Double-peak emission of hot electrons generated by femtosecond laser interaction with solid targets

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Double-peak emission of hot electrons has been observed in the interaction of a 60-fs, 125-mJ, 800-nm, *p*-polarized laser pulse with Al targets. One peak in the specular direction is due to the reflected laser light, which excites a plasma wave to accelerate electrons. The other peak, which is more consistent with theories of Y. Sentoku *et al.* [Phys. Plasmas **6**, 2855 (1999)] and H. Ruhl *et al.* [Phys. Rev. Lett **82**, 743 (1999)], is produced by the resonance absorption at approximately 15° from the target normal.

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I. INTRODUCTION

Hot electrons emission in laser plasma has been studied extensively [1–11]. For example, Malka *et al.* [10] and Tatarakis *et al.* [6] observed highly peaked MeV electrons in the laser axial direction, whereas Kodama *et al.* [2] and Bastiani *et al.* [4] found that the collimated emission of hot electrons was in the specular direction. Sentoku *et al.* [1] pointed out that the direction of the collimated MeV electrons generated by an obliquely irradiated *s*-polarized laser would be along the specular reflection, while that generated by the *p*-polarized light would be determined by the canonical momentum conservation along the target surface. In Chen's [9] report, the jet emission of outgoing fast electrons collimated in the polarization direction was observed in the case of *s*-polarized laser irradiation, while with *p*-polarized laser, the highly directional emission of outgoing fast electrons was found in the direction close to the normal of the target. Ruhl *et al.* [11] presented a scaling law about the relation of the angle of the ejected electrons with the incident laser intensity, which agreed qualitatively with the results resulted from particle-in-cell and Vlasov simulations.

Recently, Santala *et al.* [3] reported that there was a double-peak angular distribution of bremsstrahlung γ ray in large scale length L and pointed out that this could be regarded as an evidence of the generation of two separate electron beams that generate two partially overlapping γ ray beams. Krushelnick *et al.* [12] reported on a "figure 8" pattern of energetic ions (or overlapping ion beams), which may correspond to the generation of two distinct electron beams as observed in some of their previous nuclear activation measurements. These two simultaneous electron beams may give rise to a complicated magnetic field that can produce the observed magnetic field deflection pattern.

Collimated hot electrons can be accelerated by different acceleration mechanisms, such as classical and Brunel-type resonance absorption [13,14], ponderomotive $\mathbf{j}\times\mathbf{B}$ acceleration [15], wake-field acceleration [16,17], and so on. Different mechanisms lead to different angular distributions of the accelerated electrons [3]. The resonance absorption processes are expected to produce electrons mainly in the direction of the density gradient ∇n_e for *p*-polarized light, while the ponderomotive $\mathbf{j}\times\mathbf{B}$ acceleration and wake-field acceleration mechanisms would produce electrons mainly in the laser beam propagation direction.

In this paper we investigated experimentally the angular distribution of >120 keV electrons generated in the interaction of a 60-fs, 125-mJ, 800-nm, *p*-polarized laser pulse with Al targets. We measured the angular distribution of hot electrons not only on the equator (on incident plane) but also on the latitude of 80° and 70°, respectively. The results showed that there were double-peak emissions of hot electrons along the direction of specular reflection light and close to the target normal on the equator and on the latitude of 80°, respectively. While close to the normal of the target on the latitude of 70°, such kind emission disappeared, and there was only one peak of hot electrons emission.

II. EXPERIMENTAL SETUP

The experiments were conducted with the chirped pulse amplification (CPA) beam of the Ti: sapphire laser system at Laser Fusion Research Center, China Academy of Engineering Physics. The laser system worked in wavelength of 800 nm, pulse duration of 60-fs, and repetition rate of 10 Hz. The contrast ratio of the laser pulses was measured to be $\sim 10^{-6}$ at 1–2 ns before the main pulse.

Figure 1 shows a scheme of the experimental setup. The 40-mm-diameter [full width at half maximum (FWHM)] *p*-polarized laser beam was focused onto an Al target using a f/10 off-axis parabolic mirror with an incident angle of 45°. The energy irradiated on the target surface was 125-mJ. The focal spot diameter (FWHM) measured in vacuum was about 25-μm, giving a laser intensity of 4×10^{17} W cm^{-2} on the target surface.

