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Electron gas at Raman scattering of laser beam

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This paper is devoted to a study of the phase space evolution in the presence of the stimulated Raman scattering (SRS) in a non-relativistic and homogeneous laser plasma. The set of equation consisting of the Vlasov equation and the Maxwell equations in a 1D periodic slab model is treated by a transform method, developing in the configuration space in a Fourier series and in the velocity space in a Hermite series. To overcome numerical instabilities during the simulation, a simplified Fokker-Planck collision term was employed. The parameters of the computation were chosen to be compatible with the plasma in the laser corona typically generated by the nanosecond PALS system. Both the Raman forward (SRS-F) and backward (SRS-B) scattering and following nonlinear processes as formation of a non-resonant quasi-mode with a low difference ”phase velocity" $v_{ph} = (\omega_{SRS-B} - \omega_{SRS-F})/(k_{SRS-B} - k_{SRS-F})$ and a cascading scattering process of backscattered electromagnetic wave with strong tendency for particle trapping were observed.

SRS is one of the parametric instabilities, which develop in the underdense region of laser-produced plasmas. A laser beam of above threshold intensity passing through a long scale length plasma decays to a scattered electromagnetic wave and a forward-going electron plasma wave. A typical situation of this kind is encountered inside the hohlraums used in the experiments with the indirect drive. 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.

Kinetic model for the laser corona

Vlasov equation is transformed in a 1D (x-direction) form by replacing the perpendicular velocity coordinate in the y-direction by its mean value [1] 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 [3] 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 [2] for the following parameters of the incident laser beam and of the laser plasma roughly corresponding to the PALS experiment (a value of collision frequency ν_c is realistic mainly for high-Z plasmas)

Parameter	Value	Parameter	Value
I_{Las}	$1 \cdot 10^{20}$ W/m^2	T_e	$1 \cdot 10^7\ K$
λ_{vac}	1.3152 μm	v_T/c	0.0411
ω_L	$1.432 \cdot 10^{15}$ s^{-1}	$n_e/ncrit$	0.044
τ	400 ps	ν_c/ω_{pe}	0.05

Since the Maxwell-Vlasov model, as opposed to the PIC methods, does not suffer 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 (Fig. 1) the plasma wave companions of both the scattered waves appear ($k_{SRS-B}\lambda_D = 0.335$ and $k_{SRS-F}\lambda_D = 0.0431$). The amplitude of backscattered electromagnetic wave reaches a very high value, so as to undergo a cascading scattering process, which leads to origin of a backward going (with respect to the impinging laser pulse) electrostatic wave. In the spectrum thus one can identify a peak ($k_{SRS-sB}\lambda_D = 0.239$) corresponding to this cascading scattering process. Phase velocity of this mode $v_{ph}/v_T = -4.54$ lies within the bulk of the electron distribution and thus a strong interaction between this wave and plasma occurs. Particles accelerated by this relatively strong process travel in the opposite direction than the motion of electrons accelerated by SRS-B plasma wave is and they contribute to the expansion of corona (see Fig. 2). Simultaneous existence of SRS-B and SRS-F plasma waves leads to a growth of electrostatic non-resonant quasi-mode with difference wave number ($k_{quasi}\lambda_D = 0.292$). The spectrum also contains other non-linear features like the harmonics of the impinging heating laser wave.

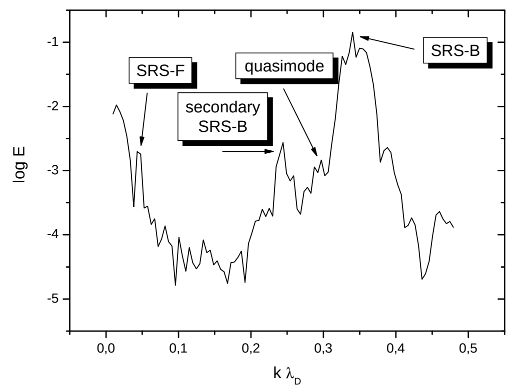

Figure 1: Perturbed part of electrostatic wave number spectra in logarithmic scale at $\omega_{pe}t = 200$.

As a representative result of the Vlasov-Maxwell code we present the electron distribution function evolution illustrated in Fig. 2 by a phase-space plot for SRS-B. The process of particle trapping and acceleration by SRS-B plasma wave with phase velocity $v_{ph}/v_T = 3.45$ is clearly visible there. From a simple analysis of particle dynamics it is possible to find a relation for the relative velocity which the particle gains from the electrostatic wave: $v_{rel} = \sqrt{\frac{2eE}{mk}}$. At $\omega_{pe}t = 160$, when the electrostatic wave reaches its maximum, the value of plasma wave amplitude is $E = 7.8 \cdot 10^9\ V/m$. It means that the resulting relative velocity of accelerated electrons is $v_{rel} = 1.5\ v_T$, which is in a good agreement with the results obtained by the numerical model. In later stages of phase-space evolution also the acceleration by SRS-sB plasma wave occurs as Fig. 2 indicates.

