Kinetic-scale turbulence in laboratory and space plasmas:
empirical constraints, fundamental concepts and unsolved problems
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Gyrokinetic Vlasov code including full geometry of non-axisymmetric field and its application to Large Helical Device experiments

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Abstract

We developed a new gyrokinetic Vlasov flux-tube code, GKV-X, which includes full geometrical effects of non-axisymmetric field configuration. The GKV-X incorporates full geometrical information of the non-axisymmetric confinement field, as well as Fourier components of the field obtained from MHD equilibrium code, VMEC. Using the code, we investigate the effects of three-dimensional geometry of the Large Helical Device (LHD) plasmas on the zonal flow (ZF) responses, the geodesic acoustic modes, and the ion temperature gradient (ITG) modes. From the linear calculation with linearized version of GKV-X, the effects on the growth rate, frequency, and mode structure of the ITG instability are clarified in the large poloidal wavenumber region where the finite gyroradius effect is also important, while the ZF responses are found to be less affected. The simulation results for the linear ITG modes are also compared with a high ion temperature discharges in the LHD experiments.

Introduction

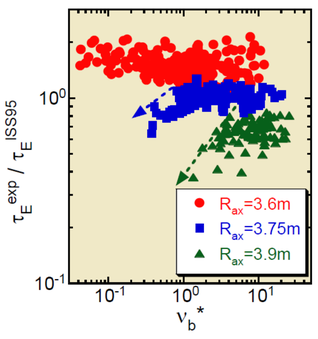
Anomalous transport by plasma turbulence

The anomalous transport problem has been one of the central subjects addressed in the long history of the magnetic fusion research.
Such transport is caused by
- Turbulent transport,
- Gradients of temperatures & densities of plasmas.

Optimized helical magnetic field

In the LHD experiment, it was observed that inward shifted LHD configuration reduced heat transport in spite of a larger amplitude of magnetic fluctuation than the outward shifted configuration.

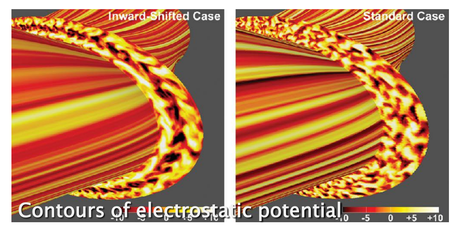
H. Yamada et al., Plasma Phys. Controlled Fusion **43**, A55 (2001)

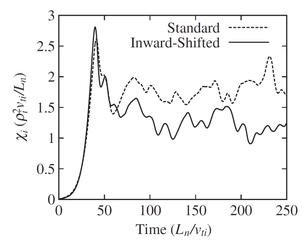


Gyrokinetic simulation

In gyrokinetic simulation with GKV code,
- In inward shifted helical model, ZFs are strongly enhanced,
- Turbulent transport is reduced by about 30% compared with standard configuration.

T.-H. Watanabe et al., Phys. Rev. Lett. **100**, 195002 (2008)





For more quantitative gyrokinetic simulations, it is a natural path to furnish a well-established gyrokinetic code with detailed geometrical information obtained from three-dimensional equilibrium calculations.

A new code " GKV-X "

M. Nunami et al., Plasma Fusion Res. **5**, 016 (2010).

"GyroKinetic Vlasov code for quantitative comparison with eXperiment"

- It calculates the time-evolution of distribution function in 5D phase space due to GKE in a flux-tube domain around the field line with fixed field-line-label.
- It incorporates full geometrical information, as well as Fourier components of three-dimensional confinement field from VMEC equilibrium.

Basic equations

Gyrokinetic equation

$$\frac{\partial \delta f}{\partial t} + v_\parallel \boldsymbol{b}\cdot\nabla\delta f + \frac{c}{B_0}\{\Phi, \delta f\} + \boldsymbol{v}_d\cdot\nabla\delta f - \mu\boldsymbol{b}\cdot\nabla\Omega_i\frac{\partial \delta f}{\partial v_\parallel} = \left(\boldsymbol{v}_* - \boldsymbol{v}_d - v_\parallel\boldsymbol{b}\right)\cdot\frac{e\nabla\Phi}{T_i}F_M + C(\delta f)$$

