ION ACCELERATION AND PLASMA JETS DRIVEN BY A HIGH INTENSITY LASER BEAM NORMALLY INCIDENT ON THIN FOILS : A VLASOV CODE SIMULATION

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Recent experimental results [1,2] have shown the advantage of thin targets for collimated ion acceleration with normally incident high intensity circularly polarized laser beams. We study this problem with an Eulerian Vlasov code [3,4] which solves the one-dimensional (1D) relativistic Vlasov-Maxwell equations for both electrons and ions, when the laser beam is normally incident on an overdense deuterium plasma. The laser wavelength λ is greater than the scale length of the plasma density gradient at the plasma surface L_{edge} ($\lambda >> L_{edge}$), and the plasma density is $n = 100 n_c$, where n_c is the critical density. The normalized amplitude of the vector potential is $a_0 = 25/\sqrt{2}$, where $2a_0^2 = I\lambda^2 / 1.368\text{x}10^{18}$, I is the intensity in W/cm^2 and λ is in microns. The laser pulse is Gaussian and only about 10 cycles long. We consider the case of a thin foil, where the thickness of the uniform flat-top plasma slab is about $\approx 1.46 c/\omega_p$ (c/ω_p is the skin depth). The radiation pressure of the laser pushes the electrons at the target surface via the ponderomotive force, producing a sharp density gradient, which gives rise to a charge separation and an electric field which accelerates the ions and leads to the formation of a neutral plasma jet. For the thin target considered, the electron phase-space shows electrons expanding from the back of the target (similar to the leaky light sail radiation pressure acceleration regime [5]), then spiralling in phase-space around the target.

The relevant equations in the Vlasov code

The 1D Vlasov equations for the electron distribution function $f_e(x, p_{xe}, t)$ and the ion distribution function $f_i(x, p_{xi}, t)$ are given by [3]:

$$\frac{\partial f_{e,i}}{\partial t} + \frac{p_{xe,i}}{m_{e,i}\gamma_{e,i}} \frac{\partial f_{e,i}}{\partial x} + (\mp E_x - \frac{1}{2m_{e,i}\gamma_{e,i}} \frac{\partial a_\perp^2}{\partial x}) \cdot \frac{\partial f_{e,i}}{\partial p_{xe,i}} = 0 \, . \tag{1}$$

Time t is normalized to ω^{-1}, length is normalized to $c\omega^{-1}$, velocity and momentum are normalized respectively to the velocity of light c, and to $M_e c$. The indices e and i refer to electrons and ions. In our normalized units $m_e = 1$ for the electrons, and $m_i = M_i / M_e$= 2.*1836 for the deuterium ions, where M_i and M_e are the ion and electron masses respectively. In the direction normal to *x*, the canonical momentum, written in our normalized units as $\vec{P}_{\perp e,i} = \vec{p}_{\perp e,i} \mp \vec{a}_{\perp}$ is conserved (the vector potential $\vec{a}_{\perp}$ is normalized to $M_e c / e$). $\vec{P}_{\perp e,i}$ can be chosen initially to be zero, so that $\vec{p}_{\perp e,i} = \pm \vec{a}_{\perp}$. $E_x = -\frac{\partial \varphi}{\partial x}$ and $\vec{E}_{\perp} = -\frac{\partial \vec{a}_{\perp}}{\partial t}$. The relativistic factor is $\gamma_{e,i} = \left(1 + \left(p_{xe,i} / m_{e,i}\right)^2 + \left(a_{\perp} / m_{e,i}\right)^2\right)^{1/2}$. The transverse electromagnetic fields $E^{\pm} = E_y \pm B_z$ and $F^{\pm} = E_z \pm B_y$ for the circularly polarized wave obey Maxwell's equation:

$$(\frac{\partial}{\partial t} \pm \frac{\partial}{\partial x})E^{\pm} = -J_y . \; ; \qquad (\frac{\partial}{\partial t} \mp \frac{\partial}{\partial x})E^{\pm} = -J_z \qquad (2)$$

Equations (2) are integrated along the vacuum characteristic *x*=*t*. In our normalized units:

$$\vec{J}_{\perp} = \vec{J}_{\perp e} + \vec{J}_{\perp i} \; ; \qquad \vec{J}_{\perp e,i} = -\frac{\vec{a}_{\perp}}{m_{e,i}} \int \frac{f_{e,i}}{\gamma_{e,i}} dp_{xe,i} . \; ; \qquad J_{xe,i} = \pm \frac{1}{m_{e,i}} \int \frac{p_{xe,i}}{\gamma_{e,i}} f_{e,i} dp_{xe,i} \qquad (3)$$

Eq.(1) is solved using a 2D interpolation along the characteristics [1,2]. From Ampère's equation $\partial E_x / \partial t = -J_x$, we calculate $E_x^{n+1/2}$ as follows: $E_x^{n+1/2} = E_x^{n-1/2} - \Delta t J_x^n$, $J_x = J_{xe} + J_{xi}$.

