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Effects of laser polarization on hot electron emission in femtosecond laser-plasmas

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ABSTRACT

Effects of laser polarization were studied on behaviors of fast electrons produced from an aluminum target irradiated by a solid target irradiated by obliquely incident laser pulses at $8x10^{15}$ W/cm^2. Jet emission of outgoing fast electrons collimated in the polarization direction was observed for the s-polarized laser irradiation, whereas for the p-polarized irradiation, very directional emission of outgoing fast electrons was found close to the normal direction of the target. The behaviors of in-going fast electrons into the target for s- and p-polarized irradiation were also investigated by observing x-ray Bremsstrahlung radiation at the backside of the target.

I. INTRODUCTION

Fast electron production and transport were extensively studied both experimentally and theoretically [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 direction of fast electrons generated by ultrashort pulse laser-solid interactions are not very consistent [2, 5-8, 10]. An angular distribution of fast electrons strongly peaked along the laser axis was observed in laser-plasma interaction [5]. Highly peaked MeV electrons was found in laser axis direction at relativistic laser intensity [6], where the cycle averaged oscillation energy (quiver energy) is close to or higher than the rest energy of an electron. By comparison, a sharply collimated jet emission of fast electrons was observed by Bastiani *et al* in the specular direction in the interaction of a p-polarized non-relativistic intensity laser with a steep density profile plasma from Aluminum targets [7]. More recently, it was demonstrated by Sentoku *et al* that the collimated electron jets could be emitted from an overdense target in the normal direction for a relativistic p-polarized laser irradiation if a low density plasma corona is present [8] using an electromagnetic relativistic 2D particle-in-cell (PIC) simulation code.

Collimated electron emission can be produced by different acceleration mechanisms, such as resonance absorption, vacuum heating, j×**B** heating, or different sorts of skin effects [11]. However, most of these mechanisms are present only for p-polarized obliquely incident irradiation. It is very important to study the strong influence of the laser polarization on the electron emission because many of the 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 in-going fast electrons generated by p- and s-polarized ultrashort laser pulses obliquely incident on an overdense plasma with and without a corona preplasma. Our measurements raised a few important disagreements with simulations for s-and p-polarized obliquely incident laser pulses. These disagreements shed new insights on the acceleration mechanisms and are certainly worth further investigation.

II. EXPERIMENTAL SETUP

The experiments were carried out with a Ti:Sapphire chirped pulse amplification (CPA) laser system 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 24 μm and produced a peak irradiance of $8x10^{15}$ W/cm^2. The I contrast ratio of the laser pulse was measured to be better than 10^{-5} (at 1ps before the main pulse). The laser beam was focused on a 70 μm-thick aluminum target with a 10-cm focal length off-axis parabola. The target surface was polished to ensure the roughness of the surface to be less than 1 μm. For some shots, 8% energy was splitted off from the main laser beam to form a low intensity prepulse 50 ps in advance of the main pulse in order to provide an optimized plasma scale-length for interaction [18]. In order to investigate the effects of polarization on behaviors of fast electrons in the interaction, ultrashort laser pulses at 45° incidence to the target normal direction with p- and s-polarization have been used respectively.

The main diagnostic of fast electrons was a magnetic spectrometer [12], fitted with a permanent magnetic field of B = 380Gs. An array of LiF thermoluminescent dosimeters (TLDs) detectors was used to detect fast electrons. The energy range of this instrument covered from 7 keV to 500 keV. The collection angle of the spectrometer was in the order of 1×10^{-3}sr. Its energy resolution was better than 2%. The angular distribution of fast electrons was measured by placing a direct-exposure film (DEF) film (LUCKY) in an 8-cm-diameter cylinder around the laser focus. Aluminum foils with different thickness covered the film to prevent exposure from stray laser light and electrons with lower energies [13]. Two calibrated γ-ray spectrometers were also used to study the x-ray Bremsstrahlung radiation from the laser-plasma [14].

