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

Contents

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Background: Possible Mechanism of ITB Formation

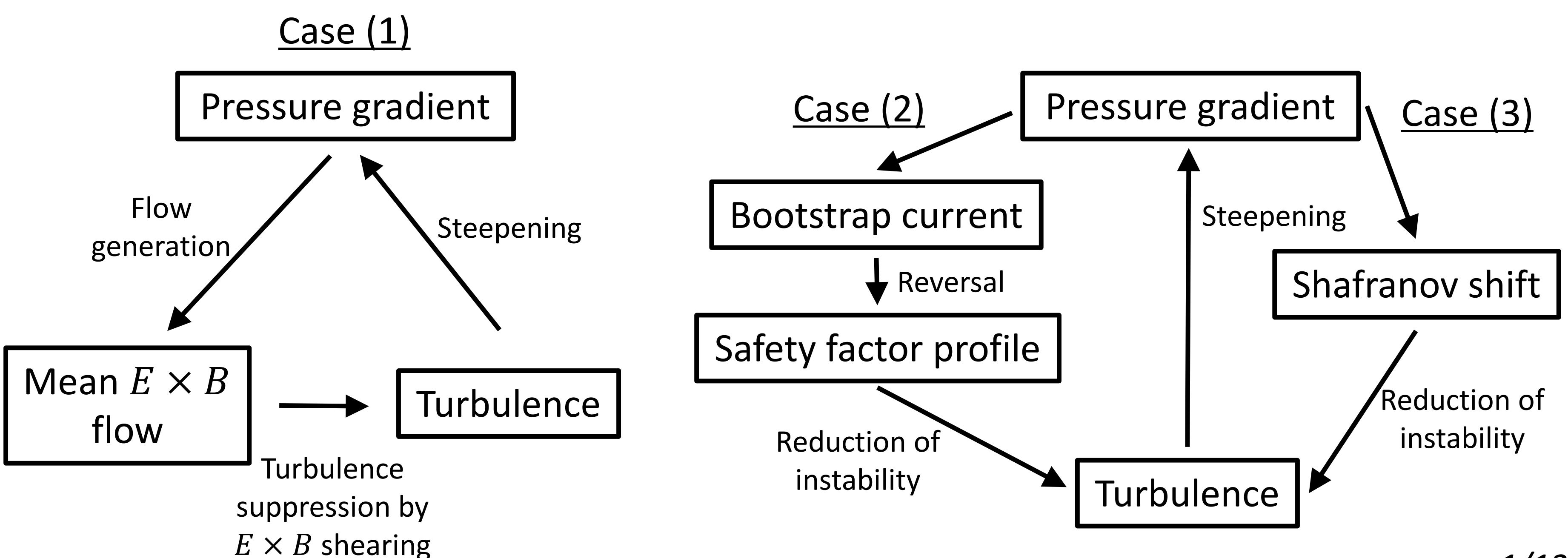
✓ Internal Transport barrier (ITB) has a crucial key to achieve a high-performance plasma confinement.

✓ 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]

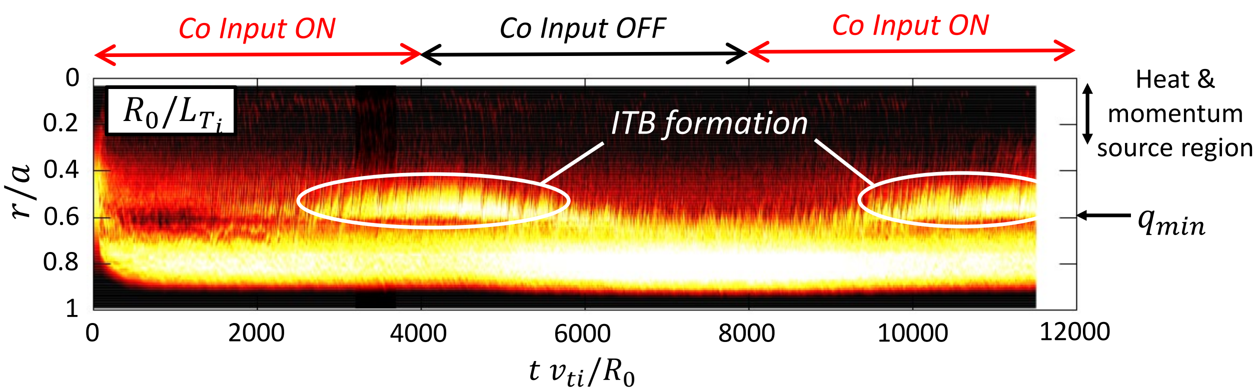
(3) Positive feedback loop via Shafranov shift + EM stabilization [Staebler, NF-2018]

