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ION ACCELERATION BY SUPER INTENSE LASER PULSES IN PLASMAS

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Ion acceleration by petawatt laser radiation in underdense and overdense plasmas is studied with 2D3V-PIC (Particle in Cell) numerical simulations. These simulations show that the laser pulse drills a channel through the plasma slab, electrons and ions expand in vacuum. Fast electrons escape first from the electron-ion cloud. Later ions gain a high energy, due to the Coulomb explosion of the cloud and inductive electric field which appears due to fast change of the magnetic field generated by the laser pulse. Similarly, when a superintense laser pulse interacts with a thin slab of overdense plasma, its pondermotive pressure blows all the electrons away from a finite diameter spot on the slab. Then, due to the Coulomb explosion, ions gain an energy as high as 1 GeV.

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It has been well known that the interaction of ultraintense laser pulses with plasmas is accompanied by the acceleration of charged particles, both ions and electrons. However, when the plasma is irradiated by a petawatt laser pulse [1], it is expected that ion acceleration becomes more efficient than in the case of laser pulses with more moderate power. Various acceleration mechanisms have been invoked in the different regimes of the laser plasma interaction, including ion acceleration during the expansion of the plasma in vacuum [2] and the "Coulomb explosion". The Coulomb explosion is associated with the break of the plasma quasineutrality when the electrons are expelled from a self-focusing radiation channel in the plasma after which the ions expand due to the repulsion of the noncompensated electrical charge [3]. The Coulomb explosion has also been invoked in order to describe the generation of fast ions during the interaction of laser pulses with clusters [4]. This ion acceleration up to high energy values can shed light on the neutron production in overdense plasmas observed in [5] and opens up a way of producing laser induced nuclear reactions in a controlled way [6].

An electron interacting with an electromagnetic wave with the intensity $I \approx 2\times$ $\times 10^{21}\,\mathrm{W/cm^2}$, acquires an energy equal to $\mathcal{E}_e = mc^2a^2/2 \approx 1$ GeV. This light intensity corresponds to laser pulses with powers in the petawatt range and to values of the dimensionless amplitude $a = eE/m\omega c$ of order $\sqrt{M/m}$. Here M/m is the ion to electron mass ratio. This means that in the wave field electrons become as heavy as ions. A short laser pulse in an underdense plasma produces a wake with the amplitude $\varphi = \mathcal{E}_e/e$, where φ is the electrostatic potential. Thus, for $a \approx 2\sqrt{M/m}$ the ions gain an energy $\approx Mc^2$ during half a period of the wake wave and the ion motion in the wake of the laser pulse in an underdense plasma becomes relativistic. We notice that this amplitude of the laser radiation is much smaller than the one for which the dimensionless amplitude calculated with the ion mass, a becomes of order M/m, i.e., when the ion quiver velocity equals the speed of light. This latter amplitude corresponds to an intensity $I \approx 7 \cdot 10^{24}\,\mathrm{W/cm^2}$ for a $1\,\mu$m laser in a hydrogen plasma.

When considering the interaction of the laser pulse with an overdense plasma we take the plasma to have the form of a thin slab of width l_s. We assume that this plasma slab is irradiated by a laser beam with amplitude a and radius $R \gg l_s$ at the focus. The electrons interacting with the laser light are expelled from their initial position in the plasma slab. If the electron energy in the pulse field $\mathcal{E}_e = mc^2a^2/2$ is high enough, they can overcome the attractive electric field due to charge separation. To blow the electrons off, the pulse amplitude must be such that $\mathcal{E}_e > \mathcal{E}_\mathrm{C}$, where the Coulomb energy is about $\mathcal{E}_\mathrm{C} \approx 2\pi^2 e^2 n l_s R$, or

$$a > \left(l_s R/d_e^2\right)^{1/2} \equiv \left(4\pi\epsilon_0 R/\lambda\right)^{1/2}. \tag{1}$$

Here $d_e = c/\omega_{pe}$ is the collisionless skin depth and $\epsilon_0 = l_s\lambda/4\pi d_e^2$ dimensionless parameter introduced in Ref. [7]. Later, the ions start to expand due to Coulomb repulsion. This is the Coulomb explosion. Ions gain an energy of the order of $\mathcal{E}_\mathrm{C}$, which, assuming $\mathcal{E}_e \approx \mathcal{E}_\mathrm{C}$, can be rewritten as $\mathcal{E}_i \approx Mc^2(m/M)a^2$. We see that ions acquire an energy of the order of the ion rest mass when $a \approx \sqrt{M/m}$.

