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INFLUENCE OF HOT BEAM IONS ON MHD BALLOONING MODES IN TOKAMAKS

by

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ABSTRACT

It has recently been proposed that the presence of high energy ions from neutral beam injection can have a strong stabilizing effect on kinetically-modified ideal MHD ballooning modes in tokamaks. In order to assess realistically the importance of such effects, a comprehensive kinetic stability analysis, which takes into account the integral equation nature of the basic problem, has been applied to this investigation. In the collisionless limit, the effect of adding small fractions of hot beam ions is indeed found to be strongly stabilizing. On the other hand, for somewhat larger fractions of hot ions, a new beam-driven mode is found to occur with a growth rate comparable in magnitude to the growth rate of the MHD ballooning mode in the absence of hot ions. This implies that there should be an optimal density of hot particles which minimizes the strength of the relevant instabilities. Employing non-Maxwellian equilibrium distribution functions to model the beam species makes a quantitative, but not qualitative, difference in the results. Adding collisions to the calculation tends to reduce considerably the stabilizing effect of the hot ions.

I. INTRODUCTION

It has been proposed recently that the presence of both untrapped [1] and trapped [2] high energy ions from neutral beam injection can have a strong stabilizing effect on high-n ideal MHD ballooning modes. In order to assess realistically the importance of such effects, a comprehensive kinetic stability analysis [3], which takes into account the integral equation nature of the basic problem, has been applied to this investigation. For the same parameters and the same model MHD equilibrium used in Ref. 1, the stabilizing trend reported when the fraction of hot ions and/or the hot-ion temperature is increased [1], is reproduced. However, if collisions are taken into account, this favorable trend is found to persist but to be considerably weaker. Results of calculations using realistic beam-species equilibrium distribution functions [4], instead of idealized Maxwellian distributions [1], are also presented and discussed.

The system of three integro-differential eigenmode equations that are solved and the solution methods are described in detail in Ref. 3. Because the ballooning formalism is employed for toroidal mode numbers $n>>1$, the equations are one-dimensional along the magnetic field lines and are radially local to lowest order in $1/n$. The analysis is fully electromagnetic, including compressional coupling to acoustic waves [5]. Complete trapped-particle dynamics are included in the calculation for all species. All forms of collisionless dissipation, including bounce, transit, and magnetic drift frequency resonances, are included in the calculation without approximations [5]. An energy and pitch-angle dependent Krook collision operator is employed to model collisional dissipation. This model collision operator has been shown [6] to yield the same results as a Lorentz collision operator in certain limits in the banana regime in the electrostatic limit. Here we are employing it in more general electromagnetic cases where its accuracy is somewhat uncertain. This general kinetic stability code can be used with arbitrary realistic numerical MHD equilibria, as well as with analytic model equilibria. In this paper, the same model MHD equilibrium employed in Ref. 1 is used, so that comparisons with the results of Ref. 1 can be made readily. This model equilibrium has circular but non-concentric magnetic surfaces.

Hot particle effects can be calculated with either an idealized Maxwellian equilibrium distribution function for the beam species, as in Ref. 1, or with a realistic, numerically calculated, equilibrium distribution function [4]. In this calculation, as in Ref. 1, growth rates are calculated for unstable modes over an appropriate range of β values with $\beta \equiv$ local plasma pressure/magnetic pressure. However, the calculation in Ref. 1 invokes many more approximations than are made in the present analysis. In contrast to these studies, Ref. 2 focuses on the issue of marginal stability; i.e., instead of growth rates, only the value of β at marginal stability (β_c) is calculated.

In Sec. II, results for the Maxwellian case, without and with collisions, are presented. In Sec. III, non-Maxwellian equilibrium distribution functions typical of parallel and perpendicular neutral beam injection [4] are considered. Conclusions are presented in Sec. IV.

II. MAXWELLIAN DISTRIBUTION FUNCTION CASE

The local parameters used are the same as those chosen in Ref. 1, namely: $T_i/T_e = 1$, $\eta_i = \eta_e = \eta_h = 1$, $Z_i = Z_h = 1$, $r_{nh} = r_{ni} = r_{ne}$, $m_i/m_H = m_h/m_H = 1$, $q = 2$, $r_{ne}/R_o = 0.1$, $\beta \equiv 8\pi p/B_o^2 = 1\%$, $(r/q)dq/dr = 0.6$, $b_{i\theta} \equiv k_\theta^2 \rho_i^2/2 = 0.0225$, and $\alpha \equiv -(8\pi R_o q^2/B_o^2)dp/dr = 0.8$. Here e, i, h, and H refer to the electrons, the background ions, the hot (beam) ions, and hydrogen, respectively. Also $\eta_j \equiv (d\ \ell n\ T_j/dr)/d\ \ell n\ n_j/dr)$, $r_{nj} \equiv -(d\ \ell n\ n_j/dr)^{-1}$, R_o is the major radius of the magnetic axis, $p \equiv \sum_j n_j(r)T_j(r)$, B_o is the magnetic field strength on the magnetic axis, and the rest of the notation is standard. In addition, we choose $T = 1$ keV, $r = r_{ne}$, and $R_o = 140$ cm, to complete the set of parameters. Initially, collisions are neglected, and the hot species equilibrium distribution function is taken as Maxwellian.

