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Small-scale kinetic Alfven waves in the presence of warm and cold magnetized plasma in plasma sheet boundary layer – kinetic approach

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Abstract – Kinetic Alfven wave has been studied by kinetic approach to evaluate the dispersion relation and damping- rate of small scale Alfven wave in homogenous plasma in both cases (warm and cold electron limit) in plasma sheet boundary layer. Kinetic effects of electrons and ions are included to study kinetic Alfven wave because both are important in the transition region. It is found that the ratio β of electron thermal energy density to magnetic field energy density and the ratio of ion to electron thermal temperature (Ti/Te) affect the dispersion relation and damping-rate in both cases (warm and cold electron limit). It is predicted that higher k⊥ρi >1 are more effective for the bi-Maxwellian distribution, here k⊥ is perpendicular wave number and ρi is the ion gyro radius. The method may be suitable to deal with the PSBL, where particle acceleration is also important along with wave emissions.

Key-words: Kinetic Alfven wave, plasma sheet boundary layer, magnetospheric plasma, particle acceleration

1. Introduction

Kinetic Alfven waves are of great importance in laboratory and space plasmas. These waves may play an important role in energy transport, in driving field-aligned currents, in particle acceleration and heating, and in explaining inverted-V structures in magnetosphere-ionosphere coupling and in solar flares and the solar wind (Hasegawa, 1976; Goertz and Boswell, 1979; Goertz, 1984). Additional support for their role in auroral phenomena comes from global distribution maps at both low (FAST satellite) and high (Polar satellite) altitude show that Alfven waves occur on auroral field lines along the entire auroral oval (Chaston et al., 2003a; Keiling et al., 2001, 2003, 2005).

Hasegawa (1976) first suggested that small-scale kinetic Alfven waves possessed parallel electric fields and could be an efficient mechanism for accelerating particles on plasma sheet field lines. The kinetic Alfven waves Hasegawa discussed had spatial scales perpendicular to B such that $k_{\perp}\rho_S \sim 1$, where ρ_S is the ion acoustic gyroradius. This is the "kinetic" limit of kinetic Alfven waves. Subsequent theoretical investigations (Goertz and Boswell, 1979) focused on kinetic Alfven waves in the electron inertial limit ($k_{\perp}\, c/\omega_{pe}$ ~1) as a mechanism for establishing parallel electric fields capable of accelerating auroral electrons. Lysak and Lotko (1996) included the effects due to small perpendicular scale sizes of the order of the electron inertial scales (c/ω_{pe}) or kinetic effects associated with electron pressure and ion acoustic gyroradius. These effects are called "kinetic Alfven waves".

Recent polar/Hydra (Scudder et al., 1995), electric field instrument (Harvey et al., 1995) spacecraft observations (Wygant et al., 2000; 2002) at altitudes of 4–7 R_E in the PSBL and deeper within the plasma sheet show that large amounts of energy are transferred earthward by the Poynting flux carried by Alfve´n waves. This enhanced Alfve´nic Poynting flux dominates other forms of energy flux along plasma sheet magnetic field lines and coincides with magnetically conjugate intense aurora. The Poynting flux due to the steady state magnetic field perturbations associated with the field-aligned currents and the convection electric field was estimated to be ~1-2 orders less than the Alfve´nic Poynting flux. Polar/Hydra (Scudder et al., 1995), electric field instrument (Harvey et al., 1995) spacecraft observations (Wygant et al., 2000; Keiling et al., 2001, 2003, 2005) provide evidence that the Alfve´nic Poynting flux is responsible for transferring the power needed for the acceleration of all the energized auroral particle populations accelerated into the ionosphere and also streaming out into the magnetosphere, as well as the Joule heating of the ionosphere.