The goal of the present paper is to analyze, with 2D-PIC (Particle in Cell) simulations, the mechanisms of the ion acceleration during the interaction of a petawatt laser pulse with underdense and overdense plasmas, when the radiation intensity reaches $\approx 10^{22}\,\mathrm{W/cm^2}$, which corresponds to $a > \sqrt{M/m}$.

In order to investigate the interaction of a laser pulse with a slab of underdense plasma we have performed 2D-PIC fully relativistic simulations using a model value of the ion to electron mass ratio, 256, and $\sqrt{M/m} = 16$. Below we present the results of our simulations of a circularly polarized pulse with amplitude $a_e = 20$. The laser pulse is gaussian along y with full width $l_\perp = 10\lambda$, and has a triangular form along the x-axis with length $l_\| = 20\lambda$ and a sharp front of order $2\,\lambda$. The plasma density corresponds to the ratio $\omega_{pe}/\omega = 0.45$ or $n = 0.2025 n_{cr}$. The plasma slab, of length $L = 125\lambda$, begins at $x = 0$ and is preceded by a vacuum region 5λ long. The laser pulse is initialized outside the plasma in the vacuum region $x < 0$. In Fig. 1 we present the x, y-distribution of the electron and ion densities and of the z-component of the magnetic field at $t = 140(2\pi/\omega)$. The laser pulse is focalized in a relatively small region due to relativistic self-focusing. However the channel behind the laser pulse is not totally evacuated as can be seen in Fig.1. Indeed, the plasma moves predominantly outward in the radial direction, but at the same time an "inverted" corona mode of a hot, inward expanding plasma is formed. Colliding on the channel axis, these hot plasma flows form a relatively dense plasma filament in the region $100\lambda < x < 120\lambda$. The phenomenon of the "inverted" corona and of the formation of a hot filament inside the channel was discussed in Ref. [8] in the framework of the gas dynamics approximation. In the present case the situation is more complex: the inward

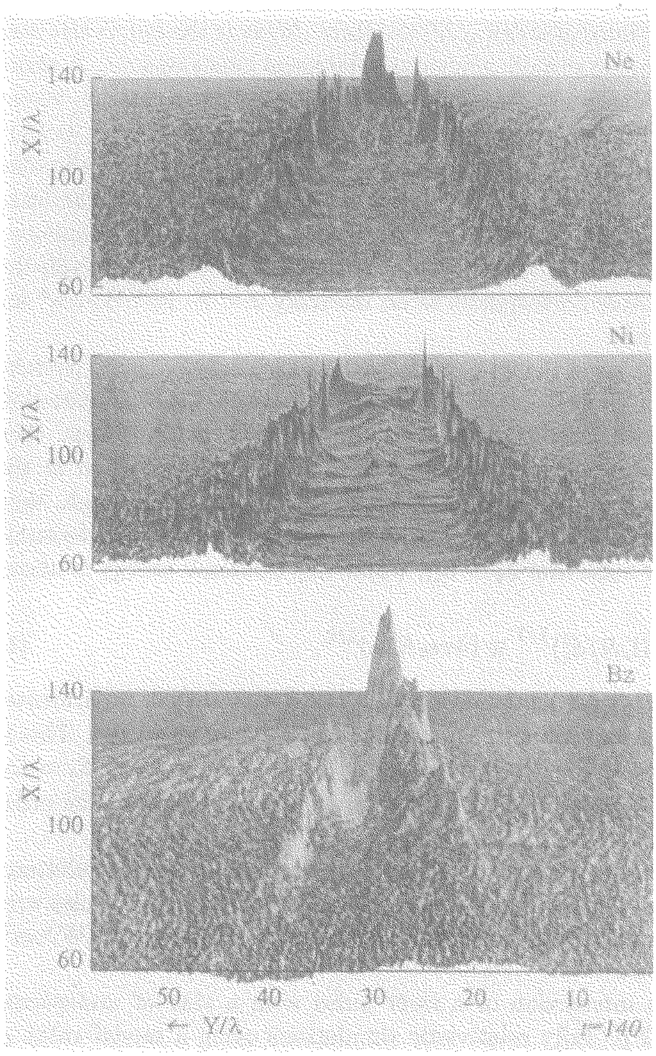

Fig.1

expanding plasma is inhomogeneous in the direction along the channel and is formed by narrow jets. In addition a significant portion of the filament is made of the plasma which enters the channel through the front region of the channel. The electric current curried by the filament sustains the dipolar magnetic field which in turm focuses the plasma toward the axis.

