# NUMERICAL STUDY OF THE INTERACTION OF A CIRCULARLY POLARIZED LASER BEAM NORMALLY INCIDENT ON AN OVERDENSE PLASMA: A COMPARISON BETWEEN A VLASOV CODE AND A PIC CODE

M. Shoucri[1], X. Lavocat-Dubuis[2], J.-P. Matte[2], F. Vidal[2]

*1-Institut de recherche d'Hydro-Québec (IREQ), Varennes, Québec, Canada J3X1S1*

*2-INRS Energie et Matériaux, Université du Québec, Varennes, Québec, Canada J3X1S2*

We study the acceleration of ions and the formation of a plasma jet due to the interaction of a high intensity circularly polarized laser beam normally incident on the surface of an overdense deuterium plasma, by comparing results obtained from two one-dimensional (1D) numerical codes (namely an Eulerian Vlasov code [1,2] and the particle-in-cell PIC code BOPS [3]), for the numerical solution of the 1D relativistic Vlasov-Maxwell equations for both electrons and ions. We consider the case when the laser beam wavelength $\lambda$ is greater than the scale length of the plasma density gradient at the plasma surface $L_{edge}$ ($\lambda >> L_{edge}$), and the plasma density $n = 100 n_c$, where $n_c$ is the critical density. The laser beam interacts with the electrons at the plasma surface via its ponderomotive pressure, producing an even sharper electron density gradient at the target surface, which gives rise to a charge separation and an electric field which accelerates the ions and leads to the formation of a plasma jet. We consider the case when the laser beam amplitude varies in time in the form of a pulse. The two codes show good agreement for the macroscopic quantities calculated. The low noise level of the Vlasov code allows a better representation of the phase-space structure of the electrons and ions.

**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 [1,2]:

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

Time $t$ is normalized to $\omega^{-1}$, 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 ions, where M and M are the ion and electron mass 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 $\vec{p}_{\perp e,i} = \pm \vec{a}_{\perp}$. $E_x = -\dfrac{\partial \varphi}{\partial x}$ and $\vec{E}_{\perp} = -\dfrac{\partial \vec{a}_{\perp}}{\partial t}$. 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:

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

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

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

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

**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 potential vector $a_0 = 25/\sqrt{2}$. In our units $E_0 = a_0$. We set $\omega_p = 10\omega$, 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 $L = 20c/\omega$. We use *N* =10000 grid points in space (so $\Delta x = \Delta t = 0.002$), and 2200 in momentum space for the electrons and ions (extrema of the electron momentum are $\pm 5$, and for the ion momentum $\pm 170.$). We have a vacuum region on each side of the plasma of length $L_{vac} = 7.85c/\omega$. The jump in density at the plasma edge on each side of the slab is $L_{edge} = 0.3c/\omega$, and the top slab density of 1 is of length $3.7c/\omega$. The incident wavelength is $\lambda = 2\pi$ , *i.e.* $\lambda >> L_{edge}$. For the PIC code, 500000 particles are used for the electrons and the ions.

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) at *t*=24. (left frame), 25.6

(middle frame) and 55 (right frame), calculated from the Vlasov code. The equivalent curves calculated from the PIC code are shown in Fig.(2) at *t*=25.6, 26 and 55. The incident laser wave is literally 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. We see in Fig.(1) that a very rapid acceleration of the ions at the edge takes place between *t*=24 and 25.6, forming a solitary-like structure. The penetration of the electric field , which is formed at the surface, in the plasma is of the order of the skin depth. Fig.(2) shows that at *t*=25.6, the PIC code is slower in showing this rapid acceleration of the ions, which happens a little later at *t*=26. The incident laser beam intensity peaks at *t*=18 at the left boundary *x*=0, and this peak travels a distance $L_{vac} = 7.85c/\omega$ to reach the plasma edge at *t*=25.85. The laser pulse then decreases. The accumulation of electrons and ions at the plasma edge increases the opacity of the plasma to the laser beam. The incident laser wave and the longitudinal electric field in Figs.(1,2) do not penetrate the plasma and are strongly damped at the edge within a skin depth. We see in Figs.(1,2) at *t*=55 that the ion and electron density peaks at the left decay slowly after the disappearance of the pulse, while at the right there is an expanding neutral plasma. This can be verified looking at the phase-space of the ions at *t*=55 shown in Figs.(3). The expansion of the plasma to the right as calculated by the PIC code in Fig.(2) at *t*=55, appears to be slightly bigger than what is calculated by the Vlasov code at *t*=55 in Fig.(1). This is in agreement with what is presented in Fig.(3), where we see the peak of the ion momentum reaching a higher value in the plot calculated by the PIC code, with respect to the plot calculated by the Vlasov code. More details on these results are presented in [4].

The contribution of X. Lavocat-Dubuis, J.-P. Matte and F. Vidal is funded by the Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) and the Ministère de l'Éducation du Québec. The authors are grateful to the Centre de calcul scientifique de l'IREQ (CASIR) for the computer time used for the Vlasov code simulation.

