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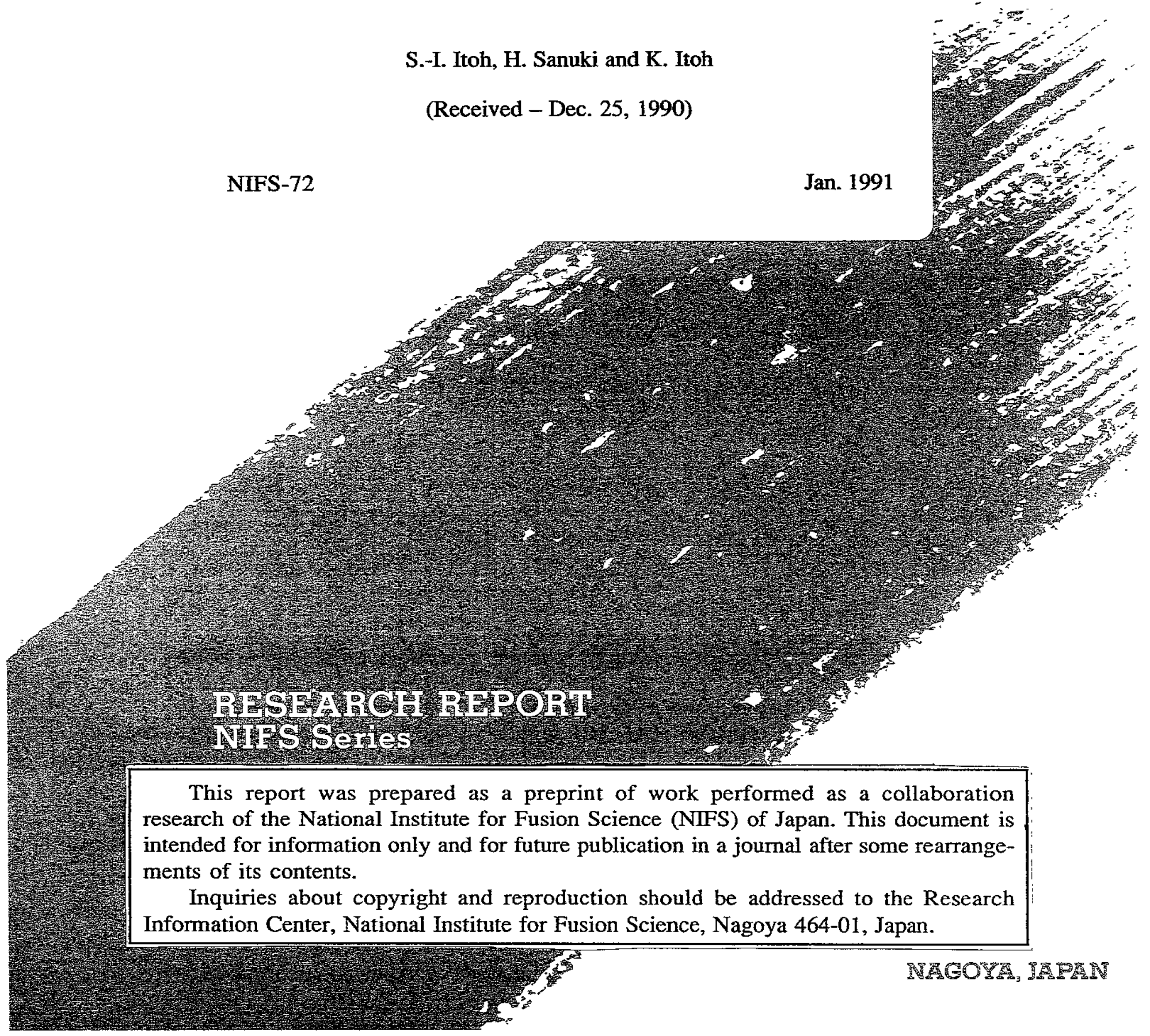

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Effect of Electric Field Inhomogeneities on Drift Wave Instabilities and Anomalous Transport

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Abstract

Effect of inhomogeneity of radial electric field on drift wave instabilities is investigated. Curvature of static potential gives rise to an additional Landau resonance. Critical conditions for the stability due to sheared ExB motion of ions are estimated for various modes. Effect on anomalous transport coefficient is also discussed.

