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EFFECT OF QUANTUM PARAMETER–H ON LONGITUDINAL ELECTRO–KINETIC WAVE CHARACTERISTICS IN MAGNETISED SEMICONDUCTOR PLASMA

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ABSTRACT

Using quantum hydrodynamic model, linear characteristics of longitudinal electro-kinetic wave have been studied both analytically and numerically, in one component magnetised dense semiconductor quantum plasma in which quantum effects are incorporated through non-dimensional quantum parameter-H. It is shown that presence of magnetic field modifies the linear dispersion characteristics of longitudinal electro-kinetic wave and the quantum parameter-H makes the excitation of two novel modes possible whereas the combine presence of quantum parameter-H and magnetostatic field induce four novel modes of propagation. The structure of the modes of longitudinal electro-kinetic wave is shown to be significantly affected by the quantum parameter-H and applied magnetostatic field.

KEYWORDS: Quantum hydrodynamic model, Quantum parameter-H, Magnetised semiconductor plasma, Longitudinal electro-kinetic wave

INTRODUCTION

During the period of last ten-fifteen years, several intense studies of quantum phenomena in plasma have been conducted [1-3] which enable them efficient enough to occupy one of the central places in plasma physics. Classical effects are considered in plasma when it is characterized by the regimes of high temperature and low density where quantum effects have virtually no impact. But when plasma tends to be described by the properties of low temperature and high density, then the thermal deBroglie wavelength of electrons may become comparable to the inter-particle distances. In such situations quantum effects in plasmas dominate over the classical plasma phenomenon. In quantum plasmas where the electron Fermi energy is of many order higher than their thermal energy, the statistical behaviour of plasma particles should be considered and should be described by appropriate statistical distribution. Such quantum plasma has approached a stormy development in the recent years owing to its wide potential applications found in a variety of environments such as metal nanostructures, astrophysical system, ultra small electronic devices, biophotonics, neutron stars, laser produced plasmas, quantum wells, quantum diodes and semiconductor devices etc. [4-12].

Semiconductor devices are emerged as the most bewildering possible application of quantum plasma. Frequency limits, which for years appeared to be a hindrance for the development of semiconductor devices, have during this period been varied by orders of magnitude by the inclusion of quantum effects. One can well consider this as a revolutionary achievement. Hence the concept of semiconductor quantum plasma becomes valid and sensible in the development of new telecommunication opto-electronic devices.

The study of advantages of quantum effects in semiconductor plasmas requires new mathematical model or empirical modifications to the traditional plasma fluid model. An embracing model was prepared for quantum plasma which is subsequently named as quantum hydrodynamic (QHD) model after the pioneering works of Manfredi and Hass [4,13]. In QHD model, the quantum effects are precisely described by quantum diffraction and quantum statistics. The former effects, which is also alternatively interpreted as Bohm potential, is represented by the terms proportional to $\hbar^2$, whereas the later effect, known as Fermi degenerate pressure, takes into account the fermionic character of electrons. Many literature have been reported where quantum corrections incorporating Bohm potential only, is valid for low density quantum plasma [14-

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15]. In the same space, many authors have considered high density quantum plasma in their reports including quantum effects pertaining to Fermi degenerate pressure [16-18]. But very few authors have reported the quantum effects skilfully combined by the both i.e. Bohm potential and Fermi degenerate pressure [19-20]. It is useful to consider the aggregation of effects of Bohm potential and Fermi degenerate pressure through a non-dimensional quantum parameter-H which is proportional to the ratio between plasma energy and Fermi energy. The analysis of impact of quantum parameter-H on the plasma wave spectrum in semiconductor plasma have become a new domain of specializing physicists and device manufacturers because it plays a decisive role in the modification and/or generation of modified as well as new modes of plasma waves.

A wide range of literature has recently been published on the physics of plasma wave instabilities in semiconductor quantum plasmas [21-22], but hardly any concise treatments based on non-dimensional quantum parameter-H are available. Hence inspired by the above status in the present paper, authors considered quantum effects through quantum parameter-H and reported the analysis of modified nature obtained in convective instability of longitudinal electro-kinetic wave (LEKW) in semiconductor plasma medium under the specific geometry of externally applied electric and magnetic fields. Authors found that the presence of quantum correction induces two new modes whereas combined presence of quantum correction and externally applied magnetostatic field induce another two new modes of propagation compared to the classical case.