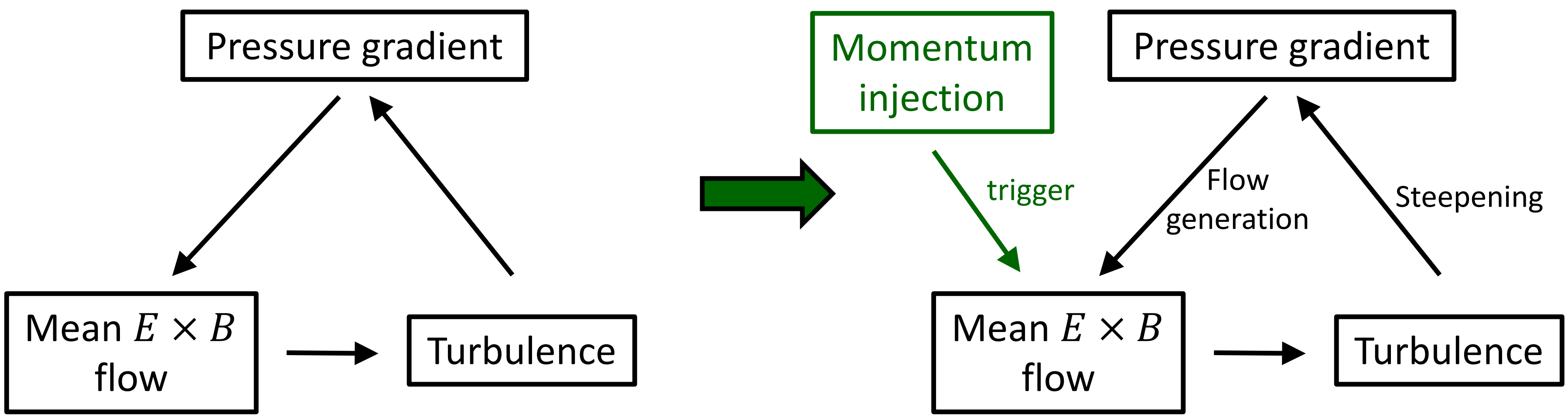


Background: ITB Formation by Momentum Injection

- ✓ 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]

- ✓ Such a mechanism can also benefit the ITB formation around q_{min} surface in reversed magnetic shear plasma.





Recover the symmetry
-> weak stabilization

Break the symmetry
-> strong stabilization

Motivation of This Research

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

[Imadera, IAEA-2014]

GKNET
Toroidal
Electrostatic
Adiabatic Electron
full-*f*

→

GKNET-KE
Toroidal
Electrostatic
Kinetic Electron
global delta-*f*

→

GKNET-KE-EM
Toroidal
Electromagnetic
Kinetic Electron
global delta-*f*

[Ishizawa, PoP-2019] [Ishizawa, *this conference, TH/4-2*]

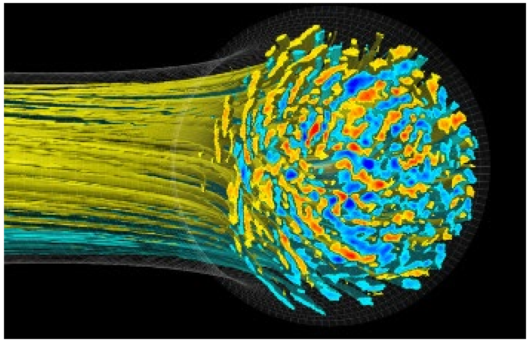
↓ (from GKNET)

[Imadera, PFR-2020]

GKNET-shaped
Magnetic flux
Electrostatic
Adiabatic Electron
full-*f*

↓ (from GKNET-KE)

