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Edge Turbulence and Drift Instabilities

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Edge turbulence and drift instabilities

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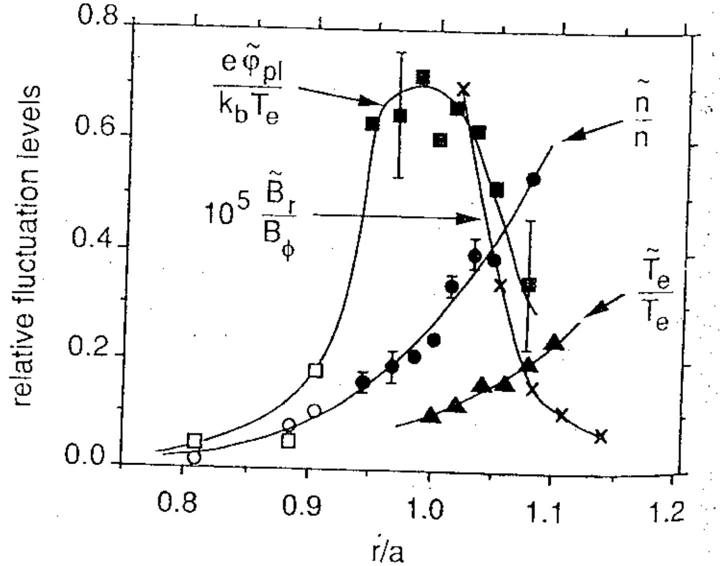
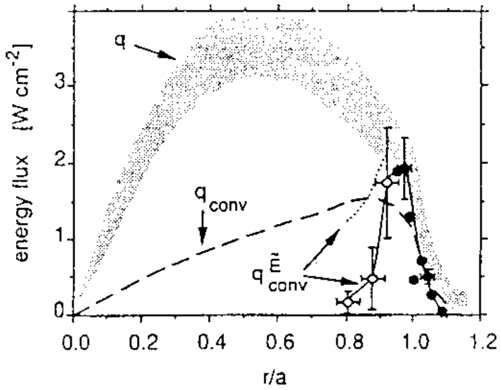




Radial profiles of the total electron and ion energy flux $q = q_e + q_i$ from power balance (shaded area, defined by the standard deviation), the fluctuation-induced convected flux $q^{\tilde{E}}_{\rm conv}$ (filled circles from Langmuir probes, and open circles from HIBP; dotted line is upper bound in presence of η_i mode), and the total convected energy flux $q_{\rm conv}(r)$ from a neutral-penetration code and H_α measurements.

図3 TEXTトカマクにおけるエネルギー束qの径方向分布。$r/a \gtrsim 0.9$ の edge plasma では、パワーバランスから求めたqとラングミュアープローブによる$q(\bullet)$および HIBP による$q(\circ)$がよい一致を示している。また、中性粒子密度から求めた$q_{\rm conv}$もよく対応している。(文献[10]より)

$$\left\{ \begin{array}{l} \text{conduction (heat)} \\ \text{convection (particle)} \end{array} \right.$$

Two-Fluid Model

$$\frac{\partial n}{\partial t} = -\nabla \cdot (n\mathbf{v}) = -\nabla \cdot (n\mathbf{v}_e)$$

$$nm_i\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{v} + \nabla(P_e + P_i) + \nabla\cdot \overleftrightarrow{\Pi}_{gi} = \frac{1}{c}\mathbf{J}\times\mathbf{B}$$

($\overleftrightarrow{\Pi}_{gi}$ is viscosity tensor)

$$\mathbf{E} + \frac{1}{c}\mathbf{v}_e \times \mathbf{B} + \frac{1}{ne}\nabla P_e = \eta_{||}\mathbf{J}_{||} + \eta_\perp \mathbf{J}_\perp$$

$$\mathbf{v}_e = \mathbf{v} - \frac{\mathbf{J}}{ne}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla\times\mathbf{E}\ ,\ \ \nabla\cdot\mathbf{B} = 0$$

$$\frac{4\pi}{c}\mathbf{J} = \nabla\times\mathbf{B}$$

$$P_e = f_e(n)\ ,\ \ P_i = f_i(n)$$

Assumptions

1. Cold ions, $T_e \gg T_i$

2. Two dimensional ion motion

$|\mathbf{v}_{\perp i}| \gg |\mathbf{v}_{\| i}|$

3. Isothermal electrons $T_e = const.$

4. $\nabla_{\|} P_e$ term is kept in Ohm's law

Vorticity equation:

- $$\frac{d}{dt}\frac{\nabla_\perp^2 \tilde{\phi}}{B_0 \Omega_i} = \frac{1}{e n_0}\frac{\partial}{\partial z} J_z$$

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{\nabla\tilde{\phi}\times\hat{z}}{B_0}\cdot\nabla$$

- $$\frac{dn}{dt} = \frac{1}{e}\frac{\partial J_z}{\partial z}$$ (electron continuity equation)

- $$J_z = \frac{T_e}{e\eta}\frac{\partial}{\partial z}\left(\frac{n_1}{n_0} - \frac{e\tilde{\phi}}{T_e}\right)$$ (Ohm's law)

Model equations for resistive drift waves

$$\frac{d}{dt}\nabla_\perp^2 \phi = -\frac{T_e}{e^2 n_0 \eta \Omega_i}\frac{\partial^2}{\partial z^2}(\phi - n)$$

$n = n_0 e^{\frac{e\hat{\phi}}{T}}$ $$\frac{d}{dt}(n + \ln n_0) = -\frac{T_e}{e^2 n_0 \eta \Omega_i}(\phi - n)$$

Hasegawa-Mima equation:

$$\frac{d}{dt}(\nabla_\perp^2\phi - n) + \nabla \ln n_0 \times \nabla\phi \cdot \hat{z} = 0$$

$$n = \phi \quad (\text{Boltzman relation})$$

$$\text{"} \; \frac{d}{dt}(\nabla_\perp^2\phi - \phi) + \nabla \ln n_0 \times \nabla\phi \cdot \hat{z} = 0 \; \text{"}$$

Normalization: $e\phi/T \equiv \phi$, $n_1/n_0 \equiv n$, $\omega_{ci} t \equiv t$, $x/\rho_s \equiv x$

(1) $$\left(\frac{\partial}{\partial t} - \nabla\phi \times \hat{z} \cdot \nabla\right)\nabla^2\phi = \bar{C}_1(\phi - n) + C_2 \nabla^4\phi + C_3\phi$$

(2) $$\left(\frac{\partial}{\partial t} - \nabla\phi \times \hat{z} \cdot \nabla\right)(n + \ln n_0) = \bar{C}_1(\phi - n)$$

$$\bar{C}_1 = -\frac{T_e}{e^2 n_0 \eta \omega_{ci}} \frac{\partial^2}{\partial z^2}, \quad C_2 \equiv \frac{\mu}{\rho_s^2 \omega_{ci}}$$

$$C_3 = \frac{\omega_*}{\omega_{ci}} \frac{T_i}{T_e}, \quad \text{if } \omega_* = \frac{v_{Ti}}{8R}$$

$$= 0, \quad \text{otherwise.}$$

extension of C_3 model:

gyrofluid model

Conservation laws

energy:

$$\frac{1}{2}\frac{\partial}{\partial t}\int [n^2 + (\nabla\phi)^2] dV$$

$$= -C_1'\int \left(\frac{\partial n}{\partial z} - \frac{\partial \phi}{\partial z}\right)^2 dV - C_2\int (\nabla^2\phi)^2 dV$$

$$- \int n\,(\hat{z}\times\vec{\kappa})\cdot\nabla\phi\, dV$$

enstrophy:

$$\frac{1}{2}\frac{\partial}{\partial t}\int (\nabla^2\phi - n)^2 dV$$

$$= -C_2\int (n - \nabla^2\phi)\nabla^4\phi\, dV - \int n\,(\hat{z}\times\vec{\kappa})\cdot\nabla\phi\, dV$$

Here $\vec{\kappa} = -\rho_s \nabla \ln n_0 > 0$, $C_1' = \bar{C}_1/k_z^2$.

$$\left(\Gamma = -\left\langle n\frac{\partial\phi}{\partial y}\right\rangle = -\int n\,(\hat{z}\times\hat{\kappa})\cdot\nabla\phi\, dV \right)$$

Linear Theory of Resistive Drift

Waves

$$\omega^2 + i\omega(b + k^2 C_2) - ib\omega^*$$
$$- [k^4/(1+k^2)]\, b C_2 = 0,$$

where

$$b = C_1[1+k^2]/k^2,$$

$$\omega_* = k_y \bar{\kappa}/(1+k^2)$$

If C_2 is ignored,

$$\omega = \frac{1}{2}\left[-ib + ib(1 - 4i\omega_*/b)^{1/2}\right].$$

If $b \gg \omega_*$,

$$\omega \simeq \omega_* + i\omega_*^2/b$$

(growth rate)

Model Equations for ITG modes

(1) $\frac{d}{dt}(\phi - \nabla_\perp^2 \phi) = -(1 - 2\epsilon_n + K \nabla_\perp^2)\frac{\partial \phi}{\partial y} +$

