TH/4-5

Spontaneous ITB formation in gyrokinetic flux-driven ITG/TEM turbulence

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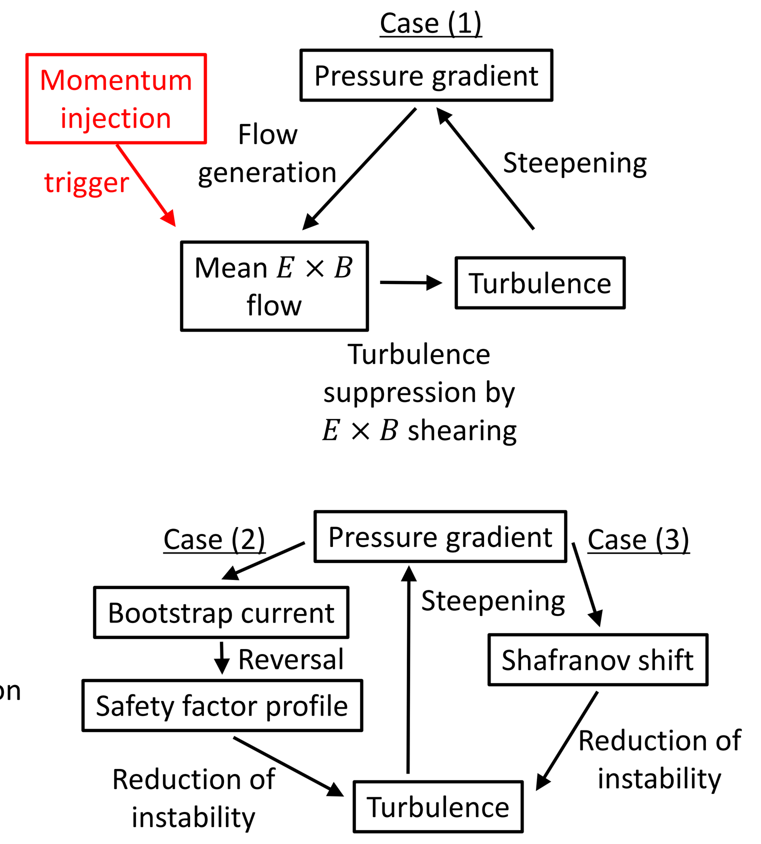
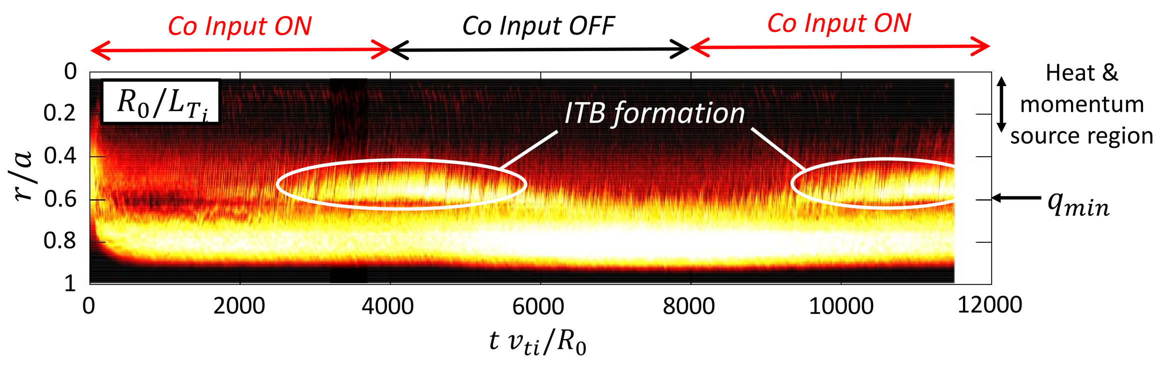
1. Background: Possible Mechanism of ITB Formation

