Stimulated Raman Scattering in a Magnetized Electron-Positron Plasma

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Abstract

Electron-positron plasma that may be found in numerous environments, such as, active galactic nuclei, pulsar magnetosphere, solar flares, ultra-short laser-matter interaction and interplanetary space, have dielectric properties appreciably different from those of classical electron-ion plasmas since modes occurring on the ion timescale disappear due to a mass symmetry effect. These properties as well as excited instabilities have been studied earlier, whereas in this note, we focus on stimulated Raman scattering instability (SRS) in a magnetized electron-positron plasma.

§.1.Introduction

Electron-positron (e-p) plasmas can be found in the early universe, in astrophysical objects such as pulsars, active galactic nuclei, supernovae remnants, in γ-ray bursts and at the center of the Milky Way galaxy [1]. These plasmas are created by collisions between particles that are accelerated by electromagnetic and electrostatic waves and/or by gravitational forces. High energy laser-plasma interactions and fusion devices can be used to produce e-p plasmas [2], e.g, in large tokamaks[3] through collisions between MeV electrons and thermal particles. As a plasma, the e-p plasma is a medium that supports many oscillation modes that transform into a host of new ones if the plasma is embedded into a magnetic field. However, due to the mass symmetry in pair plasmas, instabilities by way of which modes may be excited are inhibited[4]. We investigated earlier the excitation of parametric instabilities in unmagnetized e-p plasmas while on the other hand we introduce the magnetic field in the present paper, and study in particular the stimulated Raman scattering (SRS). The maximum growth rate of this process is calculated and compared to a previous study. The paper is organized as follows, in Sec.1 the problem is exposed whereas in Sec.2, it is solved, then we conclude in Sec.3

§.2.Theory

We consider an e-p plasma embedded in a uniform background magnetic field $\vec{\boldsymbol{B}}_{\boldsymbol{0}}$. We consider a large amplitude electromagnetic pump wave $\vec{\boldsymbol{E}}_{\boldsymbol{t}}$ which propagates parallel to $\vec{\boldsymbol{B}}_{\boldsymbol{0}}$, where, $\vec{\boldsymbol{E}}_{\boldsymbol{t}} = 2\vec{\boldsymbol{E}}_{\boldsymbol{t0}} \cos\left(\vec{\boldsymbol{k}}_{\boldsymbol{t}}.\vec{x} - \omega_{\boldsymbol{t}}\boldsymbol{t}\right)$ that induces oscillatory velocities for electrons and positrons $\vec{\boldsymbol{V}}\boldsymbol{te}^{-}$ and $\vec{\boldsymbol{V}}\boldsymbol{te}^{+}$. The pump wave $\left(\omega_t, \vec{\boldsymbol{k}}_{\boldsymbol{t}}\right)$ decays into an electromagnetic wave $\left(\omega_{t'}, \vec{\boldsymbol{k}}_{\boldsymbol{t'}}\right)$ and an electrostatic wave $\left(\omega_1, \vec{\boldsymbol{k}}_{\boldsymbol{l}}\right)$ with the following matching conditions $\omega_t = \omega_{t'} + \omega_1$ and $\vec{\boldsymbol{k}}_{\boldsymbol{t}} = \vec{\boldsymbol{k}}_{\boldsymbol{t'}} + \vec{\boldsymbol{k}}_{\boldsymbol{l}}$. The perturbed governing equations for both particles are given by,

$$\frac{\partial n_{1e^-}}{\partial t} + N_{0e^-} \vec{\boldsymbol{\nabla}}.\vec{\boldsymbol{V}}_{\boldsymbol{1e^-}} = 0, \tag{1}$$

$$\frac{\partial n_{1e^+}}{\partial t} + N_{0e^+} \vec{\boldsymbol{\nabla}}.\vec{\boldsymbol{V}}_{\boldsymbol{1e^+}} = 0, \tag{2}$$

$$\frac{\partial \vec{\mathbf{V}}_{\boldsymbol{1e^-}}}{\partial t} + \frac{3KT_{e^-}}{mN_{0e^-}} \vec{\boldsymbol{\nabla}} n_{1e^-} + \frac{e}{m}\left(\vec{\boldsymbol{E}}_{\boldsymbol{l}} + c^{-1}\vec{\boldsymbol{V}}_{\boldsymbol{1e^-}} \times \vec{\boldsymbol{B}}_{\boldsymbol{0}}\right) = -\vec{\nabla}\left(\vec{\boldsymbol{V}}\boldsymbol{te}^{-}.\ \vec{\boldsymbol{V}}\boldsymbol{t'e}^{-}\right), \tag{3}$$

