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Gyro-kinetic and Gyro-fluid Simulations of micro-turbulence and associated flow generation

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collaboration with

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Outline

Various profile formation in advanced tokamak operation
is tightly coupling with various electric field and flow generation

Equilibrium and/or neo-classically driven flow

Turbulence driven zonal flow

- simulation of zonal flow generation (ETG and ITG)
- mechanism of zonal flow generation
  - modulational instability analysis

new role of zonal flow

- Interaction among different scale fluctuation
  - possibility of coupling between ITG and ETG

Origin of radial electric field in tokamak plasma

Review：K. Itoh and S. Itoh, PPCF (1996)

- Neoclassical effect： Novakovskii, et.al (1997)

  $V_E \quad (k-1)V_{*T} - V_{*n} \qquad k = 0.5 \sim 1.1$

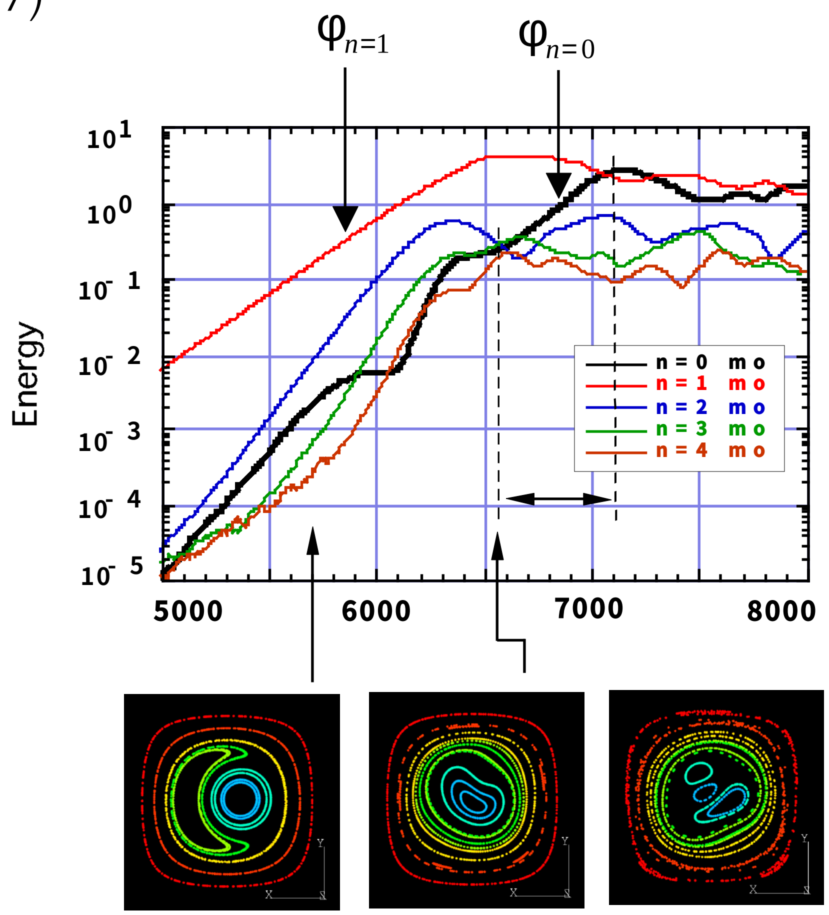
- High energy particle loss：
  Ohkawa (1995), Rosenblth et.al (1996)

- Non-local orbit effect： Cheing, et.al (1996)
  - ○ ripple of toroidal magnetic field
  - ○ large orbit effect

MHD driven flow

- E. Joffrin et.al. (2001) :
  ITB trigger by external MHD
  and resulting toroidal mode coupling

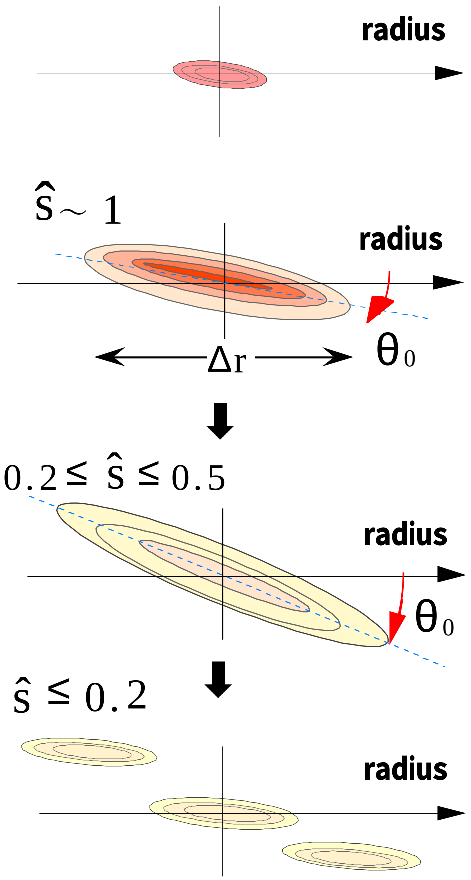
- T. Matsumoto, H. Naito, et. al (2000) :
  Gyro-kinetic MHD simulation
  (internal kink mode)

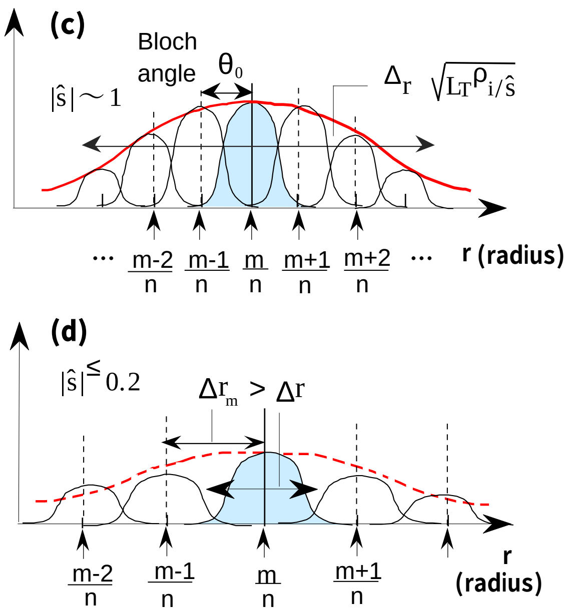


formation of radial electric field during
internal collapse of m/n=1/1 internal kink mod

