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Variation of Plasma Frequency with Applied Magnetic Fields in a Single Walled Carbon Nanotube

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Abstract

Using linearised quantum hydrodynamic model along with Maxwell's Equation the effect of static uniform magnetic field on the frequency of plasma oscillations in a single walled carbon nanotube (SWCNT) is discussed here. In presence of a static transverse magnetic field, in short wavelength limit plasma dispersion relation is found varied in accordance with the applied magnetic field.

Keywords: Plasma Oscillations, Magnetic Field, Dispersion Relation, Long Wavelength Limit.

Introduction

Plasma consists of electrons and ions with total charge zero. Plasma is usually considered as an electron gas moving in the background of positive ions. Plasma is a quasineutral gas of ions, electrons and neutral particles [1].The term plasma was first used by Langmuir [2] in 1928.

The study of carbon nanotubes (CNTs) is now an active area of research, which could lead to the development of advanced technology devices. One of the most fascinating aspects about CNTs is their surface mode excitations. During the past years, a lot of experimental and theoretical works have been done to study the high-frequency excitations (electron oscillations) in these systems. Also, it is well-known that in such systems both the positive ions and the electrons oscillate under low-frequency disturbance.

Fetter [3] used a simple hydrodynamic model to study the electrodynamics of the electron–ion plasma in a periodic array and obtained an acoustic branch in addition to the optical branch. Wei and Wang [4] studied the dispersion relation of quantum ion acoustic wave (QIAW) oscillations in single-walled carbon nanotubes (SWCNTs) with the quantum hydrodynamic (QHD) model which was developed by Haas *et al* [5, 6]. In the presence of a static magnetic field, we may expect a new excitation in carbon nanotubes (CNTs), i.e. quantum magnetosonic wave (QMSW) oscillations. Let us note that the effects of a static magnetic field on the plasmon oscillations of an electron gas in CNTs have been investigated by several authors using various methods. Shyu *et al* studied the magnetoplasmon of SWCNTs within the tight-binding model [7]. The low-frequency single-particle and collective excitations of SWCNTs were studied in the presence of a magnetic field by Chiu *et al* [8, 9]. Vedernikov *et al* [10] studied the collective oscillations of two-dimensional electrons in nanotubes in the presence of a magnetic field parallel to the tube axis. The energies of neutral and charged excitations and plasmon frequencies in nanotubes as functions of the magnetic field were analyzed by Chaplik [11]. Gumb[12], calculated the dispersion relation of the collective magnetoplasmon excitations for an electron gas confined to the surface of a nanotube when a magnetic field is perpendicular to its axis. In particular, by using the hydrodynamic model and Maxwell's equations, Kobayashi [13] studied the magneto static plasma wave oscillations of a SWCNT in the voigt configuration. Afshin Moradi [14, 15, and 16] has studied the effect of a static external magnetic field in a SWCNT.

Here we are interested in the application of transverse magnetic waves which propagate parallel to the surface of a SWCNT and concentrate on the excitations of the electron–ion system as two fluids confined to its surface. There is assumed to be a static magnetic field B0 that is normal to the cylindrical surface (Voigt configuration).

Theory and Discussions

Let us consider an infinitely long and infinitesimally thin SWCNT with a radius *a* and take the cylindrical polar coordinate x = (r, φ, z) for an arbitrary point in space. Let us consider the CNT to consist of electron and ion fluids superimposed at r = a with charges e and Ze, respectively.

The equilibrium densities (per unit area) of electrons are n_{0e} and ions $n^0{}_i$ satisfy $n^0{}_i = n_0$ and $n_e{}^0$ Z $n^0{}_i$= Zn_0

$$\frac{\partial ne}{\partial t}(x,t) + Zn_o\ \nabla_{\|} \cdot u_e(x, t) = 0, \tag{1}$$

$$\frac{\partial ni}{\partial t}(x, t) + n_o\ \nabla_{\|} \cdot u_i(x, t) = 0, \tag{2}$$

And the equation of linearised momentum

$$\frac{\partial ue(x,t)}{\partial t} = e/m\,[E_{\|}(x,t) + u_e(x, t) \times B_o]$$

$$\frac{\alpha}{Zno}\nabla_{\|}\, n_e(x, t) + \frac{\beta}{Zno}\ \nabla_{\|}[\ \nabla_{\|}^2\ n_e(x, t)] \tag{3}$$

$$\frac{\partial ui(x,t)}{\partial t} = \frac{Zm_e}{m_i}[E_{\|}(x,t) + u_i(x, t) \times B_o] \tag{4}$$

Where n_e (n_i) is the velocity of electron (ion) and

$$\nabla_{\|}= \hat{e}_z (\partial/\partial z) + a^{-1}\hat{e}_\varphi (\partial/\partial\varphi) \quad (5)$$

The three terms on the RHS of equation (3)are respectively force due to electric field and magnetic field, force due to internal interaction or can be considered as classical pressure of electron fluid and the third term comes from the quantum diffraction effect which can be considered as quantum pressure.