$2\epsilon_n \frac{\partial P}{\partial y} - \nabla_\parallel v$

(2) $\frac{dP}{dt} = -K \frac{\partial \phi}{\partial y}$

(3) $\frac{dv}{dt} = -\nabla_\parallel(\phi + P)$

$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{V}_\perp \cdot \nabla$, $\mathbf{V}_\perp = \hat{z} \times \nabla\phi$

$\epsilon_n = L_n/R$, $K = (1 + \underline{\eta_i})(T_i/T_e)$

$\underline{\eta_i} = L_n/L_T$

<u>dispersion</u> <u>relation</u>

$\omega^2(1 + k^2) - \omega k_y(1 - 2\epsilon_n - Kk^2) + 2k_y^2 K\epsilon_n$

$= 0$

Drift Alfvén Turbulence
(Braginskii equations)

(1) $(\frac{\partial}{\partial t} + \mathbf{V}_E \cdot \nabla)\nabla^2\phi = \nabla_\parallel J_\parallel - \underline{\kappa}(T + n)$

(2) $\hat{\beta}\frac{\partial \psi}{\partial t} + \hat{\mu}(\frac{\partial}{\partial t} + \mathbf{V}_E \cdot \nabla)J_\parallel = \nabla_\parallel(T + n - \phi)$

$-\hat{\mu}\nu[J_\parallel + \frac{0.71}{1.6}(\underline{q_\parallel} + 0.71 J_\parallel)]$ (ohm's law)

(3) $(\frac{\partial}{\partial t} + \mathbf{V}_E \cdot \nabla)n = -\omega_n \frac{\partial \phi}{\partial y} + \nabla_\parallel(J_\parallel - u_\parallel) -$

$\kappa(T + n - \phi)$

(4) $\frac{3}{2}(\frac{\partial}{\partial t} + \mathbf{V}_E \cdot \nabla)T = -\frac{3}{2}\omega_t \frac{\partial \phi}{\partial y} +$

$\nabla_\parallel(J_\parallel - u_\parallel - q_\parallel) - \kappa(3.5T + n - \phi)$

(5) $\hat{\mu}(\frac{\partial}{\partial t} + \mathbf{V}_E \cdot \nabla)\underline{q_\parallel} = -\frac{5}{2}\nabla_\parallel T_e - \underline{a_L q_\parallel}$

$-\hat{\mu}\nu\frac{3.5}{1.6}(q_\parallel + 0.71 J_\parallel)$

(6) $\epsilon_s(\frac{\partial}{\partial t} + \mathbf{V}_E \cdot \nabla)u_\parallel = -\nabla_\parallel(n + T) -$

$\mu_\parallel \nabla_\parallel^2 u_\parallel$

Notations

$J_\parallel = -\nabla_\perp^2 \psi$. $\quad v_E = \nabla s \times \nabla \phi$

$\nabla_\perp^2 = (\partial/\partial x - \hat{s} s \, \partial/\partial y)^2 + (\partial/\partial y)^2$

$\nabla_\parallel = (\partial/\partial s) - \hat{\beta} \nabla s \times \nabla \psi$

$\underline{\kappa} = \omega_B \, [\cos s(\partial/\partial y) + \sin s(\partial/\partial x)]$

α_L : Landau damping

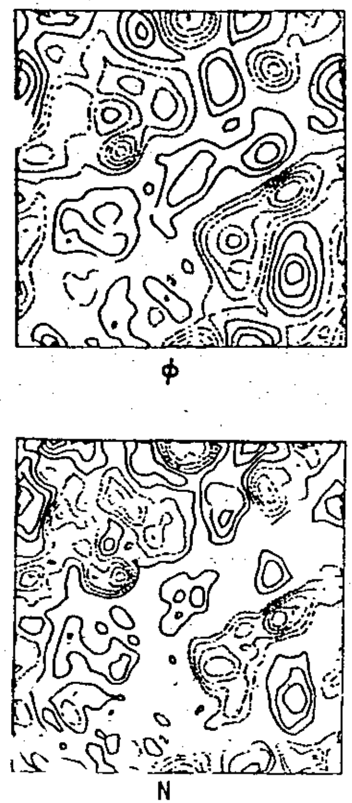
$\hat{s}$: magnetic shear

$\omega_B = 2L_\perp/R$, $\omega_t = L_\perp/L_T$.

$\omega_n = L_\perp/L_n$

$\alpha_L = \hat{\mu}\,(V_e L_\perp / C_s \delta R)$

M. Wakatani and A. Hasegawa : Phys. Fluids 27 (1984) 611.



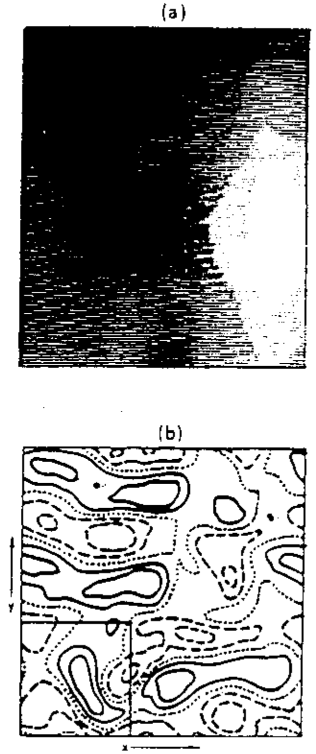
The potential contour (ϕ) and number density contour (N) in x-y plane.

$\tilde{n} \fallingdotseq \tilde{\phi}$

(Resistive Drift Wave Turbulence)

$\downarrow$

Bohm type diffusion



Structure of density turbulence in the $r-\theta$ plane. (a) Density fluctuations in the edge regions of the Caltech Research Tokamak measured using an array of 64 probes (see Section 2.2.3); (b) density fluctuations calculated from a theoretical drift wave model due to Waltz Size of Caltech array corresponds to box shown in lower left hand corner

図7 Caltech Research Tokamak で測定された (r,θ) 平面における密度ゆらぎの構造、(a) ランダミュアープローブ測定の結果。(b)Waltz[39] によるドリフト波の乱流シミュレーション結果。(文献 [41] より)

Inertial Range Cascade

Single invariant $\longrightarrow$ cascade to small scale

Two invariants $\longrightarrow$ dual cascade

Usually invariant with higher power of k goes to small scale.

Example: energy $= \int v_k^2 dV$ and enstrophy $= \int k^2 v_k^2 dV$.

Problem III : $E_r(r)$ Effects on Resistive Drift Wave and Interchange Turbulence in a Cylindrical Plasma with Magnetic and Velocity Shear

$$(\text{III}-1)\quad \frac{d}{dt}\nabla_\perp^2\phi = \frac{1}{\nu}\nabla_\parallel^2(n-\Phi) + \nabla n \times \nabla\Omega\cdot\hat{z} + \mu\nabla_\perp^2\Phi$$

$$(\text{III}-2)\quad \frac{d}{dt}(n+\bar{n}) = \frac{1}{\nu}\nabla_\parallel^2(n-\Phi) + \nabla(n-\Phi)\times\nabla\Omega\cdot\hat{z} + D_\perp\nabla_\perp^2 n$$

Normalizations : $\Phi \equiv e\Phi/T_e,\ n\equiv n/n_0,\ t=\Omega_{it},$

$r\equiv r/\rho_s,\ z\equiv z/\rho_s,\ \nu\equiv\nu_e/\Omega_o,\ \mu\equiv\mu/(\rho_s^2\Omega)$

$\rho_s = C_s/\Omega_i.\quad \bar{n}$: back ground density

$$\frac{d}{dt}\equiv\frac{\partial}{\partial t} - \nabla\Phi\times\hat{z}\cdot\nabla$$

$$\nabla^2\perp \equiv \frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}$$

$$\nabla_\parallel = \frac{\partial}{\partial z} + \nabla\Psi_h\times\hat{z}\cdot\nabla$$

