May 20th, 2024
IFERC-CSC Workshop on JFRS-1 Projects for FY2023

Report of GGHB project based on global gyrokinetic code GKNET

Contents

1. Digest of GGHB project
2. Extension of GKNET to outer-core region
3. Study of particle transport for fuel supply and impurity exhaust
4. Summary & Future plans

Kenji IMADERA

Graduate School of Energy Science, Kyoto University, Japan

Project Members

Akihiro Ishizawa, Mikiya Muto, Shuhei Okuda, Rintaro Matsumura
Shota Yamada (Kyoto U.), Masatoshi Yagi, Haruki Seto (QST)

Research Plan of GGHB Project in FY-2023

(1) Extension of GKNET-FAC to outer core region

- ✓ To treat the turbulence in outer core region by GKNET-FAC (FAC: Field aligned Coordinate), we consider how to construct numerical grid for SOL-divertor regions.

(2) Study of particle transport for fuel supply and impurity exhaust

- ✓ Based on the study of non-axisymmetric turbulent particle fluxes in FY-2022, we investigate the axisymmetric particle fluxes for fuel supply by means of full-f gyrokinetic simulations.
- ✓ In addition, we perform δf gyrokinetic simulations for hydrogen, helium and electron to study impurity exhaust.

Main Achievements of GGHB Project in FY-2023

(1) Extension of GKNET-FAC to outer core region

- ✓ We have introduced a mixed coordinate system which adopts a Cartesian coordinate near the X-point while a non-Cartesian coordinate near the divertor plate
- ✓ We have also verified the validity of our extended code (GKNET-X) through linear ITG simulations. [S. Okuda *et al*., 40th JSPF meeting (2023).]

(2) Study of particle transport for fuel supply and impurity exhaust

- ✓ By driving non-axisymmetric electron particle pinch by electron heating, we have found that the axisymmetric ion particle pinch is enhanced though the gyrokinetic ambipolarity condition , leading to the synergetic density peaking of bulk ion. [K. Imadera *et al*., FEC-2023, submitted to Nucl. Fusion.]
- ✓ Both helium ash exhaust and fuel supply can be also achieved simultaneously by the similar mechanism. [K. Imadera *et al*., 40th JSPF meeting (2023).]

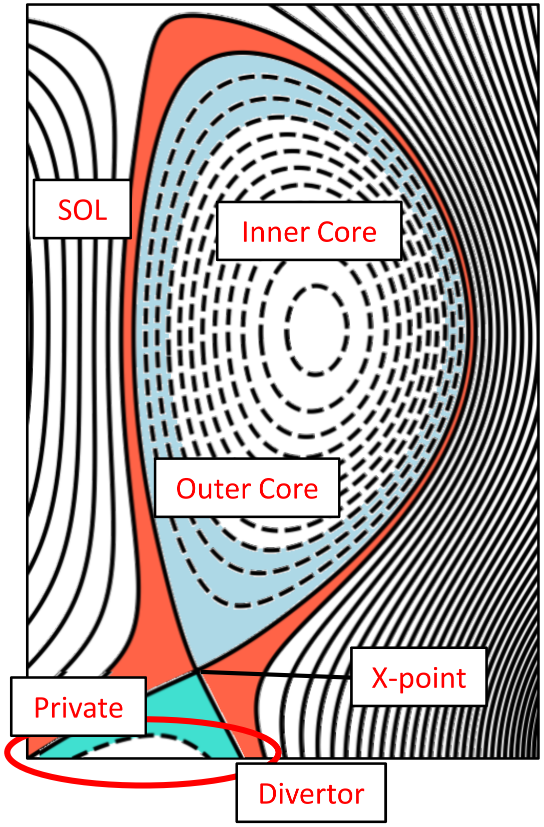
Background of Code Extension - 1

- Plasma dynamic in Tokamak edge region is directly related to
  - Fuel supply/Impurity exhaust
  - Diverter heat load
  - L-H transition

- Gyrokinetic simulation is considered to be an essential tool to study the above physics based on the first-principles.

- But, it is still challenging to apply it to the edge region due to higher *q* values and complex magnetic surface geometries that are not present in the core region.

