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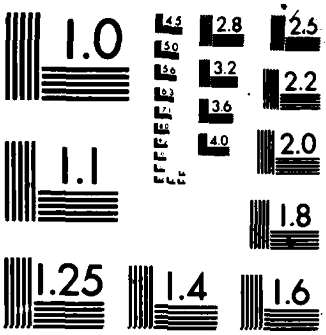

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A preliminary investigation of collisional effects on the magnetized ion-ion instability is made. It is found that ion-neutral collisions have a stabilizing influence in that they stabilize all growing modes for sufficiently large collision frequencies. On the other hand, electron-ion collisions have a destabilizing influence in that modes that are stable in the collisionless regime can be unstable because of electron-ion collisions. Applications of these results to the DNA/NRL laser experiment are discussed.

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INFLUENCE OF COLLISIONS ON THE MAGNETIZED ION-ION INSTABILITY

CONTENTS

INFLUENCE OF COLLISIONS ON THE MAGNETIZED ION-ION INSTABILITY

I. INTRODUCTION

The subject of microinstabilities, and their influence on early time HANE phenomena, had been of great interest to the DNA community in the early to mid 70's. A considerable amount of work performed at NRL indicated that microinstabilities could substantially enhance the transport of momentum and energy between debris and air plasmas over classical processes through "anomalous" wave-particle interactions (Lampe et al., 1975). Renewed interest in this area has recently been generated by the DNA/NRL laser experiment. One of the purposes of this experiment is to identify and understand the processes that could lead to the "collisionless" coupling of debris-air plasma, such as microturbulence. To this end, a number of authors have suggested parameter regimes relevant to the laser experiment in which one or more plasma instabilities could be excited (Longmire et al., 1981; Tsai et al., 1982; Smith and Huba, 1983; Brecht and Ambrosiano, 1983). The focus of these efforts has been on the collisionless regime which is relevant to HANEs. However, the laser experiment has the flexibility to explore a broad range of parameters, and can therefore operate not only in the collisionless regime but also in the collisional regime. Thus, it is possible that collisional effects could play a role in the onset and/or behavior of several microinstabilities that may be excited in certain parameter regimes.

The purpose of this paper is to explore the influence of collisions (viz., electron-ion and ion-neutral) on the magnetized ion-ion instability (Papadopoulos et al., 1971). We find that collisions can have a dramatic effect on the linear behavior of the magnetized ion-ion instability.

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Loosely speaking, ion-neutral collisions have a stabilizing influence (i.e., they can produce damped modes ($\gamma < 0$)) while electron-ion collisions have a destabilizing influence (i.e., they can lead to unstable modes in regimes in which the collisionless magnetized ion-ion instability is stable).

The organization of the paper is as follows. In the next section we derive the dispersion equation for the magnetized ion-ion instability in the presence of electron-ion and ion-neutral collisions. In Section III we present numerical results of the effects of these collisions on the instability. Finally, in the last section we summarize our results and discuss the implication of these results on the debris-air coupling process.

II. DERIVATION OF DISPERSION EQUATION

The plasma configuration and slab geometry used in the analysis is shown in Fig. 1. The ambient magnetic field is in the z direction $\left(\underset{\sim}{B} = B_0 \hat{e}_z\right)$. Two counterstreaming ion species are considered which are taken to be, for simplicity, the same type of ions of the same density. We work in the electron frame of reference so that $\underset{\sim}{V}_{0e} = 0$, and $V_{0i}^{(1)} = V_0$ and $V_{0i}^{(2)} = -V_0$, where $V_{0\alpha}$ is the equilibrium velocity of the α species and the superscripts refer to the different ion distributions. We take $n_{0i}^{(1)} = n_{0i}^{(2)} = 2n_{0e}$ where $n_{0\alpha}$ is the equilibrium density of the α species. Perturbations are taken of the form $\delta p \sim \delta p \exp[i(ky - \omega t)]$. We assume $\Omega_i << \omega << \Omega_e$, $kr_{Li} >> 1$, and $kr_{Le} << 1$ where Ω_α is the cyclotron frequency and $r_{L\alpha}$ is the mean Larmor radius of species α. We assume that the ions are cold $\left(V_0 >> v_i\right)$ (i.e., we neglect ion Landau damping) and unmagnetized. The electrons are strongly magnetized. We consider collisions between ions and neutrals $\left(\nu_{in}\right)$, and between electrons and ions $\left(\nu_{ei}\right)$. We assume weak collisions (.e., $\nu_{in} << \Omega_i$ and $\nu_{ei} << \Omega_e$). We neglect ion-ion collisions in the instability analysis since their effect is to "demagnetize" the ions when $\nu_{ii} k^2 r_{Li}^2 > \Omega_i$ (Dougherty, 1964).

