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X-Ray Spectroscopic Measurements of Energy Transport in Ultra-Intense Laser Produced Plasma

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Abstract

Experimental study on energy transport in ultra-high intensity laser plasma was made using a PW laser system. X-ray emission from a triple-layer target, involving chlorine as a seed material for the spectroscopy, was observed with x-ray spectrographs and monochromatic imagers to provide a temperature profile in the depth of the target and lateral extension of the heated region. It was found that a very shallow region (~0.5 μm from the target surface) was heated up to 650 eV but the temperature of deeper region (up to 5 μm) was around 100 eV. These depths are much shorter than those expected from the classical penetration of the hot electrons of ~500 keV predicted by calculations.

Keywords:

x-ray spectroscopic measurement, ultra-high intense laser, energy transport, hot electrons

1. Introduction

In fast-ignitor research, efficient energy transfer to and deposition in the dense plasma is one of the critical issues [1]. A new spectroscopic method providing time- and space-resolved information has been under development to provide more quantitative understanding of the energy deposition than those provided by particle measurements [2,3]. Because of the relatively low temperature available with current lasers and the high density-radius product, ρR, of the imploded core exceeding 0.1 g/cm^2, conventional K-shell line spectroscopy using near-fully ionized plasma is not suitable. To K-shell ion in a low-temperature plasma one must use a low-Z seed material; but, the implosion core would be too opaque for K-shell lines. Shifted Kα lines are group of Kα lines emitted from partially ionized ion. In case that high Z material is used as a tracer, we can use high energy photon even if electron temperature is comparatively low.

Numerous works have been done to derive the fast electron spectrum and energy transfer efficiency by observing Kα lines from double-layer targets [4,5]. X-ray spectra observed have shown that the line intensities decrease dramatically with increase in over-layer thickness of the double-layer targets at the laser intensity of 10^{17}–10^{18} W/cm^2 [6-8], indicating that the depth of hot region would be much less than those predicted by the fast electron temperatures measured or estimated from the laser-intensity scaling [9]. However, at the irradiance over 10^{19} W/cm^2 relativistic self focusing and plasma channel formation occur under such a deep relativistic regime, much better energy transport will be expected. Therefore, spectroscopic measurement at the deep relativistic laser intensity is needed to improve understanding of energy transport and deposition mechanism associated with the fast ignitor experiments.

In this paper, we will show x-ray spectroscopic measurements of a chlorine-doped triple-layer target irradiated by an ultra-intense laser at the intensity over 10^{19} W/cm^2. We observed shifted Kα lines and resonance lines such as Heα, Lyα from the tracer simultaneously in order to cover a wide range of temperatures. The thickness of over-coating layer facing to the side of laser incidence was varied to derive temperature profile in the target depth. In addition, lateral extension (the direction along the target surface) of the heated region was observed using x-ray monochromatic imager adjusted for Cl Kα and Cl Heβ lines.

2. Experimental setup

Experiment was performed using the PW laser system at the Institute of Laser Engineering (ILE), Osaka University. This system provided a laser pulse of 130 J/700 fs at the wavelength of 1053 nm. The contrast ratio of the laser pulse was better than 10^{-6}. The P-polarized pulse was focused with an off-axis parabolic mirror of f /7.5 at the incident angle of 25.9°. The laser spot size was 30 μm containing 70 % of laser

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energy to yield irradiance of 2×10^{19} w/cm^2.

The target was a triple-layer planar target: Substrate was a 2 mm CH plate. Middle layer consisted of a 1 µm C_8H_7Cl film. The third layer, in the side of laser incidence, was made of CH whose thickness was varied from 0 µm to 5 µm.

We used two spectrographs and two monochromatic imagers. One of the spectrogtraphs had a RbAP flat crystal (100) covering the energy range from 2.6 keV to 3.3 keV for Cl Heα to Heβ lines. The other had a troidally bent quartz crystal (10–11) covering the energy range from 2.6 keV to 2.85 keV for the shifted Kα lines.

One of the x-ray imagers, called x-ray monochromatic camera (XMC) [10], had a troidally bent silicon crystal (220) adjusted for Cl-Heβ line (3.27 keV). Experimentally-confirmed spatial resolution was better than 10 µm. The second imager was an x-ray pinhole camera (XPHC) having a 20 µm saran foil involving Cl as a K-edge filter. Overall spectral range was 1.8–2.82 keV, covering Cl Kα to Cl Heα lines. As will be shown below, this pinhole camera is identical to a Cl Kα monochromatic imager when the over-coating was thick. Spatial resolution was better than 15 µm.

