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NUMERICAL SIMULATION FOR AN INTENSE LASER WAVE INCIDENT ON AN OVERDENSE PLASMA

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We study the interaction of a high intensity laser wave incident on an overdense plasma, when the frequency of the wave is below the electron plasma frequency. If the intensity of the wave is sufficiently high to make the oscillation of the electrons relativistic, the plasma frequency is modified by the relativistic mass variation, and this leads to interesting interaction between the wave and the surface of the plasma. We use an Eulerian Vlasov code for the numerical solution of the one-dimensional relativistic Vlasov-Maxwell equations. Both electrons and ions are treated using a kinetic equation [1]. The results show that the incident laser wave is pushing the edge of the plasma, which results in a forward motion of the surface, with a build-up of the density at the edge which makes the plasma more opaque. There is a longitudinal electric field generated at the surface of the plasma which accelerates the ions in the forward direction. Electrons are ejected in both direction, and those ejected in the backward direction have a tendency to form cavity-like structures.

The relevant equations

The one-dimensional 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]:

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

Time t is normalized to ω_{pe}^{-1}, length is normalized to $c\omega_{pe}^{-1}$, velocity and momentum are normalized respectively to the velocity of light c, and to $M_e c$. In our normalized units $m_e = 1$ for the electrons, and $m_i = M_e / M_i$ for the ions. The indices e and i refers to electrons and ions. 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

$\vec{E}_\perp = -\frac{\partial \vec{a}_\perp}{\partial t}$, $\gamma_{e,i} = \left(1 + \left(m_{e,i} p_{xe,i}\right)^2 + \left(m_{e,i} a_\perp\right)^2\right)^{1/2}$. The transverse EM fields E_y, B_z and E_z, B_y for the circularly polarized wave obey Maxwell's equations. With $E^\pm = E_y \pm B_z$ and $F^\pm = E_z \pm B_y$, we have:

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

which are integrated along their vacuum characteristic $x=t$. In our normalized units :

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

To solve Eq.(1), we use a tensor product of cubic *B*-splines [1] for the 2D interpolation along the characteristics. To calculate E_x^n we use Poisson equation, then use the expansion::

$$E_x^{n+1/2} = E_x^n + \frac{\Delta t}{2}\left(\frac{\partial E_x}{\partial t}\right)^n + 0.5\left(\frac{\Delta t}{2}\right)^2\left(\frac{\partial^2 E_x}{\partial t^2}\right)^n ; \text{ with } \left(\frac{\partial E_x}{\partial t}\right)^n = -J_x^n ; \; \left(\frac{\partial^2 E_x}{\partial t^2}\right)^n = -\left(\frac{\partial J_x}{\partial t}\right)^n .$$

$$\frac{\partial^2 \varphi}{\partial x^2} = \int f_e(x, p_{xe}) dp_{xe} - \int f_i(x, p_{xi}) dp_{xi} \,., \qquad E_x = -\frac{\partial \varphi}{\partial x}$$

Another method used in the present work calculates $E_x^{n+1/2}$ from Ampère's equation: $E_x^{n+1/2}$ $= E_x^{n-1/2} - \Delta t J_x^n$, $J_x = J_{xe} + J_{xi}$. Both methods gave the same results.

Results

The forward propagating circularly polarized laser wave is penetrating at x=0 at the left boundary, where the fields $E^+ = 2E_0 P_r(t)\cos(\omega t)$ and $F^- = -2E_0 P_r(t)\sin(\omega t)$. The shape factor $P_r(t) = \sin(\pi t/(2\tau))$ for $t < \tau = 50$, $P_r(t) = 1$ otherwise. We choose for the amplitude of the potential vector $a_0 = \sqrt{2}$. $\omega = 0.79\omega_p$, which corresponds to $n/n_c = 1.6023$. The Lorentz factor for an oscillating electron in the field of the wave is $\gamma_0 = \sqrt{1 + a_0^2} = \sqrt{3}$, and $n/\gamma_0 n_c = 0.925$. The initial temperature temperature for the electrons is T_e=1. keV and for the ions T_i=0.1 keV. The total length of the system is $L = 87.18 c/\omega_p$. We use N =6000 grid points in space and 1400 in momentum space for the electrons and ions. We have a vacuum region on each side of the plasma of length $L_{vac} = 14.89 c/\omega_p$. The jump in density at the plasma edge on each side is $L_{edge} = 5.08 c/\omega_p$, and the flat top density of 1 is of length $47.24 c/\omega_p$. Figs.(1) show the plot of the density profiles against distance (full curves for the electrons and dash curves for the ions) at t=72.75 (left frame), t=87.18 (middle frame) and t=101.71 (right frame). The laser wave is literally pushing the plasma edge in front of the incident wave, and the plasma edge is acquiring a steep profile, with electrons and ions moving together forward and accumulating at the edge of the plasma. Note how at t=101.71 these profiles are very steep. These electrons and ions accumulations at the edge are increasing the edge density, which increases the opacity of the plasma to the laser wave. A large longitudinal electric field E_x is generated at the edge of the plasma, with a peak located at the discontinuity (shown in Fig.(4) at t=72.75 (dash-dot curve), t=87.18 (broken curve) and t=101.71 (full curve)). Electrons and ions are accelerated in this electric field. Electrons from the underdense plasma region are accelerated in the backward direction, and form cavity-like structures, surrounded by steep edges, as can be seen in Fig.(1) and the contour plots of Fig.(2). The results in Figs.(1) show that the electrons accelerated in the backward direction are continuously building up this cavity like structure. In the second plot of Fig.(2) at t=101.71, there is also a strong electron population accelerated in the forward direction, which shows a small density modulation superimposed on the flat part in the third frame in Fig.(1). In Fig.(3) we see how the ions are accelerated in the positive direction by the quasi-static electric field E_x at the plasma edge. There is also a small ion population accelerated in the negative direction by the small negative part of the electric field. This ion acceleration mechanism in the forward direction is relevant to the observed ion acceleration in laser irradiated solid surfaces [1,2]. Fig.(5) shows at t=101.71 the forward propagating wave E^+ (full curve), and the backward wave E^- (dash curve) reflected at the steep plasma surface. One can hardly speaks of a wave penetration or transparency, E^+ is strongly damped (the small modulation in the forward direction is due to the local density modulation caused by the forward ejected electrons). In our normalized units, we have in vacuum for the laser wave $\omega = k = 0.79$, hence a wavelength $\lambda \approx 8. > L_{edge}$. The laser wave is literally pushing the plasma, and electrons from the underdense region are being accelerated backward, filling cavity-like structures. These cavity-like structures can separate from the steep density profile, or remain attached to it as in the present case. Fig.(6) shows the frequency spectrum of the forward wave E^+, with a peak at $\omega / \omega_p = 0.79$ (full curve), and the frequency spectrum of the backward wave E^- (broken curve), with a frequency slightly downshifted by the Doppler effect upon reflection at the slowly moving edge.