Effect of flow shear on fluctuation

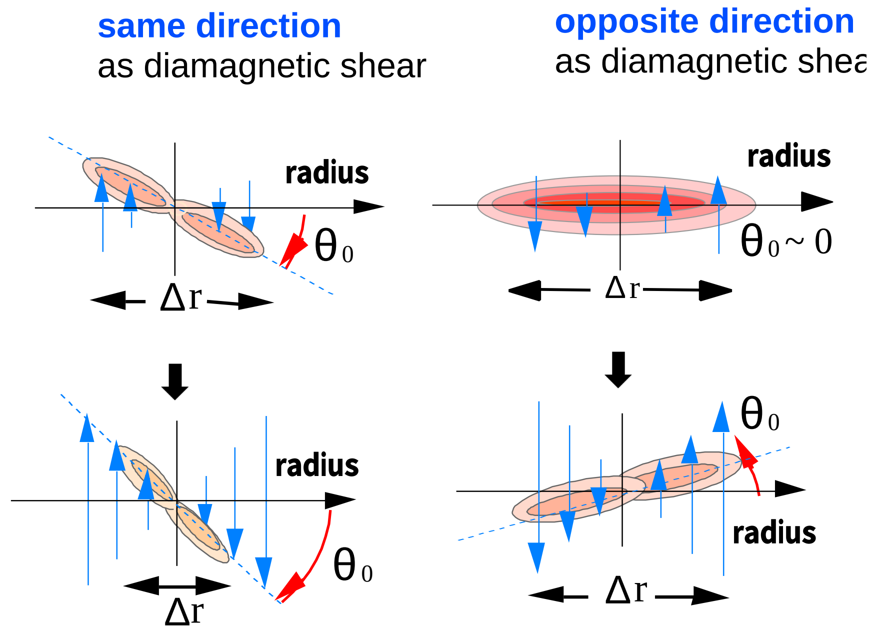
magnetic shear dependence





dependence of plasma shear rotation

(a) $\partial \omega_f / \partial r < 0$ (b) $\partial \omega_f / \partial r > 0$



$$\gamma = \gamma_0 \cos(\theta_0^{max}) \qquad (\theta_0)_{max} \mp \left| \frac{\left(\frac{\partial \omega_r}{\partial r} + \frac{\partial \omega_f}{\partial r}\right)}{2 k_\theta \gamma_0 \hat{s}} \right|^{\frac{1}{3}} \pm \left| \left(\frac{\gamma_0}{\omega_d}\right) \frac{1}{2 \hat{s} k_\theta L_T} \right|^{\frac{1}{3}}$$

Kim, Kishimoto et.al (1996)

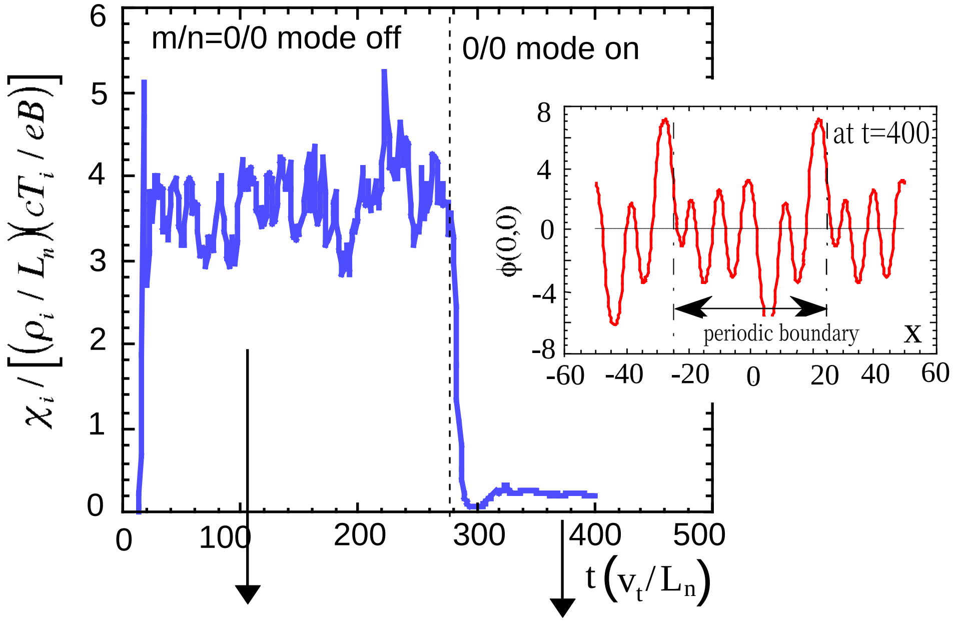
$$\omega_{E \times B} = \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi} \frac{E_r}{RB_\theta}$$

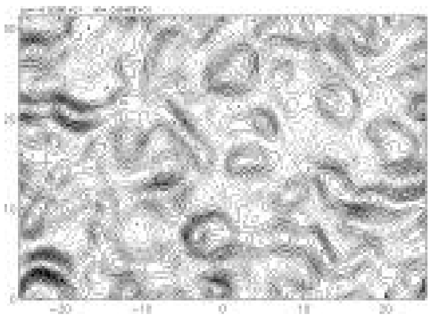
Hahm, Burrell (1995)

Fluctuation and transport is regurated by zonal flow

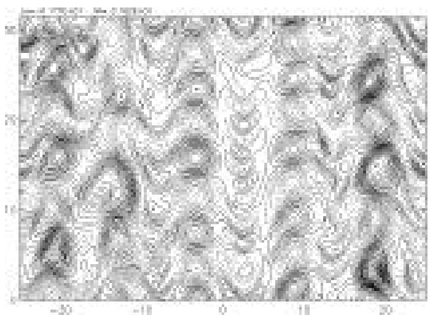
Sheard ExB zonal flow generated by nonlinear interaction among turbulences

Electrostatic toroidal ITG turbulence





t=180 (w/o zonal flow)



t=400 (with zonal flow)

Nonlinear interaction by Reynolds' stress

$$\frac{\partial V_E}{\partial t} = F_{Rey} = -\left\langle \tilde{v}_x \frac{\partial \tilde{v}_y}{\partial x} \right\rangle - \left\langle \tilde{v}_y \frac{\partial \tilde{v}_y}{\partial x} \right\rangle$$

radial scale of flow ~ turbulent scale

$$k_r^{(Z)} \left(\omega^{(z)} \quad 0 \right) \sim k_r$$

$$\omega_{E\times B} = \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi} \frac{E_r}{RB_\theta} \qquad k_r^{(z)2} \varphi^{(z)}$$

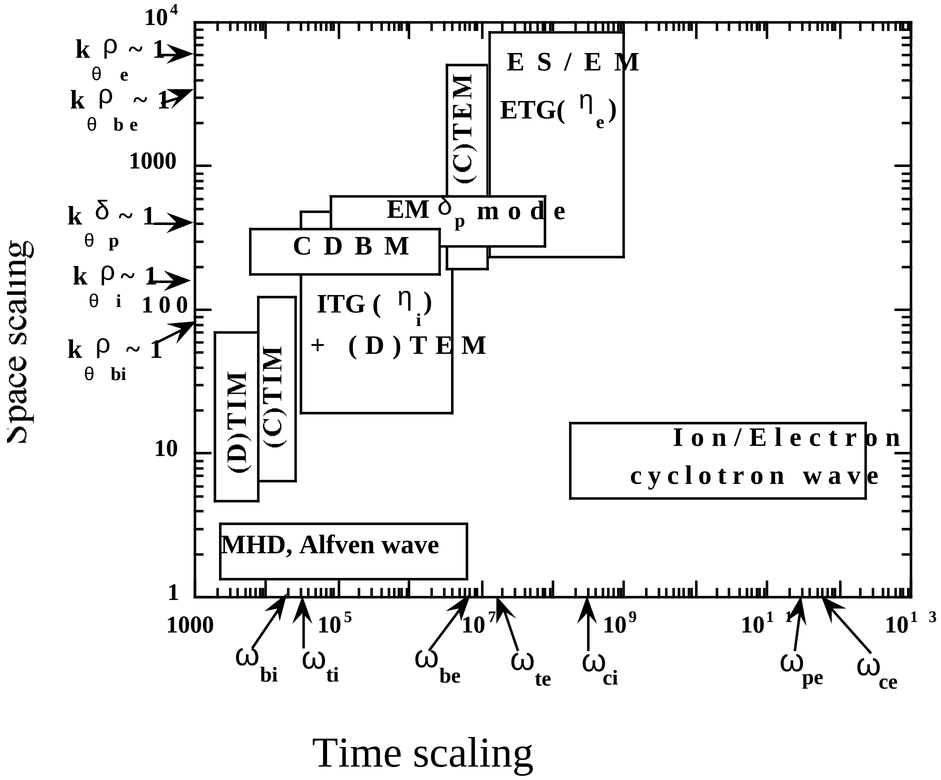
Hahm, Burrell (1995)

