Validation studies on local gyrokinetic simulations of tokamak ITG-TEM driven turbulent transport

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Motivations: Local GK sim. approach for future devices

- First principle based gyrokinetic simulation is a promising method to predict transport properties in future devices, such as ITER and DEMO.

--- Local limit --->

McMillan PRL2010

Size scaling of turbulent transport

Local(FT) vs. Global(FG/FF) on $\chi_i / \chi_{GB}$

Nakata NF2013

Conservation of turbulent transport


--- ITG-ae global simulation results are well converged to local ones, and suggest that “Local” simulation approach is well applicable for sufficiently large plasmas with $\rho^{-1} > 300$. 

$\chi_i / \chi_{GB}$ vs. plasma size $\rho^{-1} = a / \rho_{ti}$
Motivations: Validations on ITG-TEM turb. beyond ITG-ae

- Validation studies on ITG/TEM turb. with kinetic electrons are indispensable for realistic tokamaks.

- Transport shortfall (for outer core) is often reported:

  ---> Under-predicted transport levels even with “numerically converged” codes

  ---> Device dependent: DIII-D, C-Mod, AUG, etc

  ---> Sometimes sensitive against experimental error-bars

  ---> Prediction capability for tokamak ITG-TEM driven transport on the developed GK-codes should be carefully examined against existing experiments.

In this study, the first validation studies on JT-60U tokamak are carried out, and ITG/ITG-TEM/TEM turbulent transport properties are investigated.
- **A local fluxtube 5D gyrokinetic simulation code**

  - δf-model: fixed-background
  - Eulerian (Continuum) solver: spectral in 2D (kx,ky)-space, finite-difference in 3D (z, v_||, μ)-space
  - Powerful computational performance on PETA-scale system
  - Electro-static, Electro-magnetic fluctuations
  - Multi-species (MS) with kinetic electrons incl. MS-collisions
  - Realistic geometries for Tokamak and Helical systems
  - Entropy balance/transfer diagnostics

- **Multi-species (MS) GK model including kinetic electrons and MS-collisions:**

  \[
  \left( \frac{\partial}{\partial t} + v_\parallel \cdot \nabla + i \omega_{Da} - \frac{\mu b \cdot \nabla B}{m_a} \frac{\partial}{\partial v_\parallel} \right) \delta h_{ak_\perp} - \frac{c}{B} \sum_{\Lambda} b \cdot (k'_\perp \times k''_\perp) \delta \psi_{ak'_\perp} \delta h_{ak''_\perp} \\
  = \frac{e_a F_{Ma}}{T_a} \left( \frac{\partial \delta \psi_{ak_\perp}}{\partial t} + i \omega_a T_a \delta \psi_{ak_\perp} + v_\parallel \frac{\mu b \cdot \nabla B}{T_a} J_0 \delta \phi_{ak_\perp} \right) + \sum_b \int \frac{d\varphi}{2\pi} e^{ik_\perp \cdot \varphi} \left( C_{ab}^{TS} \left( e^{-i k_\perp \cdot \rho_b} \delta h_{ak_\perp} \right) + C_{ab}^{F} \left( e^{-i k_\perp \cdot \rho_b} \delta h_{bk_\perp} \right) \right)
  \]
Extension for realistic tokamak MHD equilibria

- GKV is connected to MHD/Integrated-transport solvers thorough a newly developed interface IGS.

MEUDAS (EQDSK form)
Free-boundary G-S solver

TOPICS (EQDSK form)
Integrated transport solver

\[ \Psi(R, Z), P(\Psi), I(\Psi) \]

IGS (interface)
Flux coordinate Interface
Interpolation, tracing flux surfaces
Constructing Axisymmetric, Hamada, and Boozer coordinates

\[ g^{ij}(z), J(z), B(z) \]

GKV
Local fluxtube code
Calculating metric components and advection operators
Turbulence simulation

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GKV-TOPICS/MEUDAS cooperative study enables the detailed experimental analyses and optimizations on micro-stability/turbulence.

