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NONLOCAL EFFECTS ON THE CONVECTIVE PROPERTIES OF THE
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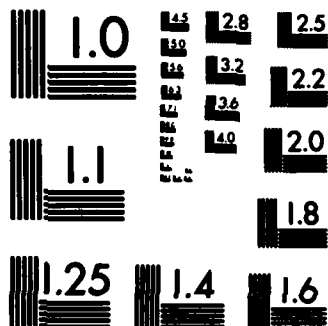
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Nonlocal effects due to magnetic shear and finite current channel width on the convective characteristics of the current driven ion cyclotron instability have been investigated. When the magnetic shear length (L_s) is smaller than the current channel width (L_c), the group velocity parallel to the external magnetic field at the origin (V_{gz}) vanishes, and there is a reduction in the group velocity perpendicular to the external magnetic field (V_{gy}). For $L_c \sim 10^{-2} L_s$ the values of V_{gz} and V_{gy} as given by local theory are recovered. When L_c is the mean ion Larmor radius, both V_{gz} and V_{gy} change sign, indicating a reversal of the direction of propagation. <i>approx 400</i> <i>Lab 3</i> <i>Pho sub i</i> <i>at office</i>				
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Nonlocal Effects on the Convective Properties of the Electrostatic Current Driven Ion-Cyclotron Instability

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NONLOCAL EFFECTS ON THE CONVECTIVE PROPERTIES OF THE ELECTROSTATIC CURRENT DRIVEN ION CYCLOTRON INSTABILITY

I. INTRODUCTION

The current driven ion cyclotron instability¹ (CDICI) has been of considerable interest to both space and laboratory plasma physicists for more than two decades. Recently, we have demonstrated the importance of nonlocal effects due to magnetic shear^{2,3} (produced by the field aligned current) and the finite extent of the current channel^{4,5}. Our past work dealing with these nonlocal aspects of the electrostatic CDICI was essentially based on a normal mode approach. The local treatment of the CDICI,^{1,6,7} which assumes an infinite extent of the width of the current channel, predicts a finite group velocity of the CDICI in both the parallel and perpendicular directions relative to the external magnetic field. For a temporally growing mode, the presence or absence of a group velocity in a finite sized region of space (as opposed to a point) makes an instability convective or absolute;⁸ these are two vastly different physical scenarios. This fact has been elucidated by Ashour-Abdulla and Kennel,⁷ in general, and more specifically for the CDICI by Ashour-Abdulla and Thorne.⁹ In our earlier work²⁻⁴ we noted a significant difference between the local and the nonlocal results as far as growth rates of normal modes are concerned. For instabilities like the CDICI which are convective, a normal mode analysis without regard to the convective growth cannot fully determine the stability of a bounded system, and hence is somewhat limited in its application. Thus, the main objective of this paper is to report the nonlocal effects due to magnetic shear and the finite current channel width on the convective aspects of the electrostatic CDICI.

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II. THEORY

In our treatment we will follow the analytical approach as given in Bakshi et al.⁴ We introduce a finite current channel width in the x direction. We take the electron distribution function to be Maxwellian with a drift velocity parallel to the magnetic field which is x dependent:

$$v_d(x) = v_d^0 g(x_g/L_c) \quad (1)$$

where $g(\xi) = \exp(-\xi^2)$ and $x_g = x + v_y/\Omega_e$. Assuming that $v_y/\Omega_e \sim 0(\rho_e) \ll L_c$, where L_c is the characteristic length scale associated with the current channel, we approximate (1) by

$$v_d(x) \approx v_d^0 g(x/L_c). \quad (2)$$

Using (2) and following the methods illustrated in Ref. 4 we arrive at the nonlocal, differential equation for the CDICI:

$$\left\{ \left(\frac{\rho_1}{L_c} \right)^2 \frac{\partial^2}{\partial \xi^2} + Q(u, v_d) \right\} \phi(\xi) = 0, \quad (3)$$

