Effects of Laser Polarization on Jet Emission of Fast Electrons in Femtosecond-Laser Plasmas

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Effects of laser polarization on fast electron emission are studied from an aluminum target irradiated by ultrashort laser pulses at 2×10^{16} W/cm^2. Jet emission of outgoing fast electrons collimated in the polarization direction is observed for *s*-polarized laser irradiation, whereas for *p*-polarized irradiation highly directional emission of outgoing fast electrons is found in the direction close to the normal of the target. The behavior of ingoing fast electrons into the target for *s*- and *p*-polarized irradiation is also investigated by observing x-ray bremsstrahlung radiation at the backside of the target.

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Fast electron production and transport have been studied extensively [1–11]. However, there is still not enough understanding of physics mechanisms that control the emission direction of fast electrons. Especially, the experimental observations made by different groups on the emission direction of fast electrons generated by ultrashort pulse laser-solid interactions are not very consistent [2,5–8,10]. Some experiments have observed highly peaked MeV electrons in the laser axial direction [6], whereas the others have found collimated emission of fast electrons in the specular direction [7] or in the normal direction of targets [8].

Collimated fast electron emission can be accelerated by different acceleration mechanisms, such as resonance absorption, vacuum heating, $\mathbf{j} \times \mathbf{B}$ heating, or different sorts of skin effects [11]. Most of these mechanisms are present only for *p*-polarized obliquely incident irradiation. It is very important to study the effects of laser polarization on the electron emission because many basic plasma behaviors are controlled by strong laser fields rather than by plasma density and temperature [7].

The main aim of this paper is to investigate the effects of the laser polarization on acceleration mechanisms by observing outgoing fast electrons and ingoing fast electrons generated by *p*- and *s*-polarized ultrashort laser pulses that are obliquely incident on an overdense plasma with or without a corona preplasma. Our measurements raised some important disagreements with simulations. These disagreements may shine new insights on acceleration mechanisms and are certainly worth further investigation.

The experiments were carried out with a Ti:sapphire laser operating at 800 nm at a repetition rate of 10 Hz. The laser delivered 5 mJ energy in 150 fs pulses into a focal spot with a diameter of <15 μm (due to the limitation of the pinhole size of 15 μm) and produced a peak intensity at the laser focus $>2 \times 10^{16}$ W/cm^2. The contrast ratio of the laser pulse was measured to be better than 10^{-5} (at 1 ps before the main pulse). The laser beam was focused on a 70-μm-thick Al target with a 10-cm focal length off-axis parabola. The Al target with a size of 4 cm × 2 cm was placed on a 3 mm thick backing glass mount. For some shots, 8% energy was split off from the main laser beam to form a low intensity prepulse, which was 50 ps in advance of the main pulse in order to provide a corona preplasma for interaction [12]. Plane polarized (*p* or *s* polarized) laser pulses were incident at 45° from the target normal.

The main diagnostic of fast electrons was a magnetic spectrometer [12]. The energy range of this instrument covered from 7 to 500 keV. The angular distribution of the fast electron emission was measured by placing an Al foil covered direct-exposure film (DEF) in an 8-cm-diameter cylinder around the laser focus [13]. Two calibrated γ-ray spectrometers were used to study the x-ray Bremsstrahlung radiation from the laser plasma [14]. The absorption of the laser beam was determined by a 4π calorimeter. Absolute measurements of fast electrons with high energies were made by measuring charge separation potential at the laser focus. As some fast electrons with high energies outwards are ejected out of the plasma, a charge separation potential is simultaneously established by the background ions at the target surface [15]. By converting the instantaneous charging current into a slow varying discharging process with an *LCR* circuit, the number of outgoing fast electrons can be counted accurately.