Growth rates are shown in Fig. 1 as a function of the hot ion density fraction, n_h/n_e, for various hot ion temperature ratios, T_h/T_e. The corresponding real frequencies are show in Fig. 2. Frequencies here are in units of ω_{*e}, the electron diamagnetic drift frequency. These results are for the kinetically-modified ideal MHD ballooning mode with the fewest nodes along the field line (none for ϕ or $A_\perp$, one for $A_\parallel$). This is usually the fastest growing eigenmode. The stabilizing trend with increasing n_h/n_e, for small n_h/n_e, reported in Ref. 1 is seen in Fig. 1 for several values of T_h/T_e. Results from Refs. 1 and 7 are also shown for $T_h/T_e = 30$ in Figs. 1 and 2 and are in reasonable quantitative agreement with the results of our more complete calculations for $n_h/n_e \lesssim 0.03$. The amount of stabilization at fixed n_h/n_e increases with increasing T_h/T_e, as is shown in Fig. 3 for $n_h/n_e = 0.02$.

On the other hand, it is found that a new mode driven by the presence of the hot ions is unstable for sufficiently large values of n_h/n_e. This is illustrated in Figs. 1 and 2 for $T_h/T_e = 30$. The same basic trend was also found in earlier studies [1, 7]. However, only the largest growth rate in the system (irrespective of origin) was plotted as a function of n_h/n_e, and the significance of the beam-driven mode was not pointed out [1]. With regard to these new modes, it should be noted that the possible presence of ballooning-type instabilities driven by energetic trapped particles has also been pointed out in recent independent analytic studies [8,9]. In fact, the growth rate of this mode increases as the fraction of hot ions increases, and it can become (for sufficiently large values of n_h/n_e) comparable in magnitude to the growth rate of the usual ballooning instability in the absence of hot ions. The eigenfunctions for both types of modes are qualitatively similar. Summarily, the basic picture in the collisionless limit is that increasing the fraction of hot ions can significantly reduce the strength of usual ballooning modes but can also drive a new instability. This suggests that, for a given value of T_h/T_e, there should be an optimum value of n_h/n_e.

In the absence of hot ions, collisions have been found to have a substantial stabilizing effect on the ideal MHD ballooning modes [5]. This feature is also displayed in Fig. 4. Here the growth rate is plotted versus ν_e^*, the ratio of the effective trapped-electron collision frequency to the bounce frequency. When hot ions are included, it is found that collisions considerably weaken the favorable influence of increasing the hot ion fraction. This is shown in Fig. 5, where the collisionless results for $T_h/T_e = 30$ is plotted along with the collisional result for $\nu_e^* = 0.22$ (a typical collisionality value in present-day beam-heated tokamaks). The corresponding real frequencies for this collisional case are shown in Fig. 2.

This weak dependence of the growth rate on the hot particle fraction in the collisional case is in qualitative agreement with the results of the calculation in Ref. 4. This earlier calculation also included collisions, but it was much more realistic in terms of the MHD equilibrium and the equilibrium density and temperature profiles employed.

III. BEAM DISTRIBUTION FUNCTIONS

Numerically calculated, non-Maxwellian, anisotropic equilibrium distribution functions, $F_{\parallel}$ and $F_{\perp}$, were presented in Ref. 4. These are realistic representations of the hot-particle species distribution function, F_h, for typical neutral-beam injection heating cases with parallel and perpendicular injection respectively. The same two distribution functions are used in the present calculation, the only change being that they have been stretched out in energy. Specifically, the beam temperatures, T_h, defined as

$$T_h \equiv \frac{(2/3)\int d^3v\ E\ F_h(E,v_\parallel/v)}{\int d^3v\ F_h(E,v_\parallel/v)} \quad ,$$

are fixed to be the same as that of the Maxwellian equilibrium distribution function, F_m, to which comparisons are being made. Here, E is the particle kinetic energy, $v_\parallel$ is the particle velocity component along the equilibrium magnetic field, and v is the magnitude of the particle velocity. Equilibrium electric fields are not considered in this calculation.

Growth rates in the collisionless limit with $T_h/T_e = 30$ are shown as a function of hot-ion fraction in Fig. 6 for the three different hot ion distribution functions. The corresponding real frequencies are shown in Fig. 7. For $n_h/n_e \lesssim 0.03$, the stabilizing effect of increasing the hot ion fraction is only slightly weaker for the non-Maxwellian distribution function than for the Maxwellian. However, for the beam-induced mode when $n_h/n_e \gtrsim 0.03$, the parallel injection distribution function, $F_\parallel$, yields a substantially higher growth rate than the perpendicular injection distribution function $F_\perp$ or the Maxwellian distribution function F_m. This may be attributed to the much smaller number of particles contribution to the (stabilizing) transit frequency resonance (Landau damping) with the wave when $F_h = F_\parallel$, compared with $F_h = F_\perp$ or $F_h = F_m$ [4]. Again, the indication is that there should be an optimum hot particle fraction which minimizes the dominant growth rate.

