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Research Article

Quantum Treatment of Kinetic Alfvén Waves Instability in a Dusty Plasma: Magnetized Ions

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Kinetic Alfvén wave instability is examined rigorously in a uniform nondegenerate quantum dusty plasma. A linear dispersion relation of kinetic Alfvén wave in inertial regime is derived by incorporating Bohm potential in the linearized Vlasov model. It is found that the quantum correction C_Q appears due to the insertion of Bohm potential in Vlasov model and causes the suppression in the Alfvén wave frequency and the growth rates of instability. A number of analytical expressions for various modes of propagation are derived. It is also found that the system parameters, that is, streaming velocity, dust charge, number density, and quantum correction, significantly influence the dispersion relation and the growth rate of instability.

1. Introduction

Theoretical and laboratory studies on current-driven electromagnetic instabilities have been a popular subject in plasma research [1, 2]. Electromagnetic and electrostatic plasma instabilities driven by the parallel or cross-field currents give rise to narrow banded spontaneous emissions and have received a lot of attention in the past few decades. It has been speculated that low frequency electromagnetic waves, that is, Alfvén waves, are the most important electromagnetic waves which take part in various dynamical processes occurring in the interior of the sun [3–5]. Recently, kinetic Alfvén waves (KAWs) have been modified via quantum effects associated with electrons; for example, Hussain et al. [6] made an attempt to study spin and nonrelativistic quantum effects on KAWs within the frame work of kinetic theory of Alfvén waves and their analysis suggested that the spin quantum effects suppress the Alfvén wave frequency in a hot and magnetized plasma.

Usually, for quantum effects to be significant in plasma, the temperature to density ratio is considered to be quite small. The quantum effects are expected to be significant on very small scales, where debye length $\lambda_D = \sqrt{kT/4\pi ne^2}$ and gyroradius ρ_j should be smaller or of the order of the de Broglie wavelength $\lambda_{DB} = \hbar/\sqrt{2\pi m_j kT}$. At such small scales the quantum kinetic theory is better suited for the proper treatment of these microphenomena. To study various aspect of quantum plasma, numerous efforts have been made whose applications are ranges from plasmonic device applications to dense astrophysical plasmas [7–16].

Recently, various researches have been performed to study the collective effects in a quantum plasma. In these investigations, the researchers have focused on the linear dispersion effects of several low frequency modes and instabilities as a benchmark problem in quantum plasma. It has been treated by means of Bohm diffraction or quantum statistical effects that include the Fermi pressure [17]. Various fluid plasma models have been developed by introducing the quantum effects through quantum corrections. This can be done either through the quantum force produced by density fluctuations originating from the Bohm potential or through the spin of particles which includes the magnetic dipole force and magnetization energy. At large scales, plasma is treated as an electrically conducting fluid and can be described by magnetohydrodynamics, while the situation has to be interpreted within the frame work of kinetic theory when microscopic scales are involved. The proper treatment of such phenomena requires the development of kinetic theory based on quantum effects [18]. The presence of dust particles is known to significantly alter the electrostatic and electromagnetic modes [19–23]. This is due to the fact that their presence gives rise to some novel modes associated with dust particle dynamics and finite divergence of the cross-field plasma current density. More recently, Mahdavi and Azadboni investigated the nondegenerate quantum effects on Weibel instability by considering its application in the absorption layer of fuel pallet. In their study, the thermal energy was taken larger than the potential and Fermi energy by taking the quantum effects negligibly small and showed that nondegenerate quantum effects and density gradients tend to stabilize the Weibel instability [24].

In this paper, we have made an effort to examine the role of quantum diffraction associated with electrons in a dense, hot, and magnetized plasma and its effect on low frequency modes. We discuss the characteristics of short wavelength dust kinetic Alfvén waves by emphasizing the quantum diffraction effects arising through Bohm potential of electrons, which is obviously dominant over the ions and the dust species due to large mass difference. The dispersion relation of quantum DKAW (QDKAW) is derived by incorporating Bohm quantum potential into the linearized Vlasov equation. Also, the coupling of electrostatic quantum dust acoustic mode (QDAW) with kinetic Alfvén wave (KAW) and the theoretical aspect of KAW instability in an inertial regime is discussed.