Figure 1 shows the cutaway view of the angular distribution of fast electrons generated by *s*-polarized irradiation without prepulses. The sharp boundary of the exposure on the DEF films and the geometry of the target ensured that the electrons recorded by the film came from the front side of the Al target. The outgoing fast electrons were found to be collimated along the laser polarization direction in a plane perpendicular to the incident plane. In the incident plane, no fast electrons were measured. It was also found that the fast electrons with higher energies have narrower angular divergence. When there was a corona preplasma in front of the target, a very small percentage of outgoing fast electrons could be found in the incident plane. This suggests that the outgoing fast electrons were mainly

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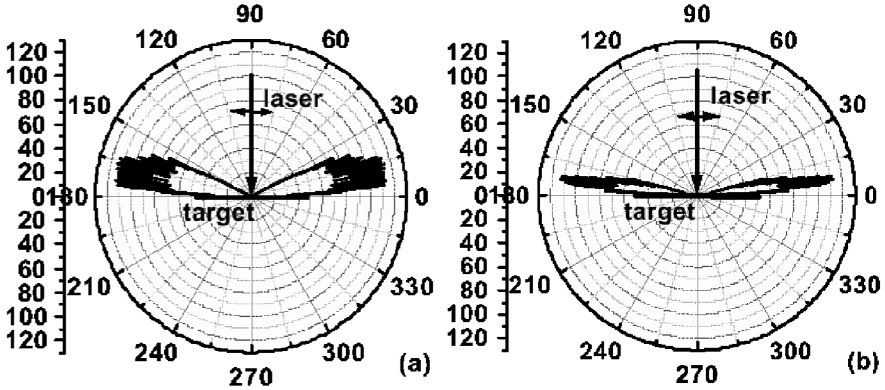

FIG. 1. The cutaway view of the angular distribution of outgoing fast electrons with energies over (a) 50 keV and (b) 250 keV in the plane perpendicular to the incident plane.

accelerated by the electric field of the *s*-polarized laser pulses. When there is a corona preplasma in front of the overdense plasma, the possible modulation of the critical surface of the preplasma will steer a very small percentage of the fast electrons out of the polarization direction. This phenomenon seems to be similar to the results of laser-accelerator injector based on laser ionization and the ponderomotive acceleration of electrons in gas, where electrons are accelerated in the polarization direction [13,16], but the heating mechanisms are obviously different.

When the target was irradiated by a *p*-polarized laser pulse with a prepulse 50 ps in advance of the main pulse, the behaviors of fast electrons were much different from those generated by *s*-polarized laser pulses. As Fig. 2 shows, almost all of the outgoing fast electrons were emitted in the normal direction. The emission direction of the fast electrons obeys the momentum conservation [8,17].

The emission angle of fast electrons over 250 keV ($\gamma > 1.4$) in the incident plane was found to be 16° from the target normal direction (Fig. 2b), where γ is the relativistic factor of the fast electrons. Further measurements, with thicker filters, of emission angle of small fraction of fast electrons over 1 MeV ($\gamma > 2.95$) gave a value of 30°. It is apparent that the emission direction of the fast electrons with higher energies moved towards the specular direction (45°). The full width at half maximum of the emission of fast electrons with energies over 20, 50, and 250 keV was measured to be 32°, 28°, and 15°, respectively.

In the interaction between ultrashort laser pulses and plasmas, the bulk of thermal electrons are generated by collisional absorption. A small fraction of fast electrons can be generated by different heating processes. It is interesting to know the fraction of fast electrons with high energies versus bulk of thermal electrons with modest energies. The lower limit of the fraction of the fast electrons with energies over 50 keV, which is the measured charge separation potential, was measured to be 2.6% of the total laser energy, assuming that the number of ingoing fast electrons is equal to that of outgoing electrons. Because the total laser absorption by the plasmas was measured to be about 74%, the fraction of energy of fast electrons was, at least, 3.5% of the total energy of thermal electrons. By measuring the fraction of fast electrons with energies over 250 keV and 1 MeV, respectively, relative to those with energies over 50 keV, the fraction of fast electrons over 250 keV and 1 MeV was estimated to be 0.35% and 0.1%, respectively, of the total energy of thermal electrons.