3. Experimental results and discussion

Figure 1 shows the spectra obtained with the x-ray flat crystal spectrometer. With increase in the over-coating thickness, the lines become much weaker except for the Kα line. The Cl Lyα, Heα, and Heβ lines, as good signatures of hot plasma formation, could be observed only for 0–0.2 µm over-coating. On the contrary, Kα line, a good signature of hot electron propagation in a cold material, was observed even for 5 µm coating. From the line intensity ratio of Lyα to Heα, one can derive electron temperature by using the spectrum analysis code FLY [11]. For the case of no-coating the ratio is 0.07 ± 0.003 then corresponding electron temperature is 650 ± 30 eV assuming that plasma concerning consists of a mixture of C and Cl (in the ratio of 8 : 1 and the total ion density is 9×10^{22} cm^{-3}). For the case of 0.2 µm coating, the ratio is below 0.01 including experimental error, therefore the electron temperature is 400 eV or less.

Figure 2 shows the spectra obtained with the bent crystal spectrometer. Between Kα and Kβ lines, inner-shell transition lines corresponding to KαCl^{9+} to KαCl^{14+}, Heα line and its unresolved Li-like satellite lines are weakly seen. We obtained electron temperature using intensity ratios of these lines in comparison with calculations by an atomic kinetic code specified for the shifted-Kα lines [12]. The calculation was made assuming plasma conditions that ion density is 9×10^{22} cm^{-3}, hot electrons temperature is 500 keV, and fractional hot electrons with respect to the total (bulk plus hot) electrons is 5 %. From comparison between the experiment and the model calculations, electron temperatures were obtained as 119 eV, 111 eV, 113 eV respectively for the case of 0.2, 0.5, 1.26 µm coating.

Figures 3(a)-(c) show monochromatic Heb line images for various coating. There is no large difference among them and lateral extension is within a few times of the laser spot size. Figure 3(d)-(f) show the images obtained with XPHC. For Fig. 3(d) and (e), contribution of Heα line emission dominants over the results as is seen in Figs. 1(a) and (b). On the contrary, Fig. 3(f) provides the image of Kα line emission.

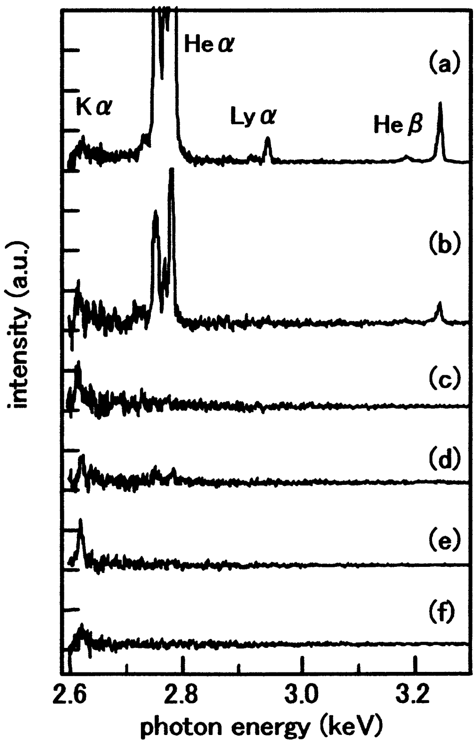

Fig. 1 X-ray spectra obtained with the flat crystal spectrograph. For various over-coating thickness: (a) 0 µm, (b) 0.2 µm, (c) 0.5 µm, (d) 1.26 µm, (e) 2 µm, and (f) 5 µm.

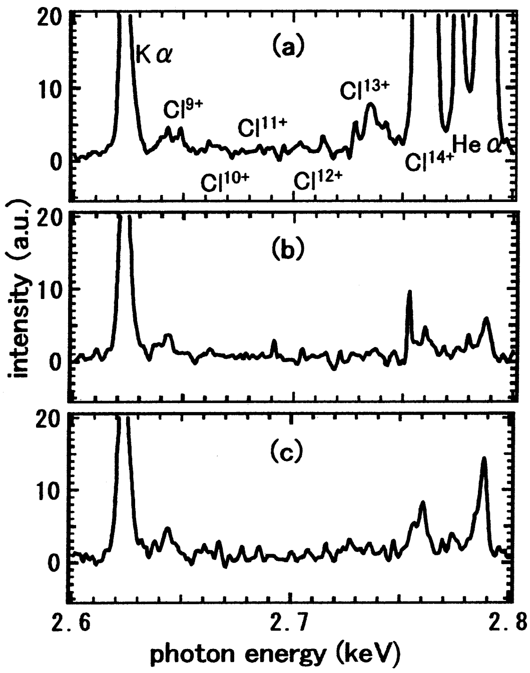

Fig. 2 X-ray spectra obtained with the x-ray bent crystal spectrograph. Thicknesses of the over-coating are (a) 0.2 µm, (b) 0.5 µm, and (c) 1.26 µm.