The manuscript is organized as follows: basic assumptions leading to the general dispersion relation are presented in Sections 2 and 3 while results and conclusions are discussed in Section 4.

2. Basic Assumptions

We consider an electromagnetic kinetic Alfvén wave in a collisionless electron-ion quantum dusty plasma. The strongly magnetized ions are considered to be Maxwellian and a beam of nondegenerate electrons drifting across an external magnetic field ($\mathbf{B}_0 \parallel \hat{z}$) with constant ion drift velocity, $V_0\hat{x}$, that is, $V_0 \perp \mathbf{B}_0$, while the dust component is cold and unmagnetized. The plasma beta β_i is assumed to be very small, that is, $\beta_i \ll 1$, where $\beta_i = 4\pi n_{i0}T_t/B_0^2$. An electromagnetic wave with a wave vector $\mathbf{k}$ lies in xz plane, $\mathbf{k} = k_\perp\hat{x} + k_\parallel\hat{z}$, making angle θ with x-plane. We have adopted two potential representations which are used in a low beta plasma to express the electromagnetic perturbations to describe the electric field $\mathbf{E}$, that is, $E_\perp = -\nabla_\perp\varphi$ and $E_\parallel = -\nabla_\parallel\psi$, where $\varphi \neq \psi$.

The linearized Poisson equation is

$$-\left(k_\perp^2\varphi + k_\parallel^2\psi\right) = 4\pi e\left[n_{e1} - n_{i1} - Z_{d0}n_{d1}\right], \quad (1)$$

where n_{e1}, n_{i1}, and n_{d1} are electron, ion, and dust number densities, respectively. In (1) $Z_{d0} = -Q_{d0}/e$ (with Z_{d0} as the number of electron charge on a grain) is the equilibrium charge on an average dust grain and e is the electron charge. For electromagnetic waves, we may ignore the dust charge fluctuation effects, that is, $Z_{d1} = 0$, [25, 26], as it causes damping (non-Landau type) which is relevant for electrostatic waves. Now, on combining Ampere's and Faraday's law, we get [27]

$$c^2k_\perp^2k_\parallel(\varphi - \psi) = 4\pi\omega\left[J_{i1\parallel} + J_{d1\parallel}\right], \quad (2)$$

where $J_{j1\parallel}$ represent the field aligned current densities for plasma species. Since the electrons are streaming perpendicular to the field direction, therefore, $J_{e1\parallel} = 0$. The linearized Vlasov equation for quantum plasma after incorporating Bohm quantum potential in the direction of field will obtain the following:

$$\frac{\partial f_{e1}}{\partial t} + v_\parallel\frac{\partial f_{e1}}{\partial z} + \left[\frac{q_e}{m_e}E_z + \frac{\hbar^2}{4m_e^2n_0}\nabla\nabla^2 n_{e1}\right]\frac{\partial f_{e0}}{\partial v_\parallel} = 0. \quad (3)$$

The perturbed distribution function of streaming electrons is given by the aid of Vlasov equation and the zeroth order distribution function f_{e0}, which is the usual distribution function and is assumed to obey a Maxwellian or a Fermi Dirac distribution.

$$f_{e0} = A_e\exp\left(\frac{v_\parallel^2 + (v_\perp - V_0)^2}{v_{te}^2}\right), \quad (4)$$

where

$$A_e = n_{e0}\left(\frac{m_e}{2\pi T_e}\right)^{3/2}. \quad (5)$$

Since the ions are hot and magnetized with finite Larmor radius effects, therefore, we can solve Vlasov equation in terms of guiding center coordinates by ignoring quantum effects and obtain the perturbed distribution for any electromagnetic wave, [28, 29],

$$f_{i1} = \left(\frac{n_{i0}e}{T_i}\right)\sum_l\sum_n\frac{k_\parallel v_\parallel\psi + n\Omega_{ci}\varphi}{\omega - n\Omega_{ci} - k_\parallel v_\parallel}\exp\left(i(n-l)\theta\right) \cdot J_n\left(\frac{k_\perp v_\perp}{\Omega_{ci}}\right)J_l\left(\frac{k_\perp v_\perp}{\Omega_{ci}}\right)f_{i0}, \quad (6)$$

where f_{i0} is the equilibrium Maxwellian distribution function for electrons, Ω_{ci} is the electron cyclotron frequency, and J_n is the Bessel function of first kind of order n.