III. POLARIZATION EFFECTS

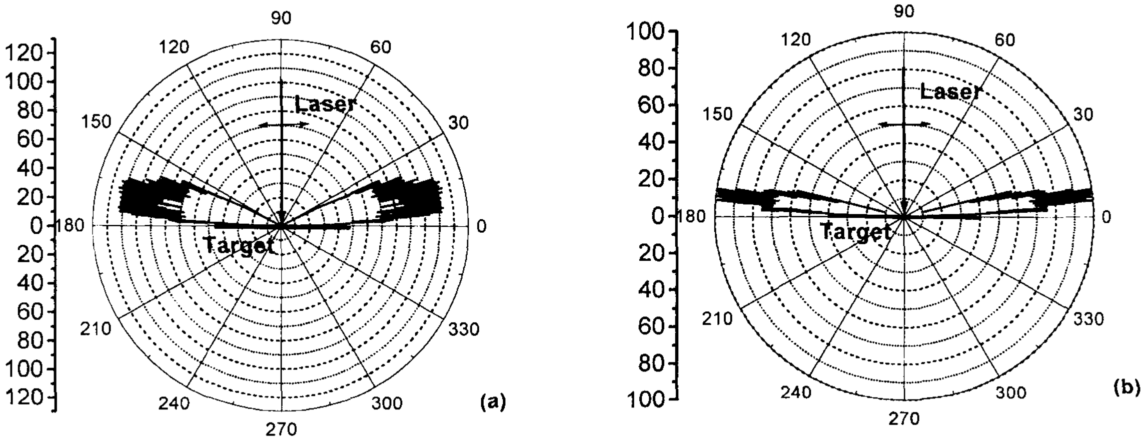

Figure 1. The cutaway view of the angular distribution of outgoing fast electrons with energies over (a) 50 keV and (b) 250 keV in the plane perpendicular to the incident plane respectively. The fast electrons were generated by s-polarized obliquely incident laser pulses without prepulses. The full width at half maximum (FWHM) is about 25° and 12 ° respectively.

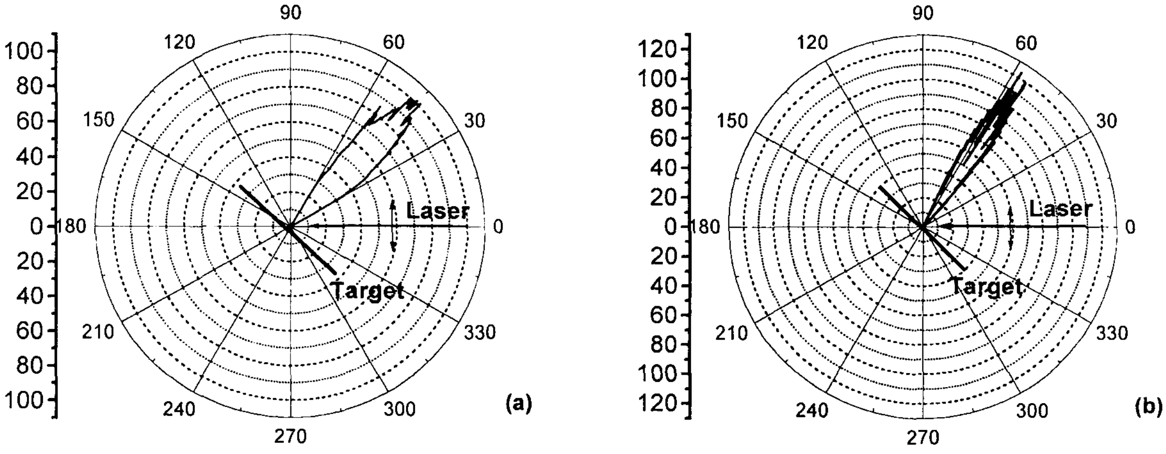

Figure 2. The angular distribution of outgoing fast electrons with energies over (a) 50 keV and (b) 250 keV in the incident plane respectively. The fast electrons were generated by p-polarized obliquely incident laser pulses with a prepulse 50 ps in advance. The FWHM is about 28° and 15 ° respectively.

Figure 1 shows the angular distribution of fast electrons generated by s-polarized irradiation without prepulses. The outgoing fast electrons with energies over 50 keV and 250 keV 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 low density pre-plasma in front of the target, most of the fast electrons were still observed in the direction of the laser electric field in the perpendicular plane. A small percentage of outgoing fast electrons over 50 keV was found in the incident plane in this case.

