2021.5.18 (Tue)
IFERC-CSC Workshop on JFRS-1 Projects
Virtual Event

Global Gyrokinetic simulation for High-Beta plasma
[Project Name: GGHB]

Contents

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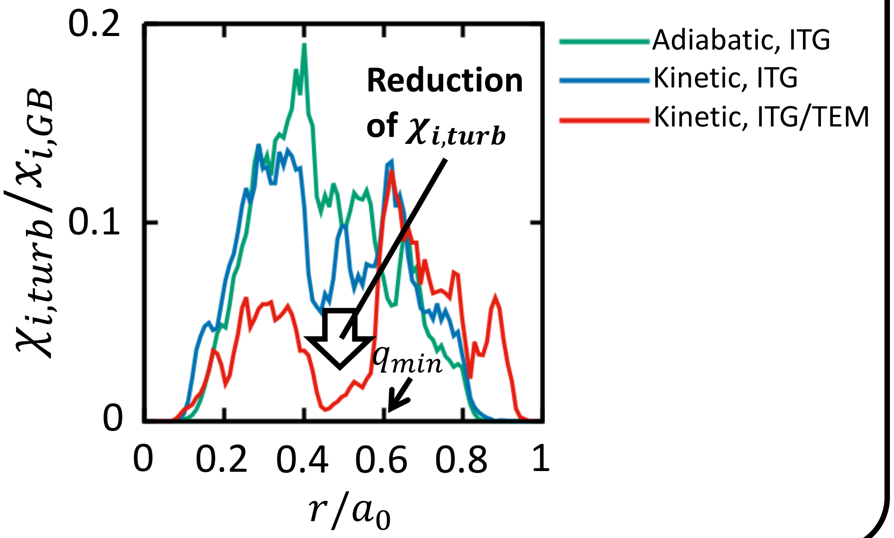
Background & Motivation

- ✓ The plasma beta value given by $\beta = 8\pi p/B^2$ is one of the important parameters for fusion plasmas because it is linked to the fusion reaction rate and also related to the production of bootstrap current.
- ✓ To achieve and sustain high-beta states, our group focuses on the following two topics;

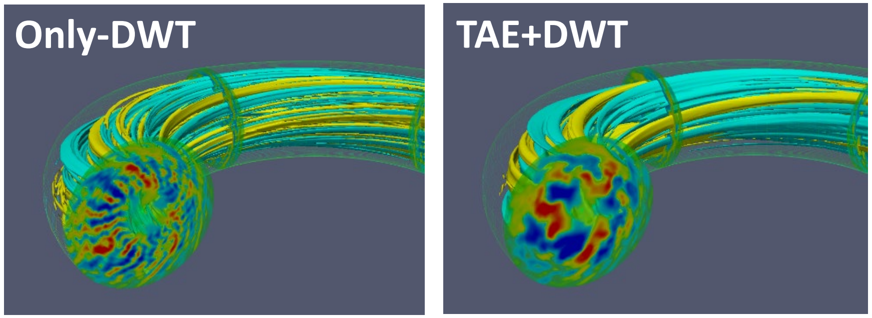
(1) Study of ITB formation for the achievement of high-beta plasma

Based on full-*f* electrostatic model with hybrid electron, we have studied the spontaneous ITB formation in reversed magnetic shear configuration.



(2) Study of TAE-KBM interaction for the sustainment of high-beta plasma

Based on delta-*f* electromagnetic model with kinetic electron, we have studied the interaction between energetic-particle-driven MHD mode (TAE) and drift-wave turbulence.



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5. Summary & Future plans (2/20)

Original *GKNET*

Gyrokinetic Vlasov equation (ion) & Gyrokinetic quasi-neutrality condition

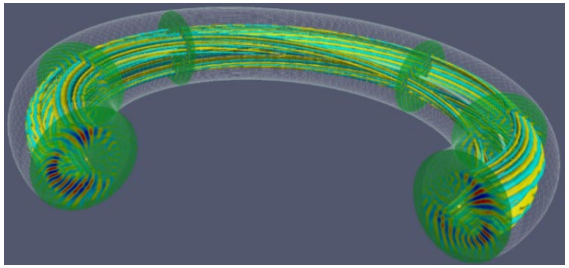
$$\frac{\partial}{\partial t}(Jf)+\frac{\partial}{\partial \mathbf{R}}\left(J\frac{d\mathbf{R}}{dt}f\right)+\frac{\partial}{\partial v_\parallel}\left(J\frac{dv_\parallel}{dt}f\right)=S_{src}+S_{snk}+C_{coll}$$

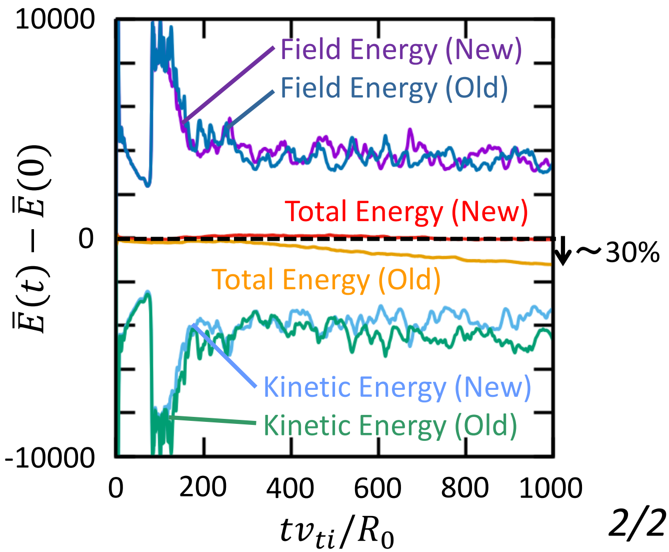
$$\frac{d\mathbf{R}}{dt}=\{\mathbf{R},H\}=\frac{\boldsymbol{B}_\parallel^*}{B_\parallel^*}\frac{\partial H}{\partial v_\parallel}+\frac{1}{B_\parallel^*}\boldsymbol{b}\times\boldsymbol{\nabla}H$$

$$-\nabla_\perp\cdot\frac{\rho_{ti}^2}{\lambda_{Di}^2}\nabla_\perp\phi(\boldsymbol{R})+\underbrace{\frac{1}{\lambda_{De}^2}\left[\phi(\boldsymbol{R})-\langle\phi(\boldsymbol{R})\rangle_f\right]}_{\text{Adiabatic electron response}}=4\pi e\iint\langle\delta f_i(\boldsymbol{R})\rangle\frac{B_\parallel^*}{m_i}dv_\parallel d\mu$$

$$\frac{dv_\parallel}{dt}=\{v_\parallel,H\}=-\frac{\boldsymbol{B}_\parallel^*}{B_\parallel^*}\cdot\boldsymbol{\nabla}H$$

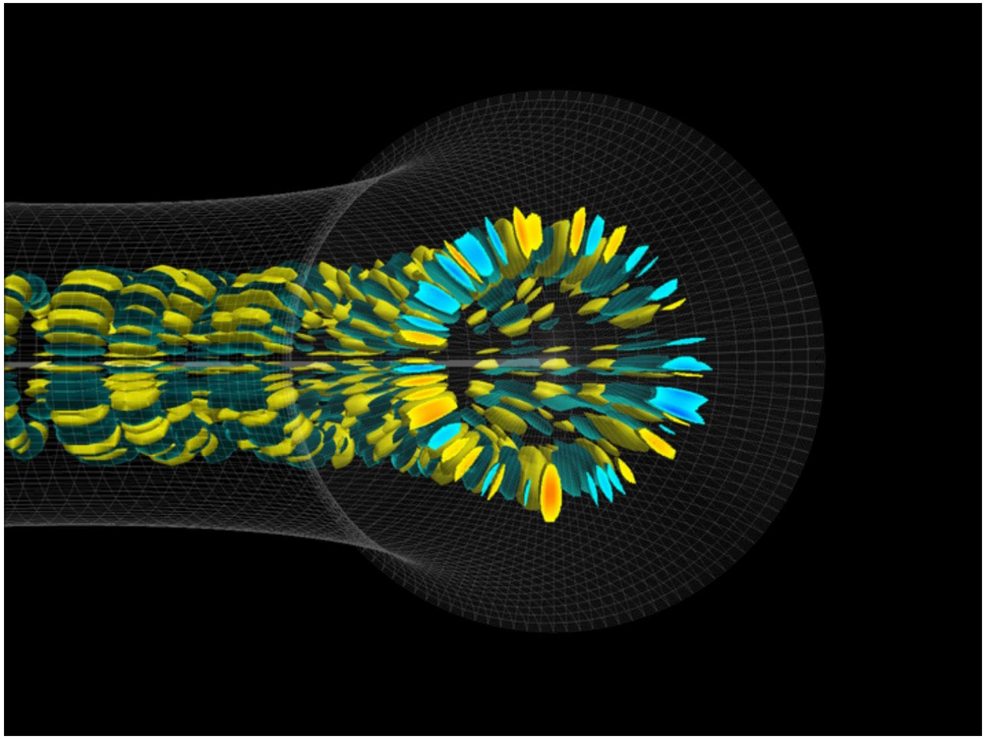
- ✓ Original *GKNET* is based on full-*f* gyrokinetic model, which trace turbulence and background profiles self-consistently [Imadera, IAEA-2014].
- ✓ We use the Morinishi scheme, which was developed for fluid simulation and introduced to rectangular gyrokinetic code, [Morinishi, JCP-2004, Idomura, 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 [Obrejan, PFR-2015, CPC-2017].

