Max-Planck-Institut für Plasmaphysik

IFERC-CSC

QST

First-Principle Simulation of Particle Transport in the inversed-density-gradient profile

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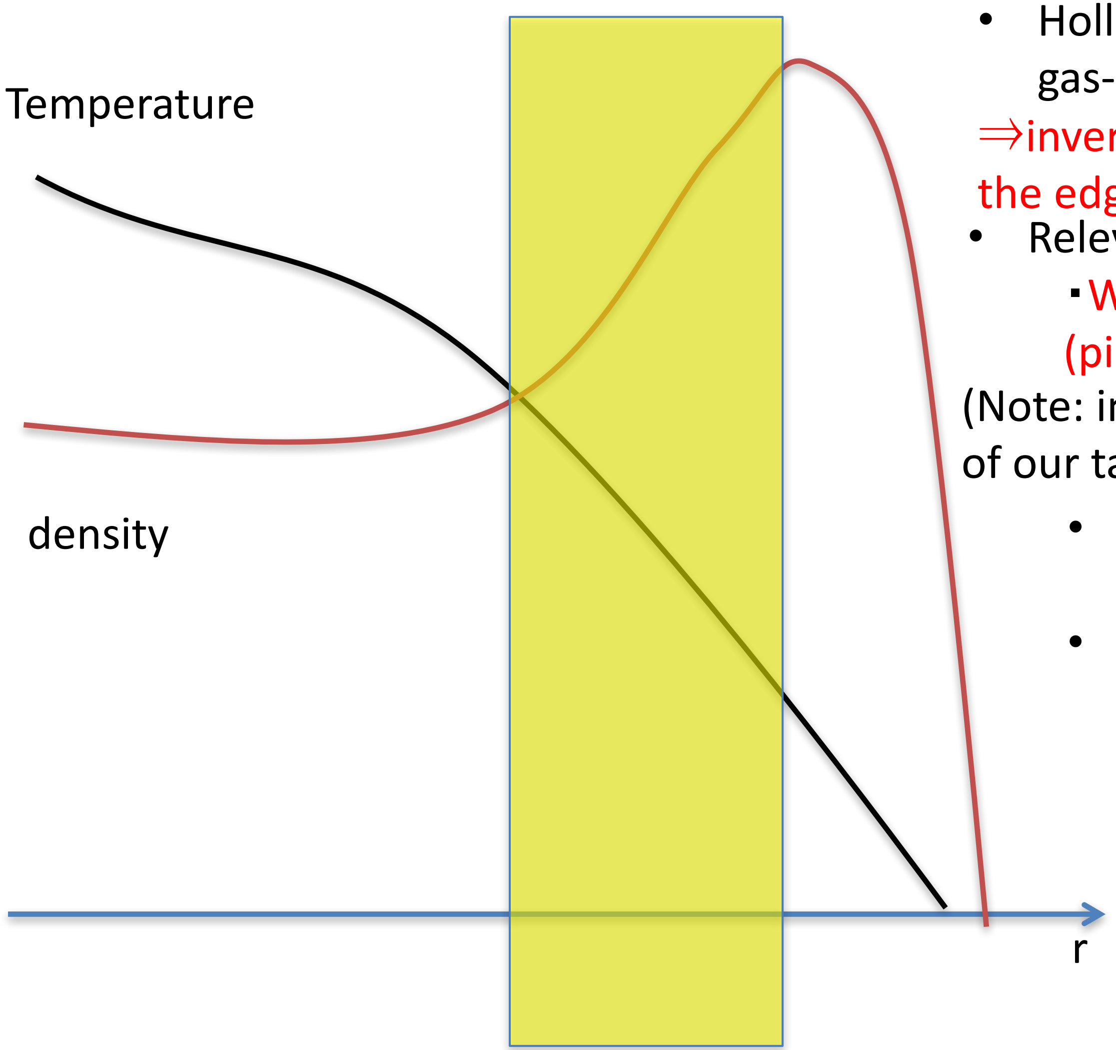
Inversed-density-gradient appears in fueling operations.



- Hollow density profile due pellet or gas-puff injection

⇒inversed density gradient appears in the edge region.

- Relevant to

  ・What mechanism of the particle flux (pinch?)

(Note: in this work, profile relaxation is out of our target, due to local approach.)