(Linear & collisionless case)

$$\left(\frac{\partial}{\partial t} + v_\parallel\boldsymbol{b}\cdot\nabla + \mu\boldsymbol{b}\cdot\nabla B\frac{\partial}{\partial v_\parallel} + i\omega_{\mathrm{Di}}\right) f_{\boldsymbol{k}_\perp} = f_0(-v_\parallel\boldsymbol{b}\cdot\nabla - i\omega_{\mathrm{Di}} + i\omega_{*\mathrm{Ti}})J_0(k_\perp\rho)\frac{e\phi_{\boldsymbol{k}_\perp}}{T_i}$$

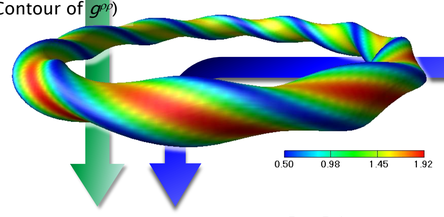
Quasi-neutrality

$$\int d^3v J_0 \delta f_{\boldsymbol{k}_\perp} - n_0\frac{e\phi_{\boldsymbol{k}_\perp}}{T_i}[1-\Gamma_0(b)] = \begin{cases} n_0 e\left[\phi_{\boldsymbol{k}_\perp} - \langle\phi_{\boldsymbol{k}_\perp}\rangle\right]/T_e & \text{if } k_y = 0 \\ n_0 e\phi_{\boldsymbol{k}_\perp}/T_e & \text{if } k_y \neq 0 \end{cases}$$

Jacobian, Metric tensor, …
$\sqrt{g_B} = \frac{\Psi'}{B^2}(B_\zeta + B_\theta/q),\ g_{ij},\ g^{ij},\ \cdots$

Experimental data
Temperature, density profiles, …

(Contour of $g^{\rho\rho}$)

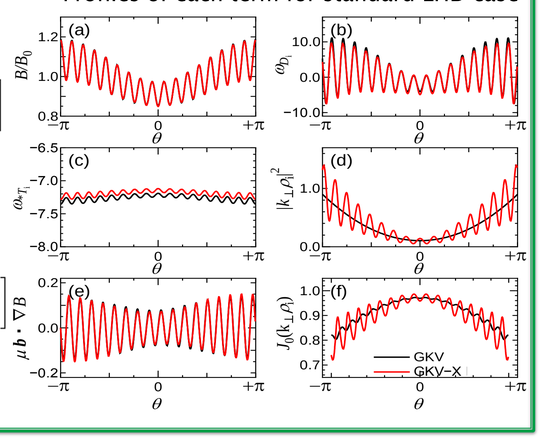


VMEC equilibrium (in Boozer coordinates)

$$B = \sum_{n=0}^{\infty} B_{0,n}(\rho)\cos n\zeta + \sum_{m=1}^{\infty}\sum_{n=-\infty}^{\infty} B_{m,n}(\rho)\cos(m\theta - n\zeta)$$

$$\boldsymbol{B} = B_\rho\nabla\rho + B_\theta\nabla\theta + B_\zeta\nabla\zeta = \nabla\Psi\times\nabla\theta + q^{-1}(\rho)\nabla\zeta\times\nabla\Psi$$

Profiles of each term for standard LHD case



$$\omega_{\mathrm{Di}} = -\frac{c}{eB^2\sqrt{g_B}}\left(\mu + \frac{1}{B}mv_\parallel^2\right)\left[k_y\left[\left(\frac{\rho_0}{q_0}B_\rho + \hat{s}\theta B_\zeta\right)\frac{\partial B}{\partial\theta} + (\rho_0 B_\rho - \hat{s}\theta B_\theta)\frac{\partial B}{\partial\zeta} - \frac{\rho_0}{q_0}(B_\theta + q_0 B_\zeta)\frac{\partial B}{\partial\rho}\right] + k_x\left[B_\zeta\frac{\partial B}{\partial\theta} - B_\theta\frac{\partial B}{\partial\zeta}\right]\right]$$

$$\omega_{*Ti} = -\frac{cT_i a^2}{eB^2\sqrt{g_B}}\left(B_\theta + q_0 B_\zeta\right)\frac{\rho_0}{q_0}k_y\left[\frac{1}{L_n} + \frac{1}{L_{Ti}}\left(\frac{mv^2}{2T_i} - \frac{3}{2}\right)\right]$$