THEORETICAL FORMULATION

To meet out the aim established in introduction section, here authors have considered a homogeneous n-type semiconductor medium subjected to a d.c. electric field $\vec{E}_0$ along z-direction which is also the direction of wave propagation. The medium is also subjected to a externally applied magnetostatic field $\vec{B}_0$ along xz-plane inclined to an arbitrary angle θ with z-axis. To derive the dispersion relation we have considered that all the perturbations vary as $\exp[i(\omega t - kz)]$. Authors have used the QHD model for the derivation and the one dimensional continuity and momentum transfer equations of the QHD model, are given below

$$\frac{\partial n_1}{\partial t} + n_0 \frac{\partial \vec{V}_1}{\partial z} = 0 \qquad \text{-----------} (1)$$

$$\frac{\partial \vec{V}_1}{\partial t} + \vec{V}_0 \frac{\partial \vec{V}_1}{\partial z} + \nu \vec{V}_1 + \vec{V}_1 \times \vec{\omega}_c = \frac{-q}{m}\left(\vec{E}_1\right) + \frac{ikV_F^2 n_1}{n_0}\left(1 + \Gamma H^2\right) \qquad \text{-----------} (2)$$

Each electron in this medium have mass m, charge $(-q)$, total number density n with its equilibrium value n_0, Fermi velocity V_F, momentum transfer collision frequency ν, drift velocity V_0 due to electrostatic field E_0 and $\omega_c (= qB_0/m)$ electron cyclotron frequency due to magnetostatic field B_0. $\Gamma = \frac{k^2 V_F^2}{4\omega_p^2}$ and $H = \frac{\hbar \omega_p}{2K_B T_F}$ are the quantum parameters in which $\hbar$ is Planck's constant divided by 2π, $\omega_p = \sqrt{q^2 n_0 / m\varepsilon}$ is plasma frequency with $\varepsilon (= \varepsilon_0 \varepsilon_L)$; ε_L being the lattice dielectric constant and $V_F^2 = 2K_B T_F / m$ with Boltzmann constant K_B and T_F Fermi temperature .

Following the procedure of Steele and Vural [23], authors obtained the general dispersion relation for LEKW in magnetised semiconductor quantum plasma in terms of quantum parameter-H as

$$\varepsilon(\omega, k) = 1 - \frac{\omega_p^2 \left[\left\{ (\omega - kV_0 - i\nu)^2 - \omega_{cz}^2 \right\} + \frac{k^2 V_F^2}{\omega_p^2}(1 + \Gamma H^2) \left\{ (\omega - kV_0 - i\nu)^2 - \omega_{cz}^2 - \omega_{cx}\omega_{cz} - i\omega_{cx}(\omega - kV_0 - i\nu) \right\} \right]}{(\omega - kV_0)(\omega - kV_0 - i\nu)\left\{ (\omega - kV_0 - i\nu)^2 - \omega_c^2 \right\}} = 0 \qquad \text{-----------} (3)$$

If one assumes the above dispersion relation in absence of magnetic field and quantum effects i.e. $(\vec{B}_0 = H = 0)$, the earlier result derived in equation (4-35) of Ref. [23] can be retrieved from equation (3). Hence it may be inferred that the above dispersion relation is significantly modified by magnetic field and quantum parameter-H.