- Fueling physics contributes ITER/DEMO development.
- Works on validation of particle transport physics. [Angioni '09][Wan '10][Tangered '16]

We here undergo the first-principle simulation on the particle transport in the inversed-density gradient region.

dFEFI: delta-*f* gyrokinetic solver for ions and electrons. [B. Scott, PoP (2010)]

- delta-f Electromagnetic GK equation

$$\frac{\partial g}{\partial t} + \frac{c}{B_0}[(J_0\psi_e), h]_{xy} - \frac{mz^2 + wB}{2e}\mathcal{K}(h) + \frac{B^s}{mB}[H_0, h]_{zs} = 0$$

$$g = \delta f + \frac{F^M}{T} e\frac{z}{c} J_0 A_\parallel, \quad h = \delta f + \frac{F^M}{T} eJ_0\phi, \quad H_0 = m\frac{z^2}{2} + wB,$$

$$\psi_e = J_0\left(\phi - \frac{z}{c}A_\parallel\right). \qquad F^M = n(2\pi T/m)^{-3/2}\exp(-H_0/T),$$

Polarization equation:

$$\sum_{\mathrm{sp}} \int d\mathcal{W} \left[eJ_0 g + e^2\frac{F^M}{T}(J_0^2 - 1)\phi\right] = 0$$

Induction equation:

$$\nabla_\perp^2 A_\parallel + \sum_{\mathrm{sp}} \frac{4\pi}{c} \int d\mathcal{W} \left[ezJ_0 g - \frac{e^2}{c} z^2 \frac{F^M}{T} J_0^2 A_\parallel\right] = 0$$

- Field-aligned coordinate
- Shifted metric
- Fixed boundary on radius
- Local code, but remains globality on the boundary conditions.

(x: radial, y: binormal, s: magnetic field line)

Benchmark on cyclone-base case(CBC) parameter

core plasma:

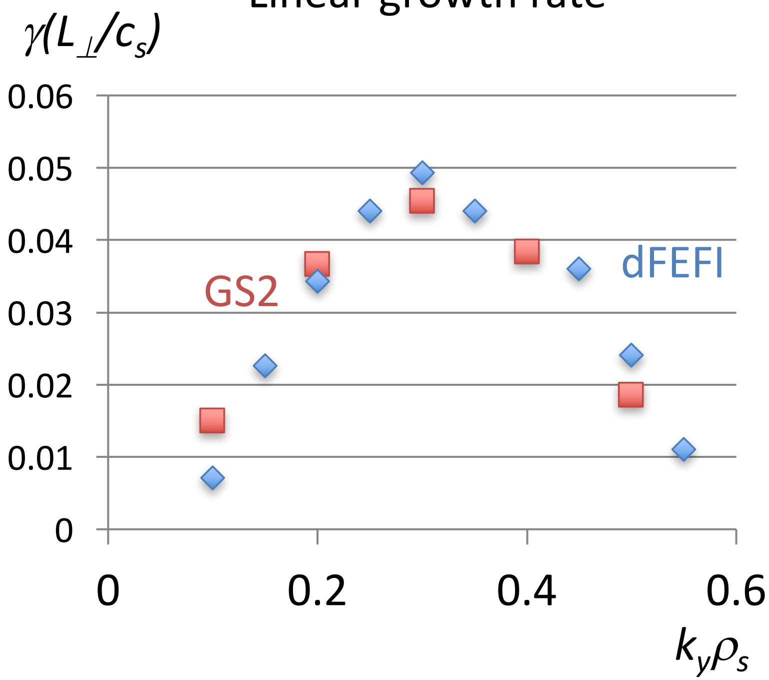
a/R = 0.184, $L_{\perp}$/R = 0.145, min($k_y\rho_s$)=0.025. T_i/T_e=1, qR/$L_{\perp}$=9.67,

$\beta_e(qR/L_{\perp})^2$=1e-3, rq'/q = 1.14, $L_{\perp}/L_n$=0.321, $L_{\perp}/L_{te}=L_{\perp}/L_{Ti}$=1.0

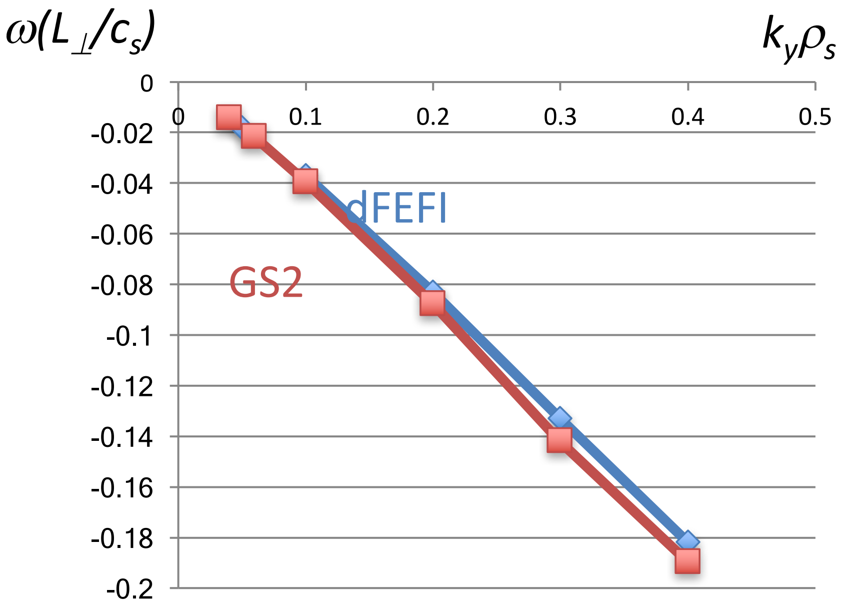
L_y/L_x=4.0, (nx,ny,ns,nz,nw)=(128,128,32,48,16)