Unlike the observation with a prepulse, a jet emission of fast electrons was observed in the specular direction,

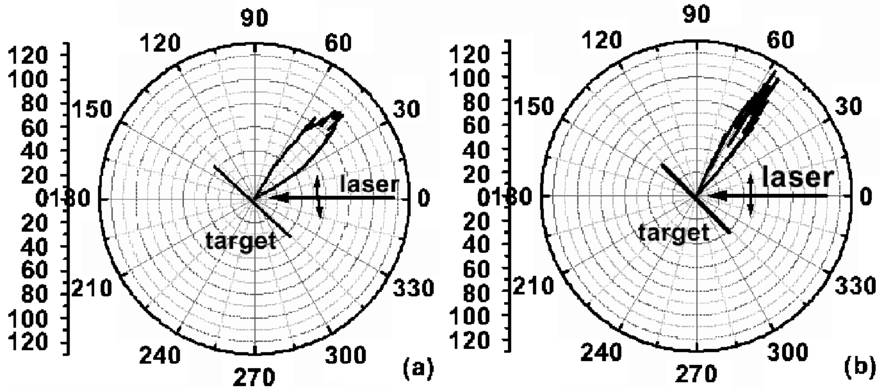

FIG. 2. The angular distribution of outgoing fast electrons with energies over (a) 50 keV and (b) 250 keV in the incident plane, respectively. The fast electrons were generated by *p*-polarized obliquely incident laser pulses with a prepulse 50 ps in advance. The FWHM is about 28° and 15°, respectively.

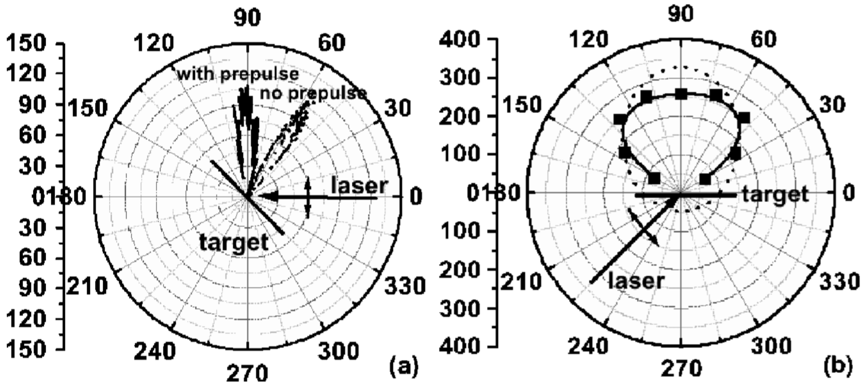

FIG. 3. (a) Angular distribution of fast electrons generated by a p-polarized laser without prepulse (solid line) and with a prepulse 50 ps in advance (dashed line) in the incident plane. (b) The x-ray distribution at the backward of the target with energies >50 keV in the incident plane, irradiated by p-polarized obliquely incident laser pulses with a prepulse 50 ps in advance. The dotted line is the theoretical calculation for the target interaction with a 50 keV electron beam.

when the target was irradiated by a p-polarized irradiation without prepulses. This agreed with Bastiani's experimental results [7]. Figure 3a shows this change. This is very different from the behaviors of fast electrons generated by p-polarized irradiation with prepulses. This suggests that a corona preplasma does play a very critical role in determining the emission direction of fast electrons.

