IFERC-CSC Workshop on JFRS-1 Projects
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Turbulent particle pinch in flux-driven ITG/TEM turbulence

Contents

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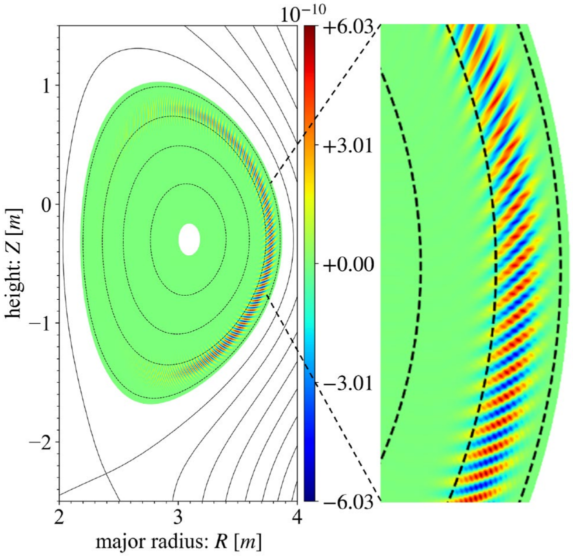
Digest of GGHB Project (2022)

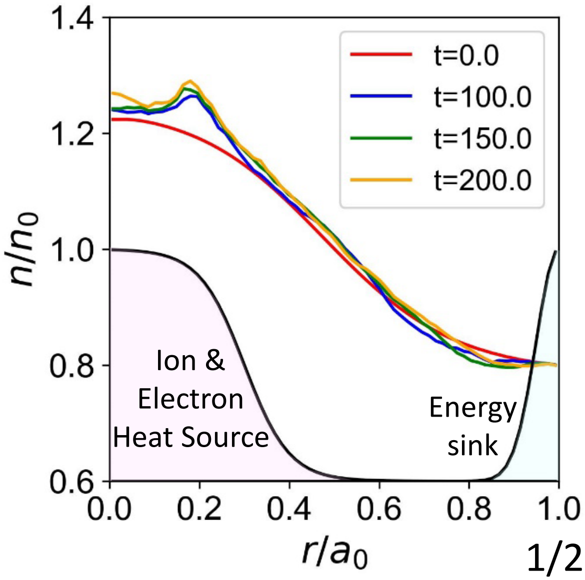
(A) Development of global GK code with field aligned coordinates [Okuda+, accepted to PFR]

- ✓ We have introduced the Field-Aligned Coordinates (FAC) with a shifted metric to our global gyrokinetic code GKNET and drastically reduced the computational cost.
- ✓ We have also implemented numerical magnetic equilibria and performed linear/nonlinear global δf simulation for the JT-60SA ITER-like plasma (Upper right).



(B) Turbulent particle pinch in flux-driven ITG/TEM turbulence [Imadera+, submitted to FAC-2023]

- ✓ By means of GKNET with the hybrid electron model, we have investigated flux-driven ITG/TEM turbulence.
- ✓ We have found that turbulence directly/indirectly drives ion particle pinch under ion/electron heating, leading to the synergetic density peaking of bulk ions (Bottom right).



Development of global GK code with FAC

For tokamak core/edge turbulence global simulations, we have developed GKNET-FAC, which includes the following two advances :

A : Field-aligned coordinate system (FAC)

- Significantly reduce the computational cost.
- A shifted metric technique [B.Scott, PoP-2001] is used to correct a cell deformation. (not included in this report)

B : Connection with a 2D equilibrium code

- Allow for simulations with realistic tokamak equilibria.

C : We have applied to a nonlinear simulation of ITG instability in a JT-60SA plasma [S.Okuda, PFR-2023].

A : Field-aligned coordinates - 1

Field-aligned coordinates

[Beer+, PoP−1995]

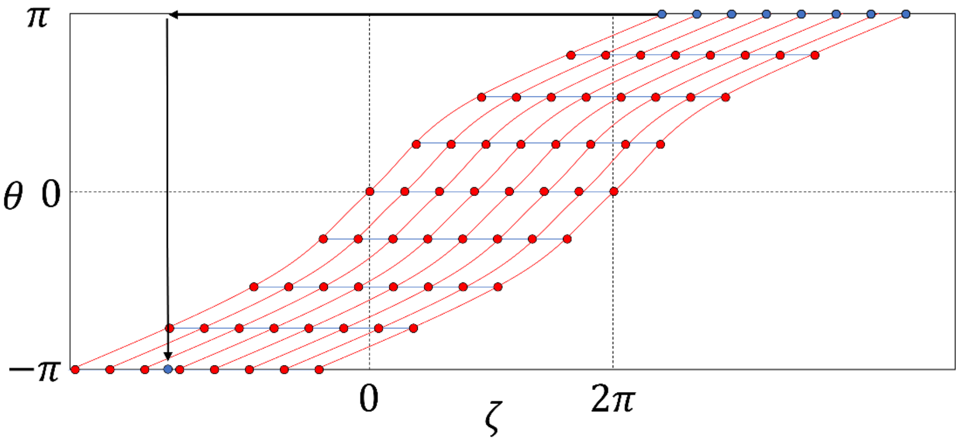
$$x = \rho \qquad [0,1]$$
$$y = y_{\text{shift}} - \zeta \qquad [0,2\pi)$$
$$z = \theta - \theta_0 \qquad [-\pi,\pi)$$

$$y_{\text{shift}} = \int_{\theta_0}^{\theta} \nu(\rho,\theta')d\theta'$$

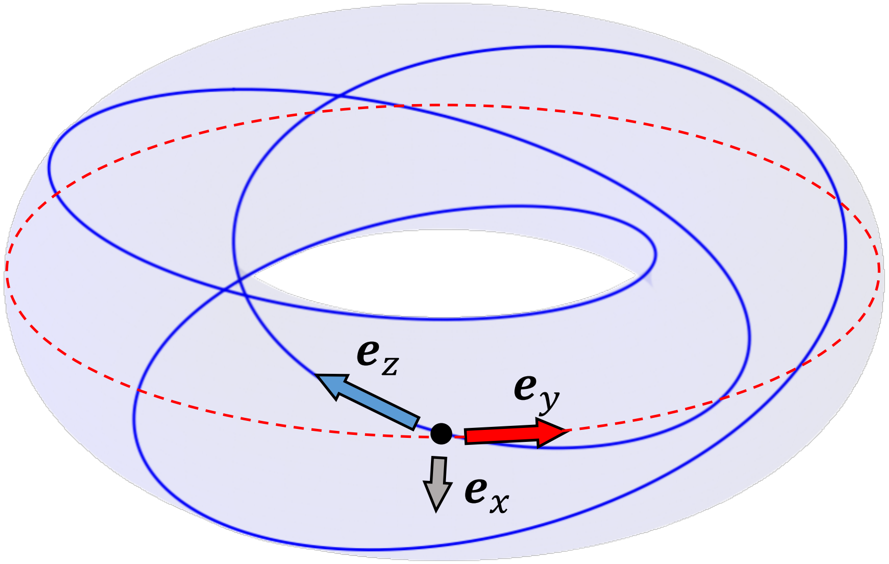
$$\nu = \frac{\boldsymbol{B}\cdot\nabla\zeta}{\boldsymbol{B}\cdot\nabla\theta}$$

- The direction of $\boldsymbol{e}_z$ is along the field line.

$$\boldsymbol{e}_z = \boldsymbol{e}_\theta + \nu\boldsymbol{e}_\zeta = \boldsymbol{B}/B_\theta$$



Computational grids on a flux surface



Covariant basis vectors with a field line(blue)

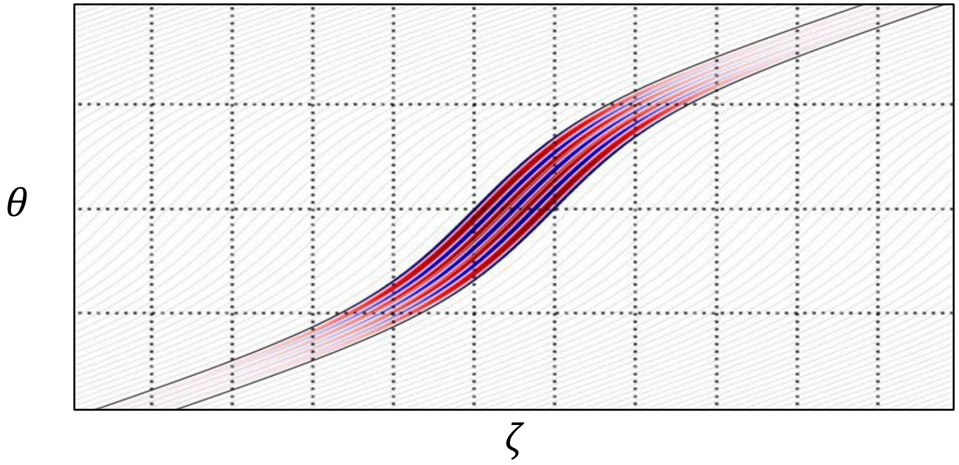
A : Field-aligned coordinates - 2

- Wavenumbers of resonant instabilities are low in the direction along the magnetic field line.