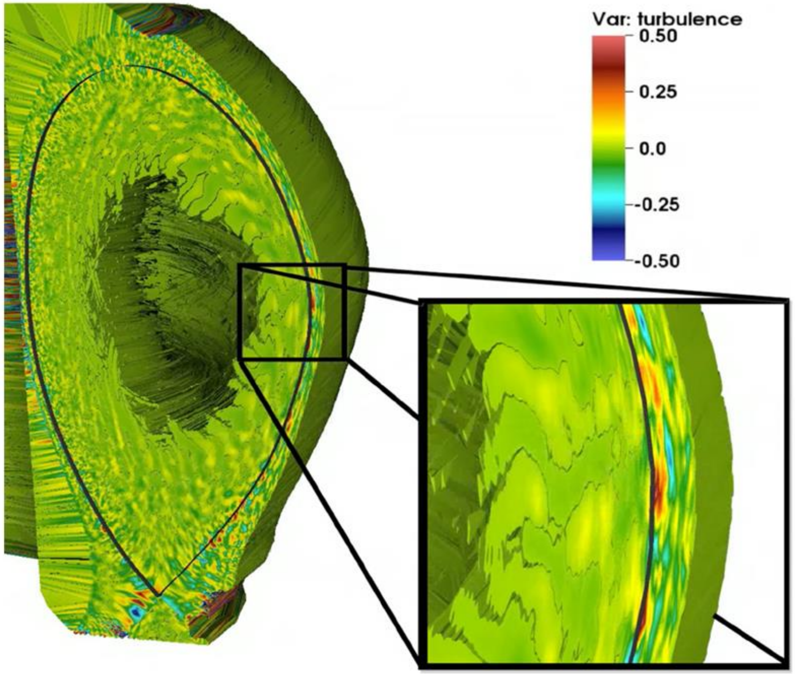
Some gyrokinetic codes to study edge region are recently developed in the world.



Background of Code Extension - 2

✓ For example, XGC (X-point Gyrokinetic Code) has been developed and studies the following topics.

- L-H transition
  [S. Ku *et al*., Phys. Plasmas **25**, 056107(2018).]
- Impurity transport
  [J. Dominski *et al*., Plasma Phys. Control. Fusion **85**, 905850510 (2019).]
- Edge turbulence
  [S. Ku *et al*., Nucl. Fusion **49**, 115021 (2009).]
- Divertor heat load
  [C. S. Chang *et al*., Nucl. Fusion **57**, 116023 (2017).]



[S. Ku *et al*., Phys. Plasmas **25**, 056107(2018).]

Some gyrokinetic codes to study edge region are recently developed in the world but there are no edge gyrokinetic code in Japan…

Strategy for Code Extension

[Imadera+, IAEA-2014]

GKNET
Electrostatic
Inner Core
Toroidal
Circular equil.

→

[Okuda+, PFR-2023]

GKNET-FAC
Electrostatic
Inner core
Field aligned
Realistic equil.

→

[Okuda+, JSPF meeting-2023]

GKNET-X
Electrostatic
Outer core
Field aligned
Realistic equil.

Field aligned coordinate (+Shifted Metric)

$$x = \psi$$

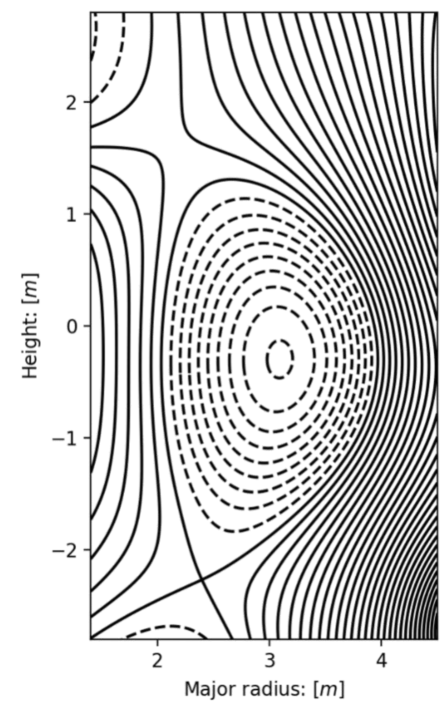
$$y = y_{\mathrm{shift},j} - \zeta \quad [0, 2\pi/N_w]$$

$$z = \theta - \theta_j \quad [-\pi/N_s, \pi/N_s]$$

$$y_{\mathrm{shift},j} = \int_{\theta_j}^{\theta} \frac{\boldsymbol{B}\cdot\nabla\zeta}{\boldsymbol{B}\cdot\nabla\theta}\, d\theta \quad (j = 0, 1, \ldots N_s - 1)$$