R/L_{Ti}=6.9
R/L_{Te}=6.9
R/L_n=2.2

Linear growth rate



frequency



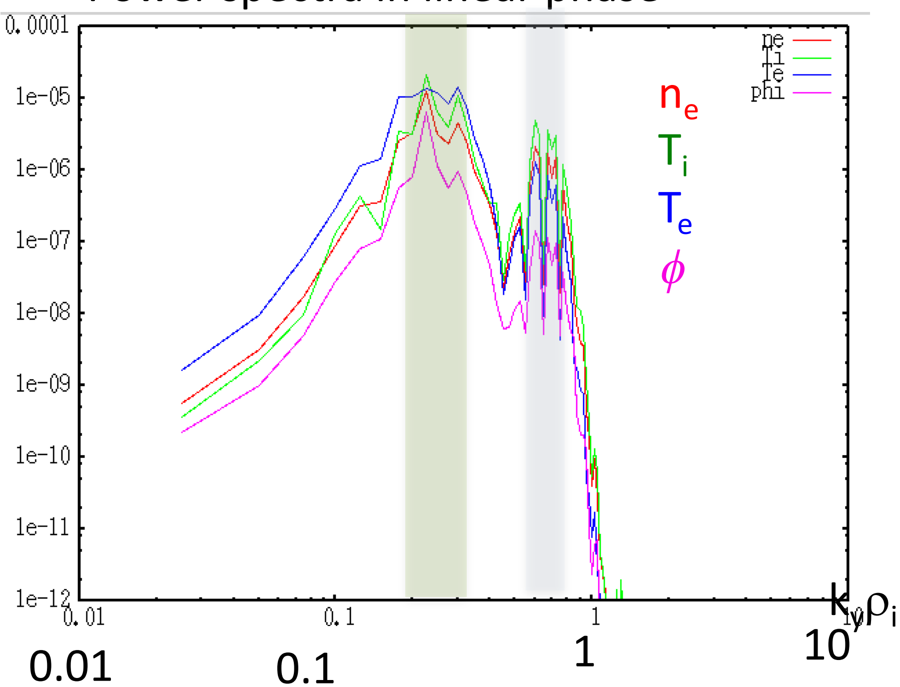
Linear calculation exhibits two modes with ion and electron direction rotation

Edge plasma parameters:

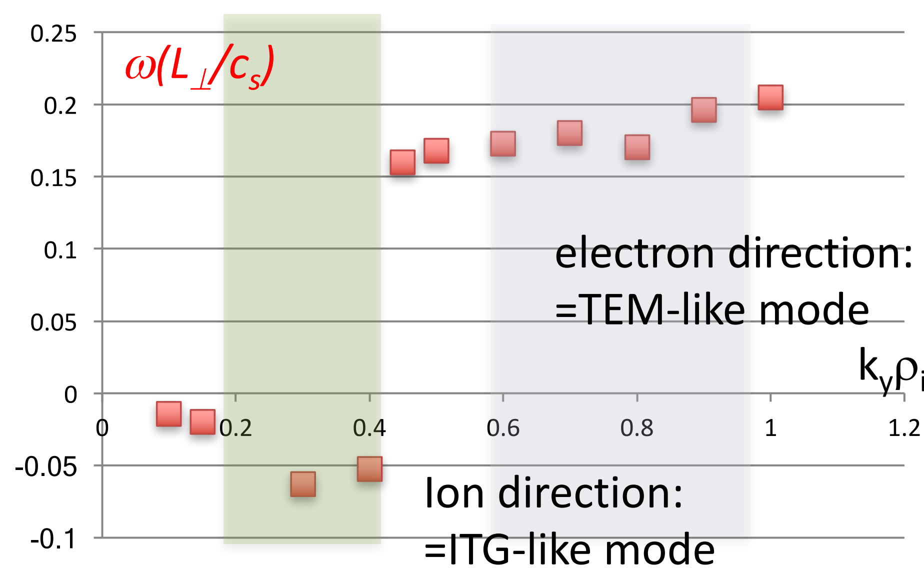
R_0=165cm, n_e=2.0x10^{13} cm^{-3}, Te=100 eV, L_n=-7cm, L_{Ti}=L_{Te}=3.5cm, B=2.5 T, T_i/T_e=1, a/R=0.303, $L_\perp/R$= 0.0212, q=3.5, Normalized beta=6.44x10^{-5}, $\nu_i(L_\perp/c_s)$=000956, ν_e=$(L_\perp/c_s)$=0.823