Keywords: Sheared E×B Rotation, Radial Electric Field, Drift Instability, Tokamaks, Ion Landau Damping, H-mode

Introduction

Recently the important role of radial electric field has been theoretically pointed out [1-3] in connection with the improved confinement of the H-mode [4]. Theories have predicted that the inhomogeneous radial electric field causes the L-/H-transition [1,2,5] and reduces fluctuations in the H-mode [2,5-7]. The experimental observations have confirmed the appearance of the strong change of inhomogeneous radial electric field associated with the L/H transition [8-10]. The theory on the reduction of the low frequency fluctuations has been either the linear theory on the collisionless trapped ion mode [2,7] (flute-like mode), or the nonlinear theory of the fluid turbulence [3,6]. The former one is applicable to the collisionless limit ($\nu_{*i} << 1$, ν_{*i} is the normalized collision frequency of trapped ions) and the actual parameter of the present experiment is in the regime of $\nu_{*i} \sim 1$ near plasma boundary. Further extension of the parameter to the more general plasma is surely needed. The latter has shown that the nonlinear saturation level can be reduced, but the quantitative evaluations on the disappearance of the fluctuations may need further studies.

The effect of the inhomogeneous radial electric field on kinetic interactions has been discussed by Timofeev [11], and it has been found that the Landau resonance can be caused by the inhomogeneous ExB drift motion. This model has been applied to the stability of Bumpy torus and mirrors and has succeeded in explaining the effect of the radial electric field on the low frequency instabilities [12,13]. These theoretical predictions have been confirmed by the experimental observations[14,15].

In this article, we investigate the effect of the inhomogeneous radial electric field on instabilities in the drift wave range of frequency in tokamaks. When the inhomogeneous radial electric field becomes strong, the mode is linearly stabilized by the ion Landau damping, although the Kelvin-Helmholtz type modes may be excited by further increasing of the inhomogeneous electric field. The critical condition is derived for the electron-driven modes and ion-driven modes. The comparison with experiments in JFT-2M [9,10] shows that the criterion is satisfied in case of H-mode plasmas.

Model and Stability

We take the slab plasma model to investigate the stability. The z-axis is in the direction of the strong magnetic field, and the density changes in the x-direction with the scale length of λ_n, i.e., $dn/dx = -n/\lambda_n$, where n is the plasma density. For the simplicity of the analysis, we consider a single species plasma (T being the temperature). The static potential $\Phi_0(x)$ generates the radial electric field $E_x = -\nabla\Phi_0$.

In this inhomogeneous plasma, drift wave appears with the frequency $\omega \simeq \omega_* = k_y \rho_i v_{Ti} / \lambda_n$ (k_y is the wave number in the y-direction, ρ_i is the ion gyroradius, v_{Ti} is the ion thermal velocity). This mode can be unstable by various causes. [The magnetic shear can cause convective damping so as to stabilize the mode; In toroidal geometry, however, the toroidal coupling annihilates the convective damping, so that we here use the local theory on the effect of ion Landau damping.]