GKNET-HE
Toroidal
Electrostatic
Hybrid Electron
full-*f*



Full-*f* Gyrokinetic Code *GKNET* - 1

GK Vlasov equation

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

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

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

+

GK quasi-neutrality condition

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

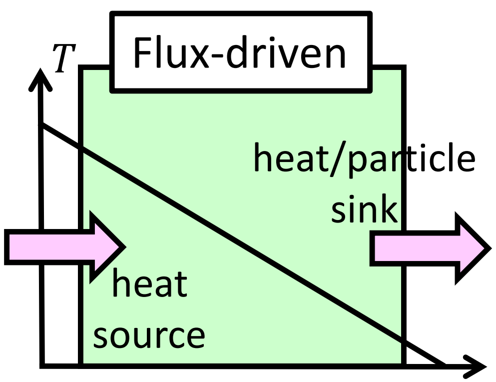
f_s: full-*f* distribution function for species $s = i, e$
$C_{s,s}$: self-collision operator for species s
S_{src}: Heat source operator
S_{snk}: Krook-type sink operator

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 following hybrid kinetic electron model [Lanti, JP-2018].

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

<u>GKNET-HE</u>
Toroidal
Electrostatic
Hybrid Electron
full-*f*



Full-*f* Gyrokinetic Code *GKNET* - 2

GK Vlasov equation

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

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

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

+

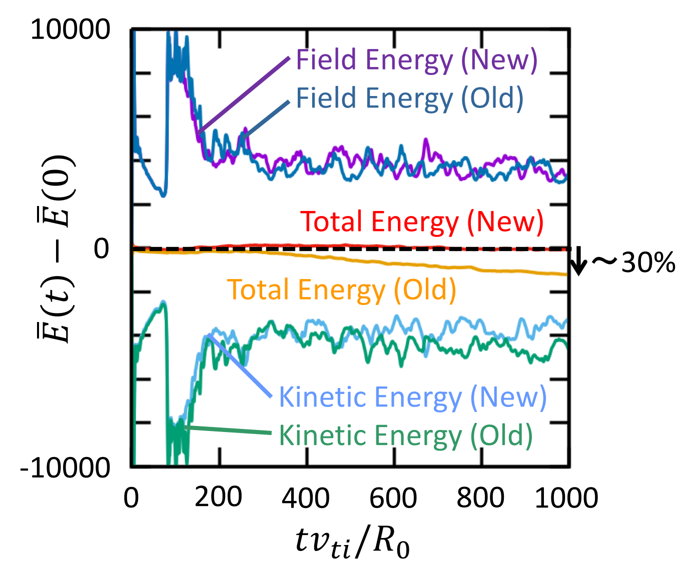
GK quasi-neutrality condition

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

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

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.
- ✓ 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.
- ✓ 3D MPI decomposition is introduced by utilizing 1D FFT and MPI_ALLtoALL transpose technique.



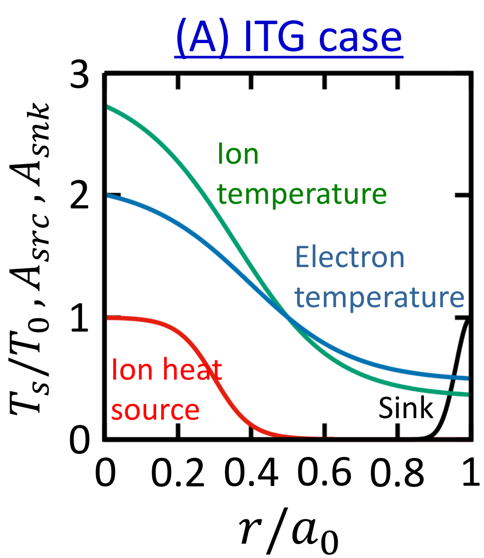
ITB Formation in Flux-driven ITG/TEM Turbulence - 1

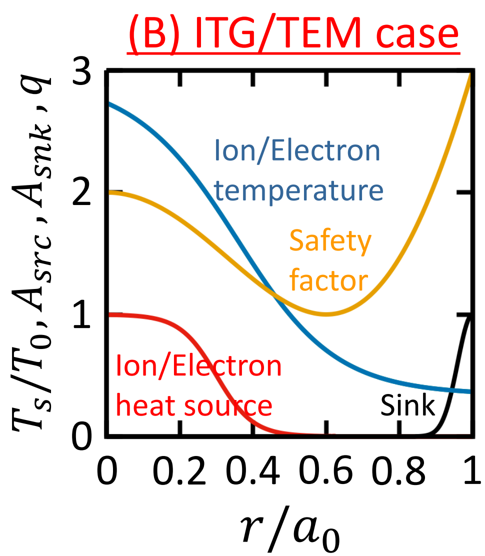
Simulation condition

Parameter	Value
a_0/ρ_i	150
a_0/R_0	0.36
$(R_0/L_n)_{r=a_0/2}$	2.22
$(R_0/L_{T\,i})_{r=a_0/2}$	10
$(R_0/L_{T\,e})_{r=a_0/2}$	(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