ψ : Poloidal magnetic flux function
θ : Label of poloidal angle
ζ : Geometric toroidal angle
N_s : Division number of domain
N_w: Toroidal wedge number

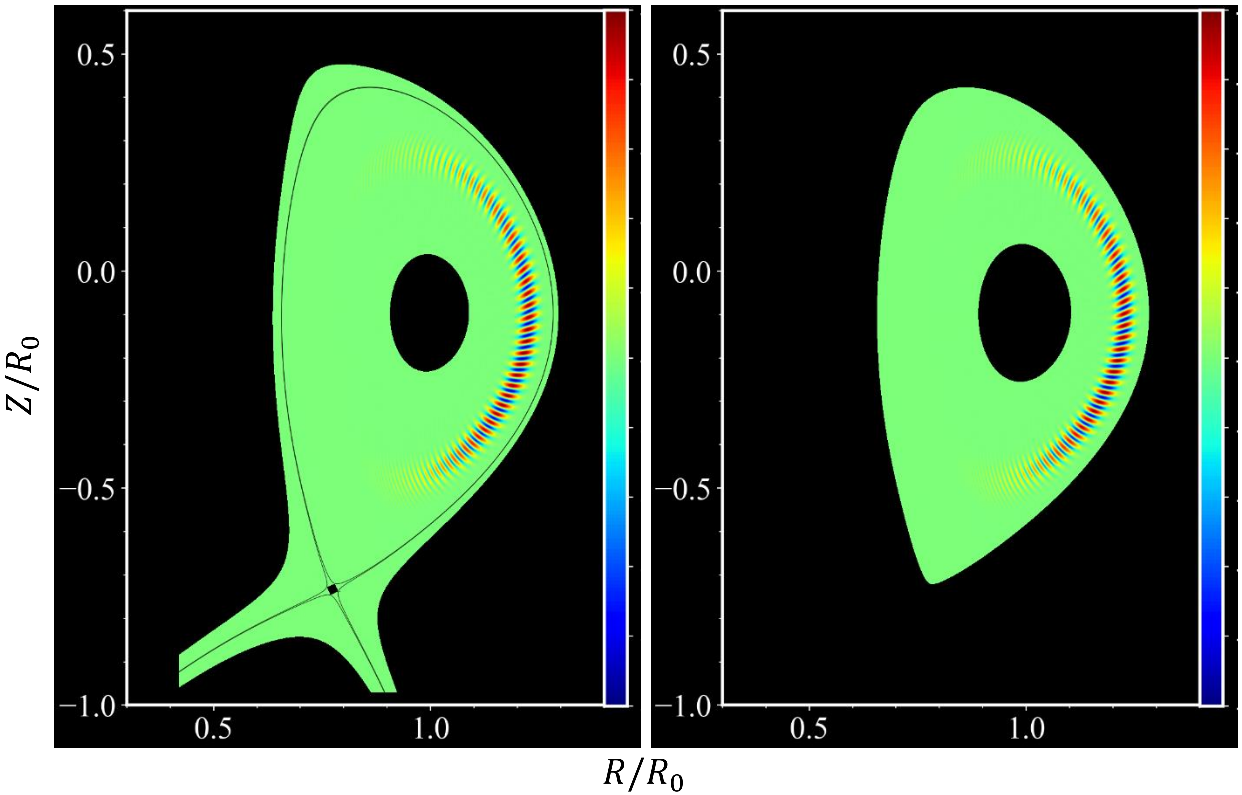
Tokamak Equilibrium (JT-60SA ITER like case)