Electron Mode

We first study the mode driven by the dynamics of electrons. The growth rate γ can be approximately given as

$$\gamma = \gamma_0 - \gamma_{LD} \tag{1}$$

in the case of $\gamma \ll \omega_r$, where γ_0 is the drive by electrons, γ_{LD} is the Landau damping by ions and ω_r is the real frequency. The Landau damping term may be written as [13]

$$\gamma_{LD} \simeq \sqrt{\frac{\pi}{2}} \frac{\Lambda_0}{1+T_i/T_e-\Lambda_0} \frac{\omega_r[\omega_r+\omega_* (1-\alpha)]}{\hat{k}_\parallel v_{Ti}} \exp[-(\frac{\omega_r}{\hat{k}_\parallel v_{Ti}})^2] \tag{2}$$

with

$$\omega_r = \omega_* \left(\frac{\Lambda_0}{1+T_i/T_e-\Lambda_0} + \alpha\right) \tag{3}$$

where $\Lambda_0 = I_0(b)e^{-b}$ with $b= k_y^2\rho_i^2$. Here α is defined as

$$\alpha \equiv \lambda_n^2 \frac{e}{T_i} \frac{d^2}{dx^2} \phi_0 \tag{4}$$

where Φ_0 is the electrostatic potential and the effective wave number $\hat{k}_{\parallel}$ in the parallel direction can be written as

$$\hat{k}_{\parallel}^2 \simeq k_z^2 + (k_y \rho_i)^2 \left(\frac{\alpha}{\lambda_n}\right)^2 \tag{5}$$

In the absence of the radial electric field, the ion damping is not effective if $\omega/k_z v_{Ti} \gg 1$. The inhomogeneous radial electric field, on the other hand, induces the Landau resonance even for $k_z = 0$ case (see, the second term in Eq.(5)). Equation (2) reduces to the conventional form of the ion Landau damping when we neglect the effect of radial electric field ($\Phi_0 = 0$) or no shear ($\Phi_0'' = 0$). Since the effective parallel wave number for ions is approximated (in the small k_z limit) as

$$\hat{k}_{\parallel} \simeq k_y \rho_i \frac{\alpha}{\lambda_n} \tag{6}$$

the ion Landau damping term (2) reduces to

$$\gamma_{LD} \simeq \sqrt{\frac{\pi}{2}}\, \frac{\omega_* \,(1+T_i/T_e)}{1+T_i/T_e-\Lambda_0}\; A\, \frac{A+\alpha}{|\alpha|} \exp\left[-\left(\frac{A+\alpha}{|\alpha|}\right)^2\right] \tag{7}$$

where $A = \Lambda_0/(1+T_i/T_e-\Lambda_0)$. It should be noted that γ_{LD} increases gradually for positive α but increases rapidly and has the maximum at $\alpha=\alpha_c\equiv-\sqrt{2}A/(\sqrt{2}+1)$ for negative α. For $\alpha < -\alpha_c$, it decreases and may change its sign(Landau growth) for $\alpha\lesssim-A$. The stability boundary is estimated by balancing the growth by electrons and ion damping. We have for $T_e\simeq T_i$,

$$\frac{\sqrt{2\pi}A(A+\alpha)}{(2-\Lambda_0)|\alpha|}\exp\left[-\left(\frac{A+\alpha}{\alpha}\right)^2\right] >\gamma_0/\omega_* \tag{8}$$

for stability. The left hand side of Eq.(8) is shown in Fig.1 as a function of α, where parameter of $k_y\rho_i=0.3$ is chosen for $T_i=T_e$. The right hand side of Eq.(8) is also plotted for the typical parameters. Generally, we obtain three roots for α from Eq.(8), namely, α_j ($j=1\sim3$) , which are indicated in the figure. The drift instability can be suppressed in the following two regions of α: (1) $\alpha_1\leq\alpha\lesssim\alpha_2$ and (2) $\alpha\gtrsim\alpha_3$. We clearly see that the effect of inhomogeneous electric field depends on its sign. When α is negative, namely, the gradient is positive, we find the narrow stability region for α ($\alpha_1\leq\alpha\lesssim\alpha_2$).