- ✓ Internal Transport barrier (ITB) has a crucial key to achieve a high-performance plasma confinement.
- ✓ Some possible mechanism for ITB formation are proposed [Ida, PPCF-2018] as
  (1) Positive feedback loop via $E \times B$ mean flow [Sakamoto, NF-2004] [Yu, NF-2016]
  (2) Positive feedback loop via safety factor profile (BS current) [Eriksson, PRL-2002]
  (3) Positive feedback loop via Shafranov shift + EM stabilization [Staebler, NF-2018]
- ✓ By our full-f gyrokinetic code *GKNET*, we found that momentum injection can change mean $E \times B$ flow through the radial force balance, which can break the ballooning symmetry of turbulence, leading to ITB formation. [Imadera, IAEA-2016]





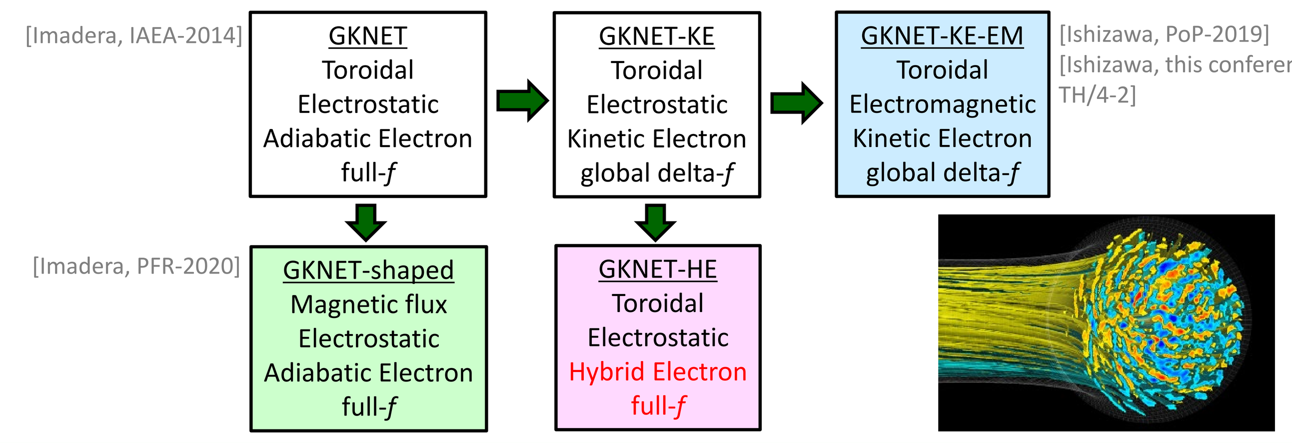
Left Fig. Time-spatial evolution of temperature gradient in the modulation test of momentum source. [Imadera, IAEA-2016]

2. Motivation

- ✓ However, in our previous study based on the original GKNET with adiabatic electron, enough large co-momentum injection is required for ITB formation in flux-driven ITG turbulence. In addition, some experiments indicate the importance of counter-intrinsic rotation. [Sakamoto, NF-2001]

Purpose of this work

- ✓ In this study, we have introduced hybrid kinetic electron model [Lanti, JP-2018] and investigated spontaneous ITB formation in flux-driven ITG/TEM turbulence.



3. Toroidal Full-f Gyrokinetic Code GKNET

GK Vlasov equation

$$\frac{\partial}{\partial t}(\mathcal{J}f_s) + \mathcal{J}\frac{d\mathbf{R}}{dt}\cdot\frac{\partial f_s}{\partial \mathbf{R}} + \mathcal{J}\frac{dv_\parallel}{dt}\frac{\partial f_s}{\partial v_\parallel} = \mathcal{J}C_{s,s} + \mathcal{J}S_{src} + \mathcal{J}S_{snk}$$

$$\frac{d\mathbf{R}}{dt} = \frac{1}{B_\parallel^*}\left[v_\parallel(\nabla\times\mathbf{A}) + \frac{B_0}{\Omega_s}v_\parallel^2(\nabla\times\mathbf{b}) + \frac{c}{e_s}H\,\nabla\times\mathbf{b} - \frac{c}{e_s}\nabla\times(H\mathbf{b})\right]$$

$$\frac{dv_\parallel}{dt} = -\frac{1}{m_s B_\parallel^*}\left[(\nabla\times\mathbf{A})\cdot\nabla H + \frac{B_0}{\Omega_s}v_\parallel\nabla\cdot(H\nabla\times\mathbf{b})\right]$$