3. Basic Theory and Dispersion Relation

The perturbed number density for electrons including nondegenerate quantum effects has been recast by the aid of Vlasov equation and is determined by the relation $n_{e1} = \int f_{e1}d\mathbf{v}$ as

$$n_{e1} = \frac{2en_{e0}\varphi}{m_ev_{te}^2}\left(\frac{1 + \eta Z(\eta)}{1 + C_Q\left(1 + \eta Z(\eta)\right)}\right), \quad (7)$$

where $C_Q = \hbar^2k^3/4m_e^2v_{te}^2k_\parallel$, which shows the quantum correction in the number density of electrons and $Z(\eta)$ is the plasma dispersion function for cross-field streaming nondegenerate electrons [30] with argument $\eta = (\omega - k_\perp V_0)/k_\perp v_{te}$.

By using (6), the number density of hot and magnetized ions is

$$n_{i1} = -\frac{n_{i0}e}{m_i}\frac{1}{k_\parallel v_{ti}^2} \cdot \sum_n \left[k_\parallel v_{ti}\psi\left(1+\xi_{in}Z\left(\xi_{in}\right)\right) + n\Omega_{ci}\varphi Z\left(\xi_{in}\right)\right] I_n\left(b_i\right) e^{-b_i}, \quad (8)$$

where I_n is the modified Bessel function with argument $b_i = k_\perp^2 v_{ti}^2/2\Omega_{ci}^2$ and $Z(\xi_{in})$ is the usual dispersion function for a Maxwellian plasma with $\xi_{in} = (\omega - n\Omega_{ci})/k_\parallel v_{ti}$.

The perturbed number density of cold and unmagnetized dust grains by using hydrodynamic model is as follows:

$$n_{d1} = \frac{n_{d0}Q_{d0}}{m_d\omega^2}\left(k_\perp^2\varphi + k_\parallel^2\psi\right). \quad (9)$$

Since the nondegenerate electrons are streaming along the x-direction, therefore the longitudinal component of current density perturbation is taken to be zero; that is, $J_{e1\parallel} = 0$. The parallel components of current density for ions and dust species are

$$J_{i1\parallel} = -\frac{n_{i0}e^2}{T_i k_\parallel}\sum_n \left[\left(1+\xi_{in}Z\left(\xi_{in}\right)\right)\left(k_\parallel v_{ti}\xi_{in}\psi + n\Omega_{ci}\varphi\right)\right] \cdot I_n\left(b_i\right)e^{-bi},$$
$$J_{d1\parallel} = \frac{n_{d0}Q_{d0}^2}{m_d\omega}k_\parallel\psi. \quad (10)$$

Using the explicit expressions of n_{e1}, n_{i1}, and n_{d1} in (1) and $J_{i1\parallel}$, $J_{e1\parallel}$, and $J_{d1\parallel}$ in (2) allows obtaining the following system of equations:

