Emission direction of fast electrons in laser-solid interactions at intensities from the nonrelativistic to the relativistic

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The emission direction of outward-ejecting fast electrons generated in laser-solid interactions by 30 fs laser pulses is measured for laser intensities varying from the nonrelativistic to the relativistic. For an *s*-polarized incident laser beam at nonrelativistic intensities, the ejected electrons are close to the polarization direction of the laser beam. With the increase of the laser intensity, the ejected electrons are still mainly within the polarization plane, but turn away from the laser polarization direction towards the opposite direction of the incident laser beam. At relativistic intensities, electrons eject towards the direction of the reflected laser beam. The increasing ponderomotive force acceleration with the laser intensities might be responsible for the observed changes.

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I. INTRODUCTION

Since the emission direction of fast electrons plays a critical role in many applications, such as the laser acceleration and the fast ignitor scheme [1], it has attracted a great deal of attention in recent years [2–8]. There are many potential mechanisms for fast electron generation, e.g., the resonance absorption [9,10], the $\mathbf{j}\times\mathbf{B}$ heating [11], and the ponderomotive force acceleration [12–14]. Different mechanisms produce different angular distributions of fast electrons. The resonance absorption processes are expected to produce fast electrons mainly in the direction of the density gradient for *p*-polarized laser, while the other two mechanisms produce fast electrons mainly in the laser propagation direction.

In recent years, several experiments were conducted to study the dependence of fast electron emission on the laser polarization, laser wavelength, and plasma density scale length, etc. [2–5]. However, the effect of laser intensity, one of the most important factors, on the fast electron emission is not well understood. With the development of laser technology [15–17], the focused intensity of a table-top laser can now easily cover a range from the nonrelativistic (less than 10^{17} Wcm^{-2}) to the relativistic (over 10^{18} Wcm^{-2}). As the laser intensity increases, the mechanisms for laser absorption and electron acceleration also change. As a result, the behavior of the fast electron emission would be different at different laser intensities. For relativistic-intense ultrashort laser pulses, one of the significant effects is the presence of a huge ponderomotive force $F_p = mc^2\boldsymbol{\nabla}(1+I_{18}\lambda^2/2.74)^{1/2}$, which can accelerate electrons to a longitudinal momentum much higher than the maximum transverse quiver momentum inside the pulse $mc(I_{18}\lambda^2/1.37)^{1/2}$. Here I_{18} is the laser intensity in unit of 10^{18} $\mathrm{W/cm^2}$ and λ is the laser wavelength in μm. Therefore, it is interesting to investigate the evolution of the angular distribution of fast electrons as the laser intensity changes from the nonrelativistic to the relativistic.

In this paper we present an experimental investigation on the angular distribution of the outward-moving fast electrons from Al targets irradiated by 30 fs laser pulses at different intensities ranging from the nonrelativistic to the relativistic. For *s*-polarized irradiation of laser light, we observe significant changes in the emission direction of fast electrons as we increase the light intensity.

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The experiments were performed with the JG-II home-made Ti:sapphire laser operating at 800 nm with a repetition rate of 10 Hz. The laser is capable of delivering up to 640 mJ energy in 30 fs pulses. The contrast ratio of the laser pulse was measured to be about 10^{-6}. The laser beam was focused with an $f/5$ off-axis parabolic mirror and incident at 45° with respect to the target normal. The targets were 5-mm-thick aluminum discs with a diameter of 35 mm. The target surface was polished to ensure the roughness less than 1 μm. The target was moved 0.5 mm per second so that laser pulses interacted with a fresh target surface for each shot. To reduce the two-dimensional (2D) or 3D effects of the plasma we deliberately adjusted the target off the best focus so that the measured results can be compared directly with our 1D simulations. The focal spot size was measured with a pinhole camera by imaging the x-ray emission. With a 10-μm-diameter aperture and a 6-μm-thick Al filter, an average 20-μm full width at half maximum focal spot was obtained. For most of the shots, 500 mJ laser energy was used, in which about 70%

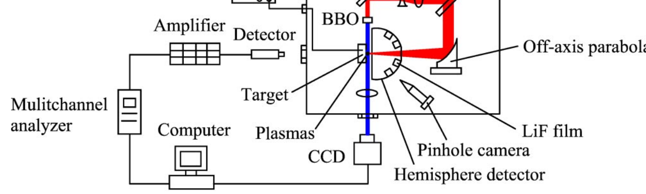

FIG. 1. The schematic experimental setup.

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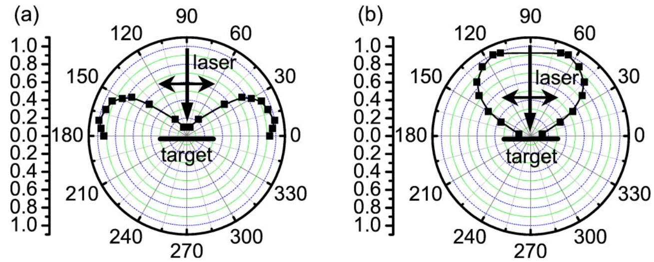

FIG. 2. Angular distributions of fast electrons in the polarization plane formed by the wave-vector of the incident pulse and the laser polarization. The laser intensity are (a) 2×10^{16} Wcm^{-2} and (b) 4×10^{17} Wcm^{-2}, respectively.