M. Nakata and A. Matsuyama et al., PFR2014
L-mode plasma on JT-60U investigated

JT-60U L-mode plasma: E45072T1010 [Yoshida, PPCF2006]

Plasma profiles

\[ n_e [10^{19} \text{ m}^{-3}] \]

\[ q(\rho) \]

\[ s(\rho) \]

\[ T_i [\text{keV}] \]

\[ T_e [\text{keV}] \]

\[ \frac{V_\phi}{v_{ti}} \]

\[ T_i < T_e \sim 2 \text{keV} \]

\[ V_\phi/v_{ti} \sim 0 \] (almost zero rotation)
- sufficiently large normalized plasma size $\rho^*^{-1}$: $1/\rho^* = a/\rho_{ti} \sim 500$
- moderate collisionality (still banana-plateau): $\nu^*_{i/e} \sim 0.1$
- weak mean Er-shear

$\gamma_{Er} \sim 0.1 R_{ax}/v_{ti} < \gamma_{lin}$

--->
Target discharge is carefully chosen such that “Local limit condition” is well satisfied for the (L-mode) plasma investigated here.
Linear micro-stability analyses

- GKV results on linear micro-stabilities at $\rho=0.25$, 0.50, 0.75

JT-60U L-mode D-plasma: E45072T1010

(a) $\rho=0.25$
- ITG-ke (kinetic elec.)
- ITG-ae (adiabatic elec.)
- TEM/ETG
- ETG-ai (adiabatic ion)

(b) $\rho=0.50$
- ITG-ke
- TEM/ETG
- ITG-ae
- ETG-ai

(c) $\rho=0.75$
- TEM/ETG
- ITG-ae
- ETG-ai

$\rho=0.25$: ITG (TEM&ETG stable)  $\rho=0.50$: ITG-TEM (-ETG)  $\rho=0.75$: TEM (-ETG)

(weak impact of kinetic (trapped) elec.)  (strong impact of kinetic elec.)

--- Different mode-structures depending on radial positions: ITG --> ITG-TEM --> TEM

--- Adiabatic electron approximation is valid only for the inner core region.

--- Quasilinear flux ($\propto \gamma/k^2$) increases towards outer region.
Nonlinear turbulence simulations

- Numerical resolution for Deuterium-electron system (No-impurities here)
  \( (168k_x, 32k_y, 64z, 64v, 32m) \)-grids, \( 0.07<k_y\rho_{ti}<2.2, 0.09<k_x\rho_{ti}<7.90, \Delta t = 6.5 \times 10^{-4} \frac{R_{ax}}{v_{ti}} \)

- Entropy balance/transfer relations are accurately satisfied in nonlinear simulations:

\[
\frac{d}{dt} \delta S_s + R_s = \sum_k J_{k}^{es} X_{ks} + \sum_k J_{k}^{em} X_{ks} + D_s, \quad s=(i, e), \quad k = (n, T)
\]

1) entropy variation  2) field-particle interaction  3) electro-static fluxes  4) electro-magnetic fluxes  5) collisional dissipation

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Kinetic turbulent dynamics for both ion and electron is accurately resolved:

Relative error \( |\Delta_i/D_i| < \sim 1\% \) for ions, \( |\Delta_e/D_e| < \sim 6\% \) for electrons

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Not only transport levels, detailed nonlinear interactions among turbulent vortices and zonal flows (ZF) can be quantified.
- Spectral-temporal evolution of ion heat flux

- Comparisons of ion & electron heat diffusivity

--- GKV with kinetic elec. shows good agreement with EXP. in core region ($\rho<~0.5$), while TGLF does only qualitatively.

--- “Transport shortfall” appears in $\chi_i$ in the outer region ($\rho\sim0.75$).
Turbulence intensity and ZF-generations in core region

JT-60U L-mode D-plasma: E45072T1010

- Radial profile of mean turb. intensity and normalized-ZF.

\[ \rho = 0.50 (\text{ITG-TEM}) \quad \rho = 0.30 (\text{ITG}) \]

Quite small error \( \sim 0.1\% \)

\[ \left| \frac{T_{zf}}{Q_i} \right| \]

\[ \left| \frac{\phi_{zf}}{\phi_{total}} \right| \]

--- ZF production rate and amplitude are similar in the core region of ITG/ITG-TEM: (ITG-comp. is dominant.)

