2016.3.10-11
21st NEXT Workshop, Kyoto, Japan

Recent progress of toroidal full-*f* gyrokinetic simulation based on GKNET

Contents

K. Imadera, K. Obrejan, W. Wang, H. Liu
R. Yoshida, S. Maeda, J. Q. Li and Y. Kishimoto

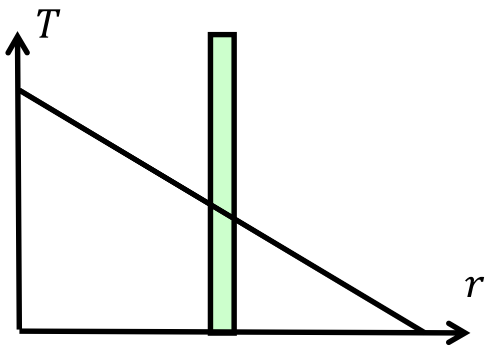
Graduate School of Energy Science, Kyoto University

Local/Global Gyrokinetics

Local approach

$$\cancel{\partial_t f_{eq}} - \cancel{[H, f_{eq}]} = \cancel{C(f_{eq})} + \cancel{S}$$

$$\partial_t \delta f - \underbrace{[H, \delta f]}_{\text{linear}} - \underbrace{[\delta H, f_{eq}]}_{\text{driving}} - \underbrace{[\delta H, \delta f]}_{\text{nonlinear}} = C(\delta f)$$



Fixed *Gradient*

$$R/L_T \neq 0$$
$$T = const$$

- ☺ Very powerful tool to estimate turbulent transport process
- ☺ Computationally efficient
  -> multi-species, EM turbulence

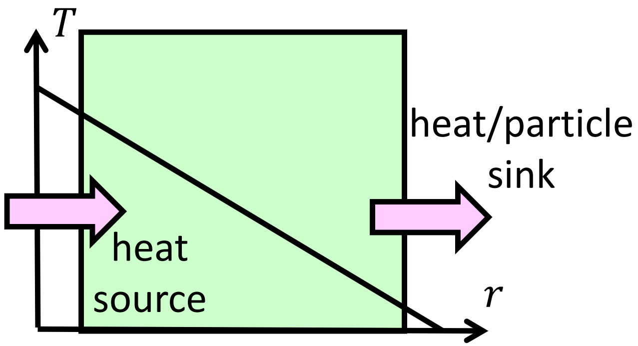
GKV(JPN), GS2(US), GENE(GER), …

Global approach

$$\partial_t f_{eq} - [H, f_{eq}] = C(f_{eq}) + S$$

self-consistently determined Mean E_r

$$\partial_t \delta f - \underbrace{[H, \delta f]}_{\text{linear}} - \underbrace{[\delta H, f_{eq}]}_{\text{driving}} - \underbrace{[\delta H, \delta f]}_{\text{nonlinear}} = C(\delta f)$$



Fixed *Flux*

$$R/L_T \neq 0$$
$$T \neq const$$

- ☺ Global profile shear effect can be taken into account (e.g. ω_r shear)
- ☺ Mean E_r is self-consistently determined
  -> ITBs, L-H transition…

GT5D, GKNET(JPN), XGC(US), GYSELA(FRA), …

Toroidal Full-*f* Gyrokinetic Code *GKNET*

GK Vlasov equation for ion

$$\frac{\partial f}{\partial t} + \frac{d\mathbf{R}}{dt}\cdot\frac{\partial f}{\partial \mathbf{R}} + \frac{dv_\parallel}{dt}\frac{\partial f}{\partial v_\parallel} = C_{coll}$$

$$\frac{d\mathbf{R}}{dt} \equiv \{\mathbf{R}, H\} = v_\parallel \mathbf{b} + \frac{c}{eB_\parallel^*}\mathbf{b}\times\left(e\nabla\langle\phi\rangle_\alpha + m_i v_\parallel^{*}\mathbf{b}\cdot\nabla\mathbf{b} + \mu\nabla B\right)$$

$$\frac{d\boldsymbol{v}_\parallel}{dt} \equiv \{v_\parallel, H\} = -\frac{\mathbf{B}_\parallel^*}{m_i B_\parallel^*}\cdot\left(e\nabla\langle\phi\rangle_\alpha + \mu\nabla B\right)$$

Vlasov solver

✓ 4th-order Morinishi scheme + 4th-order RK-Gill scheme

[K. Imadera, *et.al*. 25th Fusion Energy Conference, TH/P5-8, Oct. 16, 2014.]
[K. Obrejan, K. Imadera, J. Q. Li and Y. Kishimoto Plasma Fusion Res. **10**, 3403042 (2015).]

✓ Full-*f* (Global)

✓ Electrostatic

✓ Conservative

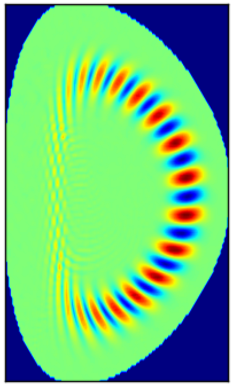
GK quasi-neutrality condition

$$\phi - \ll \phi \gg_\alpha + \frac{1}{T_{e0}(r)}\left(\phi - <\phi>_\alpha\right) = \frac{1}{n_{i0}(r)}\iint <\delta f>_\alpha B_\parallel^* dv_\parallel d\mu$$

Real space field solver

✓ Full-order FLR effect (without Tayler/Pade approximation)

✓ Field equation is solved in real space (not k-space)



Recent Progress Based on GKNET

Study of flux-driven ITG turbulence

(A-1) Flux-driven turbulent transport couple with mean flow

[Y. Kishimoto, *et al.*, submitted to IAEA-2016]
[W. Wang, *et al.*, this workshop]

- ✓ Global profile shear effect of ω_r and ω_f on ballooning structure
- ✓ Intermittent turbulent transport coupled with radially extended ballooning structure

(A-2) ITB formation in flux-driven turbulence

[K. Imadera, *et al.*, submitted to ICPP-2016 & IAEA-2016]
[S. Maeda, *et al.*, this workshop]

- ✓ ITB formation by toroidal momentum injection
- ✓ Momentum pinch originated from global profile shear effect of ω_r and ω_f

Development of GKNET

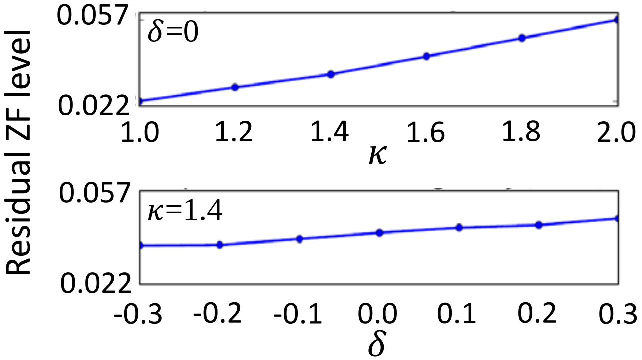
(B-1) Development of real space field solver

[K. Obrejan, *et al.*, this workshop]