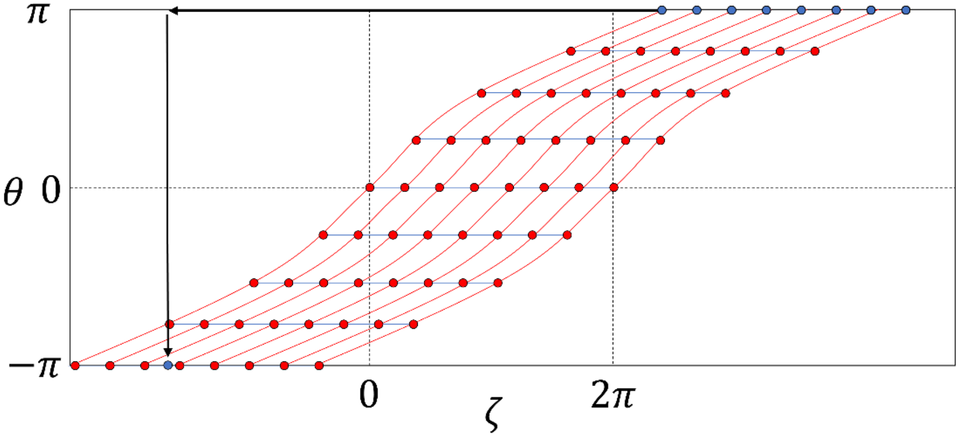
- By using a coordinate along the field lines, instabilities can be resolved with a small number of computational grids.

- It is particularly effective in the edge regions where the higher poloidal mode numbers resonate with the higher q values.

Ideal ballooning mode (n=20)



Computational grids of FAC



A : Field-aligned coordinates - 3

Simulations of the linear ITG instability were performed on GKNET-FAC and conventional GKNET.

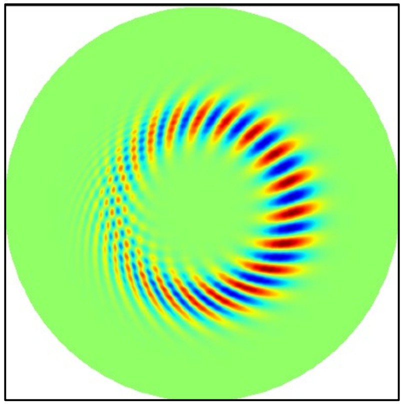
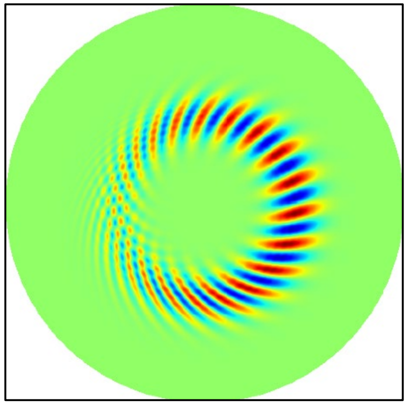
→ Are the results consistent?
How much computation time was reduced?

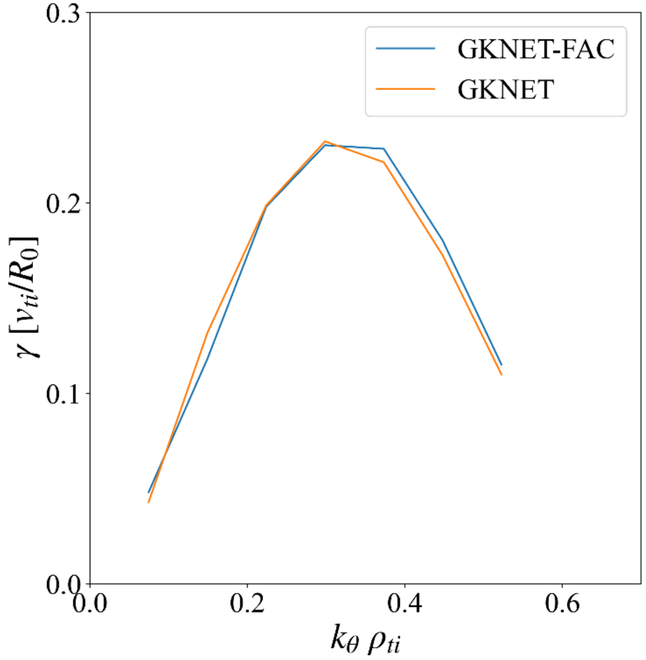
Simulation condition : concentric circular torus with the CBC parameters :

$$\frac{a_0}{R_0} = 0.36, \quad \frac{R_0}{L_n} = 2.22, \quad \frac{R_0}{L_{Ti}} = \frac{R_0}{L_{Te}} = 6.92, \quad q = 0.85 + 2.18\left(\frac{r}{a_0}\right)^2$$

- δf global model with the adiabatic electron.
- The radial domain is set to $0.1 < \rho < 1$.
- 1/4 wedge torus is assumed.
- 128CPU on JFRS-1 are used.
- $a_0/\rho_{ti} = 150$

A : Field-aligned coordinates - 4

	Conventional GKNET	GKNET-FAC
$\phi_{n=16}$		
Required grids	$(N_\rho, N_\zeta, N_\theta, N_{v_\parallel}, N_\mu)$ $= (128, 48, 256, 80, 16)$	$(N_x, N_y, N_z, N_{v_\parallel}, N_\mu)$ $= (128, 48, 16, 80, 16)$ 1/16
Time per 1 step	4.02 [s]	0.55 [s] 1/7.3



Linear growth rate

- Both results are consistent.
- The number of time steps required is reduced to 1/5.
- The computation time is reduced to 1/7.3 × 1/5 = 1/36.5 (=2.7%).

B : Realistic tokamak equilibria

Conventional GKNET

Equilibrium is set by functions.

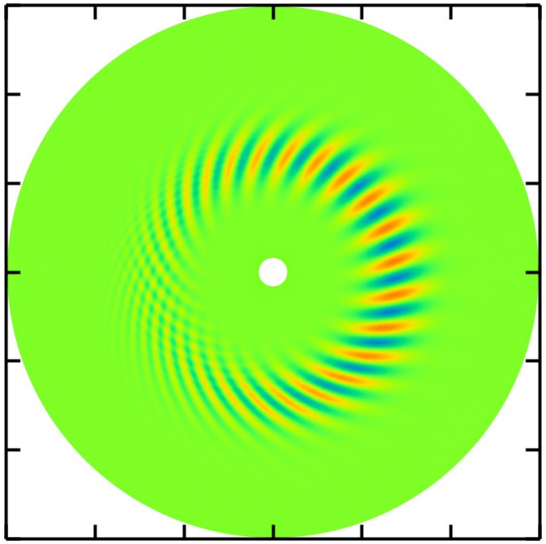
$$\boldsymbol{B} = \underbrace{\frac{R_0}{qR^2}}_{B^\theta} \boldsymbol{e}_\theta + \underbrace{\frac{R_0}{R^2}}_{B^\zeta} \boldsymbol{e}_\zeta$$