$$\Psi_h = -\int_0^r r\iota(r)dr.$$

Linear eigenmode equation

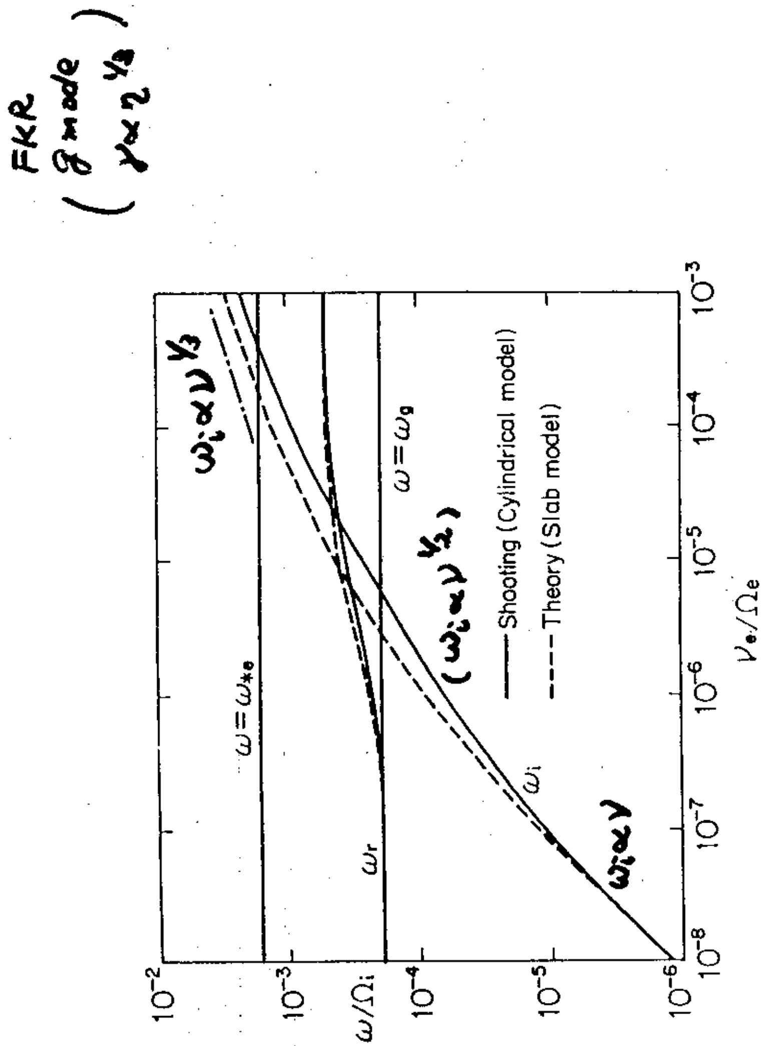
$$\Big(\frac{d^2}{dr^2}+\frac{1}{r}\frac{d}{dr}-\frac{m^2}{r^2}\Big)\tilde{\phi}$$
$$=\frac{1}{k_\parallel^2 - i\nu(\omega-\omega_g)}\Big[\Big(1-\frac{\omega_{*e}-\omega_g}{\omega}\Big)k_\parallel^2 - i\nu\frac{\omega_g(\omega_{*e}-\omega_g)}{\omega}\Big]\tilde{\phi}$$

$$k_\parallel = \frac{\rho_s}{R}(m\iota - n)\ ,$$
$$\omega_{*e} = -\frac{m}{r}\frac{d\bar{n}}{dr}$$
$$\omega_g = \frac{m}{r}\frac{d\Omega}{dr}$$

Analytic eigenvalue for $\nu\to 0$,

$$\omega = \omega_g + i\frac{\pi^2}{4}\frac{\nu}{k\prime_\parallel^2}\frac{\omega_g(\omega_{*e}-\omega_g)^2}{\omega_{*e}-\omega_g(m^2/r_0^2+2)}\ .$$

(resistive interchange branch)



Parameters of nonlinear calculations

$\rho = 1/40$, (ρ_s/a) $\qquad \epsilon = 1/13$, $(\equiv a/R)$

$\mu (\equiv \mu/\Omega_i \rho_s^2) = 4\times 10^{-4}$, $\quad D_\perp (\equiv D_\perp/\Omega_i \rho_s^2) = 4\times 10^{-4}$

back ground density profile :

$$n(r) = 0.9\ exp(-2r^2/a^2) + 0.1$$

or

$$n(r) = 0.9(1 - r^2/a^2) + 0.1\ .$$

rotational transform :

$$\iota(r) = 0.51 + 0.39 r^2/a^2\ .$$

$$10^{-2} \le \nu \le 10^{-4}\ (or\ 10^2 \lesssim S \lesssim 10^4)$$

energy :

$$E = \int \frac{1}{2}[n^2 + (\nabla_\perp \phi)^2] dv$$

$E_n \quad E_K$

enstrophy :

$$u = \int \frac{1}{2}(\nabla_\perp^2 \phi - n)^2 dv\ .$$

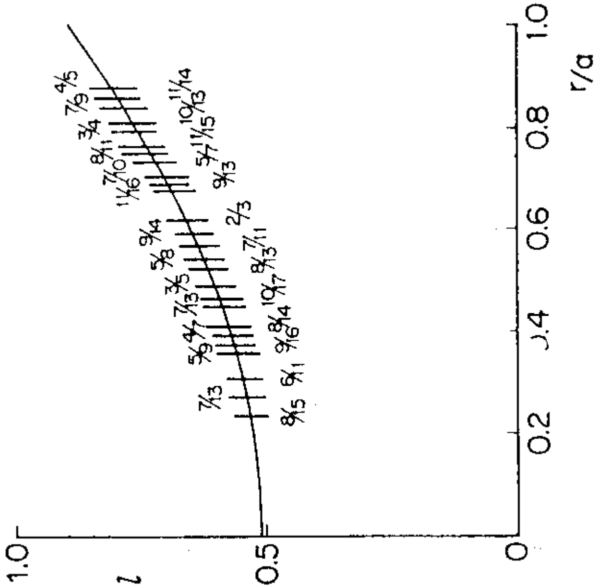


Fig.4

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Adiabatic parameter :

$$\bullet \quad \frac{\Omega_e}{\nu_e}\frac{\rho_s^2}{R^2}\frac{1}{\kappa\rho_s}$$

Hydrodynamic layer width :

$$\Delta_D/a = \left(\frac{\omega\nu_e}{\Omega_i\Omega_e}\right)^{1/2}\frac{\rho_s}{a}\frac{1}{k'_{\|}\rho_s^2}$$

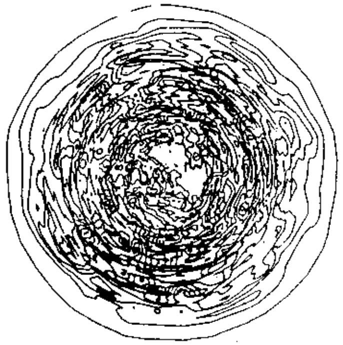
$$\left(\frac{\Delta_D}{a} \sim \frac{0.1}{\sqrt{m}} \quad for \quad \frac{\nu}{\Omega_e} = 10^{-4}\right)$$

Magnetic Reynolds number :

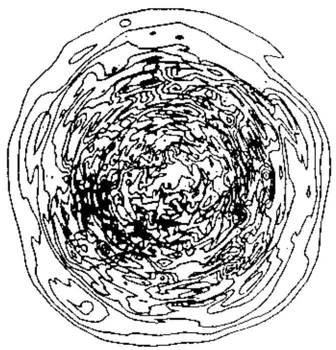
$$S = \frac{\Omega_e}{\nu_e}\frac{\omega_{pi}a}{c}\frac{a}{R}$$

$$(S \simeq 10^2 - 10^4)$$

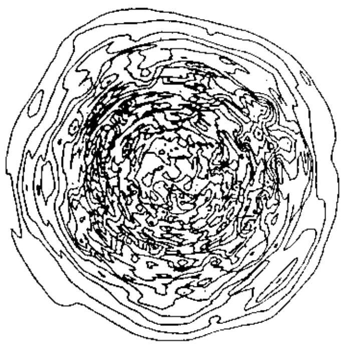
TIME=3.0



TIME=4.5



TIME=6.0

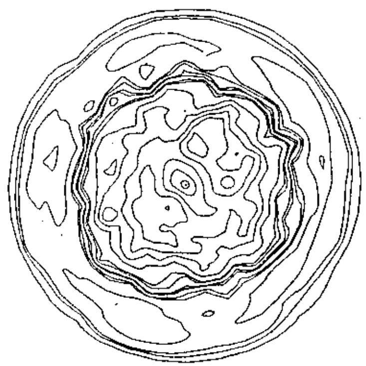


DENSITY CONTOUR

TIME=3.0

TIME=4.5

TIME=6.0



POTENTIAL CONTOUR

"zonal flow"

↓

Improvement of particle confinement

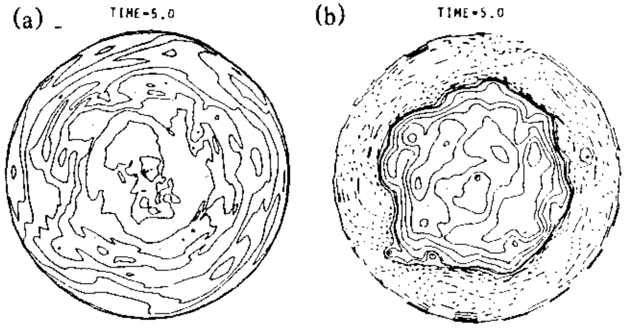


FIG. 1. (a) The density contour and (b) the potential contour from the three-dimensional computer simulation of electrostatic plasma turbulence in a cylindrical plasma with magnetic curvature and shear. In (b) the solid (dashed) lines are for the positive (negative) potential contours. Note the development of closed potential contours near the $\phi \simeq 0$ surface.