(nx,ny,ns,nz,nw)=(32,128,32,32,16), Lx/Ly=1.0, Δt=0.005

Power spectra in linear phase

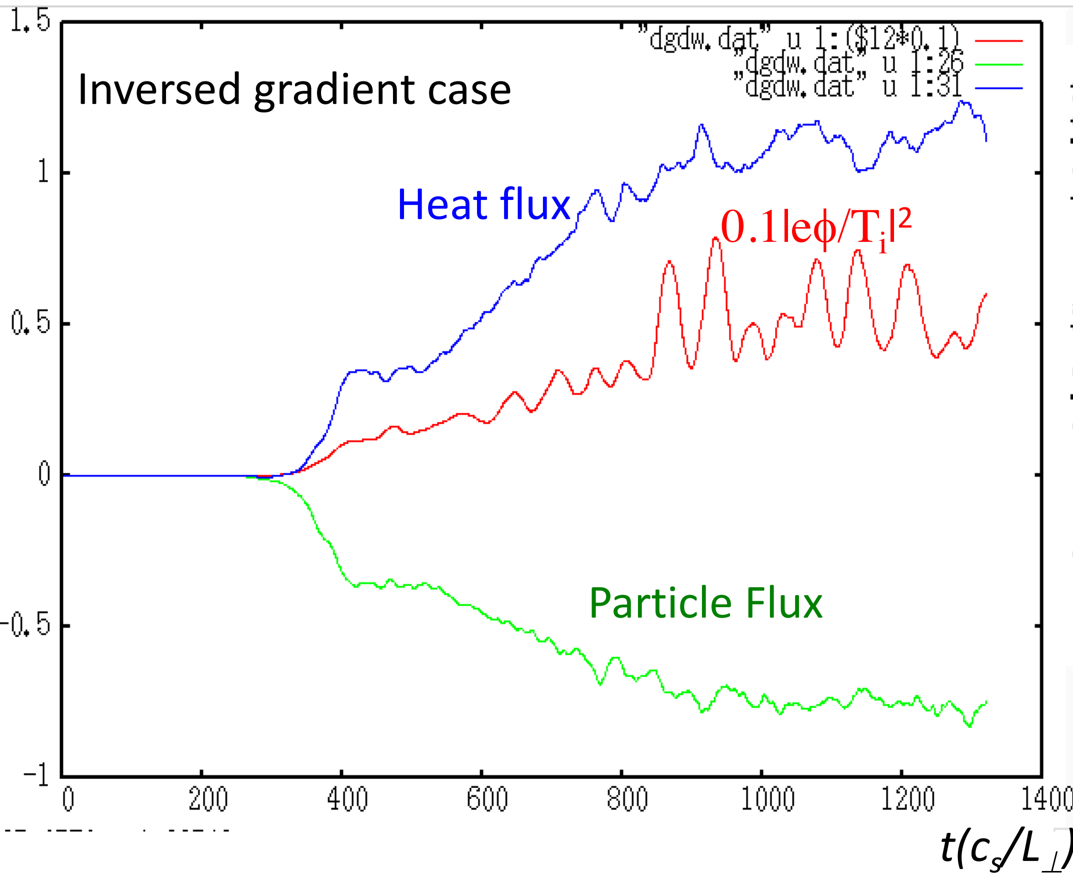


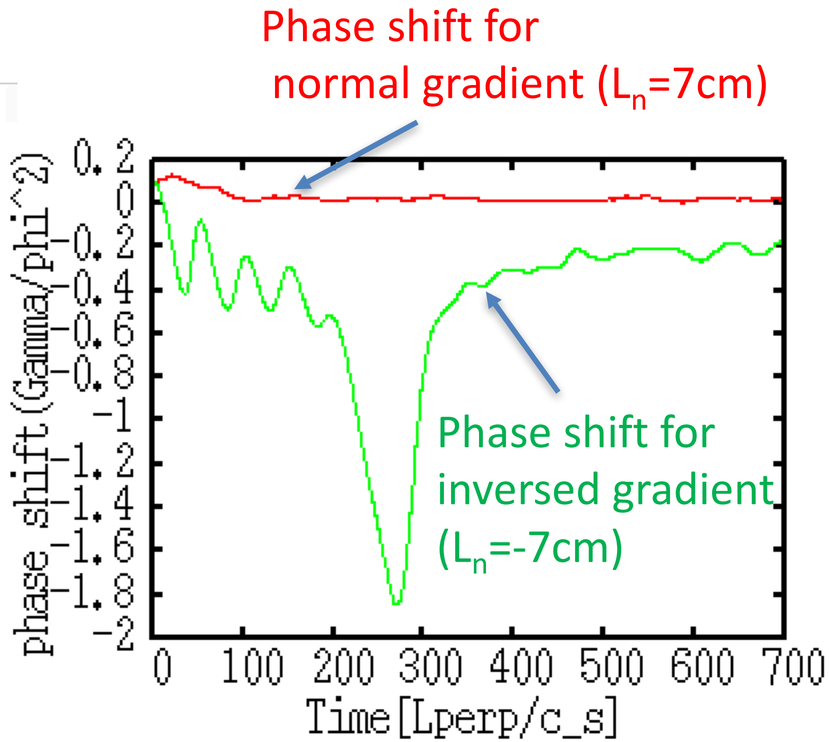
We observe ITG-like and TEM-like modes growing.



