Two-dimensional simulations of laser-plasma interaction for ion acceleration in preformed channel

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Two-dimensional particle-in-cell simulations are taken to study the interaction of a relativistic, circularly polarized laser pulse with a preformed overdense plasma channel containing a slice of micron size. The laser pulse is confined in the channel, so it can keep higher intensity on a longer time scale inside the channel than the case without a channel. The electrons, both in the slice and from the channel, are pushed forward in the channel by the large light pressure of the laser pulse, followed by the ions accelerated by the electro static field generated by the charge separation. As a result, the acceleration of the slice is more efficient and has a better collimation than in the case without a preformed channel.

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High energy ions are important for fast ignition[1], nuclear physics[2], etc., so how to accelerate ions more effectively is an attractive problem. The energy of ions has reached mega-electron-volt (MeV) or even giga-electron-volt (GeV) in simulations[3−6] and experiments[7,8]. To achieve high energy ions, one usually needs larege laser energy, while the laser energy is limited by the experimental technology. In the paper we propose the regime of preformed channel to make use of the laser energy efficiently, so that the acceleration will be more efficient. Another advantage of this scenario is the channel can help to collimate the ions.

In the scheme, the channel is overdense containing a slice with same density, and is radiated by a irrelativistic, circularly polarized laser pulse. Let's first consider a channel without a slice. The ponderomotive force will push most electrons, which are on the skin layer of the inner wall of the channel, toward the transverse direction of the channel. And then, the electrons will be attracted by the electrostatic force for charge separation. If the channel's density is high enough and the wall of the channel is thick enough, after a quite short time, these two forces will reach a balance. The channel and the pulse will reach a quasi-steady condition[9]. Thus the laser pulse can keep a higher intensity on a longer time scale inside the channel than in the case without a channel. Meanwhile, on the inner wall of the channel a small part of electrons will be pushed away from the channel[10]. This part of electrons will also be accelerated by the laser pulse. Then we discuss the case with a slice, and the slice is put inside the channel after the entrance of the channel.

We present two-dimension in coordinates and three-dimension in velocities (2D 3V) PIC simulations based on the code PPICC[11] for the ion acceleration mechanism. The circularly polarized laser is of wavelength λ_0=1 μm, with the pulse profile in time and space I=$I_0\exp^2(-\omega_2/\omega_0^2)\sin^2[\pi(x-ct)/L]$ for $0 \leq x{-}ct \leq L$, where ω_2 is the light spot radius, x is the longitudinal position and c is light velocity in vacuum. The pulse width is $L = 5.5\lambda_0$, focal spot radius is $\omega_0 = 3\lambda_0$, located at $x = 12\lambda_0$, and the peak intensity is $I_0 = 5.5 \times 10^{22}$ W/cm^2. The pulse has a sudden beginning with a=100 in the ascending front[4]. Here a=$eA/m\nu_{\rm th}^2$ is the normalized vector potential, where $\nu_{\rm th}$ is the initial thermal velocity. The overdense plasma channel is located from $x = 10\lambda_0$ to $35\lambda_0$, the hole in channel is $9\lambda_0$ in width and the wall of the channel is $2\lambda_0$ in thickness. The slice is initially $2\lambda_0$ in width and $1\lambda_0$ in thickness at $x = 12\lambda_0$. The initial density of the channel and slice is $n = 10n_{\rm c}$, where $n_{\rm c}$=m$\omega^2/(4\pi e^2)$ (ω, frequency of laser pulse) is the critical electron density. The simulation box is $70\lambda \times 36\lambda$ with grids of 1400×720 in x, y direction, where the x direction is along the direction of laser propagation and the y direction is the transverse direction. The number of ions and electrons is 2448000 respectively and the initial temperature is 0.3 keV. The boundary conditions are periodic along the y direction and absorbing along the x direction. All quantities are normalized as follows. ν'=ν/c, t'=ωt, x'=x/λ_0 and y'=y/λ_0. In the following parts, we will drop the superscript denoting the normalized various quantities.