It is clear from the definition of quantum parameter-H that if we increase the magnitude of plasma frequency which automatically increases the magnitude of quantum parameter-H, then interestingly spatial modifications occur in the

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observed plasma oscillations. Hence it becomes important to study the behaviour of convective instability of LEKW under the influence of non-dimensional quantum parameter-H particularly in

presence of $\vec{B}_0$. For this purpose we recast the above derived dispersion relation in the following polynomial

$$A_6k^6 + A_5k^5 + A_4k^4 + A_3k^3 + A_2k^2 + A_1k + A_0 = 0 \qquad \text{--------(4)}$$

where

$$A_6 = \left(-\frac{H^2V_F^4}{4\omega_p^2}\right)V_0^2$$

$$A_5 = (2\omega V_0 - i\omega_{cx}V_0 - 2i\nu V_0)\left(\frac{H^2V_F^4}{4\omega_p^2}\right)$$

$$A_4 = V_0^4\left(1-\frac{V_F^2}{V_0^2}\right) + (i\omega_{cx}\omega + \omega_{cx}\nu + \omega_{cx}\omega_{cz} - \omega^2$$

$$+\nu^2 + 2i\nu\omega + \omega_{cz}^2)\left(\frac{H^2V_F^4}{4\omega_p^2}\right)$$

$$A_3 = (3i\nu - 4\omega)V_0^3 + (2\omega V_0 - i\omega_{cx}V_0$$

$$-2i\nu V_0)V_F^2$$

$$A_2 = (6\omega^2 - 9i\nu\omega - 3\nu^2 - \omega_c^2 - \omega_p^2)V_0^2$$

$$+(i\omega_{cx}\omega + \omega_{cx}\nu + \omega_{cx}\omega_{cz} - \omega^2 + \nu^2 + 2i\nu\omega + \omega_{cz}^2)V_F^2$$

$$A_1 = (9i\nu\omega^2 - 4\omega^3 + 6\nu^2\omega + 2\omega_c^2\omega - i\nu^3$$

$$-i\nu\omega_c^2 + 2\omega\omega_p^2 - 2i\nu\omega_p^2)V_0$$

$$A_0 = (\omega^4 - 3\omega^2\nu^2 - 3i\nu\omega^3 - \omega_c^2\omega^2 + \omega_{cz}^2\omega_p^2$$

$$+i\nu^3\omega + i\nu\omega\omega_c^2 - \omega_p^2\omega^2 + \nu^2\omega_p^2 + 2i\nu\omega\omega_p^2)$$

From the above polynomial one may infer that in presence of quantum term H and magnetostatic field $\vec{B}_0$, six modes of propagation are possible. In the absence of externally applied magnetic field $(\vec{B}_0 = 0, H \neq 0)$, authors obtain only four modes of propagation. On the other hand when $\vec{B}_0 \neq 0$ and $H = 0$ again authors get four possibilities of propagation. Interestingly when $\vec{B}_0 = H = 0$ only two modes of propagation are possible. It establishes the importance of quantum parameter-H and applied magnetostatic field $\vec{B}_0$.

Result and Discussion

To get some numerical appreciation, we use the following parameters of n-InSb semiconductor plasma at liquid helium temperature (4.2°K)-
$m = 0.013m_0$; m_0 being the free electron mass, $\varepsilon_L = 17.8$, $\nu = 1.35\times10^{12}\,\mathrm{sec}^{-1}$ and $n_0 = 2\times10^{24}\,\mathrm{m}^{-3}$.
When we solve the polynomial using the above parameters, we found that for $H \neq 0$ i.e. quantum plasma, six modes are strongly supported by the medium, on the other hand for $H = 0$ i.e. classical plasma, only four modes are induced. In this theory, we consider the perturbations of the form $\exp[i(\omega t - kz)]$ to study convective instability. Hence we use here real value of wave angular frequency ω and complex value of wave number $k(= k_{Re} + ik_{Im})$ so that negative imaginary part of 'k' indicates alternating waves, whereas positive magnitude demonstrates spatially growing waves.

The numerical estimates are illustrated through Figures 1-6. In these Figures the phase constant and growth rate of the modes with varying magnetic field are depicted for different magnitudes of quantum parameter-H.