+

GK quasi-neutrality condition

$$\iint\langle\delta f_i\rangle_{\alpha,i}\frac{B_\parallel^*}{m_i}dv_\parallel d\mu + \frac{1}{4\pi e_i}\nabla_\perp\cdot\frac{\rho_{ti}^2}{\lambda_{Di}^2}\nabla_\perp\phi = \delta n_e$$

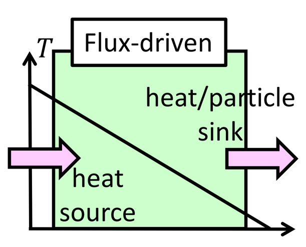
	$(m,n)=(0,0)$	$(m,n)\neq(0,0)$
$\delta n_{e,pass}$	Kinetic response	Adiabatic response
$\delta n_{e,trap}$	Kinetic response	Kinetic response

f_s: full-f distribution function for species $s = i, e$
$C_{s,s}$: self-collision operator for species s
S_{src}: Heat source operator
S_{snk}: Krook-type sink operator

Physical model

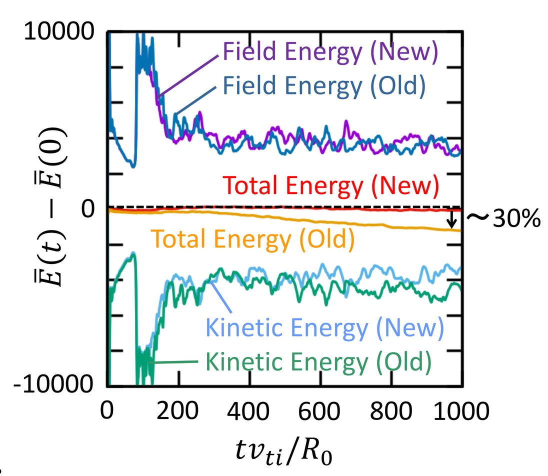
- ✓ *GKNET-HE* is based on full-f gyrokinetic model, which trace turbulence and background profiles self-consistently.
- ✓ External heat source and sink are introduced so that the turbulence is not decayed but sustained over the confinement time (flux-driven simulation).
- ✓ To study flux-driven ITG/TEM turbulence, we have introduced the above hybrid kinetic electron model [Lanti, JP-2018].

GKNET-HE
Toroidal
Electrostatic
Hybrid Electron
full-f



Numerical model

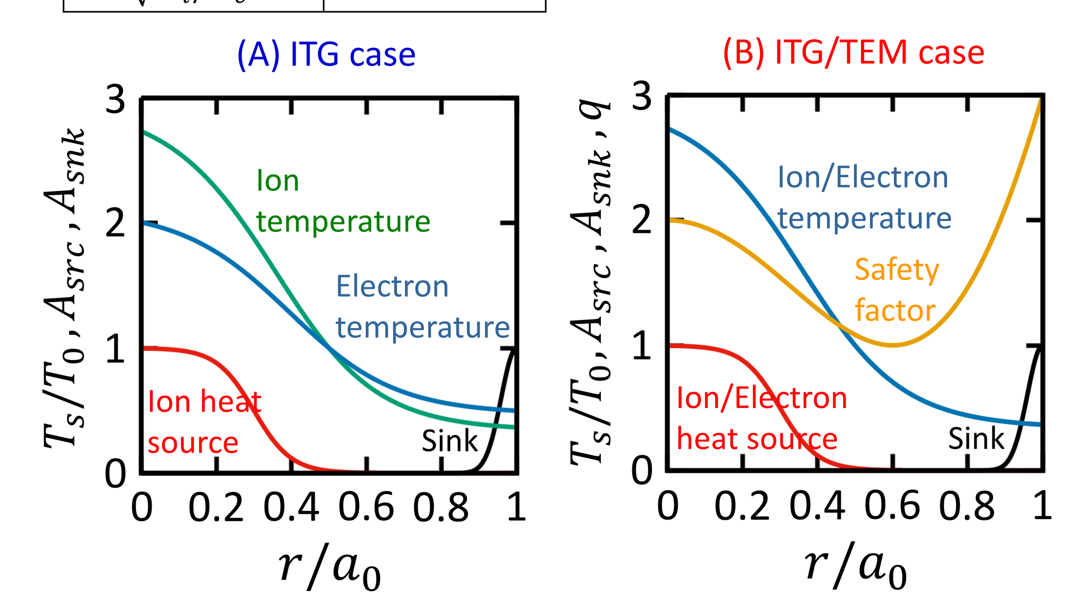
- ✓ We discretize the Vlasov equation by using Morinishi scheme, which was developed for fluid simulation and introduced to rectangular gyrokinetic code, [Morinishi, JCP-2004, Idomura, JCP-2007] to polar coordinate with new flux-conservative scheme near singularity.
- ✓ Field equation is solved in real space (not k-space) and full-order FLR effect is taken into account by using 20 point average on gyro-ring.



