Ponderomotive potential and second harmonic backward Raman scattering in dense quantum plasmas

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Abstract. A theoretical model for Raman backscattering of the second harmonic of an intense laser beam propagating through quantum plasma in presence of an external magnetic field using the quantum hydrodynamical (QHD) model is presented. The effects associated with the Fermi pressure, the Bohm potential and the electron spin have been taken into account. The ponderomotive force imparts a longitudinal velocity to the electrons and the electrostatic upper hybrid Langmuir wave is excited. The second-order quantum perturbation theory shows that the second harmonic of the ponderomotive potential arises under the phase matching condition. The dispersion relation for upper hybrid Langmuir wave has been setup.

1. Introduction

Raman backward scattering (RBS) driven by intense laser wave through plasmas has long been an issue for inertial confinement fusion (ICF). It is a physical process that decreases the efficiency in ICF or particle acceleration experiments. It can also be used as diagnostic tool in the laser and plasma interaction experiments [1,2]. Raman scattering is a parametric instability in which an incident light wave decays resonantly into an electron plasma wave and a scattered light wave. Raman scattering process in the transversely magnetized plasma includes the decay of an electromagnetic pump wave into an upper hybrid wave and two scattered Stokes/anti-Stokes sidebands. The laser and the sidebands exert a ponderomotive force on electrons driving the upper hybrid wave [3,4]. RBS is significant for a number of reasons. As the Raman backward scattering mode grows to large amplitude, it can trap background plasma electrons, thus heating the plasma and creating a fast tail on the electron distribution.

Thomas et al. [5] have recently reported experimental results on Raman shifted second harmonic (RSSH) generation in the transverse direction. They have also reported a broadband emission, as a result of initial violent relativistic electron acceleration. Krushenick et al. [6] have also reported Raman shifted second harmonic radiation along with the second harmonics of Raman scattered (SHRS) light. Liu and Tripathi [7] have given a model to understand the second harmonic generation of Raman scattered light. The intense short pulse laser produces a Langmuir wave by Raman backscattering. In the plasma channel, formed in the region of wakefield, the Raman backscattered light exerts a ponderomotive force on electrons, which drives a nonlinear current at the second harmonic. Pathak and Tripathi [8] have reported the study of dispersion and growth of Raman shifted backscattered wave. All this work has been done for classical plasma.

Traditional plasma physics has mainly focused on high-temperature and low-density regimes, where quantum-mechanical effects play no role. Quantum effects become important when the particle
approximation is not possible, i.e., whenever the de Broglie length does not vanish. A plasma can be regarded as quantum when the quantum nature of its particles significantly affects its macroscopic properties. Quantum plasma is a new emerging and rapidly growing subfield of plasma physics. The dense quantum plasma becomes increasingly important in the inertial confinement fusion, astrophysical plasmas, nanoscale plasmonic devices, quantum FEL, laser-plasma interaction, future generation plasma compression experiments, etc. [9-17]. The high-density, low-temperature quantum Fermi plasma is significantly different from the low-density, high-temperature “classical plasma” obeying Maxwell-Boltzmann distribution and understanding the quantum plasmas is challenging as physical processes deviate significantly from the classical prediction [18-21].

In the present paper, we have formulated the model for Raman backward scattering (RBS) in magnetized quantum plasma. The quantum mechanical excitation of the Langmuir wave in the RBS is analyzed, incorporating the electron density perturbation and quantum effects. A laser pulse propagating through highly dense plasma exerts a longitudinal ponderomotive force on electrons and imparts a longitudinal velocity to them. In the presence of transverse external static magnetic field, electrons also attain transverse velocity components and produce transverse current density components which may parametrically excite an electrostatic upper hybrid Langmuir wave and a backscattered Raman shifted second harmonic electromagnetic wave. The formulation has been built up using the quantum hydrodynamic (QHD) model [22-24]. The QHD model consists of a set of equations describing the transport of charge density, momentum (including the Bohm potential) and energy in a charged particle system interacting through a self consistent electrostatic potential [25,26].

The presentation of this paper as follows: In Section-2, the perturbed quantities have been obtained using the QHD model. Section-3 deals with the second harmonic Raman backward scattering generation and its dispersion relation has been established. Section-4 is devoted to discussion.