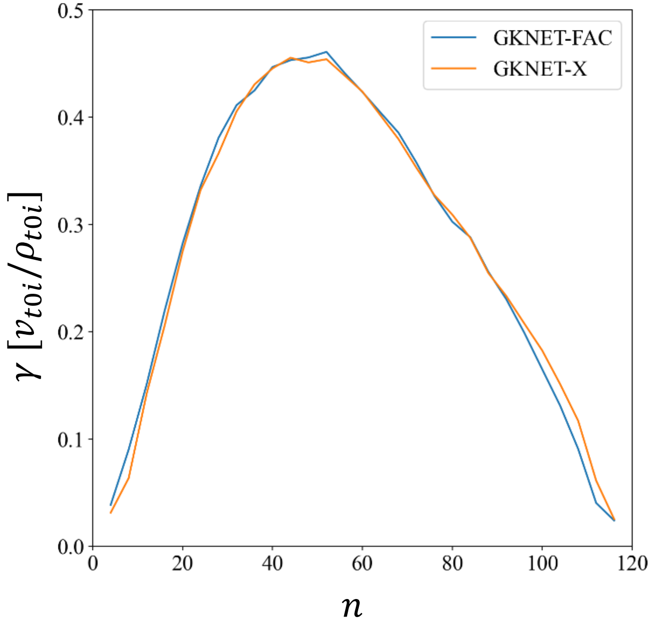
Results of Benchmark Test

$Re(\hat{\phi}_{n=60})$ calculated by GKNET-X

$Re(\hat{\phi}_{n=60})$ calculated by GKNET-FAC



Comparison of dispersion relation

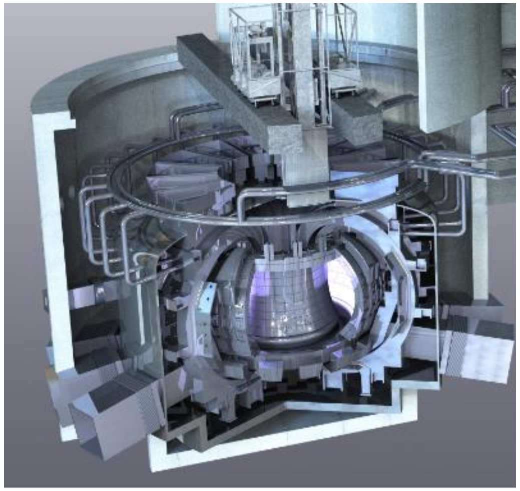


- ✓ GKNET-X and GKNET-FAC shows almost same linear results of ITG instability.
- ✓ This result demonstrates that GKNET-X precisely work to handle inner core region.

Background of Particle Transport Simulation

- ✓ 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*



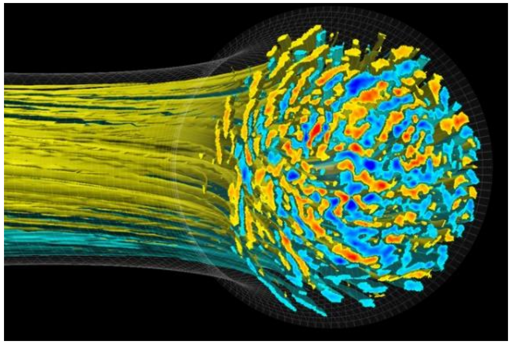
- ✓ While turbulent particle transport has been studied based on local gyrokinetic models [Angioni+, PoP-2004] , it is important to study global physics.
- ✓ The above analysis is also meaningful to investigate impurity transport such as Helium ash exhaust.

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

Purpose of Particle Transport Simulation

- ✓ 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 [Imadera & Kishimoto, PPCF-2023].

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.

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

- ✓ Third, by using δf version of GKNET with hydrogen, helium, and electron, we preliminary investigate the impurity exhaust.

Numerical Condition & Density Peaking/Flattening

Simulation Parameters

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

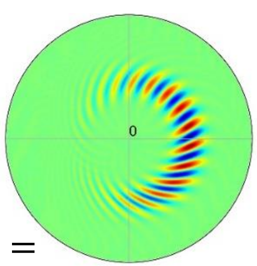
- ✓ Cyclone base case is employed.
- ✓ Hereafter, we consider the following two cases.