4. Numerical Condition

Parameter	Value
a_0/ρ_i	150
a_0/R_0	0.36
$(R_0/L_n)_{r=a_0/2}$	2.22
$(R_0/L_{Ti})_{r=a_0/2}$	10
$(R_0/L_{Te})_{r=a_0/2}$	(A) 6.92 (B) 10
Δ_r	45
$\sqrt{m_i/m_e}$	10

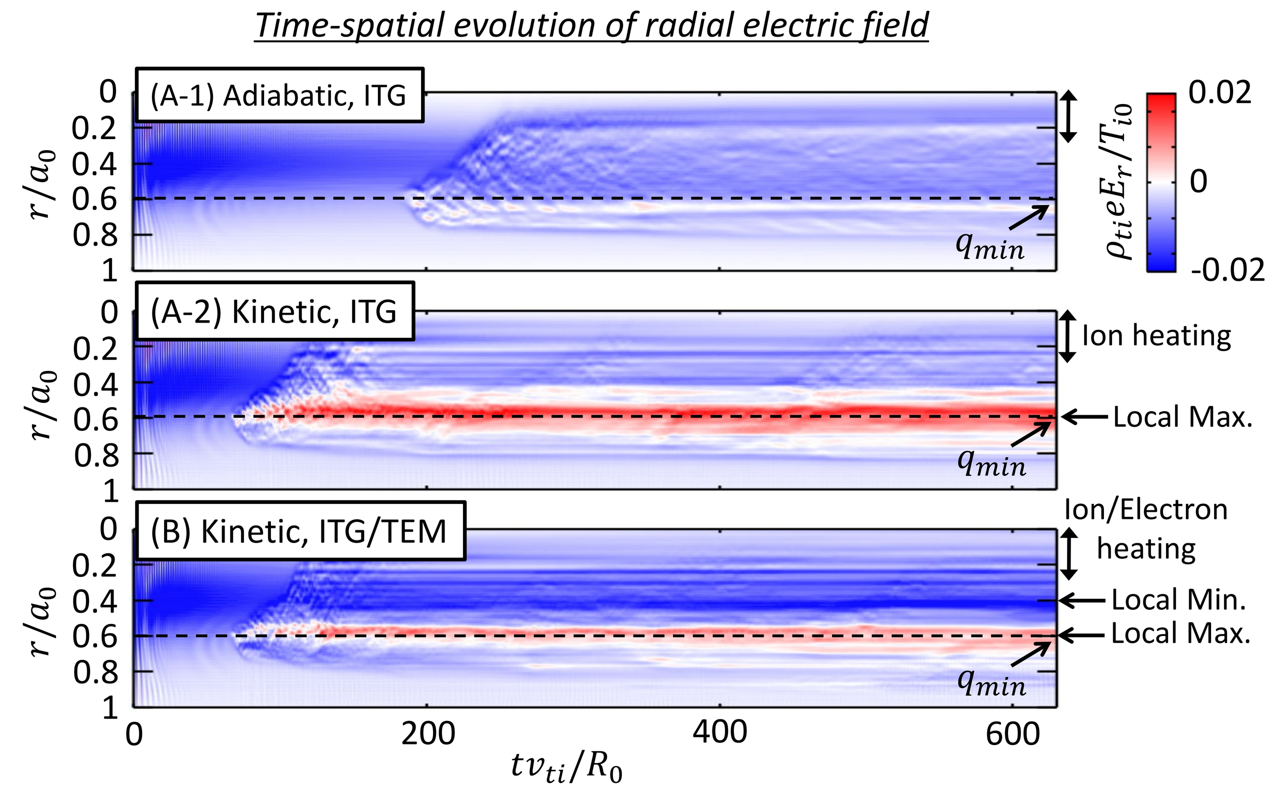
Parameter	Value
ν_i^*	0.1
ν_e^*	0.1
$\tau_{src,i}^{-1}$	0.02 -> 4[MW]
$\tau_{src,e}^{-1}$	(A) 0 -> 0[MW] (B) 0.02 -> 4[MW]
τ_{snk}^{-1}	0.1/0.36