When the collision frequency is sufficiently large, it is found that differences in real frequency and growth rate between the three distribution functions are negligibly small. The collisional curves in Figs. 5 and 7 apply for $\nu_e^* = 0.22$ for $F_h = F_m$, $F_\perp$, and $F_\parallel$. This can be understood as a result of a spreading out and weakening of the resonances in velocity space by the collisions. Hence, the differences in the distributions in velocity space corresponding to F_m, $F_\perp$, and $F_\parallel$ would have little influence on the growth rate.

IV. CONCLUSIONS

In the collisionless limit, the effect of adding small fractions of hot (beam) ions can be strongly stabilizing for the kinetically-modified ideal MHD ballooning mode. On the other hand, for somewhat larger fractions of hot ions, a new mode can occur with a growth rate roughly of the order of the growth rate of the MHD ballooning mode in the absence of the hot species. This implies that there should be an optimum value of the hot ion fraction to minimize the influence of high-n instabilities in tokamaks. This optimum value is also dependent on the hot-ion temperature. Although the particular form of the hot-ion equilibrium distribution can influence the magnitude of the growth rates, the basic qualitative trend described persists. For experimentally typical values of the collision frequency, on the other hand, the stabilizing effect of the hot ions is found to be much weaker, and the relevant modes appear to be insensitive to the specific form of the hot ion equilibrium distribution function.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1. Growth rate γ versus hot ion density fraction n_h/n_e, for various hot ion temperature ratios T_h/T_e. Here collisions are neglected, $\nu_e^* = 0$, and the hot ion equilibrium distribution functions is Maxwellian, $F_h = F_m$. The dashed curves are from Connor et al., Refs. 1 and 7.

Fig. 2. Real frequencies ω_r corresponding to Fig. 1. The dash-dot curve includes the effect of collisions for $\nu_e^* = 0.22$ and $T_h/T_e = 30$. The other curves apply for $\nu_e^* = 0$.

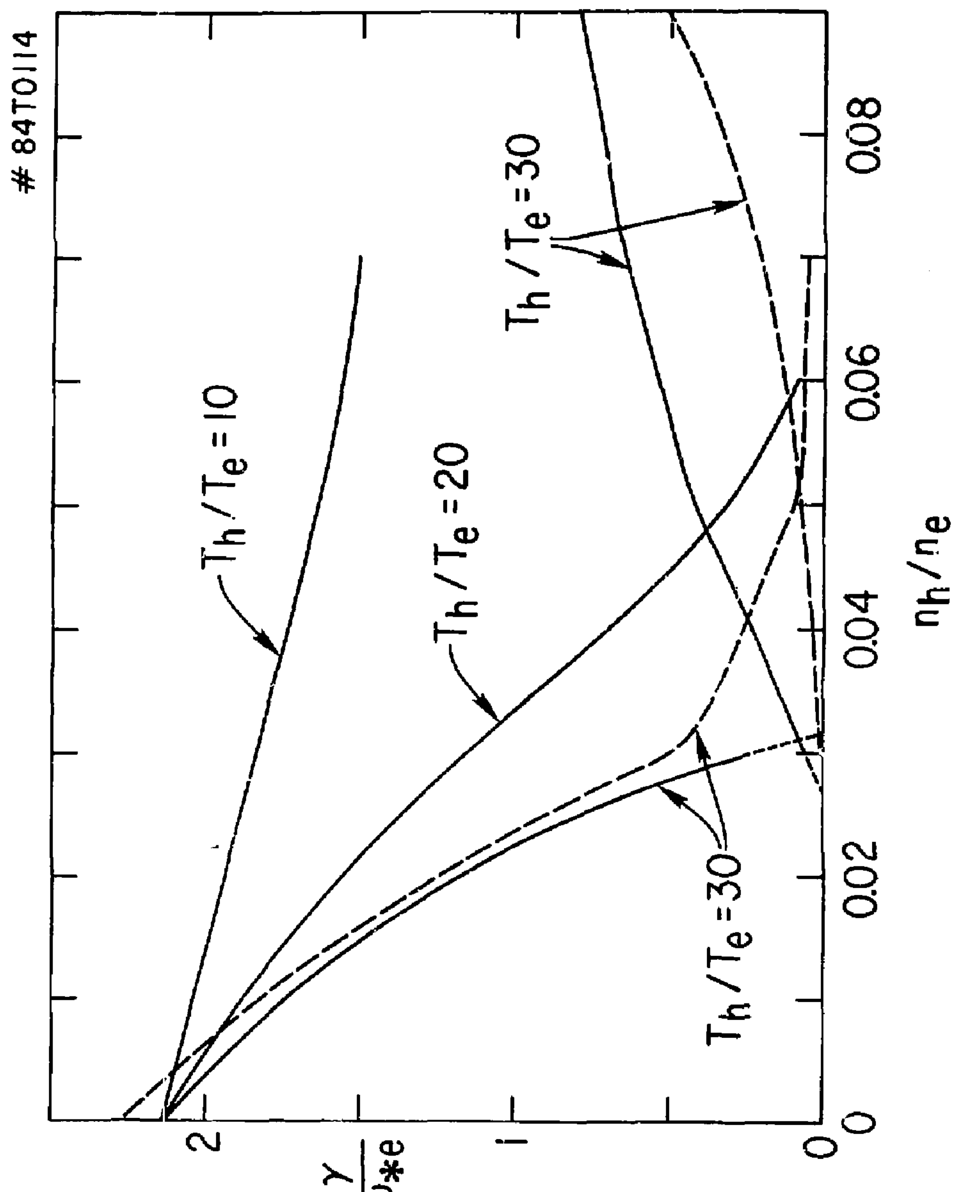
Fig. 3. Growth rate γ versus hot ion temperature ratio T_h/T_e for fixed hot ion density fraction $n_h/n_e = 0.02$, with $\nu_e^* = 0$ and $F_h = F_m$.