The basic equations considered in the analysis are continuity, momentum transfer, Poisson's equation and Ampere's law:

$$\frac{\partial n_\alpha}{\partial t} + \nabla \cdot \left(n_\alpha \underset{\sim}{V}_\alpha\right) = 0 \tag{1}$$

$$\frac{dV_i^{(1)}}{dt} = \frac{e}{m_i} \underset{\sim}{E} - \nu_{in}^{(1)} \underset{\sim}{V}_i^{(1)} \tag{2}$$

$$\frac{dV_i^{(2)}}{dt} = \frac{e}{m_i} \underset{\sim}{E} - \nu_{in}^{(2)} \underset{\sim}{V}_i^{(2)} \tag{3}$$

$$\frac{d\underset{\sim}{V}_e}{dt} = - \frac{e}{m_e} \left(\underset{\sim}{E} + \frac{1}{c} \underset{\sim}{V}_e \times \underset{\sim}{B}\right) - \nu_{ei} \underset{\sim}{V}_e \tag{4}$$

$$\nabla \cdot \underset{\sim}{E} = 4\pi \left(n_i - n_e\right) \tag{5}$$

$$\nabla \times \underset{\sim}{B} = \frac{4\pi}{c} \underset{\sim}{J} \tag{6}$$

We linearize Eqs. (1)-(6) by taking $n_\alpha = n_{0\alpha} + \delta n_\alpha$, $\underset{\sim}{V}_\alpha = \underset{\sim}{V}_{0\alpha} + \delta \underset{\sim}{V}_\alpha$, $\underset{\sim}{B} = \underset{\sim}{B}_0 + \delta \underset{\sim}{B}$, $\underset{\sim}{E} = - \nabla\phi - c^{-1} \partial \underset{\sim}{A}/\partial t$ and $\delta \underset{\sim}{B} = \nabla \times \underset{\sim}{A}$. Note that we are incorporating electromagnetic effects in the dispersion equation by allowing fluctuating magnetic field perturbations. For simplicity we are considering perturbed potentials (ϕ and $\underset{\sim}{A}$) instead of perturbed fields. We also are using the Coulomb gauge $\nabla \cdot \underset{\sim}{A} = 0$.

The perturbed velocities are given by

$$\delta \underset{\sim}{V}_i^{(1)} = \frac{e}{m_i} \frac{k\phi}{\omega - kV_0 + i\nu_{in}} \hat{e}_y \tag{7}$$

$$\delta \underset{\sim}{V}_i^{(2)} = \frac{e}{m_i} \frac{k\phi}{\omega + kV_0 + i\nu_{in}} \hat{e}_y \tag{8}$$

$$\delta \underset{\sim}{V}_e = - i \frac{c}{B} k\phi \hat{e}_x + \left[\frac{c}{B} \frac{\omega + i\nu_{ei}}{\Omega_e} k\phi - i \frac{\omega}{B_0} A_x\right] \hat{e}_y \tag{9}$$

Substituting Eqs. (7)-(9) into the continuity equation (Eq. (1)) we obtain the perturbed densities

$$\delta n_i^{(1)} = n_{0i}^{(1)} \frac{e}{m_i} \frac{k}{\omega - kV_0} \frac{k\phi}{\omega - kV_0 + i\nu_{in}} \tag{10}$$

$$\delta n_i^{(2)} = n_{0i}^{(2)} \frac{e}{m_i} \frac{k}{\omega + kV_0} \frac{k\phi}{\omega + kV_0 + i\nu_{in}} \tag{11}$$

$$\delta n_e = \frac{c}{B} \left[\left(1 + i \frac{\nu_{ei}}{\omega}\right) \frac{k^2}{\Omega_e} \phi - i \frac{k}{c} A_x\right] \tag{12}$$