- ✓ We consider (A)ITG dominant and (B)ITG/TEM dominant cases.
- ✓ Safety factor profile is reversed, which local minimum is located at $r = 0.6a_0$.
- ✓ Only heat source is applied, which does not provide particle and momentum.

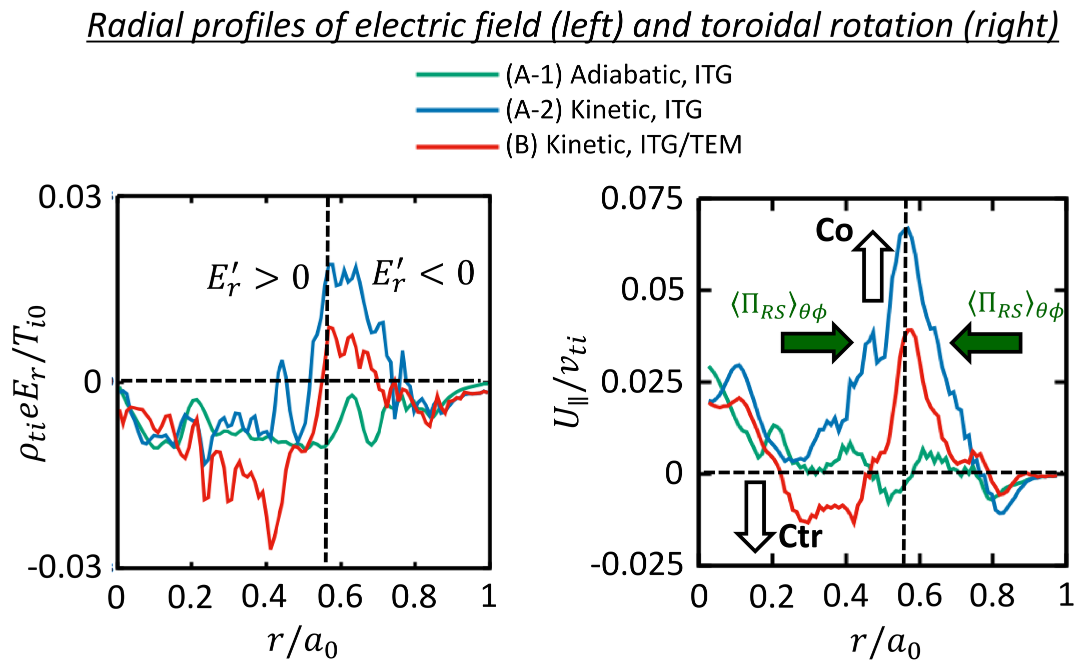
5. ITB Formation in Flux-driven ITG/TEM Turbulence