**References**

[1] M. Shoucri, B. Afeyan Laser Part. Beams **28**, 129 (2010)

[2] M. Shoucri in ´Eulerian Codes for the Numerical Solution of the Kinetic Equations of Plasmas´, Nova Science Publishers, N.Y (2011), p. 163

[3] P. Gibbon, A.R. Bell Phys. Rev. Lett. **68**,1535 (1992)

[4] M. Shoucri, X. Lavocat-Dubuis, J.-P. Matte, F. Vidal, ' Numerical Study of Ion Acceleration and Plasma Jet Formation in the Interaction of an Intense Laser Beam Normally Incident on an Overdense Plasma' (accepted for publication, Laser and Particle Beams).

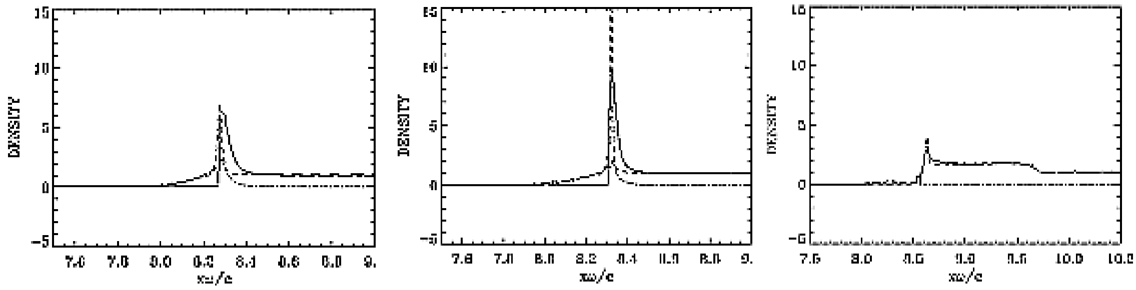


Fig.1 Electron (full curve), ion (dashed curve), elect. field (dashed-dotted curve) at the edge at *t*=24., 25.6, 55

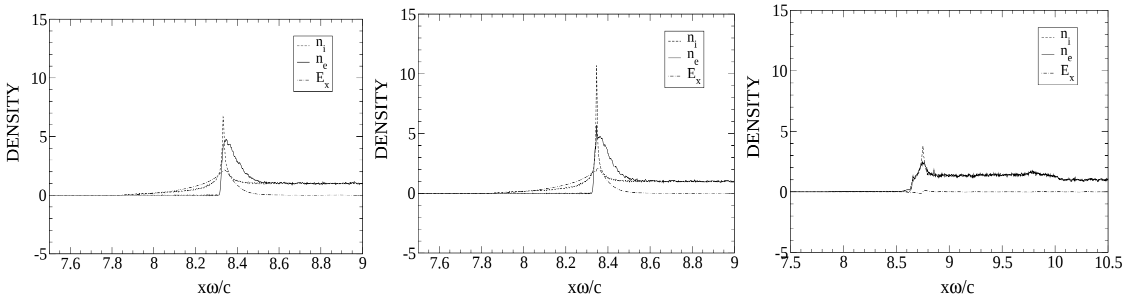


Fig.2 Electron (full curve), ion (dashed curve), elect. field (dashed-dotted curve) at the edge at *t*=25.6, 26,55

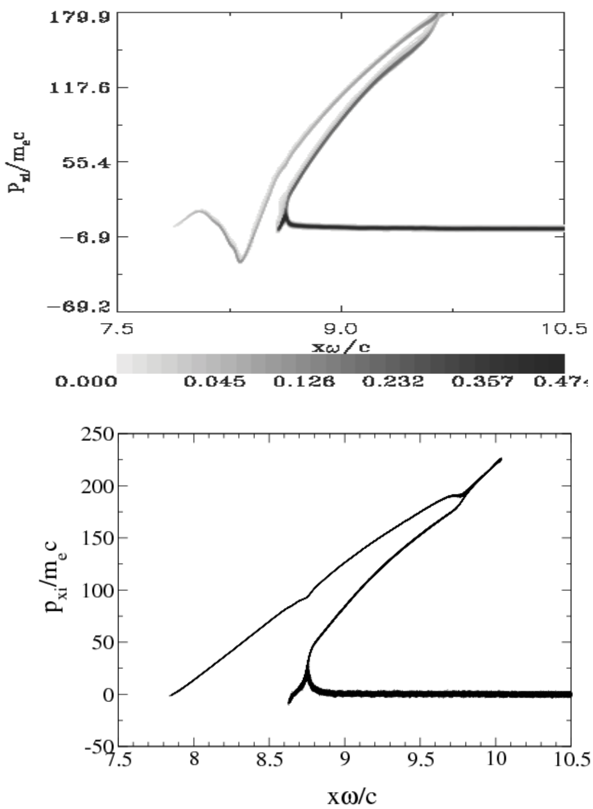


Fig.3 Phase-space for the ion distribution function at *t*=55
(Vlasov code upper figure; PIC code lower figure)