where Q is defined by,

$$Q = -\rho_1^2 \frac{Q_1}{A}, \quad (4)$$

$$Q_1 = 1 + (k_y \lambda_1)^2 + \tau + \sum_n \Gamma_n(b) \zeta_1 Z((1 - np)\zeta_1) + \tau \left(\zeta_e - \frac{v_d(\xi)}{v_e} \right) Z\left(\zeta_e - \frac{v_d(\xi)}{v_e} \right), \quad (5)$$

$$A = \frac{\rho_1^2}{2} \zeta_1 \sum_n \Gamma'_n(b) Z((1 - np)\zeta_1), \quad (6)$$

where $b = k_y^2 \rho_1^2 / 2$, $\Gamma'_n = \partial \Gamma_n / \partial b$, $\tau = T_i / T_e$, $p = \Omega_i / \omega$, $\zeta_1 = \omega / |k_1| v_1$, $\xi = x / L_c$, $\zeta_e = \omega / |k_1| v_e$, $k_1(x) = k_z + k_y (L_c / L_s) \int_0^\xi g(\xi) d\xi$, $u = k_1(x) / k_y$ and L_s is the characteristic length associated with the shear in the magnetic field.

The dispersion equation is given by:⁴

$$Q'(\omega, \xi_1) = 0, \quad (7a)$$

$$Q(\omega, \xi_1) = (2\ell + 1)(\rho_1 / L_c) \left[-\frac{1}{2} Q''(\omega, \xi_1) \right]^{1/2}, \quad (7b)$$

where Q' and Q'' are the first and second derivatives of Q with respect to ξ evaluated at ξ_1 , which is defined by 7a. We solve equations 7a and 7b numerically for the complex eigenfrequencies ω , given the perpendicular wave vector k_y , the parallel wave vector at the origin k_z , and other parameters characterizing the system. For evaluating the group velocities v_{gz} and v_{gy} we take the derivatives of the real part of the eigenfrequency ω_r , with respect to k_z and k_y , respectively, i.e., $v_{gz} = \Delta \omega_r / \Delta k_z$ and $v_{gy} = \Delta \omega_r / \Delta k_y$. In the x direction the wave energy is confined to the vicinity of $\xi_1 = x_1 / L_c$.

Figure 1a shows the parallel group velocity normalized by the ion thermal velocity v_1 versus the ratio of the current channel size L_c and the

magnetic shear length L_s for three different values of L_s . Here $b = 0.6$, $\tau = 0.5$, $\mu = 1837$ and $V_d^0/v_e = 0.28$. In order to evaluate the value of $(k_y \lambda_i)^2$ we have used the parameters of Ashour-Abdulla and Thorne⁹, i.e., $n_0 \sim 10^{-3}$, $B_0 \sim 0.06$ G, and $T_i \sim 2$ eV. For the first harmonic $(k_y \lambda_i)^2 \sim 0.01$ and that term in equation (5) contributes negligibly. The most interesting result of figure 1a is that in the limit $L_c \rightarrow \infty$, $V_{gz} \rightarrow 0$. One finds that as L_c is increased beyond L_s , V_{gz} approaches zero as $(L_s/L_c)^2$. Further, when L_c is made smaller than $10^{-2} L_s$ the value of V_{gz} attains its local value (i.e., the value predicted by local theories^{1,6}) and stabilizes at that value. However, when L_c is further reduced such that $L_c < \rho_i$, V_{gz} once again decreases.

Figure 1b is a plot of V_{gy} against L_c/L_s for the parameters of Figure 1a. Here too we find a reduction in V_{gy} in the shear dominated regime (i.e., $L_c \gtrsim L_s$) much in the same fashion as the temporal growth rate.⁴ However, the difference between the local and the nonlocal values of V_{gy} is not as striking as that of V_{gz} . As noted by Ashour-Abdulla and Thorne,⁹ V_{gy} for the CDICI near the dominant normal mode (which occurs for $b \sim 0(1)$) is extremely small; and combined with our results that $V_{gz} \rightarrow 0$ in the nonlocal regime the CDICI becomes, effectively, an absolute instability. For $L_c < \rho_i$, V_{gy} becomes negative. Figures 2a and 2b are plots similar to 1a and 1b for the second harmonic. Here we use $\tau = 1$, $V_d^0/v_e = 0.55$ and $b = 2.4$. The value of b for all the calculations corresponds to the maximum temporal growth rate. We see trends similar to figure 1a and 1b for the higher harmonic also.