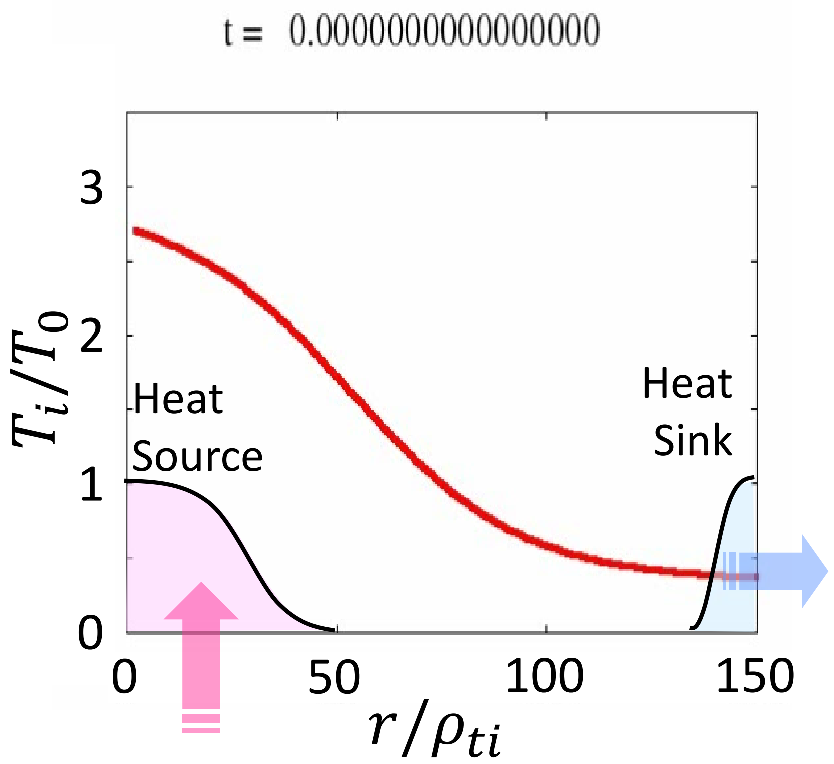




Flux-driven ITG Simulation by Original *GKNET*

Time evolution 3D electrostatic potential & 1D ion temperature





- ✓ By using external heat source/sink, we can evaluate quasi-steady state of turbulence, not decaying turbulence.
- ✓ Typical scale length L_T is tied to be globally constant, it does not largely change even if heat input power is increased (profile stiffness) -> L mode plasma

Extension of *GKNET*

Gyrokinetic Vlasov equation (ion) & Gyrokinetic quasi-neutrality condition

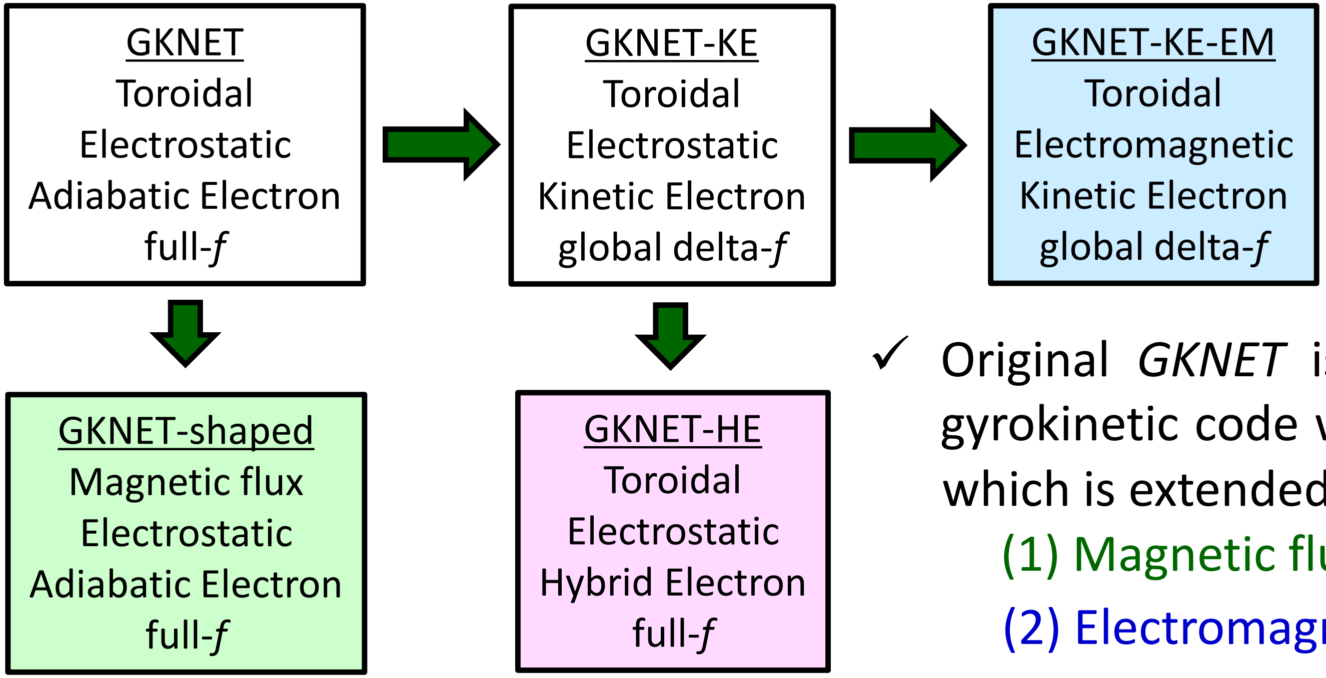
$$\frac{\partial}{\partial t}(Jf)+\frac{\partial}{\partial \mathbf{R}}\left(J\frac{d\mathbf{R}}{dt}f\right)+\frac{\partial}{\partial v_\parallel}\left(J\frac{dv_\parallel}{dt}f\right)=S_{src}+S_{snk}+C_{coll}$$

$$\frac{d\boldsymbol{R}}{dt}=\{\mathbf{R},H\}=\frac{\boldsymbol{B}_\parallel^*}{B_\parallel^*}\frac{\partial H}{\partial v_\parallel}+\frac{1}{B_\parallel^*}\boldsymbol{b}\times\boldsymbol{\nabla}H$$

$$-\nabla_\perp\cdot\frac{\rho_{ti}^2}{\lambda_{Di}^2}\nabla_\perp\phi(\boldsymbol{R})+\underbrace{\frac{1}{\lambda_{De}^2}\left[\phi(\boldsymbol{R})-\langle\phi(\boldsymbol{R})\rangle_f\right]}_{\text{Adiabatic electron response}}=4\pi e\iint\langle\delta f_i(\boldsymbol{R})\rangle\frac{B_\parallel^*}{m_i}dv_\parallel d\mu$$

$$\frac{dv_\parallel}{dt}=\{v_\parallel,H\}=-\frac{\boldsymbol{B}_\parallel^*}{B_\parallel^*}\cdot\boldsymbol{\nabla}H$$

[Imadera, FEC-2014]



GKNET
Toroidal
Electrostatic
Adiabatic Electron
full-*f*

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

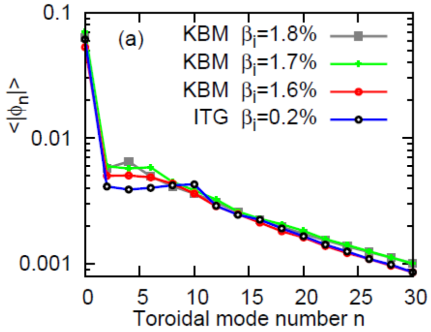
GKNET-KE-EM
Toroidal
Electromagnetic
Kinetic Electron
global delta-*f*

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

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

[Imadera, PFR-2020]

[Ishizawa, PoP-2019]



✓ Original *GKNET* is a full-*f* electrostatic gyrokinetic code with adiabatic electron, which is extended to