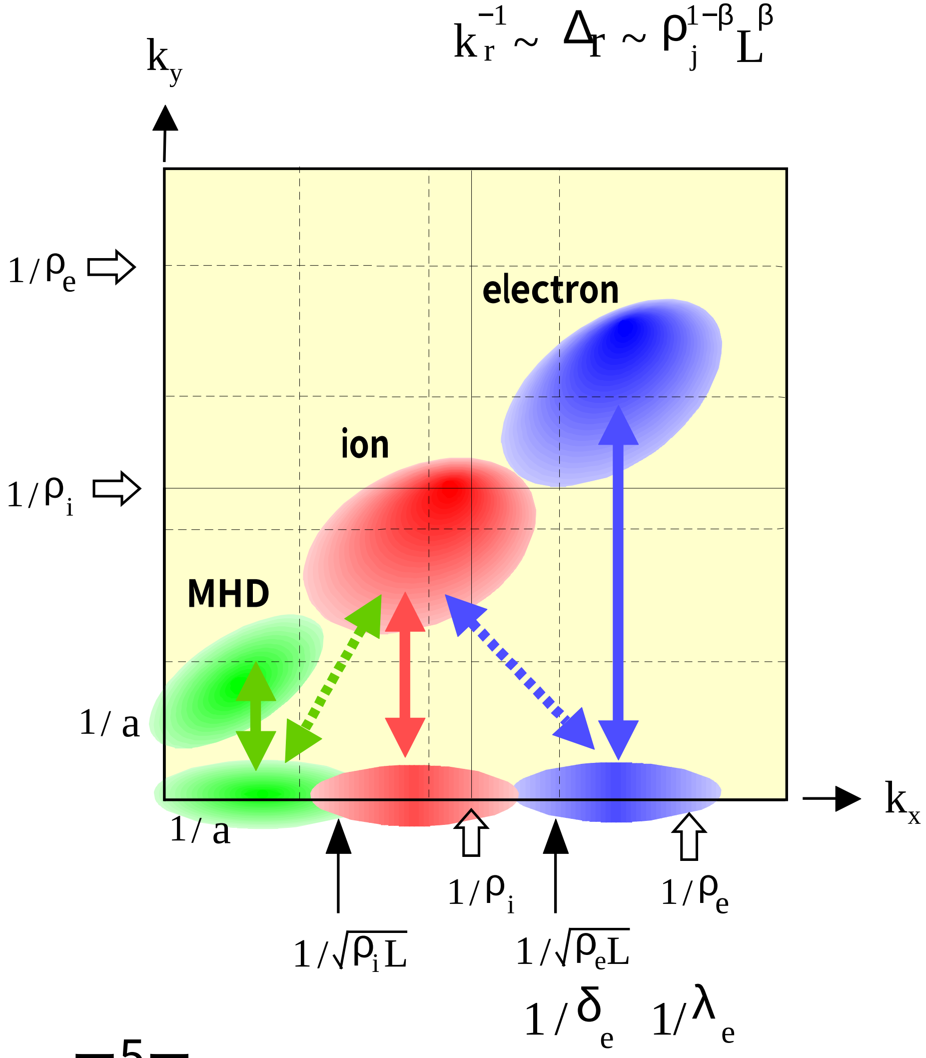
- **Regulate turbulent eddies and decreasing radial correlation length**
- **Reduction of trubulent fluctuation and transport**

However, still transport is anomalous

Various fluctuation and corresponding flow generation

zonal flow : $k_z^{(Z)} \sim k_\theta^{(Z)} \sim 0$ ⇨ **Role of coupling among different fluctuations**
$\omega^{(Z)} \sim 0$ **(except k_r)**





Nonlinear evolution of ETG turbulence in reversed shear plasma

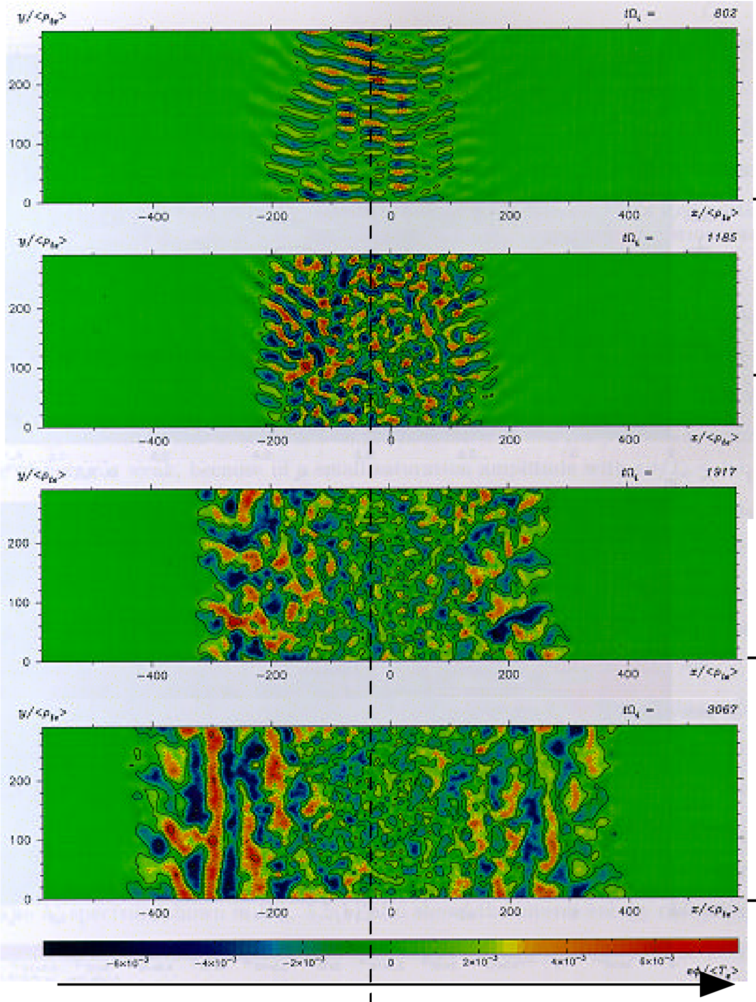
ETG (Electron Temperature Gradient Mode) turbulence is self-regulated by TEG driven Zonal flow and seconday Kelvin-Helmholtz (K-H) instability