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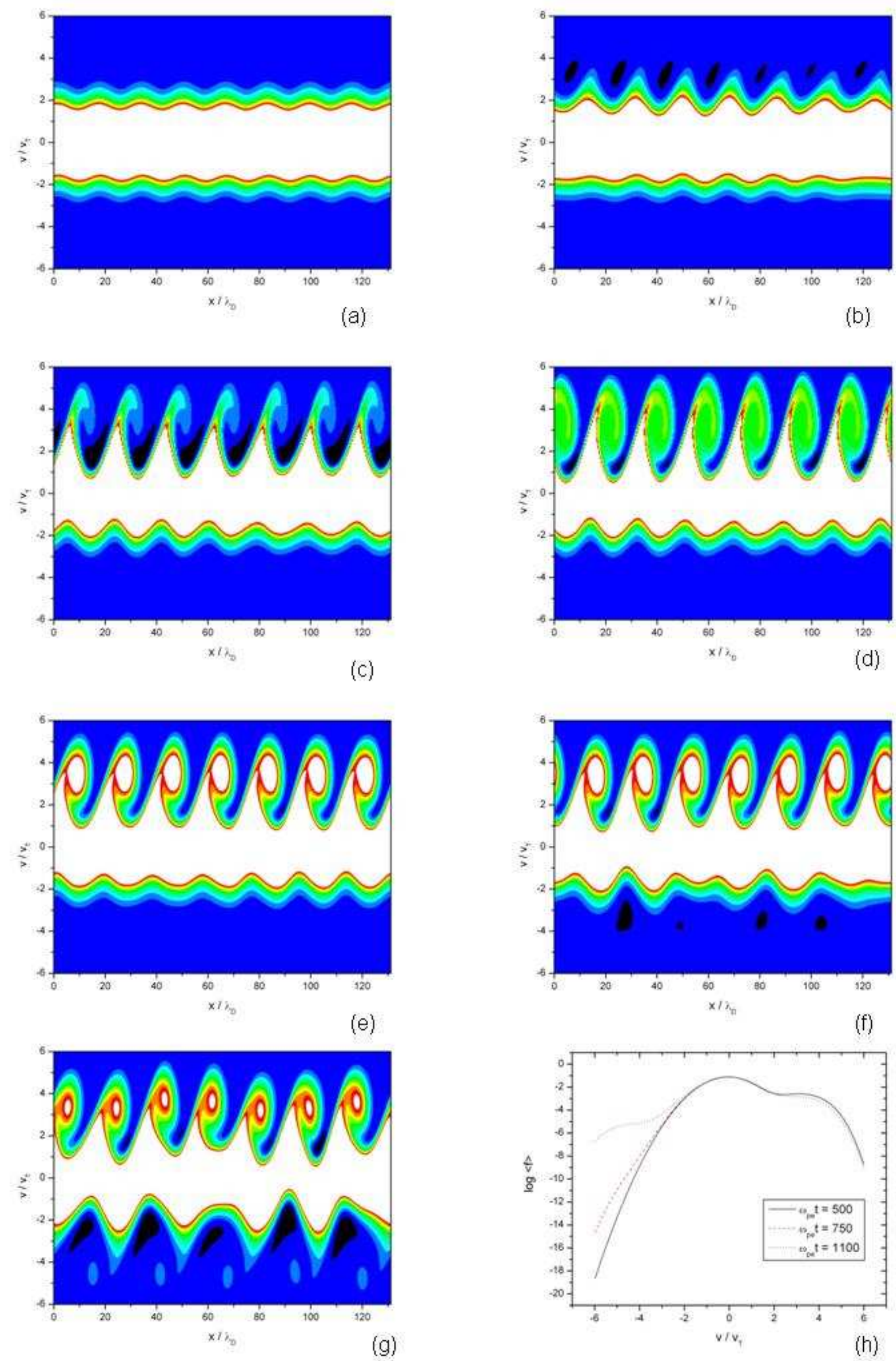

Figure 2: Phase-space contour plot of electron distribution function evolution at (a) $\omega_{pe}t = 0$ (b) $\omega_{pe}t = 100$ (c) $\omega_{pe}t = 120$ (d) $\omega_{pe}t = 140$ (e) $\omega_{pe}t = 500$ (f) $\omega_{pe}t = 750$ (g) $\omega_{pe}t = 1100$. Linear scale is used and the depicted values of distribution are in the interval between $f = 0.0$ and $f = 0.1$. Formation of plateau in vicinity of SRS-sB plasma wave phase velocity is demonstrated by (h) at $\omega_{pe}t = 500, 750, 1100$. A spatially averaged distribution function over the simulation box is depicted there. Note that logarithmic scale is used in this graph.