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Studies of hot electrons and protons generated from micro droplet plasmas irradiated by ultrashort laser pulses

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Abstract. In the two-dimensional simulation of the interaction of an ultrashort intense laser with droplet plasma, two hot electron jets generated by resonance absorption and emitted symmetrically with respect to the laser propagation direction are observed at a low laser field amplitude such as $a_0 = 0.1$. However, the emission angle of electron jets cannot be explained simply with the theory of resonance absorption for planar targets. When the laser amplitude is increased to $a_0 = 2$, electron bunches generated by the ponderomotive force separated by a laser period are superimposed into the hot electron jets. Accelerated ions have two groups at low laser intensities, one is anisotropic and associated with hot electron jets and the other is isotropic due to hydrodynamics expansion. At high light intensities, isotropic ion acceleration is found through Coulomb explosion.

Owing to the spherical geometry and small size of the micro droplet plasmas, the interaction of ultrashort laser pulses with them can result in particular phenomena. Recently, the interaction of an ultrashort laser pulse with droplets has received a great deal of attention [1–6] in both experiment and theory. In a recent experiment carried out in our group, two jets of hot electrons have been measured to emit from ethanol droplets symmetrically along about $180° \pm 45°$ in the backward direction. Motivated by these experimental observations, in this paper we use two-dimensional (2D) particle-in-cell (PIC) simulations to study the emission of fast electrons and protons from the droplets. When assuming the presence of preplasma around the droplet surface, our simulation can reproduce the main experimental results. The mechanisms of laser absorption and electron acceleration are clarified for different parameters of the droplets and laser pulses. With the increase of the incident laser intensity, the dominant absorption mechanisms are found to switch from resonance absorption to ponderomotive force acceleration, resulting in different angular distributions of fast electrons and ions.

In our 2D PIC simulation, an ultrashort laser pulse irradiates on a single droplet for simplicity and clarity, where the droplet is located on the laser axis. The droplet diameter is 5λ, with λ the laser wavelength in vacuum. A p-polarization laser pulse is incident along the x direction from left. The laser pulse has a focus radius of 10λ

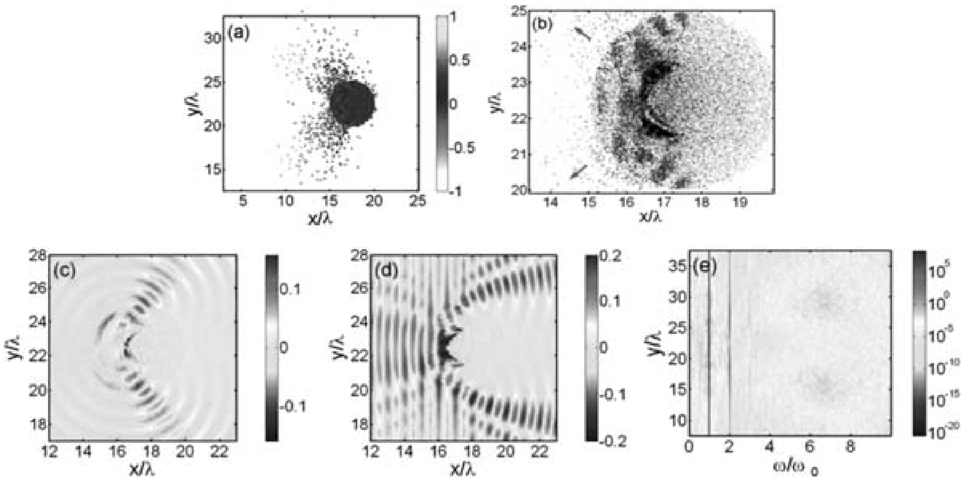

Figure 1. (a) Spatial distributions of hot electron jets at $t = 35\tau$. The gradient indicates the electron momenta $p_x = m\gamma v_x$. (b) A quiver plot displaying the velocity vectors of electrons at their positions in the polarization plane. (c), (d) The components of the electric fields E_x and E_y, respectively. (e) The Spectra of the emitted pulses through the left boundary (in arbitrary units). The detailed parameters are given in the text.

and a sine-square temporal profile with a duration of 60τ, where τ is the laser cycle. The peak laser amplitude $a_0 = eE/m\omega c = 0.1$ where ω is the laser frequency.