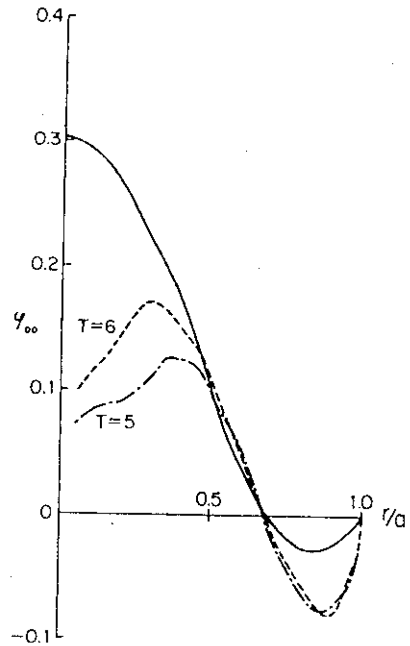


FIG. 2. Profiles of $\phi(r)$ for $m=0, n=0$ mode at two different time steps (dashed and dash-dotted lines) as compared with the predicted profile (solid line) based on the self-organization conjecture. The predicted curve is fitted at $r/a=0.5$.

"self-organization"

Poloidal Flow Profile Evolution

$$\frac{\partial \langle V_\theta \rangle}{\partial t} = -\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \langle \tilde{v}_r \tilde{v}_\theta \rangle - \frac{1}{\rho_0 \mu_0} r^2 \langle \tilde{B}_r \tilde{B}_\theta \rangle\right)$$

$$+\mu \frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(r \langle V_\theta \rangle)\right]$$

Reynolds Stress:

$$S_{ij} \equiv \langle \tilde{v}_i \tilde{v}_j \rangle - \frac{1}{\rho_0 \mu_0} \langle \tilde{B}_i \tilde{B}_j \rangle$$

ES part EM part

$$\frac{d}{dt} \int_0^a \langle V_\theta \rangle r^2 dr = 0.$$

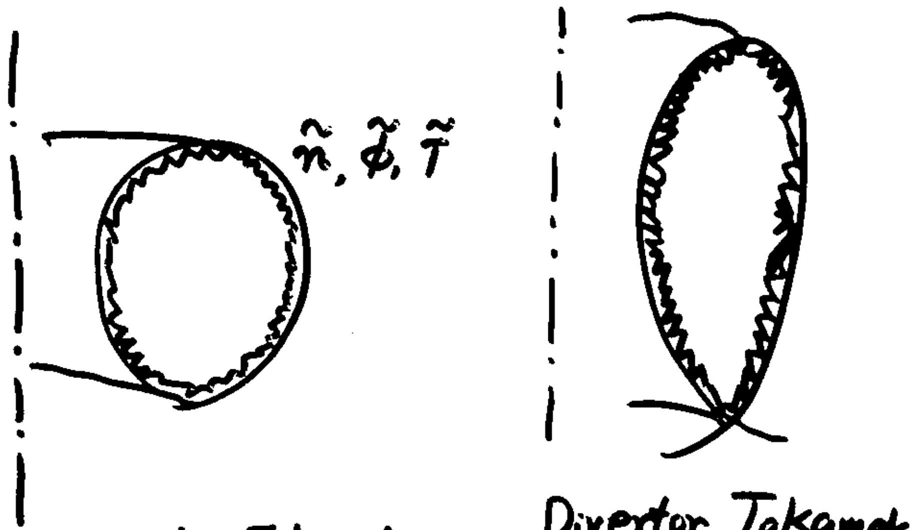
This means Reynolds stress does not create momentum; however, it does redistribute momentum along the radial direction.

Note: $\langle \cdot \rangle$ denotes averaging over magnetic surface.

Summary II

- Resistive drift turbulence is a candidate for explaining edge turbulence observed in medium size tokamaks.
- Shear flow (or zonal flows) is generated by Reynolds stress due to resistive drift interchange turbulence.

Edge Turbulence

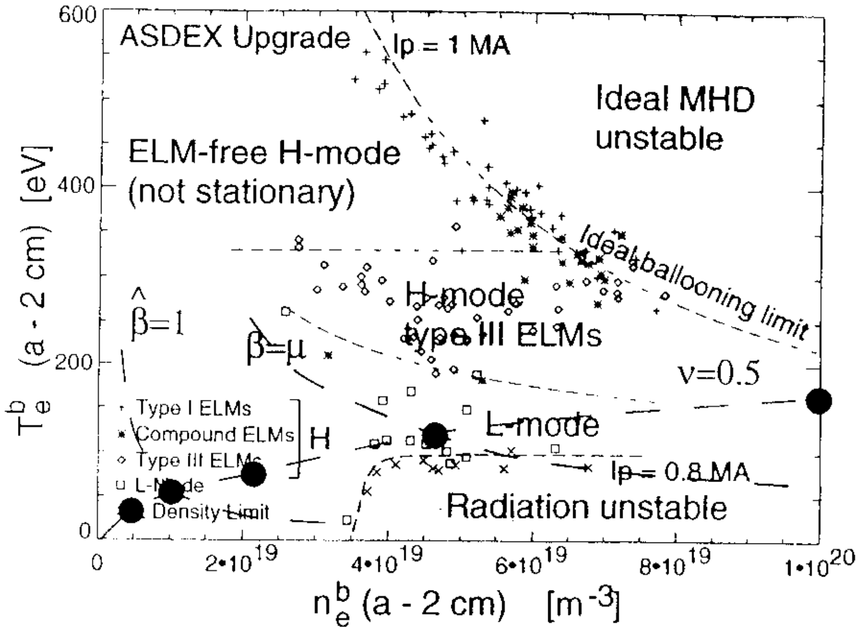


Circular Tokamak   Divertor Tokamak

Origin : resistive drift turbulence.

Is "finite β effect" stabilizing or destabilizing ?

Coupling between drift wave and shear Alfvén wave generates drift Alfvén wave.



B. Scott, IPP5/94, 1997.

Fig 16

Laboratory plasma experiment
(high density collisional plasmas)

cylindrical plasma

$B \simeq 0.1$ T, $\beta(0) \lesssim 0.1$

Wave characteristics were studied for resistive drift-Alfvén instabilities. Experimental results were compared with local linear theory.

Here we study global mode structures by solving eigenmode equations.

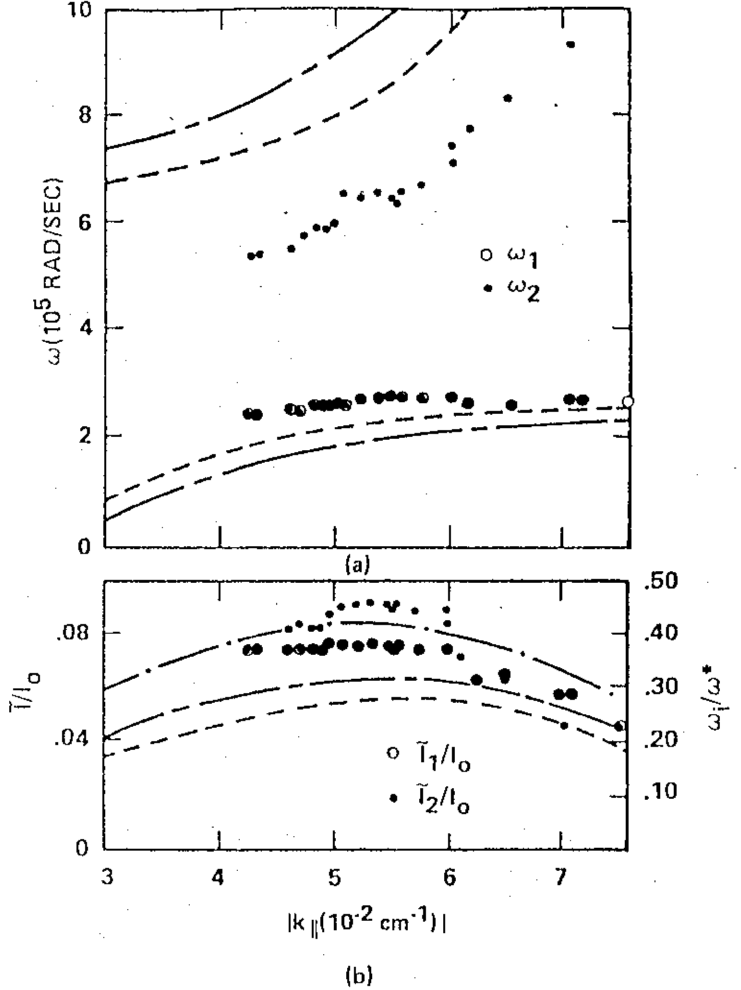


FIG. 9. (a) Dispersion of the drift-Alfvén wave showing the coupling near $\omega^* \simeq k_z V_A$ compared with the theoretical dispersion calculated from Eq. (17) for $n_0 = 5\times 10^{13}$ cm^{-3}, $B_0 = 1.6$ kG, $T_e = 4$ eV, and $k_\perp = [(1/n_0)/(dn_0/dr)] = 1.25$ cm^{-1}. The dashed-line represents the theoretical frequency and growth rate for the case of no axial current. Only the lower branch is unstable. (b) The segmented lines – – – and –·– represent theoretical values for the case of no axial current ($v_{ez0} = V_A$). Referring to the growth rate ω_i/ω^* diagram, the – – – curve is 0.2 times ω_{i1}/ω^* while the –·– curve is ω_{i2}/ω^*.