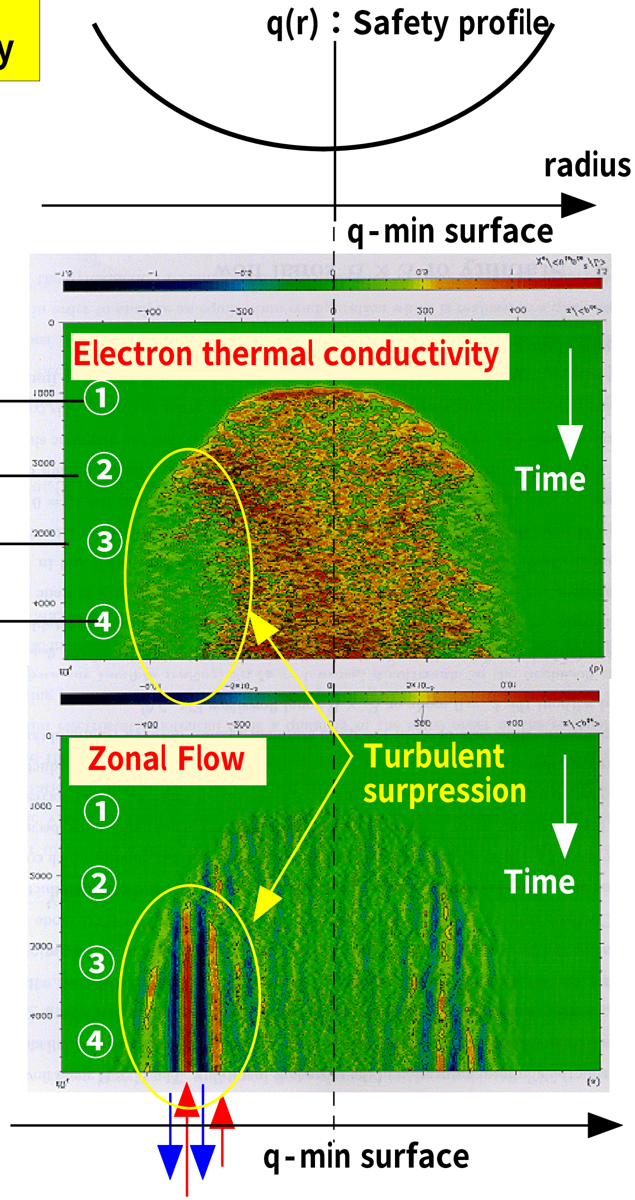
① Linear phase (t=2μsec)

② Saturation phase (t=4μsec)

③ Nonlinear phase (t=6μsec)

④ Quasi-steady state (t=8μsec)



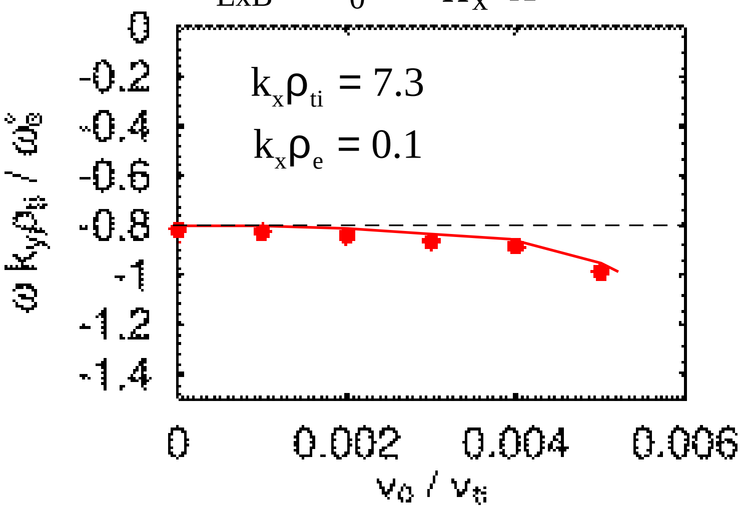


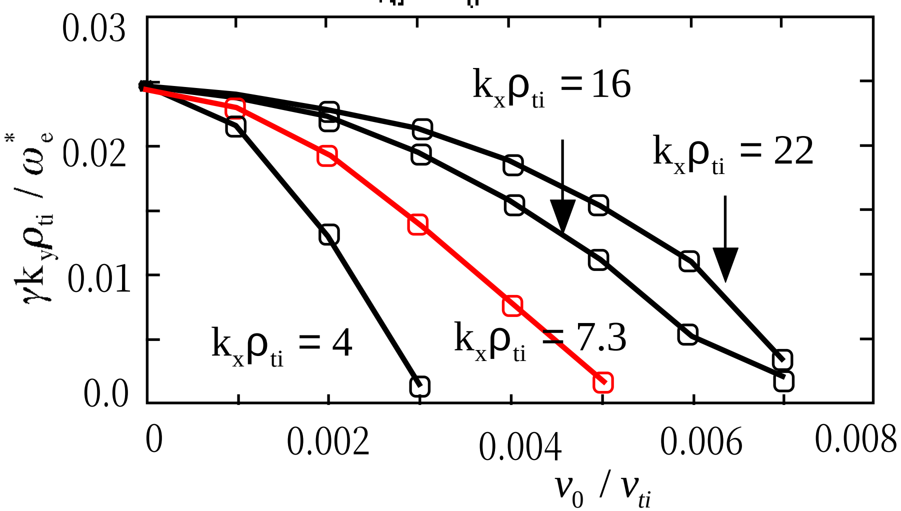
Idomura et. al IAEA (2000)

Effect of ETG driven flow on ITG linear mode

- ○ **Linearcalculation of NS-ITG mode by using Fourier particle code**
- ○ **ExB microscopic equilibrium flow driven by ETG turbulence**

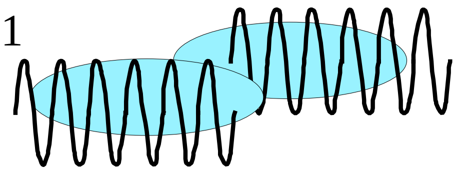
$$v_{ExB} = v_0 \sin k_x^{(Z)} x$$





finite FLR effect for microscopic ETG flow

$\rho_i / L_f^{(ETG)} \geq 1$



$$\langle v_{E\times B} \rangle = v_0 \sin\left(k_x^{(Z)} x\right) J_0\left(k_x^{(Z)} \rho_i\right)$$

- **ETG driven zonal flow stabilizes the ITG mode**

$v_0 / v_{ti} \sim 0.005$

- **Effect of zonal flow on ITG mode**

⇨ **sensitive to zonal flow spectrum**

Interaction among different spatial scale turbulence

- Interaction with different time and spatial scale turbulences
  - ○ Direct interaction of fluctuation
    - random noise
    - direct overlapping of spectrum

Yoshizawa et.al (2001)
Itoh and Itoh (2001)