We now make the appropriate substitution of δn and $\delta \underset{\sim}{V}$ into Poisson's equation and Ampere's law (Eqs. (5) and (6)) and obtain the following dispersion equation after some algebraic manipulation

$$D(\omega,k) = 1 + \left(1 + \frac{\omega_{pe}^2}{\Omega_e^2}\right)^{-1} \left(i \frac{\nu_{ei}}{\omega} + \frac{\omega_{pe}^2}{c^2 k^2}\right) \frac{\omega_{pe}^2}{\Omega_e^2} - \frac{\omega_0^2}{(\omega - kV_0)(\omega - kV_0 + i\nu_{in})} - \frac{\omega_0^2}{(\omega + kV_0)(\omega + kV_0 + i\nu_{in})} = 0 \tag{13}$$

where

$$\omega_0^2 = \frac{1}{2} \frac{\omega_{pi}^2}{1 + \omega_{pe}^2/\Omega_e^2}$$

Equation (13) reduces to the correct collisionless limit when $\nu_{ei} = 0$ and $\nu_{in} = 0$. It is clear from Eq. (13) that collisions alter the structure of the dispersion equation for the magnetized ion-ion instability.

III. NUMERICAL RESULTS

In order to understand the effects of collisions on the instability we rewrite Eq. (13) in dimensionless form and solve it numerically. That is, we consider

$$D(\hat{\omega}, \hat{k}) = 1 + i\,\frac{\hat{\nu}_{ei}}{\hat{\omega}} + \frac{2\hat{V}_0^2}{\hat{k}^2}$$

$$- \frac{1}{(\hat{\omega} - \hat{k})(\hat{\omega} - \hat{k} + i\hat{\nu}_{in})} - \frac{1}{(\hat{\omega} + \hat{k})(\hat{\omega} + \hat{k} + i\hat{\nu}_{in})} = 0 \qquad (14)$$

where $\hat{\omega} = \omega/\omega_0$, $\hat{\nu}_{ei} = \nu_{ei}/\omega_0$, $\hat{\nu}_{in} = \nu_{in}/\omega_0$, $\hat{V}_0 = V_0/V_A$, $\hat{k} = k\,V_0/\omega_0$ and $V_A = B_0/(4\pi n_{0i} m_i)^{1/2}$ is the Alfvén velocity. We consider the influence of ion-neutral and electron-ion collisions separately.

A. Ion-neutral Collisions

We consider $\hat{\nu}_{in} \neq 0$ and $\hat{\nu}_{ei} = 0$. We also take $V_A >> V_0$ so that electromagnetic corrections can be neglected and take $\omega_{pe}^2 >> \Omega_e^2$ for simplicity. The dispersion equation is then

$$D(\omega, k) = 1 - \frac{1}{(\hat{\omega} - \hat{k})(\hat{\omega} - \hat{k} + i\hat{\nu}_{in})} - \frac{1}{(\hat{\omega} + \hat{k})(\hat{\omega} + \hat{k} + i\hat{\nu}_{in})} = 0 \qquad (15)$$

We plot $\hat{\gamma}$ vs. $\hat{\nu}_{in}$ for $\hat{k} = 0.86$ in Fig. 2 (solid line). The wavenumber chosen yields the maximum growth rate in the collisionless limit. The major result of Fig. 2 is the stabilizing influence of ion-neutral collisions. As $\hat{\nu}_{in}$ increases the growth rate decreases monotonically and eventually becomes negative for $\hat{\nu}_{in} > 1$. We note that the imaginary part of the denominator in Eq. (15) is proportional to $2\hat{\gamma} + \hat{\nu}_{in}$. Taking $2\hat{\gamma} + \hat{\nu}_{in}$ = constant = 1 we find that $\hat{\gamma} = (1 - \hat{\nu}_{in})/2$ which is plotted in Fig. 2 (dashed line). Thus, this simple expression yields a relatively good value for the collisional growth rate.