This suggests that the outgoing fast electrons were accelerated by the electric field of the s-polarized obliquely incident laser pulses. When there is a low density preplasma in front of the overdense plasma, the possible modulation of the critical surface of the preplasma would steer some of the fast electrons out of the polarization direction. However, the main part of the electrons were still accelerated in the polarization direction. These results are significantly different from the prediction of simulations [8]. It was also different from the longitudal distributions of hot electrons generated by wakefield and ponderomotive acceleration when ultrashort relativistic laser pulses interact with low density plasmas [15]. This phenomenon seems to be similar with 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]. Parametric instabilities such as the ion-acoustic decay in a steepened density profile can produce hot electrons in the transverse direction at the critical surface, i.e., along the electric vector of the light [16]. Excitation of surface waves in a steep density profile also produces hot electrons in the direction parallel to the surface [17].

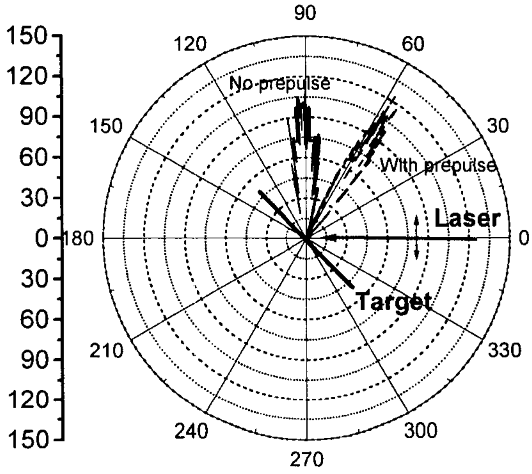

Figure 3. Angular distribution of fast electrons generated by a p-polarized laser without prepulse (solid line) and with a prepulses 50 ps in advance (dashed line) of the main pulse in the incident plane.

When the target was irradiated by p-polarized laser pulses with a prepulse 50 ps in advance of the main pulse, the behaviors of fast electrons were much different from those irradiated by s-polarized laser pulses. Figure 2a shows the angular distribution of the outgoing fast electrons with energies over 50 keV in the incident plane. Almost all of the out-going fast electrons were emitted in the normal direction. It was found that the emission direction of the fast electrons obeys the momentum conservation in the horizontal plane [8]:

$$\sin\theta' = \frac{p_{//}}{p} = \frac{\gamma-1}{\gamma}\sin\theta$$

in which θ is the laser incident angle to the target normal, θ' is the emission angle of fast electrons, γ is the relativistic factor of the fast electrons. Figure 2b shows that the emission angle of fast electrons over 250 keV ($\gamma>1.4$) in the incident plane is 13^0 from the target normal direction. It is apparent that the emission direction of the fast electrons with higher energies moves towards to the specular direction, and for the fast electrons with relativistic energies, the emission direction would be in the specular direction, as predicted by this formula. This momentum conservation rule is also valid for the hot electrons generated by s-polarized laser as figure 1 shows. The FWHM of the emission angular divergence of fast electrons with energies over 20 keV, 50 keV and 250 keV were measured to be 32^0, 28^0 and 15^0 respectively. This measurement indicates that the angular divergence decreases with increasing energy of fast electrons.

The emission direction of the fast electrons changed dramatically in the incident plane when the target was irradiated by a p-polarized irradiation without prepulses. Unlike the prediction in reference 8, a jet emission of fast electrons was indeed observed in the specular reflection direction. This agrees with Bastiani's experimental results [7]. Figure 3 shows this change.

It seems the electrons are accelerated along the polarization direction for the p-polarized irradiation without prepulses. This is very different from the behaviors of fast electrons generated by p-polarized irradiation with prepulses. This implies that a low density corona plasma does play a very critical role to determine the emission direction of fast electrons.

It is important to know the transport process of the in-going 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 conventional indiret or direct drive schemes and thereby to reduce the driver energy required for inertial confinement fusion. However, there have been no measurements of behaviors of in-going fast electrons in solid targets at a non-relativistic laser irradiation. Fast electrons injected into the target 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 in-going fast electrons in targets. Figure 4a shows the angular distribution of x-rays with energies >50 keV measured with NaI γ-ray spectrometer in incident plane produced by p-polarized obliquely incident laser irradiation with a prepulse 50 ps in advance. The angular distribution shows a symmetrical structure around the target normal. The FWHM of x-rays angular distribution is about 100^0. 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 a 50 keV energy in the normal direction injected into targets [16]. We also measured the angular distribution at the back side of 5μm-thick Al target with the wrapping film covered with 3μm aluminum foil. Hot electrons with energies over 70 keV were found to be concentrated in the normal direction but the angular divergence was much larger than that of out-going hot electrons in front of the target because of the colliding with the nuclei.

