# A VLASOV CODE SIMULATION OF ION ACCELERATION AND PLASMA JETS DRIVEN BY A HIGH INTENSITY LASER BEAM

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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 [3,4,5] 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 $\lambda$ is greater than the scale length of the jump in plasma density at the plasma surface $L_{edge}$ ($\lambda >> L_{edge}$). The plasma density in the flat top plasma slab is $n = 25n_c$, 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 $\lambda$ is in microns. The laser pulse is Gaussian and only about 10 cycles long. We consider the case of a thin target, where the thickness of the uniform flat-top plasma slab is about $\approx 4.2c/\omega_p$ ($c/\omega_p$ is the skin depth). The relevant equations are the relativistic 1D Vlasov-Maxwell set of equations previously presented in [3,4,5].

**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 transverse electromagnetic fields are $E^{\pm} = E_y \pm B_z$ and $F^{\pm} = E_z \pm B_y$ for the circularly polarized wave. Time and length are normalized to $\omega^{-1}$ and $c/\omega$ respectively. The temporal shape factor is $P_r(t) = \exp(-2\ln(2)(\tau/t_p)^2)$, where $t_p = 24$ is the pulse duration at full-width at half-maximum of the beam intensity. The Gaussian pulse reaches its peak at $t = 1.5t_p = 36$. In our units $E_0 = a_0$. We have $\omega_p = 5\omega$, which corresponds to $n = 25n_c$. 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 ($\Delta x = \Delta t = 0.002$), and in momentum space 1600 grid points for the electrons and 13000 for the ions (extrema of the electron momentum are $\pm 6$, and for the ion momentum $\pm 650$). Momentum is normalized to $M_e c$. We have a vacuum region of length $L_{vac} = 9.28c/\omega$ on both sides of the plasma slab. The jump in density at the plasma edge on each side of the slab is of length $L_{edge} = 0.3c/\omega$, and the top flat density normalized to 1 is of length $L_p = 0.84c/\omega$, or $4.2c/\omega_p$. 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, which is divided by a factor of 5 to be plotted on the same graphic). 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 target surface. This results in a charge separation and a longitudinal electric field at the edge (Fig.(1) at *t*=42). This electric field accelerates the ions. For the thin target considered, the electron phase-space in Fig.(2) shows at *t*=42 an electron population ejected from the back of the target (similar to the leaky light sail radiation pressure acceleration regime[6]). This leak from the back of the target is also observed in Fig.(1) at *t*=42, where we see the electron density and an electric field appearing in the back of the target. The incident laser beam intensity peaks at *t*=36 at the left boundary *x*=0, and this peak travels a distance $L_{vac} = 9.28c/\omega$ to reach the plasma edge at about *t*=45.29. In Figs.(1), a very rapid acceleration of the ions at the edge takes place between *t*=44 and 47, forming a solitary-like structure. The electrons phase-space in Fig.(2) shows the electrons spiralling around the central peak. This results in small sawteeth-like structures around the central peak in the density plot in Figs.(1) at *t*=47, 53. 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.(4) at *t*=42). Figs.(1) at *t*=53 to 86 show the evolution of the profiles during the decay of the incident laser pulse, when the radiation pressure on the target surface is reduced. At *t*=68 part of the electron population is caught by the ions in the solitary structure, forming a neutral bump free streaming to the right, and the excedent electron population is detaching and moving backwards to the left. This detached population is also observed in the phase-space plots if Fig.(2) at *t*=66, 76 and 86. (This mechanism is different from what we observe in Fig.(7) of [3] when the thickness of the plasma slab is increased to $\approx 5.54c/\omega_p$ for the same density, where we observed the formation of a double layer structure). The evolution of the ions phase-space, showing different phases of the ion acceleration, is presented in Fig.(3). At *t*=86, the peak is reaching a momentum

$M_i\upsilon / M_e c \approx 525$. This corresponds to a velocity for the deuterium ions of $\upsilon / c \approx 525/(2\text{x}1836)$ $= 0.143$. The same value can be calculated following the edge of the shock-like structure of the neutral plasma expanding to the right in Fig.(1) at *t*=72-86. The energy is $M_i\upsilon^2/2 =$ $M_i c^2 (\upsilon / c)^2 /2 = 938\text{x}0.02 = 19.173\text{MeV}$.We note that for the case $n = 100 n_c$ reported in [5], we had a maximum $M_i\upsilon / M_e c \approx 260$. This is a decrease by a factor of 2 with respect to the present results, corresponding to an increase by a factor of 4 in the density.