B. Electron-ion Collisions

We now consider $\hat{\nu}_{ei} \neq 0$ but take $\hat{\nu}_{in} = 0$. Again we take $\omega_{pe}^2 \gg \Omega_e^2$ for simplicity but retain electromagnetic corrections. The dispersion equation is given by

$$D(\hat{\omega}, \hat{k}) = 1 + i \frac{\hat{\nu}_{ei}}{\hat{\omega}} + 2 \frac{\hat{V}_0^2}{\hat{k}^2} - \frac{1}{(\hat{\omega} - \hat{k})^2} - \frac{1}{(\hat{\omega} + \hat{k})^2} = 0 \qquad (16)$$

In Fig. 3 we plot $\hat{\gamma}$ vs. $\hat{k}$ for several values of $\hat{\nu}_{ei}$ (specifically, $\hat{\nu}_{ei}$ = 0.0, 0.1, 1.0, and 10.0). We have taken $V_A \gg V_0$ so that electromagnetic effects are neglected. The collisionless growth rate $(\hat{\nu}_{ei} = 0)$ attains a maximum value $\hat{\gamma} = 0.5$ at $\hat{k} = 0.86$ and is stable for $\hat{k} > 1.41$ (i.e., $\gamma = 0$). However, for finite $\hat{\nu}_{ei}$ two effects occur. First, the value of maximum growth decreases from the maximum collisionless value. Second, and more interesting, the range of unstable wavenumbers is increased over the collisionless case and the "hard" collisionless cut-off at $\hat{k} = 1.41$ has become "soft". In fact, for $\hat{\nu}_{ei} > 1$ the most unstable modes shift to short wavelengths, i.e., $\hat{k} > 1$. Thus, electron-ion collisions can be thought of as being destabilizing.

In Fig. 4 we plot $\hat{\gamma}$ vs. $\hat{k}$ for $\hat{V}_0 = 2.0$ and $\hat{\nu}_{ei}$ = 0.0, 1.0, 10.0. For $\hat{\nu}_{ei} = 0$ we find that $\hat{\gamma} = 0$, i.e., the modes are stable because of electromagnetic effects. However, as $\hat{\nu}_{ei}$ increases short wavelength modes $(\hat{k} \gtrsim 1.0)$ are destabilized $(\hat{\gamma} > 0)$. And for relatively large $\hat{\nu}_{ei}$, such as $\hat{\nu}_{ei} = 10.0$, the growth rate is substantial $(\hat{\gamma} \simeq 0.3)$. Thus, the "hard" electromagnetic cut-off is mitigated by electron-ion collisions and waves can grow that are stable in the collisionless regime.

IV. DISCUSSION

We have made a preliminary investigation of collisional effects on the magnetized ion-ion instability. We find that ion-neutral collisions have a stabilizing influence on the instability in that they stabilize all growing modes for sufficiently large values (i.e., $\hat{\nu}_{in} > 1.0$). On the other hand, electron-ion collisions have a destabilizing influence on the instability in that modes that were stable in the collisionless regime can become unstable for $\hat{\nu}_{ei}$ finite.

We now consider the relevance of these results as they could apply to the DNA/NRL laser experiment. The experiment has the flexibility that it can survey a broad range of densities, and therefore a broad range of collision frequencies. The most important collisions to be considered are electron-ion. Ion-neutral collisions are probably unimportant because the coupling shell appears to be almost completely ionized (McLean, private communication). We show the values of ν_{ei} for $n = 10^{14}$, 10^{15}, 10^{16} cm^{-3} and $T_e = 10$ eV, ω_0 for $B_0 \simeq 4$ kG, and the ratio ν_{ei}/ω_0 in Table I. Clearly, a wide range of ν_{ei}/ω_0 can occur in the laser experiment. Thus, the linear behavior of the magnetized ion-ion instability could be altered by collisions and this effect may be observable in the laser experiment.

The more important question to consider though is, what is the relevance of these results to momentum coupling? The criteria that come to bear on this question are the following:

$$\nu_{ei} > \omega_0$$

$$\nu_{an} > \nu_{ii}$$

The first inequality is necessary since for $\nu_{ei} < \omega_0$ collisions do not seem to affect the instability significantly. The second criteria requires that the anomalous collision frequency between ions be greater than binary ion-ion collisions, that is, we want anomalous collisional effects to dominate Coulomb collisional effects. Taking $\nu_{an} \sim 0.1\ \omega_0$ and $\nu_{ii} \sim (m_e/m_i)^{1/2}\ \nu_{ei}$, we find that the two criteria can be combined to give

$$\left(\frac{m_e}{m_i}\right)^{1/2} < \frac{\nu_{ei}}{\Omega_e} < 0.1$$

so that only a limited range of n, T_e, and B_0 satisfy this condition. Thus, although electron-ion collisions can significantly alter the linear behavior of the magnetized ion-ion instability (drive collisionlessly stable modes unstable), this effect should only have a minimal impact of enhancing the momentum coupling of the debris-air plasmas.