In past, kinetic Alfven waves have been analyzed in view of the auroral acceleration process at much lower altitudes of about 1.4 R_E (Baronia and Tiwari, 1999; Dwivedi et al. 2002) using S3-3 satellite data (Tiwari and Rostoker, 1984). However, it is only recently, with the availability of the necessary measurements from the Polar /Hydra (Scudder et al., 1995), electric field instrument (Harvey et al., 1995) spacecraft (Wygant et al., 2000; Keiling et al., 2001, 2003, 2005), that a relatively complete inventory of the important energy transfer mechanisms along plasma sheet magnetic field lines above the bulk of the auroral acceleration region has become possible. The kinetic effect is true at higher altitudes and inertial effect at lower altitudes. The observations in the auroral acceleration region (Chaston et al., 2003 a,b; Chaston 2004; Chaston et al., 2005, 2006,2007), suggest that at altitudes of about 2-3 R_E where much of the auroral acceleration is thought to occur (Goertz and Boswell, 1979) and it has been shown that the perpendicular wavelength is closer to the electron inertial length (c/ω_{pe}) (Louarn et al.,1994; Chaston 1999) than the ion acoustic gyro-radius. Under such conditions the electrons can no longer be considered massless and so this wave will so carry a parallel electric field. This has led to a variety of models that have considered the development of parallel electric fields due to electron inertia (Seyler, 1988; Rönnmark and Hamrin, 2000; Seyler and Wu, 2001

In this paper, kinetic effects of electrons and ions are included to study kinetic Alfven wave because both are important in the transition region. The wave propagating obliquely to the ambient magnetic field B_0 is considered. The organization of the paper is as follows. An introduction is given in Section 1. Section 2 deals with the theory and results and conclusion are presented in Sect. 3 and 4.

2. Theory

2.1 Basic Assumption

To determine the dispersion relation and damping rate, zeroth-order distribution function is adopted suitable for drifting core plasma in plasma sheet boundary layer (Horwitz et al., 1987, 2000) and is given by

$$F_j = n_0 f_\perp(\boldsymbol{V}_\perp) f_{\prod}(V_{\prod}) \tag{1}$$

Here,

$$f_\perp(\boldsymbol{V}_\perp) = \left[\frac{m}{2\pi T_\perp}\right] \exp\left\{-\frac{m\boldsymbol{V}_\perp{}^2}{2T_\perp}\right\}$$

$$f_\Pi(V_\Pi) = \left[\frac{m}{2\pi T_\Pi}\right]^{\frac{1}{2}} \exp\left\{-\frac{mV_\Pi{}^2}{2T_\Pi}\right\}$$

Where, T_Π and $T_\perp$ are the parallel and perpendicular temperatures with respect to the ambient magnetic field. The "core" of magnetospheric plasma distribution functions is of prime importance in the magnetospheric plasma behavior. Horwitz et. al. (1987, 2000) described the ionosphere as the basic core plasma region for the overall magnetosphere-ionosphere system. They described the principal inner/middle magnetospheric regions-the plasmasphere, ring current, and plasma sheet boundary layer regions-and how core plasmas from the ionosphere, either with little or with substantial energization, become major components of these magnetospheric regions.

2.2 General dispersion relation for kinetic Alfven wave

Plasma with an external magnetic field B in the z-direction is considered and since the KAW has its electric vector and wave vector in the same plane, its dispersion relation can be written in matrix form as (Lysak and Lotko, 1996)

$$\begin{pmatrix} \varepsilon_{\perp}-\frac{C^2 k_{\Pi}^2}{\omega^2} & \frac{C^2 k_{\perp} k_{\Pi}}{\omega^2} \\ \frac{C^2 k_{\perp} k_{\Pi}}{\omega^2} & \varepsilon_{\parallel}-\frac{C^2 k_{\perp}^2}{\omega^2} \end{pmatrix} \begin{pmatrix} \frac{E_x}{E_z} \end{pmatrix} = 0 \qquad (2)$$