Time evolution of Particle Flux

⇒ Inward, with phase-shifted



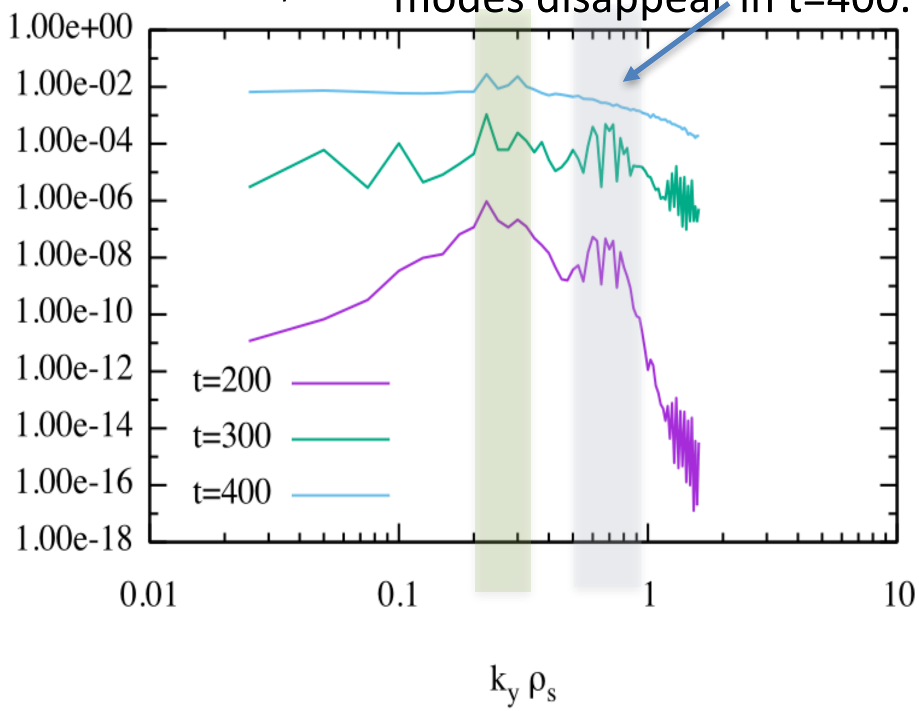


For the inversed-density-gradient case,
we expect larger phase shifts in the density-potentials.

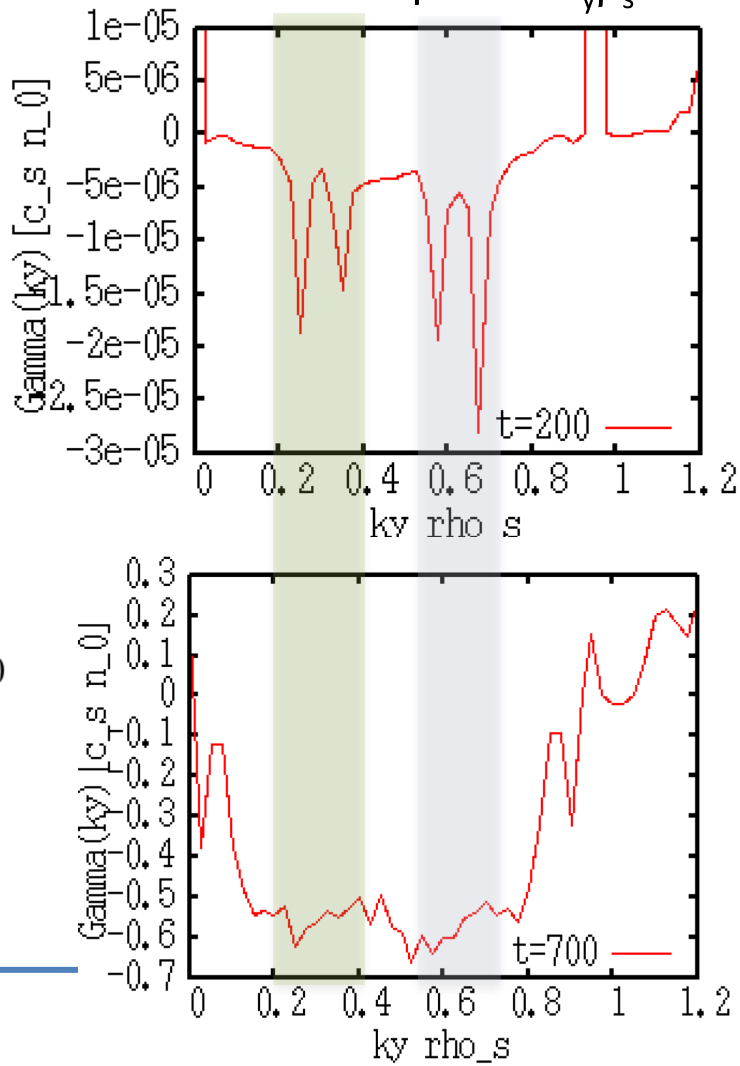
Spectral analyses on electrostatic potential and particle flux.