Case	R_0/L_{T_i}	R_0/L_{T_e}	Ion heating	Electron heating
(A) Ion/Electron	10	10	On	On
(B) Ion	10	6	On	Off

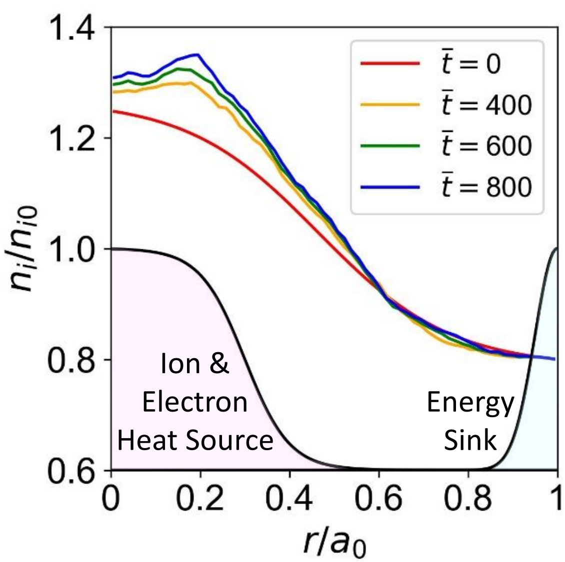
(A) Ion/Electron

$R_0/L_{T_i} = 10$

$R_0/L_{T_e} = 10$



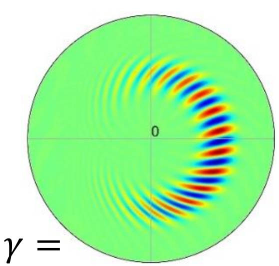
$\gamma =$
0.62



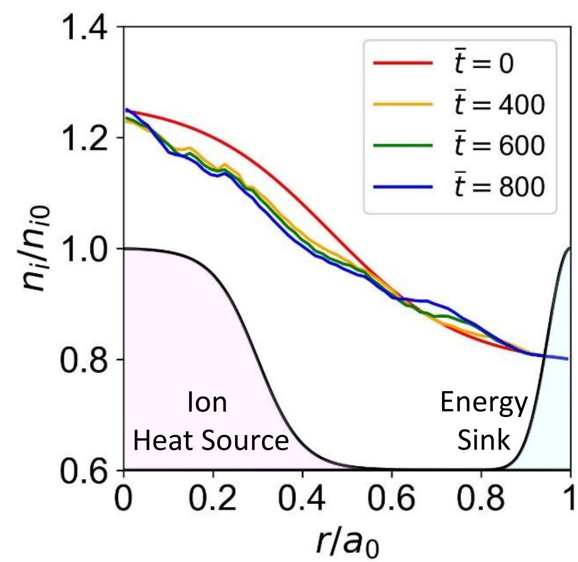
(B) Ion

$R_0/L_{T_i} = 10$

$R_0/L_{T_e} = 6$

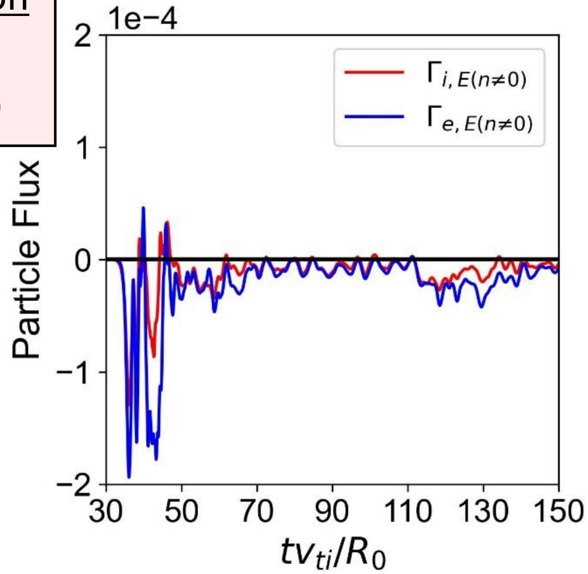


$\gamma =$
0.71

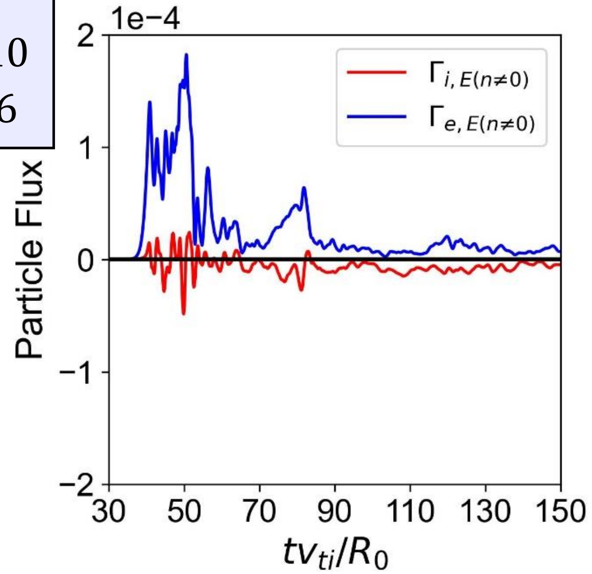


Particle Transport by E × B Drift (n≠0)