Two-Fluid Equations for Resistive Drift-Alfvén Wave

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

$$m_\alpha n_\alpha \frac{d\mathbf{V}_\alpha}{dt} = n_\alpha q_\alpha(\mathbf{E} + \mathbf{V}_\alpha \times \mathbf{B}) - \nabla P_\alpha + \mathbf{R}_{\alpha\beta} \tag{2}$$

$$\mathbf{R}_{\alpha\beta} = -m_\alpha n_\alpha \nu_{\alpha\beta}(\mathbf{V}_\alpha - \mathbf{V}_\beta) \tag{3}$$

$$\mathbf{E} = -\nabla\phi - \frac{\partial \mathbf{A}}{\partial t} \tag{4}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{5}$$

$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B} \tag{6}$$

$$\mathbf{V}_{dc} = -\frac{k_B T_e}{e B_0}\frac{1}{n_0}\frac{dn_0}{dr}\hat{\theta}, \tag{7}$$

$$T_e = \text{const.}, \quad T_i \simeq 0 \tag{8}$$

Linearized Equations

$$i(\omega-\omega_*)\frac{\tilde{n}}{n_0}=\frac{1}{n_0}\nabla_\perp\cdot(n_0\tilde{\mathbf{V}}_{e\perp})+\nabla_{\|0}\tilde{V}_{e\|} \tag{9}$$

$$+\frac{\tilde{\mathbf{B}}_\perp}{B_0 n_0}\cdot\nabla_\perp\cdot(n_0\bar{V}_{e\|})+\frac{1}{n_0}\bar{V}_{e\|}\cdot\nabla_{\|0}\tilde{n}$$

$$-k_B T_e\nabla_\perp\tilde{n}-n_0 e(\tilde{\mathbf{E}}_\perp+\tilde{\mathbf{V}}_{e\perp}\times\mathbf{B}_0+\mathbf{V}_{de}\times\tilde{\mathbf{B}}_\perp) \tag{10}$$

$$-\tilde{n}e(\mathbf{V}_{de}\times\mathbf{B}_0)=0$$

$$-k_B T_e\nabla_{\|0}\tilde{n}-k_B T_e\frac{\tilde{\mathbf{B}}_\perp}{B_0}\cdot\nabla_\perp n_0-n_0 e\tilde{\mathbf{E}}_\| \tag{11}$$

$$-n_0 m_e\nu_{ei}\tilde{V}_{ez}=0$$

$$i\omega\frac{\tilde{n}}{n_0}=\frac{1}{n_0}\nabla_\perp\cdot(n_0\tilde{\mathbf{V}}_{i\perp}), \tag{12}$$

$$n_0 m_i\frac{\partial\tilde{\mathbf{V}}_{i\perp}}{\partial t}=n_0 e(\tilde{\mathbf{E}}_\perp+\tilde{\mathbf{V}}_{i\perp}\times\mathbf{B}_0). \tag{13}$$

$$\underline{j_{z0}=-n_0 e\bar{V}_{ez}} \tag{14}$$

$$\tilde{j}_z=-\tilde{n}e\bar{V}_{ez}-n_0 e\tilde{V}_{ez}. \tag{15}$$

Eigenmode Equations

$$(\rho_s^2\omega_A^2\nabla_\perp^2+\omega\omega_1)\frac{e\tilde{A}}{T_e}+\frac{\omega_3}{j_{z0}}\frac{dj_{z0}}{dr}\frac{m}{r}\tilde{A}=\omega_1 k_\|\frac{c\tilde{\phi}}{T_e} \tag{16}$$

$$(\omega_1+b\omega)k_\|\frac{e\tilde{\phi}}{T_e}-\omega\omega_1\frac{e\tilde{A}}{T_e}-\frac{\omega_2}{j_{z0}}\frac{dj_{z0}}{dr}\frac{m}{r}\tilde{A}$$

$$=\rho_s^2\omega\frac{k_\|}{rn_0}\frac{d}{dr}\left\{rn_0\frac{d}{dr}\left(\frac{c\tilde{\phi}}{T_e}\right)\right\} \tag{17}$$

$$\omega_1=\frac{\omega-\omega_*}{1-i\omega/\nu_\|}$$

$$\omega_2=\frac{i\omega k_\|\bar{V}_{e\|}/\nu_\|}{1-i\omega/\nu_\|}$$

$$\omega_3=\frac{k_\|\bar{V}_{e\|}}{1-i\omega/\nu_\|}$$

$$\nu_\| = k_\|^2 V_{Te}^2/\nu_{ei}$$

Eigenmode equations are solved with a shooting method.

B.C.

$$\tilde{A}(r) = a_0 r^m$$

$$\tilde{\phi}(r) = b_0 r^m$$

$$\tilde{A}(a) = 0$$

$$\tilde{\phi}(a) = 0$$

(a : plasma radius)

Parameters

$$n(r) = n_0 \exp[-4(r/a)^2]$$

$$T_e = \text{const.}$$

$$a$$

$$B_0$$

$$(m,\ k_z)$$

Local Dispersion Relation (for $J_{z0} = 0$)

$$(-b\omega_A^2 + \omega\omega_1)\tilde{A} = \omega_1 k_z \tilde{\phi}, \tag{18}$$

$$(\omega_1 + b\omega)k_z\tilde{\phi} = \omega\omega_1\tilde{A}, \tag{19}$$

where $d\omega_*/dr = 0$, $\bar{V}_{ez} = 0$.

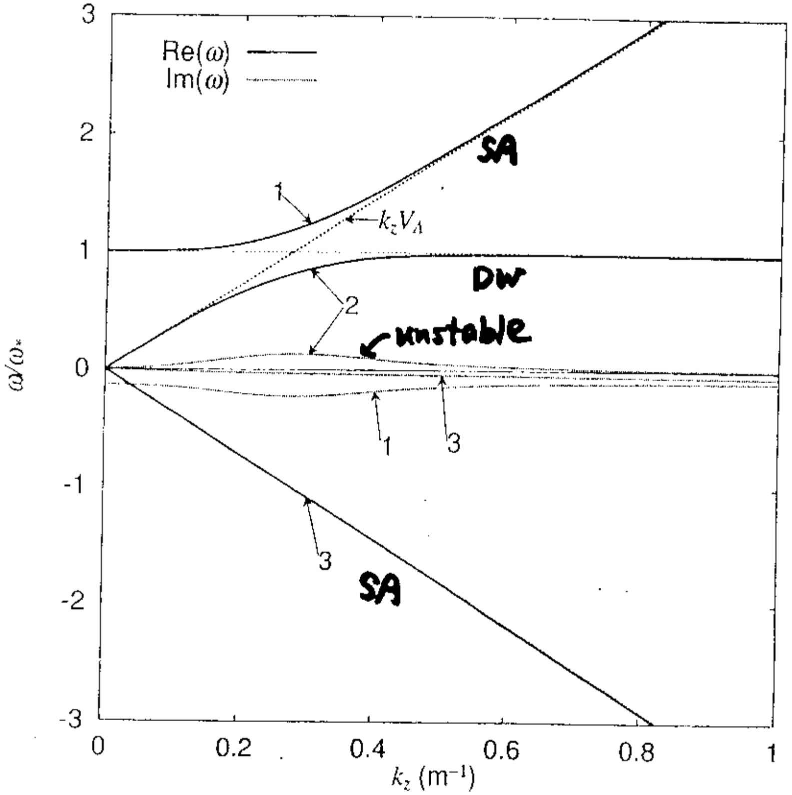
$$(\omega^2 - \omega_A^2)(\omega - \omega^*) - b\omega_A^2\omega\left(1 - i\frac{\omega}{\nu_\parallel}\right) = 0, \tag{20}$$

where $\omega_A = k_z V_A$, $b = m^2\rho_s^2/r^2$, $\rho_s^2 = T_e/m_i\omega_{ci}^2$.