$$A\varphi + B\psi = 0,$$
$$C\varphi + D\psi = 0, \quad (11)$$

where

$$A = k_\perp^2 + \frac{2\omega_{pe}^2}{v_{te}^2}\left(\frac{1+\eta Z(\eta)}{1+C_Q(1+\eta Z(\eta))}\right) + \frac{n\omega_{ci}}{k_\parallel}Z\left(\xi_{in}\right)I_n\left(b_i\right)e^{-b_i} + k_\perp^2\frac{\omega_{pd}^2}{\omega^2},$$
$$B = k_\parallel^2 + \frac{2\omega_{pi}^2}{v_{ti}^2}\left(1+\xi_{in}Z\left(\xi_{in}\right)\right)I_n e^{-b_i} - k_\parallel^2\frac{\omega_{pd}^2}{\omega^2}, \quad (12)$$
$$C = c^2 k_\parallel k_\perp^2 + \frac{2\omega_{pi}^2}{v_{ti}^2}\frac{n\omega\Omega_{ci}}{k_\parallel}\left(1+\xi_{in}Z\left(\xi_{in}\right)\right)I_n e^{-b_i},$$
$$D = k_\parallel\left(k_\perp^2c^2 + \omega_{pd}^2\right) - \omega\frac{1}{\lambda_{Di}^2}\sum_n\frac{v_{ti}}{2}\xi_{in}Z'\left(\xi_{in}\right)I_n e^{-b_i}.$$

And by eliminating φ and ψ from the homogeneous equation (11), the dispersion relation reduces to

$$AD - BC = 0, \quad (13)$$

which, after substituting the values of A, B, C, and D from (12) into (13), and some simple algebra, is given by

$$1 + \frac{2\omega_{pi}^2}{k_\parallel^2 v_{ti}^2}\sum_n\left[\left(1+\frac{\omega_{pd}^2}{k_\perp^2c^2}\right)\frac{n\Omega_{ci}}{k_\parallel v_{ti}}Z\left(\xi_{in}\right)I_n e^{-b_i} + \left(1+\xi_{in}Z\left(\xi_{in}\right)\right)I_n e^{-b_i}\right] + \frac{2\omega_{pe}^2}{k_\parallel^2 v_{te}^2}\left[\left(1-\frac{\omega_{pd}^2}{k_\perp^2c^2}\right) \cdot \left(\frac{1+\eta Z(\eta)}{1+C_Q(1+\eta Z(\eta))}\right)\right] + \left(1+\frac{\omega_{pd}^2}{k_\perp^2c^2}\right)\frac{k_\perp^2}{k_\parallel^2}\left(1 - \frac{\omega_{pd}^2}{\omega^2}\right) = 0 \quad (14)$$

and represents the general dispersion relation of KAW streaming instabilities in a quantum dusty plasma. In the limit $\omega_{pd}^2/k_\perp^2c^2 \ll 1$, we get the dispersion relation of modified two stream instabilities in a dusty plasma [31] and in a dust-free plasma the instability results are as in classical plasma [32].

When the free energy associated with streaming is increased, that is, $V_0 \gg v_{te}$, the maximum growth rates also continue to increase and the dispersion equation for all plasma components becomes nonresonant ($\xi_{in,e} > 1$). The unstable mode in a nonresonant regime is typically known as fluid instability. In the cold plasma limit,

$$A = \frac{k_\perp^2 f_i}{\omega^2}\left(\omega^2 - \omega_{dlh}^2 - \frac{\omega^2\omega_{pe}^2/f_i}{\left(\omega - k_\perp V_0\right)^2 - C_Q k_\perp^2 v_{te}^2}\right),$$
$$B = k_\perp^2 f_i - k_\parallel^2\frac{\omega_{pd}^2}{\omega^2}, \quad (15)$$
$$C = c^2 k_\parallel k_\perp^2,$$
$$D = -k_\parallel\left(k_\perp^2c^2 + \omega_{pd}^2\right),$$

where $\omega_{dlh}^2 = (\omega_{pd}^2\Omega_{ci}^2)/\omega_{pi}^2$ and $f_i = \omega_{pi}^2/\Omega_{ci}^2$.

