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Evolution of electron distribution function in a laser plasma at SRS

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Abstract

The kinetic behaviour of the electron gas in a non relativistic underdense laser plasma in the presence of Raman scattering was studied by solving the Vlasov equation simultaneously with the Maxwell equations in a 1D periodic slab model. The parameters of the computation were chosen to be compatibile with the plasma in the laser corona typically generated by the nanosecond PALS system. The Vlasov equation was treated by a transform method, developing in the configuration space in a Fourier series and in the velocity space in a Hermite series. In the collisionless case the solution was pushed to the practicable time limit of the transform method indicating the onset of particle trapping in the longitudinal electrostatic waves accompanying the Raman scattered waves. No particle trapping in the fast electrostatic partner of the Raman forward scattered wave was recorded, but there is an indication of a non-linear quasi-mode combined from both the electrostatic compagnons of the forward and backward scattered Raman waves with a strong tendency for trapping.

Introduction

Stimulated Raman scattering (SRS) belongs to fundamental non-linear mechanisms occurring if the laser beam of above threshold intensity is passing through a long underdense plasma. A typical situation of this kind is encoutered inside the hohlraums used in the experiments with the indirect drive. The Raman backscattering (SRS-B) may lead to a considerable energy loss through the light entrance holes. Moreover, due to the accompanying electrostatic plasma wave, which is created simultaneously with the scattered light wave, it may lead in a nearly collisionless plasma to changes in the electron velocity distribution, and finally at very high intensities to a generation of laser accelerated relativistic electron beams and a subsequent ion acceleration.

SRS can also couple to other plasma instabilities, which leads to a cascading, whereas the deformation of electron distribution function and the occurrence of the accelerated electron beams gives rise to new non-linear modes of which the impinging laser beam may also be scattered. A recent paper concentrating on these phenomena [1] deals with the situation in experiments with the directly illuminated thermonuclear targets, where "hot spots" may occur i.e. local foci of self focused channels of the heating laser beam reduced down to the diffraction limit and attaining thus relativistic intensities even in nanosecond plasmas, especially if the number of hot spots remains relatively low. Interesting is the role of the Raman forward scattered wave (SRS-F), where the phase velocity of the electrostatic mode lies outside the electron distribution and it can thus in a non-relativistic case hardly trap any of the plasma electrons. In the paper [2], however, based on a simulation a mechanism of a tandem acceleration was proposed when the beam formed by the SRS-B is injected into the SRS-F electrostatic mode somewhat farther down the propagation direction and re-accelerated.

In this contribution we shall examine other aspect of the simultaneous existence of the SRS-B and SRS-F. If these electrostatic modes belonging to these two kinds of scattering overlap, they can by a non-linear interaction generate a non-resonant difference quasi-mode, whose "phase velocity"

$$\frac{\omega_{SRS-B} - \omega_{SRS-F}}{k_{SRS-B} - k_{SRS-F}}$$

lies well within the bulk of the electron distribution and thus a strong interaction with the plasma electrons and a modulation of the electron distribution function is to be expected.

Model

Vlasov equation is transformed in a 1D (x-direction) form by replacing the perpendicular velocity coordinate in the y-direction by its mean value [2] and using the Coulomb gauge for the vector potential

$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + \frac{e}{m}\left(\frac{\partial \varphi}{\partial x} - \frac{e}{m} A \frac{\partial A}{\partial x}\right)\frac{\partial f}{\partial v} = \nu_c \left(\frac{\partial (vf)}{\partial v} + \frac{\partial^2 f}{\partial v^2}\right), \tag{1}$$

$$\frac{n_e}{n_0} = \int_{-\infty}^{\infty} f \, dv. \tag{2}$$

$$\left[\frac{\partial^2}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2} - \frac{\omega_{pe}^2}{c^2}\frac{n_e}{n_0}\right] A \ = 0, \tag{3}$$

$$\frac{\partial^2 \varphi}{\partial x^2} = \frac{e}{m}(n_e - n_0), \tag{4}$$

where A is the only non vanishing transverse component of vector potential $(0, A, 0)$, 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 propagation direction and n_e, n_0 is the perturbed and the initial electron number density, $\omega_{pe} = \sqrt{n_0 e^2/\varepsilon_0 m}$ is the electron plasma frequency (e the electron charge, ε_0 permittivity of vacuum and m the electron mass). The simplified Fokker-Planck collision term [4] on the right hand side of Vlasov equation (1), where ν_c is collision frequency, is added for a temporal prolongation of the solution.