Fig. 4. Growth rate versus collisionality parameter ν_e^* for $n_h/n_e = 0$. ν_e^* is the ratio of the effective collision frequency to the average bounce frequency for trapped electrons.

Fig. 5. Growth rate versus hot ion density fraction n_h/n_e in the collisionless ($\nu_e^* = 0$) and collisional ($\nu_e^* = 0.22$) cases for $T_h/T_e = 30$. The collisionless curves apply for $F_h = F_m$, while the collisional curve applies for $F_h = F_m$, $F_\perp$ and $F_\parallel$.

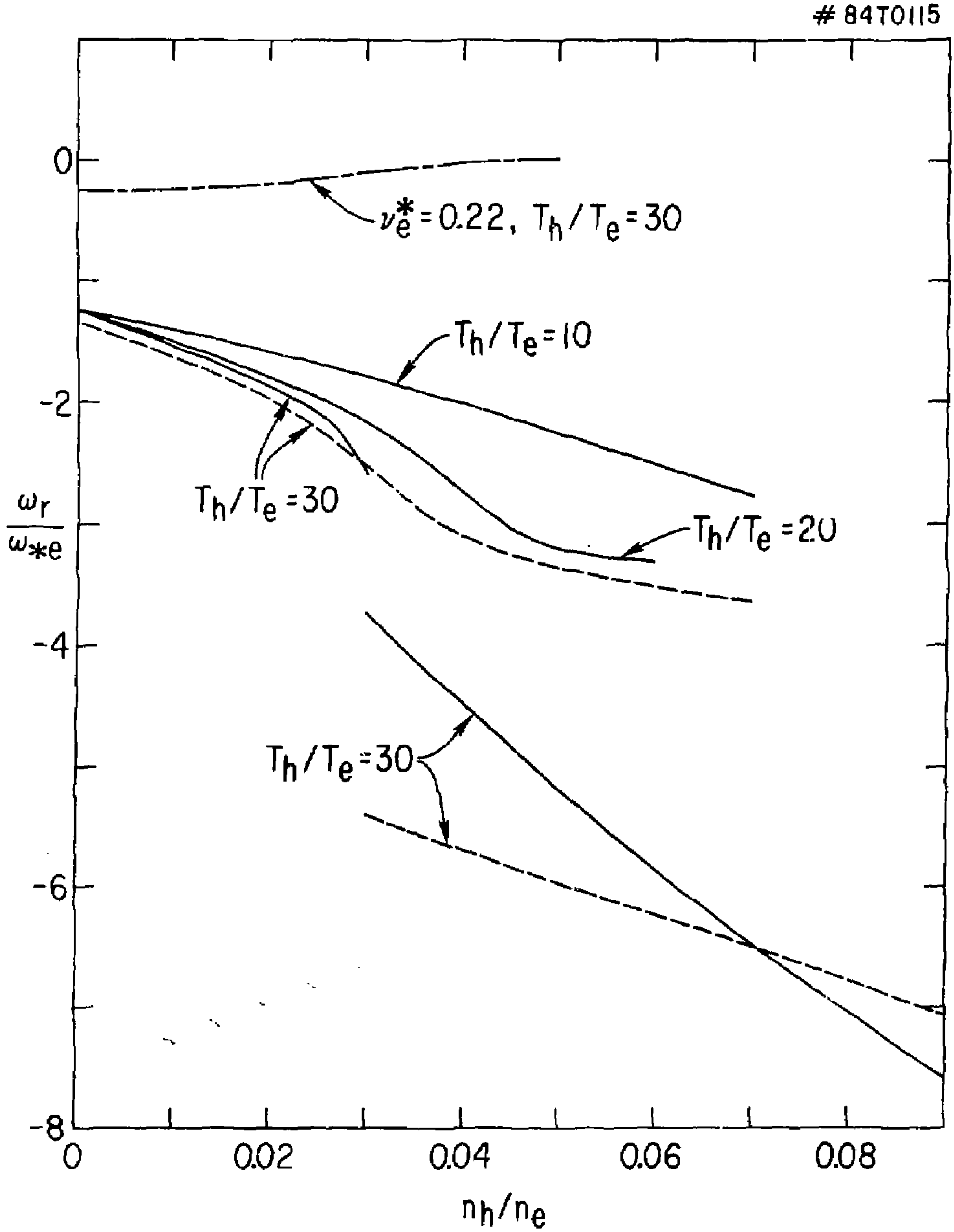
Fig. 6. Growth rate versus hot ion density fraction, n_h/n_e, for $F_h = F_m$, $F_\perp$, and $F_\parallel$, in the collisionless case.