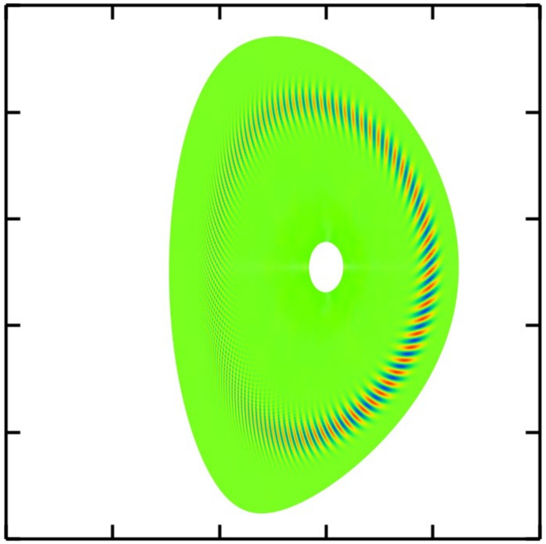
GKNET-FAC

Equilibrium is set by numerical data of a realistic tokamak equilibrium.

```
+7.996469528537010E-001 +1.002618860547062E+000
+7.996468322475245E-001 +1.002618709327794E+000
+7.996461323977480E-001 +1.002617831837318E+000
+7.996448537145523E-001 +1.002616228589929E+000
+7.996429968363297E-001 +1.002613900386063E+000
+7.996405627062098E-001 +1.002610848408238E+000
+7.996375525050876E-001 +1.002607074137095E+000
```

B^θ ⋮ B^ζ ⋮





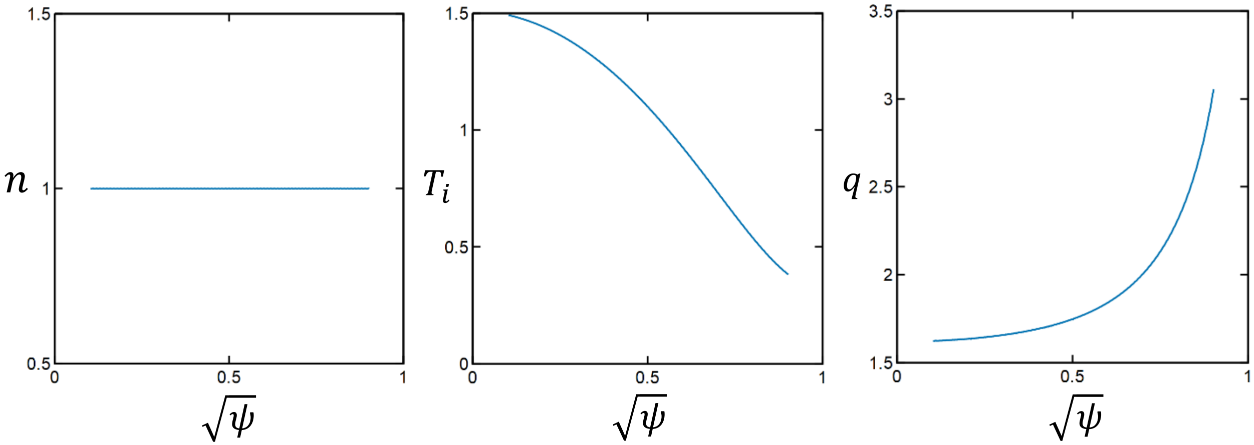
- GKNET-FAC can now handle arbitrarily shaped equilibria, including vertically asymmetric equilibria, which could not be handled by the conventional GKNET.

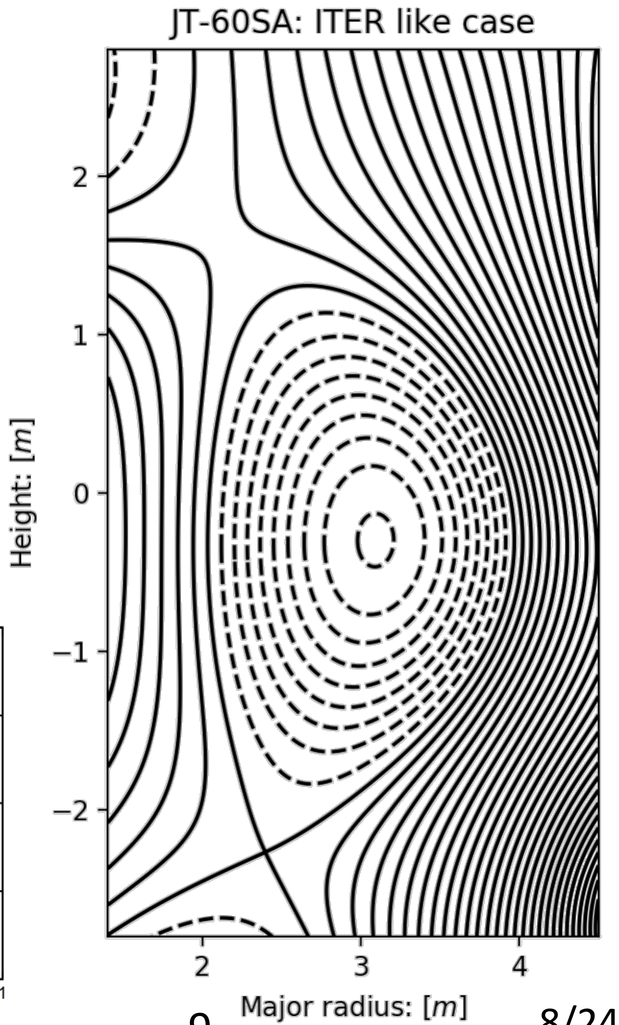
C : Nonlinear simulation of the JT-60SA plasma - 1

Finally, we have performed the nonlinear ITG simulation using the JT-60SA plasma [M.Nakata+, PFR-2014] on GKNET-FAC.

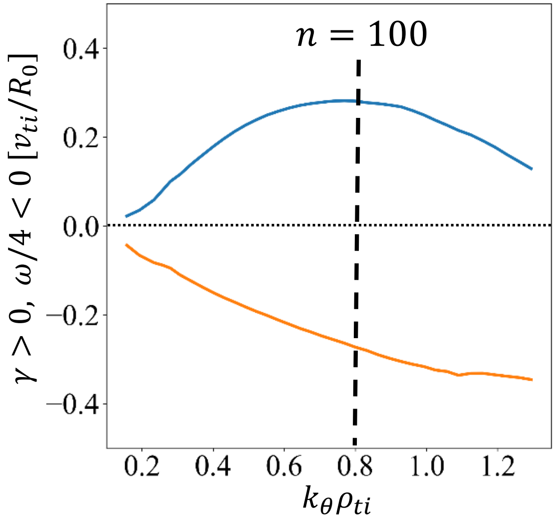
Simulation conditions :

- δf global model with the adiabatic electron.
- The radial domain is set to $0.1 < \sqrt{\psi} < 0.9$.
- 1/4 wedge torus is assumed.
- 10240CPU on JFRS-1 are used.
- $a_0/\rho_{ti} = 294$
- $(N_x, N_y, N_z, N_{v_\parallel}, N_\mu) = (720, 256, 32, 80, 16)$

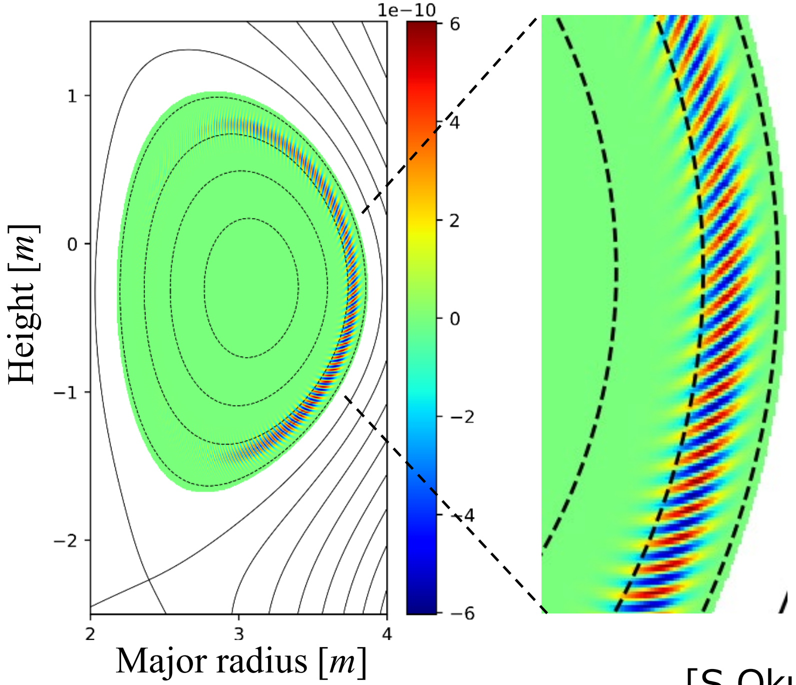




C : Nonlinear simulation of the JT-60SA plasma - 2

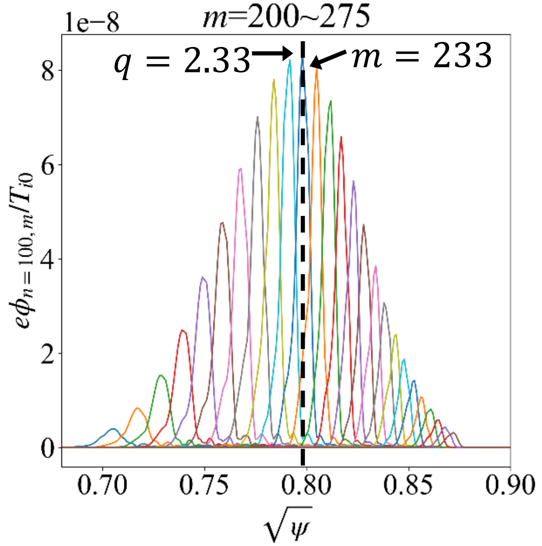


Dispersion relation



$\phi_{n=100}$ in a linear phase

[S.Okuda, PFR-2023]