In Figure 3 we plot the convective growth rate $k_{iz} = \gamma/V_{gz}$ normalized by the mean ion Larmor radius versus L_c/L_s . We see two distinct regions

joined smoothly. For very small L_c/L_s (i.e., $L_c/L_s \lesssim 10^{-3}$), $k_{iz}\rho_i < 0$ which indicates spatially damped waves. When L_c/L_s is increased the curves attain a plateau which corresponds to the local theory. Here we find a finite $k_{iz}\rho_i$ and, hence, a finite region in which the wave amplitude can be amplified by one e-fold. For $L_c \gtrsim L_s$, $k_{iz}\rho_i$ grows without bound, implying that the wave amplitude can e-fold in an insignificantly small region (Recall that the system is assumed to be infinite and uniform in the y direction, hence convection in this direction is ignorable). Thus the character of CDICI is changed from convective to absolute.

We have so far considered only one species of ions characterized by a temperature T_i . In order to make the system more realistic, especially for space applications, we added a second ion species characterized by a hotter temperature but still with a Maxwellian distribution. The general features of the group velocity behavior is still the same as in a single ion species. A more detailed parametric study of the nonlocal convective aspects of CDICI with a loss cone distribution for the hotter ion species, along with the magnetospheric application will be presented elsewhere.

III. DISCUSSION

Thus, in contrast to local theory, nonlocal theory gives zero group velocity for the CDICI along the average external magnetic field direction in the limit $L_c > L_s$. Clearly the ratio L_c/L_s is the important parameter and its magnitude must be well established before making definitive conclusions regarding the electrostatic CDICI. Depending on the value of L_c/L_s , the CDICI can be classified into three main regimes:

- (i) $\underline{L_c \gtrsim 0.1 L_s}$ This regime is purely nonlocal with a temporal growth rate much reduced from its local value. Also the instability is absolute or only very weakly convective in the z direction which is the direction of the average external magnetic field and the current flow. There is no energy flow in the x direction, and energy flow in the y direction is ignorable if $\frac{\partial}{\partial y} \equiv 0$.
- (ii) $\underline{L_c < 0.01 L_s}$ In this regime nonlocal theory reproduces the results of local theory, and the instability becomes convective in the z direction with a convective, as well as a temporal growth rate, equal to the ones given by the local theory. There is a smooth transition between regimes (i) and (ii) as is evident in all the figures.
- (iii) $\underline{L_c \sim \rho_1 \ll L_s}$ The finite channel width becomes important. There is once again a reduction in the temporal growth rate (filamental quenching⁴) but the instability remains convective, i.e., V_{gz} remains non-zero. However, when L_c is further reduced so that $L_c < \rho_1$ both V_{gz} and V_{gy} become reduced and eventually become negative.

Physically the reason for vanishing parallel group velocity can be described as follows. Figure 4 shows the angle space where the imaginary part of the local dispersion relation $D_I < 0$, and the growth rate is positive for the CDICI. The extent of this unstable angular space Δu for the CDICI in our parameter range is about 0.1. In the nonlocal theory a wave packet is formed whose size is governed by the smaller of the two scale lengths L_c and $0.1 L_s$. When $L_c < 0.1 L_s$ the drift velocity $V_d(x)$ varies sufficiently fast as a function of x , or as a function of the angle

u within the space Δu , so as to form an effective Q_I curve which has the form of a steep well. The position of the bottom of this well is at $u_0 = k_z/k_y$; thus different choices of k_z center the well in different parts of the region Δu and the corresponding wave packets (of size $\sqrt{\rho_1 L_c}$) sample different regions of Δu which lead to different growth rates γ as well as different real frequencies ω_r . On the other hand, when $L_c > L_s$, the variation of $V_d(x)$ in the domain Δu is rather weak and the effective Q_I curve is governed by the variation of u rather than that of V_d in Eq. (3). Now, if we choose different k_z , an appropriate translation in x (i.e., moving away from the center of the slab) is sufficient to provide almost the same invariant Q_I curve as a function of u . The resulting wave packet (of size $\sqrt{\rho_1 L_s}$) forms at the same position in u space (even though we choose different k_z) and has the same growth rate γ and real frequency ω_r , independent of k_z . This makes the group velocity $\partial\omega_r/\partial k_z$ vanish in the limit $L_c \rightarrow \infty$.

