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 \(L_{\text{edge}}\) \((\lambda \gg L_{\text{edge}})\). 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 \(2a_0^2 = 1.368 \times 10^{18}/I\) 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 \(\approx 4.2\sqrt{c/\omega_p}(c/\omega_p\text{ is the skin depth})\). 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 \(E^+ = 2E_0P_\tau(t)\cos\tau, F^- = -2E_0P_\tau(t)\sin\tau\), 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 \(P_\tau(t) = \exp(-2\ln(2)(t/t_p)^2)\), 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 \( L_{\text{vac}} = 9.28c / \omega \) on both sides of the plasma slab. The jump in density at the plasma edge on each side of the slab is of length \( L_{\text{edge}} = 0.3c / \omega \), 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. \( \Lambda >> L_{\text{edge}} \).

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 \( L_{\text{vac}} = 9.28c / \omega \) 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
$M_i \nu / M_e c \approx 525$. This corresponds to a velocity for the deuterium ions of $\nu / c \approx 525/(2 \times 1836) = 0.143$. 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 $M_i \nu^2 / 2 = M_e c^2 (\nu / c)^2 / 2 = 938 \times 0.02 = 19.173 \text{MeV}$. We note that for the case $n = 100n_c$ reported in [5], we had a maximum $M_i \nu / M_e c \approx 260$. 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

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 $t=44, 52, 86$.

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 $t=42$.