Where $k_{\perp}$ and k_{Π} are the components of the wave vector k across and along the static magnetic field. $k_{\perp}$ and k_{Π} are taken to be positive and ω is the wave frequency. All other symbols have their usual meanings. ε_{zz} and ε_{xx} are dielectric tensor elements among and across external magnetic field and given as:

$$\varepsilon_{xx} = 1 + \sum_j \frac{\omega_{pj}^2}{\omega} \sum_{n=-\infty}^{\infty} \int d^3v v_{\perp} \frac{\left(\frac{n^2}{\mu_j^2}\right) J_n^2(\mu_j)}{\left(\omega - n\Omega_j - k_{\Pi} v_{\Pi}\right)} \left[\frac{\partial}{\partial v_{\perp}} F_j - \frac{k_{\Pi} v_{\Pi}}{\omega} \left(\frac{\partial}{\partial v_{\perp}} F_j - \frac{v_{\perp}}{v_{\Pi}} \frac{\partial}{\partial v_{\Pi}} F_j \right) \right] \qquad (3)$$

$$\varepsilon_{zz} = 1 + \sum_j \frac{\omega_{pj}^2}{\omega} \sum_{n=-\infty}^{\infty} \int d^3v v_{\Pi} \frac{J_n^2(\mu_j)}{\left(\omega - n\Omega_j - k_{\Pi} v_{\Pi}\right)} \left[\frac{\partial}{\partial v_{\Pi}} F_j + \frac{n\Omega_j}{\omega} \left(\frac{v_{\Pi}}{v_{\perp}} \frac{\partial}{\partial v_{\perp}} F_j - \frac{\partial}{\partial v_{\Pi}} F_j \right) \right] \qquad (4)$$

Where $\omega^2_{pj}=4\pi N_0 e_j^2/m_j$ is the square of plasma frequency of species j, $\mu_j=k^2_{\perp}\rho^2_j$, $\rho_i(\rho_e)$ is the thermal ion(electron) gyroradius and $\Omega_j= e_j B_0/m_j c$ is the gyro frequency. Substituting the value of F_j from eq.(1), ε_{zz} and ε_{xx} can be written as

$$\varepsilon_{xx} = 1 + \sum_j \frac{\omega_{pj}^2}{\omega^2} \sum_{n=-\infty}^{\infty} \frac{\omega}{k_{\parallel} v_j} \frac{n^2 \Gamma_n(\mu_j)}{\mu_j} Z\left(\chi_{nj}\right) \qquad (5)$$

$$\varepsilon_{zz} = 1 + \sum_j \frac{\omega_{pj}^2}{\omega^2} \frac{\omega}{k_{\parallel} v_j} \sum_{n=-\infty}^{\infty} \chi_{nj} \Gamma_n(\mu_j) Z'\left(\chi_{nj}\right) \qquad (6)$$

Where $\chi_{nj}= \omega/kV_j$, $V_j= (2T_j/m_j)^{1/2}$,$\lambda^2_{De} =(\varepsilon_0 Te/ne^2)^{1/2}$ is the Debye length, $Z(\chi_{nj})$ is the plasma dispersion function and $\Gamma_n(\mu_j)=e^{-\mu_j} I_n(\mu_j)$ is the modified Bessel function. By expending Z function and it's derivative, ε_{zz} and ε_{xx} can be written as

$$\varepsilon_{zz} = 1+\frac{\Gamma_0(\mu_e)}{k_\Pi{}^2\lambda_{De}{}^2}\{1+\chi Z(\chi)\} \tag{7}$$

$$\varepsilon_{xx} = 1+\frac{c^2}{V_A^2}\frac{1-\Gamma_0(\mu_i)}{\mu_i} \tag{8}$$

The dispersion relation is found by taking the determinant of the matrix in equation (2) and is given as:

$$\left[1-\frac{\omega^2}{k_\Pi{}^2C_s{}^2}\frac{\Gamma_0(\mu_e)}{\Gamma_0(\mu_i)}\{1+\chi Z(\chi)\}\right]\left[1-\frac{\omega^2}{k_\Pi{}^2V^2{}_A}\frac{1-\Gamma_0(\mu_i)}{\mu_i}\right]=\frac{\omega^2}{k_\Pi{}^2V_{T\perp i}{}^2}\frac{1-\Gamma_0(\mu_i)}{\Gamma_0(\mu_i)} \tag{9}$$

