Multi-peak emission of the fast electron beams along the target surface in ultrashort laser interaction with solid targets

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Abstract: The spatial and energy distributions of fast electrons emitted from foil targets irradiated by ultrashort intense laser pulses are measured. Four groups of collimated emissions of fast electrons along the front and rear target surfaces are observed for an incidence angle of \(\theta < 60^\circ\). This multi-peak characteristic is found to be independent of the polarization states. Numerical simulations reveal that the electron beams are formed due to the deformation of the target surface and then guided by the induced quasistatic electromagnetic fields.

1. Introduction
The generation and transport of fast electrons in the interaction of ultrashort intense laser pulses with targets have attracted great interests in fast ignition (FI) scheme\cite{1} for inertial confined fusion (ICF). A three-order increase in the neutron yield than that from a plane target for a similar laser condition was achieved by Kodama et. al.\cite{2} using a re-entry cone target. Theoretic studies\cite{3} show that this can be attributed to the micro-focusing of laser light by the conical wall and/or the guiding of fast electrons along the inner surface to the tip. Our recent experiments have demonstrated a fast electron beam emitted along the target surface at a large incidence angle\cite{4,5}, which confirmed directly the second role. Lateral transport of hot electrons along the target surface generated by nanosecond CO\(_2\) laser pulses has been observed theoretically\cite{6} and experimentally\cite{7,8} for decades. Recently, lateral transport of fast electrons generated by ultrashort intense laser has also been reported by observation of x-ray\cite{9,10} and ion emissions\cite{11}. In this paper, we report as many as four groups of fast electrons emitted along the target surfaces for moderate and small incidence angles. Theoretical simulations show that these new characteristics are related to the deformation of the front target surface and lateral transport of the energetic electrons.

2. Experiment setup
The experiments were performed on the Xtreme Light II (XL-II) laser system at the Institute of Physics, Chinese Academy of Sciences. The laser system can deliver pulses with energies up to 640 mJ in 30 fs at 800 nm. The laser pulses were focused by an \(f=3\) off-axis parabolic (OAP) mirror onto
30 µm plastic or aluminum targets. The polarization state can be changed to vertical (s-polarization) or circular polarization by inserting a half-wave or quarter-wave plate before the OAP mirror. The focus spot size was measured to be ~10 µm full width at half maximum (FWHM). The laser intensity on target was adjusted by changing the laser pulse energy.

The spatial distributions of fast electrons were measured with a sandwiched detector array consisting of image plate (IP) stacks, which surrounded the laser focus in the incident plane. Each stack consists of three layers of IPs, with aluminum filters inserted in front of the first layer and between adjacent layers of IPs for the energy-selected measurement. This detector covers 340º angle range in the incident plane with an angle of 20º left for laser entrance. An electron spectrometer with magnetic field 1000 Gauss was placed 10º to the front target surface in the backward direction of laser incidence to measure the energy distribution of fast electrons. The accepted solid angle is 9×10⁻⁵ sr. The data were also recorded with IPs.

3. Experimental results

Figure 1(a) shows a typical angular distribution of fast electrons with energies larger than 900 keV for a p-polarized laser pulse interaction with a plastic target. The laser incidence angle is 45º, and the intensity on target is about 1.0×10¹⁸ W/cm². Besides the emissions in the normal direction to the target surface, four collimated fast electron beams along the front and rear target surfaces are observed, with the divergent angles of 15º–30º. To be convenient, these four groups of fast electrons are denoted as group 1 ~ 4, while those in the normal direction as group 5, as shown in Fig. 1(a) and the inset. The energy distribution of group 1 fast electrons are shown in Fig. 1(b). The distribution of fast electrons with energies ranging from 250 keV to 1250 keV can be fitted with an exponent function, which leads to a temperature of 210 keV. In the similar laser conditions, the temperatures for group 3 and group 4 fast electrons were measured to be 129 keV [12] and 305 keV [4], respectively.

To find the conditions for the multi-peak emissions along the target surfaces, we changed the laser incidence angles. At an incidence angle of <60º, a similar phenomenon of simultaneous four groups of fast electron beams along the target surfaces was observed. The only difference is the fractions of each group of fast electrons changes. At an incidence angle of 60º or larger, the fraction of group 4 can surpass 40%, but few fast electrons of group 2 and group 3 were observed. Secondly, we changed the laser polarization. The results show that the simultaneous four group fast electron beams along target surfaces were also observed for both s and circular polarizations at an incidence angle smaller than 60º. Aluminum target with the same thickness of 30 µm was used for comparison. The simultaneously four groups of fast electron emissions along the target surfaces were only observed for a laser intensity of larger than 2.0×10¹⁸ W/cm².