In Fig. 1 we present the comparison of ion density above $n_{\rm c}$ with (a) and without (b) channel at $t = 63T$, where T is the laser period. When $t = 63T$, as shown in Fig. 1, there is almost no slice above $n_{\rm c}$ for the case of no channel, but for the case of channel there still has a slice. It means that the particles in the slice disappear later in the latter case, so the particles of slice have a better collimation after they experience a same distance under the pulse pressure. It is because the channel can confine the laser pulse so that the pulse can keep higher intensity on a longer time scale than the case without a channel, and the coulomb explosion occurs more lentamente. Figure 2 shows the transverse field distribution E$_y$ at $t = 63T$ for the case with (a) and without (b) channel. Though the pulse has transmitted out of the channel, the effect of confinement of the laser pulse is obvious and its intensity is higher than the case without channel.

In order to show the advantage of channel more distinctly, we present the ion phase space plots of the slice with longitudinal velocity and transverse velocity and the ion yield versus energy of two cases at $t = 63T$ in Figs. 3 and 4, respectively. In Fig. 3(a) the maximum

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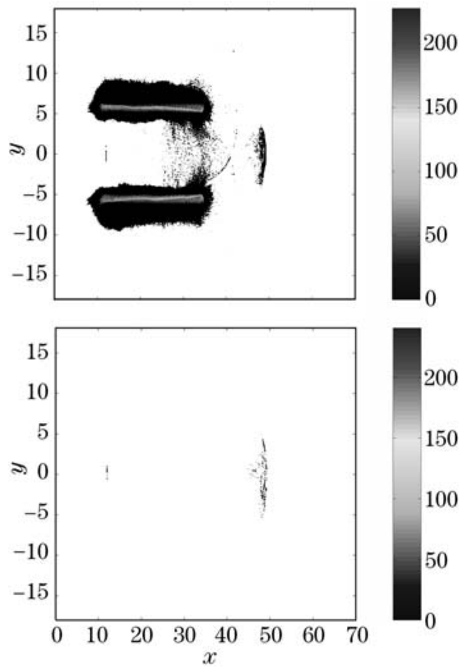

Fig. 1. Ion density above n_c at $t = 63T$, for the cases (a) with and (b) without channel.

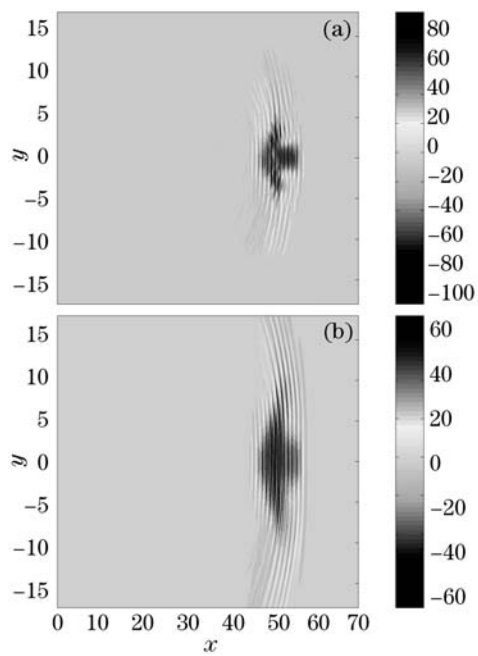

Fig. 2. Transverse field distribution E_y at $t = 63T$ (a) with and (b) without channel.

longitudinal velocity of the slice achieves $0.933c$ while in Fig. 3(c) the maximum longitudinal velocity of the slice achieves $0.922c$. Figures 3(b) and (d) show that the absolute value of transverse velocity is around $0.1c$ for most ions in the case with channel while without channel it is around $0.2c$. It proves the laser energy is converted to directed kinetic energy more efficiently than the case of no channel. Figure 4 is the ion yield versus energy which is located in the middle of the simulation box with a width 8λ along the y axis at $t = 63T$. In Fig. 4(a) the part of particles above 800 MeV is more than the case without channel.