Thus, from the dispersion relation (13), we obtain a biquadratic equation for ω in terms of various plasma parameters:

$$a\omega^4 + b\omega^3 + c\omega^2 + d\omega + e = 0, \quad (16)$$

where

$$a = \alpha + k_\perp^2c^2,$$
$$b = -2k_\perp^3 V_0 c^2 - 2k_\perp V_0\alpha - 2k_\parallel^2 V_{Ai}^2 k_\perp V_0,$$
$$c = \left(-\omega_{dlh}^2 - k_\parallel^2 V_{Ai}^2 C_Q - C_Q - k_\perp^2 V_0^2 - \frac{\omega_{pe}^2}{f_i}\right)\alpha - k_\parallel^2 V_{Ai}^2\omega_{pd}^2 - C_Q k_\perp^2 c^2 - k_\perp^4 c^2 V_0^2, \quad (17)$$
$$d = 2k_\perp V_0\omega_{dlh}^2\alpha + 2k_\parallel^2 V_{Ai}^2 k_\perp V_0\omega_{pd}^2,$$
$$e = \left(C_Q - k_\perp^2 V_0^2\right)\omega_{dlh}^2\alpha - k_\parallel^2 k_\perp^2 V_0 V_{Ai}^2\omega_{pd}^2,$$

where $\alpha = k_\perp^2c^2 + \omega_{pd}^2$.

In the absence of streaming electrons the solution of (16) is given by

$$\omega^2 = \omega_{dlh}^2 + 2C_Q + \frac{k_\parallel^2 V_{Ai}^2}{(1 + k_\perp^2 \lambda_d^2)}, \quad (18)$$

which is quantum corrected low frequency shear Alfvén wave in a dusty plasma, where $V_{Ai} = B_0/\sqrt{4\pi n_{i0} m_i}$ is the Alfvén speed and $\lambda_d = c/\omega_{pd}$ is the dust skin depth. In the limit $C_Q = 0$, we obtain the dispersion relation of KAW in inertial regime; that is, $\omega^2 = \omega_{dlh}^2 + k_\parallel^2 V_{Ai}^2/(1 + k_\perp^2 \lambda_d^2)$. When $C_Q = 0$, $k_\perp^2 \lambda_d^2 \ll 1$, we get the dust-modified dispersion relation of shear Alfvén waves, that is, $\omega^2 = \omega_{dlh}^2 + k_\parallel^2 V_{Ai}^2$, which is a natural mode of any dusty magnetoplasma and ω_{dlh}^2 provides constraint for the electromagnetic wave propagation. Our analysis also indicates that cross-field streaming effects are not coupled with perpendicular wavenumber but appear as an additional term in the dispersion relation. The reason may be the absence of $J_{e\parallel}$ due to streaming in cross-field direction and the Bohm potential induced Vlasov model. It is therefore tempting to introduce quantum correction which may significantly modify the classical modes and related instabilities.

In order to observe the effect of dust grains on the wave in a low beta plasma, the limiting case of $k_\perp^2 \lambda_d^2 \gg 1$ can be obtained from (18) in the form

$$\omega^2 = \omega_{dlh}^2 + \Omega_i \Omega_d \left(\frac{n_{d0} Z_d}{n_{i0}}\right) \frac{k_\parallel^2}{k_\perp^2}. \quad (19)$$

The second term on R.H.S can be recognized as the convective cell frequency which strongly depends on dust parameters. It can be recognized that dust inertia may play a major role in the wave dynamics, while the stationary dust excludes this mode. The heavy dust grains can be an important factor in diminishing the effect of wave frequency and unstable regions of propagation.

4. Results

In the presented work, we have investigated the cross-field streaming instability and dispersion propertied of KAW due to nondegenerate electrons in a quantum dusty magnetoplasma. We have derived the KAW instability growth rates using various parameters close to dense astrophysical plasma, that is, $n_e = 10^{26}$, $n_i = 1.001\times10^{26}$, $Z_d = 10^3$, $n_{d0} = 0.3\times10^{23}$, and $B_0 = 10^{13}$ G [33]. The influence of quantum Bohm potential is found to act against the KAW instability, while classical effects reinforce the unstable regions, as depicted in Figure 1. The cross-field nondegenerate electron beam streaming with velocity V_0 helps in the growth of unstable regions and a further increase inhibits the stabilization which maintains the wave amplitude as illustrated in Figure 2. It has also been observed that quantum parameter C_Q is inclined to suppress the instability. In Figure 3, we can observe that the growth rates are enhanced with the increase in number density, followed by increase in cross-filed ion streaming velocity. Physically, when the dust concentration is increased, it also enhances the depletion of electrons due to attachment to the dust grain surface, which in turn increases the streaming velocity and ultimately is responsible for the excitation of an electromagnetic wave. The role of dust charge is also found to enhance the wave activity which can be seen in Figure 4. Our results indicate that KAWs in inertial regime are less affected by the Bohm potential effects and hence C_Q appears to suppress the Alfvén wave frequency in a hot and magnetized nondegenerate quantum plasma which is evident from Figure 5.