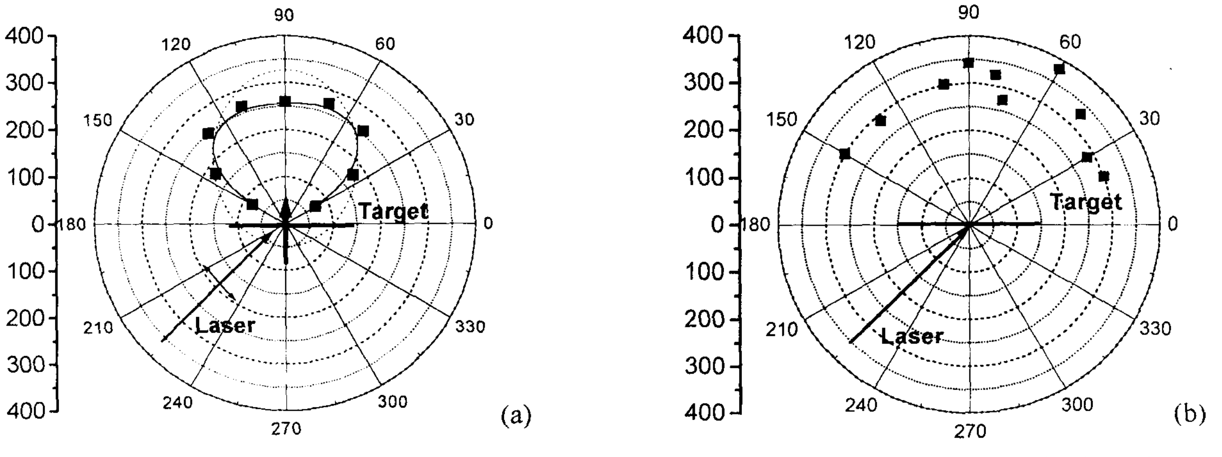

Figure 4. The x-ray distribution at the backward of the target with energies > 50 keV in the incident plane, irradiated by (a) p-polarized obliquely incident laser pulses with a prepulse 50 ps in advance. The dotted line is the theoretical calculation for the target interaction with a 50 keV electron beam. (b) irradiated by s-polarized obliquely incident laser pulses with a prepulse 50 ps in advance. The polarization direction was parallel to the target.

Figure 4b shows the angular distribution of x-rays with energies >50 keV generated by s-polarized laser irradiation with a prepulse 50 ps in advance. It shows a rather random distribution at the back side of the target and its flux was much weaker than that driven by p-polarized irradiation. Therefore, it seemed that there were no in-going electron jet formed for s-polarized irradiation and this is against the simulation prediction [8].

IV. SUMMARY AND DISCUSSION

In summary, we found that both s- and p-polarized lasers can generate jet emission of fast electrons, although the acceleration mechanisms are different for s- and p-polarized irradiation. This provides new insights on acceleration mechanisms of fast electrons in ultrashort pulse laser-plasma interaction. Our experimental results have indicated that the 2D PIC and 2D Vlasov simulations [8] can reproduce the main characteristics of outgoing fast electrons generated by interaction of obliquely incident p-polarized laser pulses with an overdense plasma with a corona preplasma in our experiment. The main acceleration mechanism for the outgoing fast electrons is the resonance mechanism in this case [12] for its $L/\lambda \sim 2$. Besides the optimum resonance absorption (RA) scale length $L/\lambda \sim 0.25$ [7], we demonstrated with its incident angular dependence that 50 ps delay time also fit for stimulating RA because the laser ponderomotive filament occurred. And then, the self generated magnetic field would pinch the electron stream in the direction determined by the canonical momentum conservation [8].

However, the simulations which was made at the intensity of $2\mathrm{x}10^{18}$ W/cm^2 failed to reproduce the jet emission of outgoing fast electrons in the specular direction produced by moderate intensity p-polarized laser pulses obliquely incident on an overdense plasma directly. 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 obliquely incident laser pulses on a steep profile plasmas [7,8]. It was found in our experiment that the main acceleration on the fast electrons is on the specular direction at a non-relativistic irradiance.

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