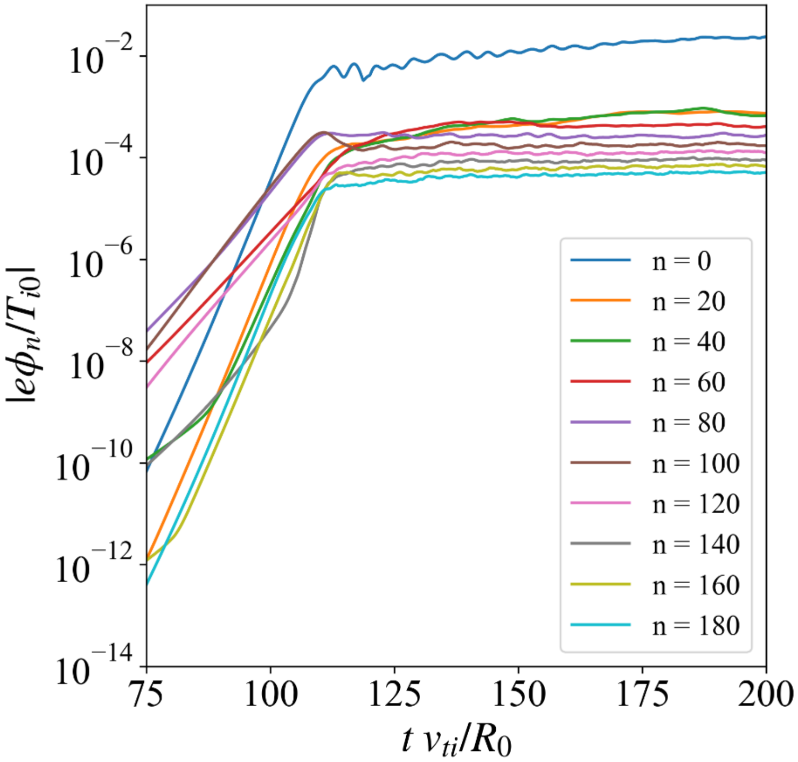


The poloidal harmonics of $\phi_{n=100}$

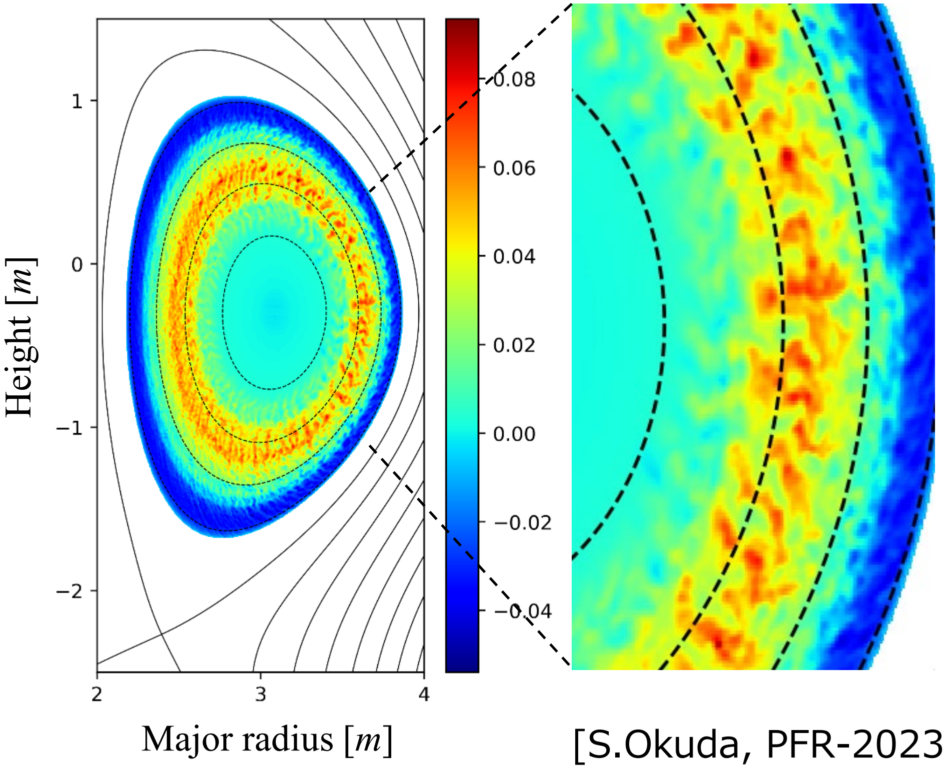
- Very high poloidal mode number instabilities, such as $(m, n) = (233, 100)$, have been resolved.

C : Nonlinear simulation of the JT-60SA plasma - 3

Time development of the amplitude of the electrostatic potential



$\phi(\zeta = 0)$ after the nonlinear saturation



[S.Okuda, PFR-2023]

- The zonal flow has been generated at the position corresponding to the linear instabilities.

C : Nonlinear simulation of the JT-60SA plasma - 4

- Consider the number of meshes required to resolve the mode $m_{\mathrm{res}} = 160 \times 2.3 \approx 370$ resonating with $n = 160$, which is unstable in this case.
  - Assume that 8 times as many meshes as the mode number are required.
  - If (ρ, θ, ζ) coordinates is used, $N_\theta = 370 \times 8 \approx 3000$ is required.
  - If FAC is used, $N_z = 32$ is enough as this case.
  - Due to FAC, the required meshes are reduced to $32 \div 3000 \approx 1/94$.

- For a simulation up to $t\, v_{ti}/R_0 = 200$, it took 12.5 hours using 10240CPU on JFRS-1.

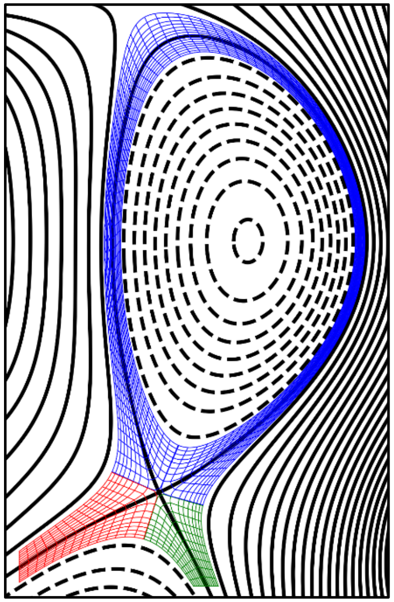
→ It cannot be calculated without using FAC.

Summary and future plans

- Summary
  - The field-aligned coordinate system has been successfully implemented into GKNET.
  - GKNET has been connected with a 2D equilibrium code.

→ It is now possible to simulate instabilities in large scale realistic tokamak equilibria such as JT-60SA.

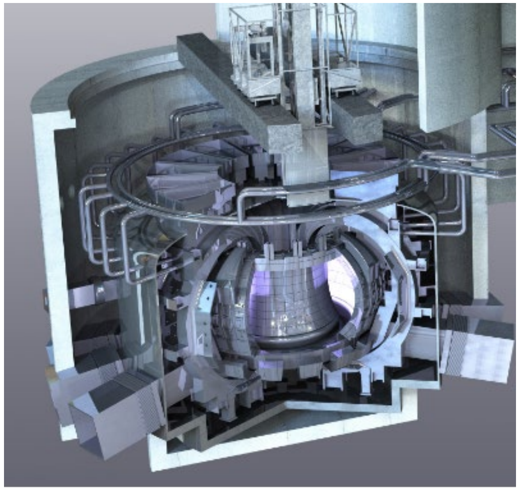
- Future plans
  - The development of GKNET will be extended to address tokamak edge turbulence.
  - Currently, an interface code is being developed to generate a computational grid in the SOL/divertor region.