(A) Ion/Electron
$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 10$



(B) Ion
$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 6$



[Nordman+, NF-1990]

- ✓ When ion/electron temperature gradients are steep and sustained by ion/electron heating, inward particle transport (particle pinch) can be observed.
- ✓ In the case (A), the magnitude of electron particle flux is slightly larger, leading to radial mean filed.

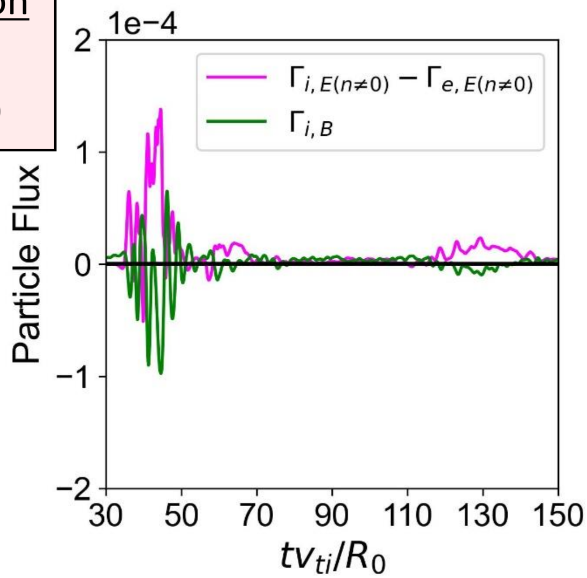
Turbulent particle transport model

$$\Gamma_s = D_{n,s}\frac{R}{L_{n,s}} + D_{T,s}\frac{R}{L_{T,s}}$$

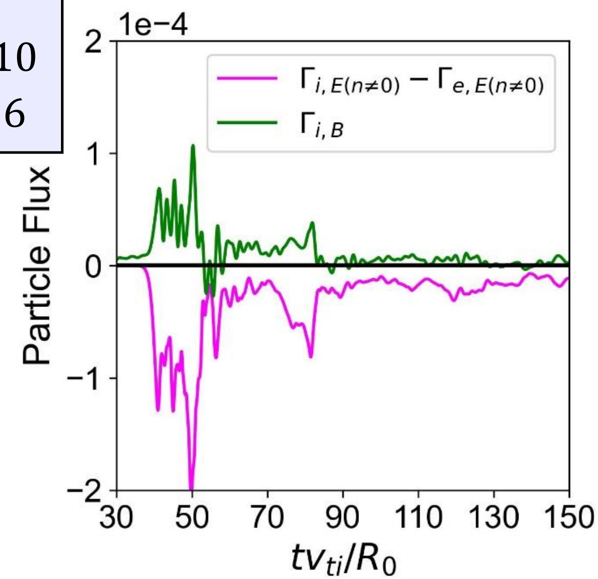
$$D_{T,s} = -\frac{4L_{n,s}}{L_B}\left(\frac{10}{3}\frac{L_{n,s}}{L_B} - \frac{\omega_{r,s}}{\omega_{*,e}}\right)$$