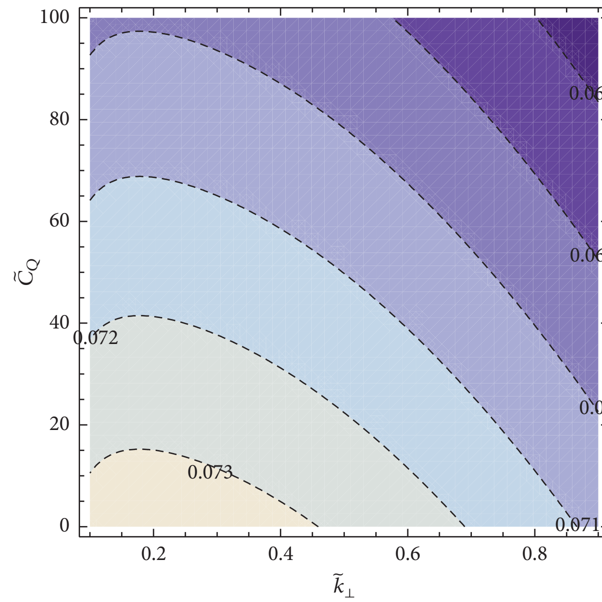

Figure 1: Contour plots between $\tilde{k}_\perp$ and C_Q for $V_0 = 10$, $Z_d = 10^3$, and $n_d = 10^{-8} n_i$.

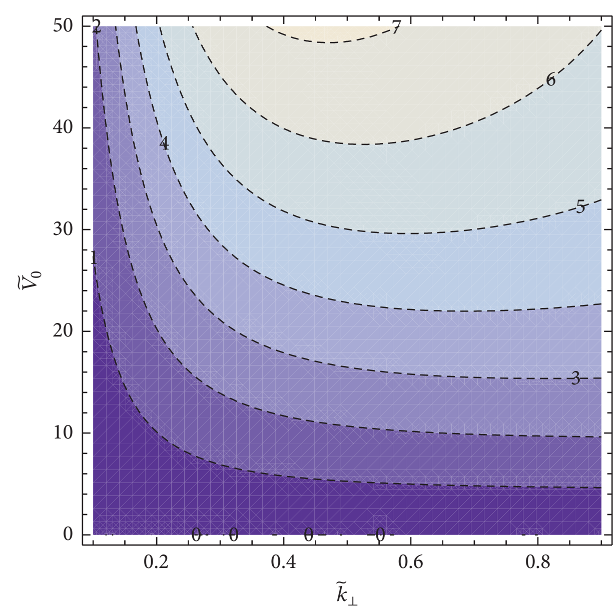

Figure 2: Contour plots between $\tilde{k}_\perp$ and V_0 for $C_Q = 10$, $Z_d = 10^3$, and $n_d = 10^{-8} n_i$.