(1) Magnetic flux coordinate version

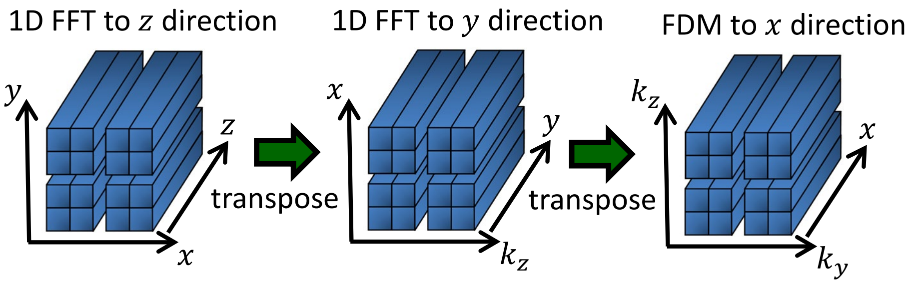
(2) Electromagnetic delta-*f* version

(3) Hybrid Electron full-*f* version

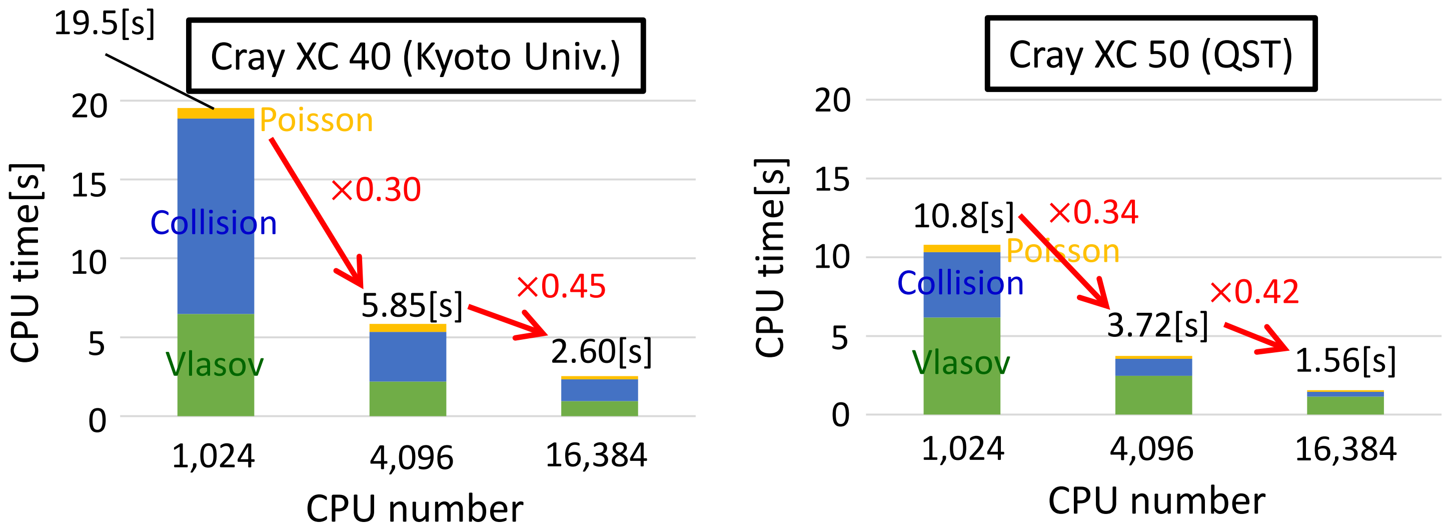
Parallelization of *GKNET*

High-efficient parallelization technique

- ✓ High efficient 2D FFT is installed by utilizing 1D FFT and MPI_ALLtoALL transpose technique with the aid of communication and computation hiding optimization.



Parallelization rate on super computer



	Processor	Flops/Node	Memory/Node	Network
Cray XC40 (Kyoto Univ.)	Intel Xeon Phi 7250 (68[core])	3.046[Tflops]	16+96[GB]	Aries (Dragonfly)
Cray XC50 (QST)	Intel Xeon Gold 6148 (20[core] × 2)	3.072[Tflops]	192[GB]	InfiniBand EDR (Dragonfly)

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  *** Background & Motivation**

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

4. Interaction between TAE and KBM Turbulence (5/20)

5. Summary & Future plans (2/20)

Background: Possible Mechanism of ITB Formation

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

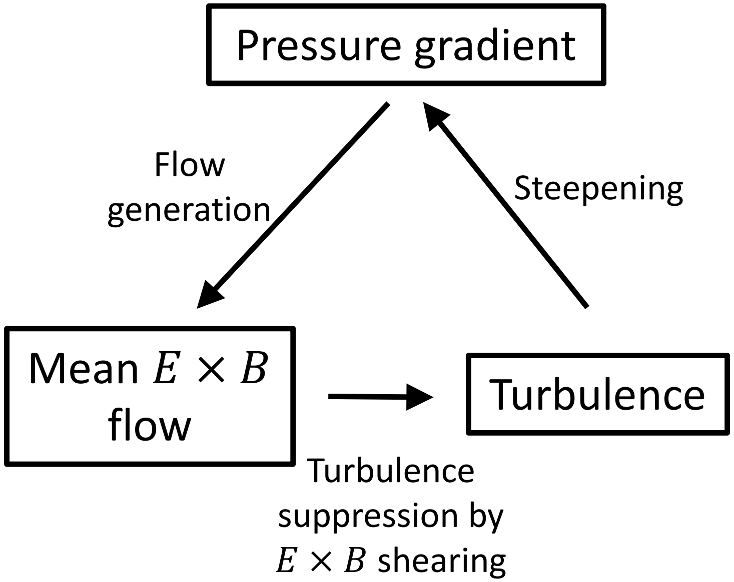
✓ Some possible mechanism for ITB formation are proposed [Ida, PPCF-2018] as

(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]

Case (1)



Pressure gradient

Flow generation

Mean $E \times B$ flow

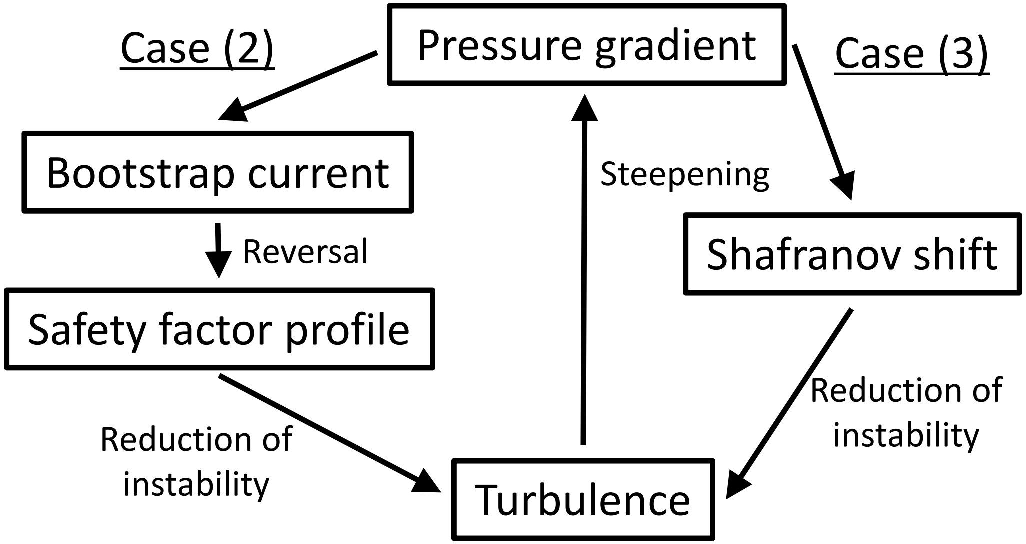
Turbulence suppression by $E \times B$ shearing

Turbulence

Steepening

Case (2)

Case (3)



Pressure gradient

Bootstrap current

Reversal

Safety factor profile

Reduction of instability

Turbulence

Steepening

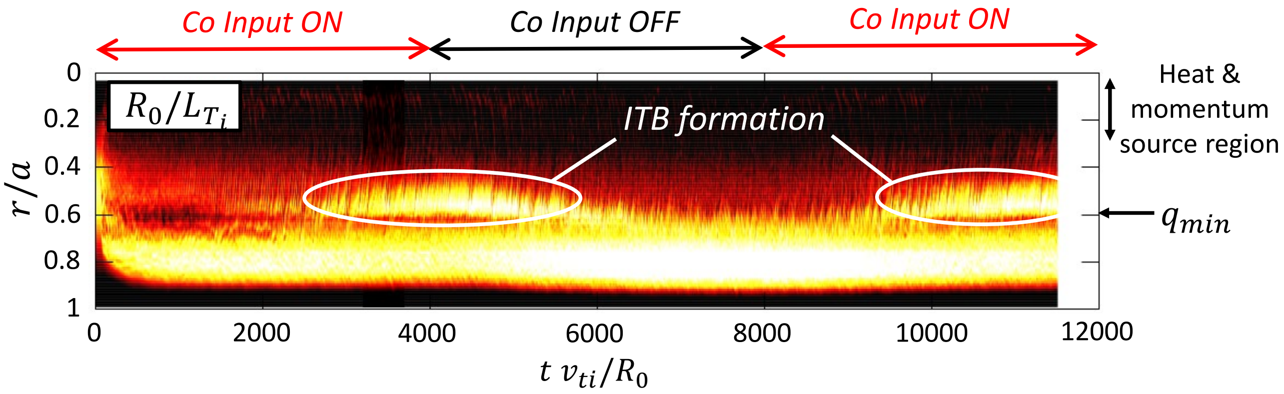
Shafranov shift

Reduction of instability

Motivation of This Research

- ✓ 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.



- ✓ 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.