Time-spatial evolution of radial electric field



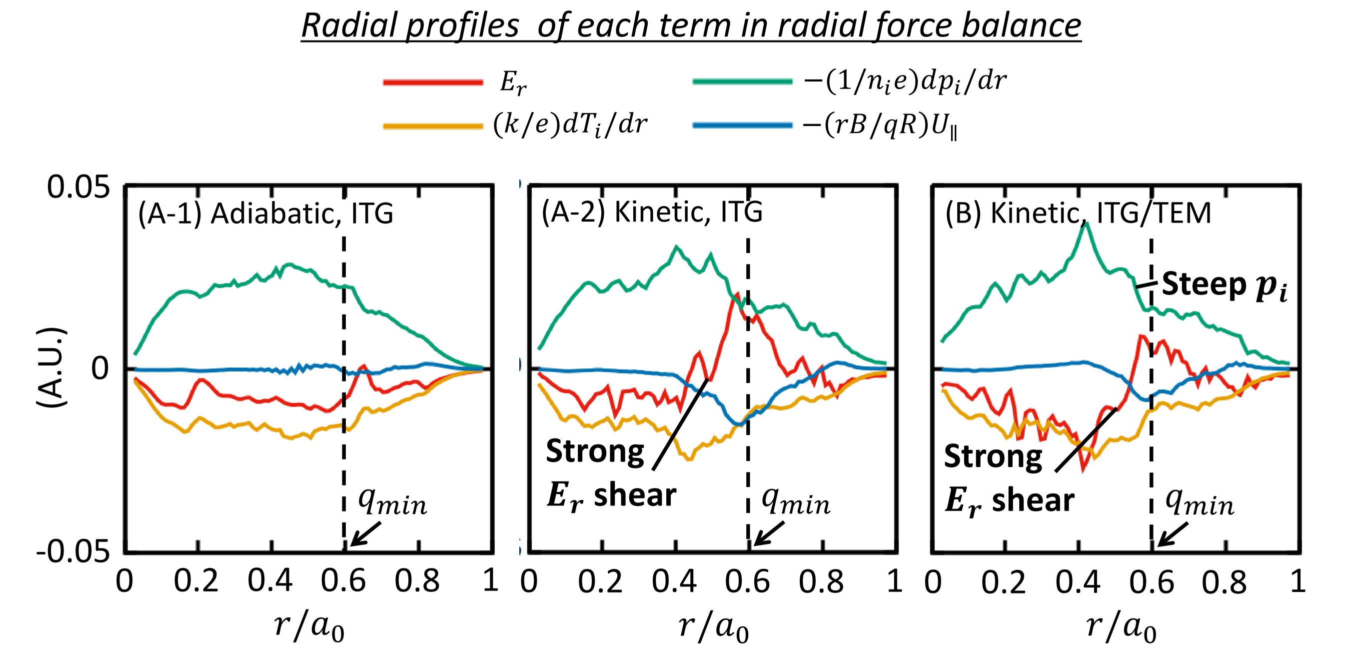
- ✓ Stable local maximum of mean E_r are formed near q_{min} surface only in kinetic electron cases.

Radial profiles of electric field (left) and toroidal rotation (right)