The above set was solved by the Fourier-Hermite transform method [3] for the following parameters of the incident laser beam and of the laser plasma roughly corresponding to the PALS experiment

Parameter	Value	Parameter	Value
I_{Las}	$5 \cdot 10^{19}$ W/m^2	T_e	$1 \cdot 10^7\ K$
λ_{vac}	1.3152 μm	$v_{T_e}/\sqrt{2}c$	0.0410632
ω_L	$1.432 \cdot 10^{15}$ s^{-1}	n_e	$2.828 \cdot 10^{25}$ m^{-3}
τ	0.5 ns	ω_{pe}	$3 \cdot 10^{14}$ s^{-1}

Since the Maxwell-Vlasov model, as opposed to the PIC methods, does not suffer

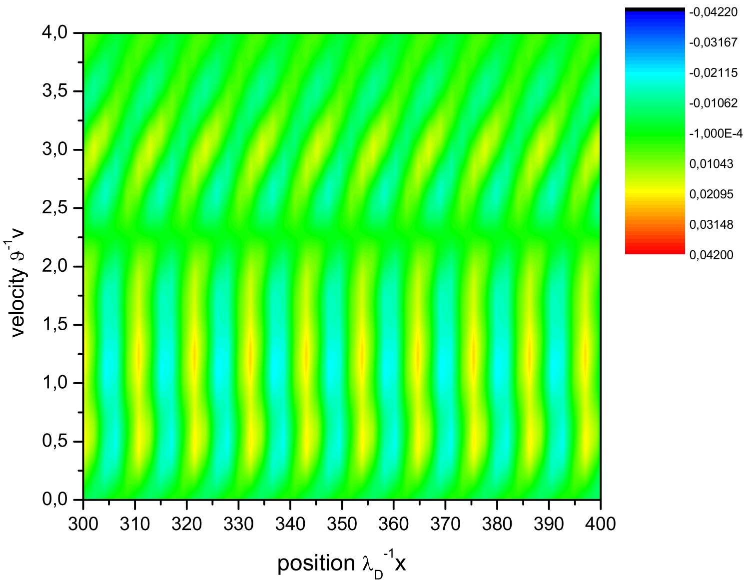

Figure 1: Perturbed part of electron distribution function at the time $\omega_{pe}t = 10.0$, $\lambda_D = \sqrt{\varepsilon_0 k_B T_e / n_e e^2}$ (Debye length), $\vartheta = \omega_{pe}\lambda_D$. The lower half of the picture is interpreted as the modulation due to the quasi-mode.

from a numerical noise it was necessary to specify non-vanishing initial conditions for the unknown coefficients of the transform series. In our model we chose a low level white noise distribution of waves over the considered interval of the electromagnetic spectrum.

Results and Discussion

The solution of the above system renders time dependence of the electromagnetic as well as of the electrostatic spectra and the evolution of the electron distribution function in the phase-space. For the above parameters we observe a strong growth of the SRS-B mode and a weaker growth of SRS-F. In the electrostatic spectrum the plasma wave companions of both the scattered waves appear. The spectra also contain other non-linear features like the harmonics of the impinging heating laser wave. It is difficult to distinguish the quasi-mode directly in the electrostatic spectrum, since it is a non-resonant wave. However, it can be recognized in the phase space since the electron distribution function is perturbed in the vicinity of its phase velocity. This perturbation appears to be comparable to that one caused by the SRS-B wave. As a representative result we present the perturbed part of the electron distribution in the phase space, Fig. 1.

The transform method is known to have its limitations. The most serious one is the inherent impossibility to extend the solution beyond a certain limiting time given by the truncation of the transform Hermite series. Thus, in the collisionless case we were unable to obtain a fully developed picture of the electron trapping in the local potential minima of the electrostatic waves and the oscillations of the trapped particles in these potential

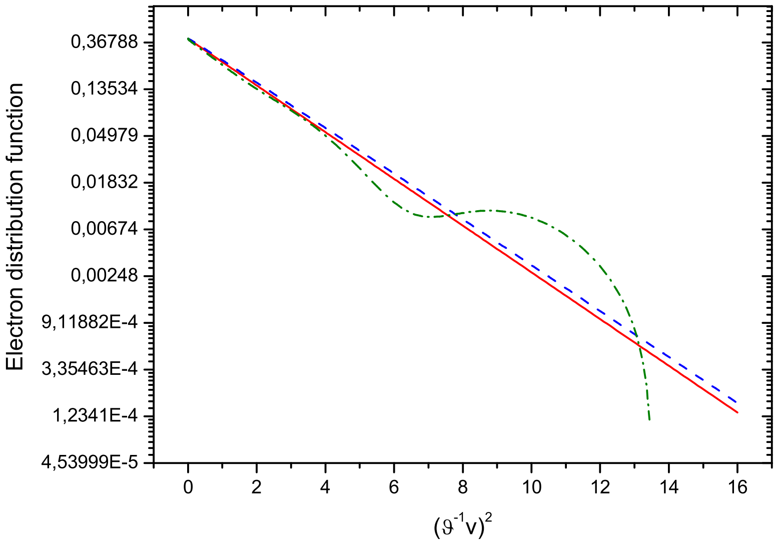

Figure 2: Comparison of EDF obtained from the collisionless (green curve) and collisional (blue curve) model. Initial Maxwell distribution is depicted as the red curve.

wells. Nevertheless, the solution can be pushed to the onset of the trapping, where our solution could serve as an initial condition for a more sophisticated method, see e.g. [5] capable of describing these complicated features in the phase space. The situation can be somewhat alleviated by including the collisions, which tend to smooth the fine structures developing in the high energy tail of the electron distribution and to allow for a temporal prolongation of the solution. Then, instead of a complex structure in the vicinity of the SRS-B phase velocity the electrons are just heated. This is illustrated in Fig. 2. However, even in the collisionless case the transform type of solution allowed us to identify the quasi-mode and its effect on the electron distribution.

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