A Vlasov code simulation of the formation and evolution of a double layer during the ion acceleration driven by a high-intensity laser beam

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We use an Eulerian Vlasov code [1,2], which solves the one-dimensional relativistic Vlasov-Maxwell equations for both electrons and ions, to study the problem of the formation and evolution of a double layer during the process of ion acceleration driven by a high-intensity circularly polarized laser beam normally incident on a thin foil. We consider the case of an overdense plasma with a plasma density $n = 100n_{cr}$ (n_{cr} is the critical density), and the laser frequency ω is therefore $\omega/\omega_{pe} = 1/\sqrt{n/n_{cr}} = 0.1$, where ω_{pe} is the plasma frequency. The Vlasov-Maxwell equations are those presented in Shoucri *et al.* (2014, 2016). Time t is normalized to the inverse laser wave frequency ω^{-1}, length to $c\omega^{-1}$, velocity and momentum are normalized to the velocity of light c and to $M_e c$ respectively (M_e is the electron mass), and the electric field to $M_e c\omega/e$. Thus, in free space $\omega = k = 1$ for the electromagnetic wave. We have a vacuum region of length L_{vac} = 2.517 on the incident side at the left of the target slab. The initial density profile consists of a flat part of density 1 (or $100n_{cr}$) and length $L_p = 1.287c/\omega$ and steep linear density ramps at both ends with $L_{edge} = 0.24$ (far less than the laser wavelength λ) each, and the remaining vacuum space at the right of the target is 5.716, for a total length of the domain of 10. So the initial plasma slab extends from 2.517 to 4.284 and the flat plateau is between 2.757 and 4.044. In our units the skin depth $c/\omega_{pe} = (c/\omega)(\omega/\omega_{pe}) = 0.1c/\omega$, the thickness of the flat top of the slab $L_p = 1.287$ is therefore about 13 skin depths. We use N=12500 grid points in space, and in momentum space we use 1000 grid points for the electrons and 2800 grid points for the ions (extrema of the electron momentum are ± 5 and ± 1400 for the ion momentum). Deuterium ions are assumed. From these parameters we have a grid size $\Delta x = 8\text{x}10^{-4}$, and the time-step $\Delta t = \Delta x$. The normalized amplitude of the vector potential of the incident laser beam is $a_0 = 80$, where $2a_0^2 = I\lambda^2/1.368x10^{18}$, I is the intensity in W/cm^2 for a circularly polarized wave and λ is the wavelength in microns. In the present simulation, we have a forward-propagating circularly polarized laser beam entering the system at the left boundary (x=0), where forward-propagating fields at x=0 are given by $E^{+} = E_y + B_z = 2E_0 P_r(t)\cos(\tau)$ and $F^{-} = E_z - B_y$ $= -2E_0 P_r(t)\sin(\tau)$, where $\tau = t - 1.5t_p$, $t_p = 12$ (slightly less than two plasma periods) is the pulse FWHM of the laser beam. In our normalized units $E_0 = a_0$. The Gaussian shape factor $P_r(t) = \exp(-2\ln(2)(\tau / t_p)^2$ reaches its peak at $t = 1.5t_p = 18$.

We observe initially a bunching of the electrons at the plasma surface (full curve), under the effect of the radiation pressure (or ponderomotive force), producing a strong charge separation with a sharp density gradient at the target surface, and hence an electric field (dashed-dotted curve) which strongly accelerates the ions (dashed curve, see Fig. (1a)). There is a heating of the electrons at the surface as we see on Fig. (3a). Later, as the intensity of the laser pulse increases, Fig. (1b) shows the increase of this electron bunching and of the resulting electric field causing the ions to accelerate. Figure (1c) shows a sudden and very rapid acceleration of the ions around the position x=4 at t=20.8. Then the ion peak and the electron peak separate (Figs. (1d,e)), forming a double layer, with an electric field between the two peaks providing the restoring force. The whole initial thin foil is transformed into a double layer and the ponderomotive force acceleration persists beyond the transition through the initial target volume. Figures (1f-1h) shows part of the electron population neutralizing the accelerated ions and the neutral population free streaming in the forward direction (the two peaks at the right in Fig. (1h)), while the excess electron population forms a third peak at the left in Fig. (1h), which slows down due to the restoring force, as indicated by the corresponding left vortex in Fig. (3d). These three peaks in Figs. (1h) are apparent in the contour plots of the electron distribution function in Figs. (3c-3d) (note the change in the vertical axis scale in Fig. (3d)). The electrons are seen to cool slowly after the initial rapid heating. In Fig.(2b) the maximum momentum is about 1250. The corresponding velocity is calculated from the deuterium ion momentum 1250 = $(M_i / M_e)(\upsilon / \mathrm{c}) / \sqrt{1-(\upsilon / c)^2}$, from which υ / c =0.37. The corresponding energy is $M_i\, \mathrm{c}^2 (1/\sqrt{1-(\upsilon / c)^2} - 1) =$ 140 MeV. The Vlasov code allows a detailed study of the mechanism of formation and evolution of the double-layer structure, until the formation of a neutral plasma jet ejected from the back of the target.