2. Mathematical model

We consider a laser beam, with electric field \( \hat{E}_y = yE_o \exp(k_o z - \omega_o t) \) and propagation constant \( k_o = \omega_o \left(1 - \omega^2 / \omega_o^2 \right)^{1/2} / c \), propagating in magnetized quantum plasma, where \( n_o \) is the initial density and \( \hat{B} = \hat{y}B_y \) is the external static magnetic field. The plasma frequency being defined as \( \omega_p = \left[ n_e e^2 / \left(m_e c_o \right)^2 \right]^{1/2} \), where \( e \) and \( m \) are electronic charge and rest mass respectively. The QHD equations for the laser and quantum plasma interaction are given as,

\[
\frac{\partial \vec{v}}{\partial t} = - \frac{e}{m} \left[ \vec{E} + \frac{1}{c} (\vec{v} \times \vec{B}) \right] - \frac{\nu_F^2}{n_o} \vec{v} n^3 - \frac{\hbar^2}{2m^2} \dot{\vec{v}} (\frac{1}{\sqrt{n}} \sqrt{\frac{\hbar}{m \omega}}) - \frac{2 \mu_B}{m \hbar} \vec{S} \nabla \vec{B},
\]

(1)

\[
\left( \frac{\partial}{\partial t} + \vec{v} \cdot \nabla \right) \vec{S} = \left( \frac{2 \mu_B}{\hbar} \right) (\vec{B} \times \vec{S}),
\]

(2)

\[
\frac{\partial n}{\partial t} + \nabla (n \vec{v}) = 0.
\]

(3)

where, \( \vec{v} \) is the velocity, \( \hbar \) is the Planck’s constant divided by \( 2\pi \), \( \nu_F \) is the Fermi velocity and \( \vec{S} \) is the spin angular momentum with \( |S_o| = \hbar / 2 \) and \( \mu = (-g/2) \mu_B \), with \( g = 2.0023193 \) and \( \mu_B = e\hbar / 2m \) being the Bohr magneton. The wave equation for the current source is.

\[
\left( \nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) \vec{E}(r,t) = \frac{4\pi}{c^2} \frac{\partial \vec{J}}{\partial t}.
\]

(4)
where, $\vec{J}$ is the current density.

The first order perturbative expansion of equations (1)-(3) gives,

$$\frac{\partial \vec{n}^{(1)}}{\partial t} = -\frac{e}{m} \vec{E}^{(1)} - \frac{v_F^2}{n_o} \varDelta \vec{n}^{(1)} + \frac{\hbar^2}{4m^2 n_o} \varDelta (\varDelta \vec{n}^{(1)}) - \frac{2\mu_B}{m \hbar} \vec{S}_e (\varDelta \vec{B}^{(1)}), \quad (5)$$

$$\frac{\partial \vec{S}^{(1)}}{\partial t} = \frac{-2\mu_B}{\hbar} (\vec{B}^{(1)} \times \vec{S}_e), \quad (6)$$

$$\frac{\partial \vec{n}^{(1)}}{\partial t} + (n_o \varDelta \vec{v}^{(1)} + \varDelta \vec{n}_o \cdot \vec{v}^{(1)}) = 0. \quad (7)$$

Simultaneous solution of the above equations gives the transverse and longitudinal quiver velocity acquired by the plasma electrons,

$$\vec{v}^{(1)}_z = \left[ \frac{2\eta k_o}{n_o \omega_o} K_q + \frac{\mu_B S_o E_o k_o}{m \hbar \omega_o} \left\{ \frac{1}{\omega_o} - \frac{\omega_z}{\omega_o^2 - \omega_z^2} \right\} \right] \exp i(k_o z - \omega_o t) - \frac{i\omega_o}{\omega_o} \vec{v}^{(1)}_z. \quad (8)$$

and

$$\vec{v}^{(1)}_z = \left[ \frac{K_q \eta k_o}{n_o (\omega_o^2 - \omega_z^2)} - \frac{\mu_B S_o \omega_o k_o E_o}{m \hbar (\omega_o^2 - \omega_z^2)} \right] \exp i(k_o z - \omega_o t). \quad (9)$$

where, $\omega_o (= eB_z / mc)$ is the cyclotron frequency and $K_q = \frac{ik_o}{n_o \omega_o} \left\{ \frac{k_o^2 \hbar^2}{4m^2} + v_F^2 \right\}$. Using the continuity equation the first ordered perturbed plasma electron density is obtained as,

$$n^{(1)} = \eta \exp i(k_o z - \omega_o t), \quad (10)$$

where,

$$\eta = \left[ \frac{2\mu_B S_o n_o k_o^2 E_o}{\omega_o (\omega_o^2 - \omega_z^2)} \left\{ \frac{1}{\omega_o} - \frac{\omega_z}{\omega_o^2 - \omega_z^2} \right\} + \frac{en_o k_o E_o}{im \omega_o^2} + \frac{\mu_B S_o k_o^2 \omega_z^2 E_o}{im \hbar (\omega_o^2 - \omega_z^2)} \right] \left( 1 - \frac{2K_q k_o^2}{\omega_o^2} - \frac{K_q k_o^2 (\omega_o - i\omega_o)}{\omega_o (\omega_o^2 - \omega_z^2)} \left( \frac{1}{\omega_o} - \frac{\omega_z}{i\omega_o} \right) \right). \quad (11a)$$