Elongation ↗ or triangularity ↗

⬇

Residual zonal flow level ↗



(B-2) Introduction of kinetic electron

[R. Yoshida, *et al.*, this workshop]

Kinetic electron ➡ slab ITG instability ↘

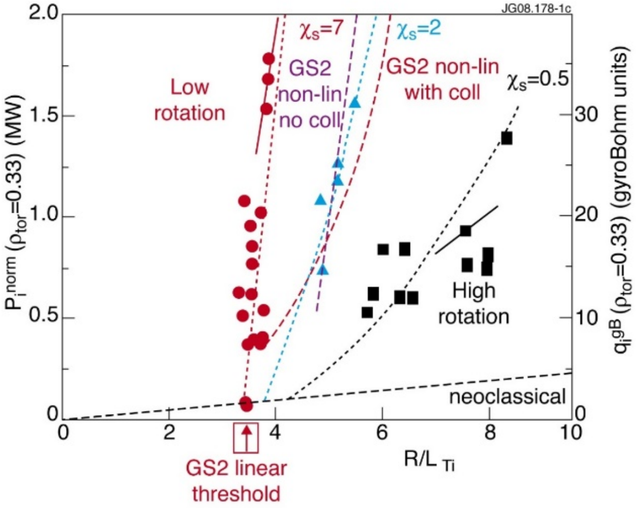
phase shift
between ϕ and δn_e

Kinetic electron ➡ GAM damping rate ↗
residual ZF level →

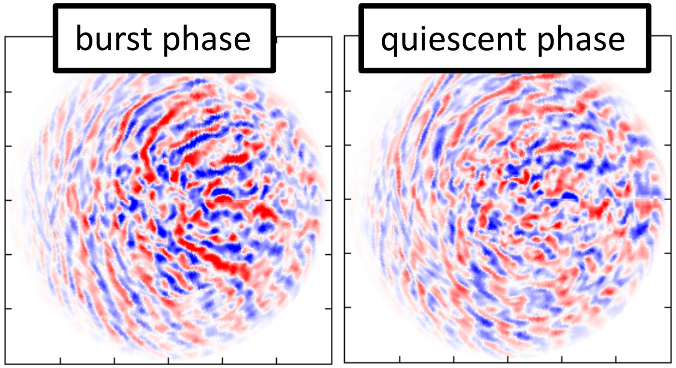
Background - Profile Stiffness in Flux-driven System -

- ✓ Profile stiffness is a long standing problem, which may limit the overall performance of H-mode plasmas.
- ✓ In the JET experiment, while strong temperature profile stiffness is observed, it can be greatly reduced by co-current toroidal rotation in weak magnetic shear plasma.
- ✓ In our flux-driven ITG simulation, we also observe a stiff temperature profile in the absence of momentum source, where not only heat avalanches but also the explosive global transport coupled with the instantaneous formation of radially extended ballooning structure become dominant.

[P. Mantica, *et.al.*, Phys. Rev. Lett., **102**, 175002 (2009).]



[K. Imadera, *et.al.*, 25th Fusion Energy Conference, TH/P5-8, Oct. 16 (2014).]



A) Why radially extended structure is formed even in the presence of MF and ZF?

B) What is the stabilization mechanism by co-current toroidal rotation?

Purpose of This Work

Purpose of this work

A) Understand the origin of radially extended ballooning structure in flux-driven ITG turbulence with MF and ZF -> **profile stiffness**

B) Control such structures by momentum injection -> **barrier formation**

Approaches

1. Non-local first-order ballooning theory
   - ✓ Notation of θ_b, Δr and γ
   - ✓ Impact of MF and toroidal rotation on toroidal ITG mode

2. Global GK ITG simulation w/o mom. source
   - ✓ Impact of MF on profile stiffness

3. Global GK ITG simulation with mom. source
   - ✓ Impact of momentum injection on profile stiffness

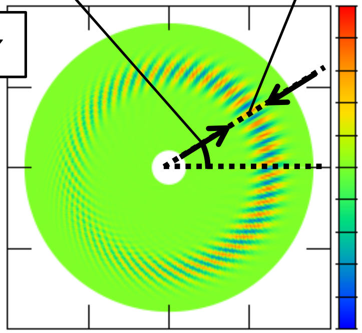


Fig. Ballooning structure of linear toroidal ITG mode

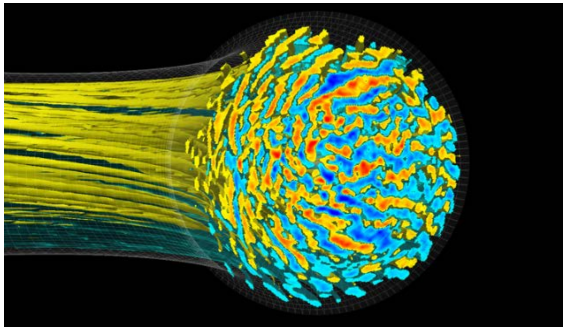


Fig. Typical structure of flux-driven toroidal ITG turbulence calculated by *GKNET*

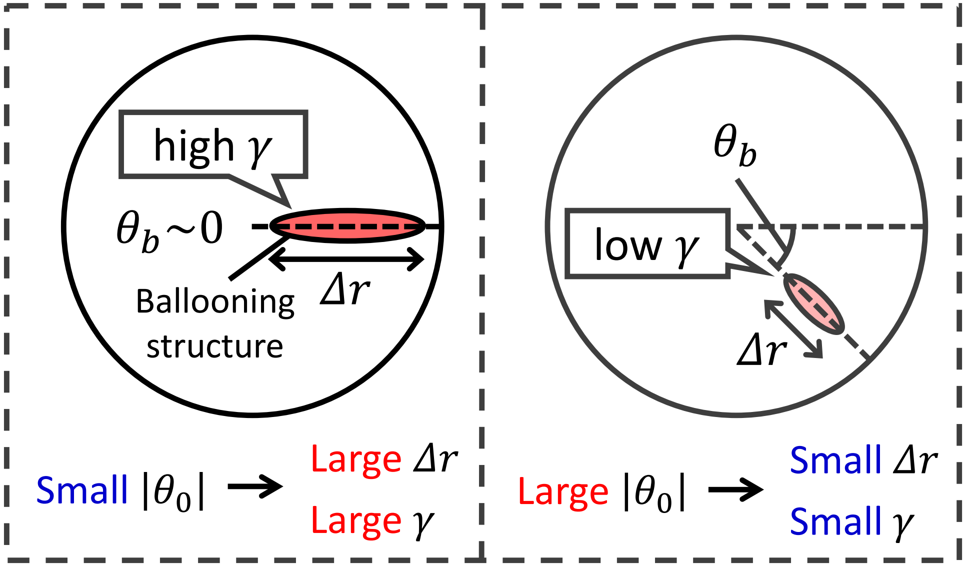
Non-Local Ballooning Theory

[Y. Kishimoto, *et.al.*, Plasmas Phys. Controlled Fusion, **40**, A663 (1998).]

