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Effects of Polarization on Super-hot Electron Generation in Femtosecond Laser–Plasma Interaction *

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The effects of laser polarization on super-hot electron (> 100 keV) generation have been studied in the interaction of femtosecond laser light (800 nm, 150 fs, 6×10^{15} W·cm^{-2}) with a pre-formed plasma from a slab Cu target. For p-polarized laser pulses, high-energy γ-rays of the energy ~400 keV were detected. The electron temperatures deduced from the γ-ray spectra were 66 and 52 keV, respectively, in normal and reflective directions of the solid target, and hot electrons were emitted out of the plasma mainly in the normal direction. In contrast, there were nearly no γ-rays >100 keV found for s-polarized laser pulses. The hot electron temperature was 26 keV and the emission of hot electrons was parallel to the laser field. The superposition of resonant field with electrostatic field excited by escaping electrons may contribute to the high-energy γ-ray or super-hot electron (> 100 keV) generation.

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With the development of femtosecond (fs) laser systems,[1] hot electrons of the temperatures from sub-keV to several MeV[2–7] have been found in fs laser–plasma interactions. The mechanism of hot electron generation is closely related to the laser intensity. At relatively strong laser fields ($q = p_{\rm osc}/mc = 8.53 \times 10^{-10}\ (I\lambda^2)^{1/2} > 1$), where $p_{\rm osc}$ is the momentum of electrons oscillating in the laser field, m is the electron mass, c is the speed of light, and I and λ are the laser intensity and wavelength in units of W·cm^{-2} and micrometres, respectively, the relativistic effect is so strong that the Lorentz force $-e\boldsymbol{V} \times \boldsymbol{B}$ and ponderomotive potential play important roles in the production process of hot electrons of several MeV.[8,9] This is in addition to the relativistic channelling effect which greatly increases the laser intensity[10,11] resulting in hot electrons with very high energy (super-hot electrons).

However, at relatively low fs laser intensity ($q < 1$), the relativistic effect is not obvious, and there are also high-energy γ-rays and super-hot electrons (> 100 keV) found in fs laser and plasma interactions.[12,13] There are several possible mechanisms, such as resonant absorption,[14,15] Raman scattering[14,16] two-plasmon decay instability,[14] inverse bremsstrahlung[14] and vacuum heating,[17,18] that can be responsible for the generation of hot electrons, so that the study of mechanisms of hot electron generation in laser–plasma interactions is still a hot topic in both theory and experiment.

In this letter, we have experimentally studied the possible mechanism of the high-energy γ-rays or super-hot electron (> 100 keV) generation by changing laser polarization. Among the possible mechanisms, only resonant absorption and vacuum heating are directly related to the laser polarization. In the measurement, we detected the γ-ray spectra in order to deduce the temperature of hot electrons and the emission direction of escaping electrons. Based on the hot electron temperatures and emission direction in p- and s-polarized laser interactions with plasma, we found that super-hot electrons (> 100 keV) found only in p-polarization may be accelerated in the superposition resonant and electrostatic field excited by escaping electrons.

Our Ti:sapphire laser system delivered 150 fs pulses at 800 nm and was operated at a repetition frequency of 10 Hz. The maximum output energy of this laser was about 4 mJ in a 12 mm diameter beam. The beam was focused on solid targets with a 5 cm focal length lens. A diameter less than 25 μm has been detected and the corresponding focal laser intensity was 6×10^{15} W·cm^{-2}. Laser pulses were incident at 45° from the target normal direction. The targets used in the experiment were 1 mm thick Cu plates. The target surfaces were polished to ensure that the roughness of the surface was less than 1 μm. The target was moved 50 μm after each shot so that a fresh surface interacted with the laser pulses. A pre-pulse was introduced by a dog-leg system, similar to Ref. [19], where the pre-pulse was produced by splitting the laser pulse into two pulses, separated 50 ps. Using mirrors with different reflectivity, the ratio of the pre-pulse to the main pulse could be adjusted. In our experiment here, the ratio of the pre-pulse to the main laser pulse was about 8% and the time interval between them was set to be 70 ps. A 20 mm diameter hole in a 50 mm thick Pb block was used to collimate the γ-ray radiation and shield the γ-ray detector, a NaI crystal detector, shown in Fig. 1. The detector apertures were located 360 mm from the plasma, hence collecting a

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solid angle of 2.4 $\times 10^{-3}$ sr from the source. These two detectors were connected with γ-ray spectrometers, which consisted of a photomultiplier, an amplifier and a multi-channel energy analyser. The NaI detectors were partially enclosed by Pb blocks and cylinders to eliminate the background noise caused by the random γ-ray scattering. The spectrometers had been calibrated using a γ-ray source ^{22}Na (511 and 1270 keV).[20] An electronic gated shutter in front of each detector was synchronized with the main laser pulse to eliminate background events and enhance the signal-to-background ratio. These NaI detectors were placed in the normal and reflective directions (Fig. 1). The γ-ray spectral distribution was determined using single-photon pulse height analysis. To avoid any overlap of photons in detectors, the distance between the detectors and the plasma and the diameter of the hole in the Pb block in front of each detectors were carefully adjusted so that the probability of detecting a γ-ray photon by the detectors for each shot was about 0.2.