It is important to know the propagation process of the ingoing fast electrons into targets because these fast electrons are critical to the concept of fast ignition [1]. Fast ignition is of importance to the inertial confinement fusion research through its potential to give higher inertially confined fusion gain than the conventional indirect or direct drive schemes and thereby to reduce the driver energy required for inertial confinement fusion. Fast electrons injected into targets will undergo multiple Coulomb scattering with nuclei and produce x-ray Bremsstrahlung radiation. Therefore, the x-ray energy spectrum at the backside of the target could provide rich information on ingoing fast electrons in targets. Figure 3b shows the angular distribution of x rays. The angular distribution shows a symmetrical structure around the target normal. The FWHM of x-ray angular distribution was about 100°. It is clear that the main characteristics of the angular distribution of x-ray Bremsstrahlung radiation is very similar to those produced by a collimated fast electron beam with 50 keV energy in the normal direction injected into the target [16]. By comparison, a rather random distribution of x rays was observed at the backside of targets irradiated by s-polarized laser pulses with a prepulse 50 ps in advance. The x-ray flux was about 10 times weaker than that driven by p-polarized irradiation. This indicated that there was no jet forming of ingoing electrons for s-polarized irradiation, and this is against the simulation prediction [8].

To explain the experiments, we have run two-dimensional particle-in-cell (PIC) simulations. The simulation box size is $24\lambda \times 40\lambda$. Particles are filled only in a limited region, typically with 25 cells per laser wavelength and 16 particles per cell. We find that the simulation can

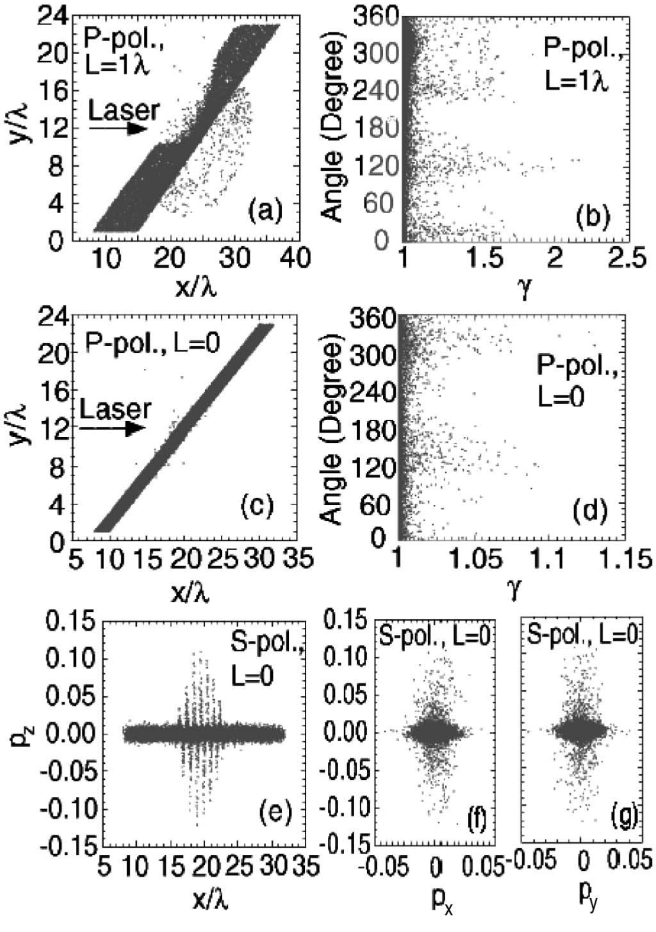

FIG. 4. Electron distributions in geometry and momentum space found from two-dimensional PIC simulations. A laser pulse with normalized amplitude $a_0 = 0.2$ and a duration of 50 laser cycles is incident obliquely at 45°. (a) plots (x, y) electron positions and (b) angular distribution at $t = 60$ laser cycles for p-polarized incidence onto plasma with scale length $L = 1\lambda$; (c) plots (x, y) positions and (d) angular distribution at $t = 50$ for p-polarized incidence onto plasma with a steep density profile; (e) plots (p_z, x) positions, (f) plots (p_z, p_x), and (g) plots (p_z, p_y) all at $t = 50$ for s-polarized incidence onto plasma with a steep density profile.