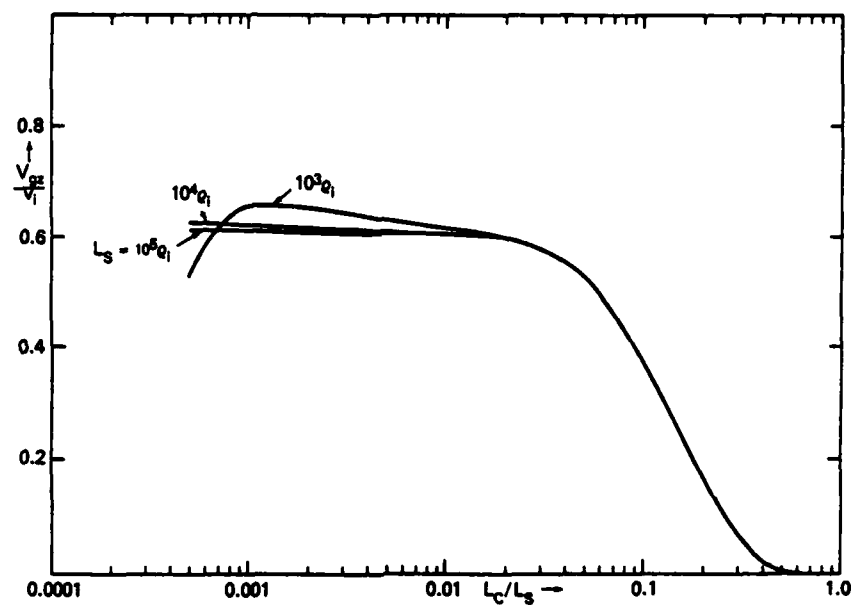
IV. CONCLUSION

We have shown in this paper that the nonlocal effects due to the magnetic shear (produced by a field aligned current) and a finite channel current width can drastically alter the character of the electrostatic CDICI by making the instability effectively absolute in the z direction. The important parameter turns out to be the ratio of the two scale lengths involved in the problem L_c and L_s . Depending on the value of L_c/L_s one can classify the CDICI in three regimes as described earlier, and a careful assessment of the value of L_c/L_s for a given physical situation becomes

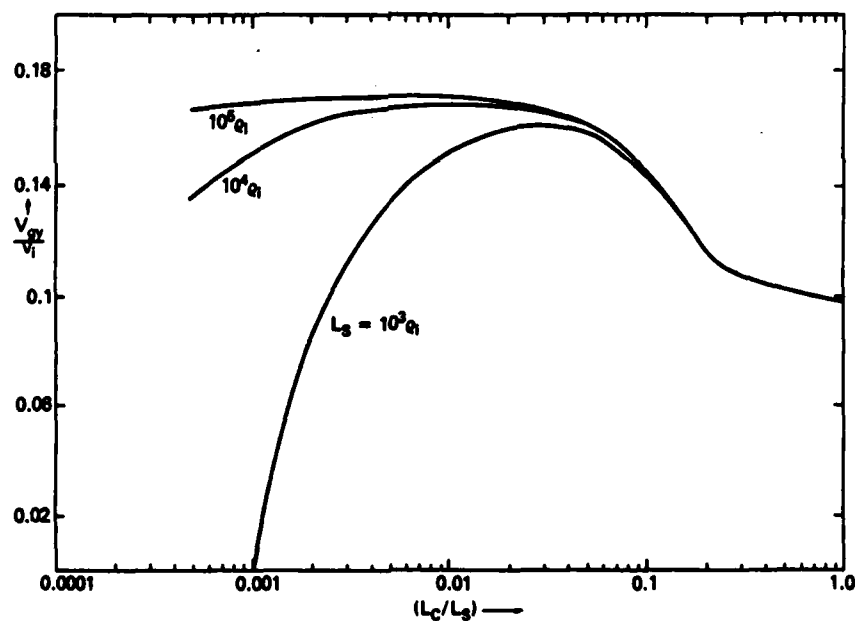
essential to draw any definitive conclusion regarding the growth and convective characteristics of the electrostatic CDICI. We would also like to note that the nonlocal effects due to magnetic shear can be expected to produce corresponding phenomena, including the vanishing of the parallel group velocity, in various other current driven instabilities as well.