Background: Refueling by Particle Pinch

- ✓ Establishment of a refueling method is an important issue to control nuclear fusion reactors.
- ✓ But, in DEMO-class high-temperature plasmas, a pellet injection reaches only up to 80-90% of the minor radius so that the central density peaking depends on particle pinch, making the prediction difficult.

Schematic picture of Japan-DEMO*



- ✓ While turbulent particle transport has been studied based on local gyrokinetic models, it is important to study global physics.
- ✓ The above analysis is also meaningful to investigate impurity transport such as Helium ash exhaust.

*[https://www.fusion.qst.go.jp/rokkasyo/ddjst/]

Background: Related Theory & Simulation

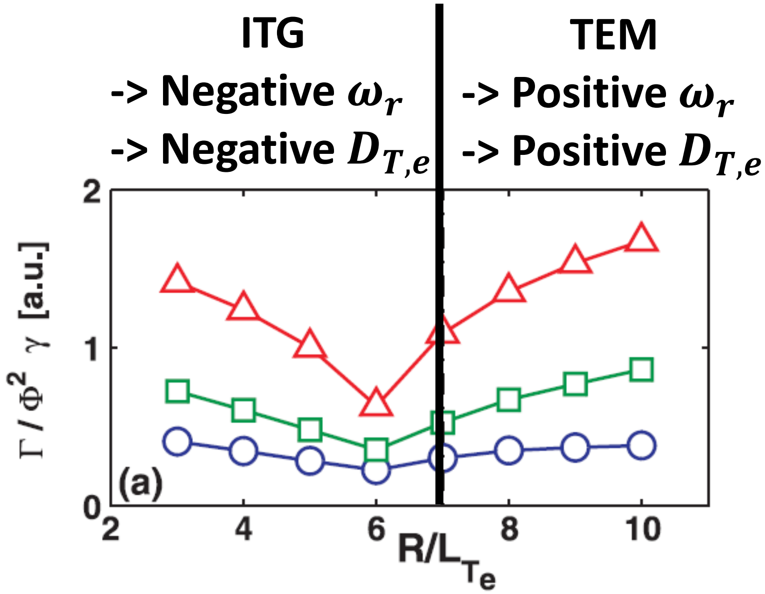
Turbulent particle flux calculated by fluid theory

[Nordman+, NF-1990]

$$\Gamma_s = \underbrace{D_{n,s}\frac{R}{L_{n,s}}}_{(1)} + \underbrace{D_{T,s}\frac{R}{L_{T,s}}}_{(2)} \qquad D_{T,s} = -\frac{4L_{n,s}}{L_B}\left(\frac{10}{3}\frac{L_{n,s}}{L_B} - \frac{\omega_{r,s}}{\omega_{*,e}}\right)$$

Turbulent particle flux calculated by GS2 simulation

[Angioni+, NF-2004]



ITG
-> Negative ω_r
-> Negative $D_{T,e}$

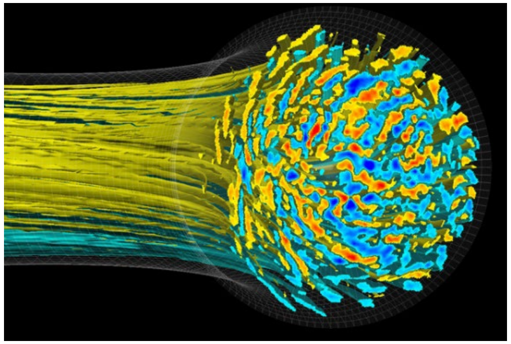
TEM
-> Positive ω_r
-> Positive $D_{T,e}$

- ✓ Turbulent particle flux mainly is provided by (1) the diagonal diffusion term and (2) the non-diagonal thermo-diffusion term.
- ✓ While the sign of (1) is usually positive, that of (2) can become negative, depending on the real frequency, etc.
- ✓ In fact, the turbulent particle flux shows the opposite tendency for temperature gradient between ITG and TEM.

Purpose of This Research

- ✓ In order to understand such view points, we perform flux-driven ITG/TEM simulations in the presence of ion/electron heating by means of the full-*f* electrostatic version of our global gyrokinetic code GKNET with hybrid kinetic electron dynamics.

3D turbulence structure of ϕ calculated by GKNET



- ✓ First, we investigate the effect of ion/electron heating on the density peaking or flattening.

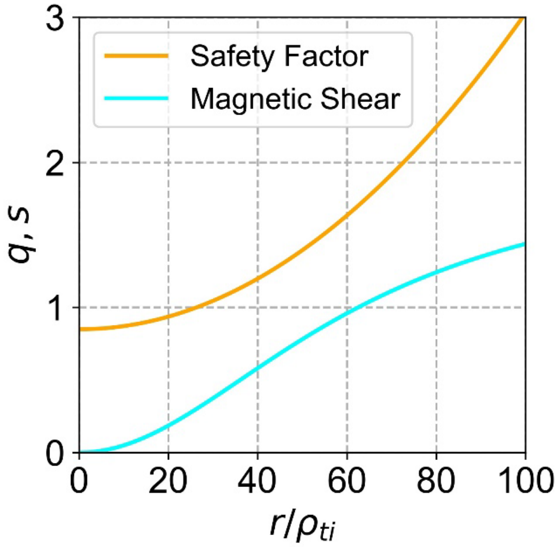
- ✓ Second, we separately discuss turbulent particle transport by (1) the E × B drift with n≠0, (2) the E × B drift with n=0, and (3) the magnetic drift (n=0) in addition to their physical mechanisms.

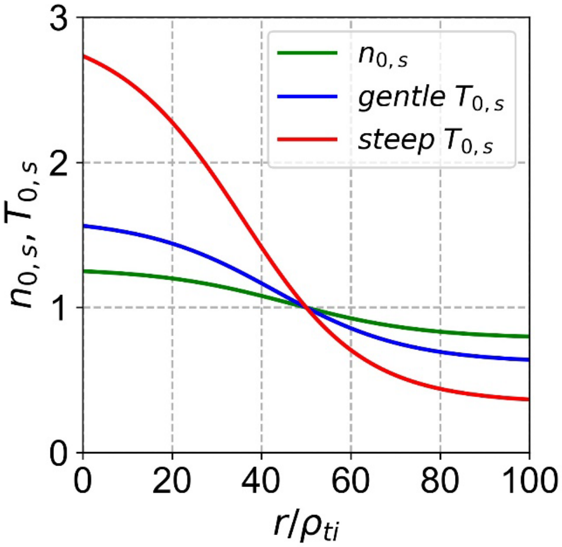
$$\boxed{\frac{dE_r}{dt} = \Gamma_{i,E\times B(n\neq 0)} + \Gamma_{i,E\times B(n=0)} + \Gamma_{i,B} - \Gamma_{e,E\times B(n\neq 0)} - \Gamma_{e,E\times B(n=0)} - \Gamma_{e,B}}$$

Simulation Condition

Simulation condition

Parameter	Value
a_0/ρ_i	100
a_0/R_0	0.36
$(R_0/L_n)_{r=a_0/2}$	2.22
Δ_r	30
$\sqrt{m_i/m_e}$	10
ν_i^*	0.025
ν_e^*	0.025



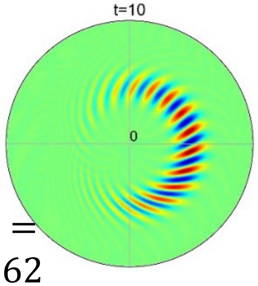


- ✓ In this study, we use GKNET-HE, the full-f electrostatic version with hybrid electron model.
- ✓ Here we consider three cases: (A)Mix $(R_0/L_{T_i} = 10,\ R_0/L_{T_e} = 10)$ under ion/electron heating, (B)ITG $(R_0/L_{T_i} = 10,\ R_0/L_{T_e} = 4)$ under ion heating, (C)TEM $(R_0/L_{T_i} = 4,\ R_0/L_{T_e} = 10)$ under electron heating.