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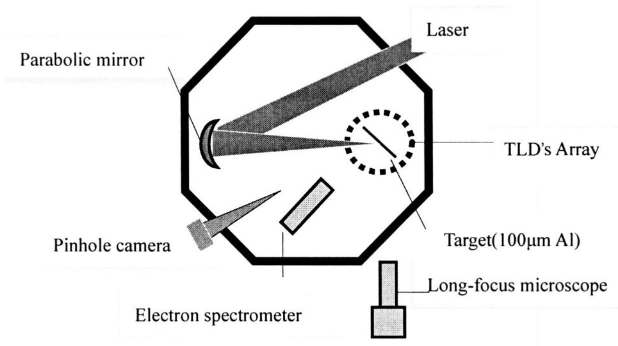

FIG. 1. The scheme of the experimental setup.

The target was 100-μm-thick $1\times 1\ cm^2$ Al foil. The target mount was controlled by step motor to ensure the laser pulses to interact with a fresh part of target surface for each shot. The parabolic mirror mount was controlled by another step motor to focalize the laser pulse. A long-focus microscope outside the chamber was used to monitor the focal spot of laser pulse.

In order to detect the angular distribution of hot electrons emitted from the front and the rear sides of the target, a detector with a 16-cm-diameter hemispherical shell was employed in the experiments. The detector was put a half space over the top of the incidence plane and the focus of the laser pulses was located at the center of the hemispherical shell. The LiF thermoluminescent dosimeters (TLD's) [18] with the size of $3.2\times 3.2\times 0.38$ mm were placed on the equator, the latitude of 80° and 70° of this shell, which were calibrated using a Cs^{137} γ-ray source [19]. In order to keep back high-energy ions, a piece of 100-μm Al foil was placed on the surface of the LiF TLD's as filter, which can eliminate high-energy protons with the energy below 3 MeV and high-energy electrons with the energy below 120 keV, and has little effect on the measurement of the x-ray emission. Because the sensitivity of LiF TLD's to energetic electrons and x-ray emission is the same, the hot electrons' angular distribution can be deduced conveniently by subtracting the dose of the x-ray emission from the experimental result.

In order to determine the mechanisms of hot electrons' emission under our experimental conditions, we measured the energy spectrum of hot electrons with a magnetic spectrometer fitted with the permanent magnetic field of $B=1200$ G. The energy range of the instrument was from 280 keV–3 MeV. The collection solid angle of the magnetic spectrometer was on the order of $\sim 10^{-3}$ sr. An array of LiF TLD's was used in the spectrometer to detect hot electrons. Because the LiF TLD's were insensitive to visible light, it was not necessary to use Al foils in front of the LiF TLD's.

III. EXPERIMENTAL RESULTS

All the experimental results presented here were obtained for *p*-polarized laser incident on 100-μm Al targets at an angle of 45° with respect to the target normal without any prepulse.

Figure 2 displays an angular distribution of hot electrons obtained on the equator of the hemispherical shell. Obviously differing from those observed in previous experiments and simulations [1–10], there are two obvious peaks of hot electrons' emission along the direction of specular reflection light and close to the normal of target and their angular widths (FWHM) are about 20° and 10°, respectively.

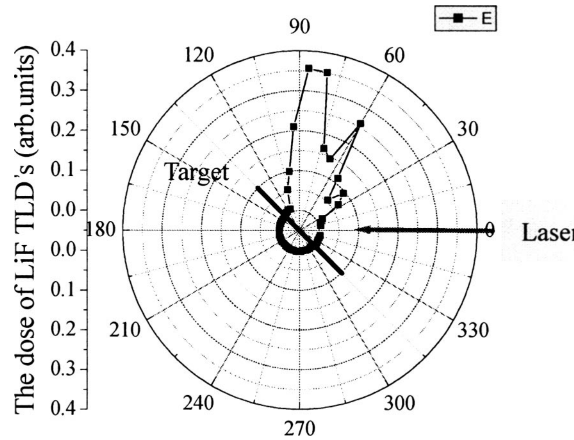

FIG. 2. The angular distribution of hot electrons with energy over 120 keV on the equator (on incidence plane). Hot electrons were generated by *p*-polarized obliquely incident laser pulses. The FWHM is about 20° and 10°, respectively.