Results

The forward propagating circularly polarized laser wave penetrates the plasma at *x*=0, with field values $E^+ = 2E_0 P_r(t) \cos\tau$, $F^- = -2E_0 P_r(t) \sin\tau$, where $\tau = t - 1.5t_p$. The temporal shape factor is $P_r(t) =$ $\exp(-2.\ln(2.)(\tau / t_p)^2)$, with $t_p = 12$ for the laser pulse. We choose for the amplitude of the vector potential $a_0 = 25/\sqrt{2}$. In our units $E_0 = a_0$. We have $\omega_p = 10\omega$, which corresponds to $n = 100 n_c$. The initial temperature for the electrons and for the ions are T_e=1. keV and T_i=0.1 keV. The total length of the simulation domain is $L = 10c/\omega$. We use *N* =5000 grid points in space ($\Delta x = \Delta t = 0.002$), and 1400 in momentum space for the electrons and 7000 for the ions (extrema of the electron momentum are ± 4, and for the ion momentum ± 350). We have a vacuum region of length $L_{vac} = 4.78c/\omega$ on the left side of the plasma slab. The jump in density at the plasma edge on each side of the slab is of length $L_{edge} = 0.15c/\omega$, and the top slab density normalized to 1 is of length $L_p = 0.146c/\omega$, or $1.46c/\omega_p$. In our normalized units $\omega = k = 1$. The incident wavelength is $\lambda = 2\pi$, *i.e.* $\lambda >> L_{edge}$.

Figs.(1) show the plot of the density profiles (full curves for the electrons, dashed curves for the ions and dashed-dotted curves for the longitudinal electric field divided by a factor of 10 to be plotted on the same graphic) at *t*=22.5 (left frame), 23.5 (middle frame) and 27 (right frame), and in Figs.(2) at *t*=30, 33.5 and 36.5. The incident laser wave is pushing the plasma edge, which is acquiring a steep density profile under the ponderomotive pressure of the wave, with electrons accumulating at the edge of the plasma, which results in a charge separation and a longitudinal electric field at the edge. The incident laser beam intensity peaks at *t*=18 at the left boundary *x*=0, and this peak travels a distance $L_{vac} = 4.78c/\omega$ to reach the plasma edge at about *t*=22.78. We see in Figs.(1) that a very rapid acceleration of the ions at the edge takes place between *t*=22.5 and 23.5, forming a solitary-like structure. Due to the thin foil limited mass, all the electrons are accelerated by the transmitted field, with the trapped ions. We note the existence of an electron population ejected from the rear of the target (see Figs.(4)). A fraction of the incident laser wave E^+ and F^- penetrates through the target and travels to the right in the forward direction, while another fraction is reflected at the target surface (see Figs.(5) at *t*=23.5). Figs.(2) show similar plots to Figs.(1), at *t*=30, 33.5 and 36.5, when the incident wave is decaying and reducing its pressure on the target surface. Then part of the electron population at the surface is moving backwards to the left, while another fraction, caught by the ions, is forming a neutral bump free streaming to the right. The electrons phase-space in Fig.(4) shows the electrons spiralling around the central peak which is neutralizing the ions, which results in small sawteeth structures in the density plot of the electrons in Figs.(1,2) at *t*=27, 30. The phase-space plots of the ions are shown in Figs.(3).

The authors are grateful to the Centre de calcul scientifique de l'IREQ (CASIR) for the computer time used for this simulation.

References

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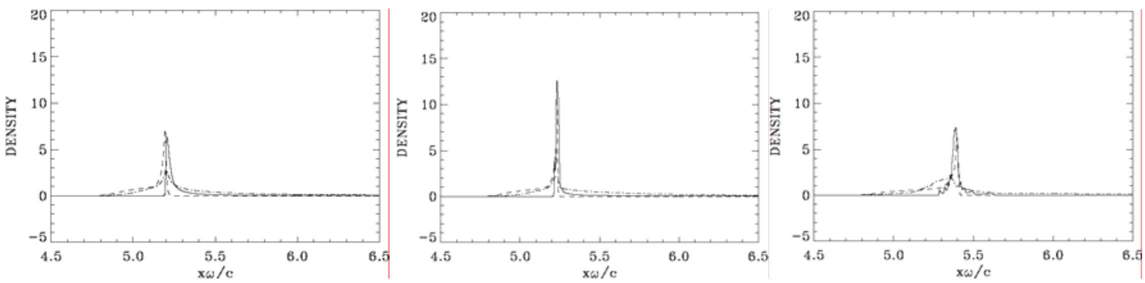

Fig.1 Electron (full curve), ion (dashed curve), elect. field (dashed-dotted curve) at the edge at *t*=22.5., 23.5, 27

