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Raman scattering from a laser plasma with enhanced collisions

M. Mašek[1], K. Rohlena[1]

[1] *Institute of Physics, Academy of Science of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic*

Introduction

The future planned experiments such as NIF, Megajoule and HiPER will include in the first phase either a compression by ns laser pulses in a direct drive scheme or a generation of ns plasma inside a hohlraum in the indirect one [1]. The interaction of ns beams with the self-generated plasma corona or the interaction with the plasma blocking the light entrance holes of the hohlraum is prone to several non-linear light scattering processes impeding an efficient energy deposition of the heating beams in the plasma. An important one is the Raman scattering [2],[3], which may reflect a substantial part of the laser energy away from the plasma. In the case of a near-infrared laser the generated plasma is only weakly collisional, the Raman scattering is accompanied by a complex kinetic evolution in the electron phase-space, such as a saturation of Landau damping, which is than translated in an unfavourable time dependence of the reflected light intensity. To avoid these unwanted phenomena the 3rd harmonics illumination is used in the visible or near UV range, by which the generated plasma is rendered more collisional and a part of the mentioned kinetic behaviour is suppressed. If the plasma is only weakly collisional the simulation revealed the following kinetic phenomena in the phase space [4],[5]: (1) saturation of the wave growth, (2) a strong reduction in the Raman reflectivity, (3) wave cascading and an additional associated reduction of the reflectivity, (4) non-linear combination of the electrostatic partners of the Raman forward- and back-scattering to form non-resonant quasi-modes, (5) presence and growth of trapped particle instability and generation od sidebands, which later dominate (6) anomalous dispersion due to a dispersion curve deformation by the trapped electron dynamics. The aim of the present contribution is to run the code in the regime of stronger collisionality and to demonstrate, which of the above mentioned kinetic phenomena are able to survive in a plasma generated by the frequency converted laser beam.

Kinetic model of laser corona

The fundamental 1D equation set for a weakly collisional homogeneous laser plasma can be written as follows

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

$$\left[\frac{\partial^2}{\partial x^2}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\frac{\omega_{pe}^2}{c^2}\frac{n_e}{n_0}\right]A\ =0, \tag{2}$$

$$\frac{\partial^2\varphi}{\partial x^2}=\frac{e}{m}(n_e-n_0), \tag{3}$$

where A is the only non vanishing transverse component of vector potential, φ is the electrostatic potential, c is the speed of light, x the spatial coordinate (propagation direction), t is the time, v_x is the velocity in the parallel direction and n_0 is the initial density of electrons and ions, $<>$ stands for the averaging over the distribution f. In the Vlasov equation the velocity in the perpendicular direction is replaced by the mean oscillatory velocity in the field of incident laser light $v_y = eA/m$. It means that in the perpendicular direction a monokinetic fluid description is considered. The simplified Fokker-Planck collision term on the right-hand side of the Vlasov equation was included. Numerically such a term also provides a satisfactory stabilization of the method, which is helpful in carrying the solution to sufficiently long times. For the normalization of the electron distribution function f we assume

$$\frac{n_e}{n_0} = \int_{-\infty}^{\infty} f \, dv. \tag{4}$$

(1)-(4) is a closed set of equations, which was solved numerically by the transform method [6]. Even if we are aware of more modern methods to solve the Euler-Vlasov system in the phase space [7], which is less computationally demanding and achieves a stabilization by averaging over the numerical grid, we resorted to the transform method, since the stabilization by the averaging is at the cost of entropy non-conservation. For the transform method the small collision term is vital, since it not only adds to the realism of the description of laser corona, but it also helps to stabilize the numerical procedure with the entropy growth well defined physically.