Finally, collisional effects could also be important to other instabilities such as the modified two stream and the unmagnetized ion-ion instability, and should be investigated. Also, a more complete analysis, i.e., including thermal effects, is probably worthwhile.

ACKNOWLEDGMENTS

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Table I

$n(cm^{-3})$	$\nu_{ei}(sec^{-1})$	$\omega_0(sec^{-1})$	ν_{ei}/ω_0
10^{16}	2×10^{10}	2×10^{9}	10.0
10^{15}	2×10^{9}	2×10^{9}	1.0
10^{14}	2×10^{8}	2×10^{9}	0.1

$T_e = 10$ eV; $B_0 = 4$ kG

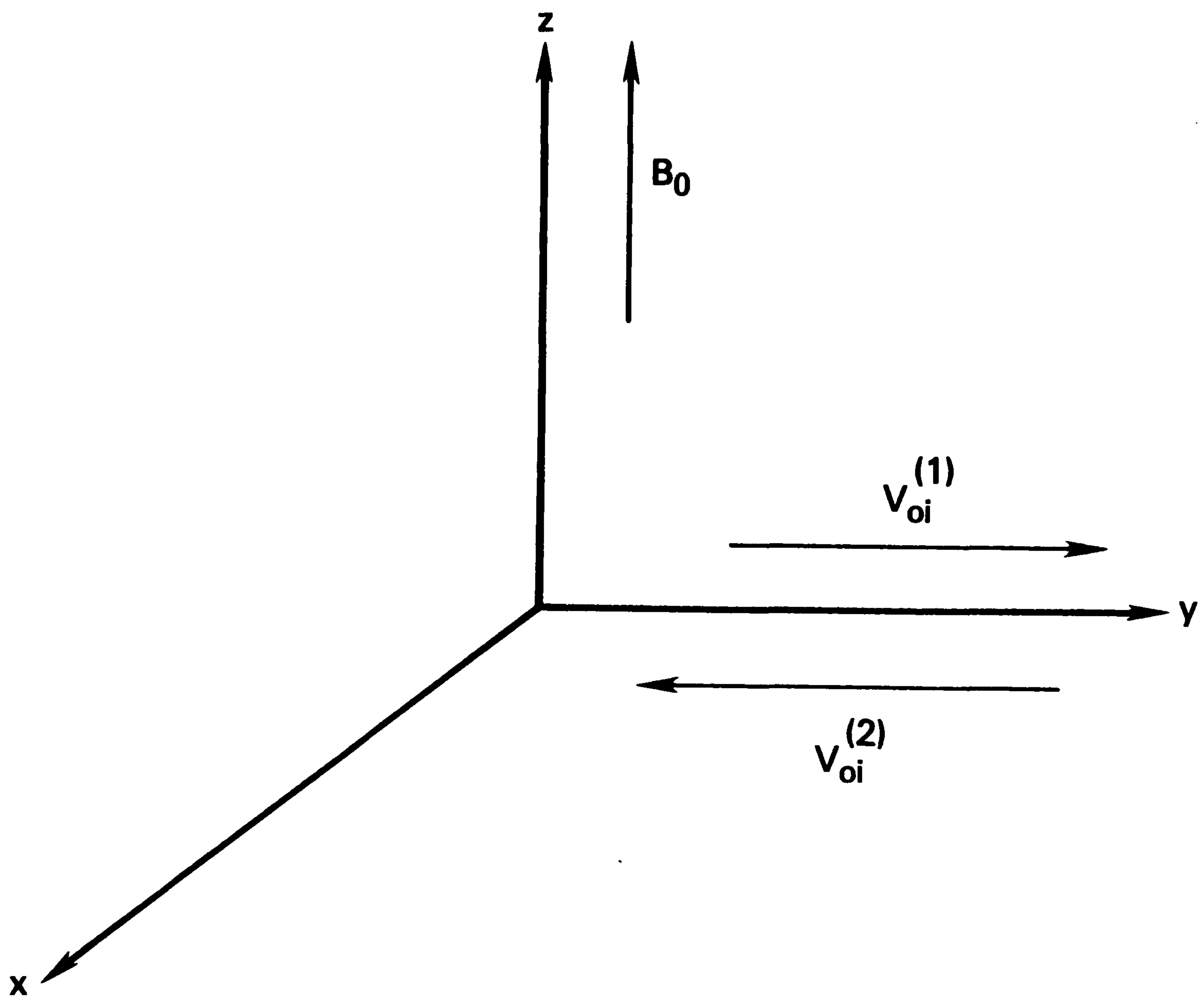

Fig. 1 Slab geometry and plasma configuration.

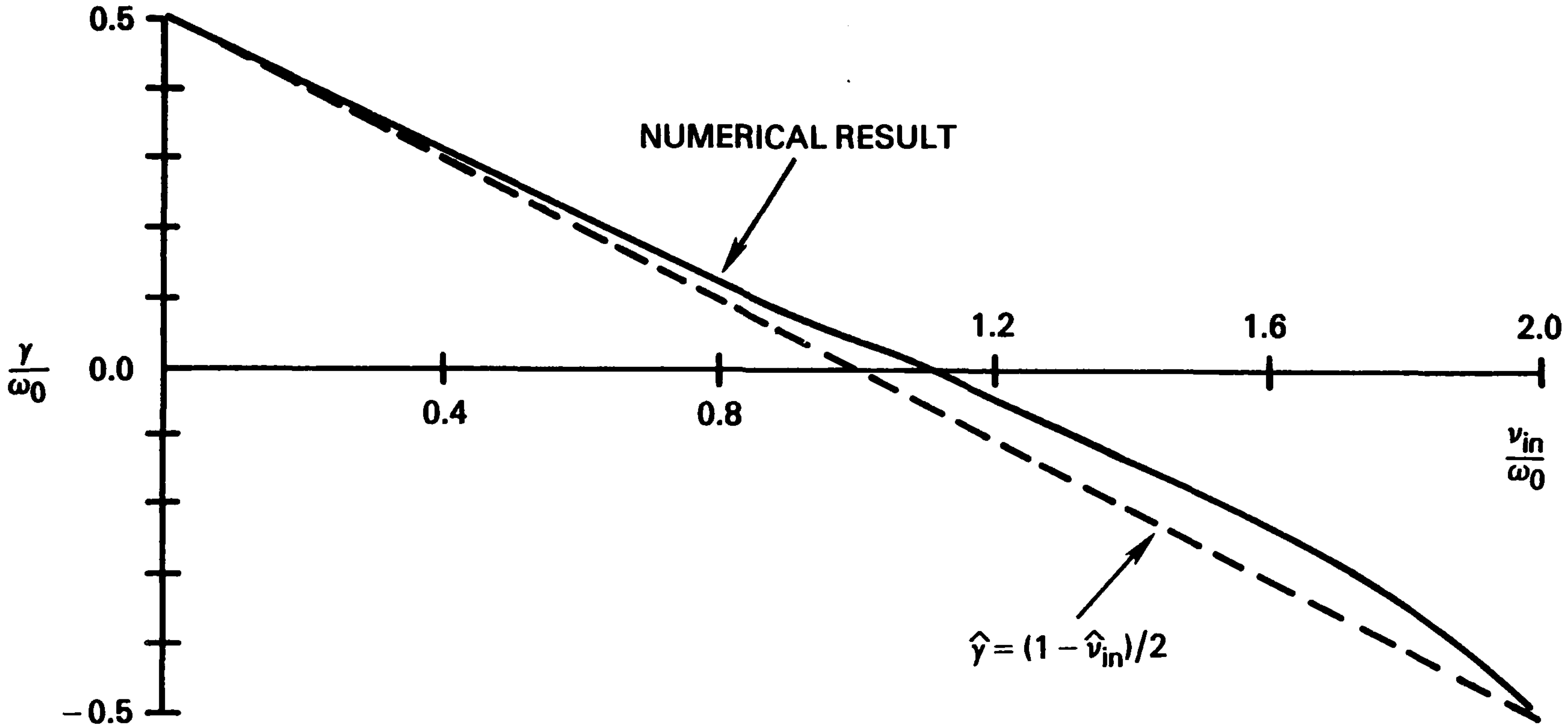

Fig. 2 Plot of $\hat{\gamma}$ vs. $\hat{\nu}_{in}$ for $\hat{k} = 0.86$. The solid curve is the solution of Eq. (15) while the dashed curve is the approximate solution $\hat{\gamma} = (1 - \hat{\nu}_{in})/2$.