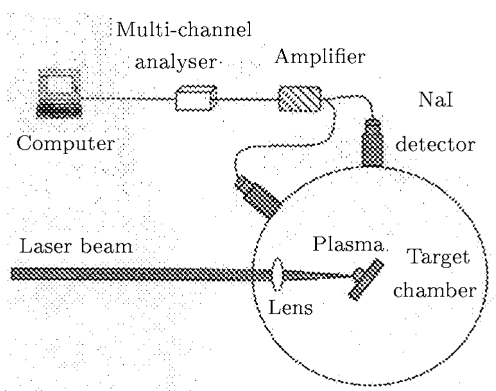

Fig. 1. Schematic diagram of the experimental set-up.

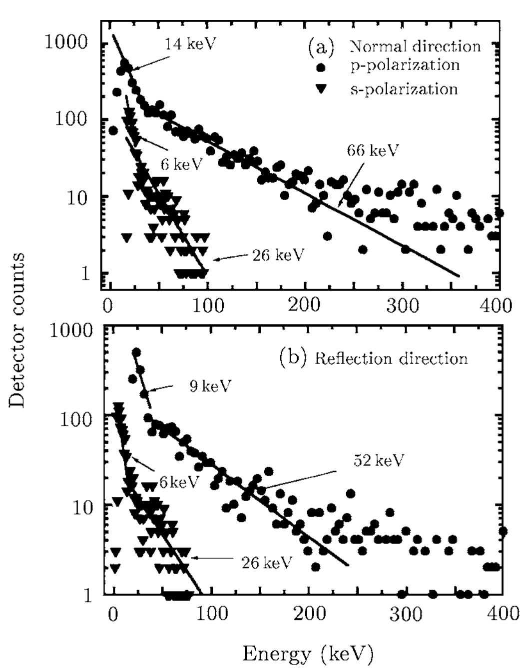

Fig. 2. Detector counts for γ-ray photons versus photon energy.

The emission direction of escaping electrons was detected by placing a direct-exposure film (LUCKY) in an 8 cm diameter cylinder around the laser focus, similar to Ref. [21]. An Al foil of thickness 0.1 mm was used to prevent the film from scattering light and lower energy electrons.

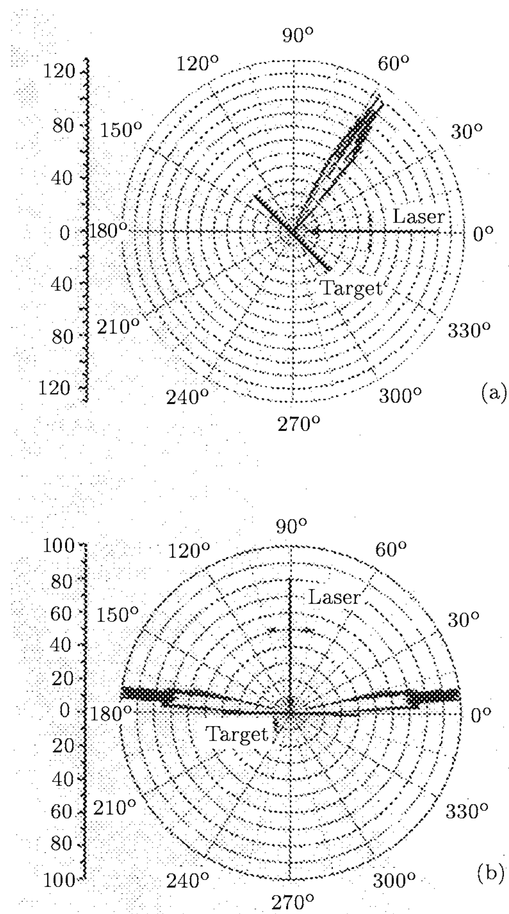

Fig. 3. Cutaway view of angular distribution of hot electrons generated from a solid target irradiated by (a) p-polarized laser pulses and (b) s-polarized laser pulses.