$$\frac{\partial \vec{\mathbf{V}}_{\boldsymbol{1e^+}}}{\partial t} + \frac{3KT_{e^+}}{mN_{0e^+}} \vec{\boldsymbol{\nabla}} n_{1e^+} - \frac{e}{m}\left(\vec{\boldsymbol{E}}_{\boldsymbol{l}} + c^{-1}\vec{\boldsymbol{V}}_{\boldsymbol{1e^+}} \times \vec{\boldsymbol{B}}_{\boldsymbol{0}}\right) = -\vec{\nabla}\left(\vec{\boldsymbol{V}}\boldsymbol{te}^{-}.\ \vec{\boldsymbol{V}}\boldsymbol{t'e}^{-}\right), \tag{4}$$

T_{e^-}, T_{e^+} being respectively the electron and positron temperatures, and n_{1e^-}, n_{1e^+}, $\vec{\boldsymbol{V}}_{\boldsymbol{1e^-}}$, $\vec{\boldsymbol{V}}_{\boldsymbol{1e^+}}$ and $\vec{\boldsymbol{E}}_{\boldsymbol{l}}$ are respectively the perturbed electron and positron densities, the perturbed electron and positron velocities, and the low frequency electric field, whereas N_{0e^-} and N_{0e^+} are respectively the equilibrium electron and positron densities. The plasma is quasineutral in the equilibrium state, so, $N_{0e^-} \approx N_{0e^+} \approx N_0$. The velocities $\vec{\boldsymbol{V}}\boldsymbol{t'e}^{-}$ and $\vec{\boldsymbol{V}}\boldsymbol{t'e}^{+}$ represent respectively the response of electrons and positrons to the sideband wave electromagnetic field $\vec{\boldsymbol{E}}_{\boldsymbol{t'}} = 2\vec{\boldsymbol{E}}_{\boldsymbol{t'0}} \cos\left(\vec{\boldsymbol{k}}_{\boldsymbol{t'}}.\vec{x} - \omega_{\boldsymbol{t'}}\boldsymbol{t}\right)$. Use have been made of $\vec{\boldsymbol{V}}\boldsymbol{te}^{-} = -\vec{\boldsymbol{V}}\boldsymbol{te}^{+}$ and $\vec{\boldsymbol{V}}\boldsymbol{t'e}^{-} = -\vec{\boldsymbol{V}}\boldsymbol{t'e}^{+}$. After some algebra, the equations are recast as follows,

$$\left(\frac{\partial^2}{\partial t^2}+\omega_u^2\right)n_1=\lambda\,E_t E_{t'}\,, \tag{5}$$

and

$$\left(\frac{\partial^2}{\partial t^2}+\omega_{t'}^2\right)E_{t'}=\mu\,E_t\,n_1, \tag{6}$$

where, $n_1=n_{1e^-}+n_{1e^+}$, $\lambda=-\dfrac{2\omega_{pe}^2 k_l^2}{\omega_t\omega_{t'}\,4\pi m}\,\vec{\boldsymbol{u}}_{\boldsymbol{t}}.\vec{\boldsymbol{u}}_{\boldsymbol{t'}}$, $\mu=-\dfrac{\omega_{t'}}{\omega_t}\dfrac{\omega_{pe}^2}{N_0}\,\vec{\boldsymbol{u}}_{\boldsymbol{t}}.\vec{\boldsymbol{u}}_{\boldsymbol{t'}}$ ($\vec{\boldsymbol{u}}_{\boldsymbol{t}}$ and $\vec{\boldsymbol{u}}_{\boldsymbol{t'}}$ indicate the polarization of the fields $\vec{\boldsymbol{E}}_{\boldsymbol{t}}$ and $\vec{\boldsymbol{E}}_{\boldsymbol{t'}}$), $T_{e^-}\,\square\,T_{e^+}\,\square\,T_e$,and $\omega_u^2=\omega_{ce}^2+\dfrac{3K\,T_e}{m}k_l^2$, where $\omega_{ce}^2=\left(\dfrac{eB_0}{mc}\right)^2$. We have used also the fact that the sideband satisfies the following wave equation, $\left(\dfrac{\partial^2}{\partial t^2}+\omega_{t'}^2\right)\vec{\boldsymbol{E}}_{\boldsymbol{t'}}=4\pi e\dfrac{\partial}{\partial t}\left(n_1\vec{\boldsymbol{V}}\boldsymbol{te}^{\boldsymbol{-}}\right)$,where, as above $n_1=n_{1e^-}+n_{1e^+}$, $\omega_{t'}^2=k_{t'}^2\,c^2+2\omega_{pe}^2$ and $\omega_{pe}^2=\dfrac{4\pi N_0 e^2}{m}$.Following Nishikawa [6],we can now deduce the expression of the maximum growth rate of the stimulated Raman scattering process $\gamma_{\max}$, which is given by,

