NUMERICAL SIMULATIONS OF HARMONICS GENERATION BY THE REFLECTION OF AN INTENSE LINEARLY POLARIZED LASER BEAM NORMALLY INCIDENT ON AN OVERDENSE PLASMA

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We use an Eulerian Vlasov code for the numerical solution of the one-dimensional relativistic Vlasov-Maxwell equations for both electrons and ions [1,2], and a particle-in-cell (PIC) code [3] to study the generation of harmonics in the reflection of a high intensity linearly polarized laser wave normally incident on an overdense plasma. The oscillation of the laser wave at the plasma edge creates an oscillating space-charge, giving rise to an oscillating electric field. If the intensity of the wave is sufficiently high to make the oscillation of the electrons relativistic, then the plasma edge oscillates nonlinearly in the field of the laser beam, which results in an important distortion in the reflected wave, associated with the generation of harmonics. We consider the case when the laser beam wavelength λ is much greater than the scale length of the gradient in the plasma density at the edge L_{edge} ($\lambda >> L_{edge}$), and $n/n_c = 100$. The two codes show general qualitative agreement for the mechanisms of harmonics generation, although some quantitative details differ somewhat.

Results

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 in [1,2]. The PIC code has been presented in [3]. Time *t* is normalized to ω^{-1}, length is normalized to $c\omega^{-1}$, velocity and momentum are normalized respectively to the velocity of light *c*, and to $M_e c$ respectively. In our normalized units $m_e = 1$ for the electrons, and $m_i = M_i / M_e$ = 2.*1836 for deuterium ions. In the direction normal to *x*, the canonical momentum written 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 $M_e c / e$). $\vec{P}_{\perp e,i}$ is chosen to be zero initially, so that for the linearly polarized wave $\vec{p}_{\perp e,i} = \pm \vec{a}_\perp$. We also define $\vec{E}_\perp = -\frac{\partial \vec{a}_\perp}{\partial t}$. The transverse EM fields E_y, B_z for the linearly polarized wave obey Maxwell's equations. With $E^\pm = E_y \pm B_z$:

$$(\frac{\partial}{\partial t} \pm \frac{\partial}{\partial x})E^{\pm} = -J_y\,; \quad \vec{J}_{\perp} = \vec{J}_{\perp e} + \vec{J}_{\perp i}\,; \quad \vec{J}_{\perp e,i} = -\frac{\vec{a}_{\perp}}{m_{e,i}} \int \frac{f_{e,i}}{\gamma_{e,i}} dp_{xe,i} \qquad (1)$$

We calculate $E_x^{n+1/2}$ from Ampère's equation: $E_x^{n+1/2} = E_x^{n-1/2} - \Delta t J_x^n$, $J_x = J_{xe} + J_{xi}$.

The forward propagating linearly polarized laser wave is penetrating at x=0 at the left boundary, where the fields $E^+ = 2E_0 P_r(t)\cos\tau$, $\tau = t - 1.5t_p$. The shape factor $P_r(t) = \exp(-2.\ln(2.)(\tau/t_p)^2)$ for $t_p = 12$. We choose for the amplitude of the potential vector $a_0 = 25$. Also $\omega = 0.1\omega_p$, with ω_p the plasma frequency, which corresponds to $n/n_c = 100$. The initial temperature for the electrons is T_e=1. keV and for the deuterons T_i=0.1 keV. The total length of the system is $L = 20c/\omega$. We use N =10000 grid points in space ($\Delta x = \Delta t = 0.02$), and 2200 in momentum space for the electrons and ions (extrema of the electron momentum are ± 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 size of the linear density ramp at the plasma edge on each side of the slab is $L_{edge} = 0.3c/\omega$, and the flat top slab density of 1 (normalized to $100n_c$) is of length $3.7c/\omega$. The incident wave wavelength is $\lambda = 6.23$, *i.e.* $\lambda >> L_{edge}$.