The linear growth rates have been reported in literatures [16,17] on collisionless trapped electron mode (CTEM), dissipative trapped electron mode (DTEM), universal mode (or collisionless circulating electron mode) (UM) and dissipative circulating electron mode (DCEM) as

$$\tau_0/\omega_* \simeq \begin{cases} \sqrt{\varepsilon} & \text{(CTEM)} \\ \sqrt{\varepsilon}\,\dfrac{\omega_*}{\nu_{eff}} & \text{(DTEM)} \\ \dfrac{\omega_*}{\omega_t} & \text{(UM)} \\ \dfrac{\omega_*}{\omega_t}\,\dfrac{\nu}{\omega_t} & \text{(DCEM)} \end{cases} \tag{9}$$

where ε is the inverse aspect ratio, $\nu_{eff}=\nu/\varepsilon$, ν is the electron collision frequency, ω_t is the electron transit frequency, v_{Te}/qR, v_{Te} is the electron thermal velocity, q is the safety factor, R is the major radius. Combining Eqs.(8) and (9), the rough estimate of the critical electric shear can be obtained. The value of α_3 in the case of small α limit is calculated by balancing τ_0 with τ_{LD}. For instance, in the the case of the collisionless trapped electron mode, the critical condition is approximately given as

$$\alpha > \alpha_3 \approx A\{\frac{1}{2}\ell n\frac{2\pi}{\varepsilon}\}^{-1/2} \tag{10}$$

Approximate conditions for various modes are listed in Table 1.

Ion Mode

The ions can also drive instabilities in the range of drift frequency. We study the effect on the η_i mode (η_i is the ratio of the density gradient scale length to that of ion temperature gradient). The critical temperature gradient and the resultant growth rate have been discussed in Refs.[16,17]. The instability has the upper bound of $k_{/\!/}$ as

$$k_{/\!/} < k_{/\!/c} = \begin{cases} k_y\rho_i \dfrac{1}{\lambda_n} \dfrac{\eta_i}{2}\sqrt{1 - \dfrac{2}{\eta_i}} & (k_y\rho_i \ll 1) \\ \\ \dfrac{1}{4\pi} \dfrac{\eta_i}{\lambda_n} & (k_y\rho_i \sim 1) \end{cases} \qquad (11)$$

If $\hat{k}_{/\!/}$ becomes large and exceeds $k_{/\!/c}$, this nonresonant mode is stabilized. The stabilization is difficult for the small k_y mode, and the critical condition for stability is given as

$$\alpha > \frac{\eta_i}{2}\sqrt{1 - \frac{2}{\eta_i}} \qquad (12)$$

The condition is also summarized in the table 1.

Effect on Anomalous Transport

Equations (8) and (9) indicate that the linear growth rate becomes negative if F becomes of the order of unity. The anomalous transport coefficient D by drift wave instabilities has been estimated by use of the mixing length theory[18,19] as

$$D = F\gamma k_{\perp}^{-2} \tag{13}$$

where F is a numerical coefficient of order of unity. The reduction of the growth rate by the enhanced Landau damping decreases the anomalous transport. Nonlinear studies [3,6] has evaluated F, and it was found that F is reduced by the inhomogeneous radial electric field. Thus radial electric field inhomogeneity can reduce D in two ways; One is the linear process and the other is the nonlinear one. One may write as $D = D_0(F/F_0)(\gamma k_{\perp}^{-2})/(\gamma k_{\perp}^{-2})_0$, where the suffix 0 denotes the value in the absence of the radial electric field inhomogeneity. The dominant contribution in F/F_0 is discussed [3] and is obtained as $1/\{1+(2eB\alpha/k_y{}^2\lambda_n{}^2 T D)^2\}$. Combining the α-dependence of the linear growth rate (Eq.(7)), we have an approximate formula of D/D_0 as (for the case of electron instabilities)

$$\frac{D}{D_0} \sim [1 - \frac{\omega_* \sqrt{2\pi} A(A+\alpha)}{\gamma_0 (2-\Lambda_0)|\alpha|} \exp\{-\left(\frac{A+\alpha}{\alpha}\right)^2\}] \frac{1}{1+\left(\frac{2}{k_y^2 \lambda_n^2}\frac{eB}{TD}\alpha\right)^2} \tag{14}$$

The terms in square bracket come from the linear contribution. The effect of the parameter α on the linear growth rate causes a sharp reduction of the transport coefficient when the parameter α

approaches to the critical value for the stabilization.