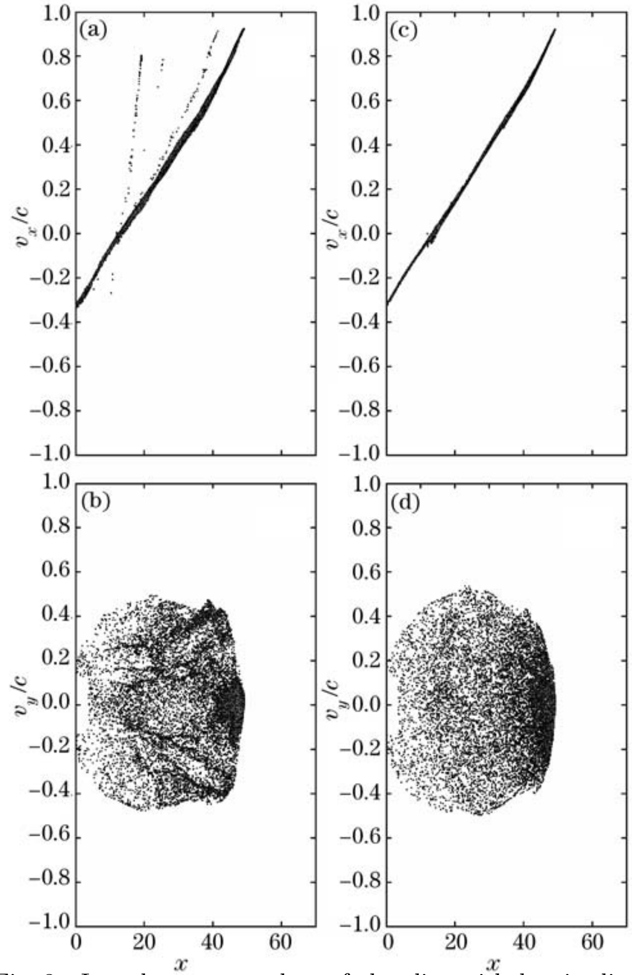

Fig. 3. Ion phase space plots of the slice with longitudinal velocity and transverse velocity at $t = 63T$ for the cases ((a), (b)) with and ((c), (d)) without channel. Only the particles of the slice are accounted.

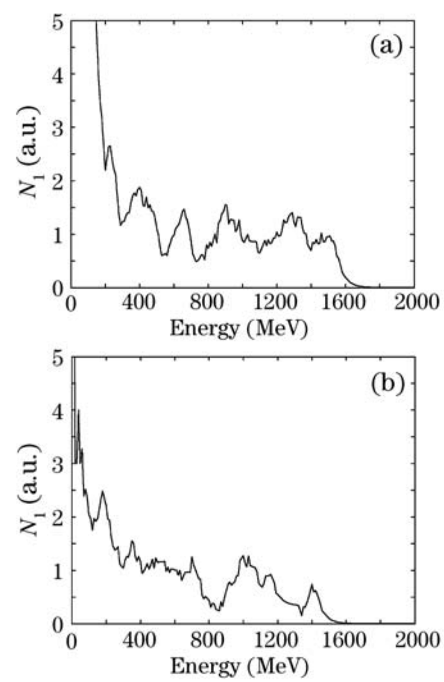

Fig. 4. Ion yield versus energy for the cases (a) with and (b) without channel at $t = 63T$. Only the particles located in the middle of the simulation box with a width 8λ along the y axis are accounted.

In conclusion, we have shown a regime of ultraintense laser-plasma interaction with 2D3V PIC simulation. The structure of channel can confine laser pulse in it. The acceleration of the slice in the channel is more efficient and it has a better collimation than without a preformed channel. The acceleration can be more efficient if suitable laser pulse, channel and slice are chosen.

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