Lateral propagation of fast electrons at the laser-irradiated target surfaces

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Abstract. Lateral propagation of fast electrons at the target surfaces irradiated by femtosecond intense laser pulses is measured by $k_{\alpha}$ x-ray imaging technique when a preplasma is presented. An annular halo surrounding a bright spot is observed in the x-ray images when the scale length of the electron density is large. For an incidence angle of $70^\circ$ the x-ray images show a non-symmetrical distribution peaked to the laser propagation direction. The x-ray photons in the halo are mainly excited by the fast electrons that flow in the preplasma when their paths intersect the high density regions near the target surface.

1. Introduction
Lateral propagation of fast electrons at the target surfaces irradiated by intense laser pulses is important to understand the physics in cones, with which Kodama et. al. have demonstrated the enhancement of neutron yield in the fast ignition (FI) experiments [1]. Evidence of the lateral transport has been found by x-ray [2,3,4] and ion emission [5]. Fast electron jets emitted into vacuum close to target surface have been also observed with simple plane targets [6,7,8, 9]. The lateral propagation of fast electrons also enlarges the x-ray source size. This has to be controlled for the imaging applications because large-size sources reduce the spatial resolution.

Recently two-dimensional x-ray imaging measurements show that a preplasma in the cone may reduce the fast electron propagation and energy deposition [10,11]. For the real conditions of fast ignition the preplasma effect on the electron propagation must be considered because the intensity of the heating short pulse is much higher. In this paper, the electron propagation at the front target surface when a preplasma is formed before the main laser pulse is studied by $k_{\alpha}$ x-ray imaging technique. The origins of the $k_{\alpha}$ x-ray photons measured are identified. The dependence of the x-ray images on the laser incidence angles and the preplasma scale length are presented.

2. Experimental setup
The experiments were carried out using the Xtreme Light II (XL-II) Ti: sapphire laser system at the Institute of Physics, Chinese Academy of Sciences. The laser system can deliver a linearly-polarized pulse with energy up to 0.6 J in 60 fs at 800 nm. The laser pulse was focused onto a target using an f/3.5 off-axis parabolic mirror. The diameter of the focal spot was ~ 4.5 μm. This gave an intensity up to 5×10^{18} W/cm^2. The contrast ratio was ~ 10^{-5} measured by a third order cross-correlator (Sequoia) at 10 ps. A prepulse with a duration of 60 fs, split from the main pulse, was used to generate a preplasma. The main diagnostic was Kα x-ray imaging technique. A spherically bent quartz crystal was used to image the Cu Kα x-ray emission at 8.048 keV onto a 16 bit charge-coupled device (CCD) camera with a magnification of 8x. The energy resolution was about 11 eV. The astigmatism-limited spatial resolution was ~ 20 μm. A Be filter was set in front of the CCD camera to remove visible light and reduce background x-ray noise.

3. Results and discussions

Figure 2 shows the x-ray images taken for three laser prepulse conditions. The laser incidence angle is 45°. For all the images a halo structure surrounding a bright spot is observed. The size of the halo increases with the preplasma scale, while the x-ray photon number decreases. Another interesting phenomenon is that a ring-like halo is presented in Fig. 2(b).

Figure 3 shows the images taken for the incidence angle 45° and 70°. The laser pulse comes in from the right. For 45° the halo is basically symmetrical, while for 70° the halo becomes non-symmetrical and more x-ray photons are excited along the laser propagation direction.

Figure 1. Schematic view of the experimental setup.

Figure 2. Kα x-ray images for different prepulse conditions. The energy of the main pulse (E_{main}), delay time between the prepulse and the main pulse (Δt), and intensity of the prepulse (I_{prepulse}) are listed on each image.

Figure 3. Kα x-ray images for different incidence angles. Preplasma density scale length.

Figure 4. Cu Kα x-ray images for different prepulse conditions.
Figure 3. $K_{\alpha}$ x-ray images for the incidence angle of 45° (a) and 70° (b).

The $K_{\alpha}$ x-ray photons measured can be possibly excited by three groups of fast electrons, as shown in Fig. 4(a). The first group transports longitudinally into the target bulk and excites x-ray photons at the deep regions (not so deep that x-ray still can escape into vacuum and seen by the imaging crystal). The second one transports laterally as a current along the initial target surface due to the confinement of the surface magnetic and electrostatic fields [6,12]. However, this current is significant only when the electron density profile is steep. The third one is the electrons that diffuse in the preplasma. $K_{\alpha}$ x-ray photons are excited when the path of such electrons intersect the high density regions near the target surface. We used a step-like target to distinguish the three mechanisms. Figure 4 (b) shows the target configuration and optical image taken by a microscope. An 18 µm thick copper foil is coated on a CH plastic substrate partially. The laser pulse shines on the CH substrate near the copper coating. In this case the Cu $K_{\alpha}$ x-ray photons are excited only by the electrons above the CH substrate. Figure 4(c) and (d) shows the comparison of the step-like target with the standard plane copper target. One can see that the signals at the halo regions are similar to each other. This indicates that the longitudinal and the lateral fast electron current under the initial surface do not contribute much to the x-ray signal measured. The measured halo mainly originates from the third group of fast electrons.

Figure 4. $K_{\alpha}$ x-ray photons excited by three groups of fast electrons at different target regions (a); configuration and optical image of a step-like target measured by a microscope (b); and the comparison of the x-ray images for the step-like (c) and standard planar copper (d) target. The white solid line shows the position of the boundary between the copper coating and the CH substrate.

When the intensity of the prepulse and the delay between the prepulse and main pulse are increased, the preplasma scale length is increased accordingly. The third group of fast electrons can go further away with the preplasma from the laser focus laterally. Therefore, the size of the x-ray halo observed is increased with the laser prepulse. When the laser incidence angle is as large as 70°, the light
pressure of the main pulse will lead to a non-symmetric distribution of the plasma. This can explain the tail-like distribution in the laser propagation direction shown in Fig 3(b).

The ring structure in Fig. 2(b) is probably caused by the self-generated magnetic field in the preplasma. It is well known that an azimuthal magnetic field can be generated due to the nonlinearity of the electron density gradient and the electron temperature gradient [13]. Recent measurements with proton deflectometry show that the strong magnetic fields can be generated at the edge of a plasma [14,15]. Such fields can modify the fast electron trajectories and result in the observed x-ray ring.

4. Conclusions
Lateral propagation of fast electrons at the front target surfaces irradiated by intense laser pulses has been studied by $k_x$ x-ray imaging technique. It is found that a halo structure is formed around the laser focus. The halo size increases with the preplasma scale length and a ring structure is presented. A non-symmetrical halo distribution is also observed for the laser incidence angle $70^\circ$. However, this does not directly correlate with the fast electron current at the initial target surface because the observed x-ray photons in the halo region are mainly excited by the fast electrons flowing and diffusing in the preplasma. One should be careful to distinguish the possible x-ray origins when using a crystal imaging technique to study fast electron transport.

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