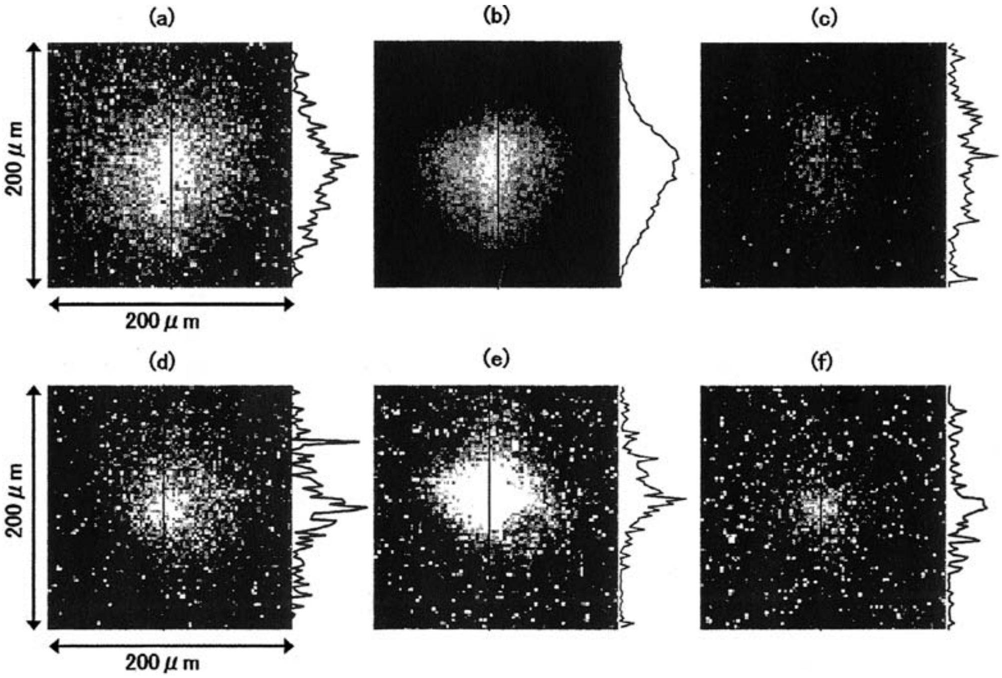

Fig. 3 Monochromatic images of Heb line for over-coating thickness of (a) 0 μm, (b) 0.2 μm, and (c) 0.5 μm. And x-ray images from XPHC for over-coating thickness of (d) 0 μm, (e) 0.2 μm, and (f) 0.5 μm.

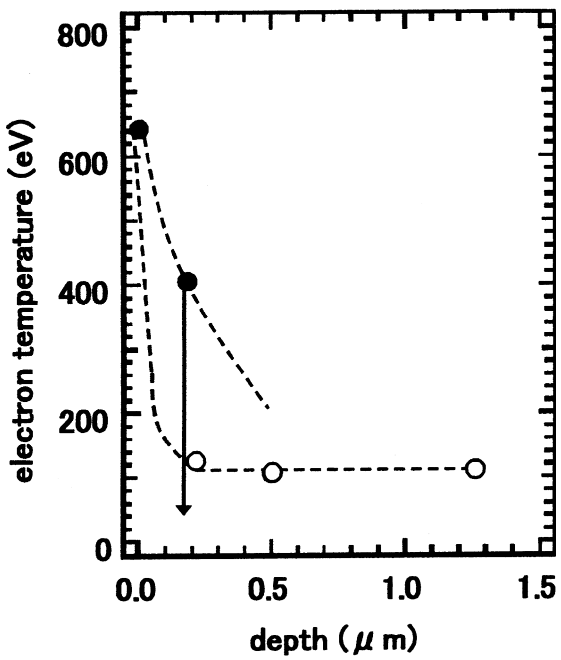

Fig. 4 Electron temperature profile obtained by the intensity ratios of the resonance lines (closed circles) and the shifted Ka lines (open circles).