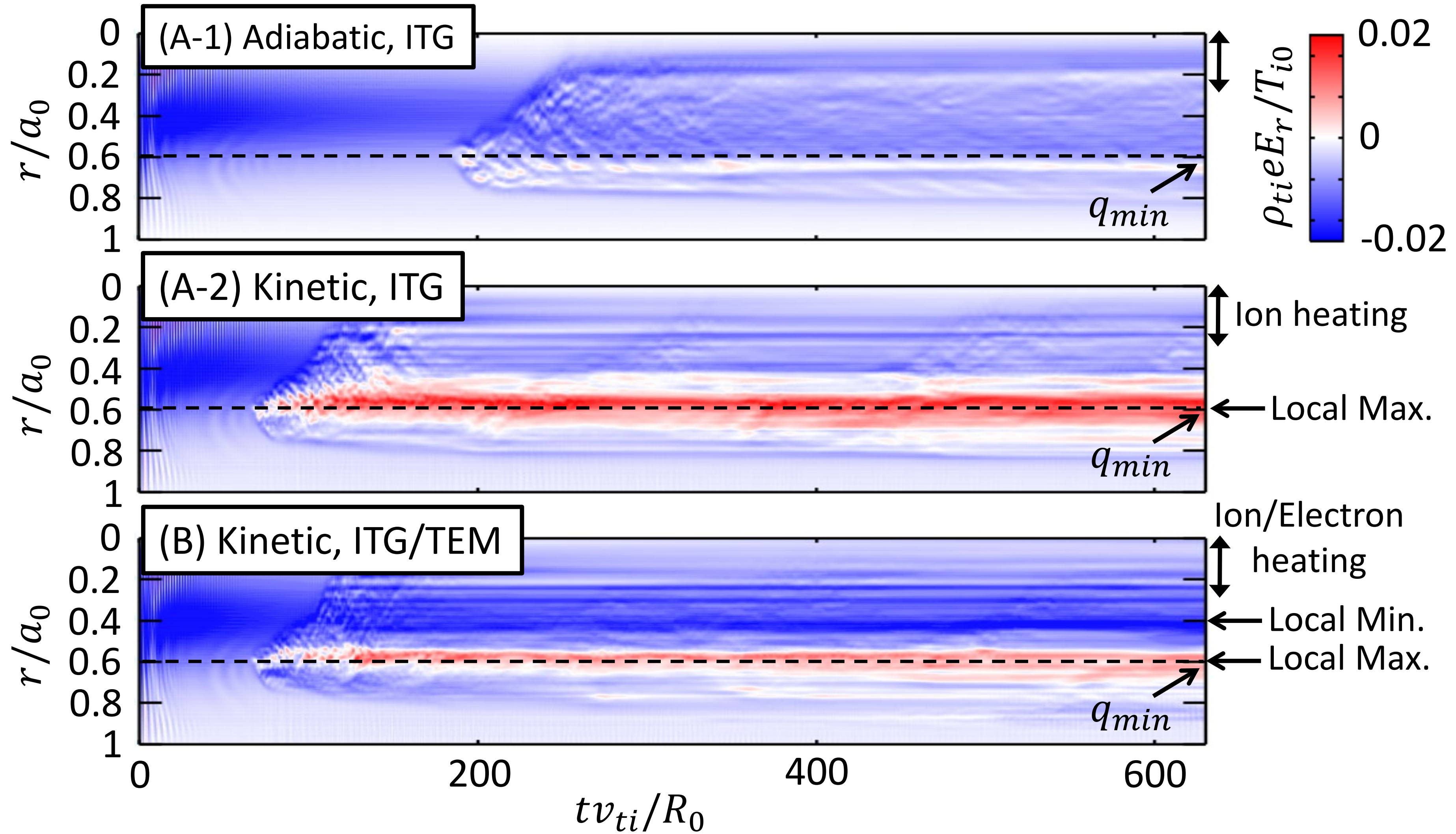
Parameter	Value
N_r	96
N_θ	240
N_φ	48
$N_{v_\parallel}$	96
N_μ	16
Δt	3.125×10^{-4}