The electric current density flowing on the surface of the cylinder is given by

$$J_e(x,t) = \sigma_e E_{\|}(x,t) \quad (6)$$

$$J_i(x,t) = \sigma_i E_{\|}(x,t) \quad (7)$$

Where $\hat{\sigma_e}$($\hat{\sigma_i}$) is the conductivity tensor of the electron (ion)

Now we can define Fourier-Bessel transform $A_m(q)$ of an arbitrary function $A(\varphi,z,t)$ by

$$A(\varphi,z,t)= \sum_{m=-\alpha}^{+\alpha} \int_{-\alpha}^{+\alpha} dq\, A_m(q) \exp [i (m\varphi + qz- \omega t)] \quad (8)$$

Using equations (1) to (7) by eliminating terms n_e and n_i we get equations for σ_e and σ_I in terms of cyclotron frequency ω. ie

$\omega_{ce} = eB_o/m_e$ ($\omega_{ci} = ZeB_0/m_i$) of electron (ion) .

In the space above and below electron – ion cylinder, the transverse electric wave satisfies

$$\begin{cases} E_{zm}(r) = E_{0z} I_m(\kappa a) K_m(\kappa r) & r > a \\ E_{zm}(r) = E_{0z} K_m(\kappa a) I_m(\kappa r) & r < a \end{cases} \quad (9)$$

Where $I_m(x)$ and $K_m(x)$ are the modified Bessel functions and $K^2 = q^2 - \omega^2/c^2$ where c is the speed of light. For the case speed of light can be taken to be infinitely large we have

$$\omega^4 - \omega^2 \left[(\alpha + \beta q_m^2)q_m^2 + \left(1 + \frac{Z^2 m_e^2}{m_i^2}\right)\omega_{ce}^2\right.$$

$$\left. + e^2 Z n_0 a \frac{e^2 Z n_0 a}{\varepsilon_0 m_e}\left(1 + \frac{Zm_e}{m_i}\right) q^2_{m\, I_{m(qa)}} K_{m(qa)}\right]$$

$$+ \frac{Zm_e}{m_i}\left[(\alpha + \beta q_m^2)q_m^2 + \left(1 + \frac{Zm_e}{m_i}\right)\omega_{ce}^2\right]$$

$$\text{x} \quad g\, \frac{e^2 Z n_0 a}{\varepsilon_0 m_e} q^2_{m\, I_{m(qa)}} K_{m(qa)}$$

$$\frac{Z^2 m_e^2}{m_i^2}\omega_{ce}^2[\omega_{ce}^2 + (q\alpha + \beta q_m^2)q_m^2] = 0 \tag{10}$$

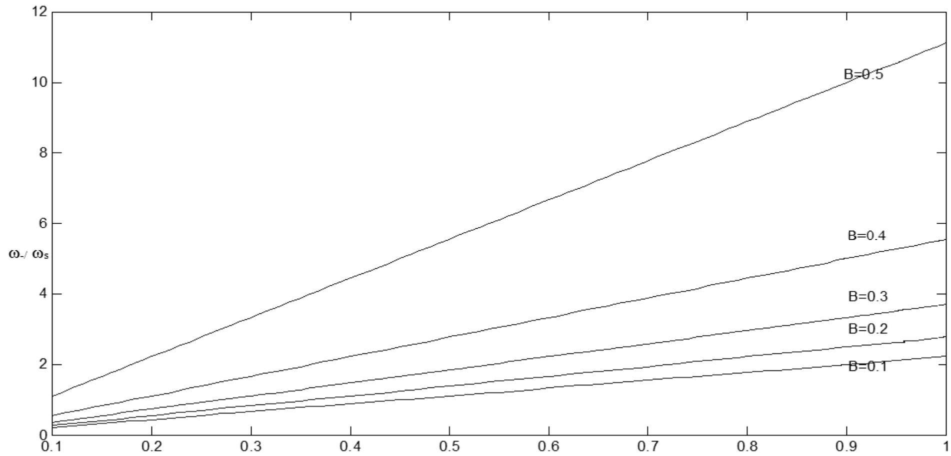
Which determines the normal electrostatic modes.

The roots of the above equation give (in the limit Zme /mi<<1) equations for ω_+ and ω_- where ω_+ for high frequency dispersion and ω- for low frequency (QMSW-quantum magneto sonic wave) dispersion.

In short wave length limit i.e. qa→α we may use the asymptotic expression of the Bessel functions $I_m(x) = e^x/\sqrt{2\pi x}$ and $K_m(x) = \sqrt{\frac{\pi}{2x}}\,e^{-x}$, so that the dispersion relation

$$\omega_-^2(q) \approx \frac{Zm_e}{m_i}(\alpha + \beta q_m^2)q_m^2\left[1 + \frac{\alpha+\beta q_m^2}{\frac{e^2 n_0}{\varepsilon_0 m_e 2q}}\right] \tag{11}$$

Using the above equation the variation of the dimensionless frequency $\omega_{-}/\ \omega_s$ with respect to the variable qaB for different values of fields applied for carbon nanotubes are studied. Here $\omega_s = (Zm_e\ \omega^2_{ce}/m_i)^{1/2}$ .The dispersion curves obtained is as shown in figure 1.



qa_B

Figure 1 : Dispersion relation $\omega_{-}/\ \omega_s$ versus the dimensionless variable qa_B

From equation (11) for a single walled carbon nanotubes

Conclusion

In conclusion we can see that the frequency is varied in accordance with the B0, for long wave length limit. The dispersion relation for different values of Bo are grouped in figure 1.This was interpreted as the applied magnetic field is increased the plasma dispersion exhibits stronger dispersions.

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