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**References**

[1] S. Kar *et al.*, Phys. Rev. Lett. 100, 225004 (2008)

[2] R. Prasad *et al.*, Appl. Phys. Lett. 99, 121504 (2011)

[3] M. Shoucri , Comp. Sc. Disc. 5, 014005 (2012)

[4] M. Shoucri, X. Lavocat-Dubuis, J.-P. Matte, F. Vidal, Laser Part. Beams 28, 129 (2010)

[5] M. Shoucri, J.-P. Matte, F. Vidal, Proc. 39th EPS Conf. Plasma Phys. (Stockholm, 2012). P2.121; also in Laser Part. Beams , accepted for publication (2013)

[6] B. Qiao, M. Geissler, S. Kar, M. Borghesi, M. Zepf, Plasma Phys. Control. Fusion 53, 124009 (2011)

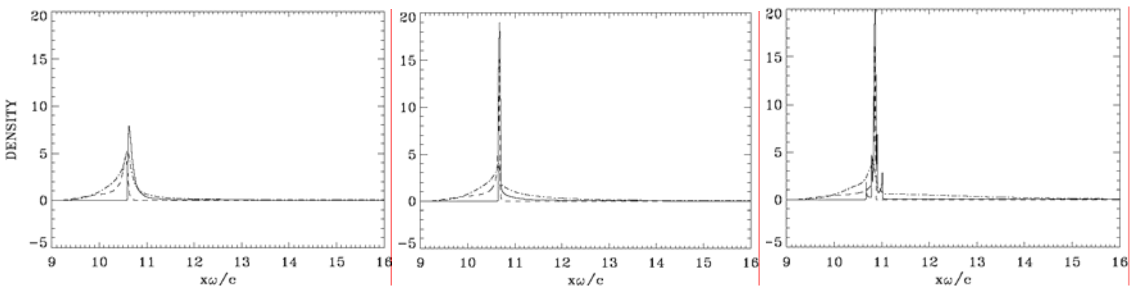
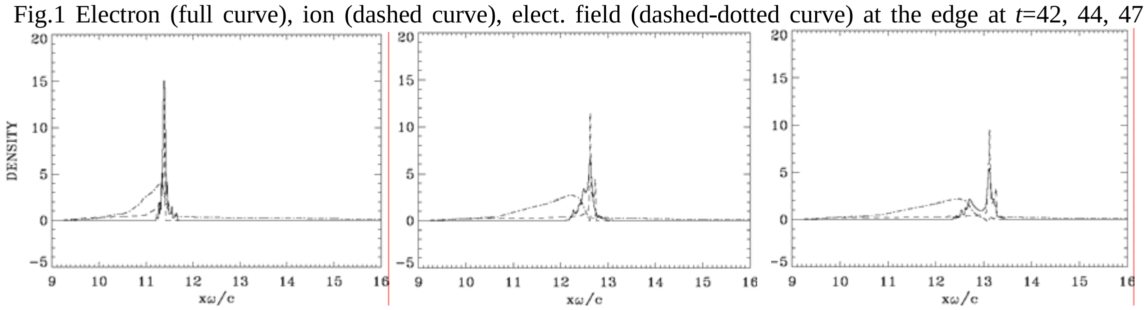
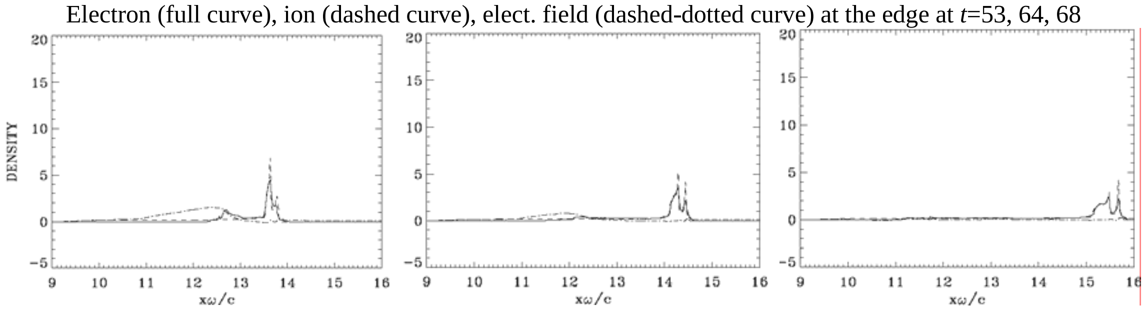



Fig.1 Electron (full curve), ion (dashed curve), elect. field (dashed-dotted curve) at the edge at *t*=42, 44, 47




Electron (full curve), ion (dashed curve), elect. field (dashed-dotted curve) at the edge at *t*=53, 64, 68



Electron (full curve), ion (dashed curve), elect. field (dashed-dotted curve) at the edge at *t*= 72, 77, 86