Figure 3 shows the angular distribution of hot electrons obtained on the latitude of 80° of the hemispherical shell. It is similar to that on the equator. Two peaks of hot electrons' emission are obviously separated. The angle width (FWHM) of the peak in the specular reflection direction is about 20° and that close to the normal of target is about 15°.

It is worth noticing that both peaks of hot electrons' emission have a trend of approach to each other in Figs. 2 and 3.

On the latitude of 70° of this shell, the angular distribution of hot electrons is obviously different, as shown in Fig. 4, from those on the equator and on the latitude of 80°. Single-peak hot electrons' emission is observed in the direction of specular reflection light. Its angular width (FWHM) is about 25°.

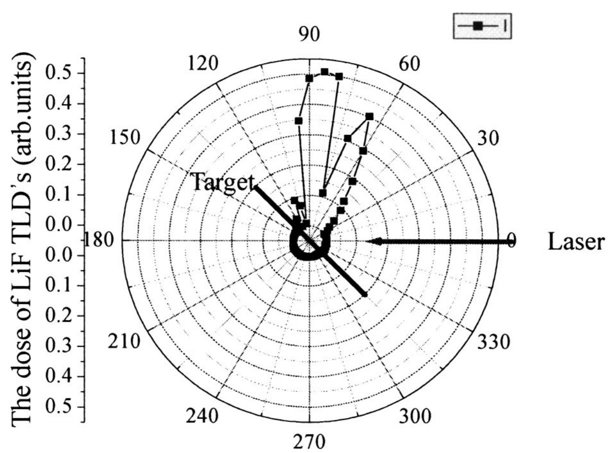

FIG. 3. The angular distribution of hot electrons with energy over 120 keV on the latitude of 80°. Hot electrons were generated by *p*-polarized obliquely incident laser pulses. The FWHM is about 20° and 15°, respectively.

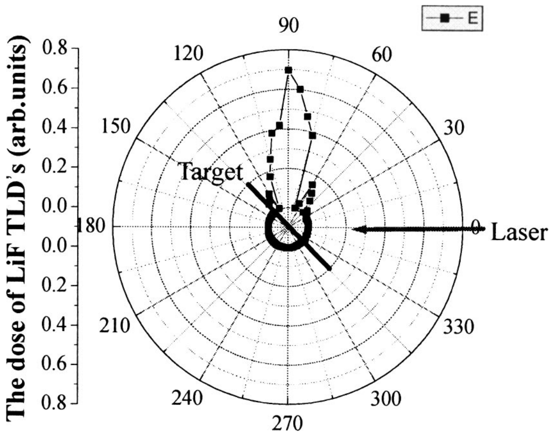

FIG. 4. The angular distribution of hot electrons with energy over 120 keV on the latitude of 70°. Hot electrons were generated by *p*-polarized obliquely incident laser pulses. The FWHM is about 25°.

The result of hot electrons' energy spectrum measured at about 15° from the target normal is shown in Fig. 5. This spectrum is a Maxwellian-like distribution [20]. Fitting the spectrum with Maxwellian distribution, one can find that the effective temperatures were about 153 and 515 keV. The temperature ($T_{hot}=153$ keV) inferred from the energy spectrum is more consistent with the scaling law of the resonance absorption mechanism $T_{hot}=100I^{1/3}$ keV (where I is 10^{17} W cm^{-2}) [21]. In addition, we found that the maximal energy of hot electrons was about 2 MeV and the average was about 700 keV.

IV. DISCUSSION

In this discussion, we would like to focus on the double-peak electrons' emission observed in our experiments. It is well known that the different direction of hot electrons' emission is due to different acceleration mechanism. The laser parameters, especially the prepulse contrast ratio, would have strong effect on the acceleration mechanism because many of the basic plasma properties are controlled by the strong laser field rather than by its own density and temperature [4]. The prepulse or pulse pedestal, which decides the preplasma density gradient $L=(\partial \ln n_e/\partial z)^{-1}$, would become important with laser intensity increasing.