Figure 2 shows the γ-ray spectra produced by p- and s-polarized lasers in the normal and reflective directions. The spectra are continuous without any obvious line structure. This implies that the γ-ray radiation was due to the bremsstrahlung of hot electrons when they propagate inside the target. An apparent effect of polarization is shown in Fig. 2. As observed in our earlier experiment,[13] the γ-ray spectra consist of two parts: the high-energy and low-energy part. We are mainly interested in the high-energy γ-ray photons. The interaction of the plasma with the s-polarized laser pulses did not produce high-energy γ-ray photons above 100 keV in both normal and reflective directions. In contrast, the high-energy γ-ray radiation in both directions was greatly increased for the p-polarized laser pulses. The temperature of hot electrons for both s- and p-polarization can be deduced from the γ-ray spectra on an assumption of exponential spectral distribution of γ-ray radiation. The deduced results are also shown in Fig. 2. Clearly two groups of hot electrons can be divided into both p- and s-polarization cases and, for convenience, we define them as the low-T group and the high-T group. The temperatures of low-T, 6 keV and high-T, 26 keV, groups are the same for s-polarization in both directions, while the temperatures of those groups are obviously different in comparison in p-polarization cases. For p-polarized laser pulses, the temperatures of high-T groups are 66 and 52 keV in the normal and reflective directions, respectively. For the p-polarization laser, the temperatures of these two groups in the normal direction are always higher than those in the reflective direction. Each curve presented here represents over 10 000 laser shots.

Figure 3 shows the cutaway view of hot electron emissions in p- and s-polarization lasers. Electrons emitted mainly in the normal direction of the solid target in p-polarization laser interaction with plasma while their emission was basically parallel to the direction laser field in the s-polarization case.

We have studied the effects of polarization on the generation of high-energy γ-ray radiation or hot electrons ($>$ 100 keV) in the interaction of fs laser pulses ($\sim 6\times10^{15}$W$\cdot$cm^{-2}) with a pre-formed plasma. From the results we found that the temperatures of high-T hot electrons produced in the interaction of the plasma with the p-polarized laser pulses were much higher than those of the s-polarized case in both directions. All the high-energy γ-rays or super-hot electrons ($>$ 100 keV) occurred in the p-polarization case, while escaping electrons emitted in the normal direction of the solid target. Among all possible mechanisms of laser absorption, including resonance absorption, vacuum heating, Raman forward scattering and two-plasmon decay, only resonance absorption and vacuum heating are closely connected with the polarization. It can be deduced that the escaping electrons were driven out of the plasma by the electric field and the direction of electron emission represents the direction of the driving field both in s- and p-polarization cases. The direction of the electric field excited by the resonance of laser and plasma waves on the plasma critical surface is just in the normal direction. Therefore our results clearly suggest the dominant role of resonance absorption in super-hot electron ($>$ 100 keV) generation.

In comparison with the scaling law for the hot electron temperature produced by resonance absorption [15]

$$T_{\rm h} = 6\times10^{-5}\left[I\,({\rm W/cm})\,\lambda\ (\mu{\rm m})^2\right]^{0.33} \qquad (1)$$

at the laser intensity of $\sim5\times10^{15}$ W$\cdot$cm^{-2}, the hot electron temperature was about 9 keV. This is nearly consistent with the first hot electron (low-T) temperatures in the p-polarization case.

However, the temperatures of high-T hot electrons in our experiment were much higher than the scaling law value. The existence of escaping electrons suggests that, in addition to the alternative resonant field, there is an electrostatic field caused by the spatial charge separation between escaping electrons and "stationary" ions. In our previous experiment,[22] using target voltage measurements, the total charge quantity of escaping electrons in p-polarization laser and plasma interaction was 10^{-9}C. In order to estimate the strength of this electrostatic field, we assumed the escaping electrons and ions form two electrodes of a capacitor C. The charge quantity Q and electric energy W of this capacitor satisfied $Q = CV$ and $W = 0.5CV^2$. If the energy W is the potential energy of these escaping electrons and possesses 0.3% to 0.5% of the total laser energy in the p-polarization case, the corresponding electric potential difference V between these two electrodes is 24 to 40 kV. However, the 0.3%–0.5% energy conversion of the total fs laser energy into high-energy γ-rays have been experimentally detected[7,23,24] and these high-energy γ-rays composed so-called "high-energy tail" of the spectrum. Therefore in our experiment, high-energy γ-rays or super-hot electrons ($>$ 100 keV) may be generated in an electric field which is the superposition of the electrostatic and alternative resonant fields.

We have experimentally studied the effect of polarization on super-hot electron generation in the interaction of a fs laser (150 fs, 6×10^{15} W$\cdot$cm^{-2}) and a pre-plasma, produced by a pre-pulse (150 fs, 5×10^{14} W$\cdot$cm^{-2}, 70 ps ahead of the main pulse). From the obvious difference of hot electron temperature and emission direction of escaping electrons for the s- and p-polarized lasers, we deduce that the superposition of electrostatic and resonant fields may be responsible for the generation of high-energy γ-rays or super-hot electrons ($>$ 100 keV).

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