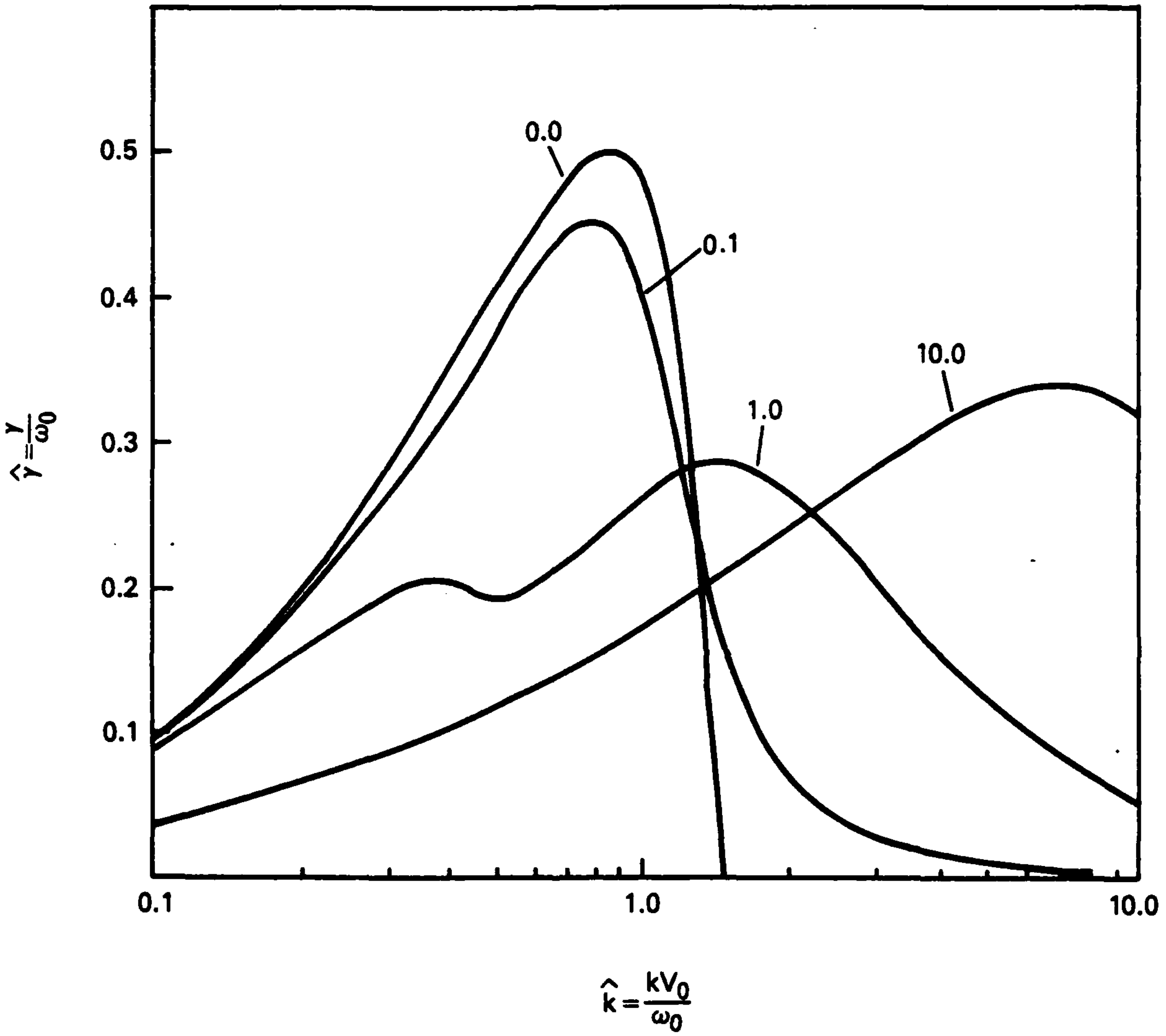

Fig. 3 Plot of $\hat{\gamma}$ vs. $\hat{k}$ for $\hat{\nu}_{ei}$ = 0.0, 0.1, 1.0, and 10.0. Equation (16) is solved assuming $\hat{V}_0 \rightarrow 0$.