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

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

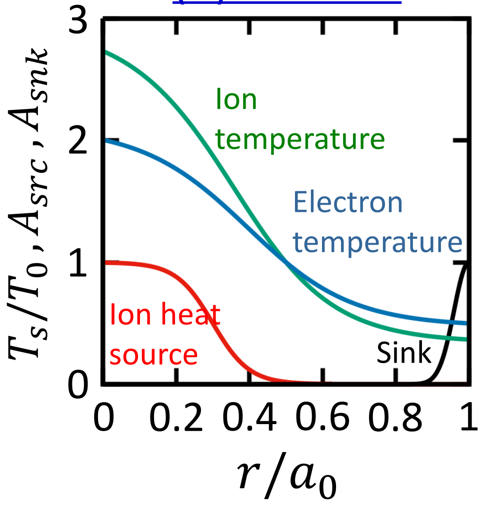
Simulation condition

Parameter	Value
a_0/ρ_i	150
a_0/R_0	0.36
$(R_0/L_n)_{r=a_0/2}$	2.22
$\left(R_0/L_{T\,i}\right)_{r=a_0/2}$	10
$\left(R_0/L_{T\,e}\right)_{r=a_0/2}$	(A) 6.92 (B) 10
Δ_r	45
$\sqrt{m_i/m_e}$	10

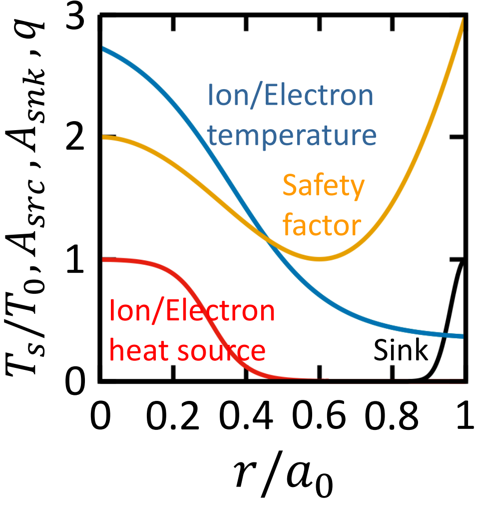
Parameter	Value
ν_i^*	0.1
ν_e^*	0.1
$\tau_{src,i}^{-1}$	0.02 -> 4[MW]
$\tau_{src,e}^{-1}$	(A) 0 -> 0[MW] (B) 0.02 -> 4[MW]
τ_{snk}^{-1}	0.1/0.36

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

(A) ITG case

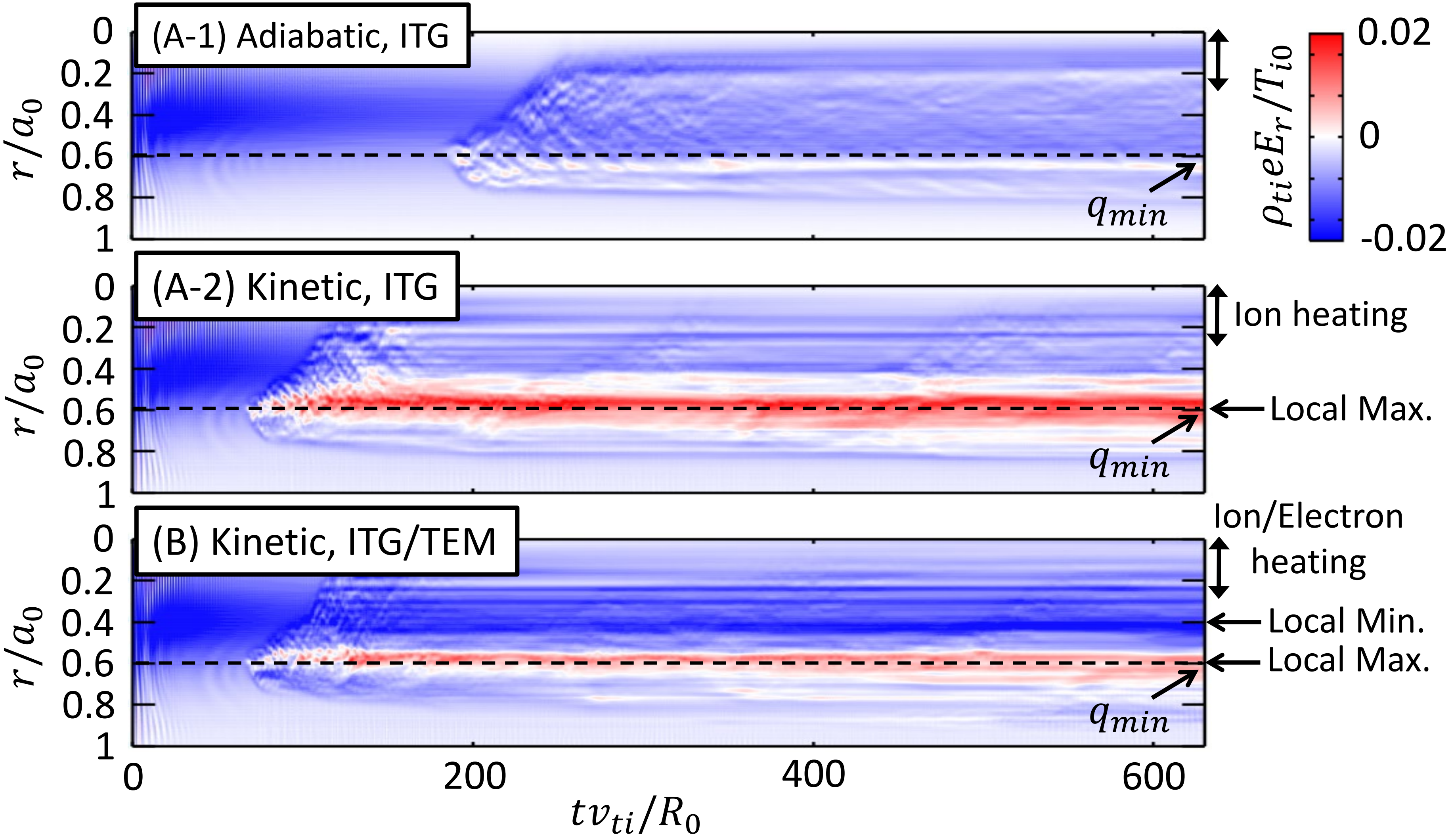


(B) ITG/TEM case



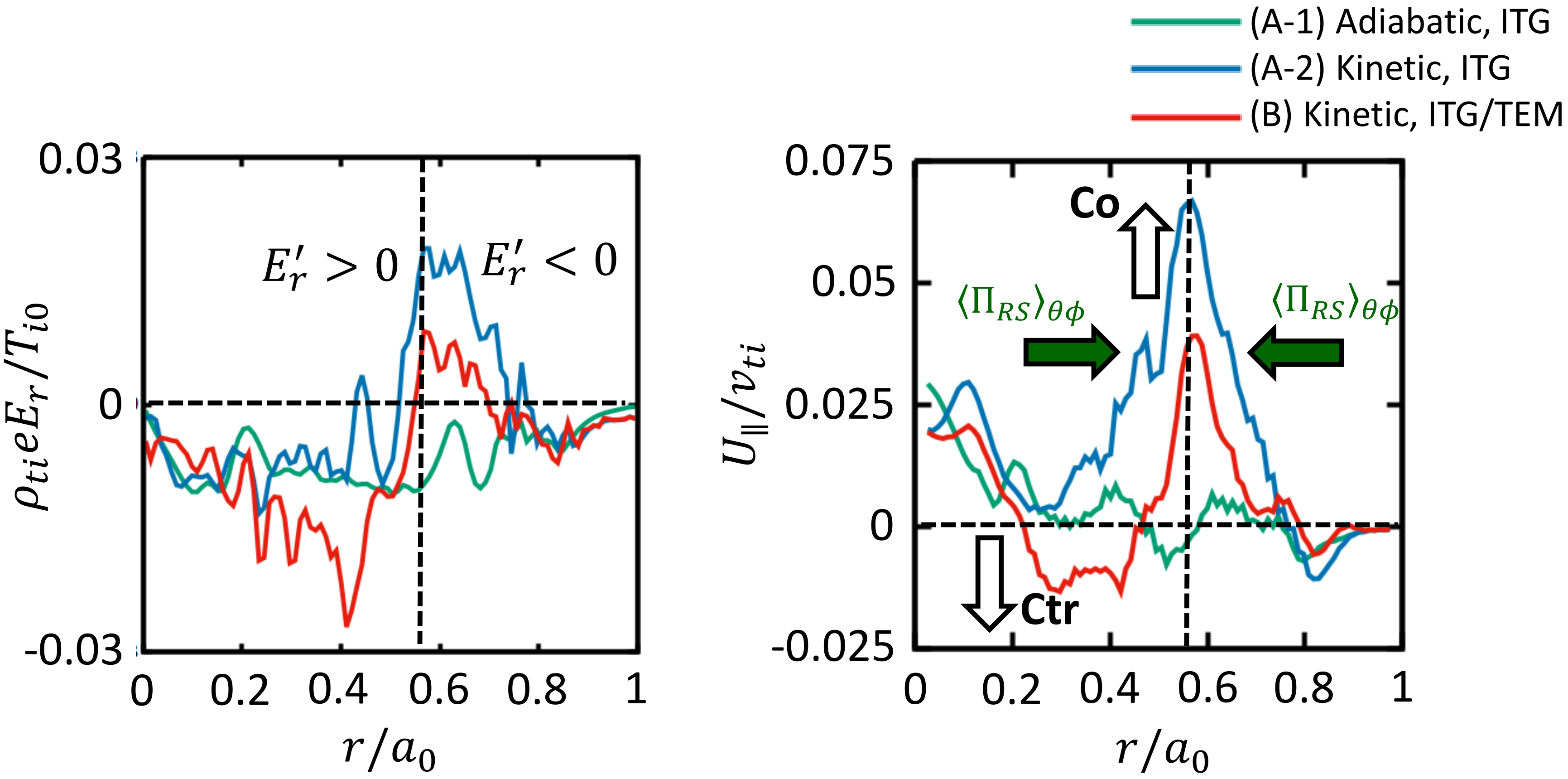
- ✓ We consider (A)ITG dominant and (B)ITG/TEM dominant cases.
- ✓ Safety factor profile is reversed, which local minimum is located at $r = 0.6a_0$.
- ✓ Only heat source is applied, which does not provide particle and momentum.