--- Stronger ZF generation for outer region, while Turb.-intensity \( \propto \gamma/k^2 \). (discussed later)
Different impact of zonal flows on each transport channel

- To identify the ZF-dependence on multiple transport channels is useful for deeper understanding of transport processes.

--- We apply a nonlinear functional technique for core ITG-TEM turbulence sim. data.

\[ F[T, Z] = c_T T^{\alpha_T} (1 + c_Z Z^{\alpha_Z} / T)^{-1}, \]

where

- \( T = \sum_{k_{\perp} (\text{trb})} k_{\perp}^2 |\delta \phi_{k_{\perp}}|^2 \)
- \( Z = \sum_{k_{\perp} (\text{zf})} k_{\perp}^2 |\delta \phi_{k_{\perp}}|^2 \)

\( C_T, C_Z \): const. \( \alpha_T, \alpha_Z \): exponents

(Turb. energy) (ZF energy)

- If \( F[T, Z] \) reproduces each transport level on simulations, the exponents \( \alpha_T/\alpha_Z \) give nonlinear turbulence/zonal-flow dependence for each transport channels:

  ion thermal transport \( \chi_i/\chi_{GB} \): \( \alpha_T = 0.38, \alpha_Z = 0.78 \)
  electron thermal transport \( \chi_e/\chi_{GB} \): \( \alpha_T = 0.93, \alpha_Z = 0.42 \)
  particle transport \( D/\chi_{GB} \): \( \alpha_T = 1.20, \alpha_Z = 0.25 \)

--- Distinct ZF-impact (\( \alpha_Z \)) on heat/particle transport is newly identified, i.e., weaker impact on \( D \) and \( \chi_e \) compared to \( \chi_i \). (useful insights for transport modeling)

--- cf. Nunami et al, PoP2013

\(*\) well fitted!
Transport shortfall in outer region

- Comparisons of ion & electron heat diffusivity

- ZF production rate and amplitude

--- TEM turbulence at shortfall region ($\rho \sim 0.75$) shows more efficient ZF generation compared to ITG region.

--- ZF oscillation is significant for TEM in the outer region.
- To identify the shortfall property, nonlinear scans with respect to equilibrium gradient parameters and maximum fluctuation scale, etc. are carried out. (cf. Told PoP2013)

$$\rho = 0.75$$

Comparison of $\chi_i$ between QL and NL

| $\rho$ | $\gamma_{\text{lin}(\text{max})}$ | $\sum \gamma_{\text{lin}}/k_\theta^2$ | $\chi_i/\chi_{i\text{GB}}$ | $|\delta \phi_{zf}|^2/|\delta \phi_{\text{total}}|^2$ |
|-------|-----------------|----------------|----------------|-----------------------------|
| 0.50  | 0.69            | 31.4           | 14.5 ($\sim \text{EXP.}$) | 0.41                        |
| 0.75  | 1.59            | 71.2           | 11.6 (shortfall)   | 0.71                        |

ZF (and/or GAM) is a key for the present shortfall

Shortfall observed here is rather insensitive to equilibrium parameters due to strong generation of TEM-driven ZF: the suppressed-ZF gives a recovery of ion heat transport.

--- Full-scale spectra? (cf. Maeyama IAEA2014)

More detailed investigations are left as a future work
Summary

- In this work, the first validation study against JT-60U tokamak experiments (L-mode) are carried out using a local gyrokinetic code GKV incorporating realistic magnetic geometry and fully-gyrokinetic electrons.

--- GKV simulations show good agreement with experimentally observed ion and electron transport levels in the core region, where the conventional adiab.-elec.- and TGLF models indicate some deviations.

--- Distinct nonlinear ZF dependence on multiple transport channels is identified, i.e., weaker impact on the electron heat and particle transport compared to the ion heat one.

--- In the outer region, transport shortfall is observed also in JT-60U case; it is found that strong ZF and/or GAM generation dominantly contributes to it, and the sensitivity on equilibrium parameters is weakened.

These findings on good agreement with core experimental results, including the ZF-impact contribute to more improvement of the prediction capability and reduced transport model.