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Increase of the Stimulated Raman Scattering due to the Langmuir Decay Instability in an inhomogeneous plasma: LDI-inflation

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Since the fundamental result set by Marshall N. Rosenbluth [1], in the frame of the parametric instabilities, concerning the stabilization of the absolute instability for a plasma linearly inhomogeneous, it is now very clear that this result is non robust [2] in regards of small perturbations around this linear profile of density.

In the context of the inertial fusion, the Stimulated Raman Scattering (SRS) is still a challenging problem to understand precisely. The fact that over 50 years we are still modeling this instability is due to the complexity of the behavior of the plasma waves which can react very differently in function, among other parameters, of the value of the parameter $k_L\lambda_{De}$ where k_L is the wave number of the Langmuir wave (LW) generated by SRS. In a homogeneous plasma, it has been shown that the ion acoustic waves (IAW) were able to saturate SRS by a process called the Langmuir Decay Instability (LDI) resulting of the coupling of the IAW with the LW. Nevertheless, in the future laser fusion facilities, the US National Ignition Facility and the french Laser MegaJoule, the plasmas will be inhomogeneous and it is consequently fundamental to consider if the LDI is still able to saturate SRS in an inhomogeneous plasma, for parameters relevant to future experiments. We focuse on the effect of the ion dynamic on the Backward Stimulated Raman Scattering (BSRS) by the way of a Zakharov fluid type model [3] taking account the inhomogeneity of the plasma. The electromagnetic wave amplitudes $\tilde{E}_\alpha$ are decomposed into their fast and slow variations in space and time as $\tilde{E}_\alpha = E_\alpha \exp -i(\omega_\alpha^{ref} t - k_\alpha^{ref} x) + c.c.$, where E_α are the complex envelope amplitudes. The frequency ω_α^{ref} and wavenumber k_α^{ref} satisfy the transverse wave dispersion relation corresponding to an electron density called 'reference' and denoted as n_e^{ref}. The langmuir wave amplitude $\tilde{E}_L$ is similarly decomposed into its fast and slow variation in time as $\tilde{E}_L = E_L \exp -i\omega_{pe}^{ref} t + c.c.$, where E_L is the complex envelope amplitude in time and ω_{pe}^{ref} represents the electron plasma frequency calculated at the reference density. For the sound waves, no envelope approximation is done. The inhomogeneity of the plasma will be always modeled by a monotonous profile in density and the reference density is arbitrary chosen in our case at the centre of the density linear profile. The coupled mode equations representing the model used in the simulations are presented below:

$$\begin{aligned}\Big(D_{parax,0}+\frac{i}{2\omega_0}\Big[\frac{n_{hydro}}{n_c}-\frac{n_e^{ref}}{n_c}\Big]\Big)E_0 &= -\frac{i}{2}\Big\{\frac{n_s}{n_c}\frac{E_0}{\omega_0}+f_{in}C_{L,R}\Big\}\\ \Big(D_{parax,R}+\frac{i}{2\omega_R}\Big[\frac{n_{hydro}}{n_c}-\frac{n_e^{ref}}{n_c}\Big]\Big)E_R &= -\frac{i}{2}\Big\{\frac{n_s}{n_c}\frac{E_R}{\omega_R}+f_{in}C_{L,0}\Big\}\\ \Big(D_L+\frac{i}{2\omega_{pe}^{ref}}\Big[\frac{n_{hydro}}{n_c}-\frac{n_e^{ref}}{n_c}\Big]\Big)E_L &= \frac{i}{2}\Big\{-\frac{n_s}{n_c}\frac{E_L}{\omega_{pe}^{ref}}+\frac{n_e^{bf}}{\sqrt{n_e^{ref}}}f_{in}C_{0,R}+S_L\Big\}\end{aligned} \quad (1)$$

where n_{hydro}, n_e^{bf} are respectively the hydrodynamic density represented by a linear profile and the low frequency density. To close the system of equations (1), n_e^{bf} is determined by $n_e^{bf} = n_{hydro} + n_s$ with n_s describing the sound waves evolution (cf. equation (2)). The terms of coupling are $C_{L,R} \sim (\nabla.E_L)E_R\exp(-ik_Lx)$, $C_{L,0} \sim (\nabla.E_L^*)E_0\exp(ik_Lx)$ and $C_{0,R} \sim \nabla[E_0E_R^*\exp(ik_Lx)]$ with E_α ($\alpha = 0, R, L$) the amplitudes of the waves and k_L the Langmuir wave number. f_{in} is a typical window function, with a hyperbolic tangent shape along the longitudinal axis x, which prevents unphysical destabilization of absolute instabilities at the density profile edge. The term $(i/2\omega_\alpha)[n_{hydro} - n_e^{ref}]$ corresponds to the inhomogeneity of the plasma and is directly related to the Rosenbluth gain G_{Ros} [1]. Written for the amplitudes of the waves, $G_{Ros} = 7.2\times10^{-4}[(I\lambda^2/10^{14}W\mu m^2/cm^2)(L_*/\lambda_0)]$ with $L_* \equiv [(1/n_{hydro})(dn_{hydro}/dx)]^{-1}$ the gradient length. In these equations, $D_{parax,\alpha}$ ($\alpha = 0, R$) denotes the paraxial propagator for the electromagnetic waves given by $D_{parax,\alpha} = (\partial_t + \nu_\alpha + \upsilon_{g,\alpha}\partial_x - i(c_\alpha^2/2\omega_\alpha^{ref})\nabla^2)$ where the quantity $\upsilon_{g,\alpha}$ ($\alpha = 0, R$) denotes the group velocity of the wave α computed with the reference plasma parameters and ν_α denotes its damping coefficient. D_L is the propagator for the Langmuir waves given by $D_L = (\partial_t + \nu_L - i(3\upsilon_{the}^2/2\omega_{pe}^{ref})\nabla^2)$ where $\upsilon_{the} = [T_e/m_e]^{1/2}$ (T_e being the electron temperature and m_e the electron mass) denotes the electronic thermal velocity and ν_L denotes the Langmuir wave damping which corresponds to the electron Landau damping plus the collisional damping. S_L represents the plasma thermal noise and is numerically generated by a Langevin system of equations. The modeling of the noise in this present case of an inhomogeneous plasma appeared to be crucial to fit at the best with the physics and we have to adapt the noise at the local resonance conditions.

