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Numerical simulation of wave-particle interaction in laser plasmas

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The propagation of intense laser beam through a plasma ablated from a solid target by a focused ns laser beam gives rise to a high-amplitude electron plasma wave, which has the ability to trap and accelerate significant amount of plasma electrons. This can be caused by many physical processes, which laser beam undergoes in the plasma corona. A very important representative of a such process is the stimulated Raman scattering, which can be characterized as a resonant decay of the incident laser light into a scattered electromagnetic wave and into the electrostatic wave. A good understanding of this mechanism is very important for the control of numerous experimental situations including the thermonuclear fusion experiments, particularly in the indirect drive, where the laser beam after entering the hohlraum faces a developed and only weakly inhomogeneous plasma inside [1]. To avoid high energy loses caused by the Raman backscattering, which is dominant process in the well underdense plasma typically occurring near the light entrance holes, carrying significant amount of energy out of the hohlraum. To achieve a high yield of x-ray radiation from the walls of the hohlraum, which is necessary for an efficient compression of fuel capsule, it is essential to set up the experiment with the values of Raman reflectivity kept within reasonable limits.

Our recent simulations based on the spatially 1D periodical kinetic model solving the Vlasov equation together with the full set of Maxwell's equations [2] showed that the growth rate of Raman backscattering can be significantly decreased, when the scattered electromagnetic wave is scattered once again (Raman cascading), which in turn results in the value of Raman reflectivity around 1% [3]. This can occur in the outer part of the laser corona ($n_e \leq n_{crit}/9$), where due to the Raman instability the electrostatic wave with a low phase velocity lying well within the bulk of plasma electrons in the phase space rises. The propagation of such wave through the plasma causes very strong non-linear interaction with the electrons. The electrons from the body of distribution are in the first stage of the instability development mostly accelerated forming a huge plateau on the particle distribution. During this process the significant amount of incoming laser energy is deposited in the plasma electrons. Simultaneously, the particle trapping in the potential wells of the plasma wave leads to a growth of the trapped particle instability [4] and consequently to the rise of sidebands of the central electrostatic wave mode, which is finally outgrown. The interaction of preaccelerated electrons with this wave packet causes a randomization of their velocity distribution even in the absence of collisions. The incoming energy is thus used for plasma heating, which in turn stops the growth of the Raman instability and lowers the Raman reflectivity [5]. However, in this contribution, which is aiming at a comparison between the hydrodynamic envelope and the kinetic Vlasov model we avoided the spectral broadening due to the sidebands by suitably tuning the simulation conditions.

Envelope model

The influence of the non-linear interaction of electrons in plasma with the electrostatic wave is demonstrated with help of the envelope model based on the magnetohydrodynamic description of the plasma. These results are compared with the results of fully self-consistent Vlasov-Maxwell model of electron gas, which, naturally, also includes the wave-particle interaction. We get desired equations for the wave envelopes from the equation of motion of the electron fluid together with the full set of Maxwell equations. These equations are coupled by the nonlinearities of the fluid motion. In the 1D case the following equation set can be derived for the longitudinal electric field E and the transversal part of the vector potential A

$$\left[c^2\frac{\partial^2}{\partial x^2}-\frac{\partial^2}{\partial t^2}-\omega_{pe}^2\right]A = -\omega_{pe}^2 A\frac{\partial E}{\partial x}, \tag{1}$$

$$\left[v_T^2\frac{\partial^2}{\partial x^2}-\frac{\partial^2}{\partial t^2}-\omega_{pe}^2\right]E = \omega_{pe}^2\frac{e}{m_e}A\frac{\partial A}{\partial x}, \tag{2}$$

Using the formalism of coupled wave modes, where the complex amplitudes of participating waves are defined as

$$A(x,t) = \frac{1}{2}A_0(x,t)e^{i(k_0x-\omega_0t)}+\frac{1}{2}A_R(x,t)e^{i(k_Rx-\omega_Rt)}+c.c. \tag{3}$$

$$E(x,t) = \frac{1}{2}E_e(x,t)e^{i(k_ex-\omega_et)}+c.c. \tag{4}$$

$A_0(x,t)$ and $A_R(x,t)$ denote the slowly varying amplitude of impinging electromagnetic wave and scattered electromagnetic wave, respectively, and $E_e(x,t)$ is the amplitude of electron plasma wave. Since the fully self-consistent model is periodic, we assume a perfect wave numbers matching

$$k_0 = k_R + k_e, \tag{5}$$

while we allow for a mismatch in the matching condition for the frequencies:

$$\omega_0(k_0)+\Delta\omega = \omega_R(k_R)+\omega_e(k_e). \tag{6}$$

Substituting (3) and (4) into the equations (1) and (2) and using the standard cancelation due to the zeroth-order dispersion relation leaves the following three-waves envelope equations:

$$\left[\frac{\partial}{\partial t}+v_{g0}\frac{\partial}{\partial x}+\nu_0\right]A_0 = -\frac{e}{4m_e}\frac{k_e}{\omega_0}A_RE_ee^{i\Delta\omega t}+\nu_0A_L, \tag{7}$$

$$\left[\frac{\partial}{\partial t}+v_{gR}\frac{\partial}{\partial x}+\nu_R\right]A_R = \frac{e}{4m_e}\frac{k_e}{\omega_R}A_0E_e^*e^{-i\Delta\omega t}, \tag{8}$$

$$\left[\frac{\partial}{\partial t}+v_{ge}\frac{\partial}{\partial x}+\nu_e\right]E_e = \frac{e}{4m_e}\frac{k_e}{\omega_e}A_0A_R^*e^{-i\Delta\omega t}, \tag{9}$$

where $v_{g0} = c^2k_0/\omega_0$, $v_{gR} = c^2k_R/\omega_R$ and $v_{ge} = 3v_T^2k_e/\omega_e$ are the group velocities of pumping laser wave, scattered electromagnetic wave, and electron plasma wave, respectively. Moreover, we added to the envelope equations a phenomenological term for the collisional damping of participating waves [6]

$$\nu_0 = \frac{\omega_{pe}^2\nu_{ei}}{2\omega_0^2}, \tag{10}$$

$$\nu_R = \frac{\omega_{pe}^2\nu_{ei}}{2\omega_R^2}, \tag{11}$$

$$\nu_e = \frac{\nu_{ei}}{2}+\gamma_L. \tag{12}$$

where $\nu_{ei} = \frac{4(2\pi)^{1/2}Z^2e^4n_i\ln\Lambda}{3\sqrt{m_e}(K_BT_e)^{3/2}}$ is an effective electron-ion collision frequency [7] and γ_L is the collisionless linear Landau damping rate, which takes into account the influence of wave-particle interaction on the level of the linear theory.

Results and discussion

The numerical simulations are projected for the iodine laser facility PALS operating in the near infrared region ($\lambda = 1.315\ \mu m$) with the pulse duration 400 ps. In the focus it reaches the power density $10^{20}\ W/m^2$. Electron temperature in the laser corona is estimated as $T_e = 0.9\ keV$.

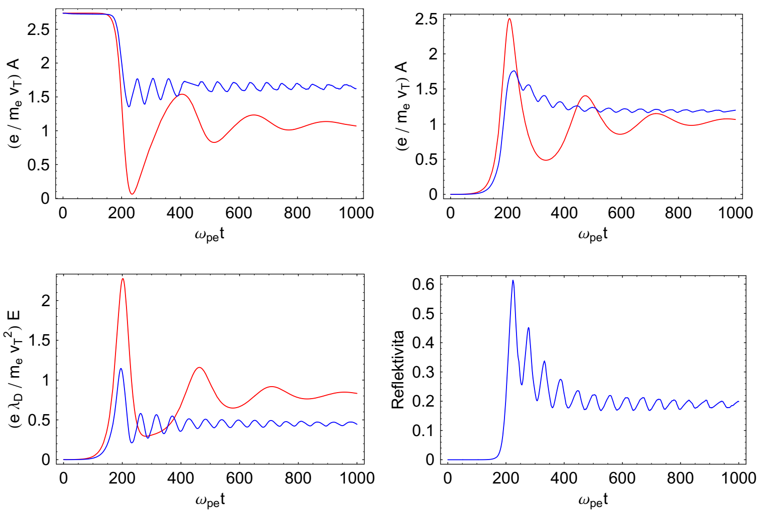

Figure 1: Comparison of the temporal evolutions of the participating wave modes obtained from the full kinetic simulation (blue) and from the envelope model (red).