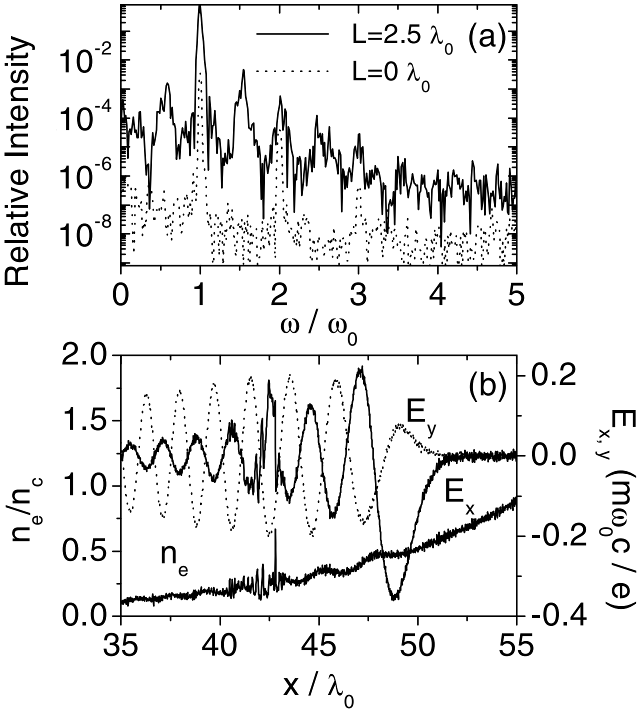

FIG. 5. The time integrated frequency spectra of the reflected p-polarized light obliquely irradiating on plasmas with different density scale lengths (a). (b) shows the density and electric field disturbance around the quarter critical density where the Raman instability has the highest growth rate under our conditions.

best reproduce our main experimental results, if we take $a_0 = 0.2$. This implies that the laser intensity at focus might be larger than 2×10^{16} W/cm^2 due to the possible self-focusing effects occurring in the laser plasma, resulting in higher intensity in the interaction. Figures 4a and 4b show the (x, y) positions of electrons and their angular directions, respectively, at $t = 60$ laser cycles, obtained for p-polarized incidence onto plasma. Initially, the electron density increases from $0.01 n_c$ exponentially with a scale length of 1λ until about $2.5 n_c$. They show evidently that electrons are pushed out around the normal to the target direction (i.e., 135° and 315°, since it assumes that the incident laser propagates in 0°). This agrees with the experiments for the case with prepulses and the theory in [17].

Figures 4c and 4d show the case with a steep density profile. Unlike the experimental observation, outgoing electrons are observed in wide angular distributions, including in a reflected direction (90°). Figures 4e, 4f, and 4g are obtained for s-polarized incidence. Note that during the laser interaction, the momentum in the polarization direction is much larger than that in the x and y directions. Thus if electrons are pulled out from the target, they must be directed in a small angle against the target surface. This is exactly what was observed in the experiments.

It appears that parametric instabilities excited around the quarter critical density are responsible for the acceleration for $L > \lambda$. This is obvious from the frequency spectra of the reflected light (Fig. 5). For $L > \lambda$, emission near half of the laser frequency as well as at one half and one half the laser frequency appear.

In summary, we found that both s- and p-polarized lasers can generate jet emission of fast electrons at moderate laser intensities. This provides new insights into acceleration of fast electrons in laser-plasma interaction. Our experimental results have indicated that the 2D PIC simulations can reproduce the main characteristics of outgoing fast electrons generated by p-polarized laser pulses with prepulses. However, the simulations failed to reproduce the jet emission of outgoing fast electrons in the specular direction produced by p-polarized laser pulses without prepulses. In this case, our experimental results have settled down the disagreement between two groups on the emission direction of fast electrons generated by p-polarized laser pulses on a steep profile plasma [7,8].

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