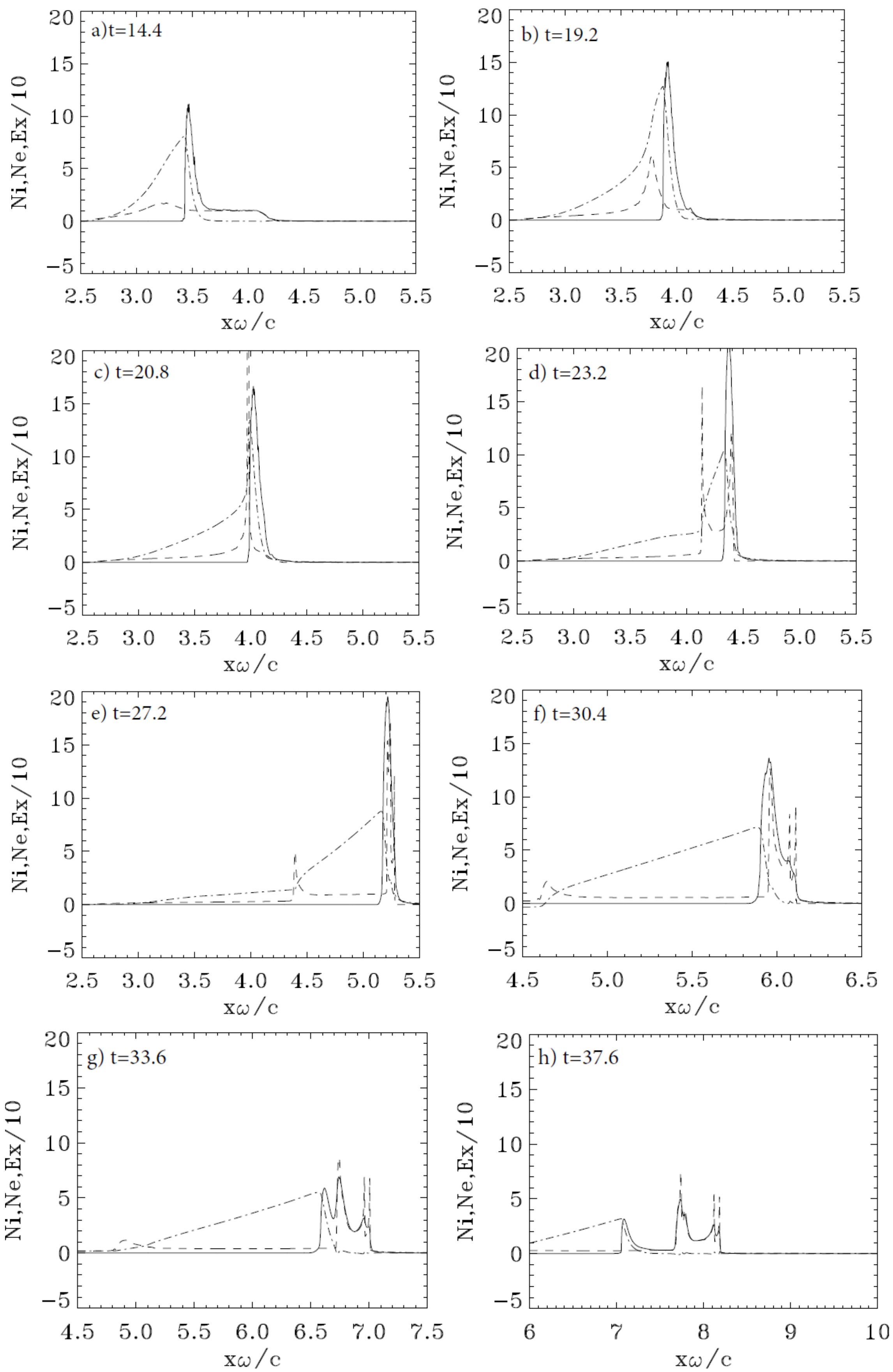

Figure 1. Plots of the electron (full curve), ion (dashed curve) densities, and the electric field (dashed-dotted curve) at different times.