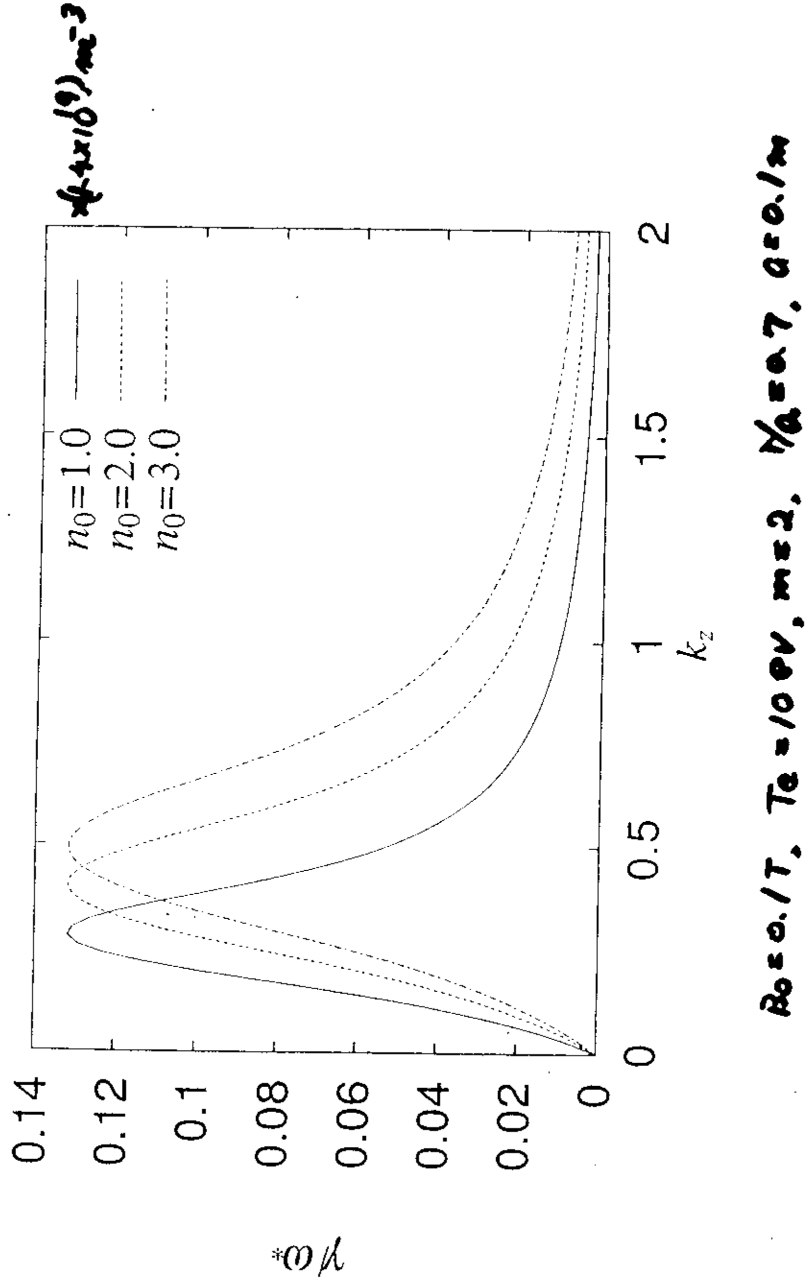
Solution of (20),

$$\omega = \pm\omega_A, \quad \omega = \omega_* + ib\omega_*^2/\nu_\parallel \tag{21}$$

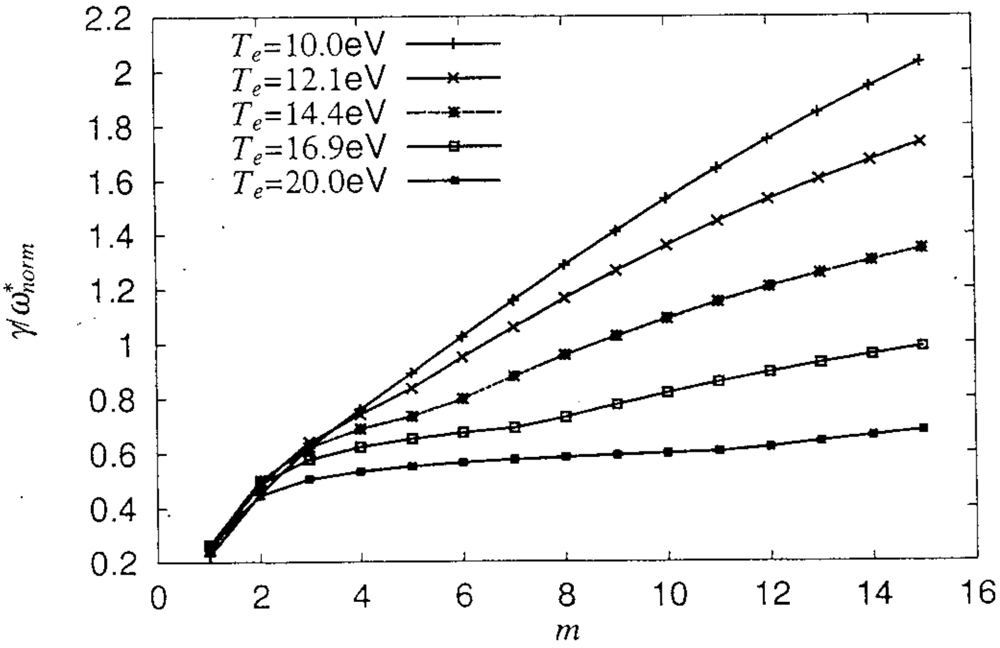
$\nu_\parallel = k_z^2 v_{Te}^2/\nu_{ei}$



$B_0 = 0.1$T, $T_e = 100$eV, $n_0 = 1.4 \times 10^{19}$ m^{-3}
$m=2$, $r/a = 0.7$, $a = 0.1$m

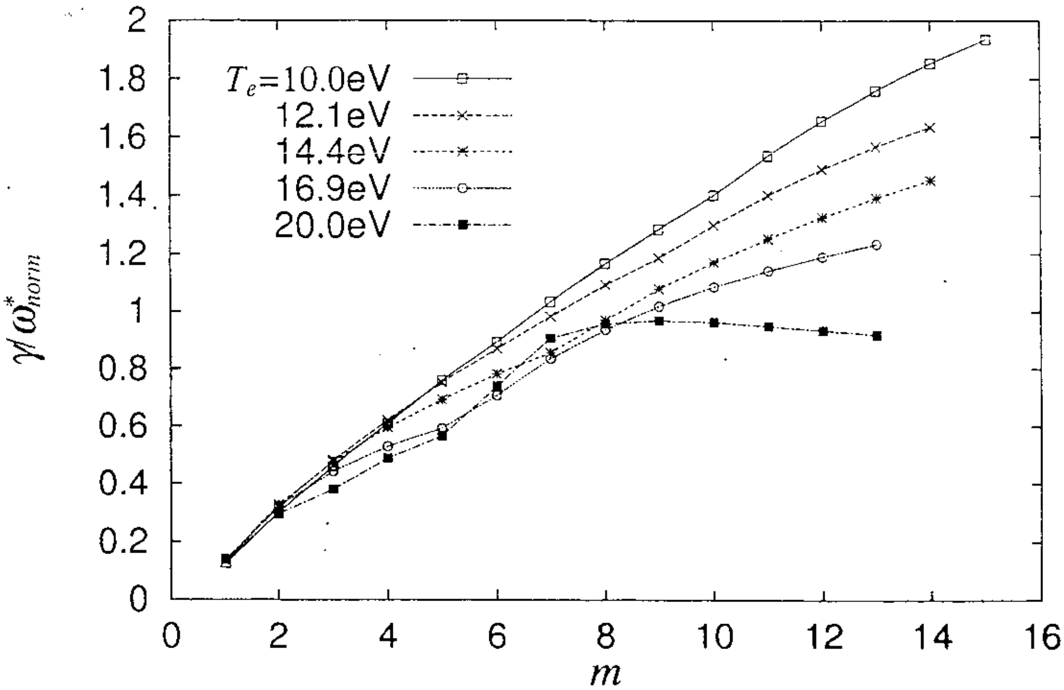


Local analysis



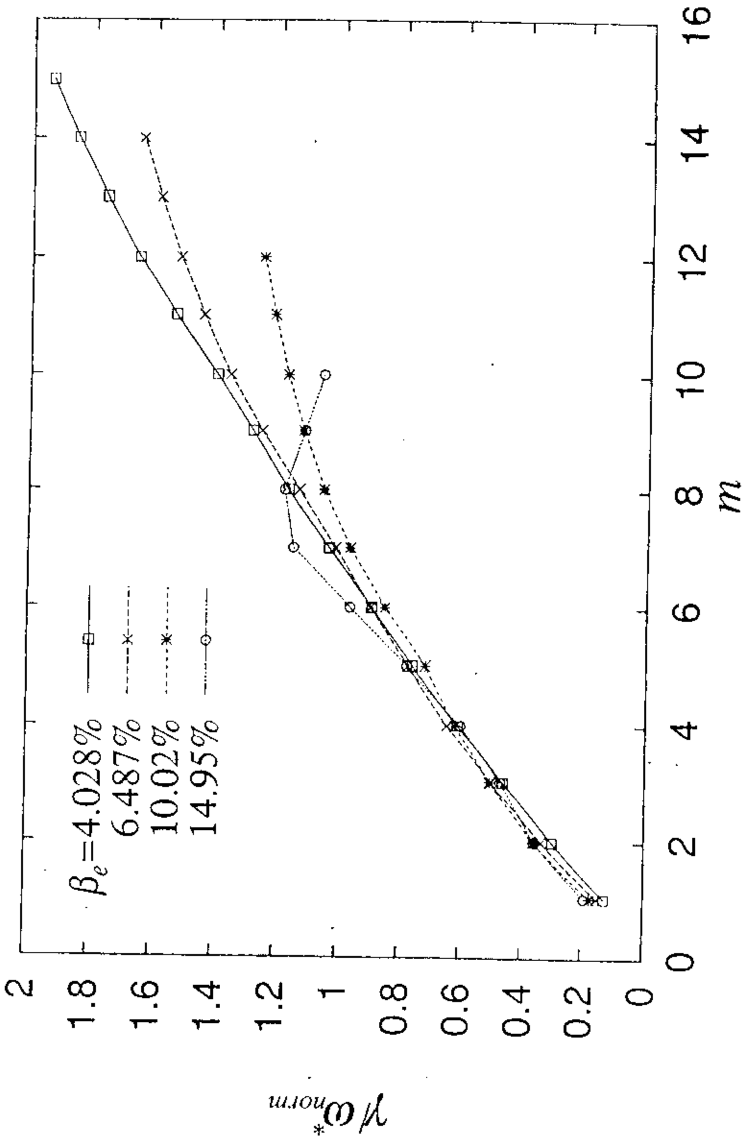
B_0=0.1T, k_z= 1, n_0=$1.4\times10^{19} m^{-3}$, a=0.1m