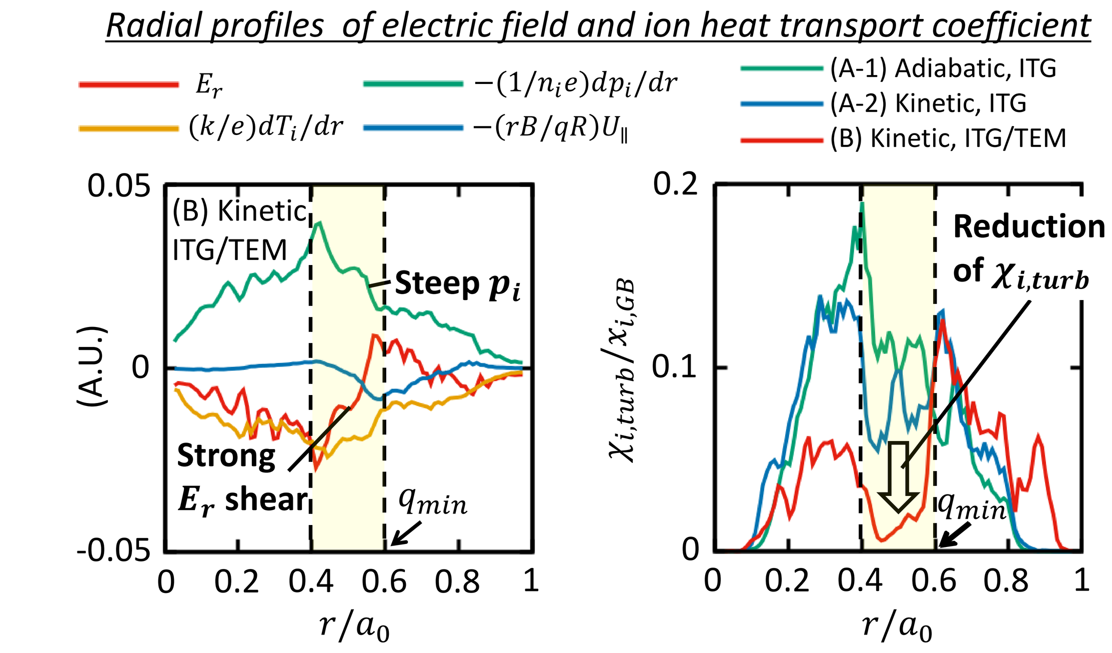
- ✓ Large co-rotation is driven around q_{min} surface in case (A-2) and (B).
- ✓ According to the momentum transport theory, $\langle\Pi_{RS}\rangle_{\theta\phi} = \alpha I E_r' + \beta I' + \gamma\langle k_\theta k_\phi \phi_k^2\rangle_{\theta\phi}$ [Kwon, NF-2012], the first and second terms can reduce momentum diffusion in this case, which can keep the stable local maximum of mean E_r through the radial force balance.
- ✓ Counter-rotation is also observed in negative magnetic shear region in case (B).

Radial profiles of each term in radial force balance



- ✓ In flux-driven ITG turbulence with kinetic electrons, the co-current toroidal rotation can balance with E_r, of which shear becomes strong just inside of q_{min} surface.
- ✓ On the other hand, in ITG/TEM turbulence with kinetic electrons, E_r is reversed in negative magnetic shear region, which makes its shear stronger and pressure gradient steeper.

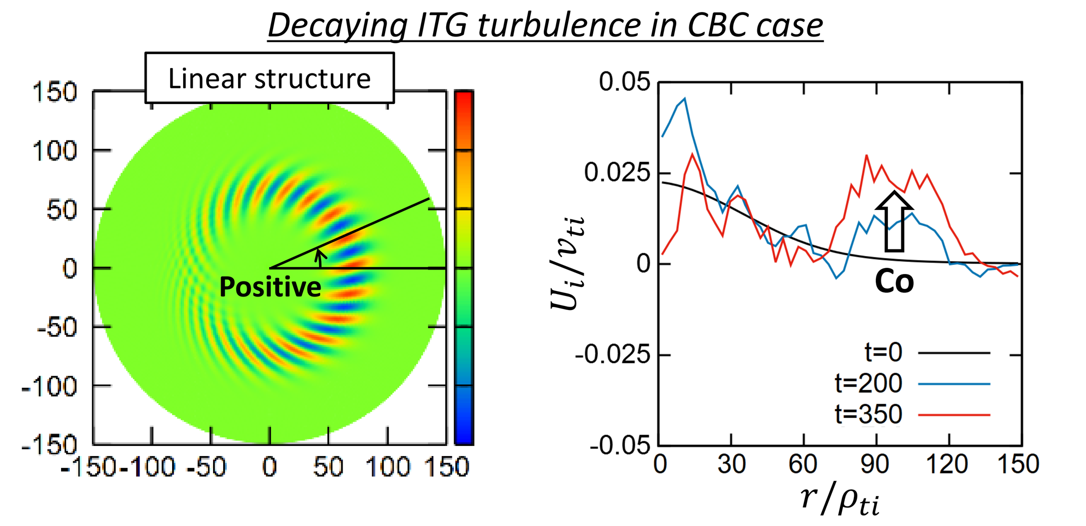
Radial profiles of electric field and ion heat transport coefficient