Let us start with the simplest case, when in the 1D geometry only Raman backscattering can occur. It happens in plasmas with electron density $n_{crit}/9 \leq n_e \leq n_{crit}/4$, where the backscattering dominates over the forward scattering [8] and where the Raman cascading is forbidden. For the simulation in such a regime the value of electron plasma frequency $\omega_{pe} = 5.5 \times 10^{14}\ s^{-1}$ was chosen. It corresponds to the electron density $n_e/n_{crit} = 0.147$. In Fig. 1 the temporal evolution of (a) pumping laser wave ($k_0\lambda_D = 0.0987$), (b) backscattered electromagnetic wave ($k_R\lambda_D = 0.0498$), (c) forward going electrostatic wave ($k_e\lambda_D = 0.1485$) and (d) Raman reflectivity defined as $R = E_R^2/E_L^2$ is depicted. The result of the full Vlasov simulation is plotted in blue colour, while the result of the envelope model is represented by the red curve. The phase velocity of the plasma wave is under the mentioned conditions relatively high ($v_{ph}/v_T = 6.95$) lying outside the body of electron distribution. As the first stage of evolution a strong growth of the instability is expected, unaffected by the wave-particle interaction. Here the results of the both models agree. When the electrostatic wave reaches a sufficiently high amplitude (peak value from the Vlasov simulation is $E = 4.43 \times 10^{10}\ V/m$, which corresponds to the amplitude of separatrix $v_{sep}/v_T = 5.57$) to trap a large amount of electrons, the growth of the instability is saturated and the amplitudes of the participating waves reaches more or less equilibrium values. Note the small amplitude fluctuations corresponding to the period of the wobbling motion of trapped electrons in the wave. Due to the weak wave-particle interaction the steady state value of Raman reflectivity is approximately 20 %.

If we move to a thinner plasma ($n_e/n_{crit} = 0.044$), we observe a much more complicated situation. Next to the Raman back-scattering, which is no longer the dominant scattering process, we find the wave modes corresponding to the forward scattering and to the Raman cascade. Moreover, the electrostatic wave modes of forward and backward scattering combine in a non-resonant electrostatic quasi-mode. The electron plasma wave of the back-scattering has the phase velocity $v_{ph}/v_T = 3.45$, thus it is strongly interacting with the electrons from the very start of the growth. The large amount of laser energy is used for their acceleration and a fast saturation of Raman backscattering occurs, which is still enhanced by the secondary decay of the back-scattered electromagnetic wave due to the Raman cascading. In Fig. 2 is the temporal evolution of the wave modes in this case using the same colours as previously. By comparison of both the models we find a totaly different behaviour represented by the fast suppression of the Raman instability in the full kinetic model. The fast saturation of the plasma wave growth leads to a very low rates of Raman reflectivity (in order of units of percents), while in the envelope model (even with the inclusion of linear Landau damping) the whole incoming energy is transferred to the daughter waves, which means an almost total reflection of the pumping wave. Note that the later stage of the system evolution is affected by the Raman cascading, which is also present in the envelope model.

From the present results it is clear that there is a significant influence of the non-linear wave-particle interaction on the growth of Raman instability. Finally, we have to emphasize that the positions of the wave modes in the discrete k-spectra of the full model were chosen in such a way so as to avoid the growth of side-bands of electrostatic wave due to the trapped particle instability, whose presence would render the interpretation of the simulation results much more complex.

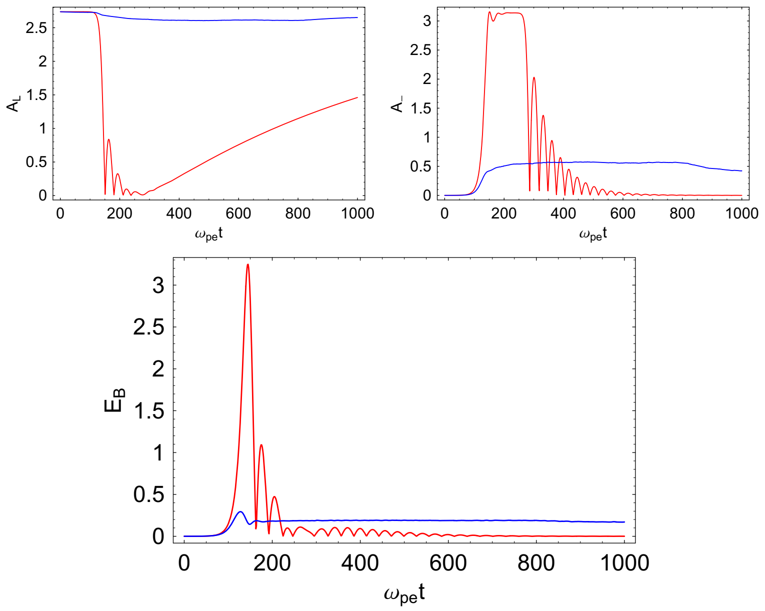

Figure 2: Comparison of the temporal evolutions of the participating wave modes obtained from the full kinetic simulation (blue) and from the envelope model (red) in a thinner plasma ($n_e/n_{crit} = 0.044$). (a) pumping laser wave ($k_0\lambda_D = 0.192$), (b) backscattered electromagnetic wave ($k_R\lambda_D = 0.143$) and (c) electrostatic wave ($k_e\lambda_D = 0.335$).

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