of M-shell electrons is very small. Nevertheless, general trend of energy shift in blue side is seen for higher ionization stages. The Kα lines observed experimentally are identified in the range of about 2610-2630 eV, which is corresponding to the emission from Cl$^+$-Cl$^{10+}$ of the calculation. Emissions from Cl$^{8+}$ and Cl$^{9+}$ ions are not calculated in the calculation, while emission from Cl$^{10+}$ can be identified in the experimental data. The spectroscopic results imply that a small temperature gradient may exist in lateral direction of the target.

Figure 3(a) shows dependence of cold Kα (Cl$^{8+}$-Cl$^{10+}$) intensity $N_0$ on the target mass, where the values of intensity were obtained by integrating the peak around 2.62 keV and normalized by laser energy. The intensities of Kα lines close to the neutral Kα line decrease with decrease in the target size. This result suggests that Kα emission from highly ionized Cl ions become more dominant over that from ions close to neutral atoms.

Furthermore, Fig.3(b) shows that dependence of shifted Kα line intensities $N_{sk}/N_k$ normalized by $N_0$ on the target mass. Here, Kα yield is described as $N_0 = N_e \int_{E_L} \int_0^\infty dE_0 f(E_0) \int_0^\infty dE \omega_0 n_{sk} \sigma_0 (dE/ds)^{-1}$, where $N_e$, $E_0$, $\omega_0$, $\sigma_0$, and $n_{sk}$ are respectively the total number of hot electrons, initial energy of hot electrons, fluorescence yield, collisional cross section between hot and bulk electrons, and the number of chlorine atoms in the target [6]. Simplifying the above equation, we can express cold and shifted Kα yields as $N_0 \sim n_{cont} f(E_L)$ and $N_{sk} \sim n_{sk} f(E_L)$ and then can obtain $N_{sk}/N_0 \sim n_{sk}/n_{cont}$, which is an indication of relative number of highly ionized ions to that of ions close to neutral atom (Cl$^+$-Cl$^{10+}$). In Fig. 3(b), the normalized intensity for Cl$^{9+}$ and Cl$^{10+}$ ions has tendency to increase with decrease in the target mass, showing progress of ionization stages in plasma. These results successfully demonstrated the effectiveness of reduced-mass target for efficient heating. Note that for type A target the laser energy was eventually lower by 1/3 ($E_0 \sim 4.7$ J) than those of another shots ($E_0 \sim 10-12$ J) and the intensity of the emission was not intensive. Nevertheless, spectral intensity is comparable to that of the case for target A within error bar, showing the effective heating.

Using an atomic kinetic code FLYCHK [24], we tried to determine the temperature from X-ray spectra. Assuming the electron density $n_e \sim 1 \times 10^{23}$ cm$^{-3}$, $n_{tot}/n_e \sim 0.01$ and $T_e = 500$ eV, we obtained a relationship between plasma temperature and the line ratios for $N_{sk}/N_k$ as shown in Fig.3(c). Dependence of electron temperature derived from comparison between the experiment and FLYCHK calculation on the target mass is shown in Fig. 3(d). The highest temperature of 70 eV is obtained for the mass reduced target.

The total energy deposited in the volume of tracer layer of solid density at 70 eV and the average Z value of 7 is only $\sim$1 % of incident laser energy. The energy needed for ionization is about $\sim$0.02 J and for heating is $\sim$0.03 J. On the contrary, surface heating by laser-matter interaction is very significant in laser energy deposition. Electron temperature derived from the X-ray spectrum for the polynvinyl
chloride foil without overcoating was around 1 keV, that is also reproduced in a collisional 1D PIC simulation as shown in Fig.4. The details of the code were described in reference [25]. This result is also consistent with previous experimental result using a monolithic Cu target [8-11]. Despite existence of hot electron refluxing, local heating of target was experimentally found. This might be attributed to the energy distribution of hot electrons[25]. Hot electrons involved in the lower energy side, components lower than the slope temperature, dominate over the overall energy carried by hot electrons. They travel in a shorter distance and deposit their energy in a plasma close to the target surface. Further experiments and simulations will be needed for different experimental conditions, for example, investigating the dependence of heating efficiency on laser intensity, for which fast electrons have different energy distribution, is important and interesting.

4. Summary
Energy deposition by hot electrons into mass-reduced target has been studied by X-ray spectroscopic measurement, and analyzed with simulations. The experimental results support the hot electron confined in a small target by the sheath self-created in the target surface. However, there still remains a target temperature gradient along the depth of the target. The PIC simulation shows the tracer layer sandwiched with a surface tamper and a rear substance is moderately uniform in terms of temperature and density so that the isochoric heating seems to be realized in the localized region. Near future, we will operate an experiment using a chlorinated and deuterated target to measure electron and ion temperature simultaneously. This will clarify physics of energy relaxation from hot electrons to bulk ions comprehensively.

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