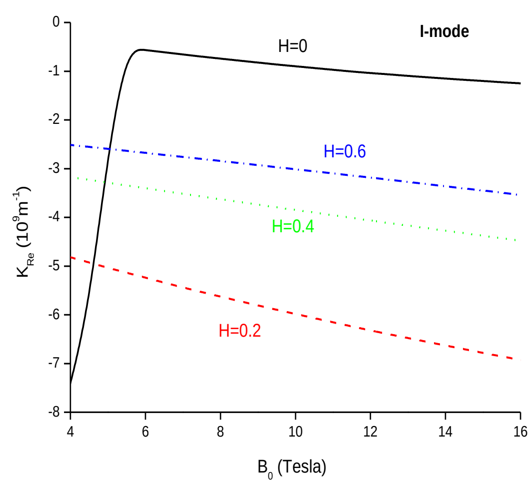

Figure 1(a): k_{Re} Vs B_0 for I-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

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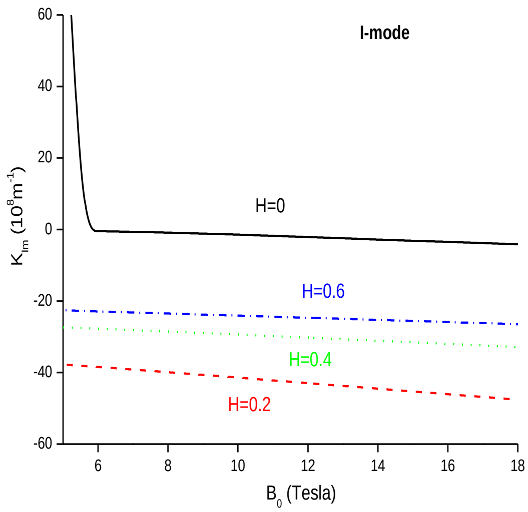

Figure 1(b): k_{Im} Vs B_0 for I-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

Figure (1) illustrates the nature of first mode with respect to applied magnetic field $\vec{B}_0$ in which Figure 1(a) depicts that first mode is always contra-propagating in nature irrespective of classical $(H = 0)$ and quantum $(H \neq 0)$ nature of plasma medium. In classical plasma, the phase velocity increases with B_0 attains maxima at $B_0 \approx 6$ Tesla, then becomes nearly independent of it; whereas in quantum plasma, with increment in quantum parameter-H, the phase velocity of the mode increases, but on increasing B_0, it becomes decreasing in nature. Figure 1(b) shows that under classical limit, the mode is growing in nature with decreasing growth constant while it is decaying in nature under quantum limits whose decay constant is a decreasing function of H and increasing function of B_0.

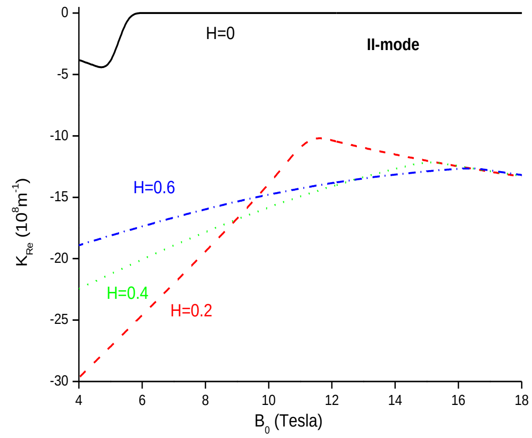

Figure 2(a): k_{Re} Vs B_0 for II-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

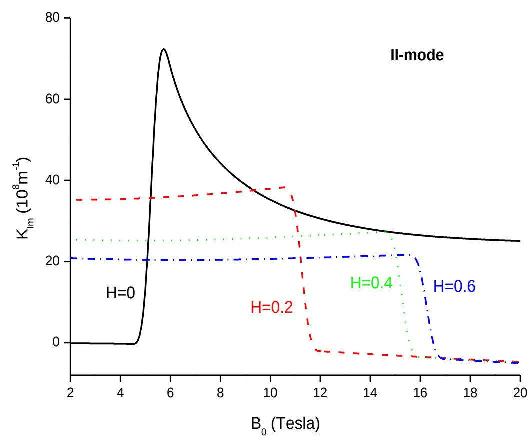

Figure 2(b): k_{Im} Vs B_0 for II-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