$$\theta_b = \mp \left| \frac{\partial_r(\omega_r + \omega_f)}{2k_\theta \gamma_0 \hat{s}} \right|^{1/3}$$

$$\Delta r = \left| \frac{sin\theta_b}{k_\theta^2 \hat{s}^2 \theta_b^3} \right|^{1/2}$$

$$\gamma = \gamma_0 cos\theta_b$$



Small $|\theta_0|$ → Large Δr, Large γ

Large $|\theta_0|$ → Small Δr, Small γ

Radial force balance

$$E_r - v_\theta B_\varphi + v_\varphi B_\theta - \frac{1}{n_i e}\frac{\partial p_i}{\partial r} = 0 \longrightarrow E_r = \frac{rB}{qR}U_\parallel - \frac{T_i}{e}\left(\frac{1}{L_n} + \frac{1-k}{L_{T_i}}\right)$$

$$\uparrow$$

$$n_i = n_{i0}\exp\left(-\frac{r}{L_n}\right), T_i = T_{i0}\exp\left(-\frac{r}{L_{T_i}}\right)$$

Eigenfrequency + Doppler shift frequency

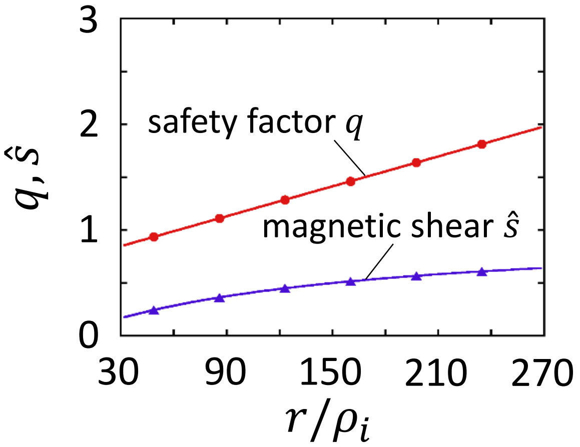
$$\boxed{\omega_r + \omega_f \sim \frac{k_\theta}{eB}\left[\left(\underline{\frac{2}{R_0}} \underline{- \frac{1}{L_n} - \frac{1-k}{L_{T_i}}}\right)T_i \underline{- \frac{erB}{qR}U_\parallel}\right]}$$

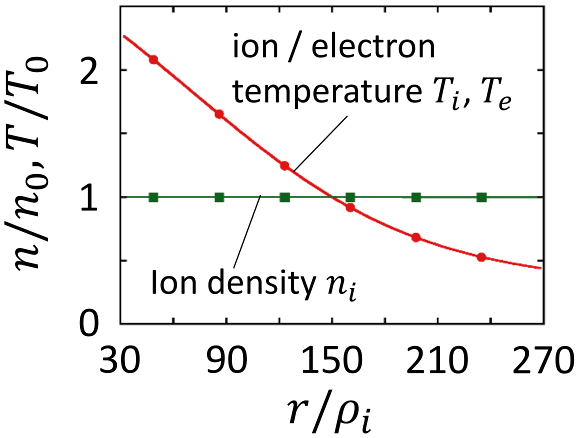
Diamagnetic drift *Mean flow* *Toroidal rotation*

- ✓ Cancellation by mean flow
- ✓ Impact of toroidal rotation

Linear Global GK ITG Simulation

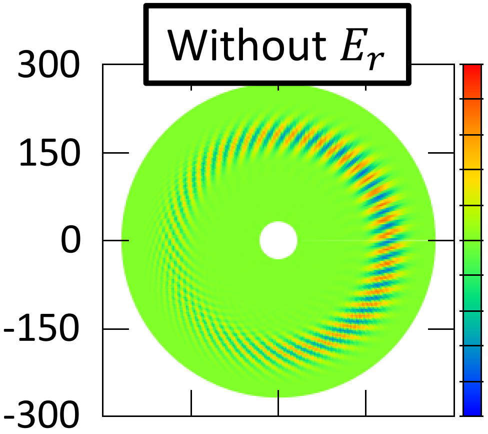
Simulation condition

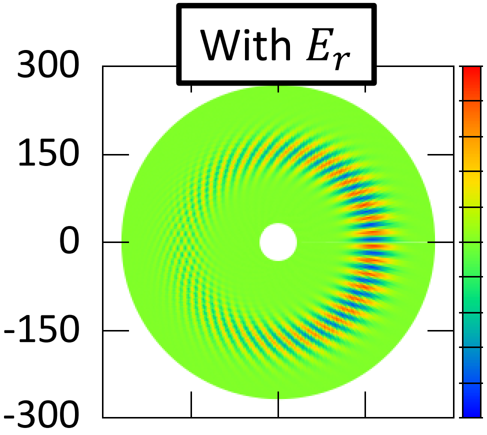


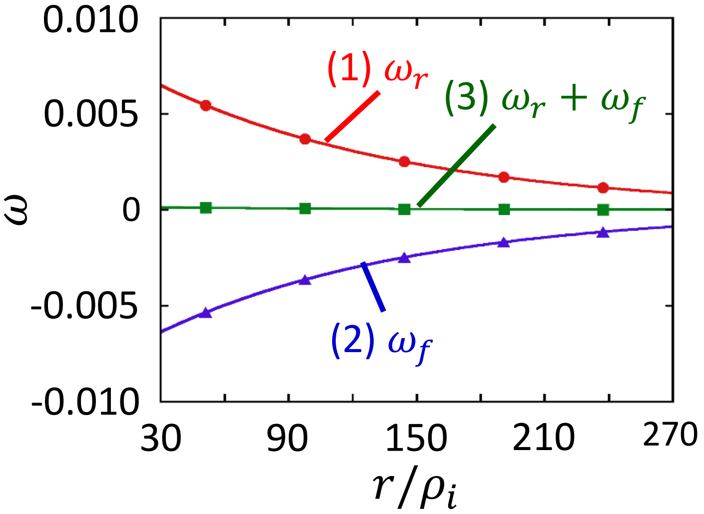


Parameter	Value
a_0/ρ_i	300
a_0/R_0	0.36
$(R_0/L_n)_{r=a_0/2}$	0
$\left(R_0/L_{T\,i}\right)_{r=a_0/2}$	6.92

Numerical results







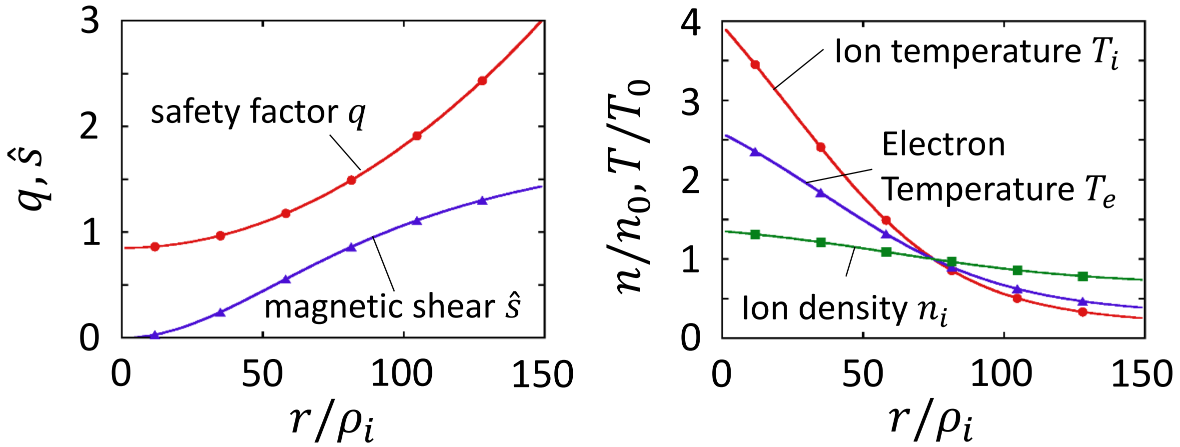
γ	0.07〜0.12
θ_b	0.5〜0.6
Δr	28〜42

γ	0.15
θ_b	0
Δr	49

$$\theta_b = \mp \left| \frac{\partial_r(\omega_r + \omega_f)}{2 k_\theta \gamma_0 \hat{s}} \right|^{1/3}$$