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.

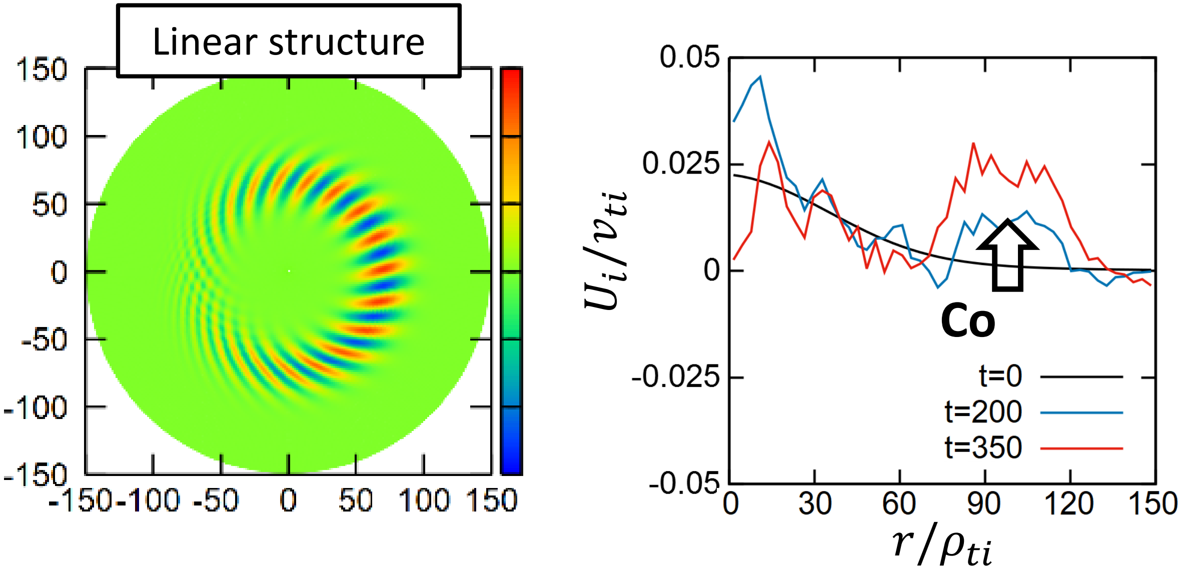
ITB Formation in Flux-driven ITG/TEM Turbulence - 3



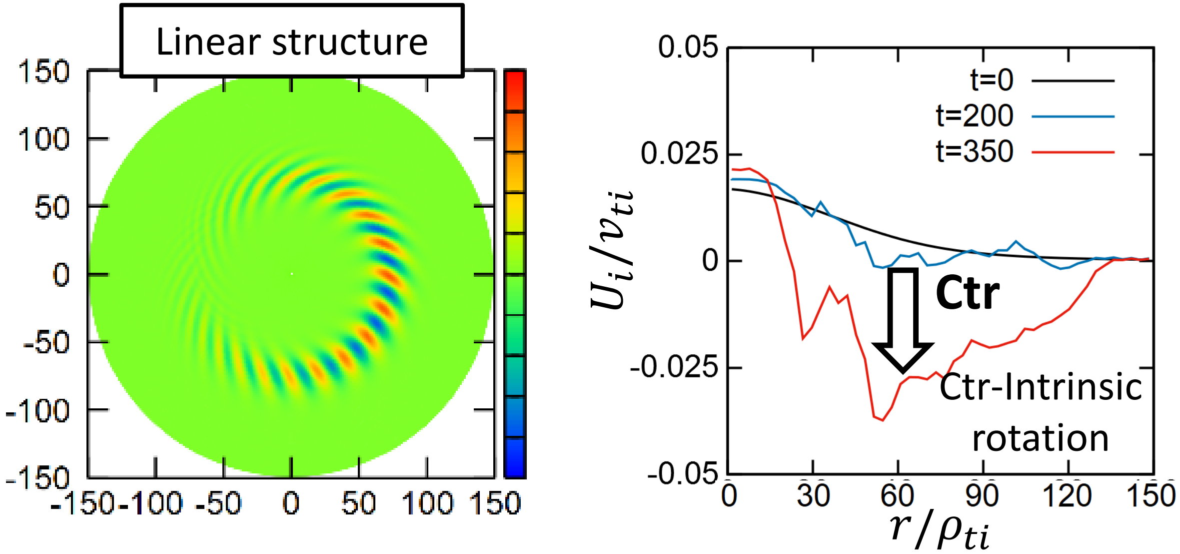
- ✓ Large co-rotation is driven around q_{min} surface in case (A-2) and (B).
- ✓ According to the momentum transport theory, $\langle \Pi_{RS} \rangle_{\theta\phi} = \alpha I E_r' + \beta I' + \gamma \langle k_\theta k_\phi \phi_k^2 \rangle_{\theta\phi}$ [Kwon, NF-2012], the first and second terms can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