This equation can be solved numerically and the dispersion relation written in form:

$$\frac{\omega^2}{k_\Pi{}^2V^2{}_A}=\frac{1}{\frac{V^2{}_A}{c^2}+\frac{1-\Gamma_0(\mu_i)}{\mu_i}}+\frac{k_\perp{}^2\rho_s{}^2}{\Gamma_0(\mu_e)\{1+\chi Z(\chi)\}+k_\Pi{}^2\lambda_{De}{}^2} \tag{10}$$

If electron gyroradius is small, $\Gamma_0(\mu_e)\approx 1$. Eq. (6) can be simplified by taking $V_A{}^2 \ll c^2$ and $k^2_\Pi\lambda^2_{De} \ll 1$ so that it becomes as

$$\frac{\omega^2}{k_\Pi{}^2V^2{}_A}=\frac{\mu_i}{1-\Gamma_0(\mu_i)}+\frac{k_\perp{}^2\rho_s{}^2}{\Gamma_0(\mu_e)\{1+\chi Z(\chi)\}} \tag{11}$$

For warm electron limit ($\chi_{ne} \ll 1$); expanding the Z function (Shrivastava & Shrivastava; 2008), the dispersion relation can be written as

$$\frac{\omega^2}{k_\Pi{}^2 V_A{}^2} \approx \left(1 + k_\perp{}^2\left(\rho_i{}^2 + \rho_s{}^2\left(1 - i\sqrt{\pi}\chi\right)\right)\right) \tag{12}$$

For cold electron limit (χ_{ne}»1), the dispersion relation can be written as

$$\frac{\omega^2}{k_\Pi{}^2 V_A{}^2} \approx \frac{\left(1 + k_\perp{}^2 \rho_i{}^2\right)}{\left(1 + k_\perp{}^2 \dfrac{c^2}{\omega_{pe}{}^2}\right)} \tag{13}$$

The dispersion relation of kinetic Alfven wave in warm and cold electron limit is similar to that derived by Shrivastava & Shrivastava (2008) using particle aspect approach and more accurate that presented by Baronia and Tiwari (1999); Dwivedi et al., (2002). The dispersion relation given in eq. (10) for kinetic Alfven waves includes full kinetic effects of ions and electrons in homogeneous plasma by kinetic approach and may be very useful for transition region where both effects are important as observed by polar/Hydra (Scudder et al., 1995), electric field instrument (Harvey et al., 1995).

For small Larmor radius limit ($k_\perp \rho_i$ <1) of ions, eq.(8) can be written as:

$$\varepsilon_{xx} = 1 + \frac{c^2}{V_A^2}\left(1 - \frac{3}{4}\mu_i\right)$$

Hence, the dispersion relation of kinetis Alfven wave is obtained as

$$\frac{\omega^2}{k_\Pi{}^2 V_A{}^2} \approx \left(1 + \left(\frac{3}{4} + \frac{T_e}{T_i}\right) k_\perp{}^2 \rho_i{}^2\right) \tag{14}$$

For large Larmor radius limit ($k_{\perp}\rho_i$ >1) of ions, eq.(8) can be written as:

$$\varepsilon_{xx} = 1 + \frac{c^2}{V_A^2}\frac{1}{\mu_i}$$

Hence, the dispersion relation of kinetis Alfven wave is obtained as

$$\frac{\omega^2}{k_{\Pi}^{2} V_A^{\,2}} \approx \left(\left(1+\frac{T_e}{T_i}\right) k_{\perp}^{\,2} \rho_i^{\,2}\right) \qquad (15)$$

Where

$$V_A^{\,2} = \frac{c^2 \Omega^2{}_i}{\omega^2{}_{pi}} \text{ is the square of Alfve'n speed.}$$

The dispersion relation of kinetic Alfven wave in both regimes is similar to that derived by Sallimullah & Rosenberg (1999) if the effect of dust is neglected.