Results of the simulations

The electron temperature of the outer corona irradiated by the 3rd harmonics with the intensity $I = 3 \times 10^{16} W/cm^2$ is estimated to be $T_e = 5 \times 10^6 K$. In order to demonstrate the influence of collisions, we will deal with two cases of electron density $n_e/n_{cr} = 0.055$ and $n_e/n_{cr} = 0.155$. They were chosen to to fulfill exactly k-matching condition in the discrete spectrum of numerical model. Since we are interested mainly in high-Z plasmas, a qualified estimate of electron-ion collision frequency renders $\nu_{ei}/\omega_{pe} = 0.05$ and $\nu_{ei}/\omega_{pe} = 0.1$, respectively. These values ensure at the same time a good stability of the numerical method. In the simulation 700 terms of Hermite and 100 terms of Fourier expansion are employed, and the position of the pumping wave within the discrete k-spectrum was chosen in such a way, as to prevent the spread of each of the generated resonant wave modes over several discrete points of the spatial k-spectrum defined in the numerical treatment.

A more complex situation we can find in the thinner plasma $n_e/n_{cr} = 0.055$, where next to the Raman backscattering also Raman cascade exists. Fig. 1(a-c) shows the temporal evolution of resonant wave modes together with the temporal evolution of Raman reflectivity defined as $R = E_R^2/E_L^2$, where E_R and E_L are the amplitude of electric field of backscattered and pumping wave respectively, expressing the ratio of reflected energy. After the initial growth of the instability the amplitudes of resonant waves are saturated and Raman reflectivity reaches its highest value $R = 12\%$. At this point the plasma wave amplitude reaches a really high value $E = 2.2 \times 10^{10} V/m$, so it influences a broad region in the phase space. The instability growth saturation occurs because of a strong wave-particle interaction, which appears as a consequence of the fact that the phase velocity of the SRS-B plasma wave lies close to the maximum of electron distribution function $v_{phB}/v_T = 5.098$. The separatrix defining velocity, which separates the trapped and the freely moving electrons in the phase space, can be derived from a simple analysis of particle dynamics

$$v_{sep} = 2\sqrt{\frac{eE}{mk}}. \tag{5}$$

In this case its value is $v_{sep}/v_T = 2.905$, so the wave traps electrons in the velocity interval $< 2.19, 8.03 > v_T$, which can be accelerated by the high field of the plasma wave. These electrons are vizualized as the closed loops in the phase space. This interaction leads also to a significant decrease in the Raman reflectivity, which in the later stage of the system evolution oscillates around 7% as the particles are alternatively accelerated and decelerated by the wave. In this case the collision frequency is not yet high enough, which can cause randomization in the phase space and, as a consequence, lead to a suppression of the SRS-B plasma wave amplitude. It is, however, interesting that the fluctations of the scattering process, including the Raman reflectivity, is even in a less collisional 3ω example no longer controlled by the trapped electrons wobbling frequency (as in 1ω case), but by a mutual interplay (oscillations) between the driving and the scattered modes. However, the alternating depletion and enhancement of the modes, is significantly slower than the oscillations of the wave amplitude due to the electron wobble.