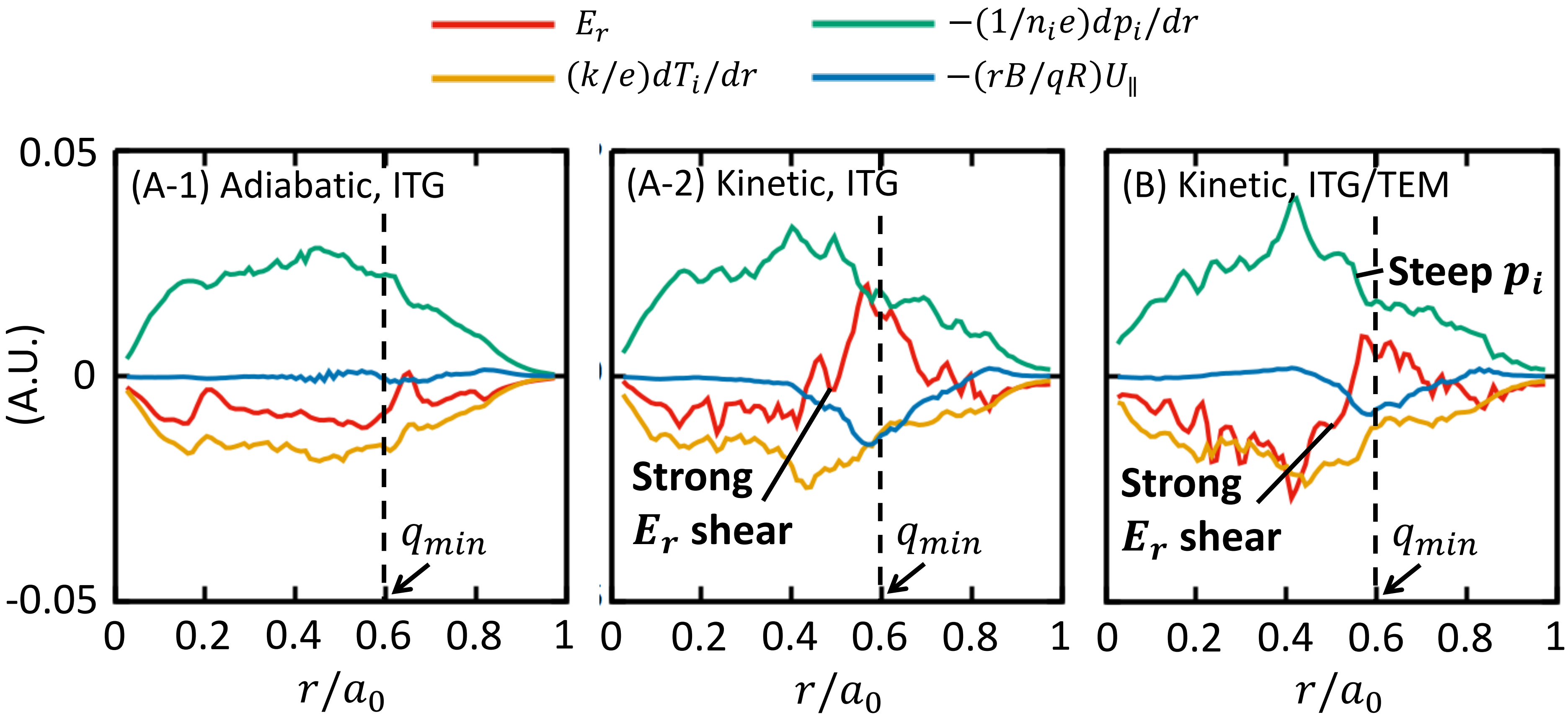


Decaying TEM turbulence in CBC case



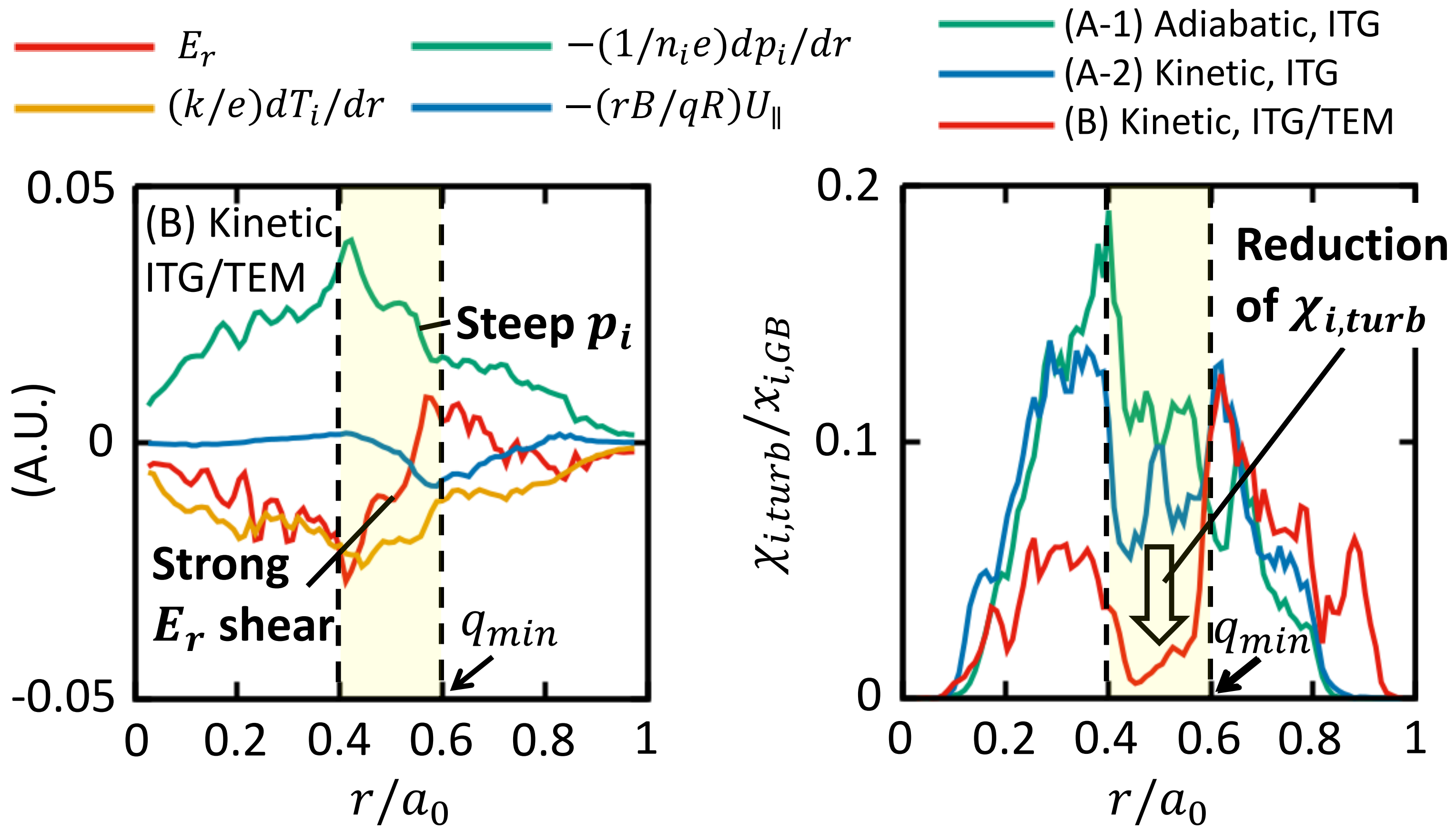
- ✓ The finite ballooning angle of the global mode structure arising from the profile shearing effect [Kishimoto, PPCF-1998] induces the residual stress part of momentum flux [Camenen, NF-2011].
- ✓ The sign of the ballooning angle between ITG and TEM turbulence is opposite (left figures) so that the 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

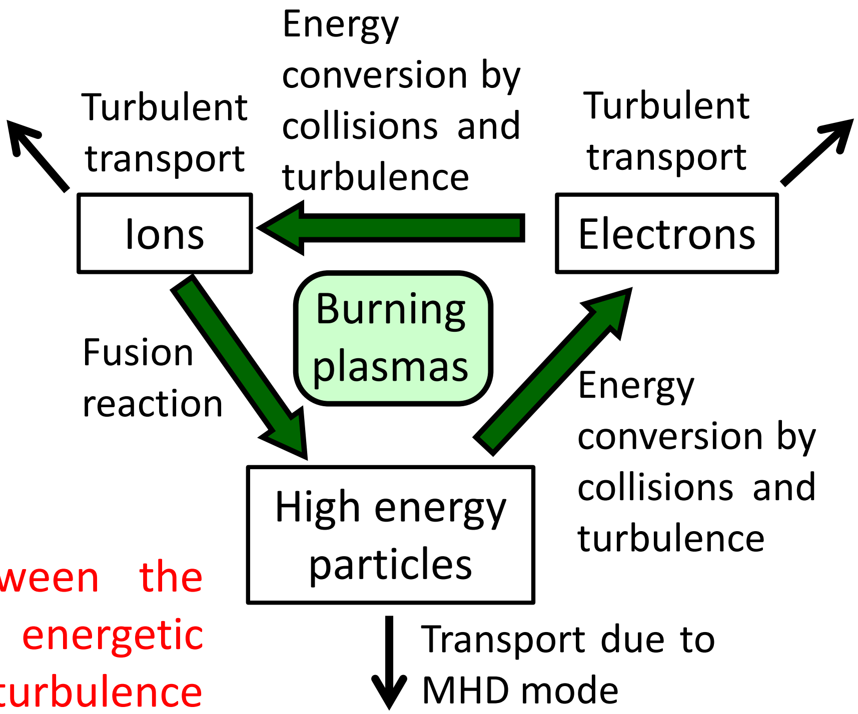


- ✓ As the result, ion turbulent thermal diffusivity in flux-driven ITG/TEM case spontaneously decreases to the neoclassical transport level among $0.4a_0 < r < 0.6a_0$, where E_r shear becomes steep.
- ✓ These results indicate that the co-existence of different modes can trigger the discontinuity near q_{min}, leading to the spontaneous ITB formation.

Contents

Background & Motivation

- ✓ In order to realize high performance burning plasmas, it is necessary to reduce both energetic alpha-particle transport and bulk plasma transport simultaneously.
- ✓ Drift-wave turbulence and MHD modes driven by energetic-particles coexist in burning plasmas, thereby the interaction between them is expected to take place and lead to new transport phenomena.
- ✓ We investigate nonlinear interactions between the toroidal Alfven eigenmode (TAE) driven by energetic particles and electromagnetic drift-wave turbulence (KBM) by using the global delta-*f* electromagnetic version of *GKENT*.



