A VLASOV CODE SIMULATION OF PLASMA-BASED BACKWARD RAMAN AMPLIFICATION IN UNDERDENSE PLASMA

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We use an Eulerian Vlasov code to study the problem of the plasma-based backward Raman amplification of an ultra-short seed laser pulse in an underdense plasma. The code solves the one-dimensional Vlasov-Maxwell set of equations [1,2]. This allows the inclusion of kinetic effects such as particle heating and trapping, in the amplification of an ultra-short seed laser pulse in an underdense plasma. The process of energy transfer from the pump to the seed is mediated by the ponderomotive beat-driven resonant plasma wave in the stimulated Raman backscattering instability [3]. We use parameters close to those used in [4]. The wavelength of the pump laser beam is $\lambda_{0p} = 1.05\mu m$, and its normalized vector potential is a_{0p} = 0.04. The ratio of the pump frequency to the plasma frequency is $\omega_{0p} / \omega_{pe} = 3.180$ (corresponding to $n / n_{cr} \approx 0.099$, where n_{cr} is the critical density for the pump). The seed pulse has a frequency $\omega_{0s} / \omega_{pe}$ = 2.1657 and a wavelength $\lambda_{0s} = 1.541\mu m$, resonating with the pump and the plasma wave, and a Gaussian shape in time of width $\tau_s \omega_{pe} = 6.2$. The length of the plasma system is $L_p = 600c / \omega_{pe} \sim 1908c / \omega_{0p}$ with an initial temperature $T_e = 200eV$. The interaction over this length of the plasma will be seen to lead to an amplification of the seed pulse by a factor close to six times the pump amplitude.

The relevant equations in the Vlasov code

The 1D 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 [1,2]:

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

Time t is normalized to the inverse pump frequency 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 $M_e c$.

The indices e and i refer to electrons and ions. In our normalized units $m_e = 1$ for the electrons, and $m_i = M_i / M_e = 1836$ for the hydrogen ions, where M_i and M_e are the ion and electron masses respectively. 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 $\vec{E}_\perp = -\frac{\partial \vec{a}_\perp}{\partial t}$. The relativistic factor is $\gamma_{e,i} = \left(1 + \left(p_{xe,i} / m_{e,i}\right)^2 + \left(a_\perp / m_{e,i}\right)^2\right)^{1/2}$. The transverse electromagnetic fields $E^\pm = E_y \pm B_z$ for the linearly polarized wave obey Maxwell's equation:

$$\left(\frac{\partial}{\partial t} \pm \frac{\partial}{\partial x}\right) E^\pm = -J_y . \; ; \tag{2}$$

Equations (2) are integrated along the vacuum characteristic x=t. In our normalized units:

$$\vec{J}_\perp = \vec{J}_{\perp e} + \vec{J}_{\perp i} \; ; \quad \vec{J}_{\perp e,i} = -\frac{\vec{a}_\perp}{m_{e,i}} \int \frac{f_{e,i}}{\gamma_{e,i}} dp_{xe,i} . \; ; \quad J_{xe,i} = \pm \frac{1}{m_{e,i}} \int \frac{p_{xe,i}}{\gamma_{e,i}} f_{e,i} dp_{xe,i} \tag{3}$$

Eq.(1) is solved using a 2D interpolation along the characteristics [1,2]. From Ampère's equation $\partial E_x / \partial t = -J_x$, we calculate $E_x^{n+1/2}$ as follows: $E_x^{n+1/2} = E_x^{n-1/2} - \Delta t J_x^n$, $J_x = J_{xe} + J_{xi}$.

Results

The forward propagating linearly polarized pump $E^+ = 2E_{0p} \cos \omega_{0p} t$ penetrates the plasma at x=0, with a constant amplitude field amplitude E_{0p}. In our normalized units $E_{0p} = \omega_{0p} a_{0p}$, $\omega_{0p} = 3.180$. The normalized amplitude of the vector potential is $a_{0p} = 0.04$, where $a_0^2 = I\lambda^2 / 1.368\text{x}10^{18}$, I is the intensity in W/cm^2 and λ is in microns. The pump reaches the right boundary at $t = 600$ (since in our normalized units $x = t$). A seed pulse is injected at $x = L_p$ in the backward direction in the form $E^- = -2E_{0s} P_{0s}(t) \cos \omega_{0s} \tau$, where $\omega_{0s} = 2.1657$ and $\tau = t - t_0$. The temporal shape factor of the seed pulse is $P_{0s}(t) = \exp(-0.5(t - t_1)^2 / \tau_s^2)$, for $t_2 < t < t_0$, with $\tau_s = 6.2$, $t_0 = 600$, $t_1 = 580$, $t_2 = 560$ and $E_{0s} = \omega_{0s} a_{0s}$, with $a_{0s} = 0.01318$.