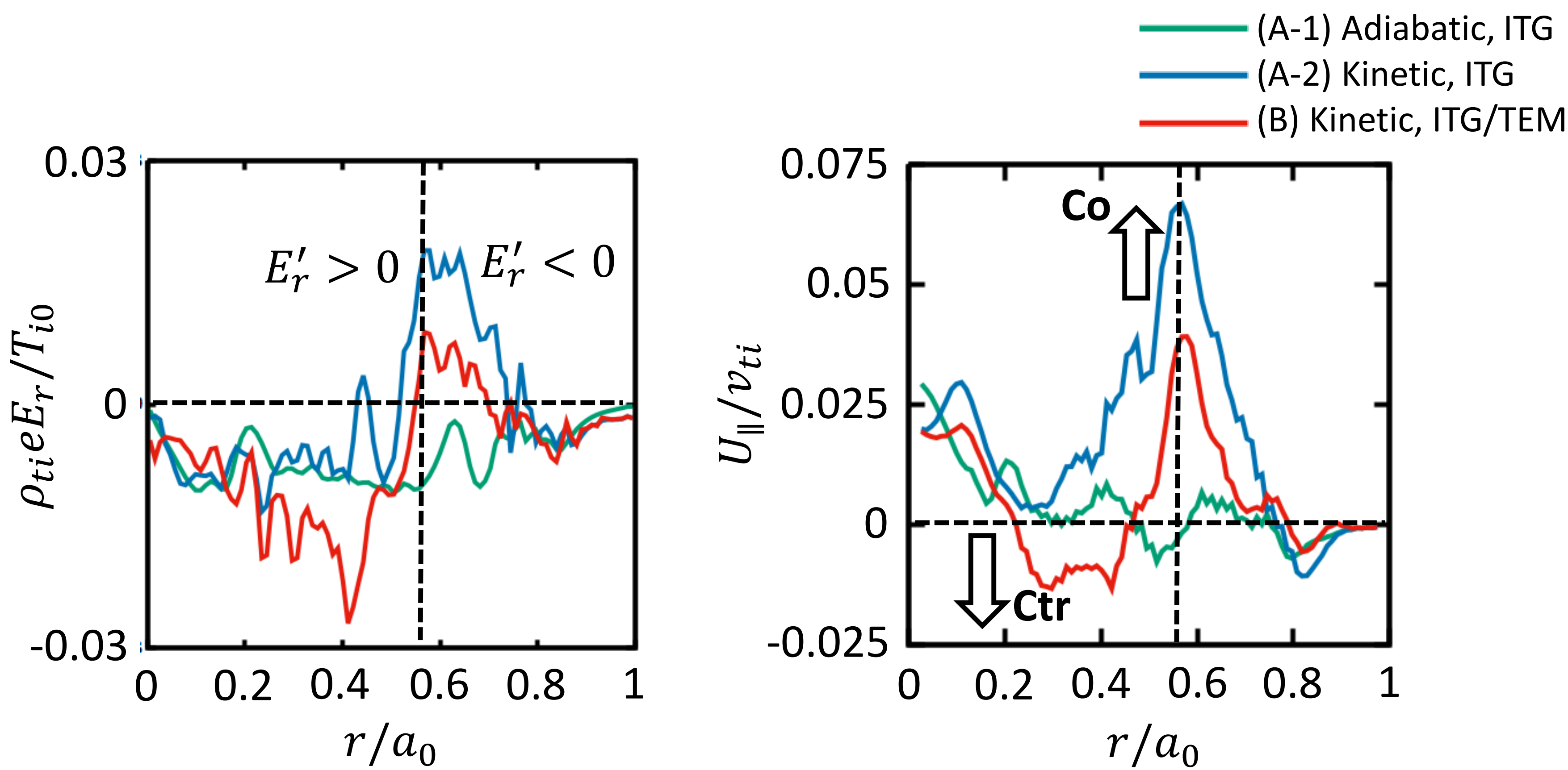
- ✓ We consider (A)ITG dominant and (B)ITG/TEM dominant cases.
- ✓ Safety factor profile is reversed, which local minimum is located at $r = 0.6a_0$.
- ✓ Only heat source is applied, which does not provide particle and momentum.