$$\gamma_{\max(e-p)}=\frac{\sqrt{2}\,\omega_{pe}^2\,k_l\left|\vec{\boldsymbol{u}}_{\boldsymbol{t}}.\vec{\boldsymbol{u}}_{\boldsymbol{t'}}\right|E_{t0}}{4\omega_t\left[\omega_{t'}\,\pi N_0\,m\left(\omega_{ce}^2+\dfrac{3K\,T_e}{m}k_l^2\right)^{1/2}\right]^{1/2}} \tag{7}$$

On the other hand, the maximum growth rate of the SRS process calculated for an electron-ion plasma (c.f.Ref.[5]) is given by,

$$\gamma_{\max(e-ion)}=\frac{\omega_{pe}^2\,k_l\left|\vec{\boldsymbol{u}}_{\boldsymbol{t}}.\vec{\boldsymbol{u}}_{\boldsymbol{t'}}\right|E_{t0}}{4\omega_t\left[\omega_{u'}\,\pi N_0\,m\left(\omega_{ce}^2+\omega_{pe}^2+\dfrac{3K\,T_e}{m}k_l^2\right)^{1/2}\right]^{1/2}} \tag{8}$$

where $\omega_{u'}^2=k_{t'}^2\,c^2+\omega_{pe}^2$.

We plot on fig.1, the growth rate ratio $\gamma_{\max(e-p)}/\gamma_{\max(e-ion)}$ versus $k_\ell \lambda_D^* (k_{t'}^2 c^2 \langle\langle \omega_{pe}^2)$ for four different temperatures relevant to interstellar plasmas, where the reference Debye length λ_D^* corresponds to $T^* = 0.009\,eV$.

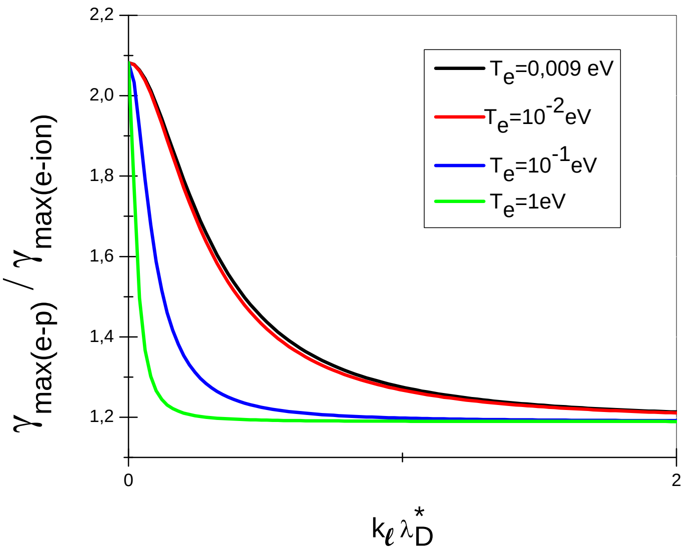

Fig.1: $\gamma_{\max(e-p)}/\gamma_{\max(e-ion)}$ versus $k_\ell \lambda_D^*$ for different temperatures T_e.

§.3.Conclusion

This note is devoted to the study of the Stimulated Raman Scattering in a magnetized electron-positron plasma. The maximum growth rate found in this work is compared to the one obtained in a previous study[5] for a magnetized electron-ion plasma containing. It is found that $\gamma_{\max(e-p)}/\gamma_{\max(e-ion)}$ that is always greater than unity, decreases when the temperature increases, as well as for short wavelengths for a given temperature.

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