Stimulated Raman backward scattering in the nonlinear interaction of short laser pulse with a warm underdense transversely magnetized plasma

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Abstarct

Nonlinear Raman backward scattering (RBS) is investigated in the interaction of linearly polarized short laser pulse with a homogenous underdense warm collisionless transversely magnetized plasma. Nonlinear and relativistic effects of electrons beside the role of thermal motions are taken into account in the presence of constant external magnetic field. Growth rate of Raman backward scattering is calculated by solving coupled equations with Fourier transformation. Results are significantly different in comparison with a cold plasma.

Introduction

Stimulated Raman backward and forward scattering (SRS) has long been an issue for inertial confinement fusion. SRS is usually described as a decay of an incident electromagnetic pump wave into a longitudinal electrostatic plasma wave plus another scattered light wave (Stokes/Anti-Stokes) when the plasma density is below the quarter critical density. Scattered wave may propagate in the forward direction backward direction, which are known as forward Raman scattering (RFS) and backward Raman scattering (RBS) respectively [1,2]. In a magnetized plasma, where the direction of the external magnetic field is perpendicular to the direction of laser pulse propagation, plasma wave is the upper hybrid wave which is excited at angular frequency $\omega_{UH} = \sqrt{\omega_p^2 + \omega_c^2}$ in which ω_p is the plasma frequency and ω_c is the electron cyclotron frequency in the external magnetic field B_0 [3,4,5]. In this work, nonlinear and relativistic effects of electrons beside the role of thermal electrons are taken into account in the presence of external magnetic field. Using the wave equation, the continuity equation and the equation of motion for electrons, two coupled equations are extracted for oscillation of electron density and scattered electromagnetic wave. Coupled equations are solved simultaneously with Fourier transformation method and the growth rate of Raman backward scattering is calculated in a warm magnetized plasma.

Model description

Here, we consider an electromagnetic wave of the form $E(z,t) = \hat{x}E_0 \cos(k_0 z - \omega_0 t)$ with angular frequency ω_0 propagates in the +z direction in a plasma, where E_0 is the amplitude of the laser field. Plasma is imbedded in an external magnetic field of $\vec{B} = B_0\hat{y}$. Consider a plasma with equilibrium electron density n_0. Also, the laser beam polarization can be assumed to remain linear while propagating through warm collisionless transversely magnetized plasma. So, the wave equation governing the propagation of the laser pulse through the plasma medium, the Lorentz force equation of plasma electrons and the continuity equation, are respectively

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E} = \frac{4\pi}{c^2}\frac{\partial \vec{J}}{\partial t} \tag{1}$$

$$\frac{d}{dt}(\gamma\vec{v}) = -\frac{e}{m}\left(\vec{E} + \vec{v}\times(\vec{B}+\vec{B}_0)\right) - \frac{3T_e}{mn_0}\vec{\nabla}n \tag{2}$$

$$\frac{\partial n}{\partial t} + \vec{\nabla}.(n\vec{v}) = 0 \tag{3}$$

Where, $\vec{J} = -ne\vec{v}$ is the plasma electron current density, in which n is the electron density, $-e$ is an electron charge and $\vec{v}$ is its velocity. Also, T_e is the electron temperature in eV, $\vec{B}$ is the magnetic vector of the radiation field and γ is the relativistic factor of electron motion. The nonlinear velocity of plasma electrons in the laser pulse radiation field $(v_x^{(1)}, v_x^{(2)}, v_x^{(3)})$ is calculated up to third order from Eq.(2) and the result will be substituted in Eq.(1) to find the nonlinear wave equation of laser pulse in plasma. Firstly, we find the nonlinear electron current density $J_x = -ne(v_x^{(1)} + v_x^{(3)})$ in the electric field of electromagnetic wave up to third order as

$$J_x = -enca_0 P_0(\omega_0) Sin(k_0 z - \omega_0 t) \tag{4}$$

$$P_0(\omega_0) = \frac{\omega_0^2}{\omega_0^2 - \omega_c^2} + 3k_0^2 v_T^2\left(\frac{\omega_c^2}{\omega_0^2 - \omega_c^2}\right) - \eta_0 a_0^2$$

$$\eta_0 = \frac{c^2 k_0^2}{4}\left[\frac{\alpha_4}{2(\omega_0^2 - \omega_c^2 + k_0^2 v_T^2)} + \frac{\alpha_3}{\omega_0\omega_c}\right] + \frac{3}{8}\left[\alpha_1(\alpha_1^2 + 3\beta_1^2) + \frac{\beta_4\omega_0\omega_c}{\omega_0^2 - \omega_c^2 + k_0^2 v_T^2}\right]$$

$P(\omega_0)$ is the nonlinear coefficient of pump light wave with frequency ω_0. Other parameters used in $P(\omega_0)$ definition such as η_0 and α_1 are constants. Thus, the nonlinear wave equation for the vector potential of the propagated wave would be obtained in a warm magnetized plasma as

$$\left[\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right]\vec{A}_0 = -\frac{4\pi n e^2}{m}P_0(\omega_0)\vec{A}_0 \tag{5}$$