2.3 Damping-rate

Imaginary term in eq.(8) gives the landau damping of the wave. Assuming $\omega \to \omega + i\gamma_l$, with $\gamma_l \ll \omega$, an expression for the collisionless damping rate of the kinetic Alfven wave in the both regimes is obtained as

$$\gamma_l = -\sqrt{\frac{\pi}{8}}\left(\frac{m_e}{m_i}\right)\left(\frac{c^2 k_{\perp}^2}{\omega_{pi}^2}\right) k_{\parallel} V_e \qquad (12)$$

The expression for the damping rate of the kinetic Alfven wave is same as derived by Sallimullah & Rosenberg (1999) if the effect of dust particles is neglected.

3. Results

In the numerical evaluation of the dispersion relation, associated currents per unit wavelength, parallel energy of resonant electrons per unit wavelength and growth/damping rate, the following plasma parameters are used suitable for the transient region at 4-7 R_E in plasma sheet boundary layer (Wygant et al., 2000, 2002; Keiling et al., 2000, 2001, 2002, 2003, 2005; Shrivastava & Shrivastava; 2008; Marklund et al., 2001; Hull et al., 2010).

B_0 =400nT; c/ω_{pe} =10 km; $kT_{\perp i}$ = 4 keV; n_0 =0.3 cm^{-3}; ρ_i =20km; ρ_e =0.3km.

Two parameters are important in understanding the propagation of the kinetic Alfven waves in plasma sheet boundary layer. The ratio of electron thermal energy density to magnetic field energy density β and the ratio of ion to electron thermal temperature (T_i/T_e) control whether there is significant Landau damping of the waves (Wygant et al., 2000, 2002). At the edge of the plasma sheet, β is ~.001 which is comparable to m_e/m_i (the electron to ion mass ratio) as discussed by Wygant et al. (2000). In the present case β is fluctuating but on the order of .001. The Polar/Hydra measurements (Scudder et al., 1995) also indicate the ratio of ion to electron thermal temperature is T_i/T_e=2. The average plasma density 0.3 cm^{-3} as observed by the Polar/ electric field instrument (Harvey et al., 1995; Wygant et al., 2000, 2002), considered in the present analysis.

Fig. 1 shows the variation of kinetic Alfven wave frequency ω with $k_\perp\rho_i$ for different values of β (in the case of warm electron limit). The dispersion relation given in eq. (6) is similar to that derived by Lysak and Song (2003), Shrivastava & Shrivastava (2008) for the warm electron limit. It is noticed that the phase velocity of the wave increases with $k_{\perp}\rho_i$ and β is more effective towards the higher perpendicular wave numbers ($k_{\perp}\rho_i > 1$). Furthermore, it is observed that the phase velocity is decreased at the higher values of β, which may be due to the increase of electron density. Wygant et al. (2002) presented the frequency range 0.17 to 4 Hz based on polar/Hydra (Scudder et al., 1995), electric field instrument (Harvey et al., 1995) spacecraft observations and which is similar as discussed in the presented paper. Wygant et al. (2000) indicated that small scale Alfven structures may undergo Landau damping and thereby accelerate electrons through small parallel electric fields and which is presented in fig. 2.

Fig. 3 shows the variation of kinetic Alfven wave frequency ω with $k_{\perp}\rho_i$ for different values of T_i/T_e for the warm electron limit. It is noticed that the phase velocity increases with $k_{\perp}\rho_i$ and is higher at $T_i/T_e = .1$. Furthermore, it is also noticed that the phase velocity of the wave is decreased at the higher values of T_i/T_e, which may be due to the decrease of electron temperature. Fig. 4 shows the variation of damping rate γ/ω with $k_{\perp}\rho_i$ for different values of T_i/T_e. It is noticed that damping rate γ/ω is negligible when electron temperature is higher as compared to ion temperature. It means small scale Alfven structures may undergo Landau damping and thereby accelerate electrons through small parallel electric fields when ion temperature is higher as compared to electron temperature. The Polar/Hydra measurements (Scudder et al., 1995) also indicate the ratio of ion to electron thermal temperature is $T_i/T_e=2$.