Figs.(1) show the plots obtained from the PIC code of the density profiles at the plasma edge (full curves for the electrons and dashed curves for the ions) and of the longitudinal electric field (dash-dot curves) at t=24.6 (left frame), 26.4 (middle frame) and 28 (right frame). Figs.(2) give the equivalent curves obtained from the Vlasov code. Figs.(3) and (4) give the incident and reflected wave E^+ and E^- at the same times, for the PIC and Vlasov code, respectively. At t=24.6 and t=28 the incident laser wave E^+ is minimum at the surface of the plasma. This corresponds in Figs.(1) and (2) to the electrons at the plasma surface moving to the left, in the backward direction. At t=26.4 however, the incident wave is maximum at the plasma surface. The electrons in Figs.(1) and (2) at t= 26.4 are being pushed to the right by the ponderomotive force of the wave. The incident laser wave is literally pushing the plasma edge, which is steepening. The density profiles in Figs.(2) show the formation of a solitary-like structure for the ions, which is appearing at a later time in the PIC code in Fig.(1) (around t=30). Although the density profiles in Fig.(1) and (2) show only a qualitative agreement, the electromagnetic field profiles in Figs.(3) and (4) show a closer agreement in amplitude and phase. The phase-space plot for the electron distribution function for the PIC and Vlasov code are given in Figs.(5) and (6) respectively. At t= 26.4 and 28, the plots in Fig.(5) and (6) show close qualitative agreement. However at t=29.2 the plot in Fig.(5) shows a stronger heating than the one presented in Fig.(6), and this difference in heating has a tendency to increase as the simulation progresses. Fig.(7) shows the phase-space plot for the ion distribution function at the edge of the plasma at *t*=29.2, from the PIC results (left) and the Vlasov code results (right). The results from the Vlasov code show a bifurcation in the phase-space plot, which will appear in the PIC results only later on. This bifurcation corresponds to the position of the solitary-like structure for the ion density which we see in Fig.(2). In Fig.(8) we present the spectrum of the reflected wave E^- calculated from the PIC code, showing the presence of odd-harmonics, as one would expect in the case of normal incidence using a linearly polarized wave.

References

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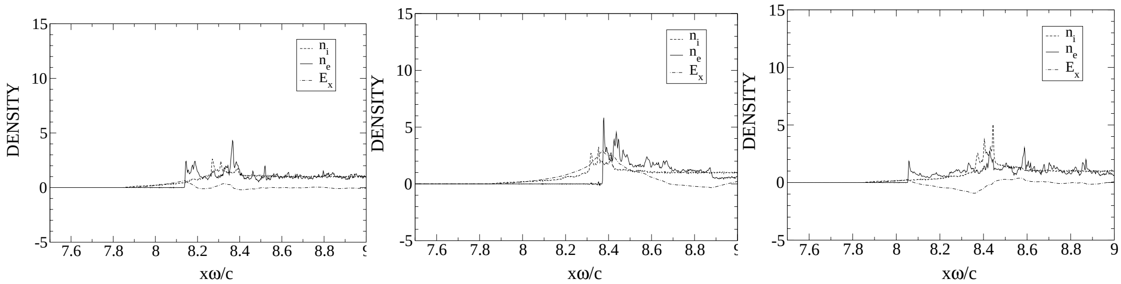

Fig.1 Electron, ion and electric field profiles at the edge at *t*=24.6, 26.4, 28. PIC code

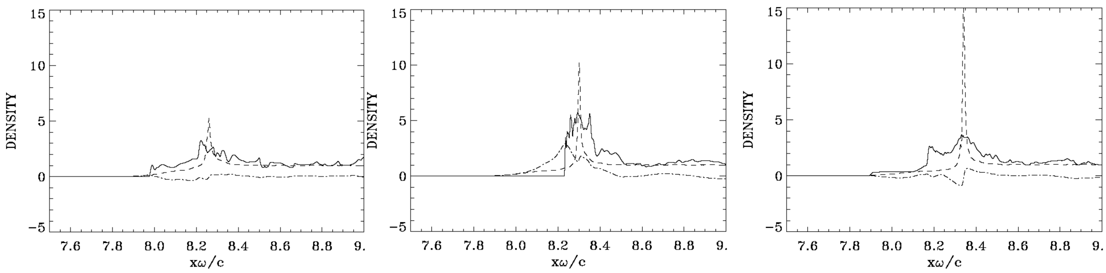

Fig.2 Electron, ion and electric field profiles at the edge at *t*=24.6, 26.4, 28. Vlasov code

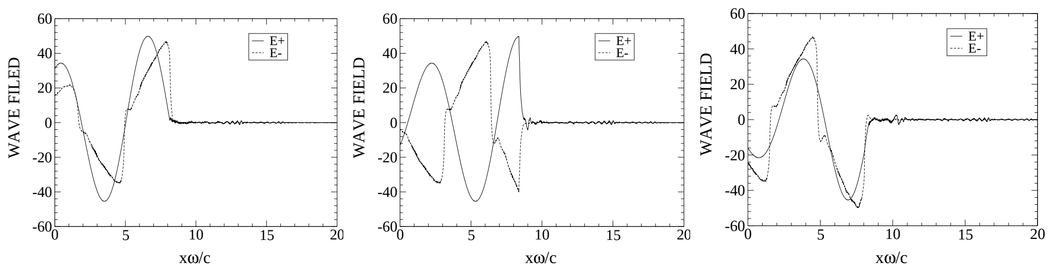

Fig.3 Incident wave E^+ (full curve),reflected wave E^- (dashed curve) at *t*=24.6, 26.4, 28. PIC code