Perturbational coupled equations

Now, using the perturbated quantities in the wave equation, in the continuity equation and in the equation of motion and combining them we find two coupled equations describing Raman scattering

$$\left(\frac{\partial^2}{\partial t^2} + \omega_{UH}^2 - 3k^2 v_T^2\right)\tilde{n} = \frac{n_0 e^2}{m^2 c^2}\frac{\partial^2}{\partial z^2}\left[P_0(\omega_0)\tilde{\vec{A}}.\vec{A}_0\right] \tag{6}$$

$$\left[\frac{\partial^2}{\partial t^2} - c^2\nabla^2 + \omega_p^2 P(\tilde{\omega})\right]\tilde{\vec{A}} = -\frac{4\pi\tilde{n}e^2}{m}P_0(\omega_0)\vec{A}_0 \tag{7}$$

Raman Scattering process in the transversely warm magnetized plasma includes the decay of an electromagnetic pump wave at frequency ω_0 into an exited plasma wave at frequency $\omega_{ek}(=\sqrt{\omega_{UH}^2 + \omega_c^2})$ and two scattered (Stokes/anti-Stokes sidebands at frequency ($\omega_0 - \omega_{ek}$) and ($\omega_0 + \omega_{ek}$), respectively [5]. Using Fourier transformation and combining Eq.(6) and Eq.(7), the dispersion relation can be found as

$$\left(\omega^2 - \omega_{UH}^2\right) = \frac{\omega_p^2 k^2 v_{os}^2}{4P(\omega_0)}\left(\frac{P_+}{D_+} + \frac{P_-}{D_-}\right) \tag{8}$$

Where, $P_\pm$ and $D_\pm(=\omega_\pm^2 - c^2 k_\pm^2 - u_\pm \omega_p^2)$ are nonlinear coefficient and the dispersion coefficient of Stokes and anti-Stokes waves, respectively. If we do the principal procedure is described for SRS analysis [1,5], then we can find the growth rate for RBS instability is a warm magnetized plasma

$$\Gamma = \left[\frac{\omega_p^2 k^2 v_{os}^2}{16\omega_{ek}(\omega_0 - \omega_{ek})}\right]^{1/2} \tag{9}$$

Where, k is the wave number of exited plasma wave, a_0 is the normalized potential vector and $v_{os} = ca_0 P_0(\omega_0)$ is the oscillation velocity of plasma electrons in the laser radiation field.

Results and discussion

In Fig.(1), we have plotted the behavior of the normalized RBS growth rate with respect to the normalized plasma frequency ω_p/ω_0 in a cold ($T_e = 0$) and warm ($T_e = 1keV$) plasma when, $\omega_c/\omega_0 = 0.01$ and $a_0 = 0.02$. As it is apparent from this figure, the instability growth is faster in a warm plasma in comparison with a cold plasma. Since, plasma electrons have randomly thermal motions in a warm collisionless plasma, it causes to rapidly resonance of plasma oscillations. Therefore, we expect that the instability increases. Thus, the present study reveals that the thermal effects are capable of altering the growth rate of Raman backward instability of a laser beam even for weakly relativistic intensities.

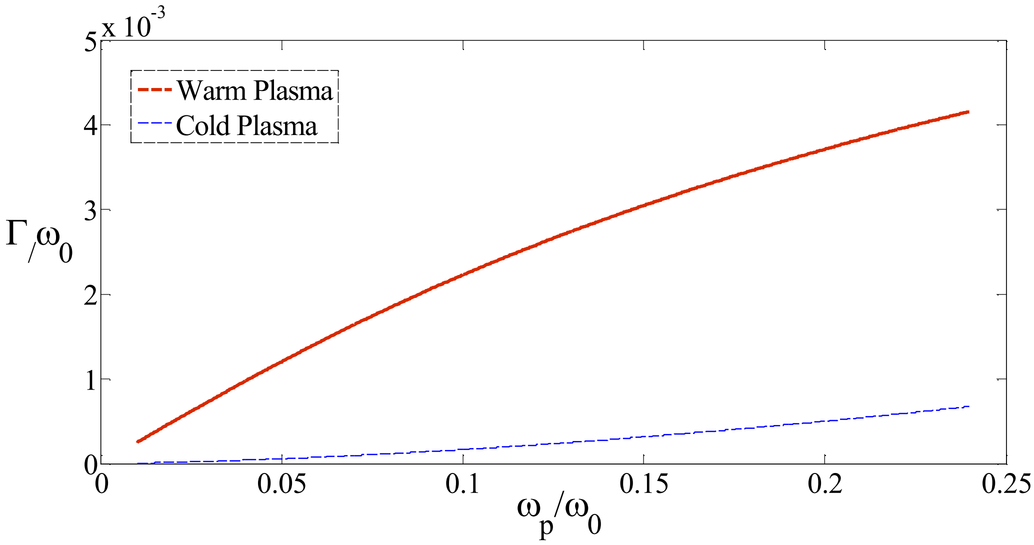

Fig1- Normalized growth rate of nonlinear RBS instability as a function of normalized plasma frequency in a cold ($T_e = 0$) and warm ($T_e = 1keV$) magnetized plasma for $\omega_c/\omega_0 = 0.01$ and $a_0 = 0.02$.

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