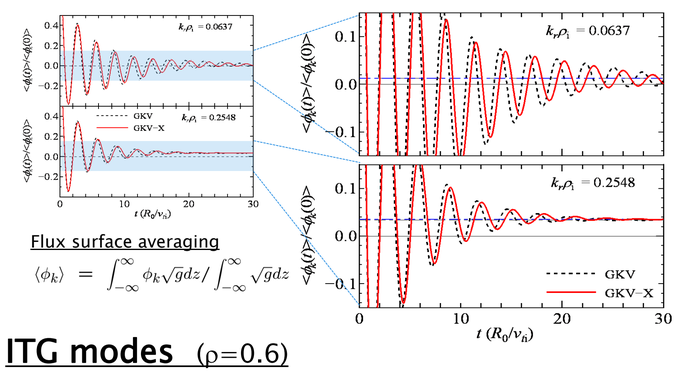
$$k_\perp^2 = k_x^2 a^2 g^{\rho\rho} + 2k_x k_y a^2\left[\hat{s}\theta g^{\rho\rho} + \frac{\rho_0}{q_0}\left(q_0 g^{\rho\theta} - g^{\rho\zeta}\right)\right] + k_y^2 a^2\left[\frac{\rho_0^2}{q_0^2}\left(g^{\zeta\zeta} + q_0^2 g^{\theta\theta} - 2q_0 g^{\theta\zeta}\right) + 2\hat{s}\theta\frac{\rho_0}{q_0}\left(q_0 g^{\rho\theta} - g^{\rho\zeta}\right) + \hat{s}^2\theta^2 g^{\rho\rho}\right]$$

$$\boldsymbol{b}\cdot\nabla = \frac{\Psi'}{q_0}\frac{1}{B\sqrt{g_B}}\left(\frac{\partial}{\partial\theta} + q_0\frac{\partial}{\partial\zeta}\right) \qquad \left(\hat{s} \equiv (\rho_0/q_0)q'\right)$$

Geometrical effects on ZFs & ITG modes

To investigate the effects of non-axisymmetric geometry on the ITG modes and zonal flows, GK Vlasov simulations using linearized versions of the GKV-X and GKV codes are compared.

Linear responses of ZF potentials (ρ=0.6)



Flux surface averaging
$\langle\phi_k\rangle = \int_{-\infty}^{\infty}\phi_k\sqrt{g}dz / \int_{-\infty}^{\infty}\sqrt{g}dz$

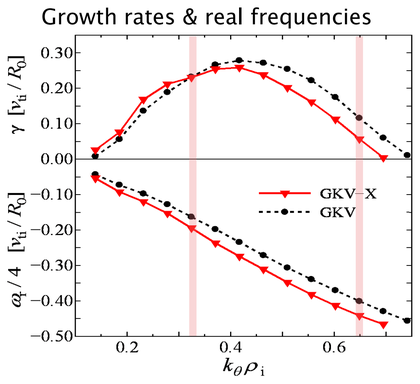
Residual Levels

For $k_r\rho_i = 0.0637$	For $k_r\rho_i = 0.2548$
$\mathcal{K}_{\mathrm{GKV-X}} = 1.25\times10^{-2}$	$\mathcal{K}_{\mathrm{GKV-X}} = 3.49\times10^{-2}$
$\mathcal{K}_{\mathrm{GKV}} = 1.21\times10^{-2}$	$\mathcal{K}_{\mathrm{GKV}} = 3.38\times10^{-2}$

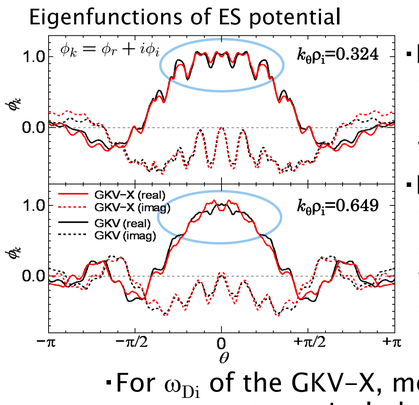
- Response functions and residual levels of ZFs agree well each other.
- We consider that the metric effect on ZFs is blinded with taking the flux surface average to determine the residual zonal flow potential.