ITB Formation in Flux-driven ITG/TEM Turbulence - 2



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

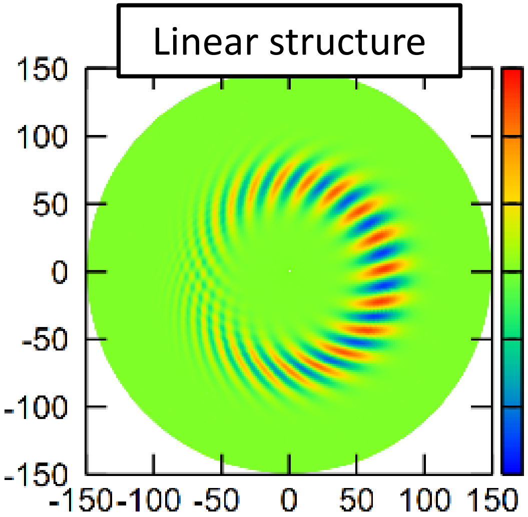
ITB Formation in Flux-driven ITG/TEM Turbulence - 3

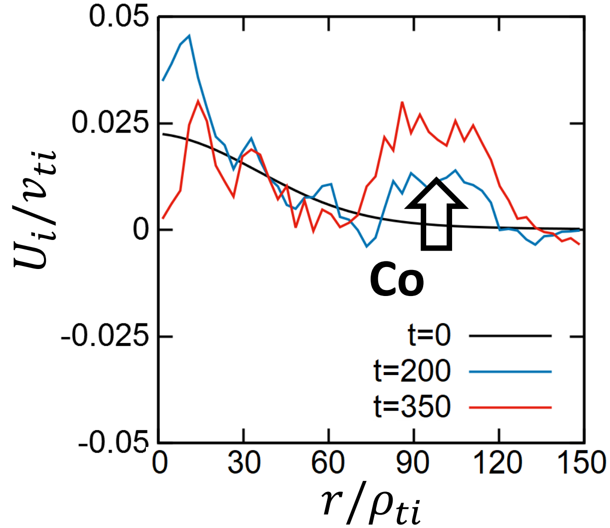


- ✓ Large co-rotation is driven around q_{min} surface in case (A-2) and (B).
- ✓ According to the momentum transport theory, $\langle \Pi_{RS} \rangle_{\theta\phi} = \alpha I E_r' + \beta I' + \gamma \langle k_\theta k_\phi \phi_k^2 \rangle_{\theta\phi}$ [Kwon, NF-2012], the first and second terms can 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).

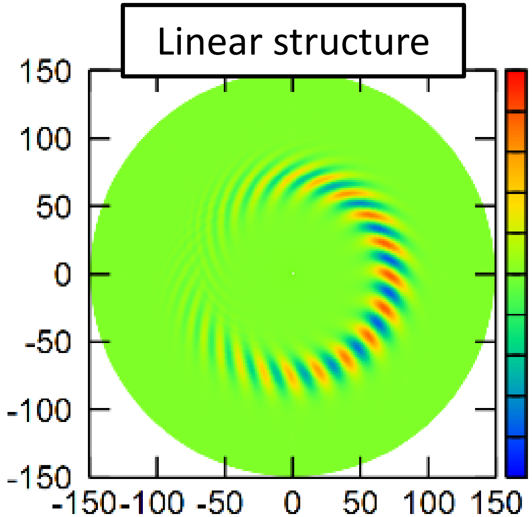
What is the Origin of Co-/Counter-Rotation?