4. Numerical simulation and discussion

To understand the underlying physical mechanisms, two-dimensional (2D) particle-in-cell (PIC) simulations are conducted. In the simulations, a p-polarized laser pulse with an intensity of 3.1×
10^{18}\text{W/cm}^2 (\alpha_0=2.0) is incident at 45° onto a plasma. The density of the plasma increases exponentially from 0.1 \text{n}_c to 2 \text{n}_c in 6 \lambda_0, then keeps to be constant for a length of 5 \lambda_0. The pulse duration is 30 T_0 and the laser focal spot size 10 \lambda_0, where \text{n}_c is the critical density of plasma, \lambda_0 the laser wavelength in vacuum, T_0 the laser oscillation period.

Emission directions of fast electrons for different energies at three different time are shown in Fig. 2(a) ~ (c). One can see the emission direction of the fast electrons varies with time. At the 100 T_0, numbers of group 1 and group 2 fast electrons are dramatically increased, and the group 3 and group 4 are also enhanced. Since the detectors on fast electrons are time-integrated, the integration of all the emissions at different time results in the multi-peak characteristics observed. The phase-space distributions of the fast electrons at the 100 T_0 are shown in Fig. 3(a). One can see a large number of high energy electrons inside the target are transported laterally away from the focus region. Four groups of fast electrons out of the target are observed along the target surfaces shown by red arrows, which is consistent with the experimental results. 2D PIC simulations are also conducted for s-polarization, and we see the similar phenomena.

This laterally guiding along the target surfaces can be attributed to the target surface deformation. Ruhl \textit{et. al.}[13] found that energetic electrons will be constrained in a magnetized channel if the ratio of target thickness to deformed depth is large or the target is thick. However, if the ratio is small enough, energetic electrons will transport laterally away from the focus area. In our simulations, we also observed the target surface deformation, as marked by dashed line in Fig. 3(a). Furthermore, the less dense plasma was, the more obvious deformation was seen. The observation of fast electrons in the normal direction for s-polarization in our experiments could indicate the surface deformation. The deformation of target surface may result from the hole-drilling effect of laser ponderomotive force. In this case, the deformed depth for plastic targets should be larger than that for aluminum targets because of lower density under the same laser conditions. This can explain why it is easier to observe the multi-peak emission for plastic targets than the aluminum targets. The increase of laser intensity will also lead to a larger deformed depth. This is consistent with the observation of multi-peak emissions with aluminum targets only for higher laser intensities. Moreover, the deformation also

**Figure 2.** Simulated emission angles of fast electrons vs. electron energies at 60 T_0 (a), 80 T_0 (b) and 100 T_0 (c). The laser incidence angle is 45° for p-polarization.

**Figure 3.** The phase space distribution of fast electrons with energy larger than 900 keV at the 100 T_0 (a). (b) and (c) are cycle-averaged quasistatic magnetic field <B_z> and electrostatic field <E_x>, respectively.
reduces the dependence of emission directions of fast electrons on laser polarization states.

Figure 3(b) and (c) show the quasistatic electrical and magnetic fields at the 100 $T_0$ averaged over one laser cycle. The electrical fields in the front and rear of target surfaces are both unipolar, while the magnetic fields are bi-polar. The presently observed multi-peak emissions along the front and rear target surfaces can be explained very well using the spatial structures of electrostatic and quasistatic magnetic field in combination with the phase-space distribution of fast electrons. The initial fast electrons transported parallel to the target surface are reflected to the electrical field area in the vacuum by the quasistatic magnetic field. Then they are reflected back into target by the electrostatic field. This repetitive process confines the fast electrons to transport away from the focus spot parallel along the front and rear target surfaces. If fast electrons have non-parallel original velocities or the electromagnetic fields are un-uniformed, the final emission directions will be deflected away from the target surface. Therefore, the emission directions are determined by the surface electromagnetic field and the original directions of fast electrons.

5. Conclusion

We have observed four groups of fast electrons along the front and rear target surfaces in the interaction of ultrashort intense laser pulses with foil targets. The phenomena are independent of laser polarization and can be observed for both aluminum and plastic foil targets at an incidence angle smaller than 60º. PIC simulations suggest that such fast electrons are generated when the target surface is deformed by strong ponderomotive force of laser pulses, and then constrained by the quasistatic electromagnetic fields. Such effects of the lateral transport of fast electrons may be taken into account for the design of re-entry cone target in fast ignition experiments [2].

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