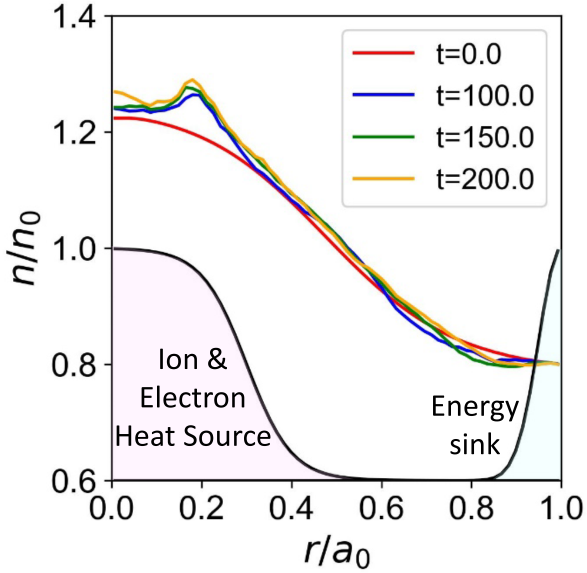
Density Peaking/Flattening

(A) Mix

$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 10$

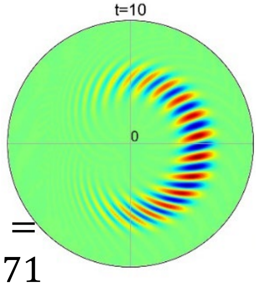


$\gamma =$
0.62

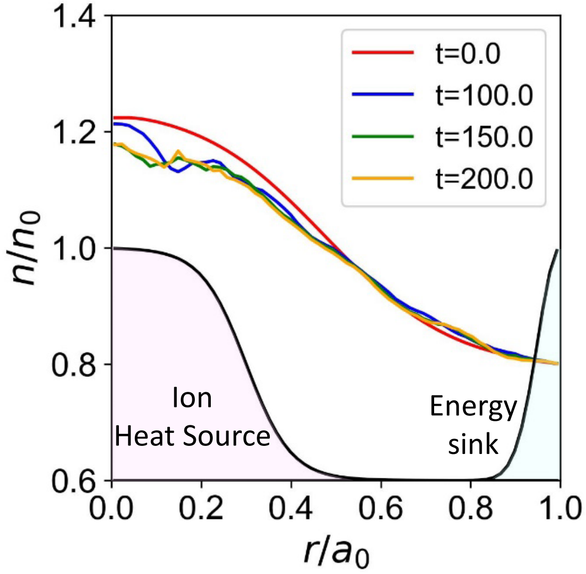


(B) ITG

$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 4$

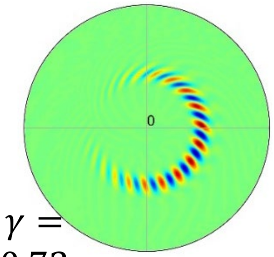


$\gamma =$
0.71

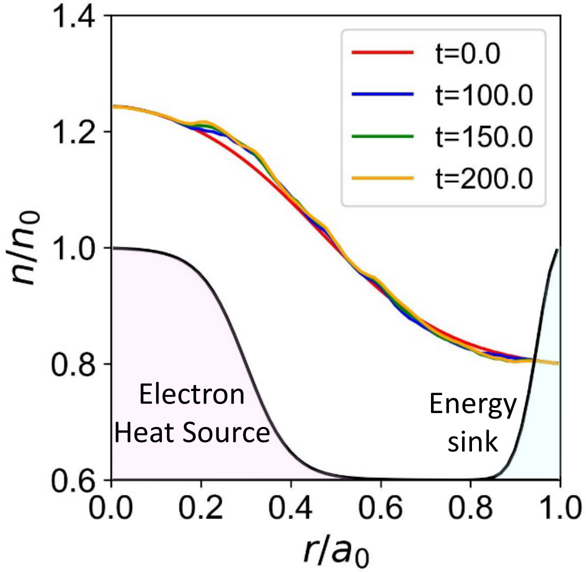


(C) TEM

$R_0/L_{T_i} = 4$
$R_0/L_{T_e} = 10$



$\gamma =$
0.73



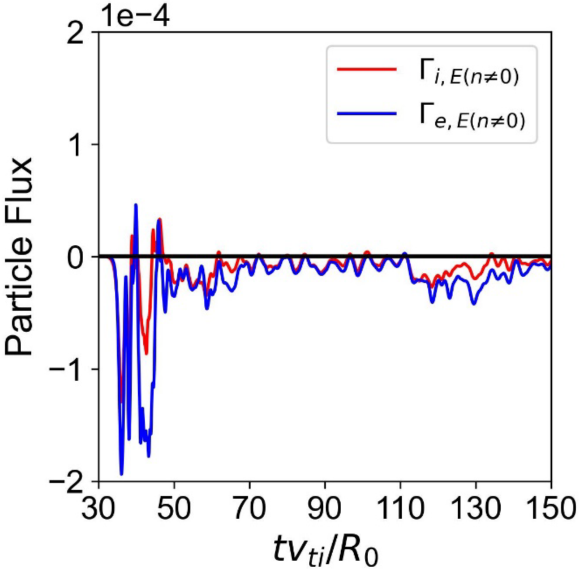
- ✓ While density profile are flattened by outer particle flux in the case (B), a density peaking can be observed in the case (A).
- ✓ The eigen structures (obtained by linear δf simulations) are almost same between the cases (A) and (B).

Particle Transport by E × B Drift (n≠0) - 1

(A) Mix

$R_0/L_{T_i} = 10$

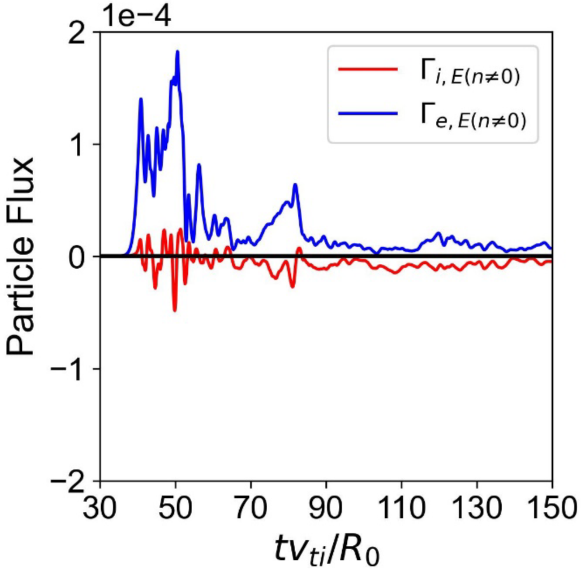
$R_0/L_{T_e} = 10$



(B) ITG

$R_0/L_{T_i} = 10$

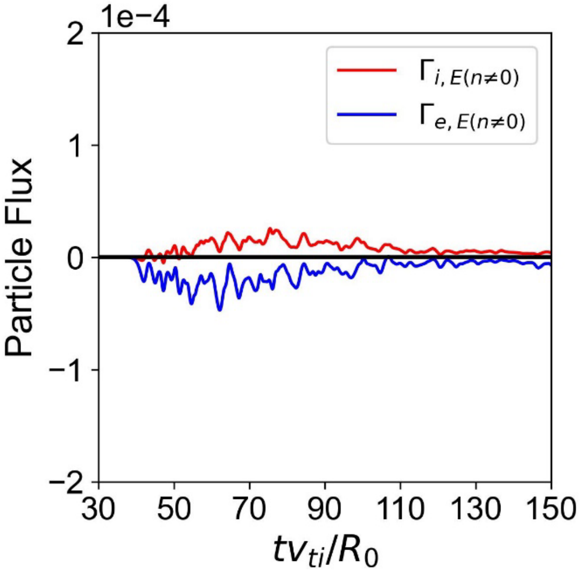
$R_0/L_{T_e} = 4$



(C) TEM

$R_0/L_{T_i} = 4$

$R_0/L_{T_e} = 10$



- ✓ When ion/electron temperature gradients are steep and sustained by ion/electron heating, inward particle transport (particle pinch) can be observed.