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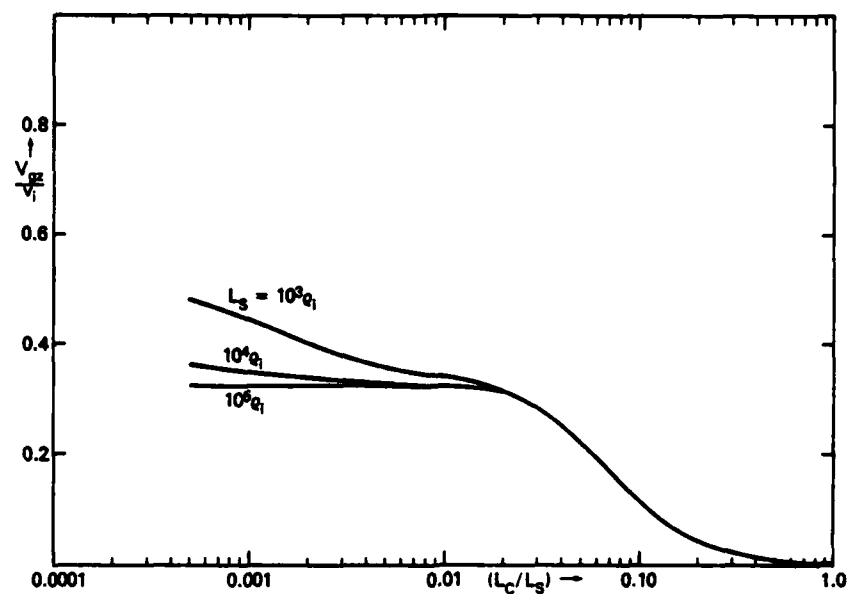
(a)



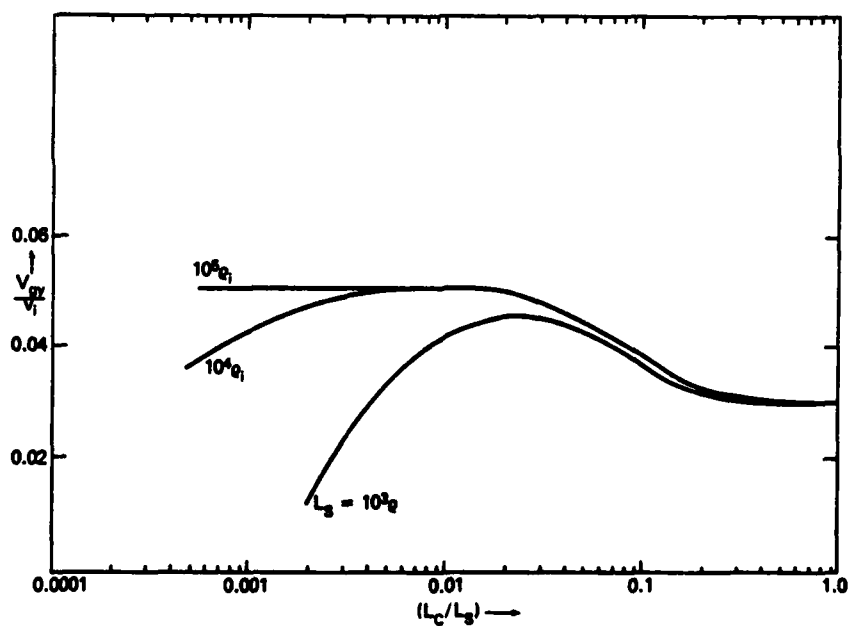
(b)

Figure 1

A plot of the group velocity against L_c/L_s for the first harmonic. Here $b = 0.6$, $\tau = 0.5$, $\mu = 1837$ and $V_d^0/v_e = 0.28$. (a) The group velocity in the $\hat{z}$ direction v_{gz}/v_1 against L_c/L_s ; (b) the group velocity in the y direction v_{gy}/v_1 against L_c/L_s .