The phase and growth profiles of second mode are displayed in Figures 2(a) and 2(b). The phase characteristics (Figure 2(a)) infer that this mode has also contra-propagating nature for both types of plasmas i.e. classical and quantum plasma. In classical regime, the phase velocity of this mode is found to be high whereas on including quantum effects, it becomes slow. But as we increase the magnitude of quantum parameter-H, the phase velocity gets modify quantitatively. For all finite magnitudes of H, the phase velocity varies with B_0 in the same manner. It firstly increases up to a certain value of B_0 and decreases. This mode always has

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growing nature under both the quantum and classical regimes of the plasma medium (Figure 2(b)). In the beginning the growth constant of this mode is nearly independent of magnetic field B_0 in both presence and absence of quantum effects. In classical plasma, the growth constant suddenly increases at $B_0 \approx 6$ Tesla and then decreases on increasing B_0 while in quantum plasma the growth constant is found to be more for small magnitude of B_0, reverse is true for higher magnitudes of B_0. Altogether after a fixed value of B_0, growth constant suddenly decreases in such a way that mode's growing nature converts to decaying nature.

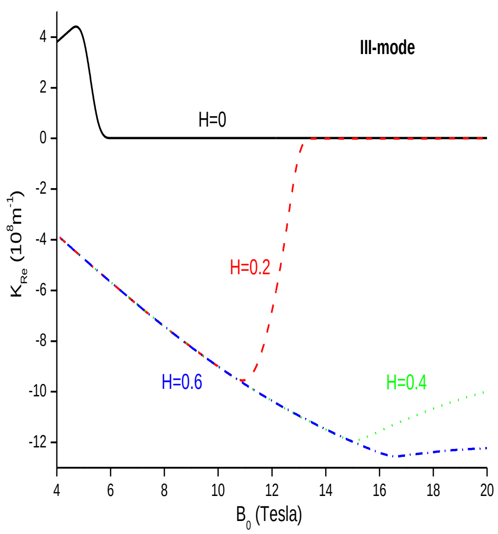

Figure 3(a): k_{Re} Vs B_0 for III-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

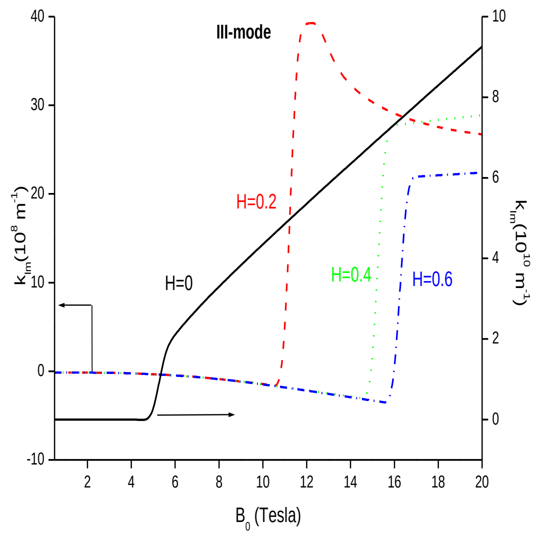

Figure 3(b): k_{Im} Vs B_0 for III-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

One may found from Figure 3(a) that third mode is co-propagating in classical regimes whose phase velocity increases with B_0 and becomes non-existing at $B_o = 5.8$ Tesla whereas it is contra-propagating in nature under quantum regimes in which the phase velocity firstly decreases with B_0 and after a fixed value of B_0 it starts increasing. This fixed value of B_0 is low for small magnitude of H and high for higher magnitudes of H. The gain characteristic of third mode is depicted in Figure 3(b). This mode is growing in nature for both the classical and quantum plasmas. The growth constant is higher by two orders in quantum plasma in comparison to classical plasma. It always has increasing nature with respect to B_0, on the other , it has decreasing nature with respect to H.

The variation of phase and growth rates with B_0 of fourth mode is illustrated in Figures 4(a) and 4(b). This mode co-propagates with such a velocity which decreases on increasing B_0 when classical effects dominate in plasma medium. But on considering quantum effects, phase velocity enhances with B_0 and reduces on increasing quantum parameter-H. In classical as well as in quantum limits, the mode is growing in nature. Inclusion of quantum effects in classical plasma media modifies the growth rate by two orders. In classical media growth constant

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decreases with B_0 after achieving the maxima while in quantum limits, increment in B_0 and decrement in H together enhance the growth constant of this mode.