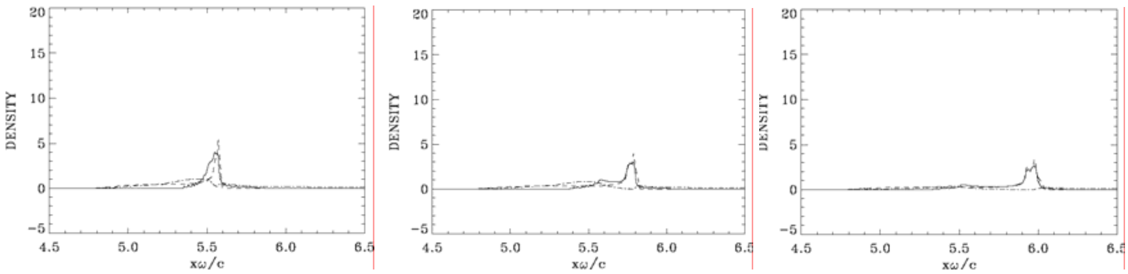

Fig.2 Electron (full curve), ion (dashed curve), elect. field (dashed-dotted curve) at the edge at *t*=30, 33.5,36.5

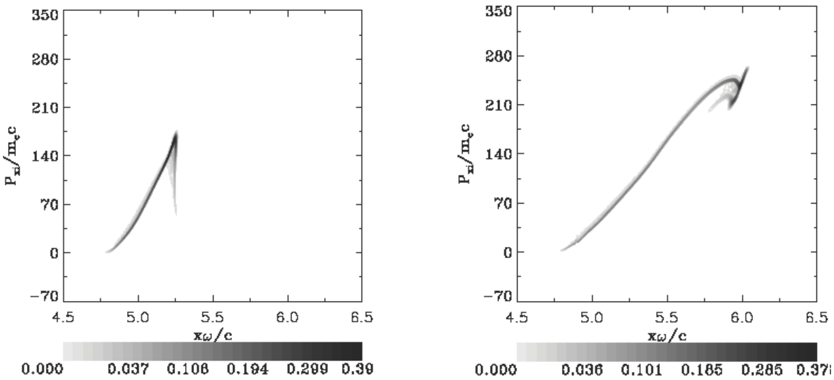

Fig.3 Phase-space for the ion distribution function at *t*=24 and 36.5

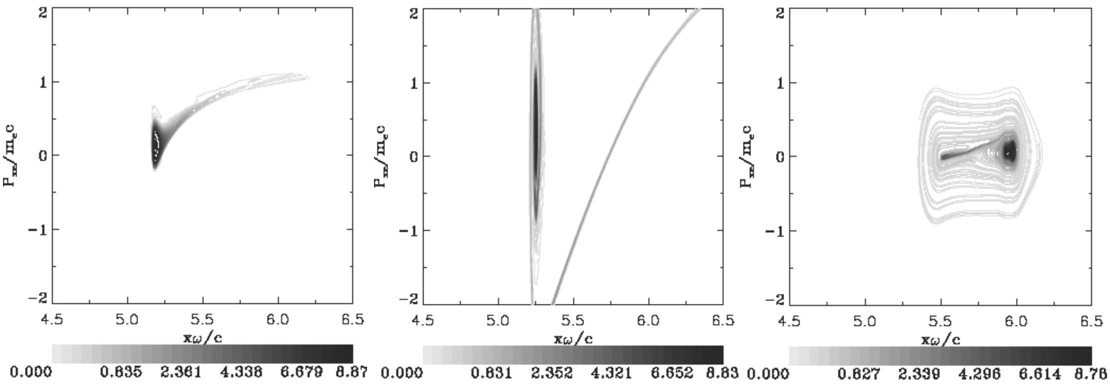

Fig.4 Phase-space for the electron distribution function at *t*=21, 24, 36.5

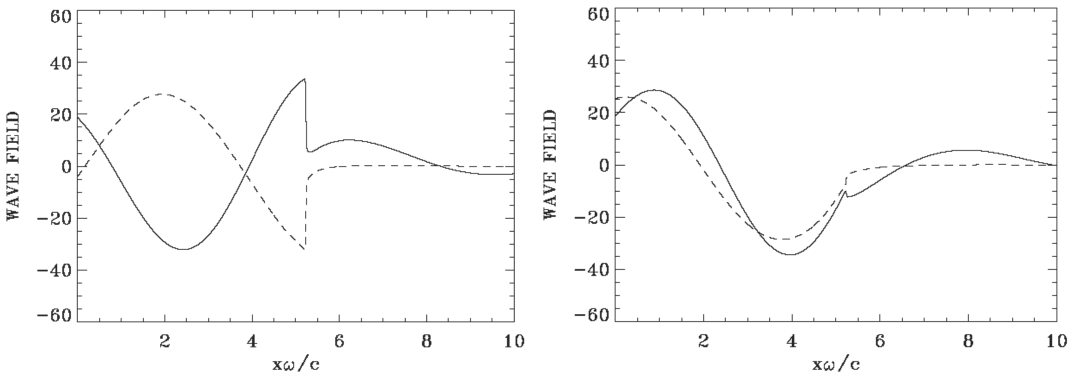

Fig.5 Right panel: Incident E^+ (full curve) and reflected E^- (dashed curve) waves at *t*=23.5

Left panel: Incident F^- (full curve) and reflected F^+ (dashed curve) waves at *t*=23.5