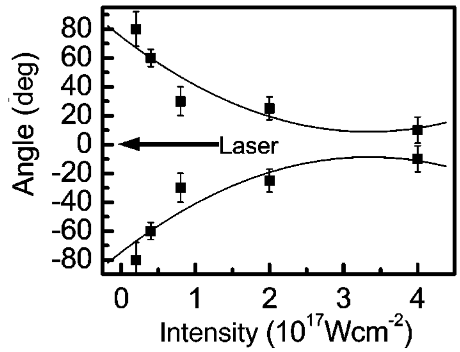

FIG. 3. Emission angles of fast electrons vs the laser intensity. The solid lines are fitting curves.

was found to be concentrated in the focus. The laser intensities in the range of 10^{16}–10^{18} Wcm^{-2} was used in the experiment to study how the characteristic of the hot electrons change when laser intensity is varied from the subrelativistic to the relativistic. The laser beam was in *s* polarization on targets.

Fast electrons were recorded by LiF (Mg, Cu, P) thermoluminescence dosimeter films with a size of $\phi 4.5\times0.8\,\mathrm{mm}^2$. More than 80 pieces of LiF films were uniformly mounted on the inner surface of a hemisphere detector [3,5]. The angular resolution of this system was about $8°$. The center of the hemisphere was superposed with the focal spot of the focusing mirror. The laser beam passed through an aperture of 25 mm diameter on the hemisphere. The LiF films were coated with a 6-μm-thick Al filter so that low energy electrons (<10 keV) and the scattered light can be blocked. In order to confirm the exposure on the LiF film was due to fast electrons, we made null tests by adding a 2000 G magnetic field near a LiF film to deflect the electrons. The recorded data on the LiF film were at least three orders of magnitude lower than the case without magnetic field. This indicated that x rays and γ rays contributed little to the exposure on the LiF film.

III. RESULTS

The angular distribution of fast electrons is measured for the interaction of obliquely incident *s*-polarized laser pulses with aluminum targets at laser intensities ranging between 10^{16}–10^{18} Wcm^{-2}. At nonrelativistic laser intensities, it is found that fast electrons are concentrated in the polarization plane formed by the wave vector of the incident beam and the laser polarization vector. Few electrons have been measured in the incident plane formed by the wave vector of the incident beam and the normal of the target surface, in agreement with our earlier experiments conducted with similar conditions [5]. Figure 2 illustrates the angular distribution of fast electrons in the polarization plane at the nonrelativistic laser intensities, where each data point represents a single shot. At the intensity of 2×10^{16} Wcm^{-2}, two bundles of fast electrons emit along the directions about 80° from the opposite direction of the incident beam symmetrically on both sides, i.e., they are close to the laser polarization direction as shown in Fig. 2(a). This suggests that the transverse electric field of the laser pulse plays a dominant role in producing the electron jets in this case. As the intensity is increased up to 10^{17} Wcm^{-2}, the fast electron bunches turn towards the opposite direction of the incident beam. At the intensity 4×10^{17} Wcm^{-2}, for example, most electrons are found to emit along the direction about 10° away from the opposite direction of the incident beam, as shown in Fig. 2(b). The relation between the emission angle of fast electrons and laser intensity is shown in Fig. 3. It is obvious that, with the increase of the laser intensity, the emission angle changes from the laser polarization direction towards the opposite direction of the incident laser beam. This suggests that the ponderomotive force of both the incident and reflected pulses begins to play a role in producing the electron jets [12].

When the intensity is increased further up to the relativistic threshold, the emission direction is no longer concentrated in the polarization plane formed with the wave vector of the incident beam, but close to a plane formed by the wave vector of the reflected beam and the polarization vector. The angular distribution of fast electrons in incident plane is shown in Fig. 4 for the intensity 2×10^{18} Wcm^{-2}. As one can see that the emission of fast electrons, turning completely away from the incident laser beam, is concentrated in the direction about 10° away from the direction of the reflected beam. This electron jet appears to have higher energies than those shown above for lower intensities. Since the ponderomotive force is much larger in this case, this

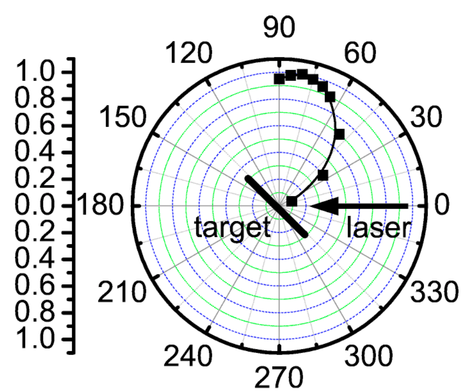

FIG. 4. Angular distributions of fast electrons in the incident plane formed by the wave vector of the incident pulse and the normal of the target surface. The intensity of the incident laser pulse is 2×10^{18} Wcm^{-2}.

electron jet is expected to be concerned with ponderomotive force acceleration by the reflected beam. The tendency of the experimental observation is in qualitative agreement with the theoretical prediction given in Ref. [6], which suggests that an outward-moving electron beam with very high energies will emit in a direction close to the reflected beam and those with low energies will emit close to the normal to the target surface.

IV. CONCLUSION

In summary we have observed the electron emission from a solid target irradiated by 30 fs laser pulses at intensities ranging from less than 10^{17} Wcm^{-2} up to over 10^{18} Wcm^{-2}. At intensities less than 10^{17} Wcm^{-2}, it is found that the emission direction of fast electrons is mainly close to the laser polarization direction, in agreement with previous experimental results [5]. With the increase of the laser intensity, the electron jets turn away from the laser polarization towards the opposite direction of the incident pulse. With the further increase of the laser intensity up to over 10^{18} Wcm^{-2}, the longitudinal ponderomotive force along the propagation axis of the reflected pulse increases. As a result, fast electrons eject away from the polarization direction towards the direction of the reflected laser pulse. This is qualitatively in agreement with the theory [6]. For a quantitative analysis of the experimental data, three-dimensional simulations are necessary to take into account different laser absorption and electron acceleration mechanisms under different laser intensities in the oblique incidence geometry, as well as the intersecting laser fields in front of the solid target formed by the incident and reflected laser pulses.

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