Turbulent transport

Energy conversion by collisions and turbulence

Turbulent transport

Ions

Electrons

Burning plasmas

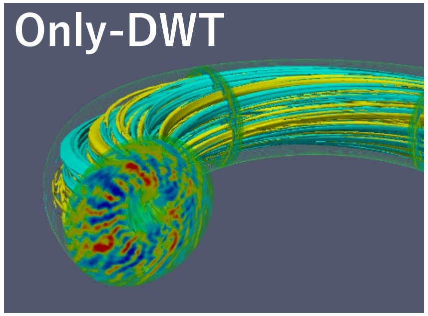
Fusion reaction

Energy conversion by collisions and turbulence

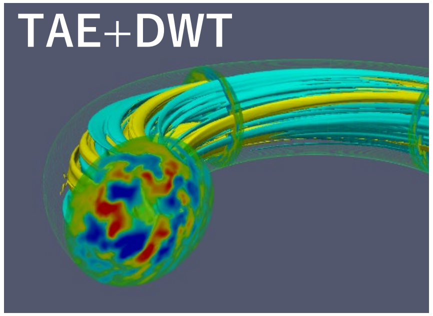
High energy particles

Transport due to MHD mode

<u>GKNET-KE-EM</u>
Toroidal
Electromagnetic
Kinetic Electron
global delta-*f*



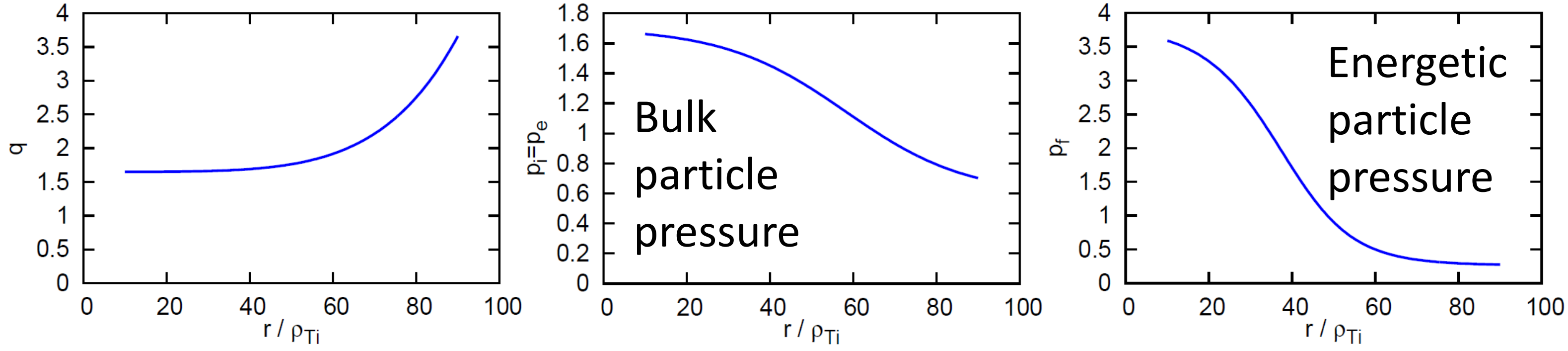
Only-DWT



TAE+DWT

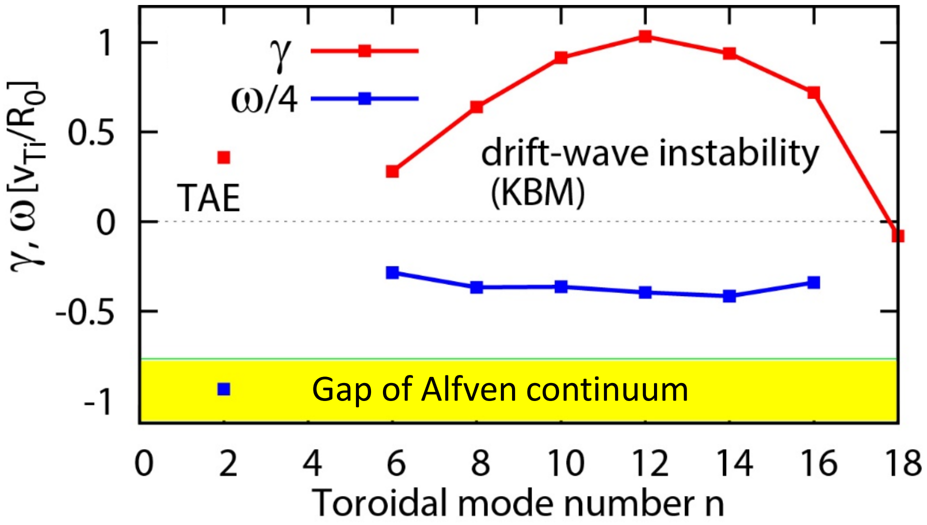
Simulation Set-up & Linear Analysis of TAE & KBM

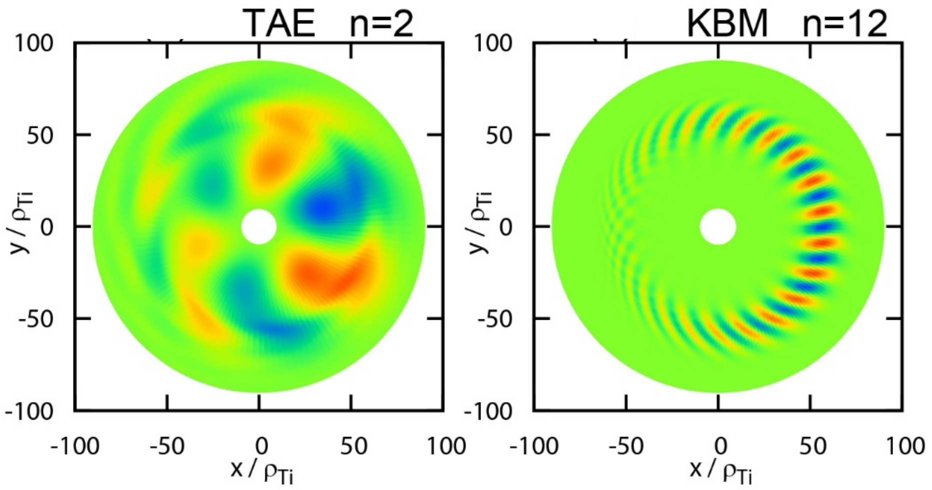
Simulation set-up



$$\beta = 1.28\%$$
$$\rho_* = 1/100$$
$$M_i/M_e = 100$$
$$T_f/T_i = 25$$
$$n_f/n_i = 0.025$$

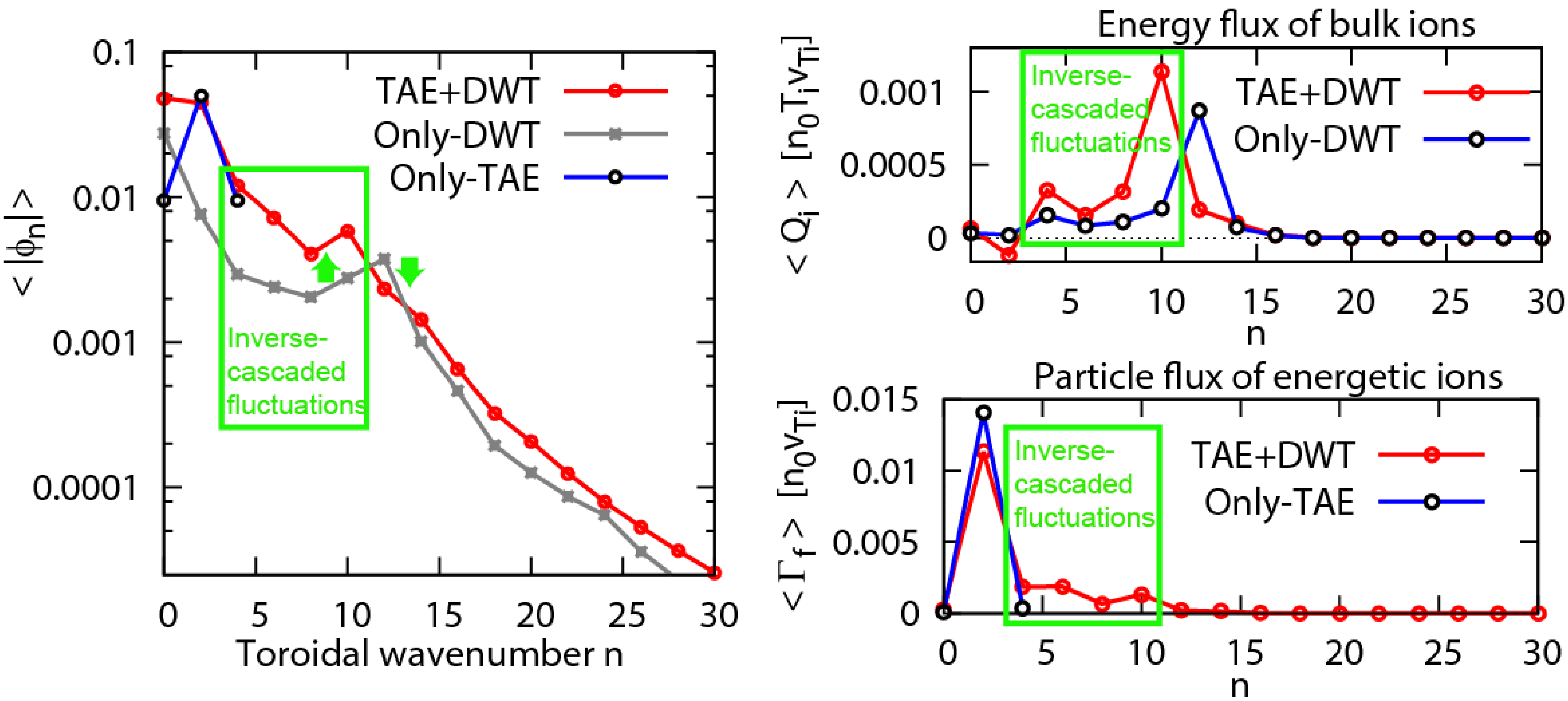
Linear dispersion relation & eigenfunctions