In the simulations, we find that the emission of hot electrons is concerned significantly with the density and scale length of the droplet. With very short scale lengths such as less than 0.1, hot electrons are emitted nearly homogenous in all directions, where the $\mathbf{J} \times \mathbf{B}$ heating or vacuum heating is the main interaction mechanism. With slightly larger scale lengths, two distinguished jets of hot electrons are emitted symmetrically along about $180^\circ \pm 45^\circ$ in the backward direction in the plane of laser polarization, quite similar to the experimental observations.

Figure 1 presents a typical example of the generation of hot electron jets, where the droplet is with a preplasma on its surface with the electron density increasing from $0.2n_c$ to $2n_c$ exponentially with the scale length $L \approx 0.9\lambda$. It illustrates the spatial distributions of electrons at $t = 35\tau$, assuming $t = 0$ when the front of the laser pulse arrives at the left boundary of the droplet. The gradient indicates longitudinal momentum of the electrons $p_x = m\gamma v_x$, where $\gamma = 1/(1-|v/c|^2)^{1/2}$ is the relativistic coefficient and v_x the velocity along the x direction. The quiver plot given in Fig. 1(b) displays the velocity vectors of the electrons in the polarization plane by arrows at their positions. To make it clearer, we add arrows to mark the directions of the major electrons. One can see periodic structures along the laser propagation direction. When the incident laser propagates away from the droplet plasmas, the directions of the hot electrons are not as distinguished as before. When the laser is s-polarized, the hot electron jets are not found. In order to understand the mechanism for the electron jets clearly, the electric fields are shown in Figs 1(c) and (d). The longitudinal component of the electric fields is found to be larger than the incident laser field near the critical surface, where there is also an electron density peak. This is a direct indication of resonance excitation of plasma waves through linear mode conversion. Figure 1(e) gives the spectra of the emitted pulses through the left boundary. One can see clearly the second and third harmonics and some $\frac{3}{2}$ harmonics, which are the good indications of laser-induced parametric instabilities.

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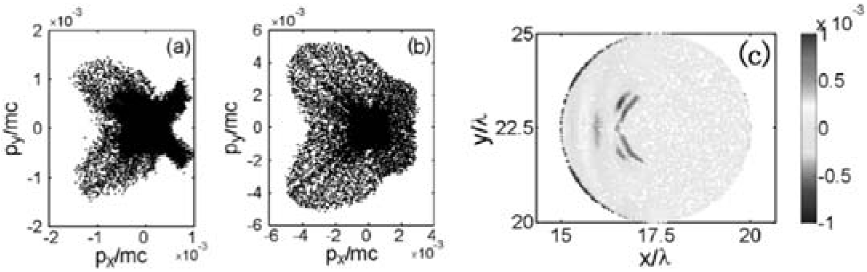

Figure 2. Proton distributions in momentum space after the laser interaction with a droplet at (a) $t = 35\tau$ and (b) $t = 55\tau$ for laser and plasma parameters as given in Fig. 1. (c) Spatial distributions of protons $t = 35\tau$. The gradient indicates the proton momenta $p_x = m\gamma v_x$.

By the simple expressions of the resonance absorption coefficient given in [7] for an obliquely incident p-polarized light wave irradiating on a planar target, the maximum absorption should appear at the angle $180° \pm 23°$ under the scale length of 0.9λ, which is much smaller than the angle $180° \pm 45°$ observed in the simulations and experiments. In a series of simulations by changing the scale length from 0.2λ to 2.0λ or changing the laser's focus radius and position, we find the emission angle of hot electrons changes weakly, although the maximum energy and the duration of the hot electrons are different. Therefore, the resonance absorption for planar targets cannot explain the hot electron jets observed in our experiments and simulations. This is probably related with the spherical shape of the droplets, which results in modified incident field distributions around the target surface. Moreover, the plasma waves generated in the droplets will interact with each other.