Particle Transport by E × B Drift (n≠0) - 2

Turbulent particle flux by fluid theory

[Nordman+, NF-1990]

$$\Gamma_s = \underbrace{D_{n,s}\frac{R}{L_{n,s}}}_{\text{Positive}} + \underbrace{D_{T,s}\frac{R}{L_{T,s}}}_{\text{Negative}} \qquad D_{T,s} = -\frac{4L_{n,s}}{L_B}\left(\frac{10}{3}\frac{L_{n,s}}{L_B} - \frac{\omega_{r,s}}{\omega_{*,e}}\right)$$

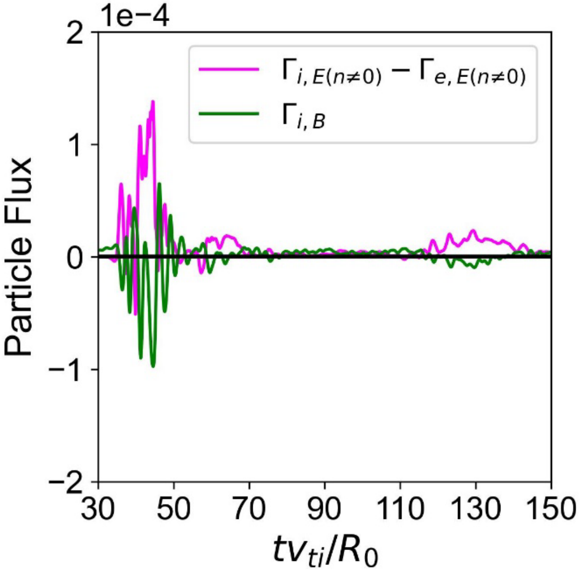
- ✓ In the present cases, $L_{n,s}/L_B \sim 1/2.22$ and $0.5 < \omega_{r,TEM}/\omega_{*,e} < 1$ are assumed so that $D_{T,s}$ is still negative even in the TEM case.
- ✓ When the temperature gradient is steep, the non-diagonal thermo-diffusion term becomes dominant, leading to the inward particle transport.
- ✓ As the result, the balance of particle fluxes breaks, leading to the charge separation.

	$\frac{R_0}{L_{T_i}} = 10, \frac{R_0}{L_{T_e}} = 10$	$\frac{R_0}{L_{T_i}} = 10, \frac{R_0}{L_{T_e}} = 4$	$\frac{R_0}{L_{T_i}} = 4, \frac{R_0}{L_{T_e}} = 10$
$\Gamma_{i,E(n\neq0)}$	Negative	Weakly Negative	Weakly Positive
$\Gamma_{e,E(n\neq0)}$	Strongly Negative	Positive	Weakly Negative
$\Gamma_{i,E(n\neq0)} - \Gamma_{e,E(n\neq0)}$	Positive	Negative	Positive

Ion Particle Transport by Magnetic Drift (n=0) - 1

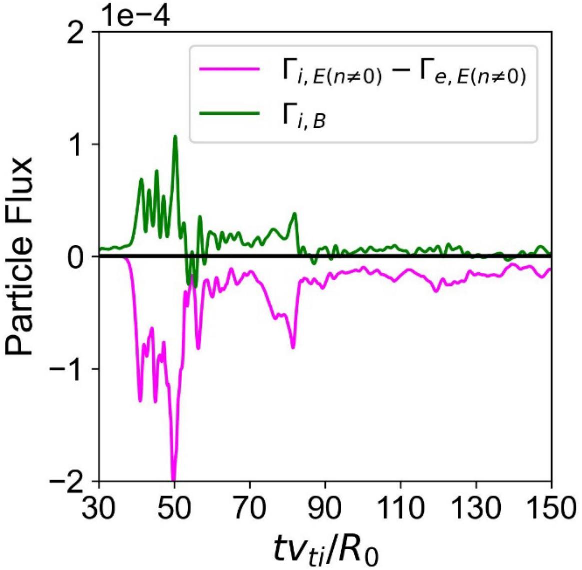
(A) Mix

$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 10$



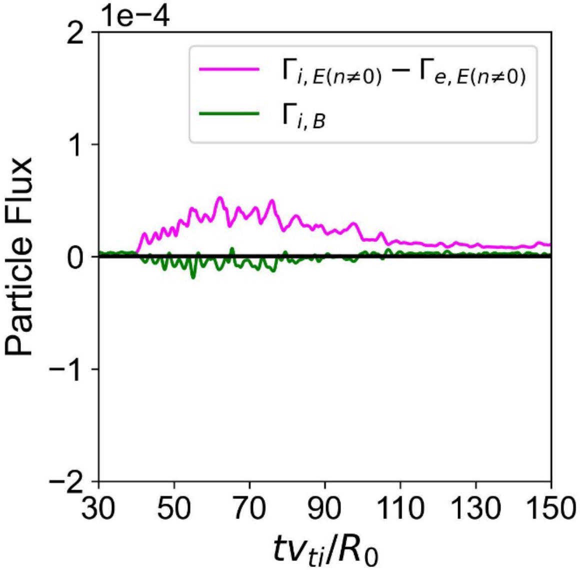
(B) ITG

$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 4$



(C) TEM

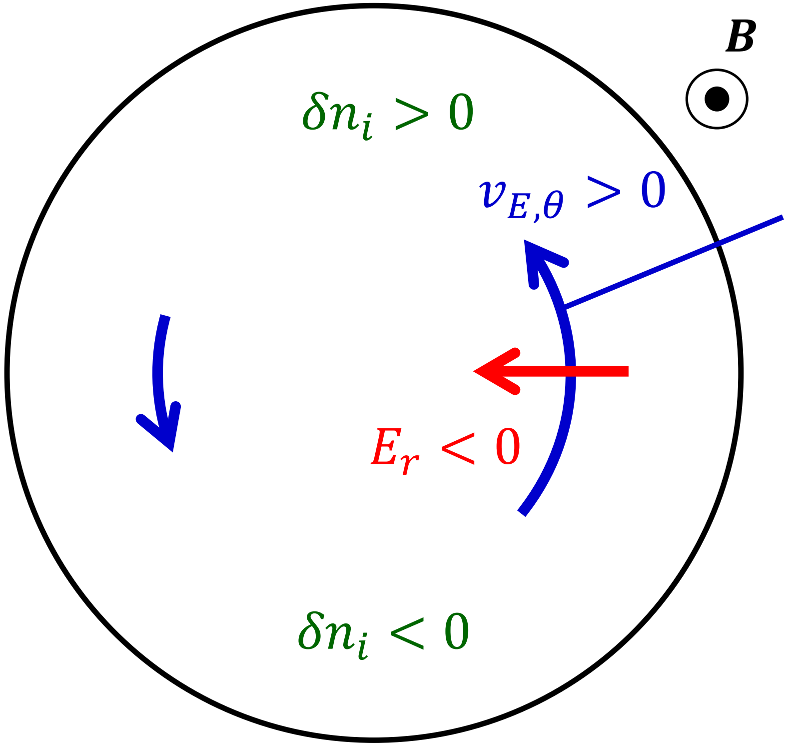
$R_0/L_{T_i} = 4$
$R_0/L_{T_e} = 10$



- ✓ When the E × B drift (n≠0) drives particle transport, the particle transport by the magnetic drift (n=0) is enhanced, which cancels with the E × B drift (n≠0) driven transport.
- ✓ Such a tendency was observed in the impurity transport [Idomura+, PoP-2021].

Ion Particle Transport by Magnetic Drift (n=0) - 2

- ✓ When $\Gamma_{i,E(n\neq0)} - \Gamma_{e,E(n\neq0)} > 0$, negative mean radial electric field E_r with $(m,n) = (0,0)$ is triggered as below.
- ✓ Resultant poloidal $E \times B$ flow $v_{E,\theta}$ has a poloidal up-down asymmetry, leading to ion density perturbations with $(m,n) = (1,0)$.
- ✓ Such density perturbations can provide negative particle flux by magnetic drift.



$$v_{E,\theta} = -\frac{1}{B}E_r = -\left(1+\frac{r}{R_0}\cos\theta\right)E_r$$

⬇

$$\frac{\partial \delta n_i}{\partial t} = -\frac{1}{r}\frac{\partial v_{E,\theta}}{\partial \theta} n_0 = -\frac{1}{R_0}E_r n_0 \sin\theta$$

