Effect of target shape on fast electron emission

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Abstract. Fast electrons emission from the interaction of femtosecond laser pulses with shaped solid targets has been studied. It is found that the angular distributions of the forward fast electrons are closely dependent upon the target shape. The important role played by the electrostatic fields built up near the target surfaces in the confinement of fast electrons is identified. Our two-dimensional particle-in-cell simulations can reproduce the main observations.

1. Introduction
How to control and guide the forward fast electron beam in the interaction of a high intensity relativistic laser pulse with plasmas is of significance for fast ignition in inertial confined fusion [1], high-energy ion generation [2], x-ray emission [3], etc. Recently how to manipulate the fast electrons using non-irradiated target surfaces attracts much attention. Preliminary simulations suggest that collimated propagation of fast electrons through solid targets can be achieved using vacuum gaps and/or radially graded materials that results in confining electric fields [4]. Measurements of the ultraviolet optical emission from the rear surface of an aluminum plane foil attached to a solid cylindrical or a tapered target indicates the feasibility of the guiding of fast electrons through careful shaped target. Guiding of high-density MeV electrons by a fine fiber attached to a hollow cone target has also been demonstrated [5].

In this paper we present direct observations of fast electron emission from the interaction of short-pulse laser pulses with various shaped solid targets. We find that the angular distribution of the escaped fast electrons is closely dependent on the target shape. With our two-dimensional (2D) particle-in-cell (PIC) code and the Monte Carlo code, ITS 3.0 (Integrated TIGER Series of Coupled Electron/Photon) [6], the roles of the electrostatic fields generated at the interface between the target and the vacuum as well as the collisional effect in the target played in fast electron emission are identified.

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2. Experiment
The experiments were carried out using the Xtreme Light II (XL-II) laser system at the Institute of Physics, Chinese Academy of Sciences. The laser system can produce a linearly polarized pulse with an energy up to 500 mJ in a duration of 30 fs at a wavelength of 800 nm. The laser pulse was focused by an f/3.5 off-axis parabolic mirror to a focal spot size of 10-15 µm in diameter. Planar and wedged copper targets were used, respectively. The standard planar target was 65 µm thick copper disk with a diameter of 1000 µm. The wedged target was isosceles with a tip angle of 25°, height of 150 µm (from the tip to the top surface), and length of 2000 µm (between the two isosceles surfaces). The angular distributions of the forward fast electrons behind targets were measured by an array of sandwiched imaging plate (IP) stacks, which surrounded the laser focus region in the plane of laser incidence.

3. Experimental results and discussions
First, we compare the fast electrons emitted from the wedged targets with those from the planar targets. Figures 1(a)-1(c) show the angular distributions of the forward fast electrons with energies greater than 300 keV in the laser incident plane for the planar and wedged targets, respectively. The laser pulse was incident with an angle 25° relative to the front target normal direction. The angle 0° in Fig. 1 corresponds to the front target normal. For the wedged target the laser pulse was focused on one of the side surfaces, rather than the top surface opposite the tip (see the inset in Fig. 1). The laser focus was close to the wedge tip where the target thickness was 65 µm, the same thickness as that of the planar target. The laser energies were 60-80 mJ for the shots. For the standard plane target, the fast electron emission peaks between the laser propagation and target normal direction. However, for the wedged target the peak of the fast electrons is approximately shifted towards the normal direction of the rear target surface, significantly deviated from the laser propagation and the front target normal direction. More interestingly, when the wedged target is rotated by 180°, the distribution is also rotated correspondingly, as shown in Fig. 1(c). One may note that the divergence angles of the fast electrons from the wedged target are also larger than that from the planar target. These results demonstrate that the target shape, especially the orientation of the rear surface, can significantly modify the fast electron emission.

We have used the 3D Monte Carlo code, ACCEPT, which is one of subcodes of the ITS 3.0, to model the pure collisional effect of the fast electron transport in the copper targets. In the MC simulations we assumed a disk electron source with a radius 10 µm. The energy spectrum was a Maxwellian distribution with a temperature 200 keV. The electrons were injected into the target at 25° with respect to the front target normal with a 50° cosine-law angular distribution. The distributions of the escaped electrons from the target rear surface modeled by the MC code are also shown in Fig. 1 (see the dashed lines). For comparison all experimental and theoretical distributions are normalized. One can see even for the E>300 keV electrons, which have much longer penetration ranges than the target thickness, the collisional effect still plays a role in the modification of the distributions. The collisions always make the electrons slightly deflected to the thin tip of the wedge. However the deflections are not large enough to reproduce the observed distributions. This indicates that the self-generated fields should be more important than the collisions in the fast electron emission.

