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Hot electrons and protons generated from micro-droplet plasmas irradiated by ultrashort laser pulses

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Because of the spherical geometry and small size of the micro droplet plasmas, the interaction of ultrashort laser pulses with them can result in particular phenomena [1-9]. There have been a few studies on the laser absorption [1, 2], generation of energetic electrons and ions [3-6], induced nuclear fusion [7, 8], and harmonics emission [9] in the interaction of ultrashort laser pulses with micro-droplet plasmas.

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 45^o 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.

In our 2D PIC simulation, a p-polarization ultrashort laser pulse irradiates on a single droplet from left, where the droplet is located on the laser axis. The droplet diameter is 5λ, with λ the laser wave length in vacuum. The laser pulse has a focus radius of 10λ and a duration of 60τ. The peak laser amplitude $a_0=eE/m_ec=0.1$, corresponding to a laser intensity about $10^{16}W/cm^2$.

With very short scale lengths such as less than 0.1λ, hot electrons are emitted nearly homogenous in all directions, where the $\vec{J}\times\vec{B}$ heating or vacuum heating is the main interaction mechanism. With slightly larger scale lengths, two distinguished jets of hot electrons are emitted symmetrically along 45^o in the backward direction in the plane of laser polarization, quite similar to the experimental observations. In this case, the resonance absorption is expected to play a role. 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 $t=37.5\,\tau$, assuming t=0 when the front of the laser pulse arrives at the left boundary of the droplet.

The color indicates longitudinal momentum of the electrons $p_x=\gamma v$. The electric fields are shown in Figs. 1 (b). The electric field 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. Fig. 1(c) gives the spectra of the emitted pulse through the left boundary. One can see clearly the second and third harmonics and some 3/2 harmonics, which are indications of laser induced parametric instabilities.

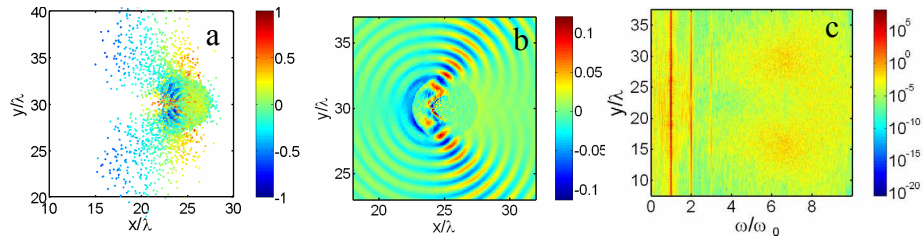

Fig. 1. (a) Spatial distributions of hot electron jets at t=37.5 τ . The colorbar indicates the electron momenta $p_x=\gamma v_x$ truncated to -1 and 1; (b) The electric fields E_x. (c) The Spectra of the emitted pulses through the left boundary (in arbitrary unit). The detail parameters are given in the text.