Fig. 7. Real frequencies corresponding to Figs. 5 and 6. The dash-dot curve for $\nu_e^* = 0.22$ applies for $F_h = F_m$, $F_\perp$, and $F_\parallel$. The other curves apply for $\nu_e^* = 0$.



84T0114
$T_h/T_e=10$
$T_h/T_e=20$
$T_h/T_e=30$
$T_h/T_e=30$
$\frac{\gamma}{\omega_{*e}}$
0
1
2
0
0.02
0.04
0.06
0.08
n_h/n_e

Fig. 1



84T0115
0
-2
-4
-6
-8
ω_r / ω_{*e}
0
0.02
0.04
0.06
0.08
n_h/n_e
$\nu_e^* = 0.22,\ T_h/T_e = 30$
$T_h/T_e = 10$
$T_h/T_e = 30$
$T_h/T_e = 20$
$T_h/T_e = 30$

Fig. 2

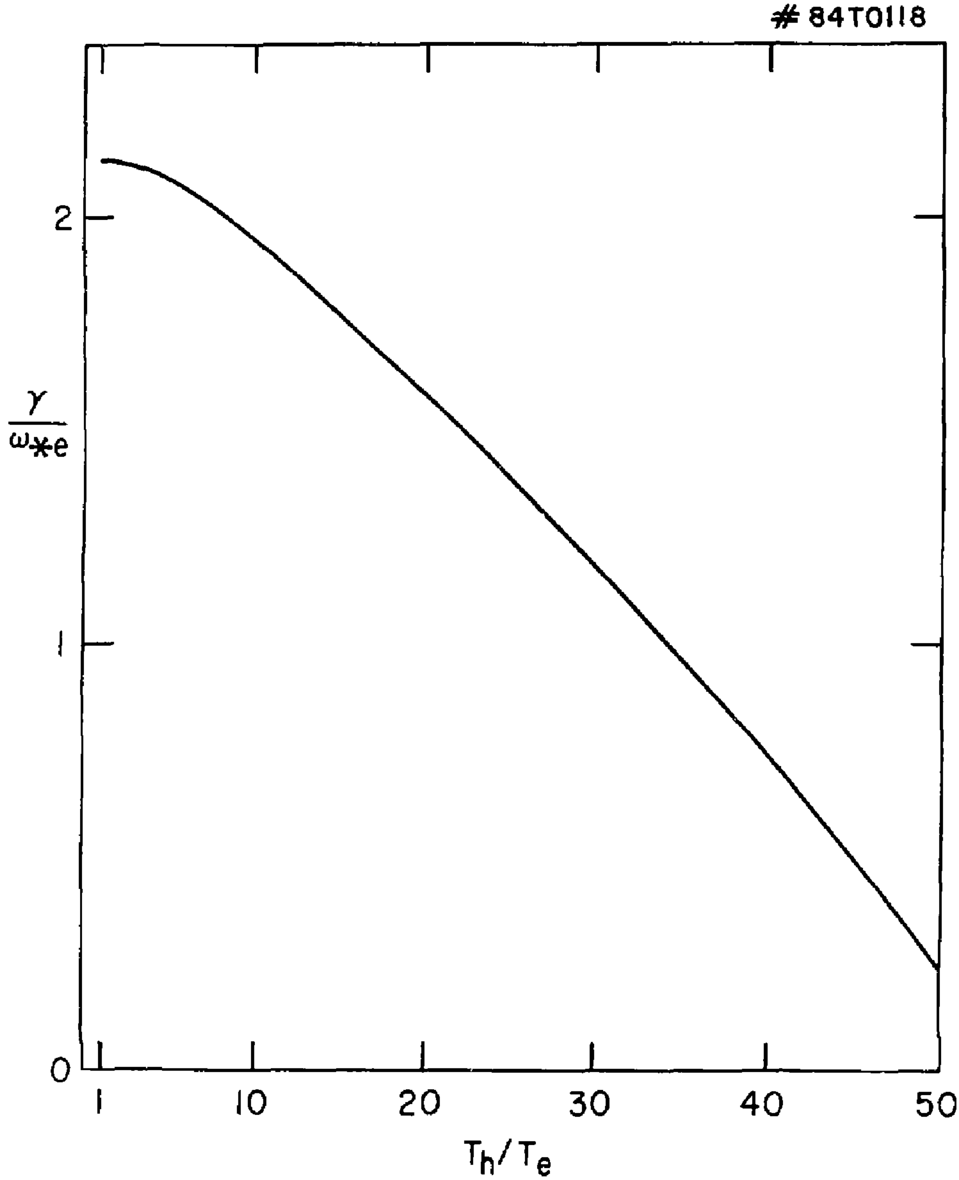


Fig. 3

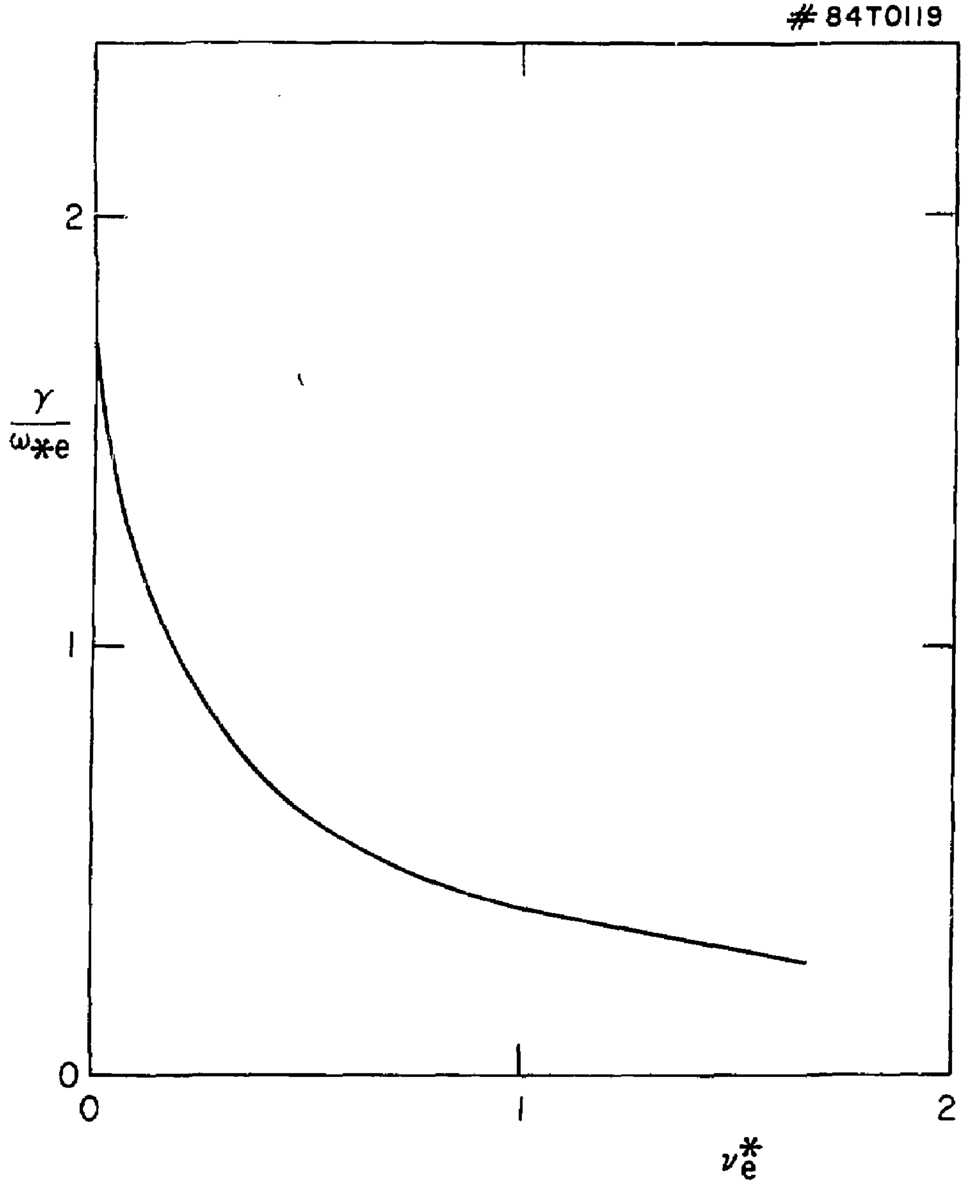
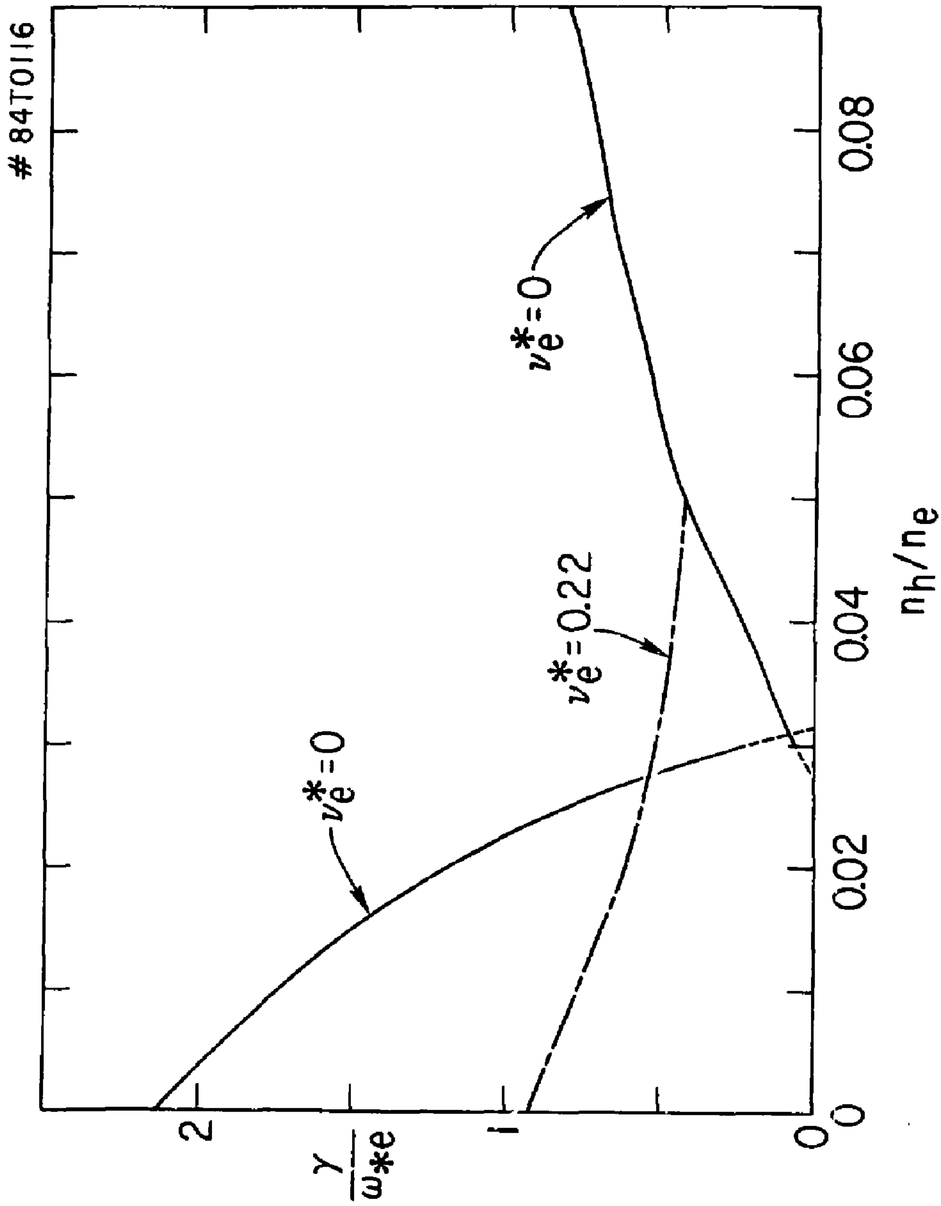
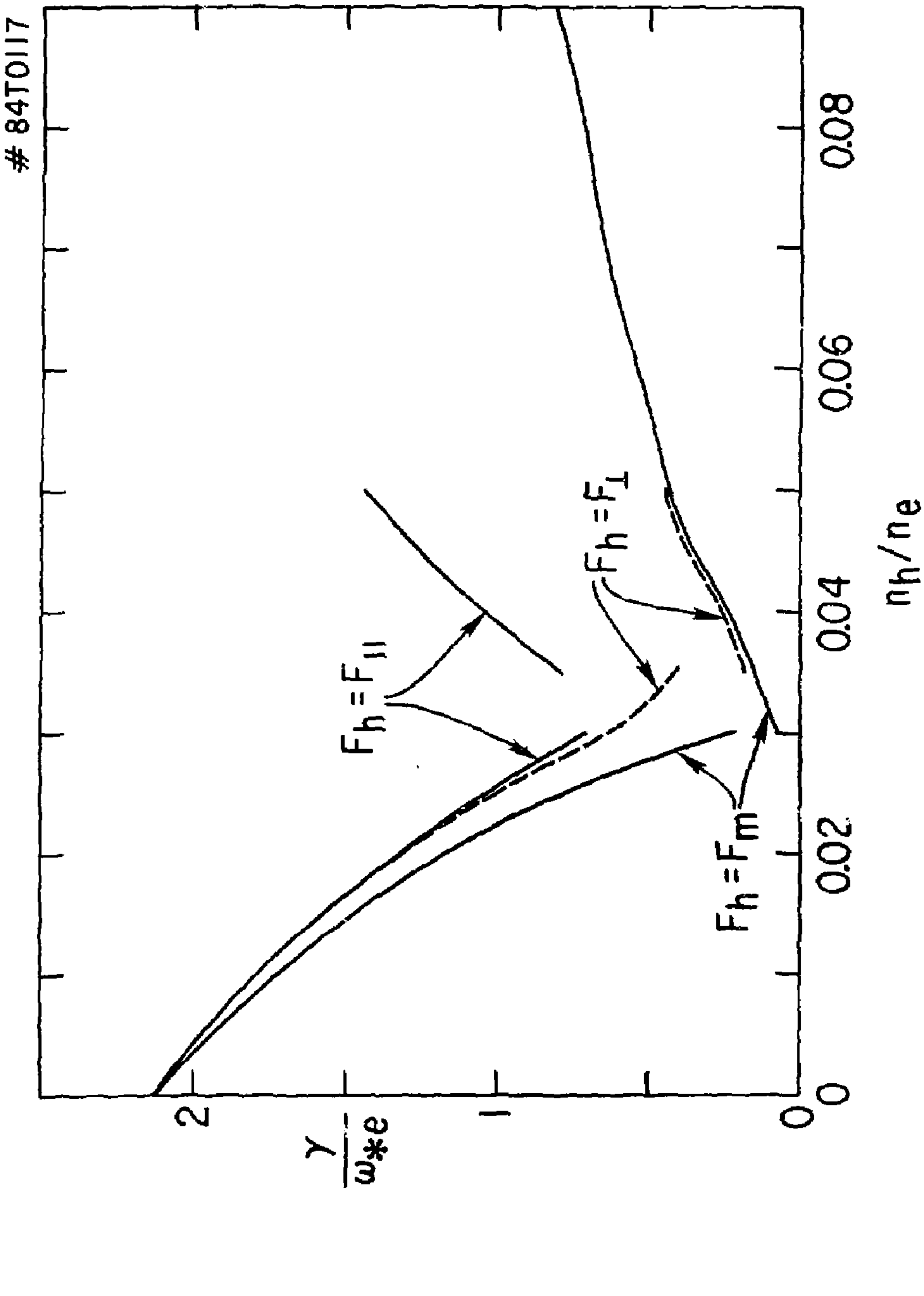