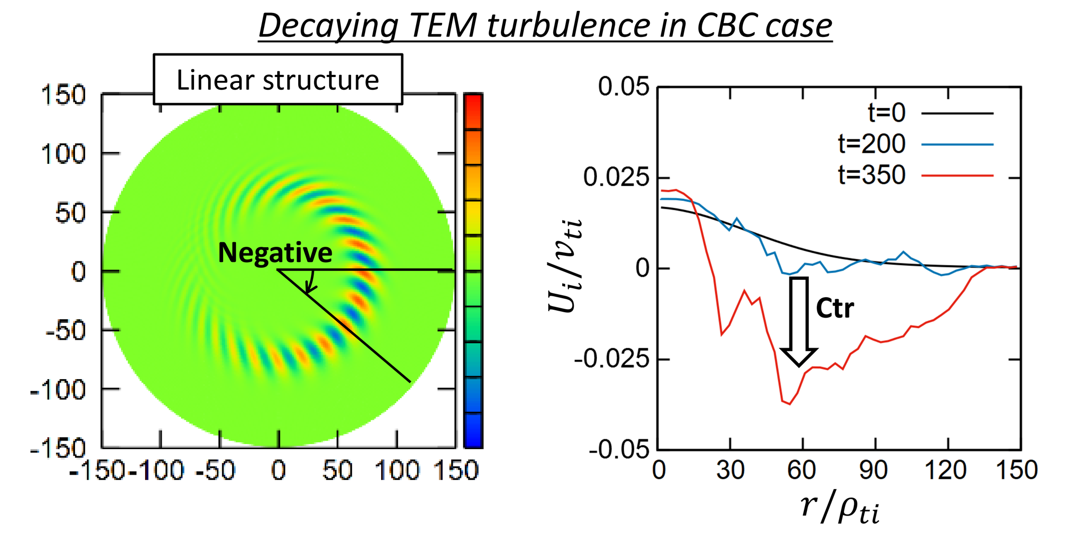
- ✓ As the result, ion turbulent thermal diffusivity in flux-driven ITG/TEM case spontaneously decreases to the neoclassical transport level among $0.4a_0 < r < 0.6a_0$, where E_r shear becomes steep.

6. What is the Origin of Co-/Counter-Rotation?

Decaying ITG turbulence in CBC case



Decaying TEM turbulence in CBC case



- ✓ The finite ballooning angle of the global mode structure arising from the profile shearing effect [Camenen, NF-2011] induces the residual stress part of momentum flux [Camenen, NF-2011].
- ✓ The sign of the ballooning angle between ITG and TEM turbulence is opposite so that the direction of intrinsic rotation is reversed.
- ✓ The steep electron temperature gradient is considered to destabilize TEM in the negative magnetic shear region.

7. Summary & Future Plans

Summary

- ✓ We have performed the flux-driven ITG/TEM simulation in reversed magnetic shear configuration by using hybrid kinetic electron model.
- ✓ In the presence of both ion and electron heating, a counter-intrinsic rotation by TEM turbulence is driven in negative magnetic shear region, leading to stronger E_r shear and the resultant spontaneous larger reduction of ion turbulent thermal diffusivity.

Discussion

- ✓ An increase of counter intrinsic rotation in the narrow region of the ITB located just inside of q_{min} is also observed in JT-60U reversed magnetic shear discharge with balanced momentum injection [Sakamoto, NF-2001]. -> Qualitative agreement!
- ✓ It can conclude that counter intrinsic rotation is a possible candidate to trigger the positive feedback loop via $E \times B$ mean flow, leading to spontaneous ITB formation.

Future plans

- ✓ By reflecting bootstrap current and shafranov shift effects to the analytical magnetic equilibrium [Imadera, PFR-2020] in time, we can take them into account, which can help us to understand the overall positive feedback loop.

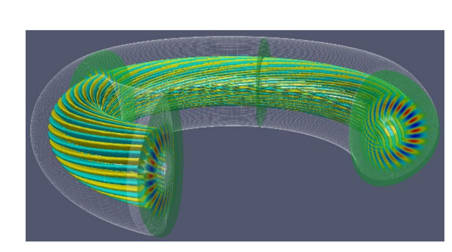


Fig. A typical 3D eigenfunction of toroidal ITG mode in a non-circular tokamak configuration with $\kappa_0 = 1.5$, $\delta_0 = 0.3$.