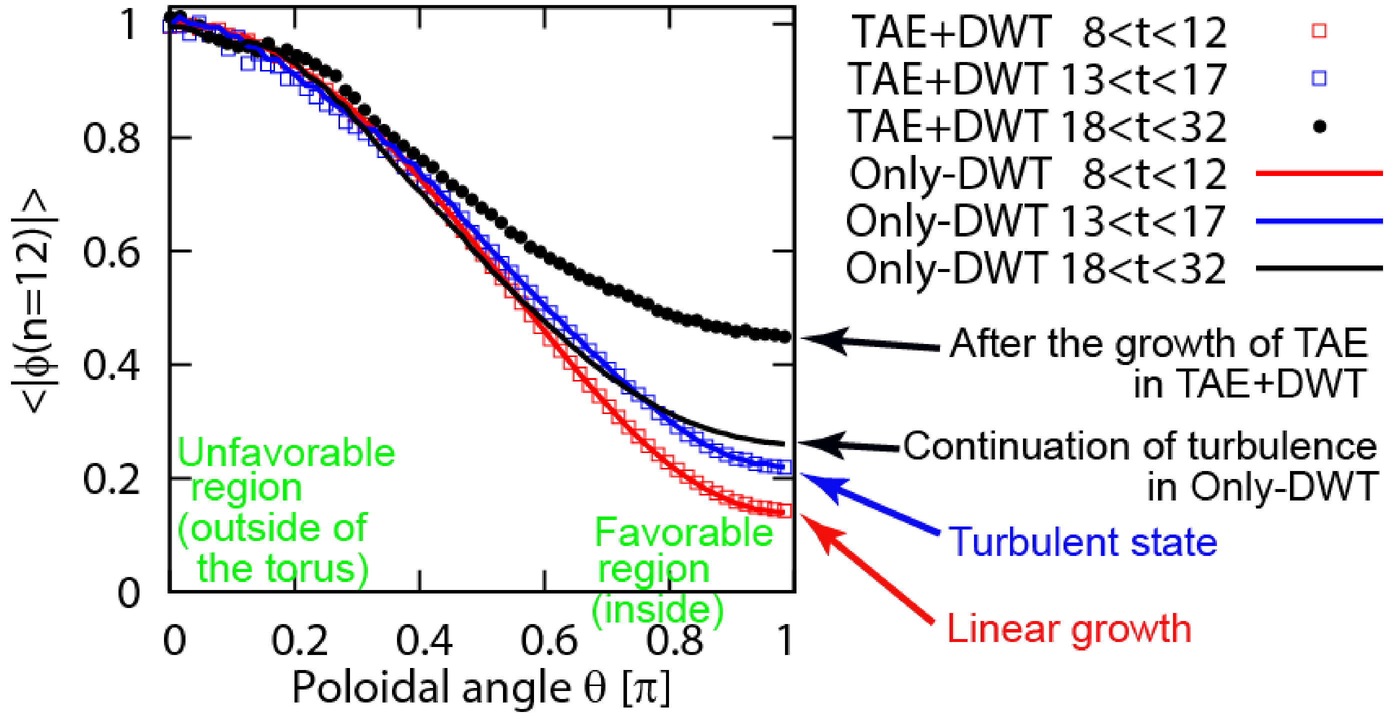
- ✓ The plasma is unstable against a TAE at low toroidal mode number $n = 2$ while kinetic ballooning mode (KBM) is unstable at high toroidal mode number $n > 6$.

Nonlinear Analysis of TAE & KBM -1



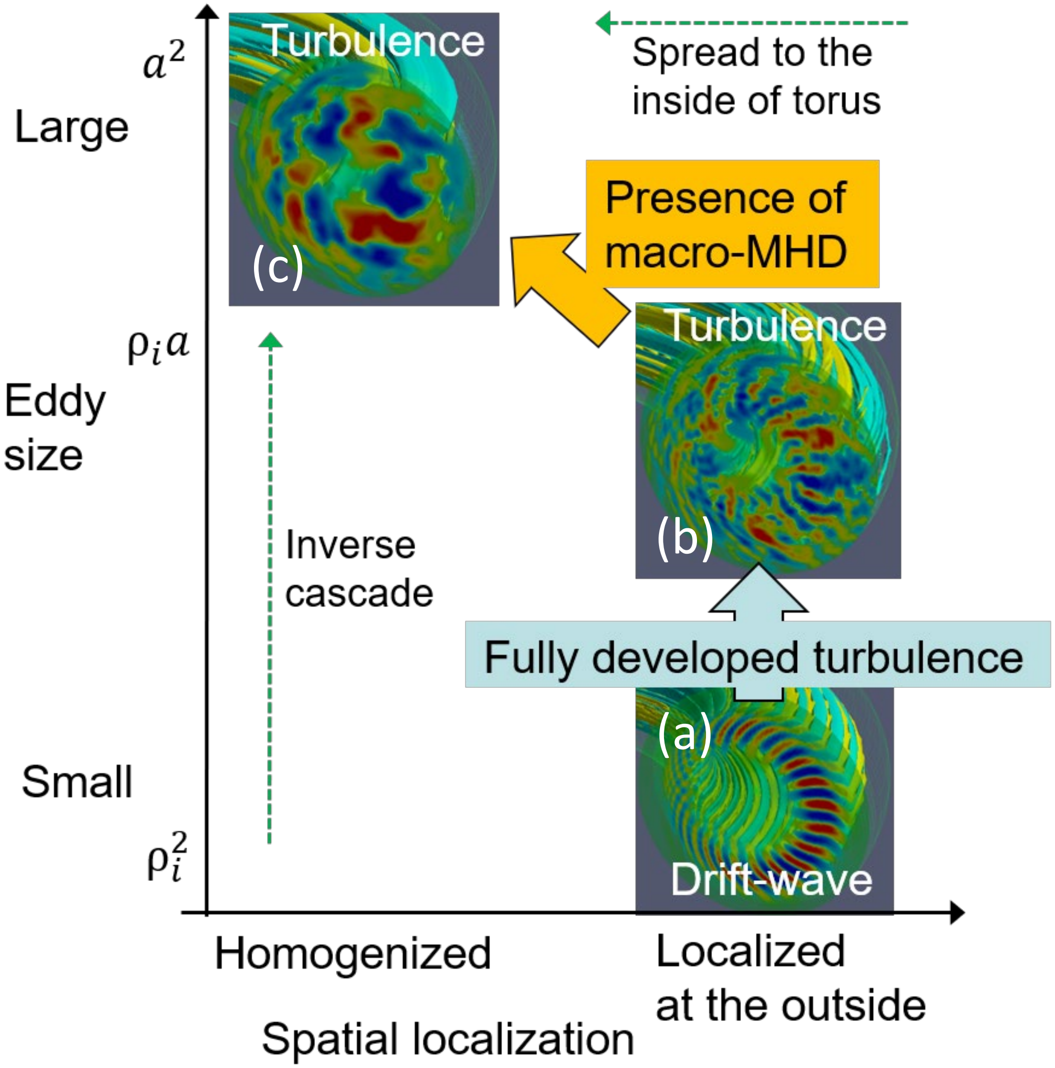
- ✓ TAE suppresses the most unstable drift-wave mode but enhances a smaller toroidal wavenumber mode, causing the inverse cascade.
- ✓ Due to the inverse-cascaded fluctuations, the energy flux of bulk ions Q_i in TAE+DWT is enhanced at middle wavenumbers ($4 < n < 10$).
- ✓ The interaction slightly suppresses the particle flux of energetic ions Γ_f at $n < 2$ but enhances Γ_f by the inverse-cascaded fluctuations.

Nonlinear Analysis of TAE & KBM -2



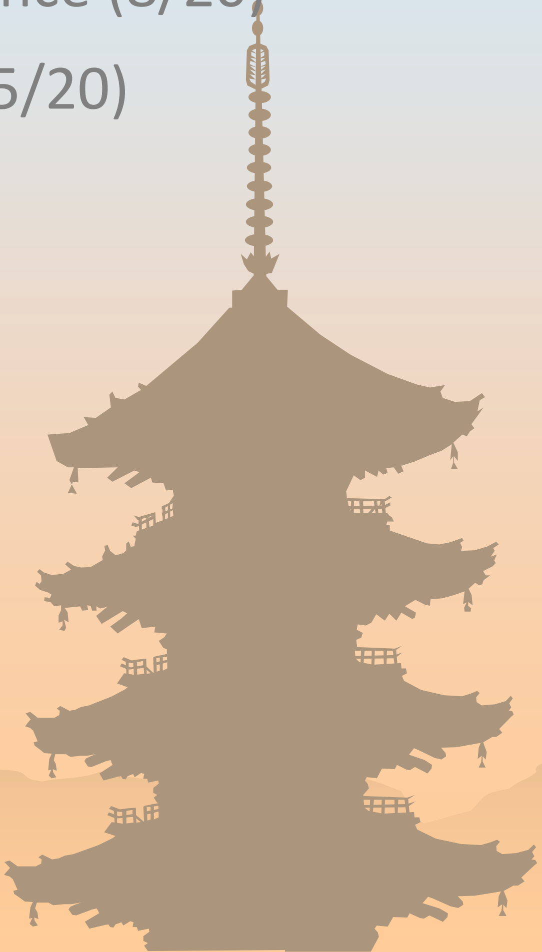
- ✓ Before the growth of the TAE, the drift-wave turbulence is poloidally localized in the unfavorable curvature region.
- ✓ Then, after the development of the TAE, the turbulence spreads to the favorable curvature region because of the global structure of the TAE, suppressing the most unstable drift-wave mode through the geometrical damping effect.

Nonlinear Analysis of TAE & KBM -3



- ✓ The drift-wave grows at the outside of the torus at the frame (a).
- ✓ Then becomes turbulence with the inverse cascade at the frame (b).
- ✓ The nonlinear mode coupling of turbulence with the macro-scale MHD instability, by contrast, transfers the energy to the homogenized and large-scale structure at the frame (c).

Contents



Summary & Future Plans - 1

Summary: Interaction between TAE and KBM turbulence

- ✓ We have performed the global electromagnetic simulation to study multi-scale nonlinear interactions between micro-scale drift-wave turbulence and the toroidal Alfven eigenmode, which is a macro-scale MHD instability driven by energetic particles.
- ✓ As a result of the interactions, the TAE transfers the energy of turbulence from high n modes to low n modes, causing the inverse cascade.
- ✓ The inverse-cascaded fluctuations enhance both the bulk ion energy transport and fast ion particle transport.
- ✓ Before the growth of the TAE, the drift-wave turbulence is poloidally localized in the unfavorable curvature region. Then, after the development of the TAE, the turbulence spreads to the favorable curvature region, suppressing the most unstable drift-wave mode through the geometrical damping effect.

Summary & Future Plans - 2

Summary: Spontaneous ITB formation in ITG/TEM turbulence

- ✓ 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.
- ✓ 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!

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.

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