ITG modes (ρ=0.6)

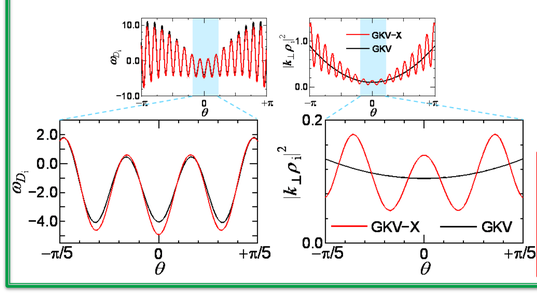
Growth rates & real frequencies



Eigenfunctions of ES potential



- Differences between the GKV and GKV-X codes are magnified as the poloidal wave number k_θ increases.
- For large poloidal wave number, the profiles have different ripple structure in the bad curvature region around θ=0.



- For ω_{Di} of the GKV-X, more helical ripple components are included, the difference appears with more negative than the GKV case.
- For $k_\perp\rho_i$, there is obvious difference.
- Differences in magnitude are enhanced for large k_θ.

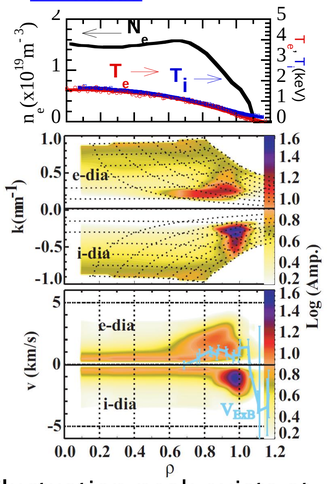
Effects of full geometry & helical ripples on ITG modes are enhanced for the higher k_θ.

Application to LHD experiment

Fluctuation in high-T_i discharge in LHD

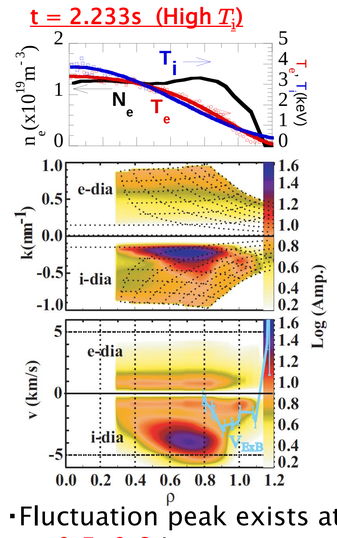
K. Tanaka et al., to be appeared in Plasma Fusion Res.

t = 1.833s



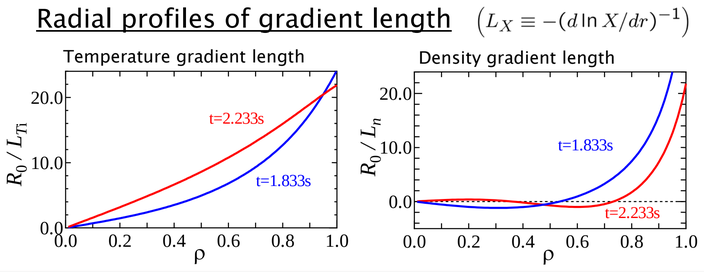
- Fluctuation peak exists at ρ=0.8-1.0 in space, $k_p\rho_i$~0.26 in wavenumber.

t = 2.233s (High T_i)



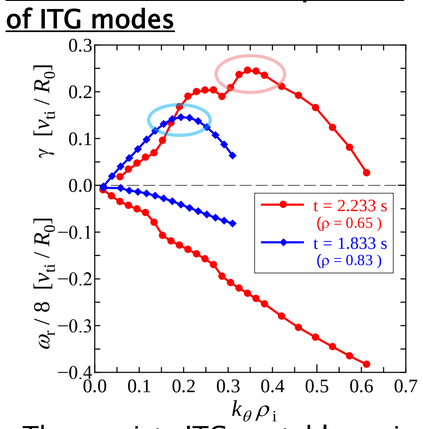
- Fluctuation peak exists at ρ=0.5-0.8 in space, $k_p\rho_i$~0.45 in wavenumber.