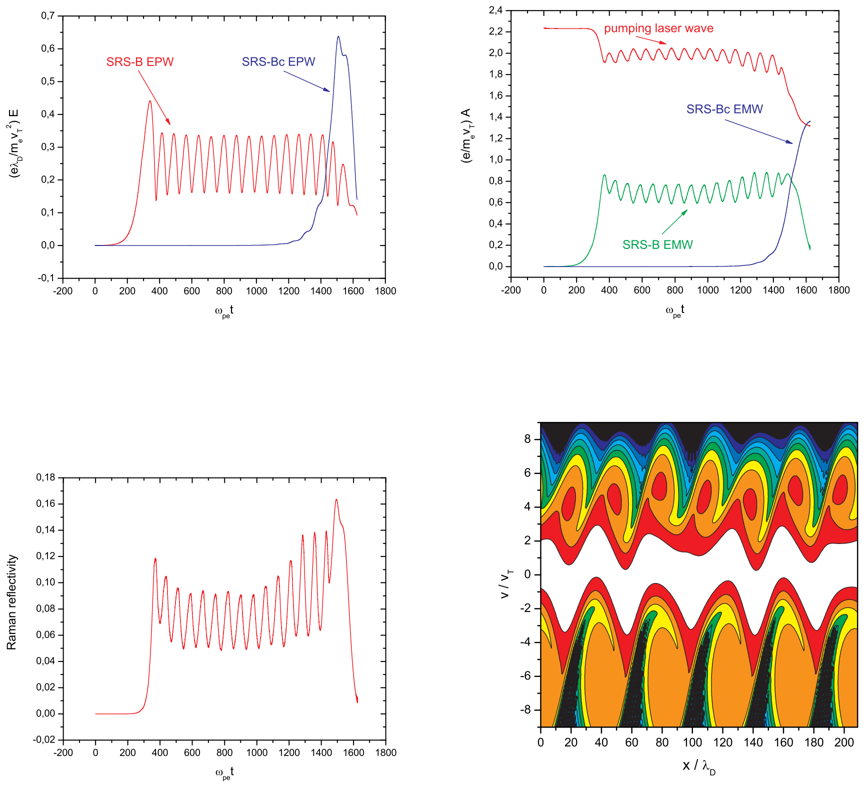

Figure 1: Temporal evolution of resonant wave modes (a) electrostatic modes (b) electromagnetic modes. (c) Temporal evolution of Raman reflectivity. (d) Phase space plot of electron distribution function in logarithmic scale $f \in < 1\times10^{-9}, 1\times10^{-1} >$.

On the other hand, there is another mechanism acting in parallel, which significantly influences the system evolution. It is the Raman cascading, a secondary scatter of the once scattered Raman wave. This contribution is demonstrated by the phase space plot in Fig. 1(d). During the Raman cascading another plasma wave propagating this time against the laser beam propagation also with a strong particle trapping ability is generated. Its phase velocity $v_{phRc}/v_T = 7.148$ lies again close to the bulk of the electron distribution and due to its high amplitude $E = 3.2\times10^{10} V/m$ the associated separatrix velocity reaches the value $v_{sep}/v_T = 4.207$. These accelerated electrons move away from the target and thus they contribute to the acceleration of the corona expansion, which is desirable in the laser driven ion sources experiments. Another consequence of the Raman cascading is a dramatic decrease in the Raman reflectivity to a nearly zero value.

Due to the relatively high collision frequency we cannot expect such strong kinetic effects in the second case studied (deeper inside the 3ω corona) as in the first case. Moreover, the relatively high phase velocity of SRS-B plasma wave $v_{phB}/v_T = 10.03$ prevents the strong wave-particle interaction, thus its amplitude can reach very high value $E = 5.8\times10^{10} V/m$ and the separatrix velocity then will be $v_{sep}/v_T = 5.211$. Other important parameter characterizing the trapped particle motion is the bouncing frequency of electrons inside the plasma wave potential minima $\omega_B = \sqrt{eEk/m}$, which in this case is $\omega_B/\omega_{pe} = 0.264$. This value, unlike the previous case ($\omega_B/\omega_{pe} = 0.303$), is comparable to the electron-ion collision frequency. As a result, the tail of the electron distribution is randomized by the collisions and there is no particle trapping by the SRS-B plasma wave. Consequently, no fast electron groups are formed. Due to a weak wave-particle interaction the value of Raman reflectivity is relatively high and oscillates around 20% at the saturated level, while its peak value reaches 65%.

Conclusions

The Raman scattering process was studied numerically in the collisional 3ω laser generated plasma and compared with the case of 1ω. Although, as expected a strongly increased collisionality deeper inside the corona suppresses the kinetic effects in the corona as obvious from the detailed phase space evolution, the collisionality not in all the cases can substitute the suppressed Landau damping. The effect of enhanced collisions can thus be summarized in the following points:

(1) With the suppression of Landau damping and of the associated higher order kinetic effects (such as a generation of hot electrons) the Raman reflectivity goes up. Although, the Raman instability is, in addition, damped by the electron-ion collisions its value in the denser 3ω plasma may reach 20% or more.

(2) The trapped electron wobbling frequency is no longer significant for the fluctuations of the scattered wave amplitudes. It is rather the mutual energy interplay between the driving and the scattered modes, which controls the scattered amplitude oscillations around the saturation values, which is also reflected in a modulation of the phase space evolution.

(3) The most efficient suppression of the primary local Raman reflectivity is due to a cascading process. By the secondary scattering of backward going scatted electromagnetic wave the flow of energy is very efficiently returned to the forward direction and the back-scatter is significantly diminished.

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