Nonlinear Flux-Driven GK ITG Simulation

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
$(R_0/L_{Ti})_{r=a_0/2}$	10.0
$(R_0/L_{Te})_{r=a_0/2}$	6.92
ν_*	0.28
P_{in}	4, 8, 16, 24 [MW]

Source operator

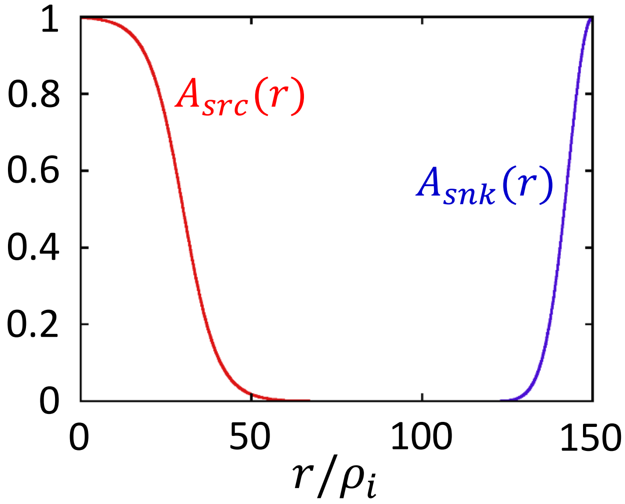
$$S_{src} = A_{src}(r)\tau_{src}^{-1}[f_M(2\bar{T}) - f_M(\bar{T})]$$

✓ Constant power input near magnetic axis

Sink operator

$$S_{snk} = A_{snk}(r)\tau_{snk}^{-1}[f(t) - f(t=0)]$$

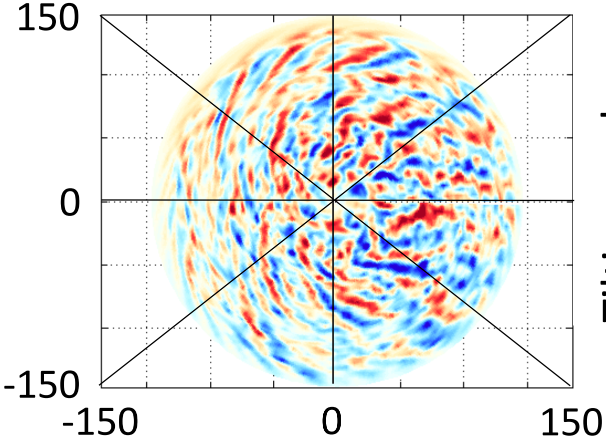
✓ Krook-type operator to f in boundary region

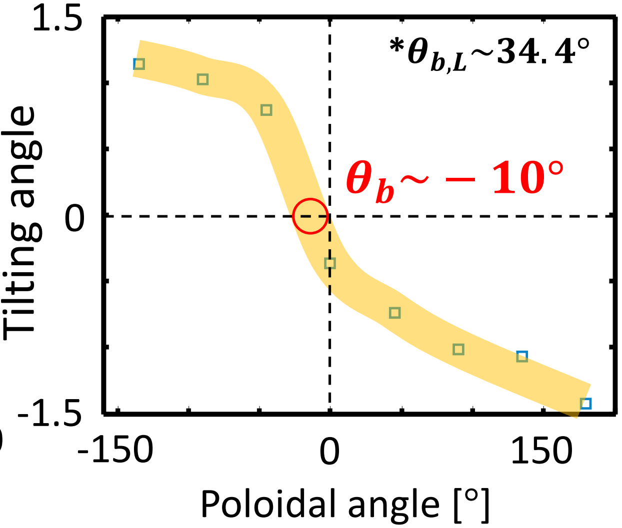


[Y. Idomura, *et. al.*, Nucl. Fusion, **49**, 065029 (2009).]

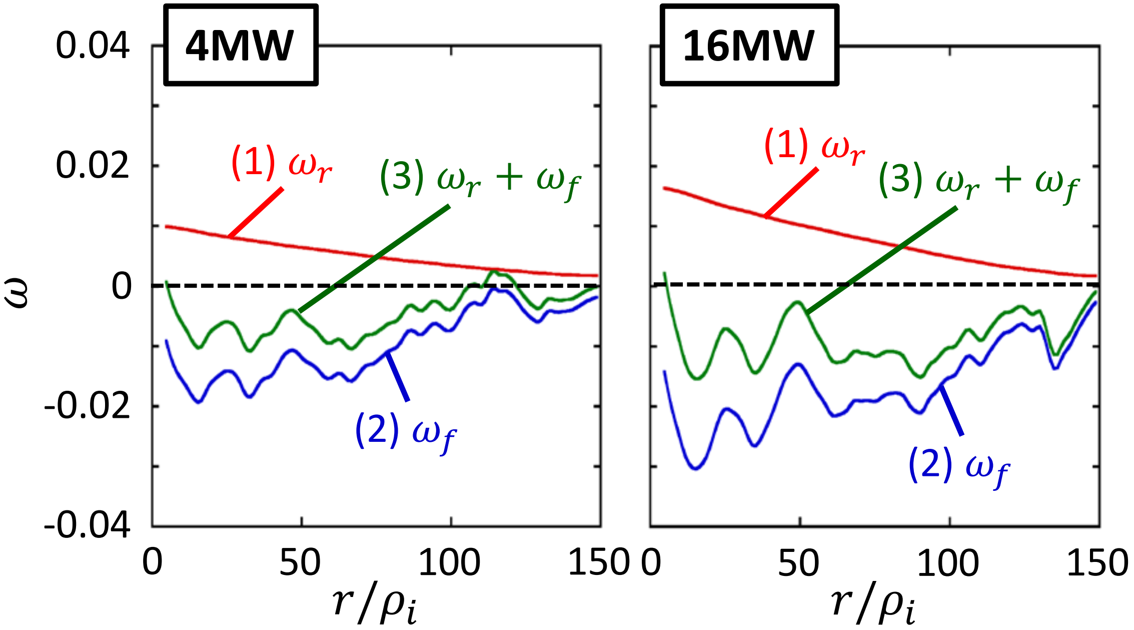
Poloidal Symmetry and Profile Stiffness

2D spatial correlation analysis for potential structure (16MW)