Spectrum of ϕ

High wave number (TEM-li modes disappear in t=400.



Particle Flux Spectra with respect to $k_y \rho_s$



- In the nonlinear phase, the lower wave number mode survives.
- Both peaks contributes to inward particle fluxes. In the nonlinear phase, modes with $0.1 < k_y \rho_s < 0.8$ contributes the inward flux.

Candidate? Ion-Mixing-Mode[Coppi '78 PRL]

- Slab fluid Model

$k_\parallel^2 v_{th,i}^2 / \nu_i < \omega \le k_\parallel^2 v_{th,e}^2 / \nu_e$ $\nu_e > k_{||} v_{the}, \omega$

6.7x10^{-3} 0.05 0.12 0.823 0.26 0.05

- Mode dispersion

$$1 + iA + k_\parallel^2 \frac{T_e}{m_i}\frac{\omega_{Ti}}{\omega^3} - \frac{\omega_{*e}}{\omega} = 0 \qquad A = \frac{3}{2}\eta_e \frac{\omega_{*e}}{\omega_\chi}(1+\alpha_T)$$

- Non-trivial mode:

$$\omega = -[(k_\parallel^2 T_e / m_i)\omega_{Ti} / (1 + A^2)]^{1/3}(1 - iA)^{1/3}$$

→ ITG-like mode

Electron adiabaticity is affected by the electron thermal force.

$$\frac{\tilde{n}_e}{n} = \frac{e\tilde{\phi}}{T_e}\left[1 + (1+\alpha_T)\frac{i}{\omega_\chi}(\omega - \omega_{*e} + \frac{3}{2}\eta_e\omega_{*e})\right] \qquad \omega_\chi \equiv \hat{\chi}_e k_\parallel^2 T_e / (m_e \nu_e)$$

Assumption: $\omega \sim \omega_{*e} < \omega_\chi$ → Diagonal effects (prop. to grad n) are cancelled, remaining off-diagonal (prop. to grad Te) term.

Particle Flux: $\Gamma = \langle \tilde{n}\tilde{v}_{E_x} \rangle = -(2c/B)\mathrm{Im}(\sum_k k_y \tilde{\phi}_k \tilde{n}_k)$

$$= 3(1+\alpha_T) D_B' n \sum_k k_y^2 \left|\frac{e\tilde{\varphi}}{T_i}\right|^2 \frac{1}{\omega_\chi}\frac{cT_i}{eB}\frac{d\ln T_e}{dx}$$

However, Is this assumption correct？ Estimate from simulation results ~ -0.73

Validation of Ion-Mixing-Mode

$\omega \sim \omega_{*e} < \omega_{\chi}$ Is correct?

$$\frac{\tilde{n}_e}{n} = \frac{e\tilde{\phi}}{T_e}\left[1 + (1+\alpha_T)\frac{i}{\omega_{\chi}}\left(\omega - \omega_{*e} + \frac{3}{2}\eta_e\omega_{*e}\right)\right]$$

dTe/dr dependency

$$\omega(k_y = 0.1) \sim -0.063(c_s / L_{\perp})$$

$$\omega_{*e} = \frac{k_y c T_e}{eB}\frac{d\ln n}{dr} \sim -\ 0.1\ (c_s / L_{\perp})$$

Measures degree of the cancellation.

