Laser intensity dependence of the stimulated Raman scattering in the context of inertial confinement fusion

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The physical situation consisting in the interaction of a strong electromagnetic wave with a long rarefied plasma occurs several times in the context of laser inertial fusion. The prime example occurs in the indirect drive configuration where the plasma at the light entrance holes of hohlraum is heated by the entering ns laser beams. The expanding plasma has just a week density gradient and the heating beams are passing through a relatively long stretch of plasma before reaching the inside hohlraum wall, as described in [1]. Another example is a more recent proposal of shock ignition [2], when a pre-compressed target is to be heated by colliding shocks, with a (converging) secondary shock meeting the primary (diverging) shock after its reflection from the center of the compressed target. The secondary shock is generated by a sudden jump in the heating beams intensity in the direct drive situation. However, the compressed target is surrounded by an expanding plasmatic corona, through which the heating beams are forced to pass. In both these fusion relevant situations the energy transport from the beams to the target is influenced by various kinds of scattering phenomena accompanying the passage of the intense beams through the plasma corona, mostly in a non-linear stage. In this contribution we shall concentrate on the stimulated Raman back-scattering (SRS-B). To make predictions on the instability development and to find its contribution to the total laser reflectivity in competition with other parametric instabilities various authors usually employ the method of coupled mode equations [3, 4]. Even though this method is relatively simple, it still renders the key features of 'wave-wave' interaction, but it does not include the kinetic behavior of electron gas, which might play an important role in the instability development. Contrary to this, we use a more precise Vlasov-Maxwell computer code with a Fokker-Planck collision term, which solves the Vlasov-Maxwell set of differential equations in 1D employing a transform method [5]. The number of possible wave modes was kept at a moderate level giving essentially a similarly simple system of interacting modes as it was considered in the case of coupled mode equations, but with the full electron dynamic present in the model. The Fokker-Planck collision term stabilizes the method of numerical integration used in the model and at the same time it desribes the electron-ion collisions in a natural manner. Although recent experiments concerning the shock ignition have been run on the (frequency tripled) ns laser system of Prague Asterix Laser System PALS (fundamental wavelength $\lambda = 1.315\ \mu$m) [6, 7, 8] our computer code was applied to the more common 3rd harmonics of Nd:glass systems (fundamental wavelength $\lambda = 1.053\ \mu$m), for which our results have been re-calculated. This was done in view of other systems of this kind used for shock ignition experiments and in expectation of even larger systems to be built for the purpose of shock ignition fusion studies. The present contribution focuses on the laser intensity dependence of the SRS evolution in such plasmas.

Numerical model

To extend the results of the 'wave-wave' interaction theory, we developed a non-linear 1D kinetic model of electron gas, which numerically solves the Vlasov equation (1) simultaneously with the Maxwell equations (2-3):

$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + \frac{e}{m}\left(\frac{\partial \varphi}{\partial x} - \frac{e}{m} A_y \frac{\partial A_y}{\partial x}\right)\frac{\partial f}{\partial v_x} = \nu_{ei}\left(\frac{\partial (v_x f)}{\partial v_x} + < v_x^2 > \frac{\partial^2 f}{\partial v_x^2}\right), \tag{1}$$

$$\left[\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{\omega_{pe}^2}{c^2}\Big(1+\frac{n}{n_0}\Big)\right] A_y \ = 0, \tag{2}$$

$$\frac{\partial^2 \varphi}{\partial x^2} = \frac{e n_0}{m}\int_{-\infty}^{\infty} f dv. \tag{3}$$

The Maxwell equations were derived using the Coulomb gauge $\nabla \cdot \mathbf{A} = 0$. Moreover the plasma is assumed as initially homogeneous, which enables us to rewrite the electron density as $n_e(x,t) = n_0 + n(x,t)$, where n_0 is the initial electron density. Ions are in our model immobile, their number density must thus be $Zn_i = n_0$ and the ion charge is $q_i = Ze$. The perpendicular velocity is replaced by the mean oscillatory velocity in the field of incident laser light $v_y = eA_y/m$. The vector potential has the only non-vanishing component A_y in the perpendicular direction.

A natural and simple way how to solve the above set of equation (1-3) is to use the Fourier-Hermite transform method first described in [5]. The Fokker-Planck term introduces a realistic value of collision frequency together with a satisfactory stabilization of the method. In the present paper we chose the option to set the Fourier spectrum as sparse as possible in order to study the kinetic effects connected with the pure Raman resonant mode only. Making the spectrum denser would introduce side modes (connected e.g. with the trapped particle instability) and thus complicate the physical situation. For a more detailed information see [9].