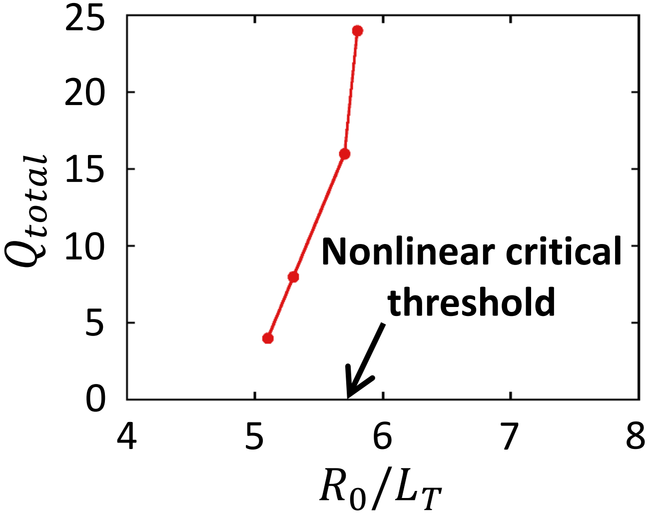




- ✓ Ballooning angle is smaller than that estimated from linear analysis without E_r.



Gradient-Flux relation in power scan test



Discussion - How we can break profile stiffness ? -

Radial force balance: $E_r + \frac{k}{e}\frac{\partial T_i}{\partial r} - \frac{rB}{qR}U_\parallel - \frac{1}{n_i e}\frac{\partial p_i}{\partial r} = 0$

✓ Mean flow shear recovers the symmetry or weakly reverses the ballooning angle so that its stabilization effect is small.

⬇

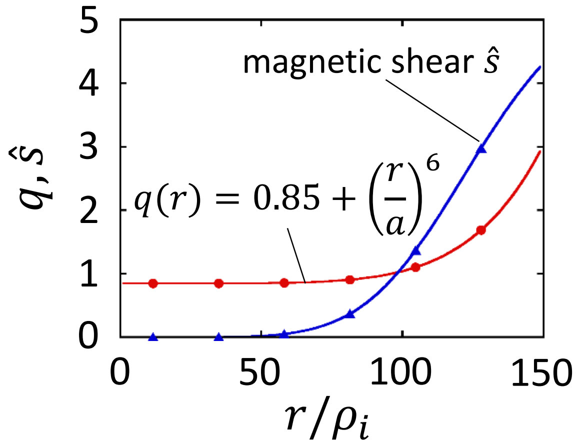
✓ Toroidal rotation can change the mean flow shear through radial force balance, by which we may enhance its stabilization effect.

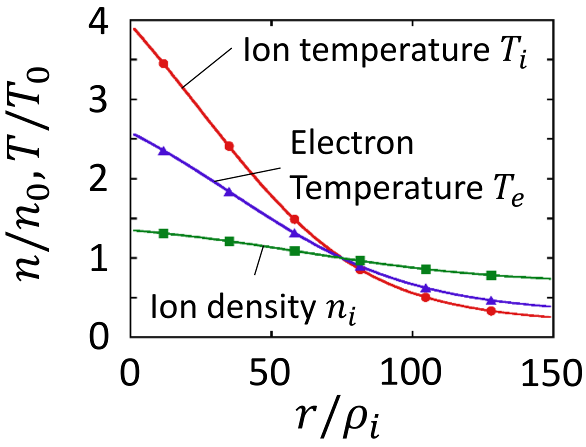
⬇

✓ Especially, toroidal rotation in outer region with small safety factor (weak/reversed magnetic shear) can be effective.

Flux-Driven ITG Simulation with Momentum Source

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
$(R_0/L_{T\,i})_{r=a_0/2}$	10.0
$(R_0/L_{T\,e})_{r=a_0/2}$	6.92
ν_*	0.28
P_{in}	4 [MW]
T_{in}	11.2 [N・m]

Momentum source operator

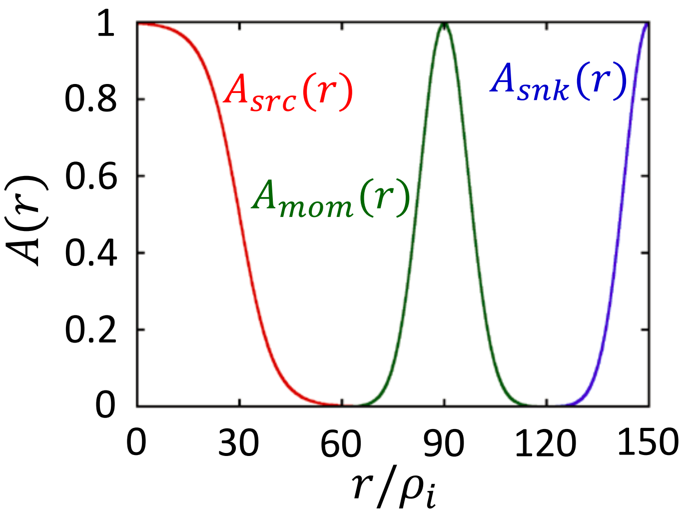
$$S_M = \tau_M^{-1} A(r)[f_{LM}(n_0, 0.5v_{ti}, T_0) - f_{LM}(n_0, 0, T_0)]$$

$$f_{LM}(n, U_{||}, T) = \frac{n}{\sqrt{2\pi T^3/m_i^3}} exp\left[-\frac{0.5(v_\parallel - U_\parallel)^2 + \mu B}{T/m_i}\right]$$

