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The semi-classical properties of the electron spin on the plasma unstable electromagnetic modes

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ABSTRACT

Effects of the semi-classical properties of the electrons' spin on the growth rate of the temperature anisotropy electromagnetic instabilities, is shown in plasma systems. The obtained results lead to new properties of the instability in the system, where the instabilities will be purely growing without any oscillation and damping. In fact, it is expected that, the semi-classical properties of the electrons' spin lead to generating a free energy in the systems, so that, the non resonant instabilities will be present even in the absence of the temperature anisotropy. In that case, the particles are able to transmit easily from the magnetic tails.

1. Introduction

Quantum plasma physics has an important role in the field of high intensity laser plasma interaction [1,2], metal and semi conductor [3,4] and space/astrophysical plasmas [5,6]. The application of quantum field plasmas is well known in the field of laboratory plasmas and laser plasma interaction, particularly inertial confinement fusion. Also note here that, the quantum fuel expenditures of the fuel pellets plasma leads to reducing the compression. In addition, the studies imply the importance of using the spin-polarized fuel such as the spin polarized D - T fuels. Corresponding investigations have shown that the ignition thresholds can be reduced and the fraction of the fuel burnt will be increased before target disassembly, because of the increase of the thermonuclear cross - section of about 50% due to the spin polarized fuels. It is found that, the hot spot temperature, real density and the required driver energy to achieve a high gain scale will be reduced for a fully polarized spin nuclear fuel. It is also observed that, the spin polarized nuclear fuel leads to an anisotropic emission of α-particle in the fusion reaction product which spatially concentrates the plasma self-heating and leads to development of the fuel ignition [7,8]. Reaching a high gain scale of energy needs a convert of large portion of the driver energy to the fusion energy of the nuclear fuel. In this order, the heat, as energetic electrons, must be flown from the absorption region of the laser energy to an interior region of the target where, the transport mechanism can be intensely affected by the strong magnetic fields.

It is well known that the electromagnetic instabilities excited due to the free energy in the velocity space (Weibel, Filamention and ...) will be responsible for such fields [9–12]. The studies on the temperature anisotropy electromagnetic instabilities, responsible for strong turbulent magnetic fields, imply considerable negative effects of phenomenons such as particle dispersive and quantum tunneling on the growth rate of the instabilities [13,14]. These effects correspond to the

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particle dispersive effects. It will disappear at moderate temperature and densities. Also the de Broglie wave length of particles is smaller than the scale length of plasmas while the effects resulted from the particle spin may survive [15–17].

In a uniform static magnetic field, the mechanism of the non resonant instabilities can be affected because of the free energy stored in the temperature anisotropy which can excite instabilities due to the cyclotron resonance with the plasma particle. In fact the presence of the non resonant electromagnetic instabilities is necessary for exciting these instabilities for example the non resonant Weibel like instabilities for the electromagnetic electron-cyclotron waves (whistler) along an external magnetic field [18]. In addition, studies show that there also exist spin waves in dense magnetized plasmas, which can be excited by intense neutrino fluxes where an electromagnetic pulse can drive a spin-polarized plasma [19] so that the spin-orbit interactions can lead to non polarized plasmas.

Recently, studies have been done to investigate the spin effects on different waves such as whistler and oblique Langmuir waves [19,20]. In this paper we investigate the spin effect on the growth rate of the non resonant electromagnetic unstable wave which is excited by temperature anisotropy in laser produced plasmas. The spin effects are confined to the semi-classical properties of the particles spin. Consequently, the magnetic dipole force and the precession of the spin variable as two dependent variables and its' effect are included, where the polarization of the spin, for example the modification of the magnetic dipole force resulting from the spread out nature of the spin probability distribution are ignored. In Section 2, theory and basic models for deriving the dispersion relation and the growth rate of the electromagnetic unstable modes are presented and in Section 3, the results are discussed.

2. Theory and basic model

In this paper, the effects due to the electron spin on the electromagnetic unstable waves that may survive even when the scale length of plasma is longer than the de Broglie wavelength are investigated. For classical plasmas, the semi-classical properties of the electron spin due to its magnetic moment will be studied on the unstable waves and the full quantum aspects of the electron spin are ignored.