○ Indirect interaction through zonal flow

turbulent spectrum ⇆ zonal flow spectrum

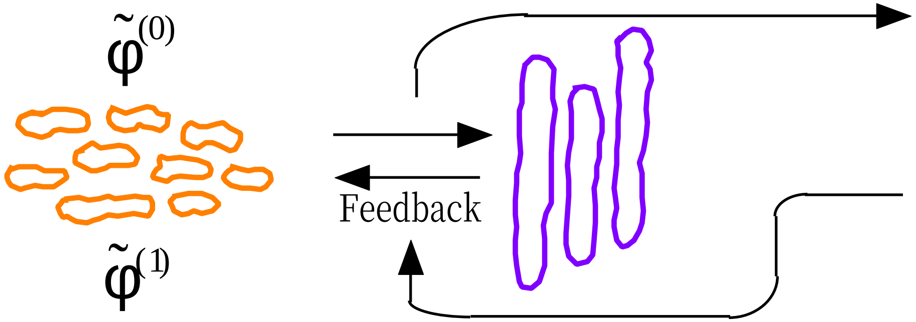
- Mechanism of zonal flow generation
  - linear stability
  - saturation mechanism and the level
  - steady state zonal flow spectrum (wave number and frequency)
  - damping mechnism

Zonal Flow Instability

- **Inverse cascade：energy transfer from micro-scale to macro-scale turbulence**
- **Physical mechanism：positive feedback of coupling dynamics between micro- and macro-scale structure ("modulational instability")**

$\varphi = \tilde{\varphi} + \bar{\varphi}$ $\tilde{\varphi} = \tilde{\varphi}^{(0)} + \tilde{\varphi}^{(1)}$

Manfredi et.al (2001)



$$\frac{\partial}{\partial t}\,{}^{2}\bar{\varphi} = -\left\langle\left\{\tilde{\varphi},\ {}^{2}\tilde{\varphi}\right\}\right\rangle$$

$$\left(1 - {}^{2}\right)\frac{\partial}{\partial t}\tilde{\varphi}^{(1)} = \left\{\bar{\varphi},\ {}^{2}\tilde{\varphi}^{(0)}\right\} + \left\{\tilde{\varphi}^{(0)},\ {}^{2}\bar{\varphi}\right\}$$

- **Dispersion relation for large scale fluctuation：Smolyakov, Diamond et.al. (1999)**

scale separation： $|\mathbf{q}| << |\mathbf{k}|$ $|\Omega| << |\omega_{\mathbf{k}}|$

$$-i\Omega = -q^2 C_S^2 \int d^2k \frac{k_\theta^2 \rho_s^2}{\left(1 + k^2\rho_s^2\right)} k_r^2 \frac{\partial N_k^0}{\partial k_r} \frac{i}{\Omega - qV_{gr}}$$

$$\gamma = -q^2 \int \pi\delta\left(\Omega - qV_{gr}\right) k_\theta^2 k_r \frac{\partial N_k^0}{\partial k_r} d^2k$$

instability： $\frac{\partial N_k^0}{\partial k_r} < 0$

- **Saturation mechanism and saturation level of zonal flow**

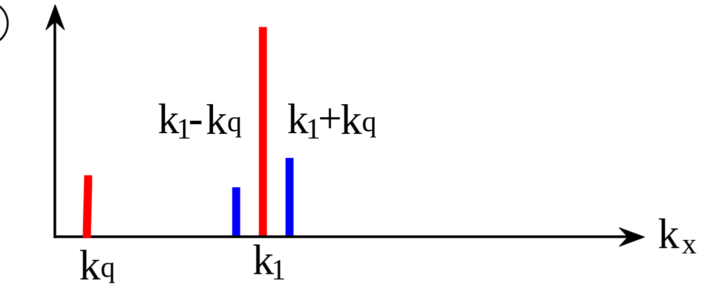
Modulational instability analysis

Formation of feedback loop depending on initial states Li, Kishimoto (2002)

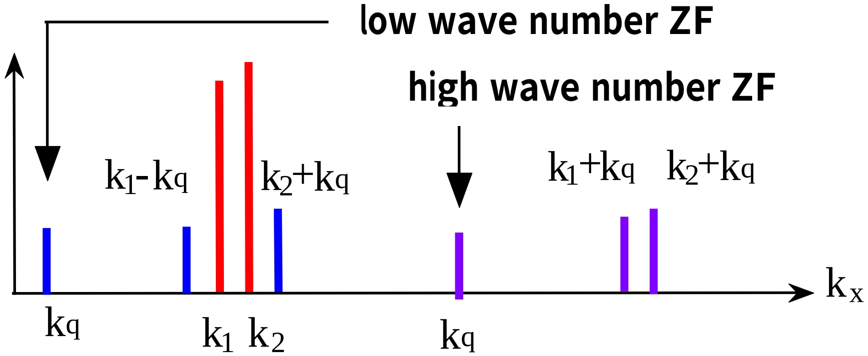
Three fundamental mode coupling processes

ETG turbulence - zonal flow system

$$(1 - {}^2)\frac{\partial}{\partial t}\varphi = \frac{\partial}{\partial y}\varphi + [\varphi, {}^2\varphi]$$

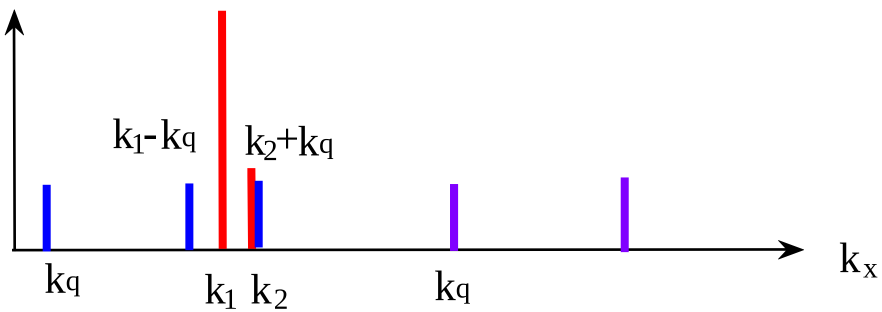
①


- one dominat pump wave
- a zonal flow seed

②


- two dominat pump wave (comparable amplitude)

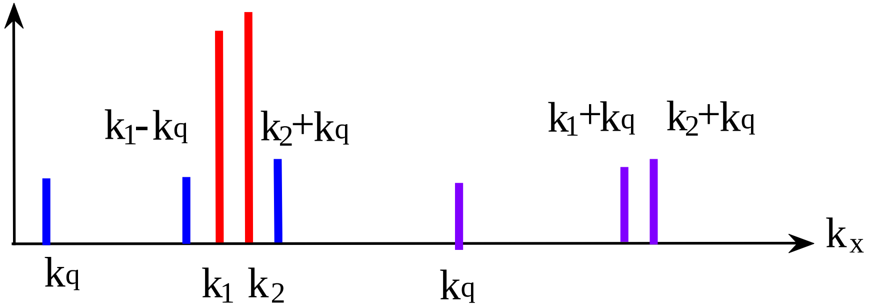
no seed necessary

③


- one dominat pump wave
- a side band of small amplitude

no seed necessary

Modulational instability analysis (continue)



dispersion relation

$$\omega^2 = \frac{k_y^2 k_q^2 \left(k_{x1} + k_{x2}\right)}{8\left(1 + k_q^2\right)} \left[\frac{k_{x1}^2 + k_y^2 - k_q^2}{1 + k_{x2}^2 + k_y^2} \varphi_1^2 - \frac{k_{x2}^2 + k_y^2 - k_q^2}{1 + k_{x1}^2 + k_y^2} \varphi_2^2 \right]$$

$$- \frac{k_y^2 k_q^3 \left(k_{x2} - 3 k_{x1}\right)}{8\left(1 + k_q^2\right)} \frac{k_{x1}^2 + k_y^2 - k_q^2}{1 + \left(2 k_{x1} - k_{x2}\right) + k_y^2} \varphi_1^2$$

$$- \frac{k_y^2 k_q^3 \left(3 k_{x2} - k_{x1}\right)}{8\left(1 + k_q^2\right)} \frac{k_{x2}^2 + k_y^2 - k_q^2}{1 + \left(2 k_{x2} - k_{x1}\right) + k_y^2} \varphi_1^2$$