Fig. 4



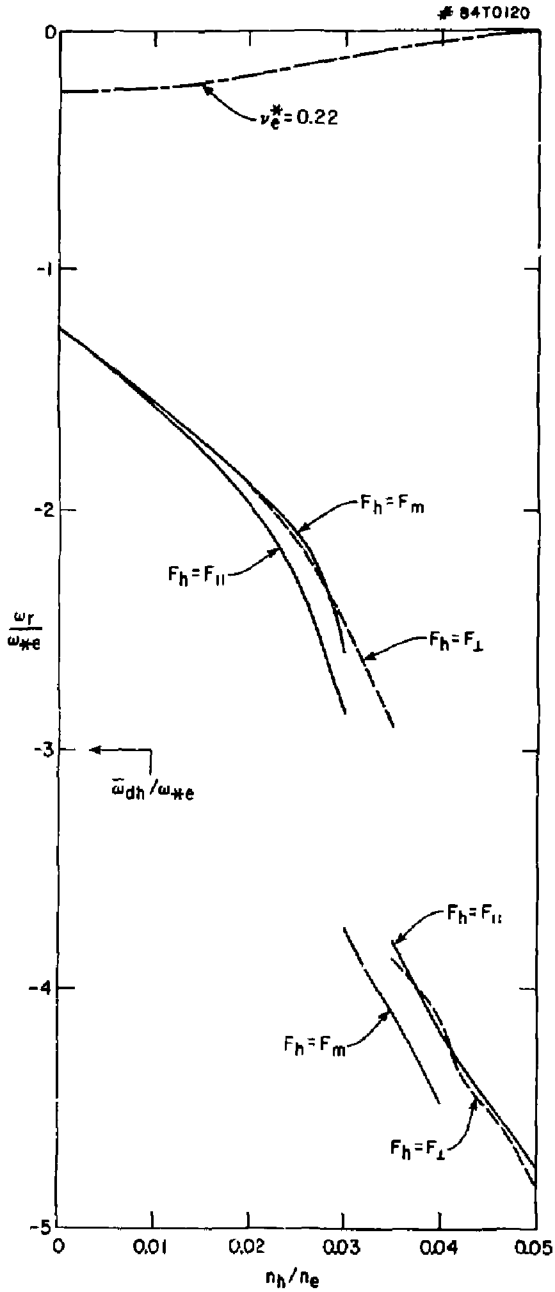
84T0116
$\nu_e^* = 0$
$\nu_e^* = 0.22$
$\nu_e^* = 0$
$\frac{\gamma}{\omega_{*e}}$
0
1
2
n_h/n_e
0
0.02
0.04
0.06
0.08

Fig. 5



84T0117
$\frac{\gamma}{\omega_{*e}}$
0
1
2
0
0.02
0.04
0.06
0.08
n_h/n_e
$F_h = F_{II}$
$F_h = F_{\perp}$
$F_h = F_m$

Fig. 6



84T0120
0
-1
-2
-3
-4
-5
0
0.01
0.02
0.03
0.04
0.05
$\nu_e^* = 0.22$
$F_h = F_m$
$F_h = F_\parallel$
$F_h = F_\perp$
$\frac{\omega_r}{\omega_{*e}}$
$\bar{\omega}_{dh}/\omega_{*e}$
$F_h = F_\parallel$
$F_h = F_m$
$F_h = F_\perp$
n_h/n_e

Fig. 7

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