Results of numerical simulation

We chose the simulation parameters based on hydrodynamic simulations of the shock ignition experiment on OMEGA, where the resulting electron temperature varied from $T_e \approx 1.6$ keV in the thinner outer part of plasma corona to $T_e \approx 2.1$ keV in the regions close to the quarter-critical density, [10]. We fixed its value at $T_e = 2$ keV for all the numerical simulations presented. With a sparse discrete Fourier spectrum of the wave modes in our simulations we are limited in choice of the electron density value. To fit the resonant wave modes to the discrete Fourier spectrum, we are restricted to a few allowed values, of which we chose $n_e/n_c = 0.139$ and $n_e/n_c = 0.219$. Such plasma is irradiated by the laser pulse with the wavelength $\lambda = 351$ nm with intensity in the interval from $I = 2\times 10^{15}$ W/cm^2 to $P = 1\times 10^{16}$ W/cm^2. The electron-ion collision frequency was set as $\nu_{ei}/\omega_{pe} = 7.34\times 10^{-3}$ (lower density case) and $\nu_{ei}/\omega_{pe} = 9.2\times 10^{-3}$ (higher density case). It corresponds to the average ion charge $Z = 6$. Fig. 1 shows the temporal dependence of SRS-B plasma wave amplitude. In the fully non-linear case we found the collisional instability threshold to be slightly below $I = 2\times 10^{15}$ W/cm^2 at $n_e/n_c = 0.139$ and $I = 3\times 10^{15}$ W/cm^2 at $n_e/n_c = 0.219$, when a weak growth with a fast saturation appeared. These values lie almost by an order higher than those predicted by the coupled mode thery. At higher intensities the initial growth is followed by the SRS-B plasma wave amplitude oscilations as the wave is damped by both the collisional and collisionless processes and resonantly amplified by the ns laser pulse, which is pumping the energy into the plasma during the whole simulation time. At higher electron density, where the SRS-B plasma wave phase velocity is farther from the body of electron distribution $v_{ph}/v_T = 6.98$ contrary to $v_{ph}/v_T = 4.62$ at the lower electron density and the electron trapping in the plasma wave has a weaker influence on the wave amplitude evolution, the oscilations are not so strong (Fig. 1(b)). In this case these oscilations are caused mostly by the 'wave-wave' interaction and by the energy exchange between the resonant wave modes. The instability is in a linear regime as it is shown on Fig. 2(b). This is also visible in the phase space, where structures of well trapped electrons are not formed and only a minor part of plasma electrons are

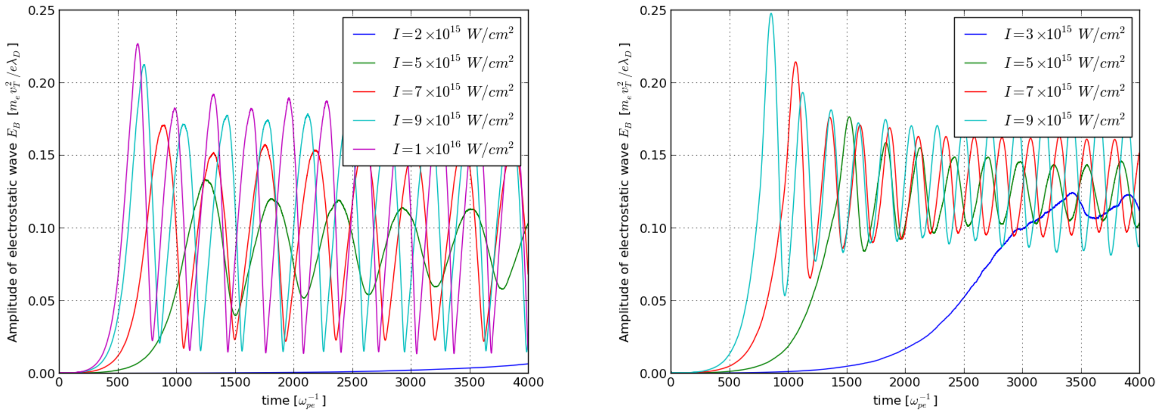

Figure 1: Temporal evolution of resonant plasma wave mode from the full Vlasov-Maxwell simulation at different laser intensities and electron density (a) $n_0/n_c = 0.139$ and (b) $n_0/n_c = 0.219$.