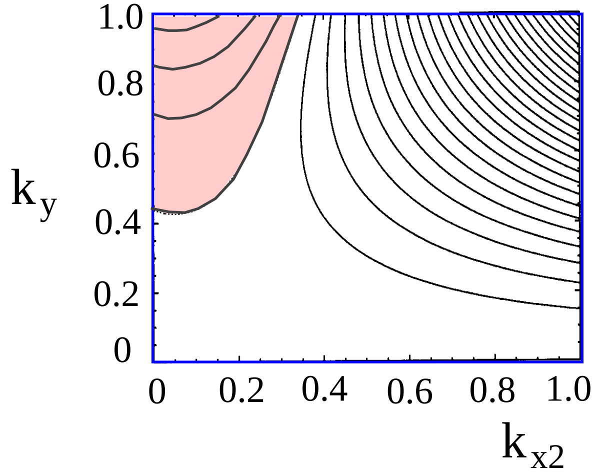
$\omega_1^2 < 0$ ⇨ **modulational instability (exponential grow of zonal flow)**

zonal flow evolution

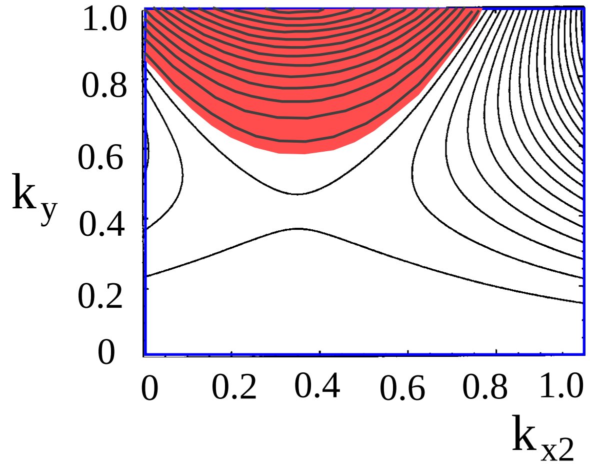
$$\bar{\varphi}_z(t) = \frac{b_2}{\sqrt{\omega^2}} \sin\left(\sqrt{\omega_2^2}\, t\right) \qquad b_2 = \frac{k_y k_q^2 (k_{x1} + k_{x2}) \varphi_1 \varphi_2}{4(1 + k_q^2)}$$

dependence of zonal flow stability on background fluctuation

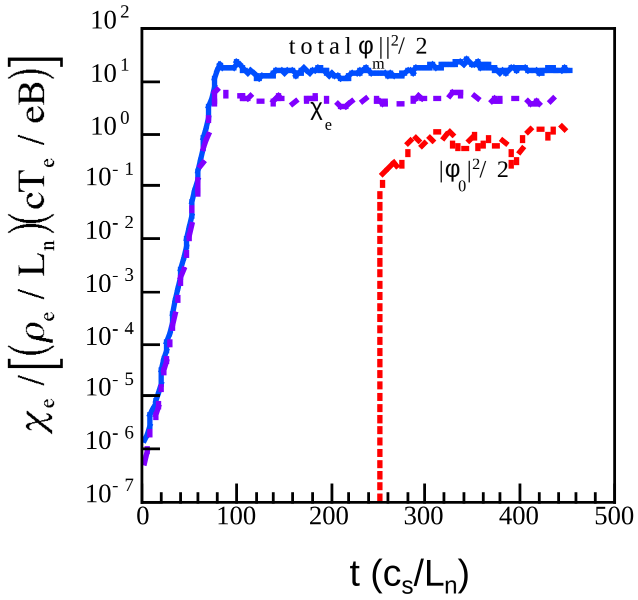
$k_q = 0.1 \quad \omega^2 = -2.4 \times 10^{-5}$

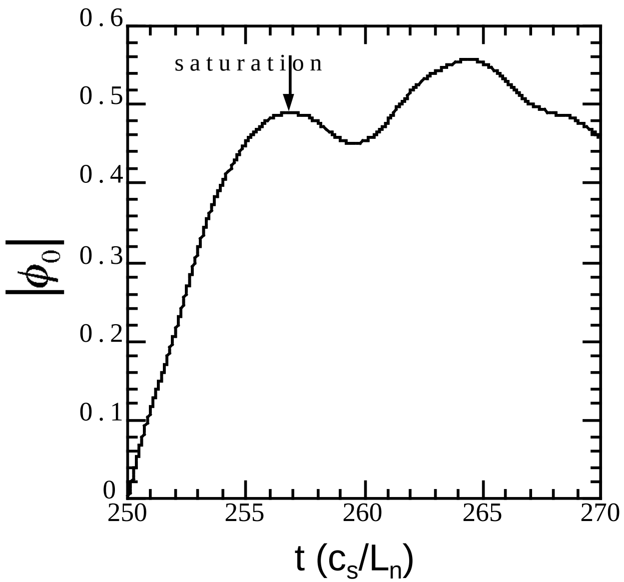


$k_q = 0.7 \quad \omega^2 = -1.6 \times 10^{-2}$



Modulational instability zonal flow excitation and saturation





two dominant pump wave

$$(k_{x1}, \pm k_y) = (0.25, \pm 0.6)$$
$$(k_{x2}, \pm k_y) = (0.42, \pm 0.6)$$

$k_q = k_{x2} - k_{x1} = 0.17 \quad : \omega_2^2 > 0$ stable

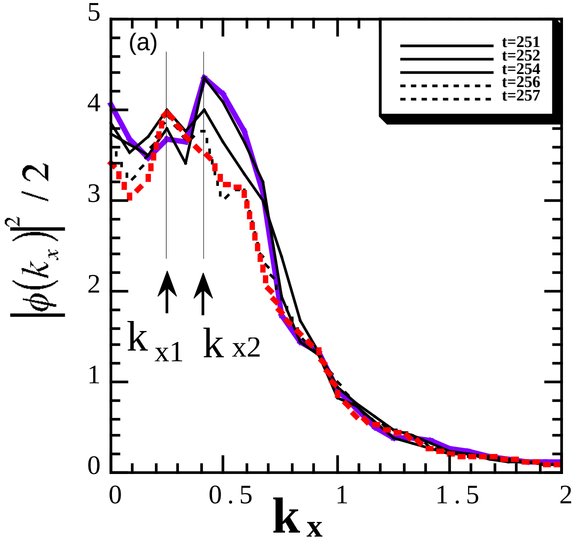
⇨ $k_q = k_{x2} + k_{x1} = 0.67 \quad : \omega_2^2 < 0$ unstable