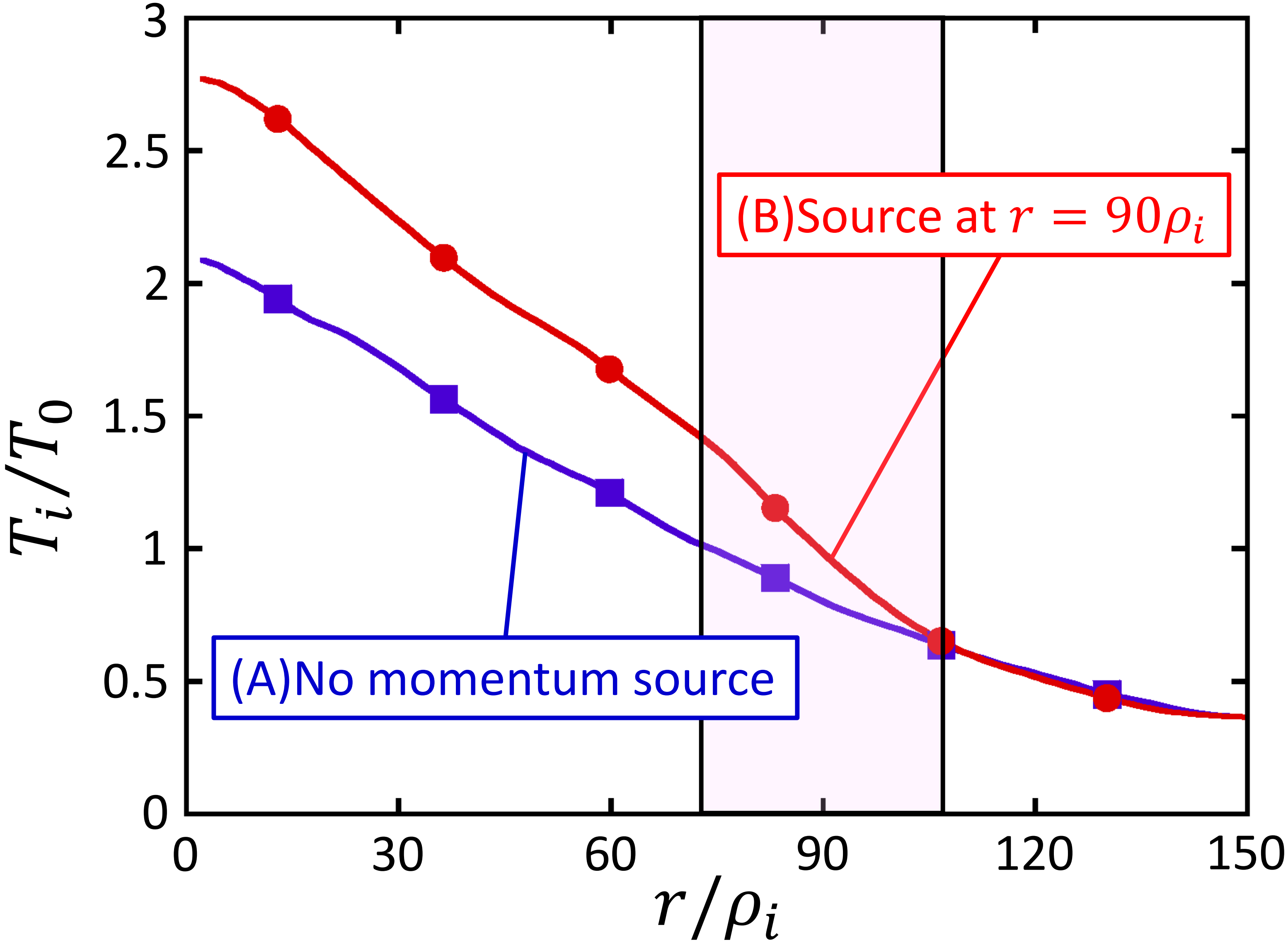
✓ We compare two cases;