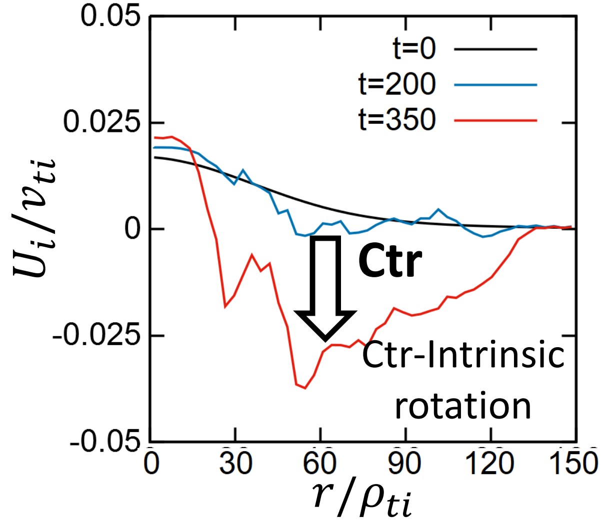
Decaying ITG turbulence in CBC case





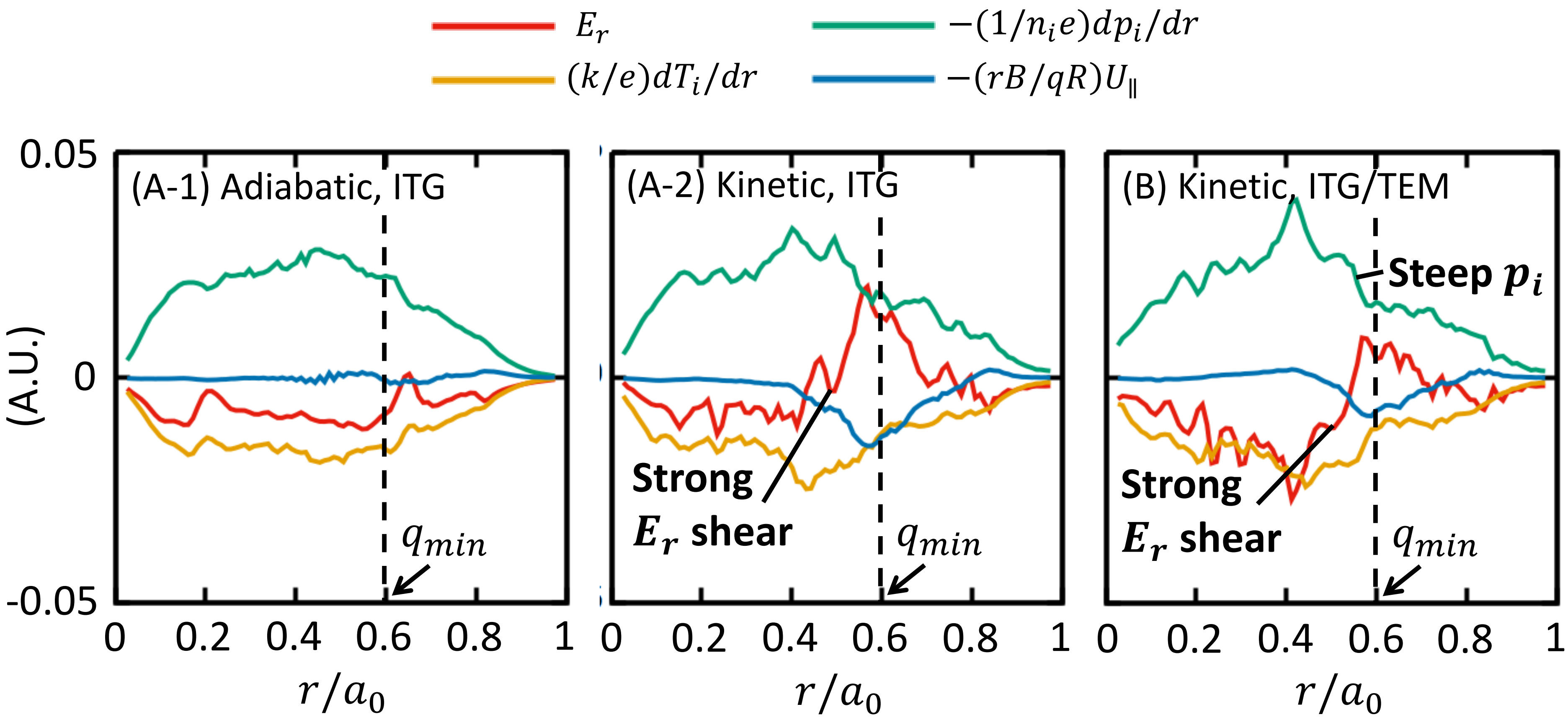
Decaying TEM turbulence in CBC case





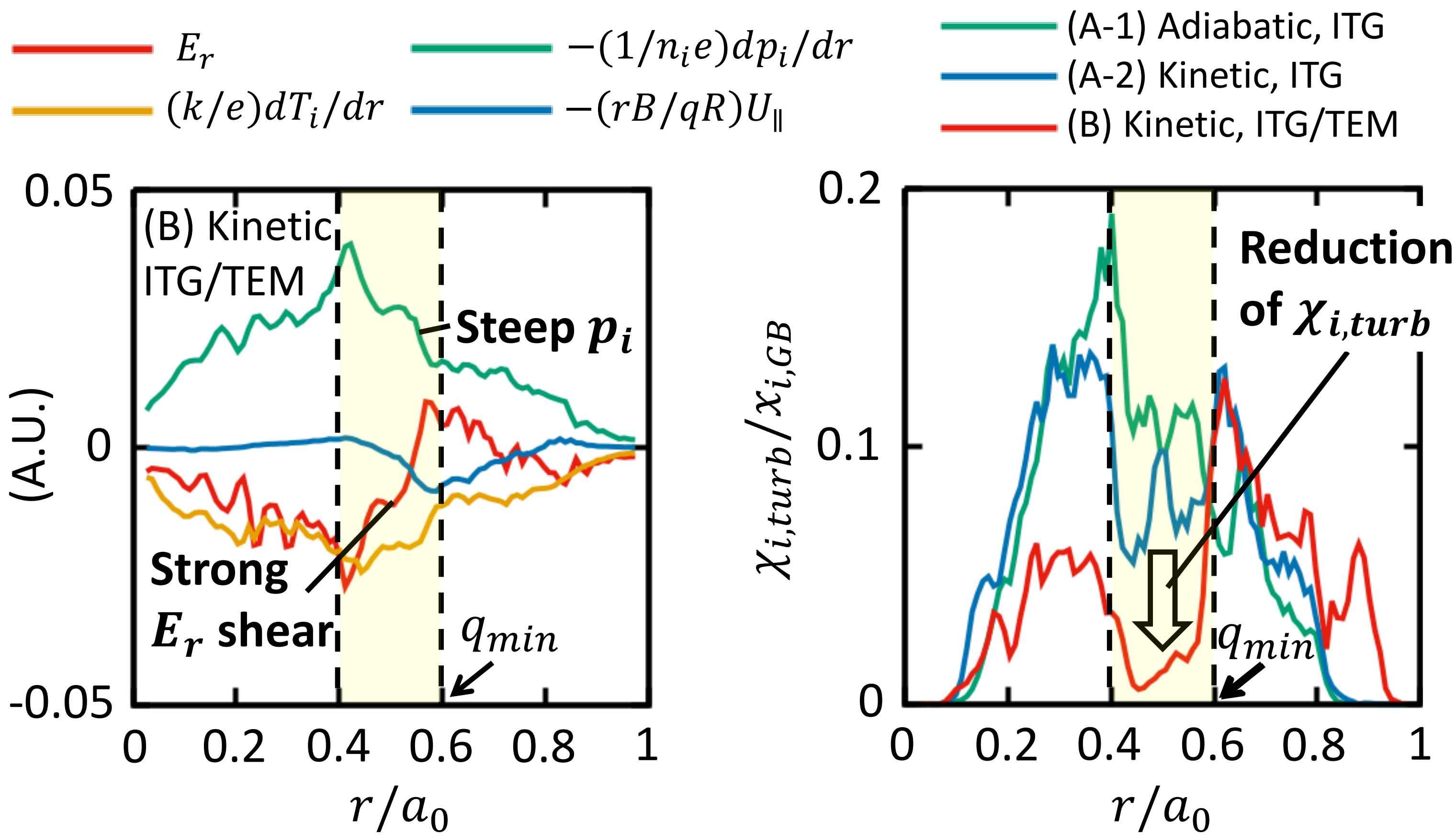
- ✓ The finite ballooning angle of the global mode structure arising from the profile shearing effect [Kishimoto, PPCF-1998] induces the residual stress part of momentum flux [Camenen, NF-2011].
- ✓ The sign of the ballooning angle between ITG and TEM turbulence is opposite (left figures) so that the direction of intrinsic rotation is reversed.
- ✓ The steep electron temperature gradient is considered to destabilize TEM in the negative magnetic shear region.

ITB Formation in Flux-driven ITG/TEM Turbulence - 4



- ✓ 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.

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



- ✓ 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.
- ✓ These results indicate that the co-existence of different modes can trigger the discontinuity near q_{min}, leading to the spontaneous ITB formation.

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 steeper 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 other positive feedback loop.