Fig.2 shows the phase planes p_x, x of electrons (a) and ions p_x, x (b) and p_x, y (c). Fig.2c shows the x, y-distribution of the z-component of the magnetic field for $t = 175(2\pi/\omega)$ when the laser pulse has drilled a hole through the slab of the plasma. We see that the electron cloud expands into the vacuum in the forward direction. In the phase plane (p_x, y) shown in Fig.2c we see that the ion motion is well collimated. The collimation of the ion motion can be explained by the pinching in the self-generated magnetic field which changes polarity at the ion jet axis as seen in Fig.2d.

The mechanisms that accelerate the ions can be described by invoking the pull on the ions by the electrons that are expanding in the forward direction, the Coulomb repulsion in the electrically non neutral ion cloud that is formed when the electrons are ripped

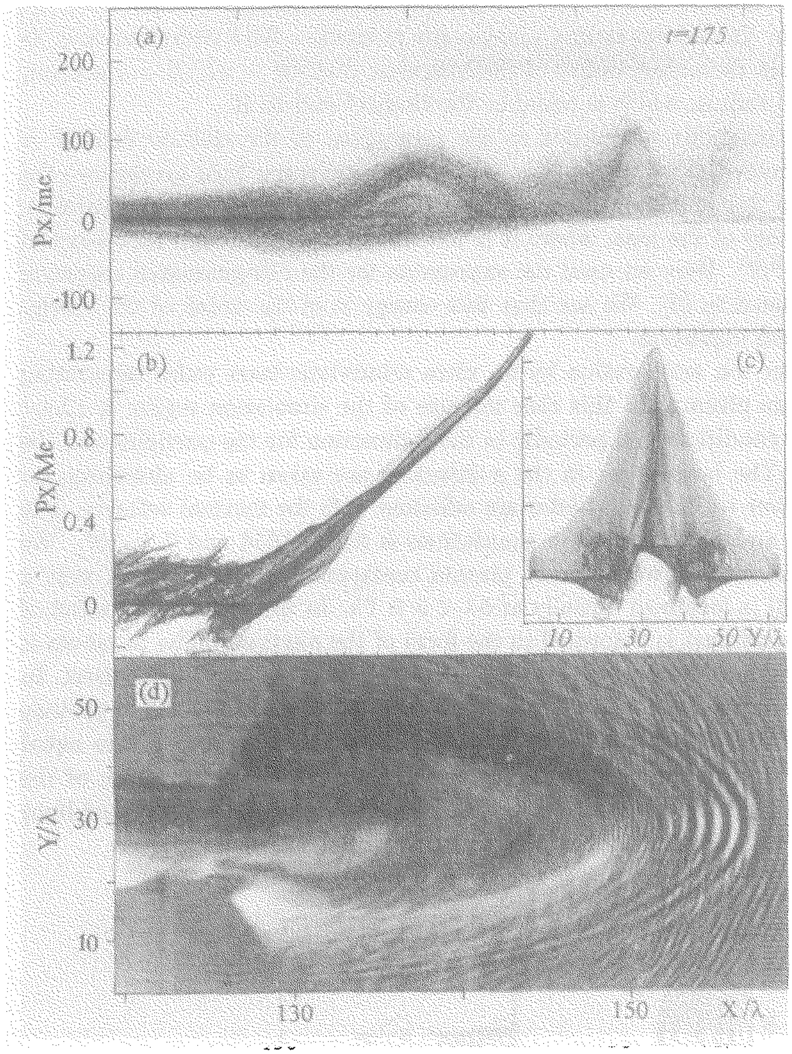

Fig.2

away by the ponderomotive pressure of the laser radiation, and the inductive electric field generated due the fast change of the magnetic field during expansion of the magnetized plasma cloud. These three mechanisms work together with a continuous change from one to the other and provide an energy gain of the same order of the magnitude.

We note that, when the high energy cloud appears at the end of the channel, the electrons expand in vacuum faster than the ions. This forms an ion cloud with a non compensated electric charge. It is easy to show that typical ion energy is equal to $\mathcal{E}_i \approx \approx 4\pi^2 ne^2 R^2 \approx \pi\,\mathrm{mc}^2 (R/d_e)^2$ in the relativistic case.