Again lateral size is within a few times of the laser spot, indicating that there is no largely diverging or converging propagation of hot electrons for the over-coating investigated in this experiment.

By combining the results from the spectroscopic measurements, we could derive temperature profile in the depth of target as shown in Fig. 4. In the thin surface region, electron temperature are around several hundreds eV. But in the depth of target, electron temperature is around 100 eV. Temperature of hot electrons, considered as a primary energy carrier for the target heating, was predicted by particle-in-cell (PIC) code calculation [13]. For the experimental condition of our case, the hot electrons consist of two components whose slope temperatures are 500 keV and 2 MeV. It has been shown that the former 500 keV component has an important role in heating the compressed core on the basis of classical transport [13]. According to this result, we can predict depth of heat transport over 200 μm in solid CH [14], contrary to the result of this experiment.

Typical absorption depth for x-ray photons of 2.6 keV in solid CH is 100 μm, therefore possibility of x-ray absorption by the surface coating can be excluded. Overall ionization energy, consumed in generation of experimental plasma of 300 eV in temperature, 9×10^{22} cm^{-3} in density, and 1 μm in depth, was calculated to be about 0.4 J. This corresponds to only 0.3 % of incident laser energy. Then ionization loss can be neglected. Another possibility is due to inhibition of heat transport attributed to space-charge effect in the depth of target. However, as is evidenced in the study of ref. [8], this possibility is also excluded as far as electron conductivity between metallic material and fully ionized plasma are nearly the same. The most plausible mechanism will be anomalous resistivity caused by electromagnetic fields self-induced in surface plasma by hot electrons [15]. The electric currents carried by hot electrons in the vacuum-plasma interface induced self-organized magnetic-fields but the current values are well above the Alfvén limit [16]. The induced magnetic fields prevent their penetration in overdense region. Furthermore, the cold bulk electrons in the return flow are scattered by the magnetic fields. As a result, the plasma becomes resistive and longitudinal electric fields are created and maintain global current neutralization. In this experiment, the scale length of the magnetic fields is calculated to be 0.4 μm [17], corresponding to the depth of heated region by PW laser.

4. Conclusion

Energy transport in ultra-high intensity laser produced plasma has been studied by x-ray spectroscopic measurements. The depth of heated region is much less than that expected from the hot electrons generated by laser. The lateral extent of the heated region is closed to the laser spot, consistent with this hot region. This might be attributed to the anomalous resistiivity by self-induced field formation.

References

[1] R. Kodama *et al*., Nature **418**, 933 (2002): ibid. **390**, 490 (2001).

[2] G. Guethlein, M.E. Food and D. Price, Phys. Rev. Lett. **77**, 1055 (1996).

[3] Y. Kitagawa, Y. Sentoku *et al.*, Phys. Plasmas. **9**, 2202 (2002).

[4] K.B. Wharton, S.P. Hatchett *et al.*, Phys. Rev. Lett. **81**, 822 (1998).

[5] D. Batani, J.R. Davies *et al.*, Phys. Rev. E **61**, 5725 (2000).

[6] H. Chen and B. Soom, Phys. Rev. Lett. **70**, 3431 (1993).

[7] U. Teubner, I. Uschmann *et al.*, Phys. Rev. E **54**, 4167 (1996).

[8] H. Nishimura, T. Kawamura *et al.*, JQSRT **81**, 327 (2003).

[9] S.C. Wilks and W.L. Kruer, IEEE J. Quantum Electron. **33**, 1954 (1997), and references therein.

[10] M. Vollbrecht, I. Ushmann *et a*l., JQSRT **58**, 965 (1997).

[11] R.W. Lee, J.T. Larsen *et al.*, JQSRT **56**, 535 (1996).

[12] T. Kawamura, H. Nishimura *et al.*, Phys. Rev. E **66**, 016402 (2002).

[13] T. Johzaki, K. Mima *et al.*, *Ann. Prog. Rep. of ILE Osaka U.* **95** (2002): Y. Sentoku and K. Mima, *submitted to* Phys. Plasmas.

[14] W. Bambynek, B. Crasemann *et al.*, Rev. of Mod. Phys. **44**, 716 (1972).

[15] Y. Sentoku, *Ann. Prog. Rep. of ILE Osaka U.* 1343 (2001).

[16] H. Alfvén, Phys. Rev. **25**, 425 (1939).

[17] A.R. Bell and J.R. Davies, Phys. Rev. E **58**, 2471 (1998).