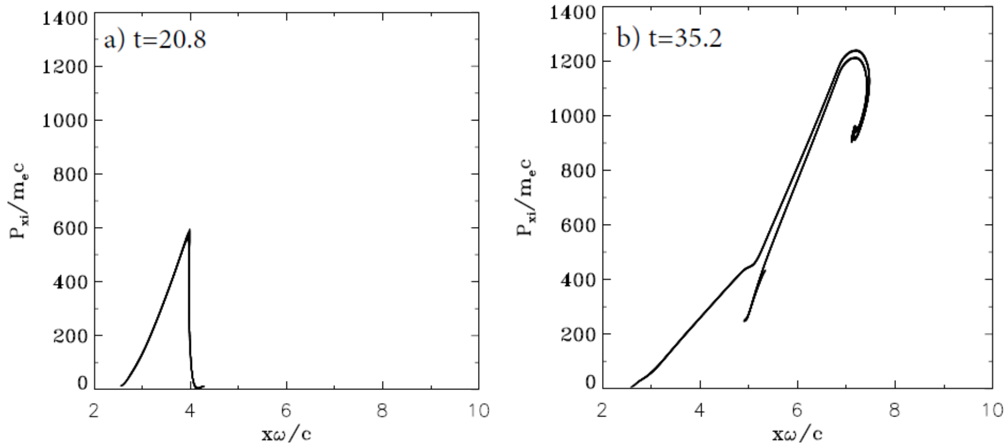

Figure 2. Phase-space contour plots of the ion distribution function

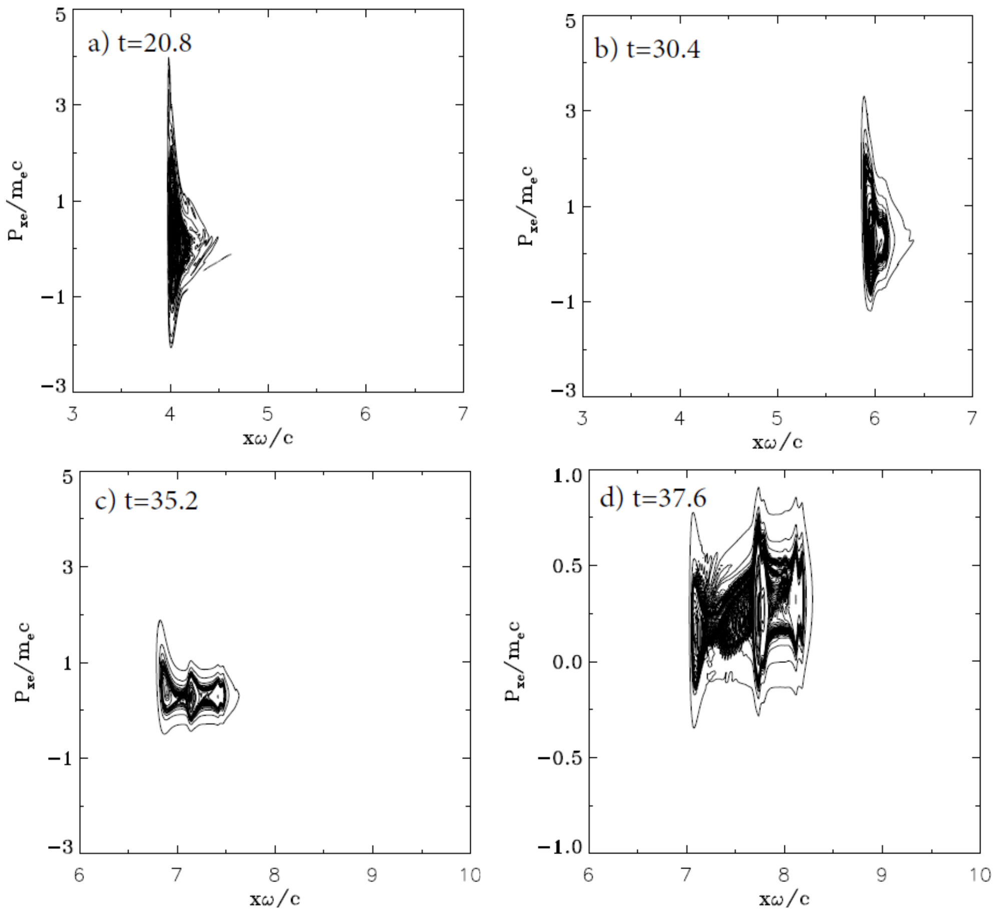

Figure 3. Phase-space contour plots of the electron distribution function

References

[1] M. Shoucri, F. Vidal, and J.-P. Matte, Laser Part. Beams (2016); doi:10.1017/S0263034616000057

[2] M. Shoucri, J.-P. Matte and F. Vidal, EPJ D 68, 257 (2014).