Non-local model

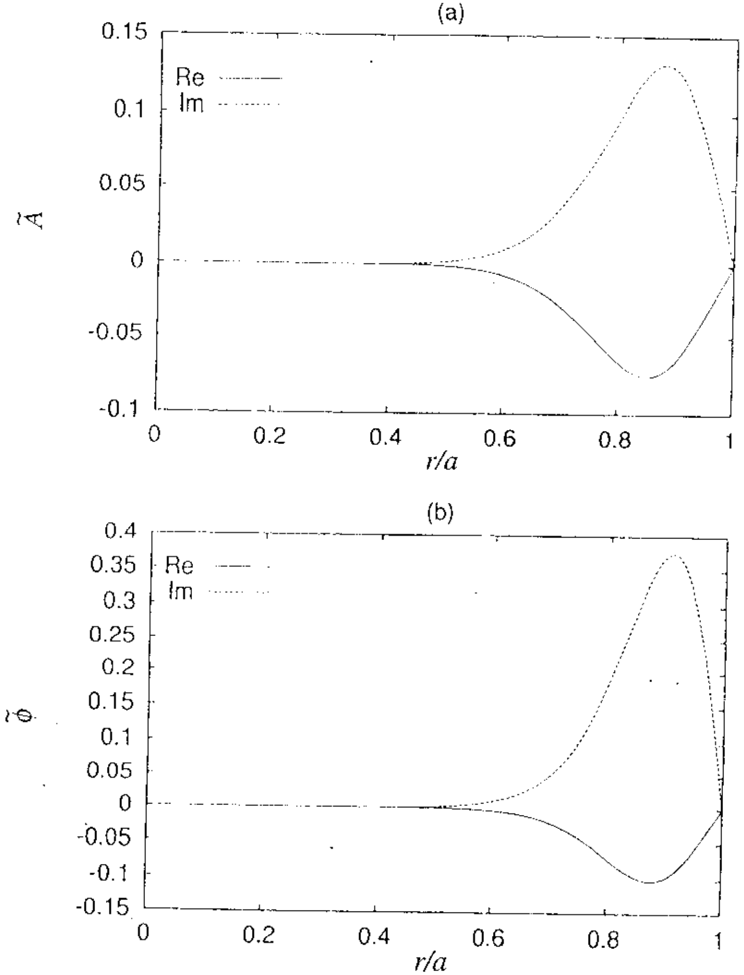


B_0=0.1T, n_0=$10^{20} m^{-3}$, k_z = 1

Non-local model



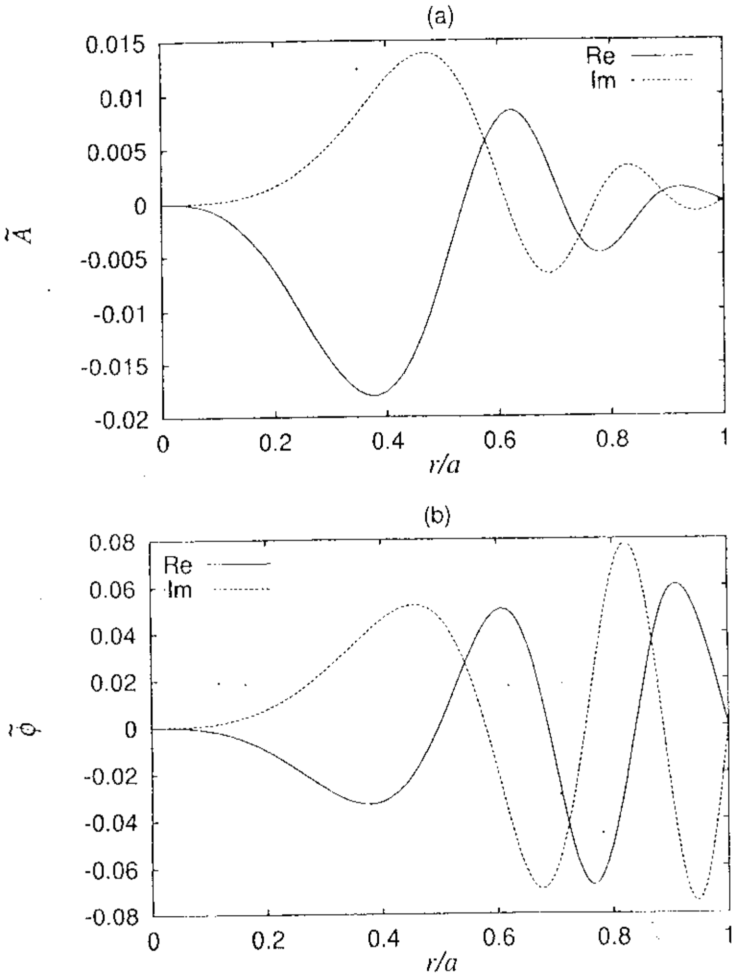
B_0=0.1T, k_z=1, a=0.1m



m=10

B_0=0.1T, k_z=1, T_e=10ev

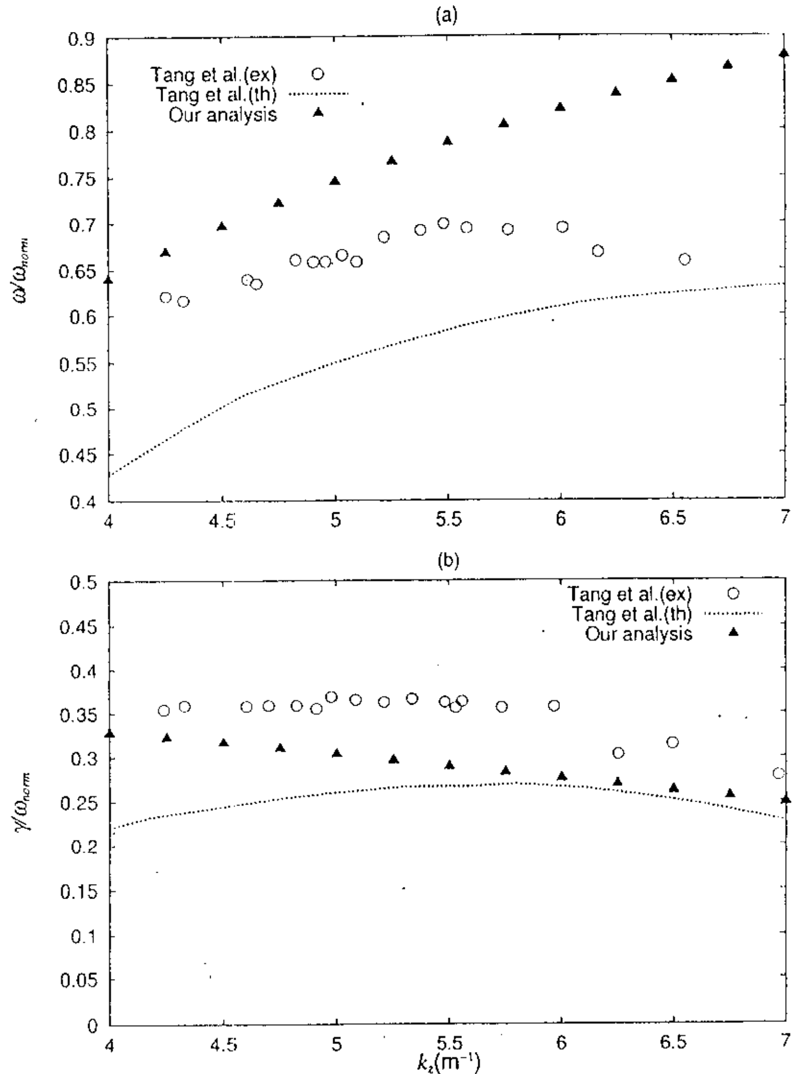
a=0.1m, n_0=$10^{20}m^{-3}$



$m=3$

$B_0=0.1T$, $K_z=1$, $T_e=10ev$.