In the simulations presented above the ratio of the channel radius to the collisionless skin depth is about 10 to 30 which gives $\mathcal{E}_i \approx 300\,\mathrm{mc}^2$ to $\approx 900\,\mathrm{mc}^2$, in an agreement with the energy of fast ions seen in Fig.2.

Now we consider the ion acceleration in the inductive electric field generated by the fast change of the magnetic field during expansion of the magnetized plasma cloud. As seen in Figs.1 and 2, the self-generated magnetic field vanishes at the axis and changes its sign in the upper and lower regions. When the electron-ion cloud leaves the channel it carries the magnetic field B frozen into the plasma at the distance larger than the collisionless skin depth. In the expanding plasma the magnetic field decreases and its value can be found from the conservation of the magnetic flux: $\Phi = \pi L^2 B =$ constant, where $L(t)$ is the cloud radius, which is equal to the channel end to R.

The change of the magnetic field leads to the generation of the electric field $E = \dot{L}B/c = \dot{L}\Phi/\pi L^2$ directed along the laser beam axis. This electric field accelerates the ions in the forward direction and slows down the electrons. A relativistic charged particle, accelerated in the vicinity of the axis, where it is not magnetized, acquires an energy of the order of $\mathcal{E}_i \approx 8\pi n e^2 R^2$. Here we used the expression for the self-generated magnetic field $B = 4\pi neR$ obtained in [9]. We see that this energy is of the order of the energy gain during the Coulomb explosion.

Now we discuss the ion acceleration by an ultra relativistic laser pulse interacting with a slab of overdense plasma. In this case the size of the simulation region is $12.4 \times 15\lambda^2$. The boundary conditions are periodic in the y-direction for the particles and the electromagnetic field. The boundaries in the x-direction are taken to be absorbing for the electromagnetic waves while the particles are reflected with the thermal velocity. The number of grid points and particles in the simulations is 850×1024 and $7.2 \cdot 10^6$. We performed PIC simulations for two different plasma configurations. In the first case a plasma slab (a thin foil) is localized initially at $5\lambda < x < 7\lambda$. In the second case a foil of thickness 2λ in the central part is deformed in the form of the parabola. The parabola is given (at $x < 6\lambda$) by the formula $x = 4\lambda + 0.16(y - 7.5\lambda)^2/\lambda$ and the curve is 2λ thick. In both cases the maximum plasma density is $n = 30 n_{cr}$ and the plasma consists of protons (ion mass $M = 1840\,\mathrm{m}$) and electrons with initial electron and ion temperature equal to 800 eV. We expect that in the case of the deformed foil, the high absorption of the obliquely incident p-polarized pulse and the additional focusing of the transmitted light should lead to a more effective ion acceleration than in the flat foil configuration.

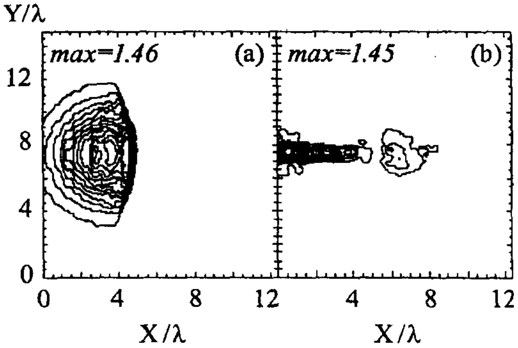

Fig.3

An ultra intense p-polarized laser pulse is initiated at the left hand side boundary. The pulse has a gaussian profile both in the longitudinal and in the transverse direction. The pulse length and spot size (its width) are 5.5λ and 5λ, respectively. The normalized vector potential of the incident pulse is equal to $a_e = 89$, and is larger than $\sqrt{M/m} \simeq 43$. Thus we expect that the ions are accelerated to extremely high energy directly by the laser light. For a 1 μm laser, the intensity corresponds to $1.6 \cdot 10^{22}\ \mathrm{W/cm^2}$ and the pulse length to 18 fs.

For the chosen parameters of the laser pulse and of the plasma the dimensionless parameter $\epsilon_0 = \omega_{pe}^2 l_s/2\omega c$ (see (1)) is equal to 180. The normalized laser amplitude $a = 89$ is smaller than ϵ_0. In this case, according to Ref.[7] the foil is not transparent to the laser radiation and only a relatively small portion of the radiation can be transmitted through the foil.