We use N =30000 grid points in space ($\Delta x = \Delta t = 0.02$), and 800 points in momentum space for the electrons and 200 for the ions (extrema of the electron momentum are ± 1.2, and for the ion momentum $\pm 1.$). The ions were included in the calculation, but did not play any role in the physics except establishing a small self-consistent sheath at the edges. The grid size is such that $\Delta x / \lambda_{De} \approx 1.01$, where λ_{De} is the Debye length. We have a vacuum region of length $L_{vac} = 6.6$ on either side of the plasma slab. The jump in density at the plasma edge on each side of the slab is of length $L_{edge} = 8$, and the flat top slab density normalized to 1 is of length 570.8, for a total length $L_p = 600$

Figs.(1) show the incident laser wave E^+ (full curve) and the seed pulse E^- (dashed curve) at *t*=820 and *t*=1180. At *t*=820 the seed pulse (which was injected at the right boundary *x*=600 in the backward direction at the time $t_2 < t < t_0$, as explained above), has already amplified to an amplitude above the incident laser wave E^+, leaving behind a depleted wave E^+. At *t*=1180 the front edge of the wave E^- has developed into a solitary-like shock structure whose amplitude is six-time higher than the amplitude of the original incident pump laser wave E^+, and leaving behind a more depleted wave E^+. In Fig.(2,left) we present the electron density plot at *t*=1180, and in Fig.(2,right) we magnify the front edge of the density plot. We note that the wavelength between two peaks in Fig.(2,right) is $\lambda_{pe} \approx 1.27$. Indeed the wavenumber associated with the pump is $k_{0p} = 3.0185$, the wavenumber of the backscattered mode is $k_{0s} = 1.921$. The resulting wavenumber of the excited plasma mode k_{pe} is such that $k_{0p} = -k_{0s} + k_{pe}$, from which $k_{pe} = 4.94$. Hence the wavelength for the excited plasma mode is $\lambda_{pe} \approx 1.27$, which is the distance between two peaks observed in Fig.(2,right). In Fig.(3) we show the contour plots of the electron distribution function at the front edge of the wave, in 50<*x*<100 and in 100<*x*<150. The vortical structures in Fig.(3) are also separated by the dominant wavelength $\lambda_{pe} \approx 1.27$. We note to the right, close to *x*=150, a more chaotic behaviour appearing, due to the vortices interacting together.

Acknowledgments

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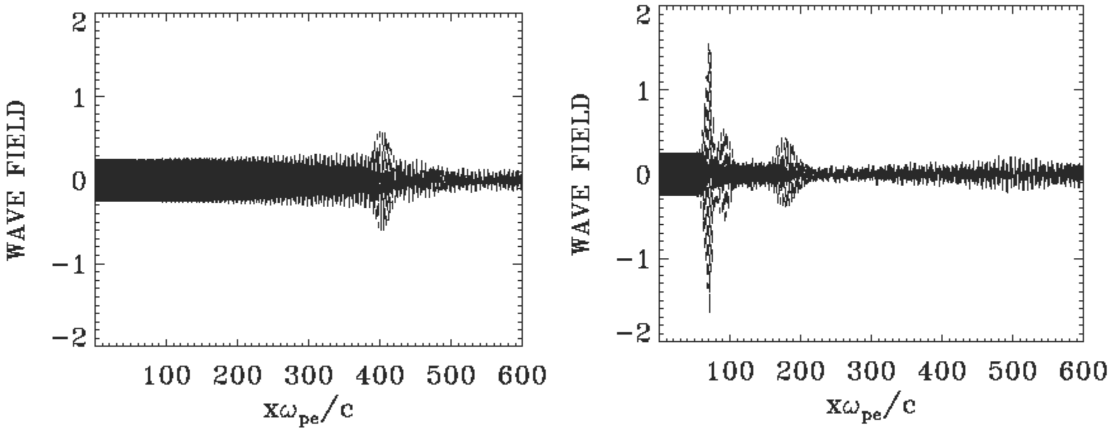