The Pauli Hamiltonian can be introduced by including the magnetic moment of the particle spin as:

$$H_i = -\left(\frac{\hbar^2}{2m_i}\right)\left[\vec{\nabla}_x - \left(\frac{iq_i\vec{A}}{\hbar}\right)\right]^2 + \mu_i\vec{\sigma}\cdot\vec{B} + q_i\phi \tag{1}$$

where $2\pi\hbar$ is the Plank constant, m_i and q_i are the particle mass and charge respectively, (i is introducing the particle species), $\vec{A}$ is the vector potential while ϕ is the scalar potential, μ_i is introducing the particle magnetic moment, $\vec{\sigma}$ is the vector consisting of the Pauli spin matrices and $\vec{B}$ is the magnetic field. For quantum plasmas, in the absence of spin effects, a kinetic evolution equation will be derived for Wigner function which is reduced to the Vlasove model for long scale-length [21,22]. In the presence of the spin degrees of freedom and independence spin variables, a Wigner transform and Q-transform in phase and spin space, respectively, can introduce a suitable evolution equation [16,17]. Here, the spin vector complements such as dependence variables in the phase-space are interest in semi-classical plasma systems, since the Vlasove-like method is used for deriving the evolution equation instead of the Wigner and Q transform for scalar distribution. In this order, for the distribution function $f(x, v, s)$; according to the Liouville equation; we have [15]:

$$\frac{df_i}{dt} = \frac{\partial f_i}{\partial t} + \vec{v}_i\cdot\vec{\nabla}_x f_i + \frac{d\vec{v}_i}{dt}\cdot\vec{\nabla}_v f_i + \frac{d\vec{s}_i}{dt}\cdot\vec{\nabla}_s f_i = 0 \tag{2}$$

where, it is assumed that the number density of particles with the expectancy value of the velocity between v and $v+dv$ and spin vector between s and $s+ds$ is constant in small volume of the phase space and the distribution function f is sum of the unperturbed and perturbed distribution, so that $f(r, v, s, t) = f_0(v, s) + f_1(r, v, s, t)$. Using relation $\frac{df}{dt} = \frac{\partial f}{\partial t} + \frac{1}{i\hbar}[\rho, H]$ with operator ρ and Hamiltonian, (Eq. (1)), the position and momentum in the Heisenberg picture can be derived:

$$\frac{d\vec{x}_i}{dt} = \frac{1}{m_i}\left(\vec{p}_i - q_i\vec{A}\right) \equiv \vec{v}_i \tag{3}$$

$$\frac{d\vec{v}_i}{dt} = \frac{q_i}{m_i}\left(\vec{E} + \vec{v}_i\times\vec{B}\right) + \frac{2}{m_i\hbar}\mu_i\vec{\nabla}_x\left(\vec{B}\cdot\vec{s}_i\right) \tag{4}$$

and

$$\frac{d\vec{s}_i}{dt} = -\frac{2}{\hbar}\mu_i\vec{B}\times\vec{s}_i \tag{5}$$

where the terms proportional to $\vec{B}\times\vec{s}$ and $\vec{B}.\vec{s}$ show the spin precession and the magnetic dipole force, respectively. Placing Eqs. (4) and (5) into Eq. (2), the evolution equation can be rewritten as [15]:

$$\frac{\partial f_i}{\partial t} + \vec{v}\cdot\vec{\nabla}_x f_i + \left[\frac{q_i}{m_i}\left(\vec{E} + \vec{v}\times\vec{B}\right) + \frac{2\mu_i}{m_i\hbar}\vec{\nabla}_x\left(\vec{s}.\vec{B}\right)\right]\cdot\vec{\nabla}_v f + \frac{2\mu_i}{\hbar}\left(\vec{s}\times\vec{B}\right)\cdot\vec{\nabla}_s f = 0 \tag{6}$$

Combining Eq. (6) with the Maxwell equation will present the dispersion relation of plasma waves, where the current density is introduced as:

$$\vec{J} = \sum_i \vec{J}_{i,free} + \sum_i \vec{J}_{i,Mag} \tag{7}$$