The interaction of the laser pulse with the foil is shown in Fig.3. Frame (a) shows the distribution of the electromagnetic energy density for $t = 9(2\pi/\omega)$ and for $t = 15(2\pi/\omega)$ in frame (b). The electromagnetic energy density is nomarlized by the peak value in the incident laser pulse. The contour levels vary from 0.1 to 1.2 with the interval 0.1. We see the deformation of the foil surface under the ponderomotive pressure which pushes the electrons in the forward direction. A relatively small fraction of pulse is transmitted: the fraction of the transmitted and reflected energy is about 6.1% and 42.2%.

In Fig.4 the phase plane of electrons, with energy above 1.5 MeV, is shown in frame (a) at $t = 15(2\pi/\omega)$. We see that the electrons are accelerated in the forward direction twice per laser period due to $\mathbf{v} \times \mathbf{B}$ force [10, 11] and the energetic electrons are accelerated in the backward direction once per laser period as observed in Ref. [12]. The phase plane of the fast ions is shown in Fig.4b. We see that the ions are accelerated both in backward and in the forward direction. The forward ion acceleration is predominant. The maximum momentum reached by the ions is $P_x/Mc \sim 1$, that corresponds to the GeV energy range. Also in this case the acceleration mechanism must be attributed to the Coulomb explosion which gives a final ion energy of the order of $\mathcal{E}_C \approx 2\pi^2 e^2 n l_s l_\perp = 2\pi^3 mc^2 (\omega_{pe}/\omega)^2 (l_s l_\perp/\lambda^2)$. For the parameters of the simulations $\mathcal{E}_C \approx 2Mc^2$ i.e., $\approx$2 GeV.

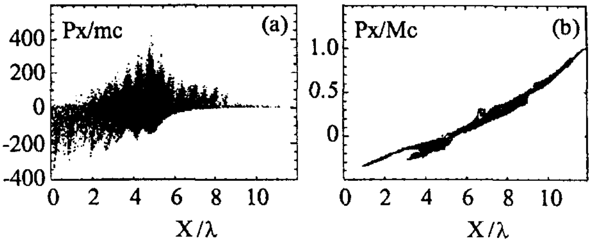

Fig.4

The spatial distribution of the fast electrons and ions shown in Fig.5, we present the energy density of electrons (a), ions (b) in the x, y-plane at $t = 15(2\pi/\omega)$. We see that the inside the plasma expanding in the forward direction the electron distribution is much less structured that the ion distribution. The ion density shows very clear filaments with scalelength of the order of the laser wavelength. In order to explain this structure we invoke the electromagnetic filamentation instability. In the expanding plasma the average energy of the electrons is approximately equal to the ion average energy. In this case the high energy electrons move faster than the ions. As is well known, a plasma with relative motion of electrons and ions is unstable. This instability is similar to the electron filamentation istability considered in Ref. [13]. It is easy to show that the growth rate of the filamentation instability is approximately equal to ω_{pi}.

In conlusion, with the help of 2D3V-PIC simulations, we have investigated the ion acceleration during the interaction of petawatt laser pulses with underdense and overdense plasma slabs.

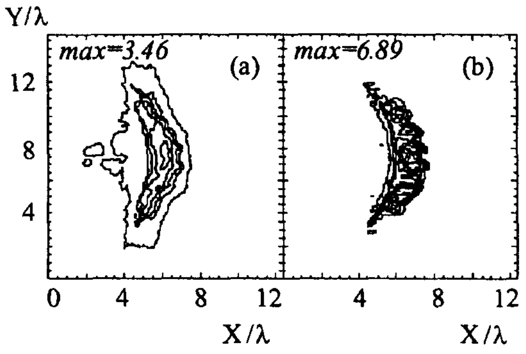

Fig.5

For what it concerns the ion acceleration in underdense plasmas, we emphasize the ions are accelerated predominantly in the forward direction when the laser pulse reaches the end of the slab. In this case, the plasma filament formed at the channel axis begins to expand at the channel end. High energy electrons expand faster and remained the ions that have been left behind form a well collimated relativistically moving jet. The jet is confined in the transverse direction by the pinching in the self-generated magnetic field. In the longitudinal direction the ion jet expands because the electric charge is not compensated inside the jet. We call this mechanism of ion acceleration "anisotropic Coulomb explosion". For the parameters that are characteristic of the interaction of a petawatt laser pulse with a near critical plasma the ions gain a relativistic energy.

In the case of the interaction of petawatt laser with a thin slab of overdense plasma, the relativistic ions are also accelerated via the anisotropic Coulomb explosion. The magnetic pinching of the jet in the transverse direction can appear due to the electromagnetic filamentation instability.

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