⇨ $\omega_2^2 > 0$ ⇨

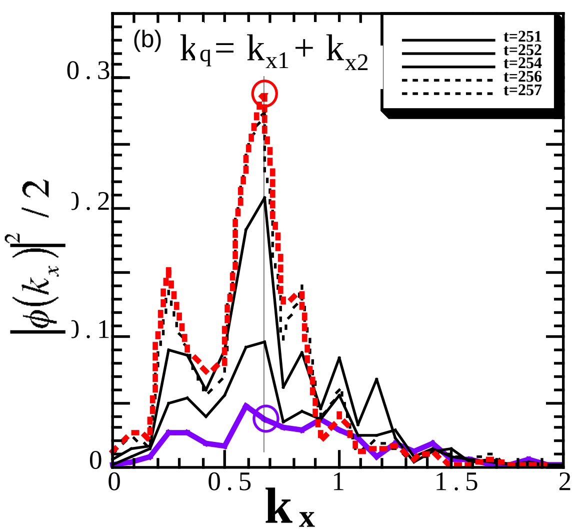
zonal flow stable after saturation

zonal flow cascade to lower kx

turbulent kx spectrum



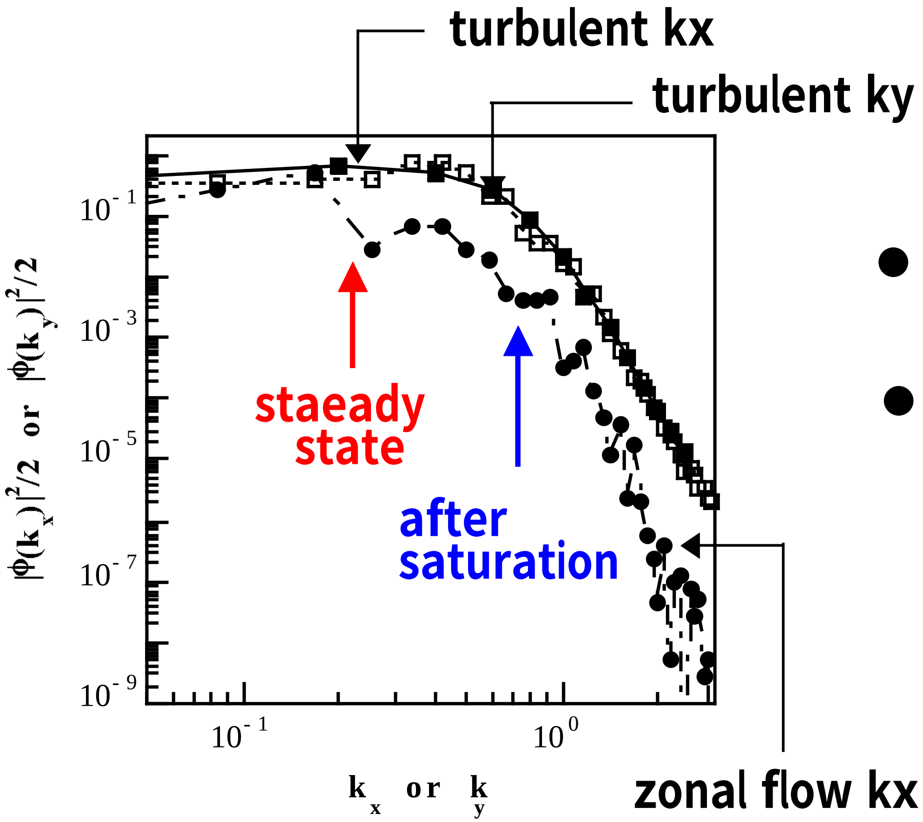
zonal flow kx spectrum



Modulational instability zonal flow excitation and saturation

(continue)

Steady state spectrum of zonal flow

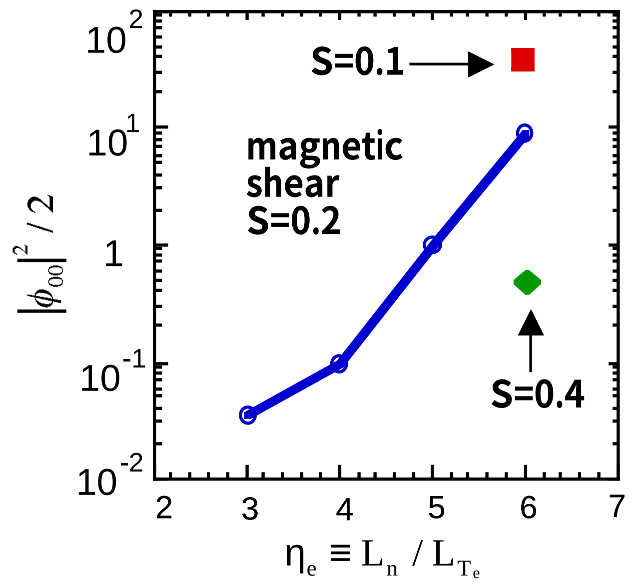


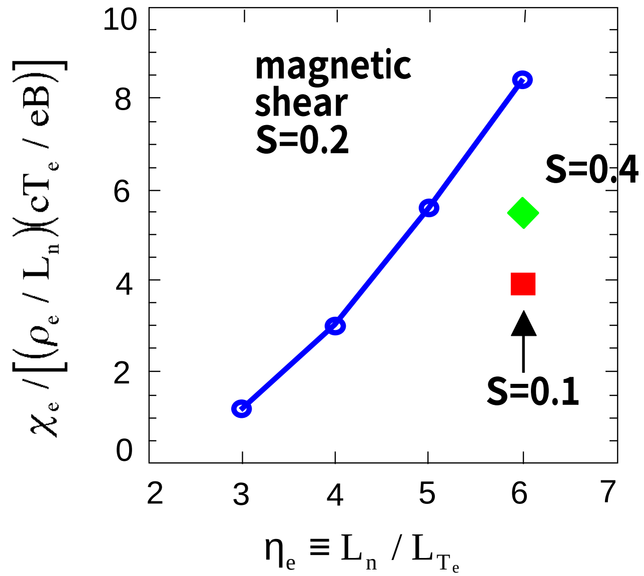
- High wave number zonal flow "unstable"
- Cascade of zonal flow spectrum to lower wave number