(a)



(b)

Figure 2

A plot similar to Fig. (1) for the second harmonic. Here $b = 2.4$, $\tau = 1.0$, $\mu = 1837$ and $V_d^0/v_e = 0.55$. (a) V_{gz}/v_1 against L_c/L_s ; (b) V_{gy}/v_1 against L_c/L_s .

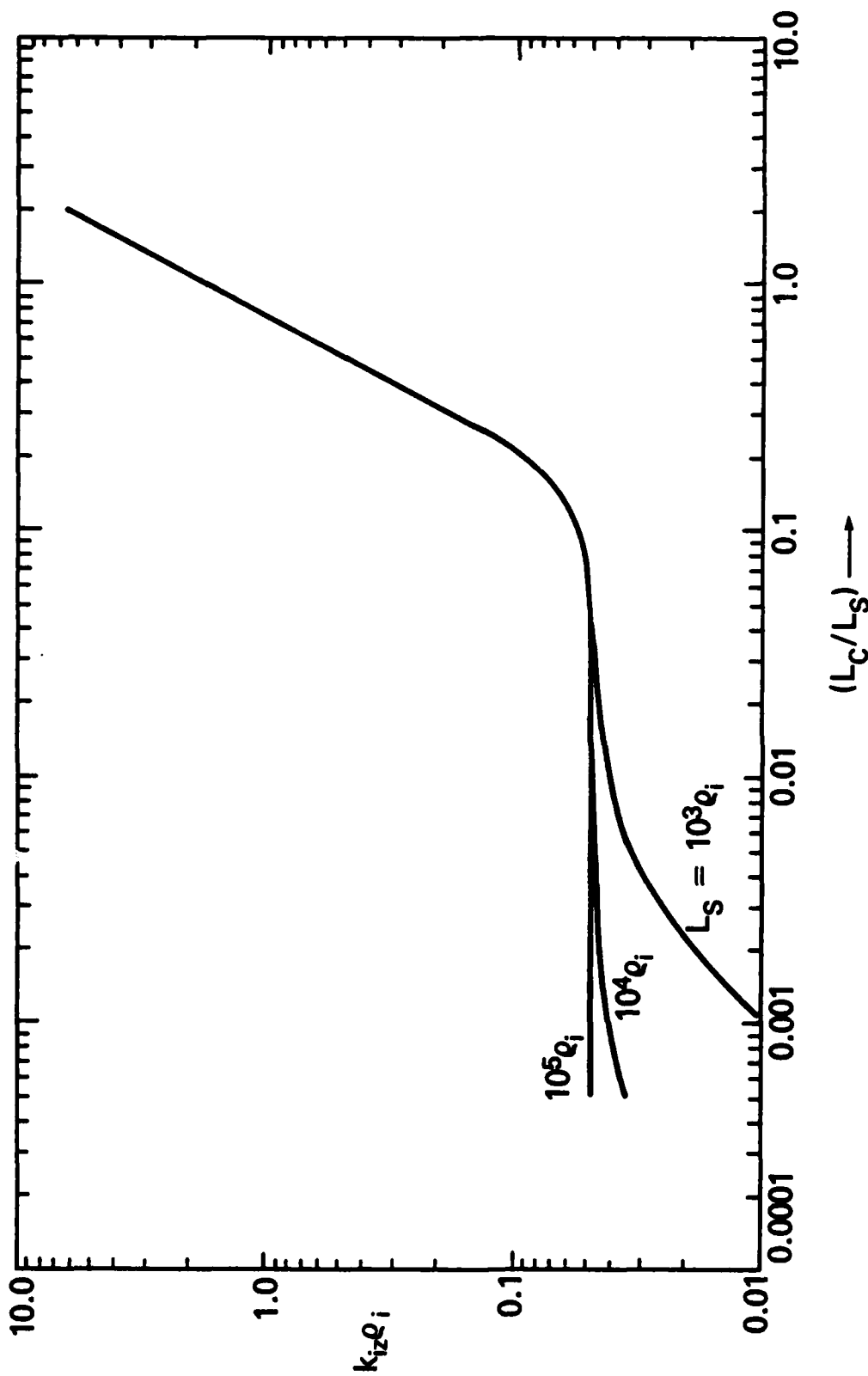


Figure 3

A plot of the convective growth rate normalized by the ion Larmor radius $k_{iz}\rho_i$ versus L_c/L_s for the first harmonic. The other parameters are identical to la.