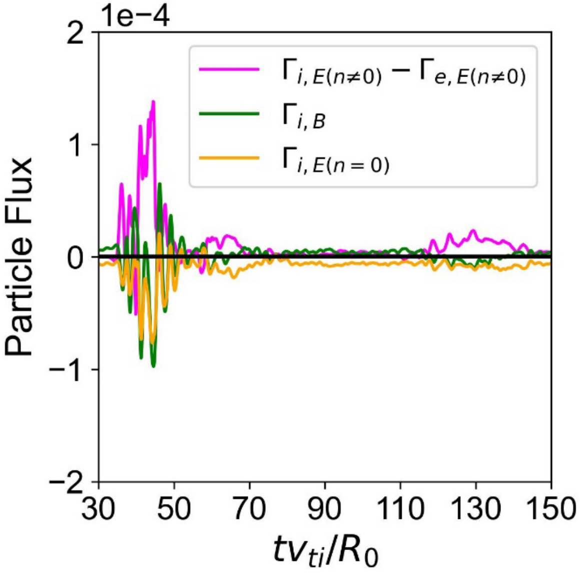
⬇

$$\frac{\partial}{\partial t}\left\langle v_{B,r}\,\delta n_i\right\rangle_f \propto E_r\langle \sin^2\theta\rangle_f < 0$$

Ion Particle Transport by E × B Drift (n=0)

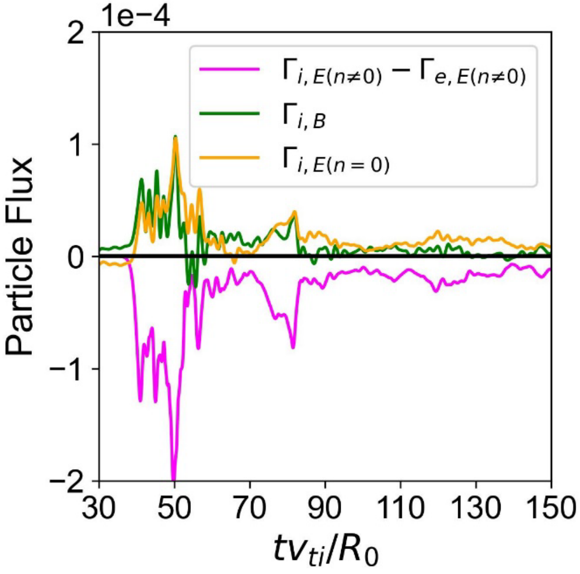
(A) Mix

$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 10$



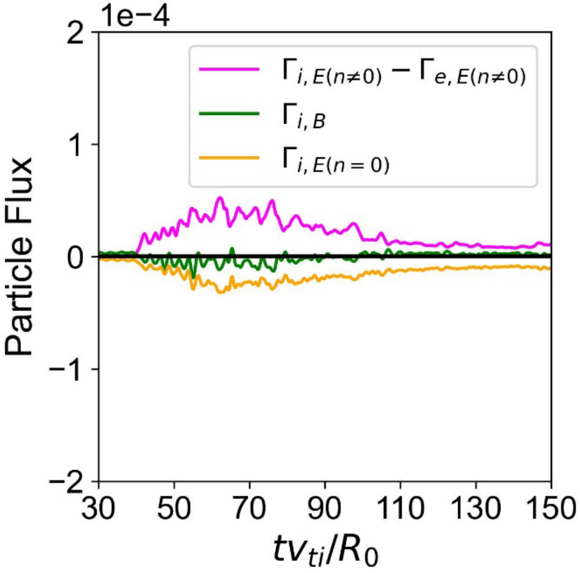
(B) ITG

$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 4$



(C) TEM

$R_0/L_{T_i} = 4$
$R_0/L_{T_e} = 10$



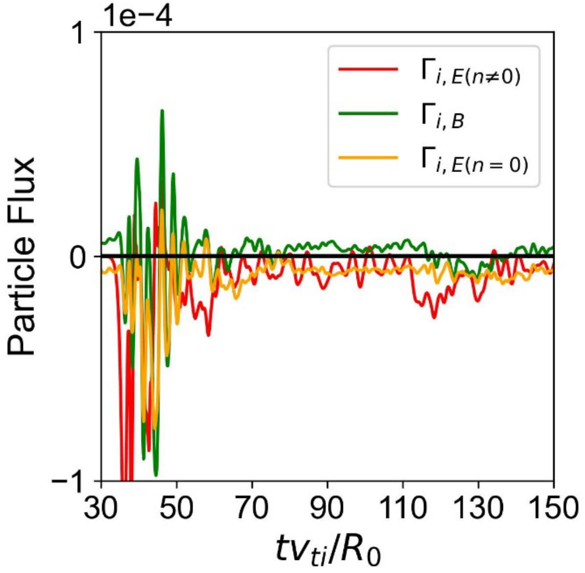
- ✓ It is newly found that particle transport by not only magnetic drift (n=0) but also E × B drift (n=0) are enhanced, which also cancels with E × B drift (n≠0) driven transport.

Summary of Turbulent Ion Particle Pinch

(A) Mix

$R_0/L_{T_i} = 10$

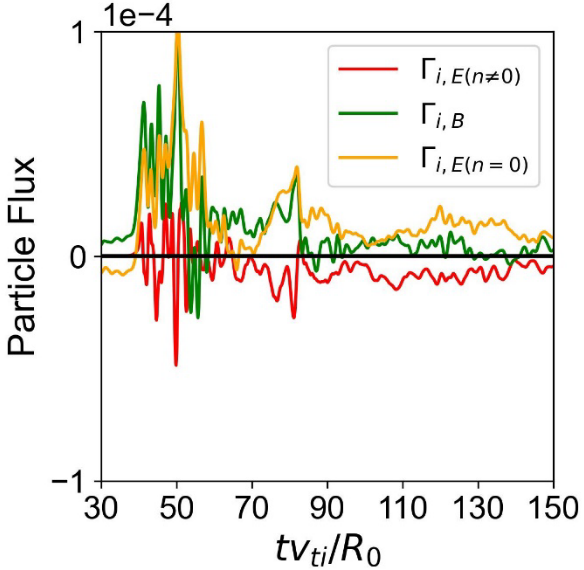
$R_0/L_{T_e} = 10$



(B) ITG

$R_0/L_{T_i} = 10$

$R_0/L_{T_e} = 4$



Step-1: Particle transport by E × B drift (n≠0) determined by temperature gradients

$$\underbrace{\Gamma_{i,E(n\neq0)}}_{\text{Negative}} + \Gamma_{i,E(n=0)} + \Gamma_{i,B} \underbrace{- \Gamma_{e,E(n\neq0)}}_{\text{Strongly Positive}} = 0$$

$$\underbrace{\Gamma_{i,E(n\neq0)}}_{\text{Weakly Negative}} + \Gamma_{i,E(n=0)} + \Gamma_{i,B} \underbrace{- \Gamma_{e,E(n\neq0)}}_{\text{Negative}} = 0$$

Step-2: Particle transport by E × B (n=0) and magnetic drift to satisfy the above balance

$$\underbrace{\Gamma_{i,E(n\neq0)}}_{\text{Negative}} \underbrace{+ \Gamma_{i,E(n=0)}}_{\text{Negative}} \underbrace{+ \Gamma_{i,B}}_{\text{Weakly Negative}} \underbrace{- \Gamma_{e,E(n\neq0)}}_{\text{Strongly Positive}} = 0$$

$$\underbrace{\Gamma_{i,E(n\neq0)}}_{\text{Weakly Negative}} \underbrace{+ \Gamma_{i,E(n=0)}}_{\text{Positive}} \underbrace{+ \Gamma_{i,B}}_{\text{Positive}} \underbrace{- \Gamma_{e,E(n\neq0)}}_{\text{Negative}} = 0$$

Summary

- ✓ We have performed flux-driven ITG/TEM simulations in the presence of ion/electron heating by means of the full-*f* electrostatic version of our global gyrokinetic code GKNET with kinetic electron dynamics.
- ✓ Enough steep ion temperature gradient can directly provide ion particle pinch by E × B drift (n≠0) through the thermo-diffusion term.
- ✓ Enough steep electron temperature gradient can also provide electron particle pinch, which can indirectly trigger ion particle pinch by E × B (n=0) and magnetic drifts though the ambipolarity condition.
- ✓ These two findings indicate that turbulence directly/indirectly drives ion particle pinch under ion/electron heating, leading to the synergetic density peaking of bulk ions.

$$\underbrace{\Gamma_{i,E\times B(n\neq 0)}}_{\text{Become negative by steep } T_i \text{ gradient}} + \underbrace{\Gamma_{i,E\times B(n=0)} + \Gamma_{i,B}}_{\text{Become negative to satisfy this condition}} \underbrace{- \Gamma_{e,E\times B(n\neq 0)}}_{\text{Become positive by steep } T_e \text{ gradient}} \underbrace{\cancel{- \Gamma_{e,E\times B(n=0)}} \cancel{- \Gamma_{e,B}}}_{\text{Canceled with each other}} = 0$$