Fig. 5 shows the variation of kinetic Alfven wave frequency ω with $k_{\perp}c/\omega_{pe}$ for different values of β for the cold electron limit. The dispersion relation given in eq. (7) is similar to that derived by Lysak and Song (2003) using kinetic approach for the cold electron limit. It is observed that the phase velocity increases with $k_\perp c/\omega_{pe}$ but decreases with β.

4. Conclusion

The present study predicts that the wave frequency and damping/growth-rate in both cases (warm and cold electron limit) are influenced by the ratio of electron thermal energy density to magnetic field energy density β and the ratio of ion to electron thermal temperature (T_i/T_e). It is predicted that higher $k_\perp \rho_i$ ($k_\perp \rho_i > 1$) is more effective for the bi-Maxwellian distribution. The present model also predicts that there is no landau damping occurred in the case of cold electron limit hence the expressions obtained for warm electron limit are more appropriate for polar observations. Recent observations as well as theoretical considerations presented here suggest that Alfven waves occurred in the upward current region (primary current) and can be efficient accelerators of auroral electrons. Landau dissipation in plasma sheet can convert significant amounts of wave energy into the field-aligned acceleration of auroral electrons. While the calculations presented here only give a preliminary picture of these wave-particle interactions, they provide the basis for more sophisticated further studies of this interaction.

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Caption to figures:

Fig. 1 ω versus $k_{\perp}\rho_i$ for different β at fixed ratio of ion to electron thermal temperature T_i/T_e =2.

Fig.2 Damping rate versus $k_{\perp}\rho_i$ for different β at fixed ratio of ion to electron thermal temperature T_i/T_e =2.

Fig.3 ω versus $k_{\perp}\rho_i$ for different ratio of ion to electron thermal temperature T_i/T_e at fixed β =.001.

Fig.4 Damping rate versus $k_{\perp}\rho_i$ for different ratio of ion to electron thermal temperature T_i/T_e at fixed β =.001.

Fig.5 ω versus $k_{\perp}c/\omega_{pe}$ for different β at fixed ratio of ion to electron thermal temperature T_i/T_e =2.