Ion Particle Transport by Magnetic Drift

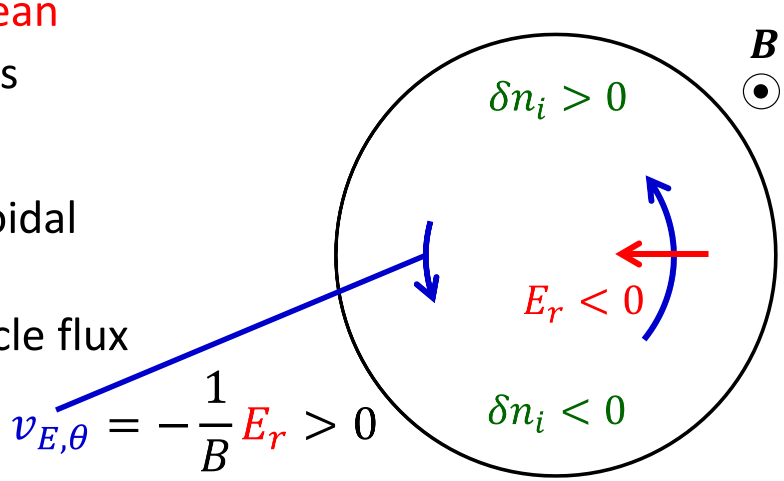
(A) Ion/Electron
$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 10$



(B) Ion
$R_0/L_{T_i} = 10$
$R_0/L_{T_e} = 6$



- ✓ 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 $(m,n) = (1,0)$ and particle flux by magnetic drift. [Idomura+, PoP-2021]

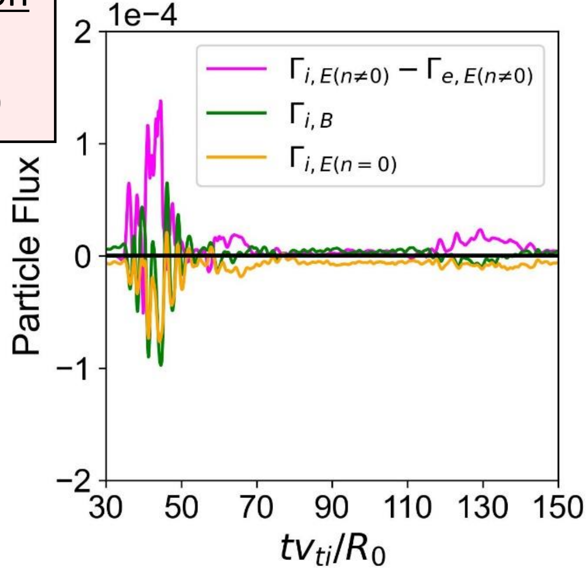


Ion Particle Transport by E × B Drift (n=0)

<u>(A) Ion/Electron</u>

$R_0/L_{T_i} = 10$

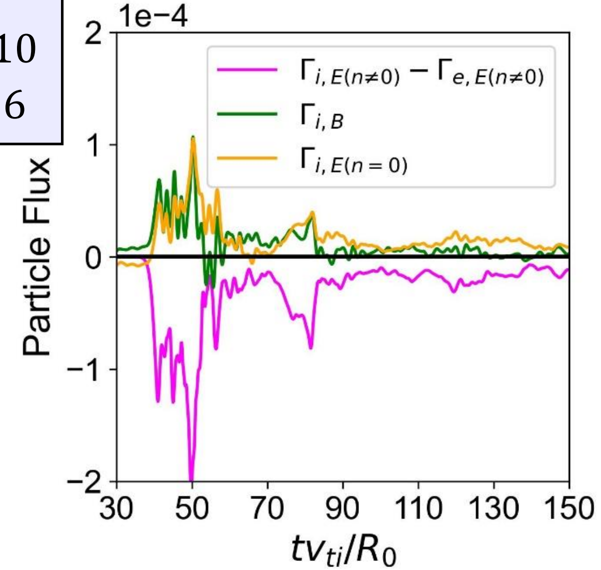
$R_0/L_{T_e} = 10$



<u>(B) Ion</u>

$R_0/L_{T_i} = 10$

$R_0/L_{T_e} = 6$



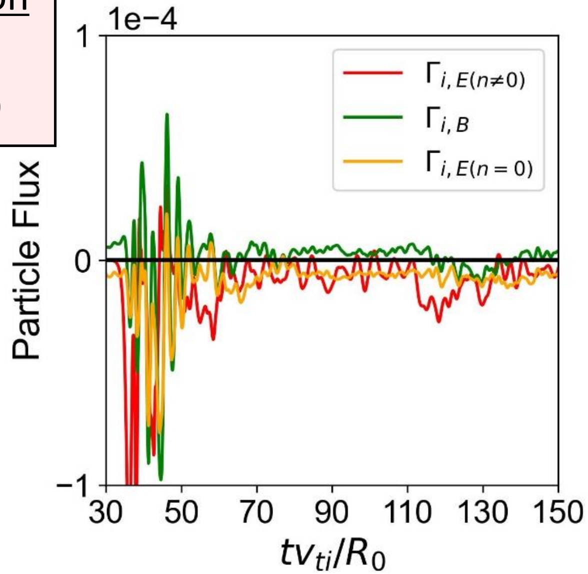
- ✓ It is newly found that particle transport by not only magnetic drift (n=0) but also E × B drift (n=0) are enhanced, which also cancels with E × B drift (n≠0) driven transport.
- ✓ On the other hand, electron particle transport by E × B(n=0) drift cancels with that by E × B drift (n=0) with each other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