$$k_x^{(z)} = 0.1 \sim 0.3$$

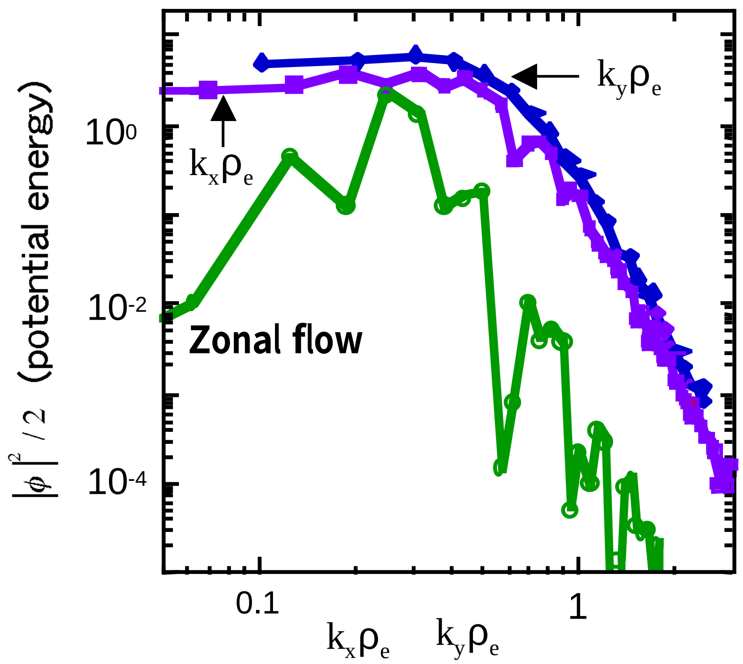
Gyro-fluid simulation of slab ETG mode

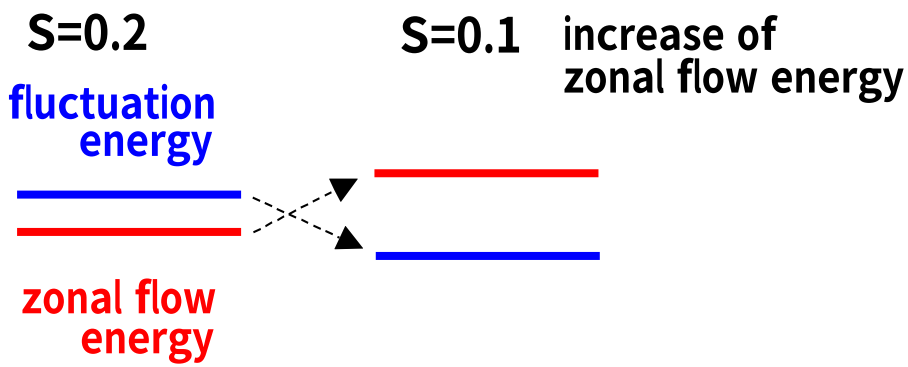
parametric dependence of zonal flow energy : Is zonal flow controlable?





S=0.2 case

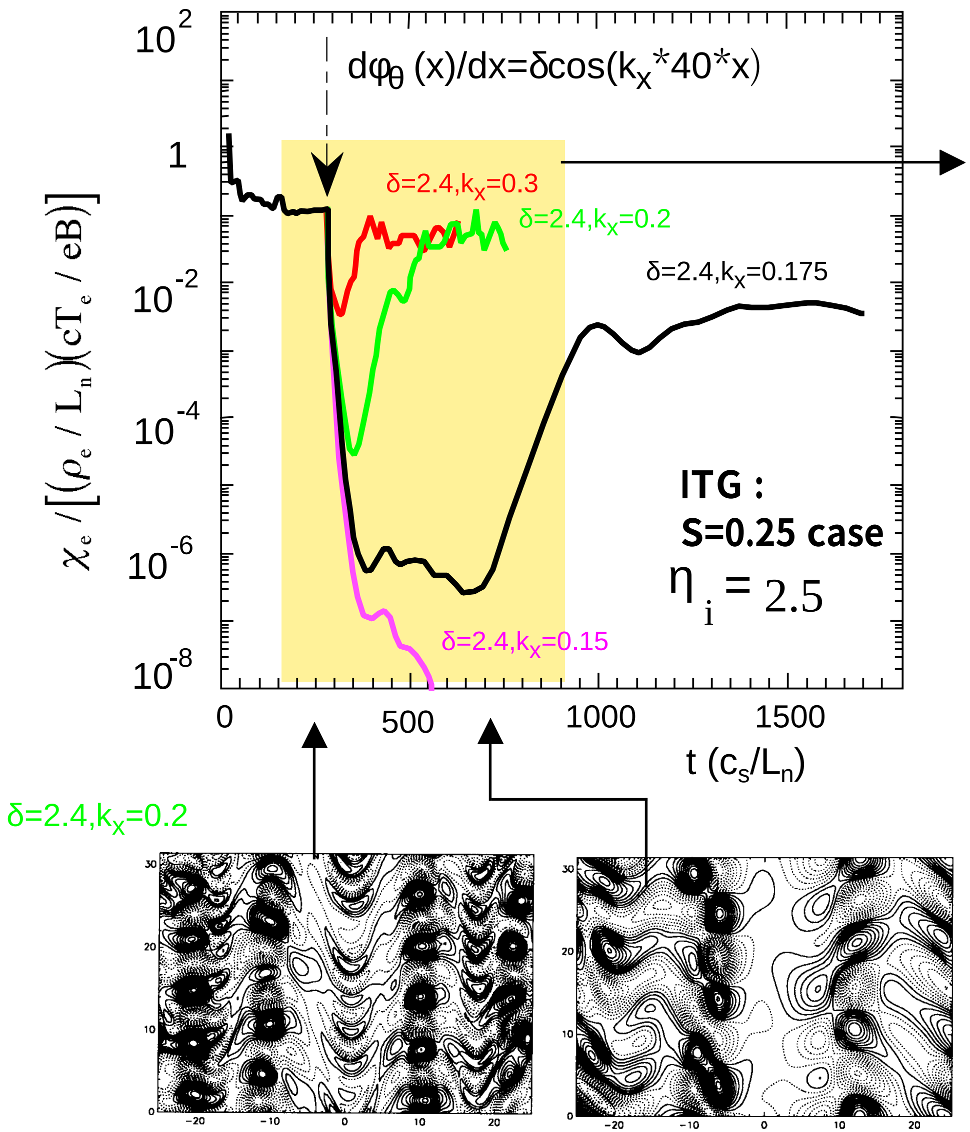


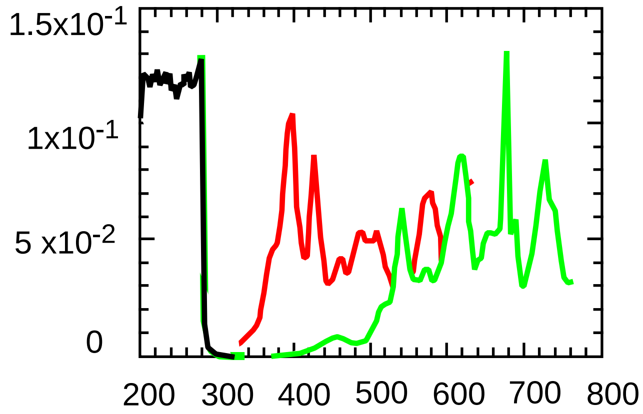


Effect of ETG driven zonal flow on toroidal ITG turbulence

ETG driven zonal flow is effective for reducing ITG-driven transport.

ETG : S=0.1 case





- **Effect of ITG turbulence suppression (or phase scrambling)exists by small scale zonal flow**

  ⇨ **sensitive to zonal flow spectrum**

- **Intermittent behavior of transport**

  ⇨ **complicated interaction between ITG and external ETG flow**

Summary

- Effects of radial electric field and related flow on micro-instabilty and turbulent fluctuation are investigated based on theory and kinetic/fluid simulations.

- Zonal flow generation and saturation is studied by modulational instability and also nonlinear fluid simulation

  High kx zonal flow is more unstable,
  but cascade to lower kx in nonlinear steady state.

- Possibility of coupling among different scale fluctuation through self-generated zonal flow are discussed.

- ETG driven zonal flow plays an important role not only for the self-regurating the turbulent level, but also possibility to suppress and kill the long wavelength fluctuation.

<u>future works</u>   zonal flow damping / kinetic effect / full-scale simulation ・・・