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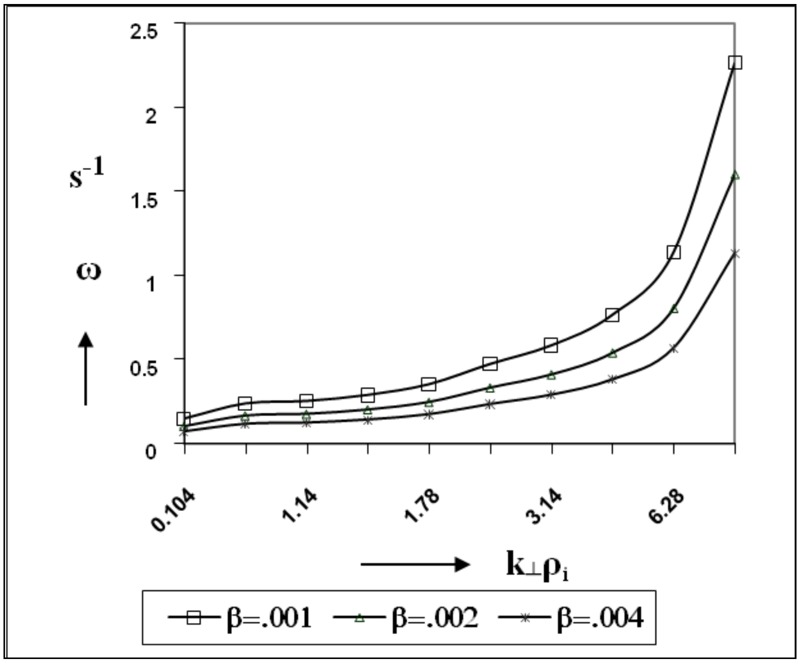
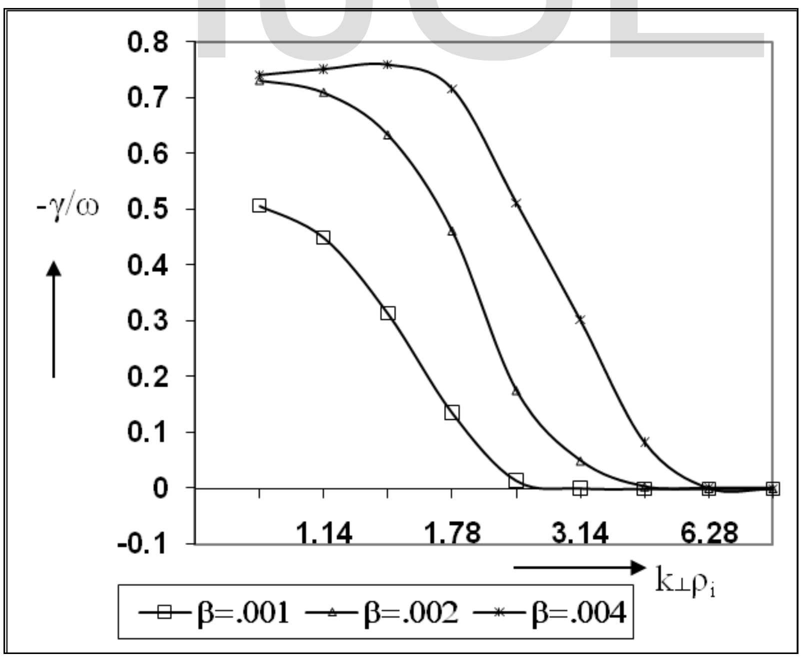
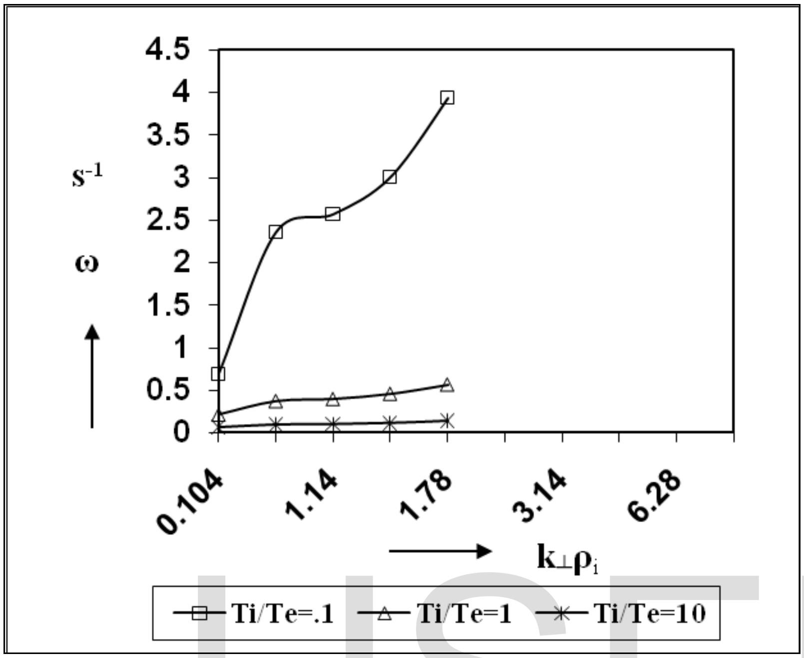
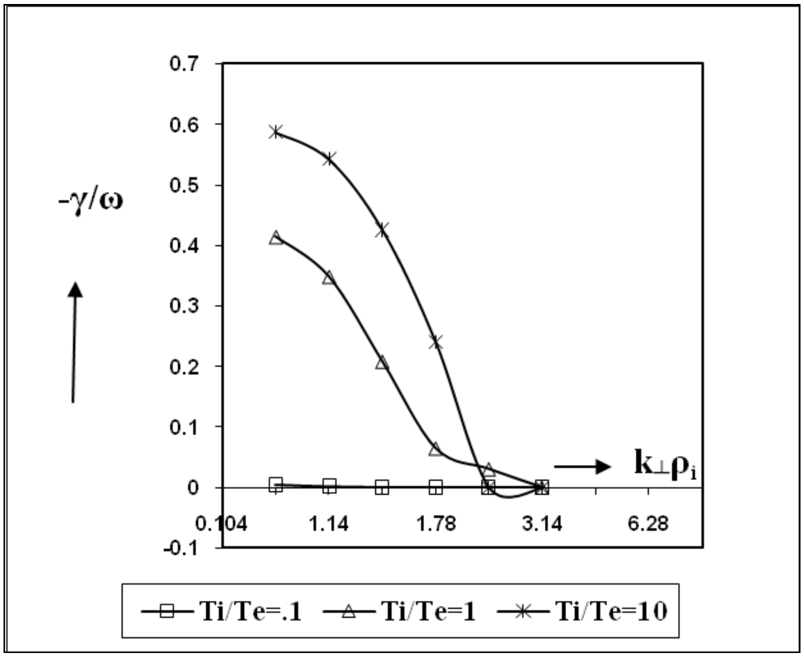
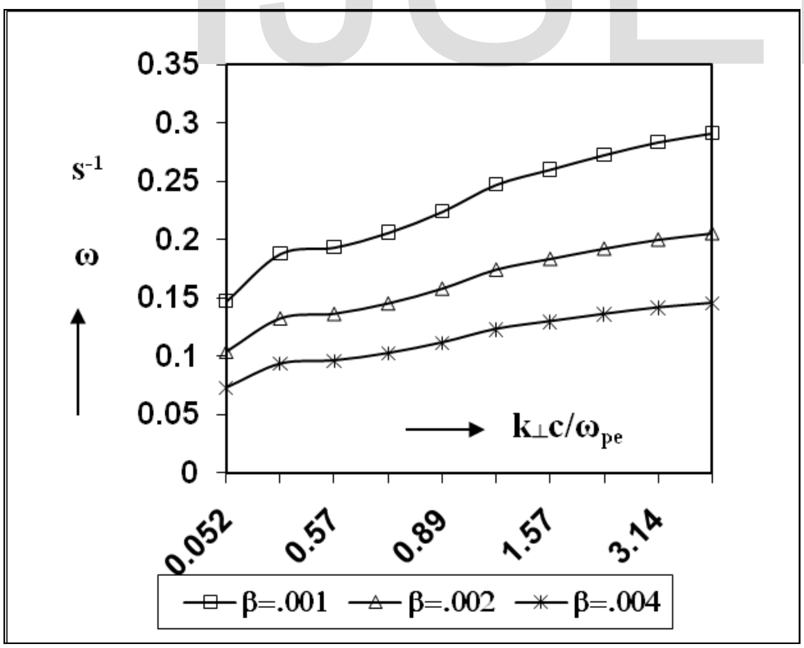





4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
s-1
ω
0.104
1.14
1.78
3.14
6.28
k⊥ρi
Ti/Te=.1
Ti/Te=1
Ti/Te=10


0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-γ/ω
0.104
1.14
1.78
3.14
6.28
k⊥ρi
Ti/Te=.1
Ti/Te=1
Ti/Te=10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0.3
0.25
0.2
0.15
0.1
0.05
0
s-1
ω
0.052
0.57
0.89
1.57
3.14
k⊥c/ωpe
β=.001
β=.002
β=.004