The quiver velocity exerts an oscillatory nonlinear ponderomotive force on electrons, $\vec{F}_p^{(2)} = -\vec{v}^{(1)}_z \times \vec{E}^{(1)} / 2$, where $\vec{B}^{(1)} = k_o \times \vec{E}^{(1)} / \omega_o$. This ponderomotive force impart an oscillatory velocity to the electron, which couple with the external magnetic field to give transverse and longitudinal velocity components at frequency $2(\omega_o, 2k_o)$ as,

$$\vec{v}^{(2)}_x = \left[ -\frac{\omega_o}{2i\omega_o} \vec{v}^{(2)}_z - \frac{\omega_o k_o B_z S_o \mu_B^2 E_o}{(m \omega_o^4 h^3 + 2\mu_B \hbar^2 \omega_z^4 B_z^2)} \right] \exp 2i(k_o z - \omega_o t), \quad (11a)$$
\[
\tilde{v}_{z}^{(2)} = \left[ \frac{e^2 \omega^2}{4 cm^2 \omega^2} + \frac{k_o k_1 \eta E_o}{4 \omega^2 \omega_k^2} + \frac{2 \omega \omega_k k_o S_o B_j \mu^3 h^3 (B)^2}{(2m \omega h^3 + 2 \mu_m \omega_h h^2 (B)^2) 4 \omega^2 - \omega_k^2 + \omega_p^2} \right] \exp 2i(k_o z - \omega_k t). \quad (11b)
\]

The laser pump via current density \( J_2 = -en_o \tilde{v}_{z}^{(2)} + J_s^{(2)} \), parametrically excites a Langmuir wave \( \phi_o = A \exp(i(kz - \omega t)) \) and a backscattered electromagnetic wave with electric and magnetic fields \( \tilde{E}_i = A_i \exp(i(k z - \omega t)) \) and \( \tilde{B}_1 = \tilde{\nabla} \times \tilde{E}_i / i \omega \), respectively, where \( \omega = 2 \omega_o + \omega_1 \) and \( \tilde{k} = 2 \tilde{k}_o + \tilde{k}_1 \).

The scattered wave and the external magnetic field impart oscillatory velocity to electrons and the scattered wave exerts a ponderomotive force on electrons at \((\omega,k)\). The components of ponderomotive force are,

\[
(F_{P_o})_z = \frac{e}{2c} \tilde{v}_{z}^{(2)} B_y^{(1)} + \frac{e \omega_c \tilde{v}_{z}^{(2)} (k_1 + k_o)}{2i \omega_o \omega_k \left( 1 - \frac{\omega_k^2}{\omega_1^2} \right)} \left[ \left( E_{1x} - \frac{\omega_c}{i \omega_1} E_{1z} \right) - \frac{imK_{q1}k_1^2}{\omega_1 \omega_o \delta_q} \left( E_{1z} + \frac{\omega_c}{i \omega_1} E_{1x} \right) \right], \quad (12)
\]

\[
(F_{P_o})_z = \frac{e \omega_c}{4i \omega_o c} \tilde{v}_{z}^{(2)} B_y^{(1)} - \frac{e \omega_c \tilde{v}_{z}^{(2)} (k_1 + k_o)}{2i \omega_o \omega_k \left( 1 - \frac{\omega_k^2}{\omega_1^2} \right)} \left[ \left( E_{1z} + \frac{\omega_c}{i \omega_1} E_{1x} \right) - \frac{mK_{q1}k_1^2}{\omega_1 \omega_o \delta_q} \left( E_{1z} + \frac{\omega_c}{i \omega_1} E_{1x} \right) \right], \quad (13)
\]

where,

\[
K_{q1} = \left( \tilde{v}_{p}^2 + \frac{m^2 k_1^2}{4m^2} \right) \text{ and } \delta_q = 1 - \frac{K_{q1}k_1^2}{\omega_1}.
\]