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References

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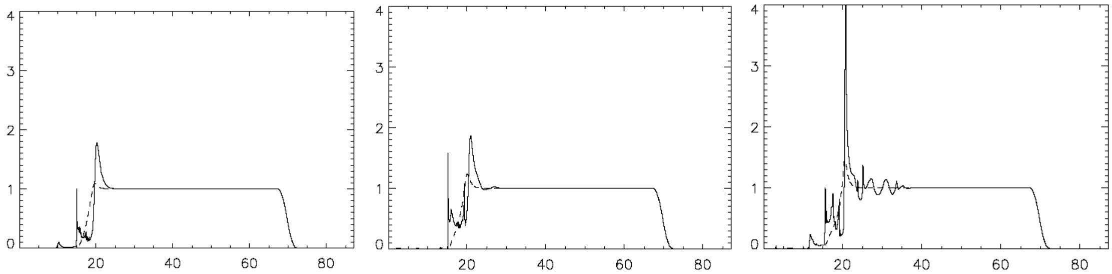

Fig.1 Electron (full curve) and ion (dash curve) density profiles at *t*=72., 87. and 101.

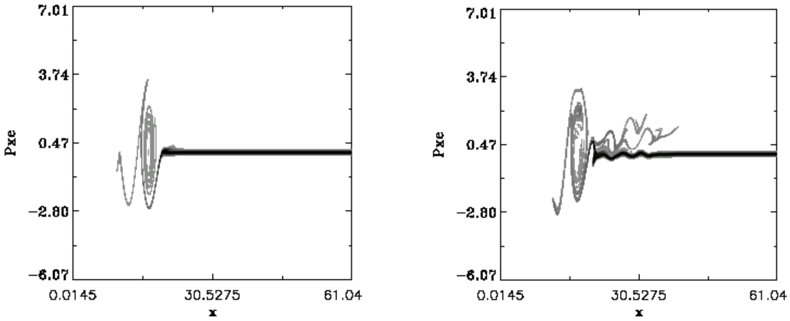

Fig.2 Phase-space for the electron distribution function at *t*=72 and *t*=101.

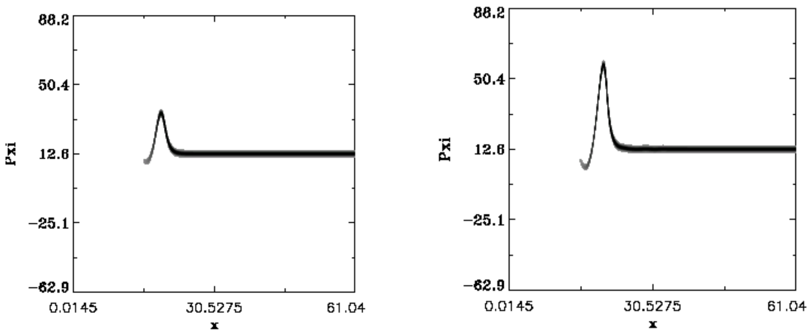

Fig.3 Pase-space for the ion distribution function at *t*=72 and *t*=101

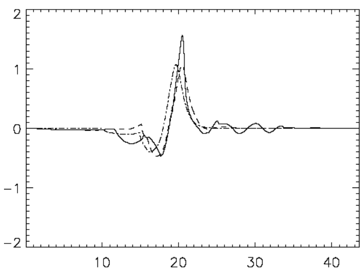

Fig.4 Electic field at *t*=72, (dash-dot curve), *t*=87 (dash curve), *t*=101 (full curve)

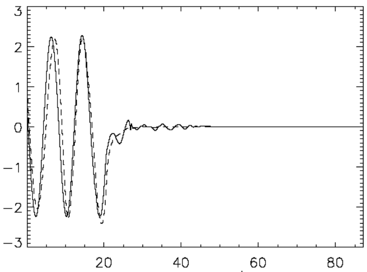

Fig.5 Laser wave E^+ (full curve) E^- (broken curve).

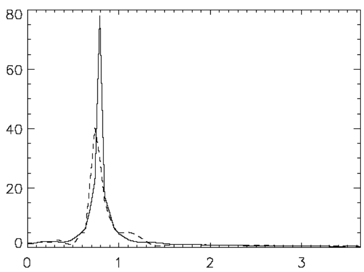

Fig.6 Frequency spectrum for E^+ (full curve) and E^- (dash curve).