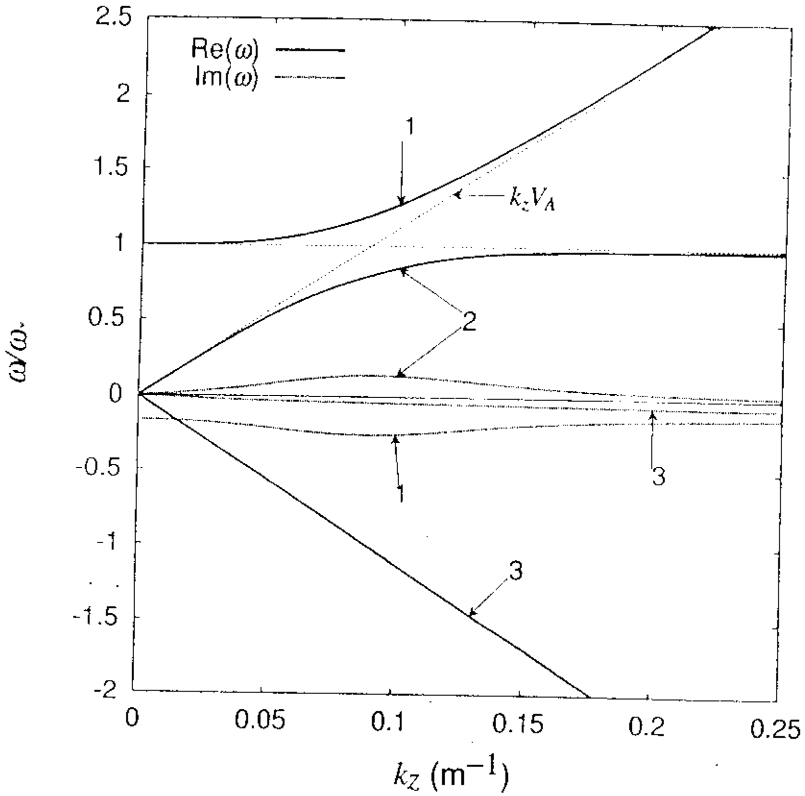
$a=0.1m$, $n_0=10^{20}m^{-3}$



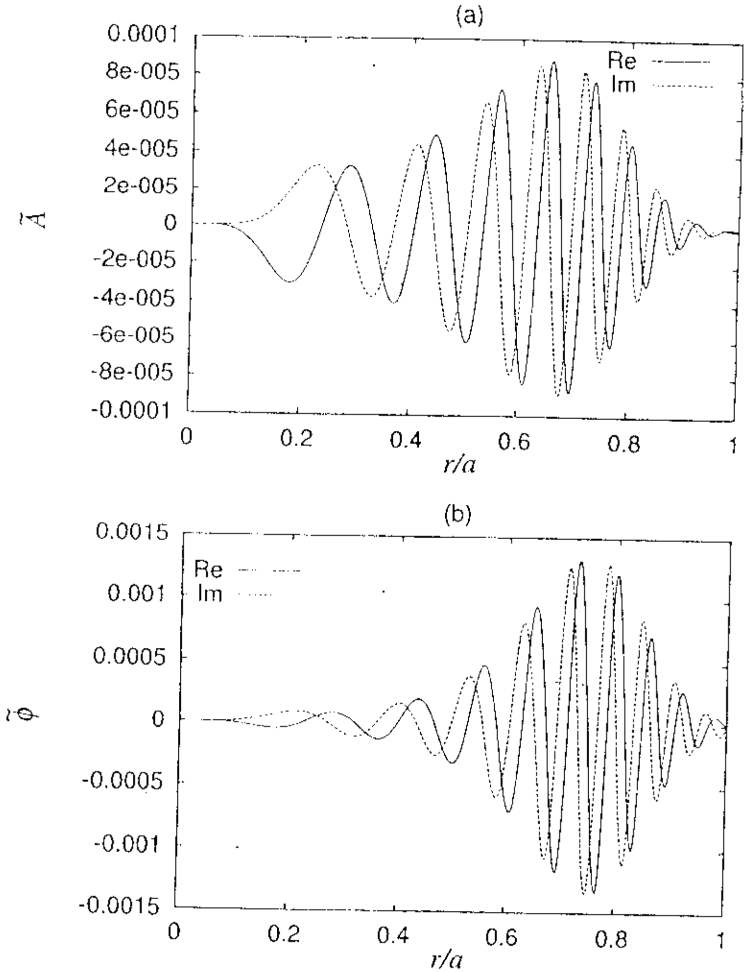
$m=1$

$B_0=0.16T$, $T_e=T_i=4eV$, $a=0.018m$

$n_0=4\times10^{19}m^{-3}$



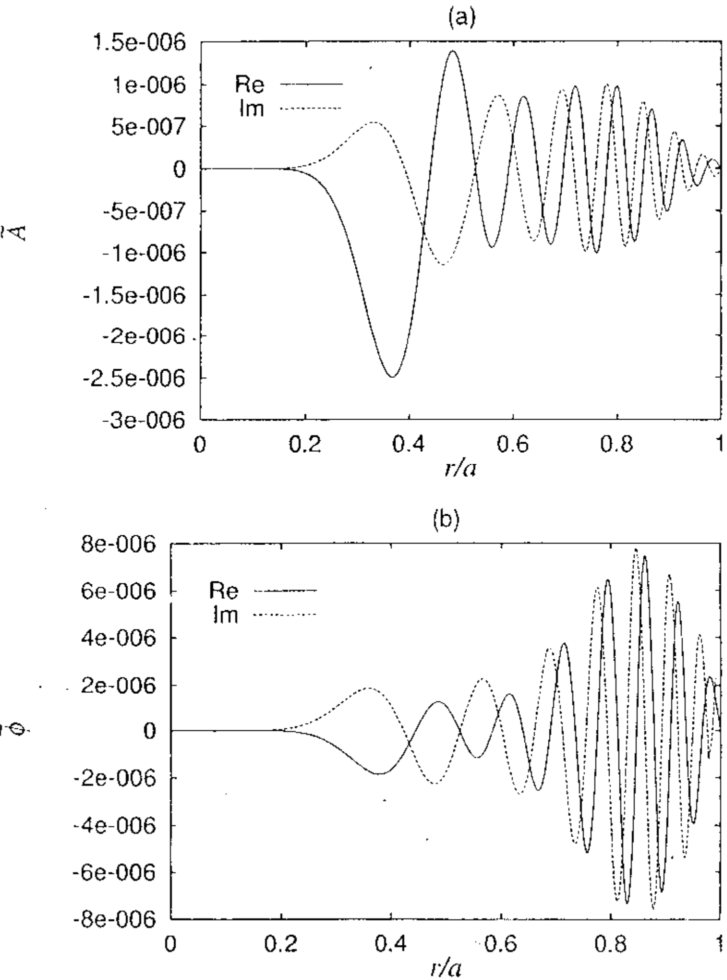
$B_0 = 1T$



$m=5$

$k_z = 0.1$, $T_e = 50$ eV, $a = 0.1$ m

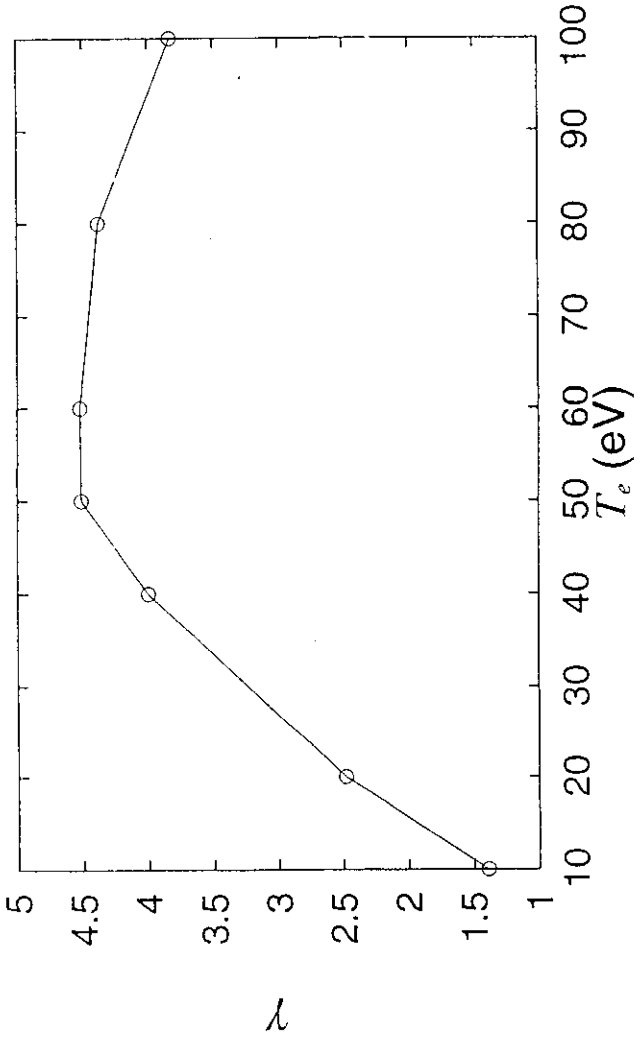
$n_0 = 10^{20}$ m^{-3}, $B_0 = 1.0$ T



$m=10$

$k_z=0.1$, $T_e=50\,eV$, $a=0.1m$

$n_0=10^{20}m^{-3}$, $B_0=1.0T$



$m=5$

$B_0=1.0T$

Concluding Remarks

1. Resistive drift-Alfvén(RDA) instabilities may be relevant to the edge physics of tokamaks including the L-H transition.

2. When T_e or β_e is increased, growth rates of RDA instabilities decrease.

3. ∇T_e, ∇T_i and $J_{||}$ effects will be studied soon.