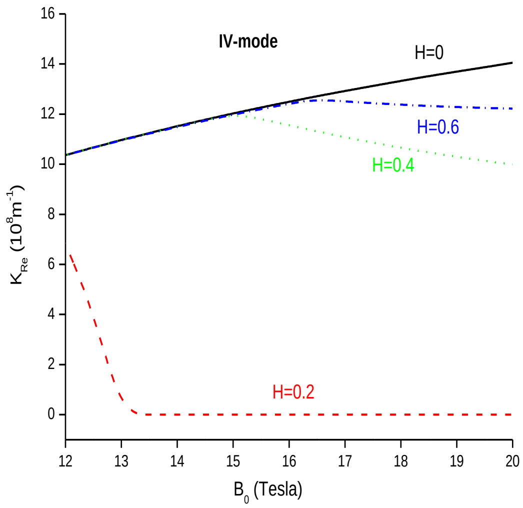

Figure 4(a): k_{Re} Vs B_0 for IV-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

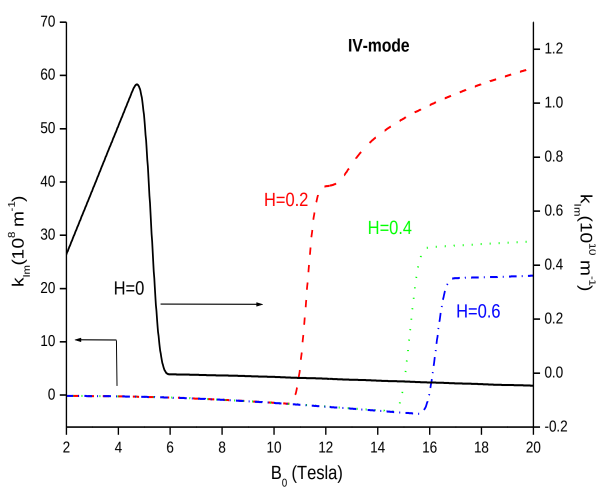

Figure 4(b): k_{Im} Vs B_0 for IV-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

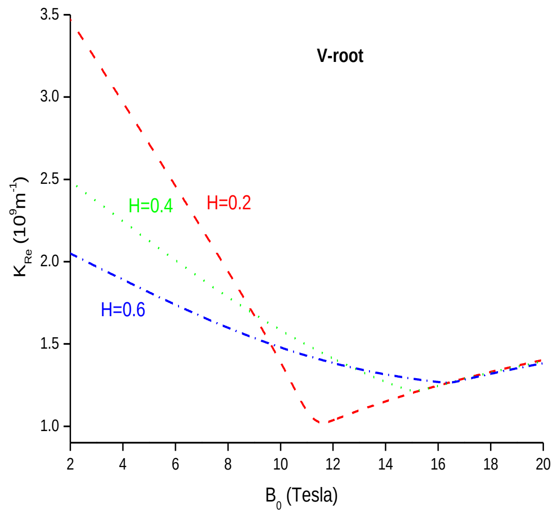

Figure 5(a): k_{Re} Vs B_0 for V-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

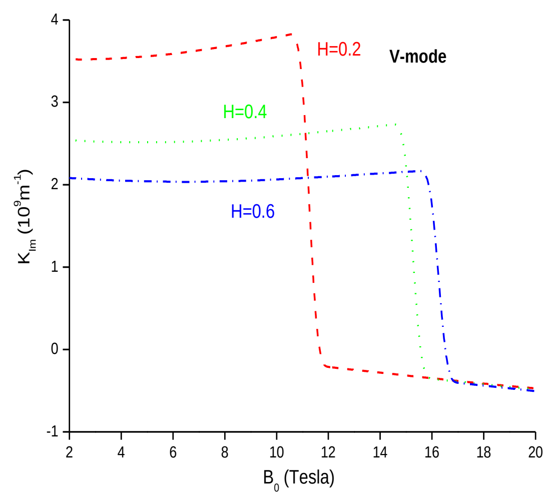

Figure 5(b): k_{Im} Vs B_0 for V-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