influenced by the plasma wave electric field. A similar behavior shows the back-scattered electromagnetic wave but the oscilations around the saturation levels, which increase with the increasing laser intensity, are smaller. The average value of reflectivity $R = E_-^2/E_0^2$ lies in the interval $R \approx 5\%$ ($I = 5\times10^{15}$ W/cm^2) and $R \approx 7\%$ ($I = 1\times10^{16}$ W/cm^2) for $n_e/n_c = 0.139$. In the higher density case ($n_e/n_c = 0.219$) the reflectivity decreases with the increasing intensity from $R \approx 11\%$ ($I = 3\times10^{15}$ W/cm^2) to $R \approx 8\%$ ($I = 9\times10^{15}$ W/cm^2). This result is fully consistent with our observations that showed a faster instability growth saturation in the presence of strong particle trapping. At lower intensities the electric field generated by the electron plasma wave cannot influence the electrons so much and the instability is saturated with a higher reflectivity level than in the case of higher pumping laser intensity. Contrary to this for the lower density case, where the phase velocity lies close to the body of distribution, the electron kinetics is influenced by the plasma wave almost in every case.

Electron trapping in the potential wells of SRS-B EPW is closely connected with our observation of two different regimes of the Raman backscattering growth. This behavior is demonstrated in Fig. 2, where the amplitude growth rates from Vlasov-Maxwell simulations (red points) are compared with the growth rate calculated from the linearized coupled-mode equations with both the collisonal and collisionless damping taking into account (blue lines). The SRS-B growth rate can be expressed as [11]

$$\Gamma_{SRS-B} = \frac{\Gamma_B^2 - (\gamma_B + \gamma_L)\gamma_-}{(\gamma_B + \gamma_L) + \gamma -}, \tag{4}$$

where $\gamma_{-,B} = (\omega_{pe}^2/\omega_{-,B}^2)(\nu_{ei}/2)$ is the resonant waves collisional amplitude damping rate, γ_L is the Landau amplitude damping rate and Γ_B is the SRS-B amplitude growth rate with no damping mechanism assumed. The instability development in the higher density case is due to the relatively high phase velocity of the plasma wave mostly in the linear regime (Fig. 2(b)) with the only exception of the highest laser intensity, where the SRS-B EPW amplitude is high enough to influence significantly the plasma electrons. In this case the non-linear interaction between the wave and the electrons starts to be dominant and the resulting instability growth rate is lower than that predicted by the linear theory. In contrast to this the instability evolution in the lower density case is mostly in the kinetic regime. The phase velocity of the plasma wave is lower, which enhances the non-linear

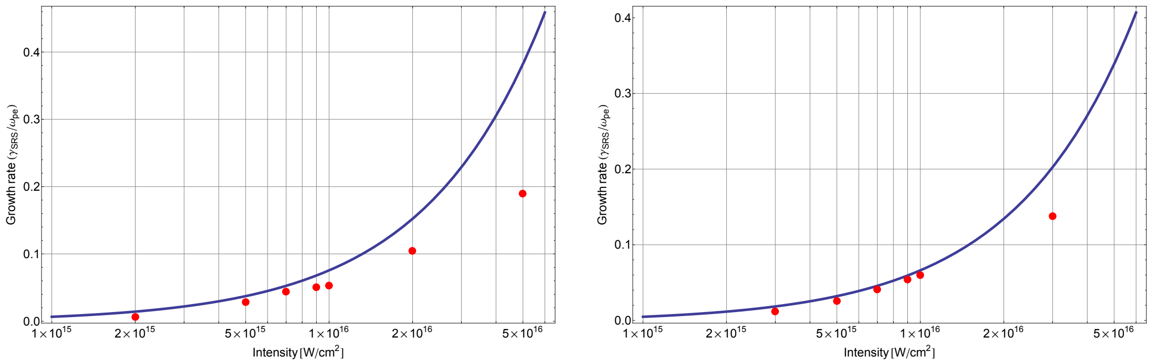

Figure 2: SRS-B amplitude growth rate Γ_{SRS-B} as a function of laser intensity obtained from the linear theory (blue line) is compared with the results of Vlasov-Maxwell simulations (red points) for the electron density (a) $n_0/n_c = 0.139$ and (b) $n_0/n_c = 0.219$.

'wave-particle' interaction at a significantly lower laser intensity, the Raman instability is in the kinetic regime and the results do not correspond to the values predicted by the linearized coupled modes theory.

Conclusions

The kinetic Vlasov-Maxwell code was employed to model realistic situation of shock ignition experiment. Although a simplified version of the code preventing the development of the trapped particle instability, the Raman cascading and the forward SRS, our simulations clearly indicated two regimes of the Raman instability connected with the electron kinetics. When the electron distribution is not strongly affected by the plasma wave, the Raman instability grows as predicted by the coupled modes theory. As the laser intensity increases, the instability goes over to a kinetic regime, in which the electron motion is strongly affected and the resulting Raman reflectivity can decrease significantly.

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