This force drives the Langmuir wave at \( \phi_o \). The electron’s response at \((\omega,k)\) is obtained, on solving the above equations of force which give the velocities as

\[
\tilde{v}_{ex} = -\frac{k_o e \tilde{v}_{z}^{(2)} E_{1x}}{2cm i \omega_o \omega_1} + \frac{e \omega_c \tilde{v}_{z}^{(2)} (k_1 + k_o)}{2i \omega_o \omega_k \omega \left( 1 - \frac{\omega_k^2}{\omega_1^2} \right)} \left[ \left( E_{1x} - \frac{\omega_c}{i \omega_1} E_{1z} \right) - \frac{\omega_m K_{q1}k_1^2}{i \omega_o \omega_1 \delta_q \left( 1 - \frac{\omega_k^2}{\omega_1^2} \right)} \left( E_{1z} + \frac{\omega_c}{i \omega_1} E_{1x} \right) \right] \quad (14)
\]

and

\[
\tilde{v}_{ex} = -\frac{e \phi_o \omega}{m \omega_1 \left( 1 - \frac{\omega_k^2}{\omega_1^2} \right)} + \frac{\omega \omega_k k_1}{2m c \omega_o \omega \omega \left( 1 - \frac{\omega_k^2}{\omega_1^2} \right)} \left( \chi_1 - \omega_c e \alpha \chi_3 + eK_{q1} \omega_1 \right) \tilde{v}_{z}^{(2)} E_{1x}
\]
\[ \mathbf{A} = -\omega_p^2 \left\{ \frac{\omega}{2\omega_0} \frac{g}{c} \chi_5 - \frac{\omega_m}{k\omega} \chi_5 + \frac{\alpha}{k\omega} K_q \chi_2 \right\} v_z^2, \]

\[ \mathbf{B} = \omega_p^2 \left\{ \frac{\alpha m}{k\omega} \chi_4 - \frac{\alpha}{k\omega} K_q \chi_3 \right\} v_z^2, \]

and

\[ \mathbf{C} = \left\{ 1 - \frac{\omega_p^2}{\omega^2 - \omega_c^2} \right\}. \]

3. Dispersion relation

The current density at \((\omega, k)\) represent current density due to free electrons, coupling of Langmuir wave with the ponderomotive force at \((2\omega_0, 2k_0)\) and current due to spin magnetic moment. The current density of this source current is,

\[ \mathbf{j} = \mathbf{j}_c + \mathbf{j}_e = -e\mathbf{v}\times\mathbf{B} + \frac{2\mu_0}{\hbar} \mathbf{\tilde{v}} \times (\mathbf{n}\mathbf{S}), \]

whose components are,

\[ \mathbf{j}_{1x} = \mathbf{j}_{c1x} + \mathbf{j}_{s1x} \]


\[
\begin{align*}
E_{1s} & = \frac{e^{2}n_{s}\omega_{s}}{m\omega_{s}^{2}} \left\{ 1 + \frac{m\omega_{c}K_{q}k_{1}^{2}}{\omega_{i}\delta_{q}} + \frac{2\mu_{b}\omega_{s}S_{s}k_{1}^{2}}{\delta_{q}\omega_{i}^{2}h} \right\} - \frac{4S_{s}n_{s}k_{1}^{2}\mu_{b}^{2}}{h^{2}\omega_{i}^{2}} \phi_{o}, \\
E_{1z} & = \frac{e^{2}n_{s}\omega_{z}}{m\omega_{z}^{2}} \left\{ 1 - \omega_{s} + \frac{mK_{q}k_{1}^{2}}{\omega_{c}^{2}\omega_{i}^{2}} + \frac{2\mu_{b}\omega_{z}S_{z}k_{1}^{2}}{\delta_{q}\omega_{i}^{2}h} \right\} - \frac{\omega_{s}}{m\omega_{z}^{2}h^{2}\omega_{i}^{2}(h + 2\mu_{b}\omega_{i}^{4}(B_{s})^{2})} \left( e^{2i(k_{z}z - \omega_{z}t)} \right) \phi_{o}, \\
\end{align*}
\]

and

\[
\begin{align*}
\tilde{J}_{z} = \tilde{J}_{c_{z}} + \tilde{J}_{d_{z}},
\end{align*}
\]

Using Maxwell’s equation and the current density component from equations (18) and (19), we get the governing wave equations for the Raman scattered wave,

\[
\begin{align*}
[A_{1}] & = [B_{1}]E_{1z} = [C_{1}]\phi_{o}, \\
[A_{2}] & = [B_{2}]E_{1z} = [C_{2}]\phi_{o},
\end{align*}
\]

where,

\[
A_{1} = \begin{bmatrix}
\omega_{c}^{2} - \frac{\omega_{c}^{2}}{c^{2}} - \frac{\omega_{p}^{2}}{c^{2}} \left( 1 + \frac{m\omega_{c}K_{q}k_{1}^{2}}{\omega_{i}\delta_{q}} + \frac{2\mu_{b}\omega_{s}S_{s}k_{1}^{2}}{\delta_{q}\omega_{i}^{2}h} \right) - \frac{4iS_{s}m\omega_{c}^{2}\omega_{p}k_{1}^{2}\mu_{b}^{2}}{e^{2}h^{2}\omega_{i}^{2}} \\
\end{bmatrix}
\]