Summary of Turbulent Ion Particle Pinch

(A) Ion/Electron

$R_0/L_{T_i} = 10$

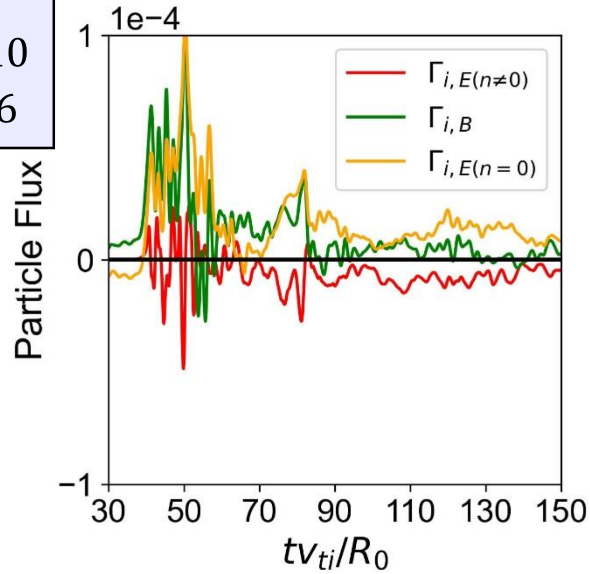
$R_0/L_{T_e} = 10$



(B) Ion

$R_0/L_{T_i} = 10$

$R_0/L_{T_e} = 6$



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

(A): $\Gamma_{i,E(n\neq0)} + \Gamma_{i,E(n=0)} + \Gamma_{i,B} - \Gamma_{e,E(n\neq0)} = 0$

- $\Gamma_{i,E(n\neq0)}$: Negative
- $\Gamma_{e,E(n\neq0)}$: Strongly Positive

(B): $\Gamma_{i,E(n\neq0)} + \Gamma_{i,E(n=0)} + \Gamma_{i,B} - \Gamma_{e,E(n\neq0)} = 0$

- $\Gamma_{i,E(n\neq0)}$: Weakly Negative
- $\Gamma_{e,E(n\neq0)}$: Negative

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

(A): $\Gamma_{i,E(n\neq0)} + \Gamma_{i,E(n=0)} + \Gamma_{i,B} - \Gamma_{e,E(n\neq0)} = 0$

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

(B): $\Gamma_{i,E(n\neq0)} + \Gamma_{i,E(n=0)} + \Gamma_{i,B} - \Gamma_{e,E(n\neq0)} = 0$

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

Summary & Future Plans

(1) Extension of GKNET-FAC to outer core region

- ✓ In addition to appropriate mesh allocation for SOL/divertor region, we have confirmed the validity of GKNET-X through global linear ITG simulations. [S. Okuda *et al.*, 40th JSPF meeting (2023).]

(2) Study of particle transport for fuel supply and impurity exhaust

- ✓ By driving non-axisymmetric electron particle pinch by electron heating, we have found that the axisymmetric ion particle pinch is enhanced though the gyrokinetic ambipolarity condition, leading to the synergetic density peaking of bulk ion. [K. Imadera *et al.*, FEC-2023, submitted to Nucl. Fusion.]
- ✓ Both helium ash exhaust and fuel supply can be also achieved simultaneously by the similar mechanism. [K. Imadera *et al.*, 40th JSPF meeting (2023).]

Future plans

- ✓ Extension of GKNET-FAC/GKNET-X to electromagnetic version
- ✓ Extension of GKNET-FAC/GKNET-X to full-f version
- ✓ full-f simulation for deuterium, helium, electron