Figure (1). The incident laser wave E^+ (full curve) and the seed pulse E^- (dashed curve) at t=820 (left), and t=1180 (right)

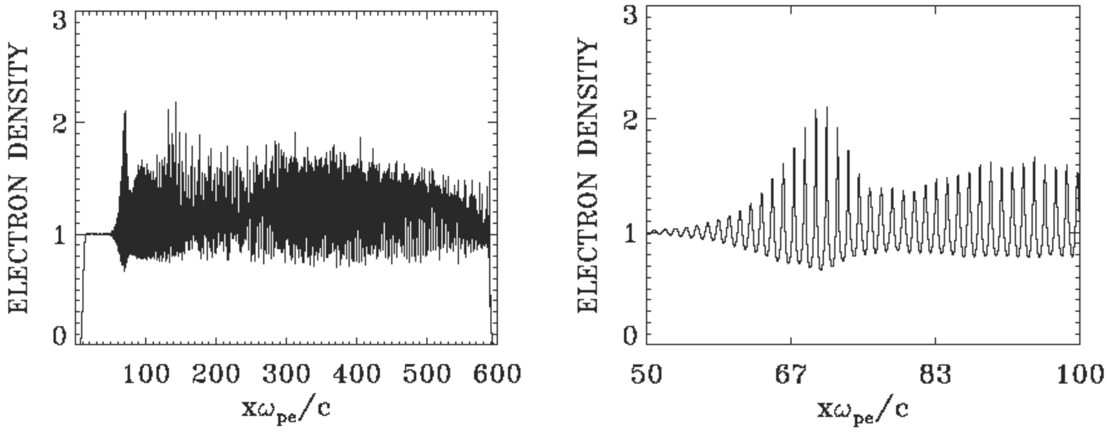

Figure (2). Plot of the electron density at t=1180. Full profile, and for 50<x<100.

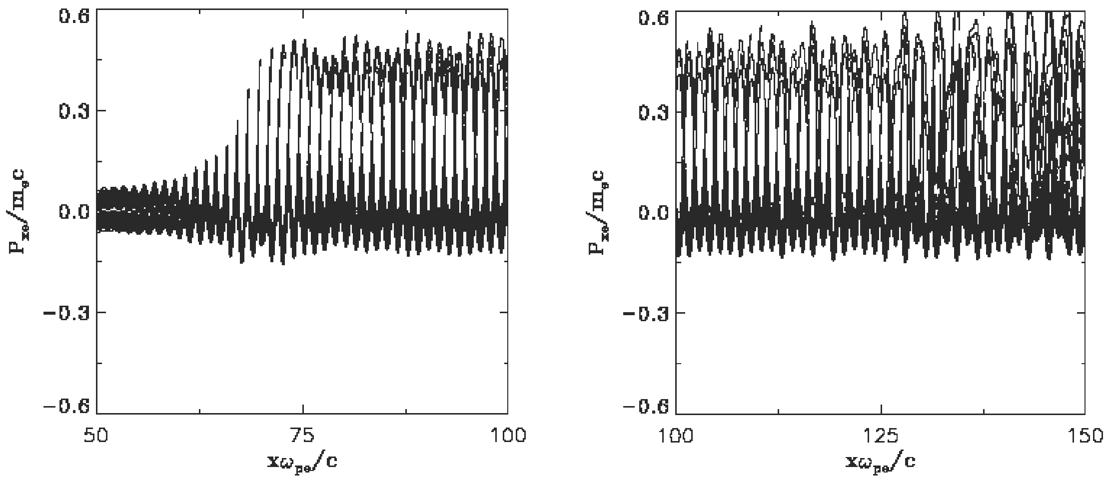

Figure (3). Contour plots of the electron distribution function at the front edge of the wave at t=1180. For 50<x<100 (left), and for 100<x<150 (right).