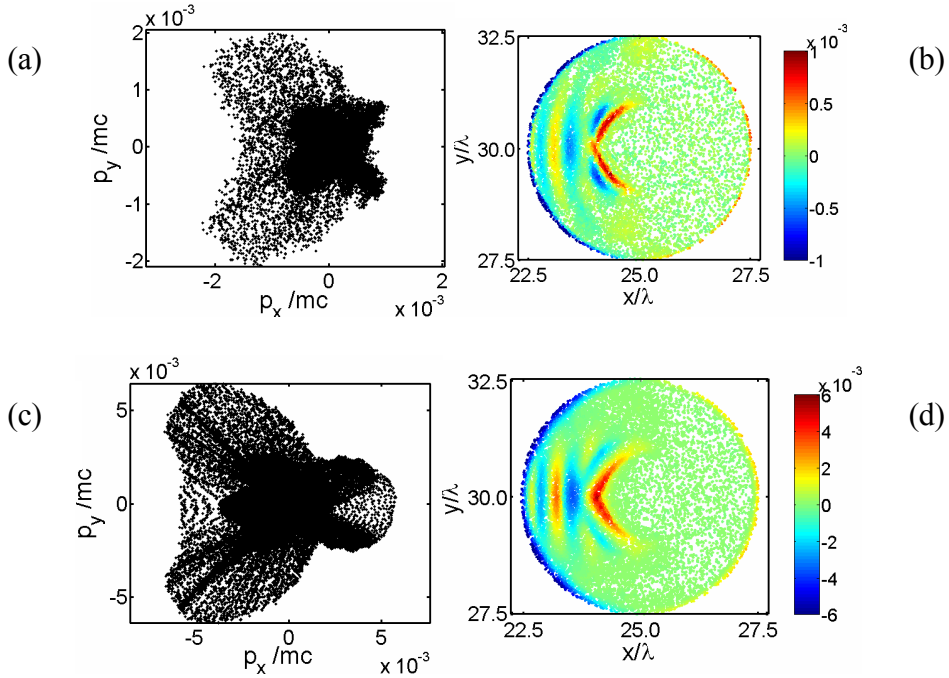

Fig. 2. Proton distributions in momentum and coordinate space (the color indicates longitudinal momentum of the protons) at t =37.5 τ for the laser a_0=0.1, focus radius 10λ (a, b) and a_0=1, focus radius 1λ (c, d). Plasma parameters are same as in Fig. 1.

Figure 2 illustrates snapshots of proton distributions in momentum and coordinate space (the

color indicates longitudinal momentum of the protons) at t =37.5 τ for the laser a_0=0.1, focus radius 10λ (Fig 2(a, b)) and a_0=1, focus radius 1λ (Fig 2(c, d)). The energetic protons can be separated into two groups: one with higher energies is anisotropic, which are accelerated by the electrostatic fields induced by the hot electron jets due to the resonance absorption, and another with lower energies is nearly isotropic, which is generated by the hydrodynamic ambipolar expansion. The emission of energetic protons is quite large both in the simulation and experiment. We also found that the focus radius has little influence on the emission direction of the energetic protons, but it can enlarge the number of the proton along the horizontal direction [Comparing Fig. 2(a, b) with Fig. 2(c, d)].

When we minish the laser focus radius form 10λ to 1λ and enhance the peak amplitude a_0 from 0.1 to 0.2, or change the plasma scale length to 0.2λ or 2λ, we find the emission angle of hot electrons 45° changes weakly, although the maximum energy and the duration of the hot electrons are different. But by the simple expressions of the resonance absorption coefficient given in references [10, 11] for an obliquely incident p-polarized light wave irradiating on a planar target, the maximum absorption should appear at the angle θ=23° under the scale length of 0.9 λ. Therefore the resonance absorption for planar targets cannot explain the hot electron jets observed in our experiments and simulations. Probably this is 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.

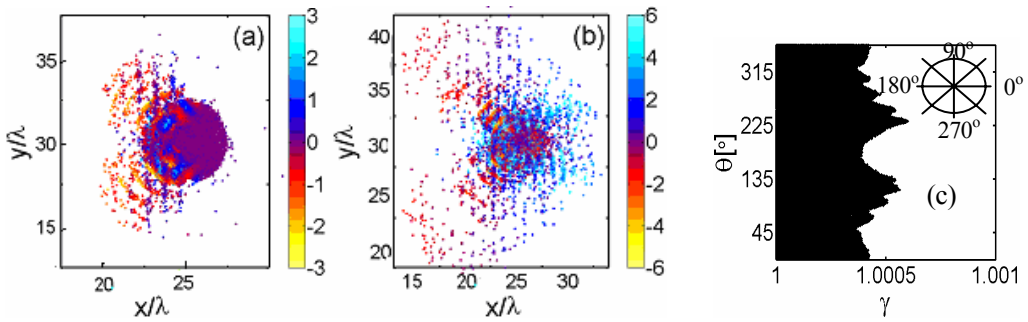

Fig. 3. Spatial distributions of hot electron jets at t=17.5 τ (a) and t=27.5 τ (b) and angular distributions of protons at t=37.5 τ (c). The colorbars show the electron longitudinal momentum $p_x=\gamma v_x$. The peak laser amplitude is a0=2. The other parameters are same as Fig. 1.

When laser amplitude parameter is increased to a_0=2, electron bunches separated by a

laser-period are superimposed into the hot electron jets (Fig. 3). This structure is produced directly by the laser fields. Though hot electron emission still appears to be anisotropic, they are in broad angle distributions. The protons are emitted nearly homogenously in all directions.

In summary, we have used 2D PIC simulations to explore the interaction of ultrashort intense laser light with droplet plasma. Through the studies of the electrons density and electric field distribution and irradiated harmonics, we found that the resonance absorption play a role in the generation of the two electron jets emitted symmetrically with respect to the laser propagation direction. The emission angle of hot electron jets changes weakly with the laser's situation and the plasma scale length, which cannot be explained simply with the theory of resonance absorption for planar targets. This is due to the spherical geometry of the droplets and the presence of surrounding preplasma, which leads to resonance absorption to play a role. 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 another one is isotropic due to hydrodynamics expansion. At high light intensities, isotropic ion acceleration is found through Coulomb explosion.

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