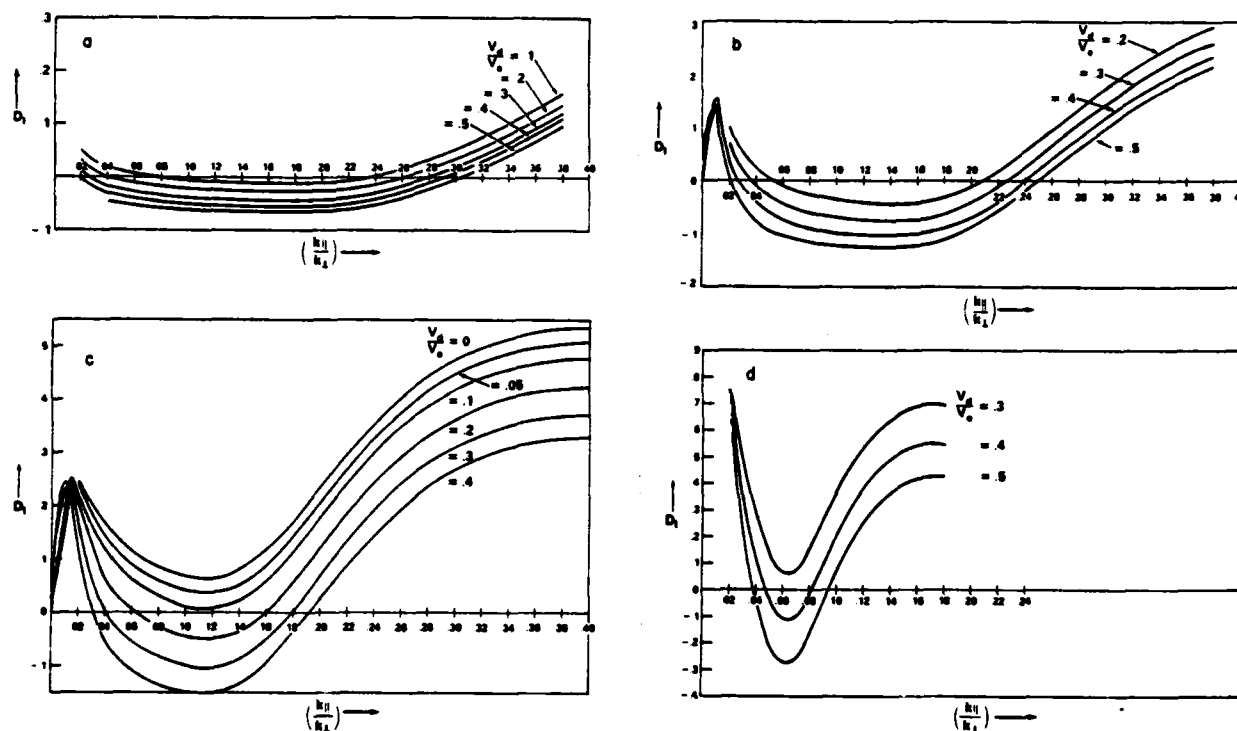


Figure 4

A plot of imaginary part of the local dispersion relation $D_I(\omega, k)$ against k_z/k_1 (reproduced from Ref. 2) for various V_d^0/v_e . Here $b = 0.5$, $\mu = 3674$ and four different values of the temperature ratio τ : (a) $\tau = 0.1$, (b) $\tau = 0.2$, (c) $\tau = 0.33$, and (d) $\tau = 1.0$.

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