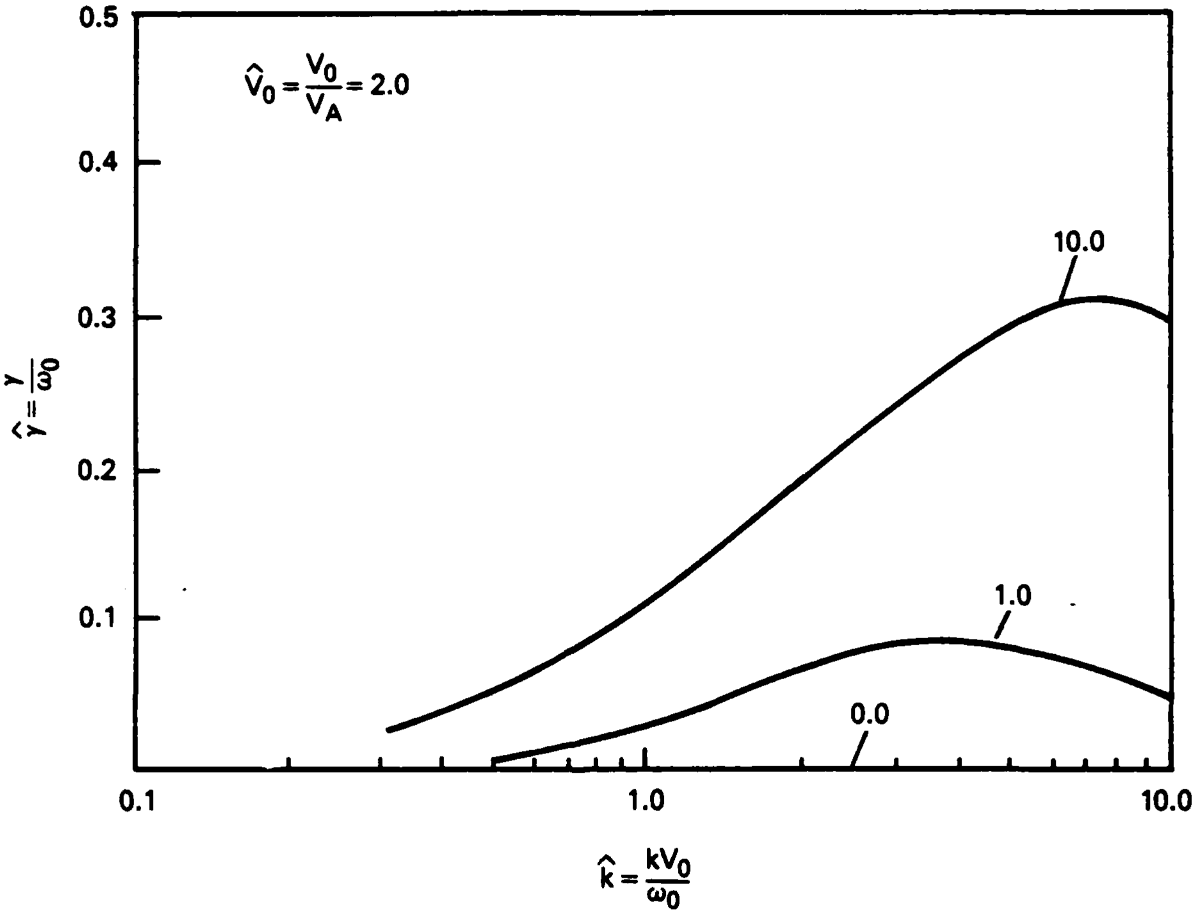

Fig. 4 Plot of $\hat{\gamma}$ vs. $\hat{k}$ for $\hat{V}_0 = 2.0$ and $\nu_{ei} = 0.0$, 1.0, and 10.0. The growth rate for $\nu_{ei} = 0.0$ is $\hat{\gamma} = 0$. Note the "destabilizing" influence of electron-ion collisions.

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