The phase and gain characteristics of two novel modes (i.e. fifth and sixth mode) are depicted in Figures (5) and (6). Figures 5(a) and 6(a) infer that both the modes are co-propagating in nature. The magnitude of phase velocity of both the modes increase with the increment in H but it varies differently with B_0. The phase velocity of sixth mode

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reduces on increasing B_0 while phase velocity of fifth mode firstly increases, achieves maxima and then starts shrinking with B_0.

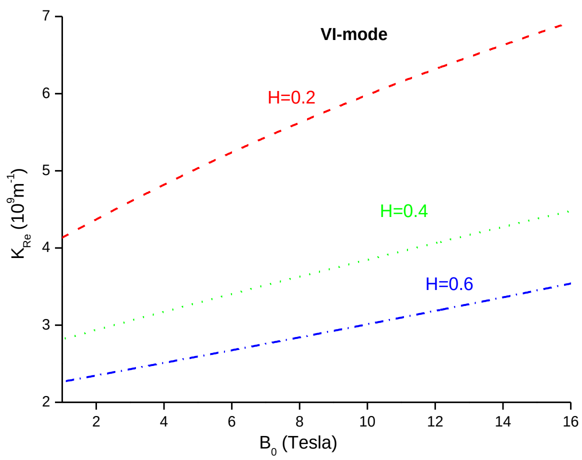

Figure 6(a): k_{Re} Vs B_0 for VI-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

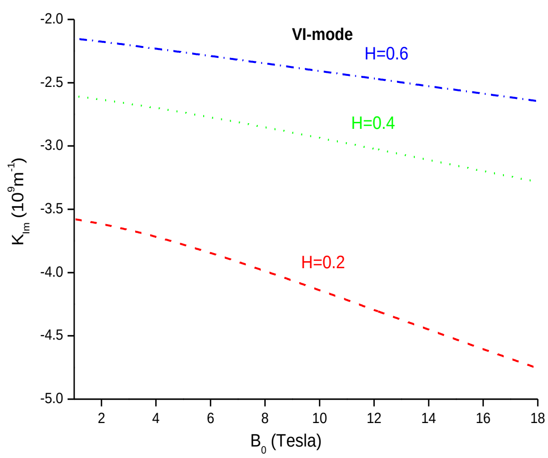

Figure 6(b): k_{Im} Vs B_0 for VI-mode (solid, dashed, dotted and dashed with dotted lines represent curves corresponding to H=0, H=0.2, H=0.4 and H=0.6 respectively)

The gain spectra of these modes are described by Figures 5(b) and 6(b). Fifth mode is initially growing in nature whose growth constant slightly increases with B_0 and on further increasing the strength of magnetic field it suddenly drops to a minimal value and afterwards it starts decaying. The sixth mode is decaying in nature for full range of magnetic field with increasing decay constant but on enhancing the quantum effects through quantum parameter-H its decay constant decreases.

CONCLUSION

The role of quantum correction through non-dimensional quantum parameter-H and magnetic field on convective instability of LEKW in magnetised semiconductor quantum plasma has been investigated. It is found that the quantum parameter together with magnetic field significantly modify the dispersion relation of LEKW. The derived general dispersion relation in absence of quantum parameter-H and magnetic field reduces to the usual dispersion relation of electron plasma wave. The analytical and numerical analysis depicts that out of six possible modes, four modes are found to be growing in nature and two modes are decaying in nature whose decay constant reduces on enhancing the magnitude of quantum parameter-H. On the other hand one may conclude from the phase characteristics of these modes that three modes have co-propagating nature and remaining three modes have contra-propagating nature. In most of the cases phase velocity of these modes increases in magnitude with increasing quantum parameter-H. The result presented in this paper is probably have not been reported so far. It may be hoped that our results will put a forward step to understand the origin of LEKW in semiconductor quantum plasma medium.

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