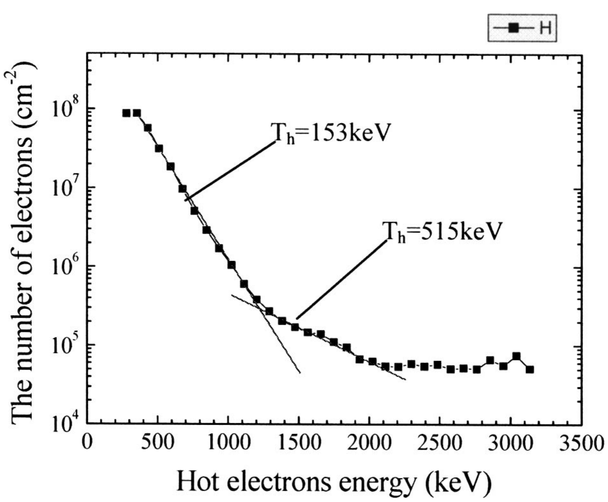

FIG. 5. Hot electrons spectrum from Al target irradiated by *p*-polarized femtosecond laser pulses at 4×10^{17} W cm^{-2}.

In our experiment, the intensity of 4×10^{11} W cm^{-2} of prepulse or pulse pedestal is above the target damage threshold. According to Zhidkov *et al.*'s simulation [22] with a HYADES code, the prepulse or pulse pedestal can create a larger density gradient $L/\lambda\sim1$–2 for the laser pulse with $I\sim10^{17}$ W cm^{-2}, $\tau<100$-fs, $\lambda=780$-nm, and contrast ratio of $1:10^{-6}$, which are similar to ours. In the case of the plasma scale length $L\sim(0.1$–$0.2)\lambda$ (where $L=(\partial \ln n_e/\partial z)^{-1}$), which is optimal for resonance absorption, the absorption efficiency can be over 50% [22]. When the plasma has a longer scale density profile, the interaction surface is deformed and corrugated, and no clear jets are observed [4]. For an intermediate density gradient $L/\lambda\sim1$–2, it is possible that the resonant absorption mechanism is excited and the laser reflectivity reaches a considerable value.

We think that the double-peak emission of hot electrons in our experiment is not due to the filamentation or self-focusing of the laser beam in the underdense plasma, or hosing instability [3], but different acceleration mechanisms. The peak in the specular reflection direction has a larger angular width (FWHM) than that close to the normal of the target. In addition, single-peak emission of hot electrons is observed only in the specular reflection direction on the latitude of 70°, which was also different from that on the equator and on the latitude of 80°. Assuming that hot electrons' emission is symmetrical in the incidence plane, its jet angle on the longitude (>40°) is larger than that close to the normal of the target (~20°).

The peak in the specular reflection direction is produced by the specular reflection laser, which excites a plasma wave to accelerate electrons. When an intense laser is irradiated obliquely on the target, the reflected laser light, which is modulated at the reflection point, accelerates the electrons in the coronal plasma. The electron acceleration is enhanced by the modulation and self-focusing of the reflected laser light. The quasisteady magnetic channel occurs simultaneously and collimates the energetic electrons along the specular direction [1].

The peak close to the normal of the target is due to the resonance absorption mechanism. Sentoku *et al.* [1] studied the plasma jet formation and magnetic-field generation in the case that the laser wavelength λ and the intensity were 1 μm and 2×10^{18} W/cm^2, respectively and the density scale length was shorter than the wavelength $\lambda[L=n_e(dn_e/dx)^{-1}\ll\lambda]$. They pointed out that the emission direction of hot electrons generated by the *p*-polarized light was determined by the canonical momentum conservation along the target surface. They gave an equation of the jet angle of electrons θ' with the angle of laser incidence θ and the averaged energy of bunched electrons for the *p*-polarized light. By Sentoku *et al.*'s formula [1], the jet angle of hot electrons

$$\sin\theta' = \frac{\gamma - 1}{\gamma}\sin\theta,$$

where, γ is the relativistic factor of averaged energy of bunched electrons; θ is incidence angle of laser from the normal of the target; and θ' is the hot electron jet angle from the normal of target. Applying the theory in our experiment, the average energy of hot electrons is about 700 keV, and then the relativistic factor $\gamma \approx 1.370$. It can be concluded that the angle of outgoing direction θ' is about 11°, namely, about 56° to the incidence direction of laser. This result is better consistent with our experimental result.