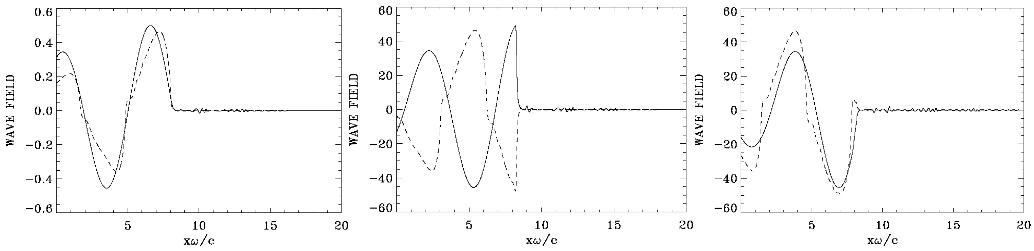

Fig.4 Incident wave E^+ (full curve),reflected wave E^- (dashed curve) at *t*=24.6, 26.4, 28 Vlasov code

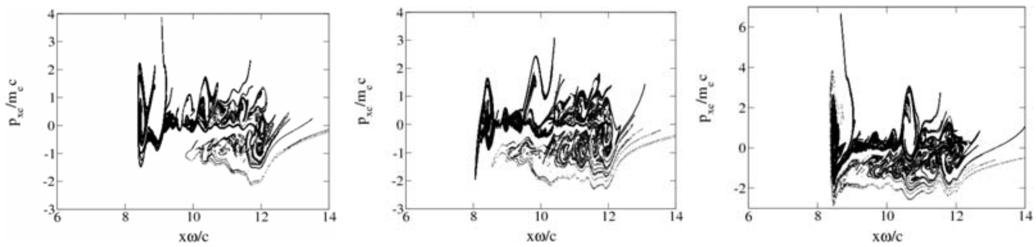

Fig.5 Phase-space for the electron distribution function at *t*= 26.4, 28.,29.2 -PIC code

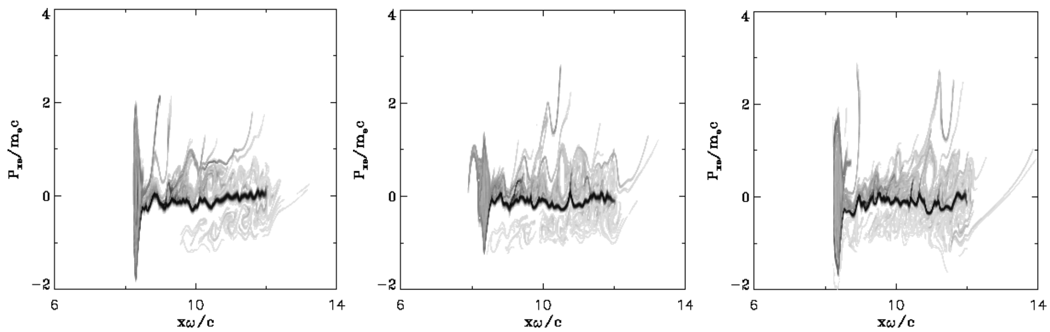

Fig.6 Phase-space for the electron distribution function at *t*= 26.4, 28.,29.2-Vlasov code

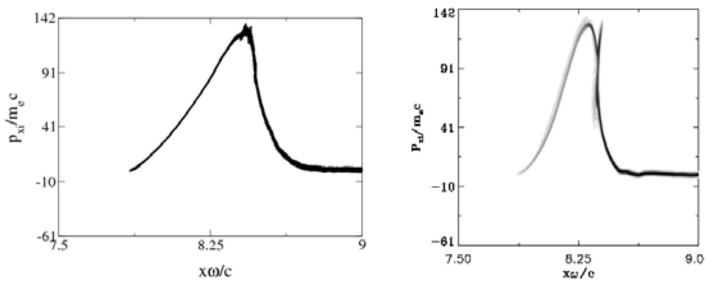

Fig.7 Phase-space for th ... right, Vlasov code)

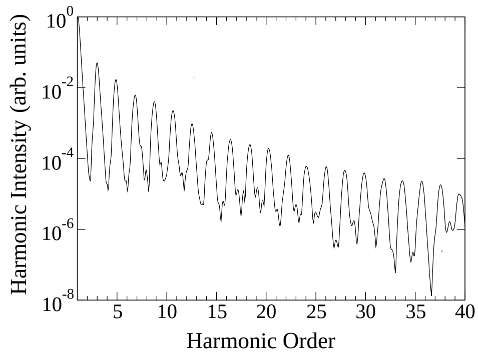

Fig.8 Frequency spectrum for the reflected wave E^- ., as obtained from the PIC code