The energetic protons from the interactions are also investigated. Figure 2 illustrates snapshots of proton distributions in momentum space. They can be separated into two groups: that with higher energies emits predominantly along some particular directions within the laser polarization plane, and is accelerated by the electrostatic fields induced by the hot electron jets due to the resonance absorption; and the other with lower energies emits nearly homogenously in all directions, and is generated by the hydrodynamic ambipolar expansion of the micro droplet plasma after the laser interaction, similar to what is found in laser–cluster interactions [1]. Also one notes that the emittance of energetic protons is quite large both in the simulation and experiment.

When laser amplitude parameter is increased to $a_0 = 2$, electron bunches generated by the ponderomotive force separated by a laser period are found to propagate backward at about $180° \pm 45°$ from the laser axis as shown in Fig. 3(a). Electron bunches in the top and bottom of the droplet are all superimposed with the hot electron jets produced through resonance absorption. Another periodic structure, directed towards the laser propagation, is also clear in Fig. 3(b). This is produced by the laser fields propagating forward surrounding the spherical surface of the droplet, similar to what is shown in Fig. 1(d). The periodic structures in the upside of the droplet and in the bottom of the droplet intersect each other in certain regions. Although hot electron emission still appears to be anisotropic, they appear in broad angle distributions. As a result, the protons are emitted nearly homogenously in all directions. Also the mechanism of ion acceleration switches from hydrodynamic ambipolar expansion at low light intensities to Coulomb explosion in the present case [1]. Figure 3 shows the angular distribution of protons, which is almost uniform in all directions except small emission peaks found around $180° \pm 45°$.

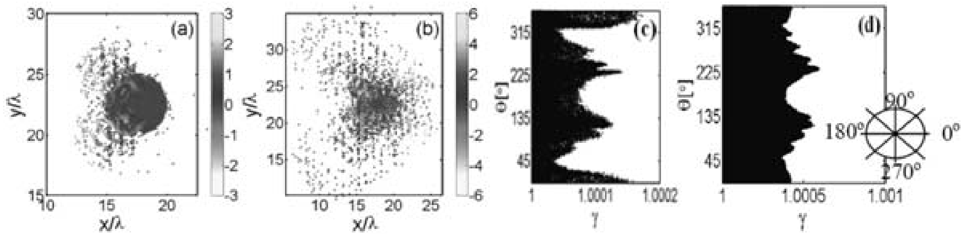

Figure 3. Spatial distributions of hot electron jets at (a) $t = 15\tau$ and (b) $t = 25\tau$. The gradients show the electron longitudinal momentum $p_x = \gamma v_x$ which is truncated within 3 or 6 to make the figure clearer. Spatial distributions of protons at (c) $t = 25\tau$ and (d) $t = 35\tau$ are also shown. The peak laser amplitude is $a_0 = 2$. The other parameters are the same as in Fig. 1.

In summary, we have used 2D PIC simulations to explore the interaction of ultrashort intense laser light with droplet plasma. Two hot electron jets emitted symmetrically with respect to the laser propagation direction are observed within the polarization plane at a low laser field amplitude such as $a_0 = 0.1$. This is due to the spherical geometry of the droplets and the presence of surrounding preplasma, which leads to the resonance absorption playing a role. However, the emission angle of electron jets cannot be explained simply with the theory of resonance absorption for planar targets. When the laser amplitude is increased to $a_0 = 2$, electron bunches generated by the ponderomotive force separated by a laser period are superimposed into the hot electron jets. It is found that accelerated ions have two groups at low laser intensities, one is anisotropic and associated with hot electron jets and the other is isotropic due to hydrodynamics expansion. At high light intensities, isotropic ion acceleration is found through Coulomb explosion.

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