The equation describing the ion dynamic is given by:

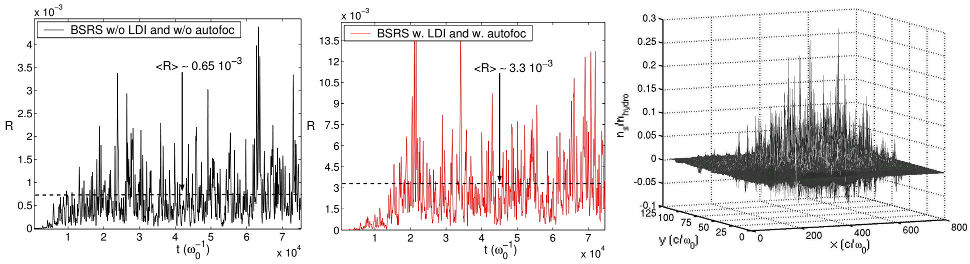
$$D_s \ln\Big(1 + \frac{n_s}{n_{hydro}}\Big) = \frac{Zm_e}{m_i}\nabla^2\Big\{\frac{|E_L|^2}{\omega_{pe}^{ref^2}} + \frac{|E_0|^2}{\omega_0^2} + \frac{|E_R|^2}{\omega_R^2}\Big\} \quad (2)$$

$D_s = (\partial_t^2 + 2\nu_s\partial_t - c_s^2\nabla^2)$ is the propagator for the sound waves where $c_s = [(ZT_e + 3T_i)/m_i]^{1/2}$ denotes the sound wave velocity (T_i being the ion temperature and m_i the ion mass) and ν_s denotes the ion wave damping which corresponds to the ion Landau damping plus the collisional damping. The Langmuir ponderomotive force $|E_L|^2$ describes the LDI cascades and the ponderomative term $|E_0|^2 + |E_R|^2$ describes the self-focusing of the laser and the scattered light. In this model, we are well aware that the envelope approximation in space for the electromagnetic waves prevents considering large ranges of densities. Nevertheless, the goal here is to prove an effect and we focuse on parameters which do the model right.

We show results of 2D simulations in the case of an inhomogeneous plasma where the laser beam is monospeckle. In 2D, the parameters of the simulations are the following: the laser wavelength λ_0 is $1.06\mu m$ and the numerical aperture $f_\sharp$ of the focusing optics is 3. The monospeckle laser beam has an intensity in the focal plan corresponding to $2 \times 10^{15} W/cm^2$, the longitudinal length is $L_\parallel = 127\lambda_0$, the transversal length is $L_\perp = 16\lambda_0$, the electron temperature is $T_e = 1keV$, the ion temperature is such as $ZT_e/T_i = 10$ with $Z/A = 1$ and $Zm_e/m_i = 1/1836$. The range of density along the linear profile is $[0.08 : 0.12]n_c$, the reference density, at the middle of the plasma, is $n_e^{ref} = 0.1n_c$ and the parameter $k_L\lambda_{De}$ defining the Landau damping is, calculated for n_e^{ref}, 0.21. The fluid approximation is justified for such values of $k_L\lambda_{De}$ where the kinetic effects do not play a dominant role. The Rosenbluth gain, calculated at the hot spot, is $G_{Ros} \sim 4.5$. The reflectivity is $R = |v_{g,R}| \int_0^{L_\perp} |E_R(0,y)|dy / |v_{g,0}| \int_0^{L_\perp} |E_0(0,y)|dy$.

On FIG. 1, we observe that the averaged reflectivity is higher, by a factor 5, in the case where the BSRS is coupled with LDI and with self-focusing FIG. 1 (b) than in the case where the BSRS is considered without coupling to the sound dynamic FIG. 1 (a). An important point is that the mean Raman reflectivity, in the range of parameters considered, does not change if we put off the self-focusing and only keep the LDI effect in the model.

This is a clear new result [4]: the LDI is able to increase the Raman reflectivity in an inhomogeneous plasma. The snapshot of the sound waves at $t = 33ps$ (FIG. 1 (c)) shows



(a) (b) (c)

FIG. 1: 2D case. Reflectivities versus time for 2D simulations duration corresponding to the time interval $T = 45ps$ $(7.5 \times 10^4 \omega_0^{-1})$ in the cases of BSRS without LDI and without autofocusing (solid black line) where the averaged in time reflectivity is $< R >= 0.65 \times 10^{-3}$ (a) and BSRS with LDI and with autofocusing (solid red line) where the averaged in time reflectivity is $< R >= 3.3 \times 10^{-3}$ (b) and snapshot of the sound waves in the plasma slab for $t = 33ps$ $(t = 5 \times 10^4 \omega_0^{-1})$ (c)

destructured fluctuations without apparent spatial coherence and with high and very peaked amplitudes in the order of 10^{-1}. This is the signature of a turbulent regime of the Langmuir waves which are developed in each point of the linear profile of density. The sound fluctuations generate the destabilization of the absolute modes. The Random Phase Approximation (RPA) conditions are satisfied by the waves and we interpret our result by the combined effects of incoherence and inhomogeneity [5].

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