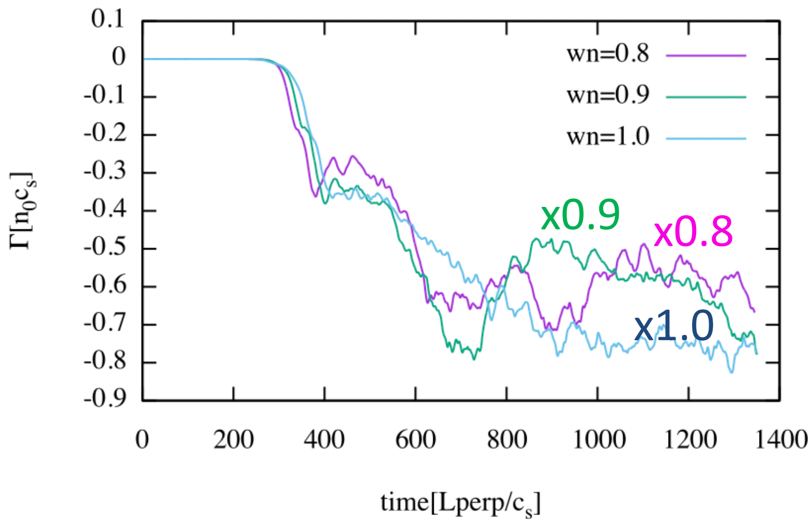
$$\omega_{\chi} = \hat{\chi}_e k_{\parallel}^2 T_e / m_e \nu_e \sim 0.7(c_s / L_{\perp}) > \omega_{*e}$$

$$A = \frac{3}{2}\eta_e \frac{\omega_{*e}}{\omega_{\chi}}(1+\alpha_T) \sim 0.73 > \sqrt{\frac{m_e}{m_i}}$$

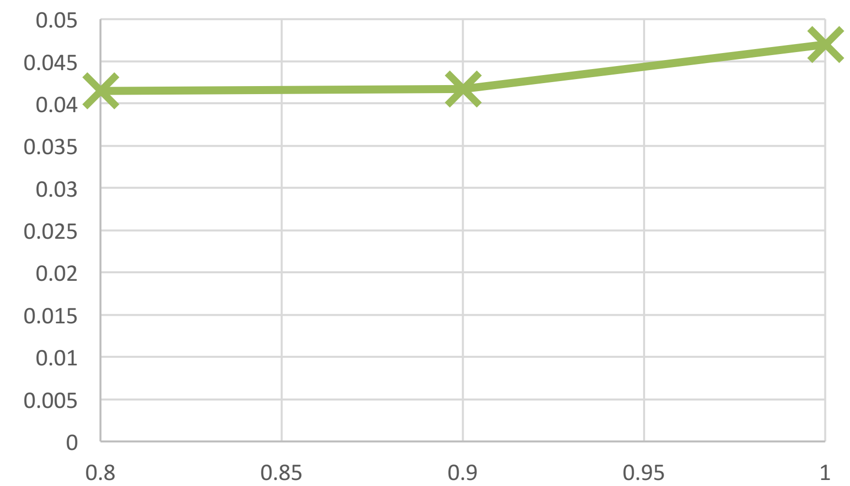
This mode is enough large compared with collisional effects.