Differing from Sentoku's model, for the laser beam intensity of 2.0×10^{18} W/cm^2 and 1.0×10^{17} W/cm^2, Ruhl *et al.* [11] studied the electrons jet for oblique incidence of a *p*-polarized laser beam on a fully ionized plasma with a low density plasma corona by particle-in-cell and two-dimensional Vlasov simulations. They found that the jet angle of fast electrons was approximately 17° from the target normal and a single narrow self-focused current jet of energetic electrons was projected into the corona almost normal to the target. Assuming that the laser target interaction in the boosted frame was quasi-one-dimensional, the plasma-vacuum interface was a steplike density profile with $n(x)=n_0$ for $x>0$ and the ions were immobile. They wrote the Vlasov equation for the boosted frame and solved it for an initial Maxwellian. The equations of lateral canonical momentum conservation in boost frame coordinates were given. Transforming back to the lab frame yields, they obtained a relation of the jet angle θ' with the angle of laser incidence θ and the laser intensity I. According to Ruhl *et al.*'s formula [11],

$$\tan\theta' = \frac{\sqrt{1+\alpha \mathrm{I}\lambda^2} - 1}{\sqrt{\alpha \mathrm{I}\lambda^2}}\tan\theta,$$

where θ is incidence angle of laser from the normal of the target; θ' is the hot electron jet angle to the normal of the target; and $\alpha^{-1}\approx 8.0\times10^{17}$ W cm$^{-2}\mu$m^2. For our experiment, $\mathrm{I}\lambda^2 = 2.56\times10^{17}$ W cm$^{-2}\mu$m^2 which gives a $\theta' \approx 14.8°$, namely, about 59.8° to the incidence direction of laser. It is well consistent with our experimental result.

On the other hand, the hot electrons' energy spectrum in Fig. 5 shows that the temperature of hot electrons ($T_{\mathrm{hot}}=153$ keV), is in good consistency with a scaling law of the resonance absorption mechanism $T_{\mathrm{hot}}=100\mathrm{I}^{\frac{1}{3}}$ keV (I is 10^{17} W cm^{-2}) [21]. The vacuum heating is not the main mechanism [23] for the plasma whose scale length $L=(\partial \ln n_e/\partial z)^{-1}$ significantly exceeds the electron quiver amplitude $x_{\mathrm{osc}}=eE_0/m_e\omega_0^2$ in our experiment.

The proximity to each other of the two peaks of hot electron emission in Figs. 2 and 3 is due to the magnetic field. The energetic electrons, which are pinched by the quasistatic magnetic field, move along the magnetic corridor. On the other hand, the interaction is produced via the magnetic field that is excited by two beams of energetic electron emission. That is the same as two parallel leads with the same current. Ultimately, two peaks of hot electrons emission are deviated from the original direction and become close to each other, as shown in Figs. 2 and 3. The direction of the single peak on the latitude of 70° is consistent with the specular direction because of the absence of a peak of hot electrons' emission close to the normal of the target.

V. CONCLUSION

In summary, we have observed the double-peak emission of hot electrons in the interaction of a 60-fs, 125-mJ, 800-nm, *p*-polarized laser pulse with Al targets. It is not a random angular distribution produced by filamentation and self-focusing of the laser beam in the underdense plasma or, hosing instability [3]. The emission peak in the specular direction is due to the reflected laser light which excites a plasma wave to accelerate electrons. The emission peak close to the normal of the target, which is much more consistent with the theories of Sentoku [1] and Ruhl [11] *et al.*, is caused by the resonance absorption. The reason of two peaks close to each other may be due to the magnetic field produced by two beams of energetic electrons emission.

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