\[
B_{1} = \begin{bmatrix}
\frac{1}{c^{2}} \left( 1 - \frac{\omega_{c}^{2}}{\omega_{i}^{2}} \right) \left\{ -\frac{\omega_{c}}{\omega_{i}} + \frac{mK_{q}k_{1}^{2}}{\omega_{c}^{2}\omega_{i}^{2}} + \frac{2i\mu_{b}\omega_{s}^{2}k_{1}^{2}}{\delta_{q}\omega_{i}^{2}h} \right\} \\
\end{bmatrix}
\]
The quantum terms contribute to

\[ C_1 = \left[ \frac{i \omega_1 S_n B_0 k_o k^2 \mu_B^2}{m c^2 \hbar^2 \omega_1^3 (\hbar + 2 \mu_B \omega_1^2 (B_0))^2} \left( e^{\frac{2i(k_o z - \omega_1 t)}{c}} \right) \right] \]

\[ A_2 = \left[ -\frac{1}{c^2} \omega_p \omega_1^2 \left( 1 - \frac{\omega_p^2}{\omega_1^2} \right) \left( \frac{m K_q k_1^2}{\omega_q \delta_q} + \frac{2 \mu_B S_o k_1^2}{e \omega_1 \hbar \delta_q} \right) - \frac{4i S_q n_o \omega_p^2 k_1^2 \mu_B^2}{e^2 \hbar^2 \omega_1^4} \right] \]

\[ B_2 = \left[ -\frac{\omega_1^2}{c^2} \omega_p \omega_1^2 \left( 1 - \frac{\omega_p^2}{\omega_1^2} \right) \left( \frac{m K_q k_1^2}{\omega_q \delta_q} + \frac{2 \mu_B S_o k_1^2}{e \omega_1 \hbar \delta_q} \right) \right] \]

and

\[ C_2 = \left[ \frac{i \varepsilon_o \omega_v k^2 (v^{(2)})^2}{2 c^2} \right] \]

Combining the equations (16), (20) and (21), we get the nonlinear dispersion relation for the coupling of second harmonic pump and decay wave as,

\[
\begin{align*}
\left( k_1^2 - \frac{\omega_1^2}{c^2} \right) & \left( 1 - \frac{\omega_p^2}{\omega_1^2} \right) \left\{ \frac{m \omega_e K_q k_1^2}{\omega_q \delta_q} + \frac{2 \mu_B S_o k_1^2}{\delta_q e \omega_1} \right\} - \frac{4i S_q m \omega_p^2 k_1^2 \mu_B^2}{e^2 \hbar^2 \omega_1^4} \\
& = B_1 \times \left\{ (C_2 \times A) - (A_2 \times C) \right\}
\end{align*}
\]

(22)

where,

\[
R = \left\{ \frac{i \omega_1 \alpha \omega_p^2 k_1^2 (m \chi_4 - K_q \chi_3) (\omega_1^2 - \omega_p^2) v^{(2)}}{2 k_0 c^2 \left( \omega_1^2 - \omega_p^2 \right) \left( \omega^2 - \omega_e^2 - \omega_p^2 \right)} \right\} + \frac{\omega_p^2}{c^2} \left( 1 - \frac{\omega_p^2}{\omega_1^2} - \omega_e^2 \right) \left\{ \frac{i K_q k_1^2}{e \omega_1 \delta_q} \right\} + \frac{2i \mu_B S_o k_1^2}{\hbar \omega_1 \delta_q} \right\}.
\]

4. Discussion

A model for excitation of Raman shifted harmonic electromagnetic waves in plasma has been formulated using the recently developed quantum hydrodynamic (QHD) model. The effects of quantum statistical pressure, the Bohm potential and the electron spin have been taken in to account. The applied static field is responsible for the transverse velocity attained by the electrons and for dispersion of the Raman shifted harmonic backscattered wave. The dispersion relation contains the term due to the interaction of electron quiver velocity with the constant magnetic field under the influence of electron’s spin and ponderomotive force exerted by the radiation field on plasma electrons under the influence of electron spin and other quantum effects. The quantum terms contribute to diffraction and results in an increase in dispersion. The second harmonic backscattering can be employed as a diagnostic tool for the presence of transverse static magnetic field in laser produced quantum plasma and also to study the properties of excited plasma wave in various experiments.
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