Summary and Discussion

In summary, we have investigated the effect of the inhomogeneous radial electric field on the ion Landau damping of drift instabilities. The critical value of the inhomogeneity of the radial electric field to stabilize the mode is obtained. It is found that if the inhomogeneity parameter α reaches of the order of unity (for the electron mode) and $(\eta_i/2)\sqrt{1-2/\eta_i}$ (for the ion mode), the mode of drift wave range of frequency can be stabilized by the ion Landau damping.

The recent observation on the radial electric field in JFT-2M has shown that α can reach of the order of 1 to 100 in the vicinity of the edge in case of the H-mode. This value is large enough to suppress instabilities for the wide range of collision frequency and plasma parameters. Because the linear instability is suppressed, the expected fluctuation level and anomalous transport may be drastically reduced for these parameters. The establishment of the inhomogeneous radial electric field in H-mode can suppress the anomalous transport near edge.

This analysis is made in the slab geometry. The stabilization by this mechanism is effective for the modes with large poloidal mode numbers. Recent study on the toroidal drift mode has shown that the mode with small poloidal mode number can be stabilized in the real tokamak geometry[20]. This may reduce the critical inhomogeneity for stabilization. The calculation in the toroidal geometry and more precise determination of the critical value need further analysis.

When the large potential change is present in space, the localization and the structure of the mode also changes. In this article we showed the local analysis and the estimate may not be applicable. In this case, we need the nonlocal analysis of these modes. Further study is underway.

We finally note that the criterion derived in this article is much smaller than that obtained previously[2]. The critical value may be satisfied even in the core region for the case of the peaked profile modes [21,22]. The inhomogeneous radial electric field was predicted [23] to appear associated with the inward pinch of particles in such improved modes. The application of this analysis to the model of the peaked profile mode will be reported in a separate article.

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Table Caption

Table 1 : Linear growth rates normalized by ω_* and values of α_3 in the small α limit are tabulated for the electron and ion modes. All notations are defined in the text.