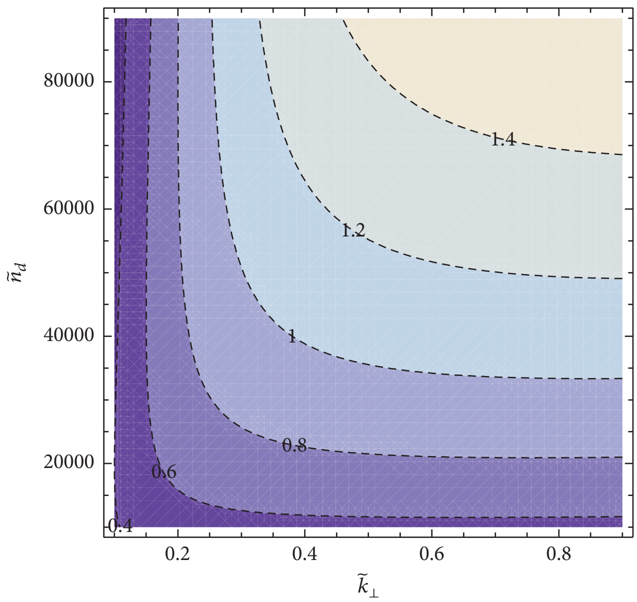

FIGURE 3: Plots between $\tilde{k}$ and n_d for $V_0 = 10$, $C_Q = 10$, and $Z_d = 10^3$.

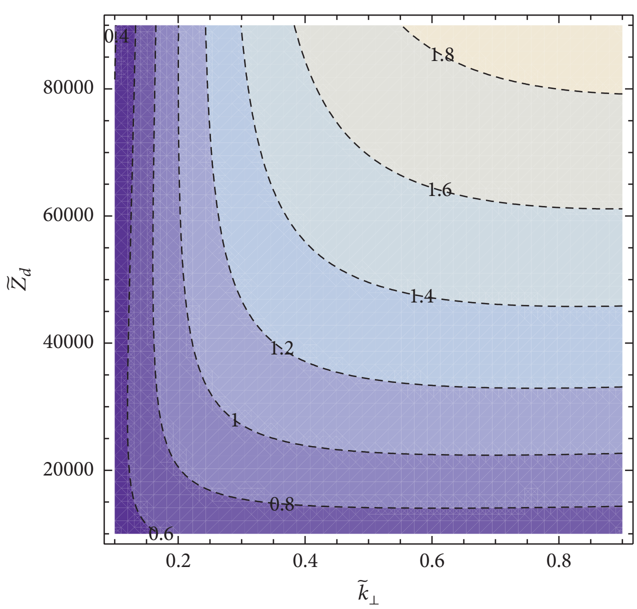

FIGURE 4: Effect of Z_d on the dispersion characteristics.

To summarize, we have investigated the effects of quantum contribution on the growth and dispersion of low frequency kinetic Alfvén wave in inertial regime by using Vlasov-Maxwell equations. We have neglected the quantum effects of ions as they are heavier than electrons. It is found that quantum effects suppress the instability in a hot and magnetized plasma. The density fluctuations are not accompanied by pure electromagnetic nonstreaming dense plasma; therefore, applying quantum corrections makes sense to electromagnetic waves when density fluctuations are involved especially in the inertial turbulent range. We therefore have

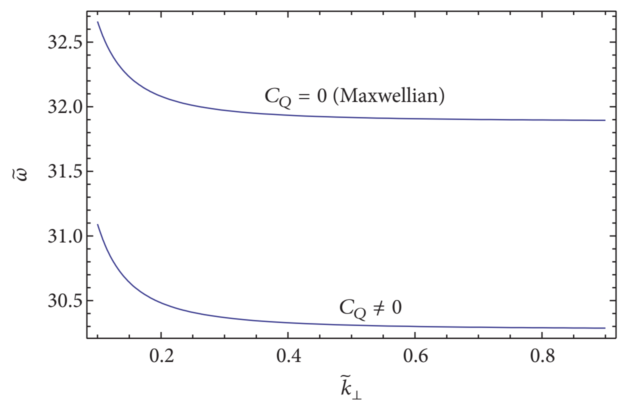

FIGURE 5: Effects of C_Q on the real part of the dispersion relation.

recast the perturbed nondegenerate electron density which has a strong dependence on quantum correction parameter C_Q. Our analysis is based on linear approximation and we believe that we have contributed to the analysis of KAWI in a nondegenerate quantum plasma and there is a large set of nonlinear investigations which should be addressed. The present analysis could be applied to dense astrophysical streaming and ICF plasmas where quantum diffraction effects are nonnegligible and significant.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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