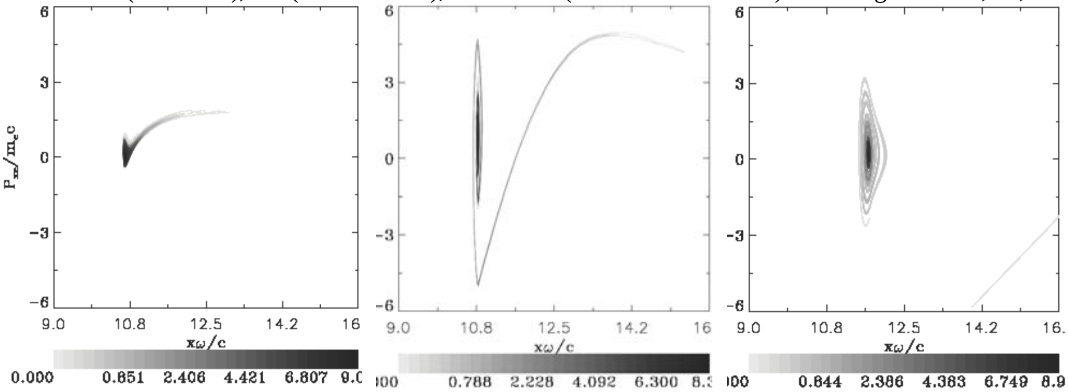
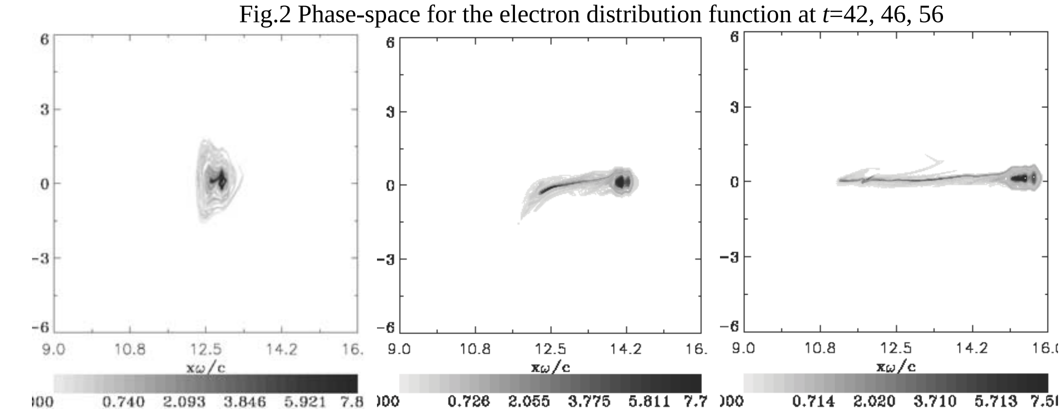



Fig.2 Phase-space for the electron distribution function at *t*=42, 46, 56




Phase-space for the electron distribution function at *t*=66, 76, 86

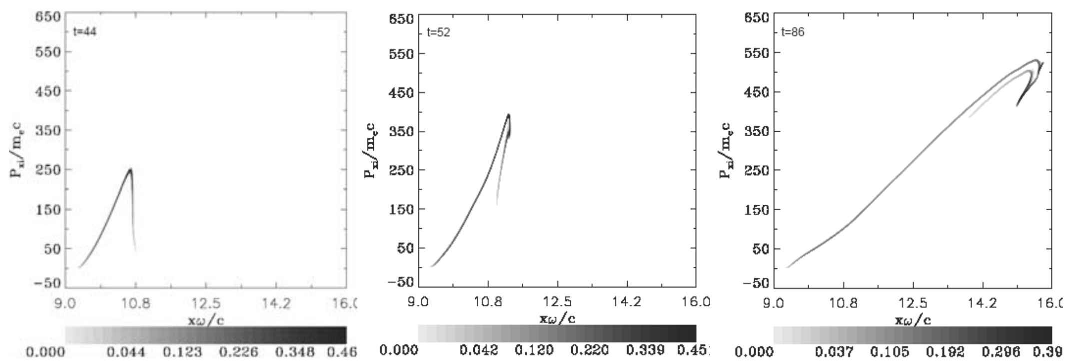



Fig.3 Phase-space for the ion distribution function at *t*=44, 52 and 86

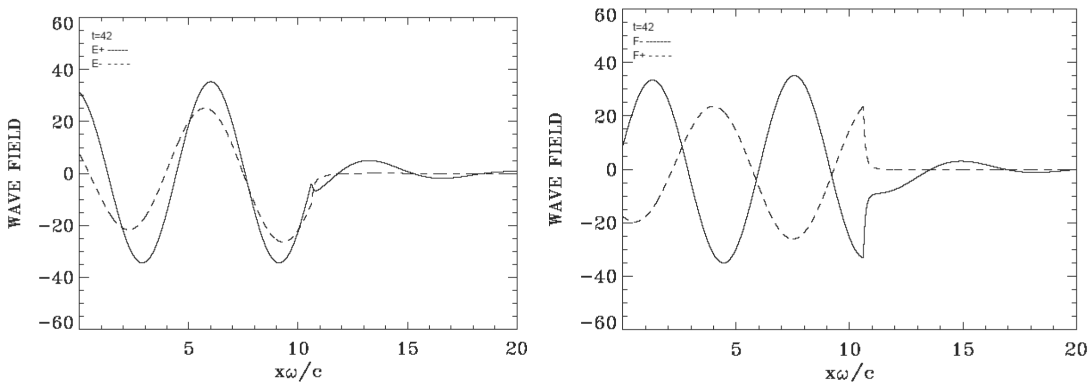



Fig.4 Right panel: Incident $E^+$ (full curve) and reflected $E^-$ (dashed curve) waves at *t*=42

Left panel: Incident $F^-$ (full curve) and reflected $F^+$ (dashed curve) waves at *t*=42