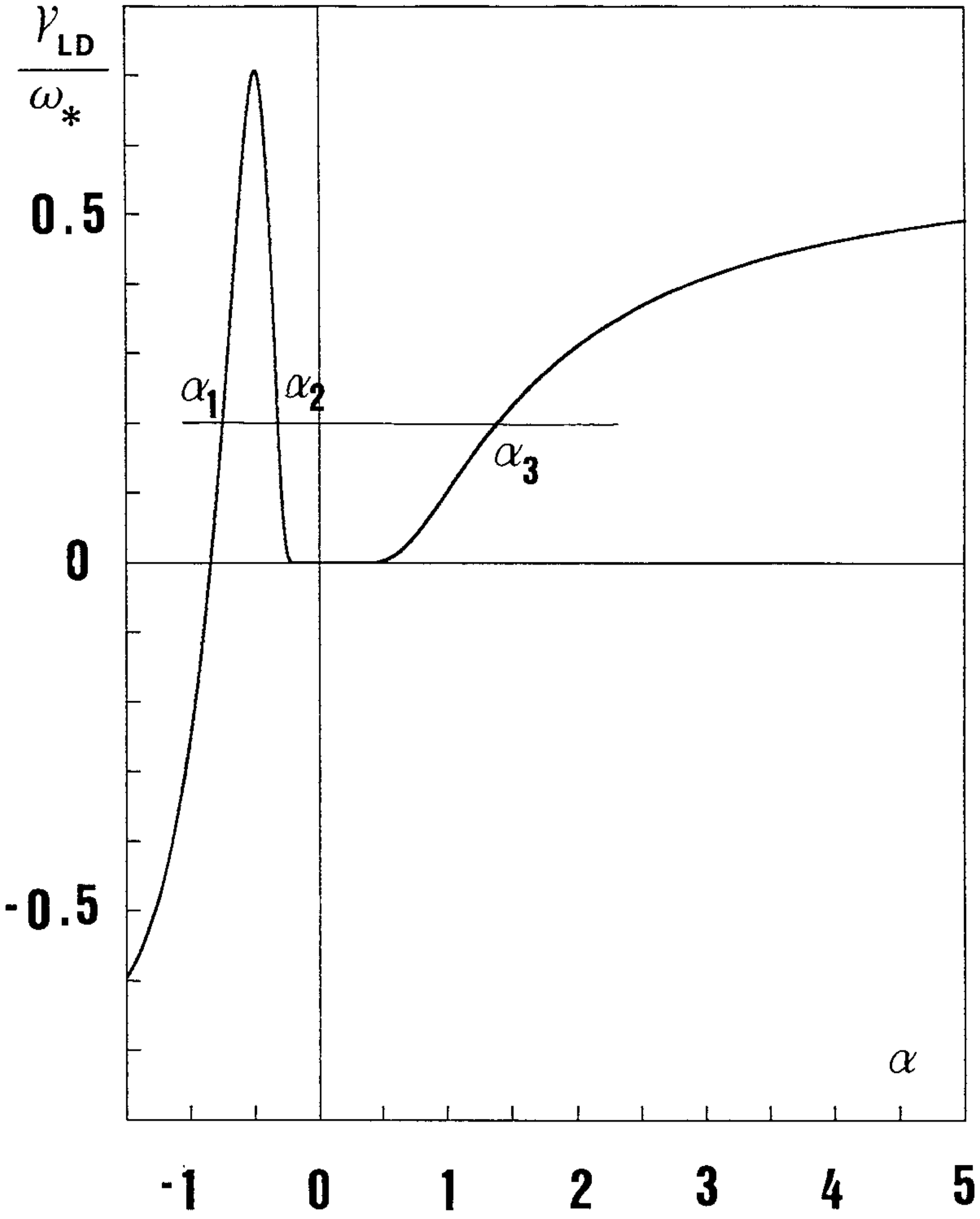
Figure Caption

Fig. 1 : Ion Landau damping rate normalized by ω_* versus α is plotted. Critical stability condition for α estimated from Eq.(8) is also shown for the case of $\tau_0/\omega_*=0.2$. Drift instabilities can be suppressed in the regions of $\alpha_1\leq\alpha\leq\alpha_2$ and $\alpha\geq\alpha_3$.

Table I

Mode		γ_0/ω_*	critical α_3
Electron Mode	CTEM	$\epsilon^{1/2}$	$A[\frac{1}{2}ln(\frac{2\pi}{\epsilon})]^{-1/2}$
	DTEM	$\sqrt{\epsilon}\omega_*/\nu_{eff}$	$A[\frac{1}{2}ln(\frac{2\pi}{\epsilon}\frac{\nu_{eff}}{\omega_*})]^{-1/2}$
	UM	$\frac{\omega_*}{\omega_t}$	$A[\frac{1}{2}ln(2\pi\frac{\omega_t}{\omega_*}]^{-1/2}$
	DCEM	$\frac{\omega_*}{\omega_t}\frac{\nu}{\omega_t}$	$A[\frac{1}{2}ln(2\pi\frac{\omega_t}{\omega_*}\frac{\omega_t}{\nu})]^{-1/2}$
Ion Mode	ITGM	η_i	$\frac{\eta_i}{2}\sqrt{1-\frac{2}{\eta_i}}$

Fig. 1



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