(A) without momentum source

(B) with momentum source at $r = 90\rho_i$



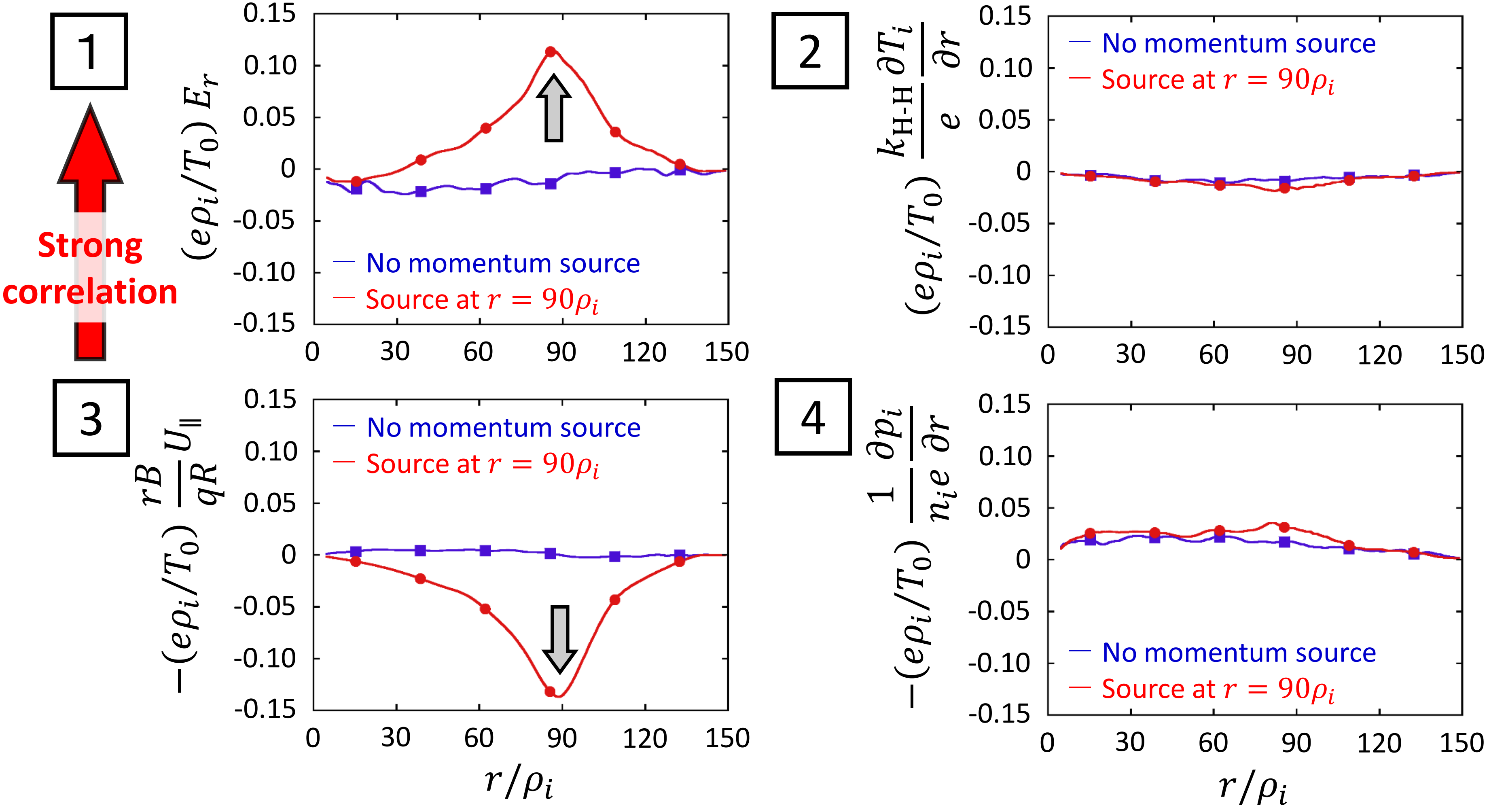
Impact of Momentum Source - 1



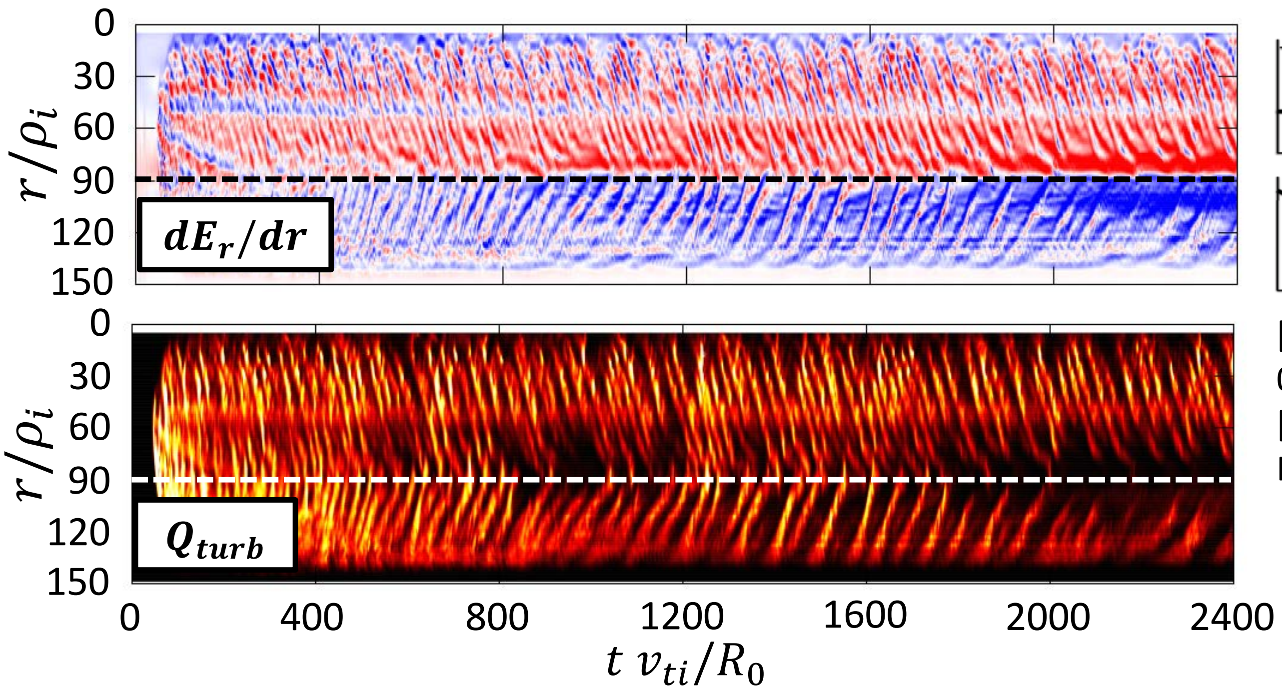
- ✓ Strong impact of momentum source at outer region on temperature build up.

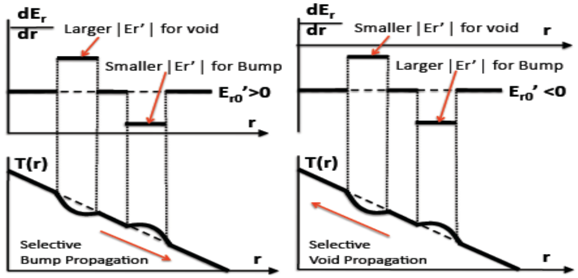
Impact of Momentum Source - 2

Radial force balance: $\overset{\boxed{1}}{E_r} + \overset{\boxed{2}}{\frac{k}{e}\frac{\partial T_i}{\partial r}} - \overset{\boxed{3}}{\frac{rB}{qR}U_\parallel} - \overset{\boxed{4}}{\frac{1}{n_i e}\frac{\partial p_i}{\partial r}} = 0$