Angular distributions of the fast electrons were also measured when the laser pulse was incident from the top surface opposite the tip of the wedge [see the inset in Fig. 2(a)]. To check the collision effect we first ran MC simulations in which an electron beam was injected into the wedge from the top. Figure 2(a) shows the simulated results for the E>600 and E>120 keV electron beams. The central part of the electron beam is depressed much due to the collisions. This manifests itself as two peaks on both sides of the isosceles surfaces. The separation of the peaks is larger and the concavity is deeper for the low energy electrons than that for the high energy electrons.

Figures 2(b) - 2(d) show the measured angular distributions for the planar and wedged targets, which top was irradiated by a laser pulse with energies of 150-180 mJ, respectively. The laser incidence angle was ~15°. The E>600 keV fast electrons are emitted with a single smooth peak for the
planar [see Fig. 2(b)], while with double peaks on the both sides for the wedged [see Fig. 2(c)]. This is similar to the predicted profile by the MC code. However, the measured distribution of the $E>120$ keV fast electrons is very different from the MC simulations. A large number of electrons are also emitted in the tip direction [see Fig. 2(d)], resulting in a distribution without an obvious concavity.

**Figure 1.** IP Images of the $E>300$keV fast electrons for a planar (a), wedged (b), and wedged target rotated by 180° (c), respectively. The black solid lines are the scanned intensity distributions. The blue dashed lines are theoretical results simulated by the MC code. The insets illustrate the target shape and orientation.

**Figure 2.** Angular distributions of the $E>600$keV (black solid) and $E>120$keV (blue dashed) fast electrons simulated by the MC code (a); IP images of the $E>600$keV fast electrons from a planar (b), $E>600$keV (c) and $E>120$keV (d) electrons from a wedged target, respectively.

We attribute the discrepancy between the MC simulations and the measurement for the $E>120$ keV fast electrons to the setup of the electrostatic fields at the rear target surfaces. The fields are induced when the forward fast electrons are transported to the rear surface. The high energy component of the fast electrons reaches the rear surfaces in advance of the low energy electrons. The induced fields are weak at the early stage because the number of such high energy electrons is small. Consequently, those high energy electrons are less influenced by the fields when escaping into vacuum. However, as large numbers of electrons with moderate and low energies reach the rear surface, the fields grow up rapidly. Then the fields will inhibit the low energy electrons from escaping into vacuum and confine them propagating along the target. (Note the fields also accelerate ions by the normal sheath acceleration (TNSA) mechanism [2]). Therefore the low energy electrons tend to emit towards the wedge tip.

2D PIC simulations have been conducted to understand the effect of the *self-generated fields* on the fast electron emission. The laser conditions are similar to the experiments. The initial electron density of the plasma slab is $6n_c$, where $n_c$ is the critical density. The diameter of the laser focus is $12\lambda_0$, where $\lambda_0$ is the laser wavelength. The laser electric field is in the Y-direction. Figures 3(a) and 3(b) show the distributions of the electrostatic filed, $E_x$, and the fast electrons with the relativistic factor, $\gamma>2$, at the time of $t=55$ laser cycle for a right-angle wedge, one of which side surfaces was irradiated by a laser pulse at 20° from the left, respectively. This represents the similar interaction geometry to Fig. I(c). Strong electrostatic fields are induced at the rear target surface. The rear fields at the region in line
with the laser axis are stronger due to more fast electrons propagate along the laser axis. The fields reflect most electrons back to the target bulk. However, there are still some fast electrons ejected not only in the laser propagation direction but also close to the rear target normal, as shown by the arrows indicating the moving directions of the electrons in Fig. 3(b). This basically agrees with the experimental result shown in Fig. 1(c).

Figure 3. Distributions of the electrostatic filed $E_x$ (a) and $\gamma$>2 fast electrons (b) at the time of $t=55$ laser cycle. The arrows guiding the eye in (b) show the moving directions of the fast electrons.

Figures 4(a) and 4(b) show the distributions of the fast electrons at $t=60$ and 100 laser cycle, respectively, when the wedge is irradiated by a laser pulse from the left. In this simulation the normalized amplitude of the laser pulse, $a_0$, is set to be 4, which leads to much stronger electrostatic fields. One can see numerous electrons are injected into the target from the interaction region at early stage. As the electrons propagate in the target, the strong fields induced on both side surfaces of the wedge reflect the scattering electrons back into the target. Consequently, the fast electrons are guided to the tip of the wedge.

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