Radial profiles of gradient length $\left(L_X \equiv -(d\ln X/dr)^{-1}\right)$



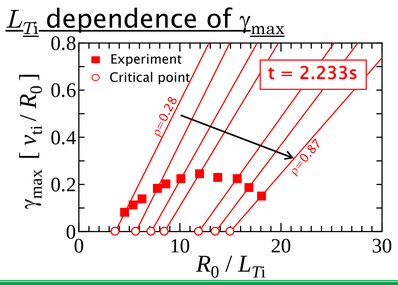
Linear analyses by GKV-X

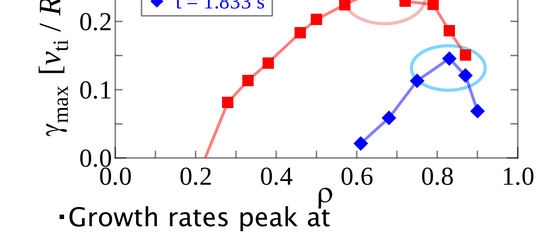
Growth rates & real frequencies of ITG modes



- There exists ITG unstable region.
- Maximum growth rates exist at $k_\theta\rho_i$~0.35 (t=2.233s), $k_\theta\rho_i$~0.20 (t=1.833s), in poloidal wavenumber space.

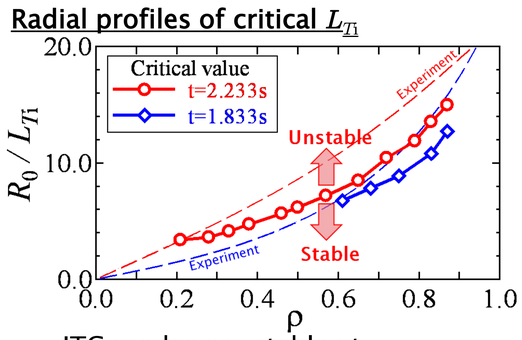
L_{Ti} dependence of γ_{max}





- Growth rates peak at ρ~0.65 (t=2.233s), ρ~0.85 (t=1.833s).

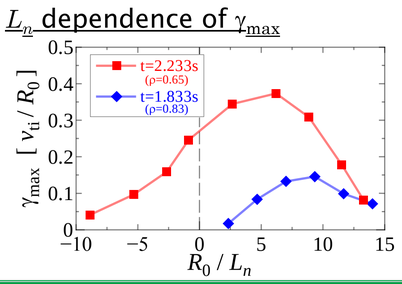
Radial profiles of critical L_{Ti}



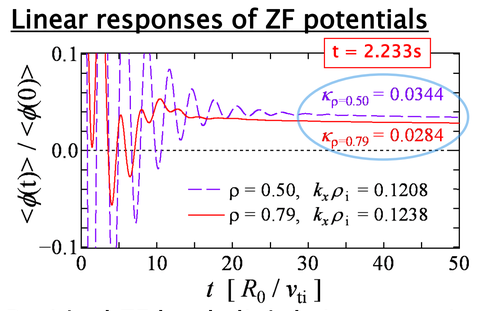
- ITG modes are stable at ρ<0.22 (t=2.233s), ρ<0.60 (t=1.833s).

In High-T_i phase, ITG modes are enhanced due to much steep ion temperature gradient.

L_n dependence of γ_{max}



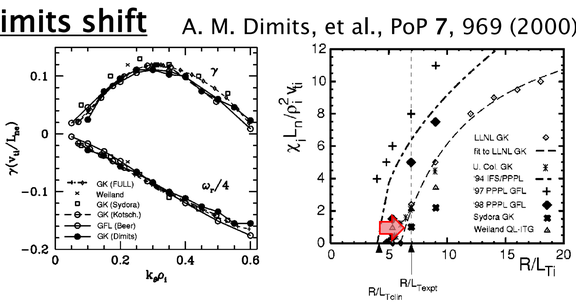
Linear responses of ZF potentials



- Residual ZF level slightly increases in inner radial region.

ZFs may reduce the ITG modes in inner region?

Dimits shift A. M. Dimits, et al., PoP **7**, 969 (2000)



Now, we are analyzing turbulent transport by nonlinear GK simulation with GKV-X.

Acknowledgement

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