Heating of solid target in electron refluxing dominated regime with ultra-intense laser

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Abstract. Propagation of electron beams generated in laser-plasma interactions is strongly influenced by self-induced electrostatic fields at target-vacuum interfaces, resulting the refluxing of electrons. We confirmed the refluxing and propagation of electrons with three different kinds of target configurations; thin-wide foil, thin-narrow foil, and long-wire geometry. Enhancement of target heating, effective guiding and collimation of high density MeV electrons were observed.
1. Introduction
The study of fast electron generation and transport in intense laser interactions with dense plasmas is crucial important for the fast ignition (FI) approach to inertial confinement fusion (ICF), and for high-energy density science. The fast electrons propagate inside the solid plasmas with a divergence angle of 30°- 50° [1]. These electrons’ motion is influenced by self-induced electric fields at the target-vacuum interfaces, resulting the refluxing of electrons [2]. We confirmed the electron refluxing with three different kinds of target configurations.

2. Experiment and discussion

2.1. Longitudinal refluxing of electrons in thin-wide foil geometry
We have investigated the heating of solid target with various thickness (5 ~ 81 μm) using the Vulcan PetaWatt laser [3]. The ~400 J, 0.45-0.75 ps pulses provided focused intensity on target up to 4x10^20 W/cm^2. Various materials were used for targets, such as Al, Cu, CH, Mo, Ni, and V. Laser pulse was focused onto the targets at 40° from the target normal. The optical emission from the rear side of the target was obtained by innovative streak camera with two-dimensional spatial resolution [4], with temporal and spatial resolutions of ~35 ps and 35 μm, respectively. The obtained wavelength range was 350 – 650 nm except 500 nm - 550 nm (factor ~10^-5 reduction) to avoid the strong 20th emission from coherent transition radiation (CTR). By suitable choice of the angle of the collecting lens with respect to the laser axis (48-60°), further reductions in CTR were made. The origin of the observed emission was thus dominantly due to heating of the target (Planckian). The rear emission was temporally separated from any other hydrodynamic heating such as a shock wave.

The spatial peak brightness at the target rear side taken at the temporal peak of the laser pulse was plotted as a function of the foil thickness in Fig. 1. The absolute temperatures of the targets werecalibrated by comparison with the measured optical emission intensity and line fitting of X-ray emission spectroscopic measurements taken on the same shots [5]. Despite the variation in target materials, a clear trend is visible in Fig. 1(b). Significant increase in temperature has been observed with thinner target. This is likely due to the refluxing of electrons in the longitudinal direction. The curves are the results modeled by the hybrid code [6], with take the electron refluxing into account (solid line) or not (dotted line). The very high temperature at the very thin target agrees well with the modeling including the refluxing effect. Relatively lower temperature shown in thinner target in some shots is most likely due to the preplasma formation at the rear surface [7]. Since the target is optically thick at visible wavelength, the scale length of the rarefaction is always much longer than the visible

![Fig. 1 (a) Typical optical image at the rear side of the target. Target was consisted of Al50/Cu5/Al11 um. (b) The spatial peak brightness at the target rear side taken at the temporal peak of the laser pulse as a function of the foil thickness. (c) Images of the electron refluxing in the longitudinal direction inside the target for a thin foil.](image)
absorption length and the brightness seen from the rear surface decreased.

2.2. lateral refluxing of electrons in small area foil targets

Since the electrons propagate with 30-50° divergence angle inside the solid [1], it is expected that the refluxing of electrons in the lateral direction should be exist when the area of the target foil was narrow enough. The effect was confirmed by the experiment conducted at the LULI 100 TW laser system which delivers about 10-13 J on target at a wavelength of 1.06 μm, 400 fs pulse duration. The laser was irradiated onto the target with normal direction. The laser was slightly defocused until the spot size on target became ~70 μm. The thickness of the target was 40 μm (20μm Cu, 20μm Al), and the target size was changed from ~350 μm square to larger than 2 mm square. The optical emission at the target rear surface was obtained using the 2D space-resolved streak camera [4], with similar set-up as described in the previous section except that the collecting lens was set on the laser axis here.

Fig. 2 shows the (a)(b) typical optical images of the target rear surface (at the temporal peak of the pulse) and (c)(d) line-out of them. The target area size was (a)(c) 0.41mm \times 0.36mm (b)(d) larger than 2mm \times 2.5mm, respectively. Figure 2(e) shows the brightness at the margin (expressed as “B” or triangles in the figure) as a function of the target size. The brightness at the margin strongly decreases with the target size. In contrast, when we subtracted the brightness of the margin from the brightness of the central peak, the value was not change with the target size (“A” or circles in the figure). The most likely explanation of the results is the lateral refluxing of the electrons in small area target results in the enhanced heating throughout the target [8][9].

2.3. Maximum lateral refluxing and negligible longitudinal refluxing in long-wire geometry

When the lateral size of the target is further reduced, electron refluxing in the lateral direction is dominant over the longitudinal direction. We performed the experiment using the fine-wire target which had 5μm thickness and 1 mm long [10]. The carbon wire was attached to the gold hollow-cone which can guide the laser light and electrons effectively to the wire [11] (Fig.3 (a)). Trajectories of the MeV electrons with wire plasmas modelling by two-dimensional particle-in-cell (PIC) simulation is shown in Fig. 3(b). Since a strong radial electric field was created surrounding the wire plasma, electrons were confined and reflux in the lateral direction in many times. The lateral emittance of the electron beam is reduced by a loss of its lateral energy to the bulk plasma and/or energetic ions via the radial electric field [10][12]. Figure 3(c) shows the > 3.5 MeV electron beam contour escaped from the

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Fig. 2 (a)(b) Typical optical images at the rear side of the target. The colour contour is normalized to the peak intensity for each image. (c)(d) The intensity profiles from a horizontal line through the centre. Target size was (a)(c) larger than 2mm \times 2.5mm supported by large metal holders and (b)(d) 0.41mm \times 0.36mm supported by thin (< 100μm) insulator stalk to isolate the target. (e) Obtained emission intensity vs. target size. (f) Pictorial representation of the electron lateral refluxing.
wire measured at 3 cm after the wire end. The divergence of the electron beam from the wire is about 5°, which was much smaller than the 30-40° from the plane target case.

3. Conclusion
We have systematically studied the fast electron refluxing inside the solid plasmas with three different kinds of target plasma geometry. These results were crucial important for FI concept for ICF; i.e., the longitudinal refluxing can increase the energy deposition from the fast electron to the implosion core plasmas, and the lateral refluxing can reduce the divergence angle during the energetic electron propagation and significantly enhance the energy deposition at the implosion core.

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