Parameter Scan(1) n scan

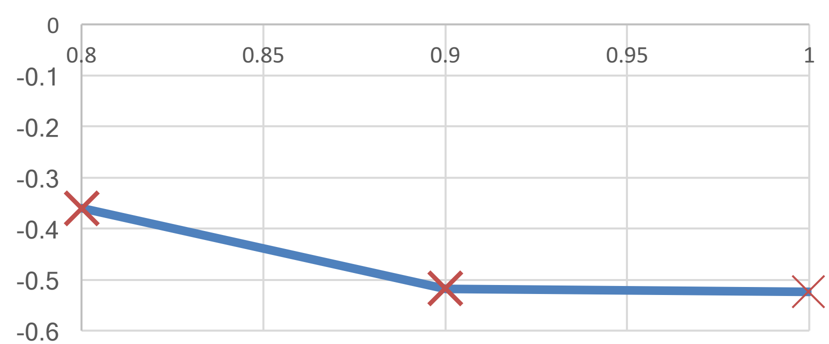
$\Gamma(n_0c_s)$



Growth rate γ



$\delta(=\langle nv\rangle/\phi^2)$ $(\nabla n)/(\nabla n)_{ref}$

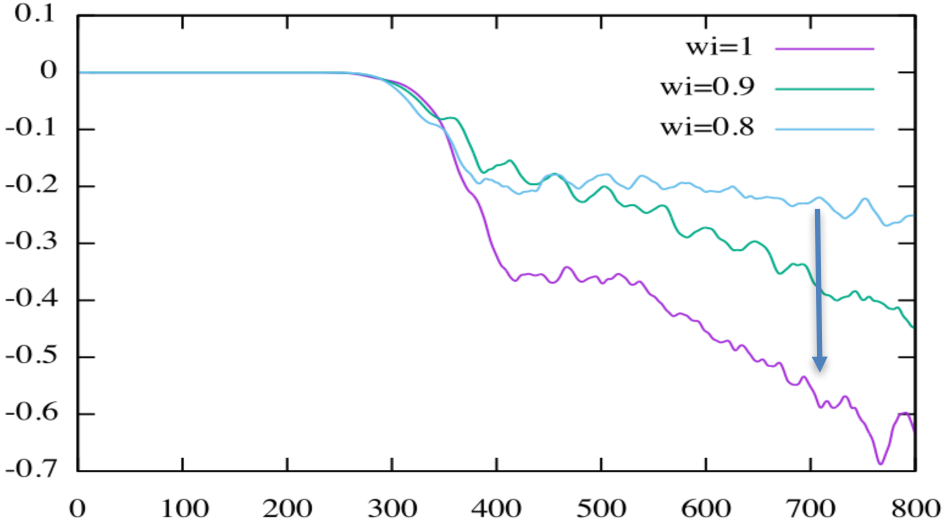


- **∇**n scan on saturated particle flux is almost similar within fluctuations.
  - Diffusive part is not significant
- Higher **∇**n gives (slightly) higher growth rate.

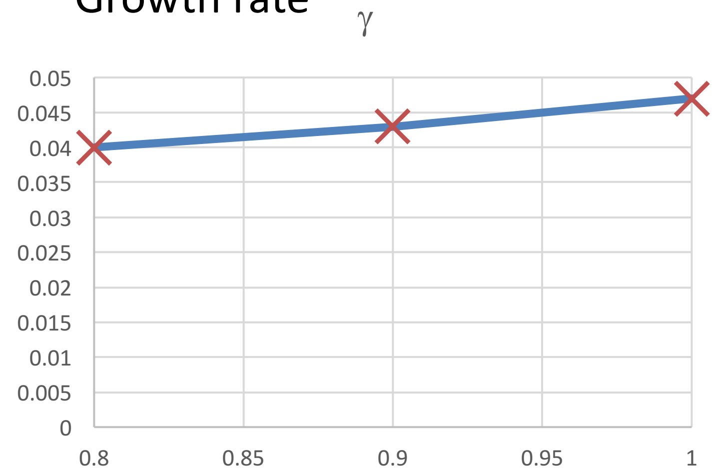
In the IMM theory, a diffusive part on particle flux is not significant, since $\omega \sim \omega_{*e}$ is satisfied.

Parameter scan(2) Grad Ti Scan

$\Gamma(n_0 c_s)$ Grad Ti scan (x1.0, x0.9, x0.8)



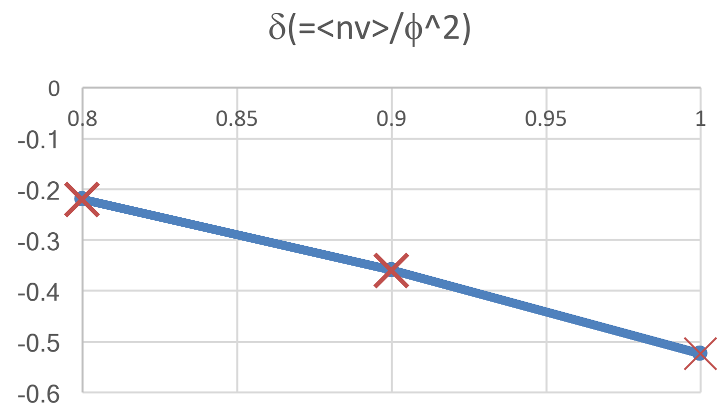
Growth rate



$(\nabla T_i)/(\nabla T_i)_{ref}$

Phase shift

$(\nabla T_i)/(\nabla T_i)_{ref}$



- Higher ∇T_i gives higher saturated inward particle flux.
- Higher ∇T_i gives higher growth rates, related to ITG mode.
- Highter ∇T_i gives drastically higher phase shift $(\delta=\Gamma/\langle\phi_2\rangle)$.

Higher ∇T_i => higher Inward flux, originated from phase shift, as well as increase of growth rates

summary

- We have simulated the turbulence in case that density gradient inversed. In linear phase, two modes appear; one is ITG-like, and the other is TEM-like modes.
- The TEM-like modes disappears in the nonlinear phase.
- The ITG-like mode may be identified as the ion-mixing-mode. Note that the IMM is unique to the inversed-density-gradient case.
- In future work, toroidal IMM model should be derived for further understanding of the simulation results.

Implications:

- Further physics should enter in hollow density profile.
- Electron temperature is a key for the case, in that electron thermal fluctuation can modulate the phase shift.