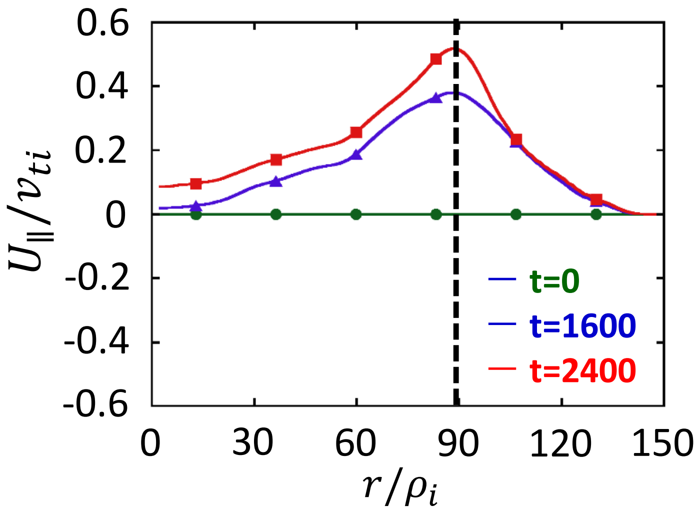
Impact of Momentum Source - 3

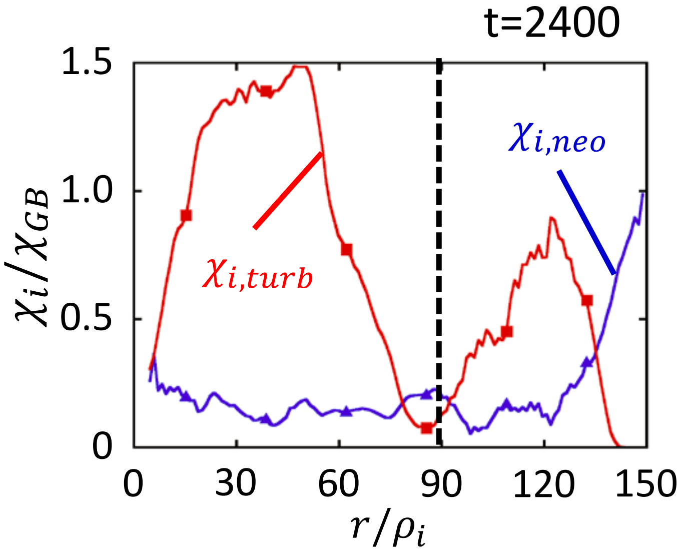




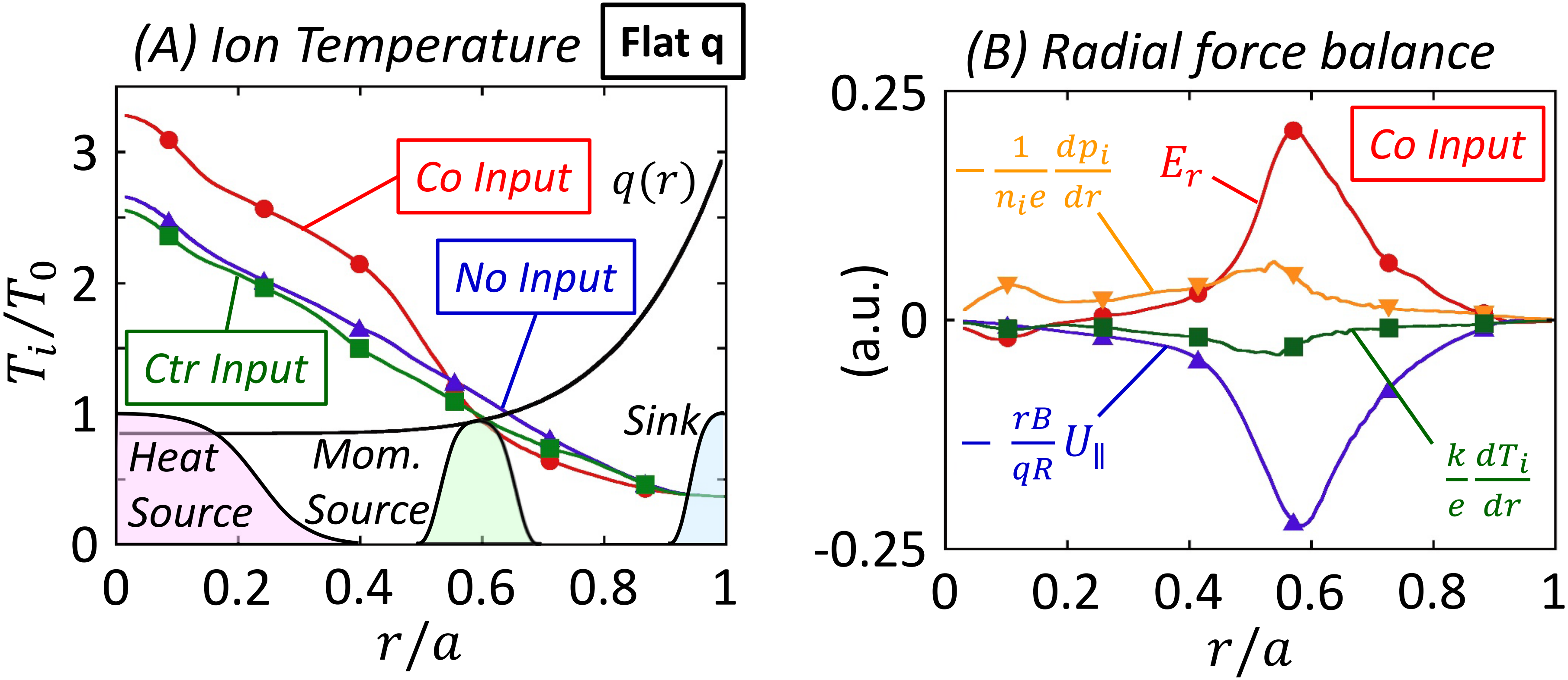
[Y. Idomura, *et al*. Nucl. Fusion, **49,** 065029 (2009).]
[M. Kikuchi and M. Azumi, Rev. Mod. Phys. **84**, 1807 (2012).]

✓ Strong E_r shear triggered by toroidal rotation in outer region suppresses the turbulence, leading to a transport barrier formation.





Effect of Rotation Direction



✓ Only co-current toroidal rotation can benefit the ITB formation in weak magnetic shear plasma.

→ qualitative agreement with the observations in the JET experiment

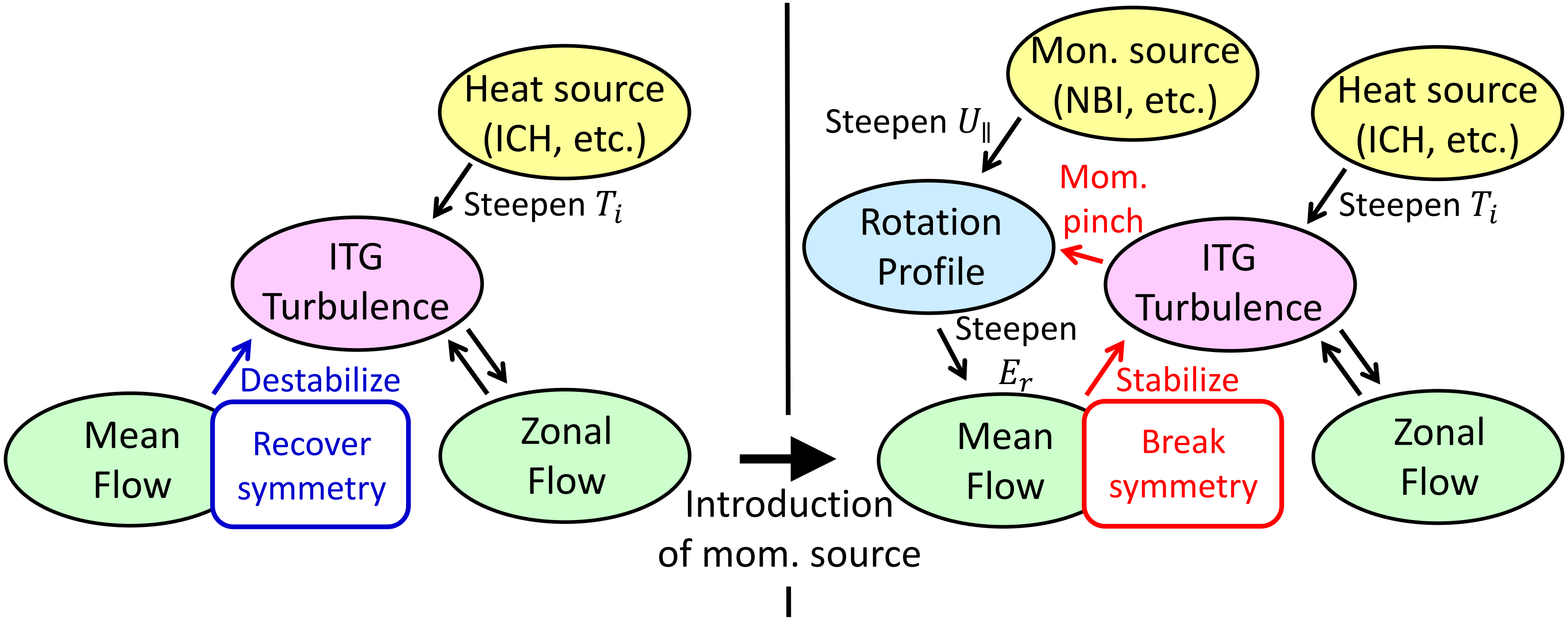
Summary

Summary

✓ We have newly developed 5D toroidal full-*f* gyrokinetic code *GKNET*.

✓ We found that a momentum source can change the mean E_r through the radial force balance, leading to ITB formation.

✓ The underlying mechanism is identified to originate from a positive feedback loop between the enhanced mean E_r shear and resultant momentum pinch, which can be observed only in co-input case.



Future Plans

Future Plans

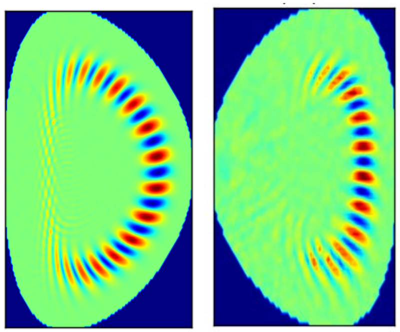


Fig. Poloidal structure of global toroidal ITG mode in positive (left) and negative (right) D shape.

Flux-driven turbulent transport couple with mean flow

ITB formation in flux-driven ITG turbulence

(Yoshida)

Introduction of kinetic electron

(Kevin)

Magnetic shaping effect on ZF/GAM dynamics

ITB formation in flux-driven ITG/TEM turbulence

- ✓ Opposite ballooning angle
- ✓ Density transport
- ✓ Momentum transport

Magnetic shaping effect on ITG/TEM instability

- ✓ Impact of elongation and triangularity on ITG/TEM turbulence

Control of barrier formation by multi-sources and magnetic shape