Finite orbit width effect on the neoclassical toroidal viscosity in the superbanana-plateau regime

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Outline

1. Introduction

2. Numerical verification of NTV by global kinetic simulations

3. Finite orbit width effect on NTV

4. Another application of GT5D for 3D geometry

5. Summary
3D effect is a key issue for plasma confinement in tokamaks.

- Small resonant 3D perturbation affects on tokamak plasmas.
  - stability: ELM mitigation
  - transport: Neoclassical Toroidal Viscosity (NTV), Rotation

Discrepancy of NTV prediction:

\( \nu_b^* \)-dependency

- [Shaing, PPCF2009] \( \nu_b^* \)-independent NTV (Superbanana-plateau theory)
- [Satake, PRL2011] \( \nu_b^* \)-dependency by FORTEC-3D code.

Purpose

Clarify the cause of the discrepancy by using two different types of global kinetic simulations.
Superbanana-plateau theory for NTV

- Local, bounce-averaged drift-kinetic equation.
- Toroidal precession, $\langle \omega_B \rangle_{bc} = 0$, gives the resonant condition.
- Magnetic shear shifts the resonance $\kappa^2$ towards the boundary [Shaing, JPP2015].
- Non-axisymmetric part of $\delta B$ is only retained through the perturbed radial drift.
- **Independent of collisionality.**
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Circular tokamak with $\delta B$

- $B_{\text{ax}} = 1.91$ T
- $a_0 = 0.47$ m / $R_{\text{ax}} = 2.35$ m
- $1 / \rho^* = 150$
- $q = 0.854 + 2.184 (r / a_0)^2$ (positive shear)
- $E_r = 0$ (fixed)
- $\nu_b^* = 0.12$ (base case)

In the superbanana-plateau regime
scan: $\nu_b^* \times 0.01, 0.1, 1, 5, 10, 50$

- $\delta B / B_{\text{ax}} = 0.5\%$ with $m/n = 7/5$
- resonant surface with $q = 1.4$ at $r/a_0 \approx 0.5$.

Global kinetic code

- **GT5D**; Full-f Eulerian code for gyrokinetic simulations
- **FORTEC-3D**; $\delta f$ Monte Carlo (particle) code for drift-kinetic (neoclassical) simulations
\( \nu_b^*\)-dependency of NTV arises in global sims.

NTV of global kinetic simulations reproduce similar \( \nu_b^*\)-dependency over the wide ranges of collisionalities.

- SBP theory gives constant NTV.
- GT5D/FORTEC-3D gives lower NTV.
- GT5D/FORTEC-3D shows \( \nu_b^*\)-dependency.

NTV of SBP theory \((E_t = 0)\) is evaluated as:

\[
\langle e_\zeta \cdot \nabla \cdot P \rangle = -\eta_1 n_i m_i v_{th}^2 R_{ax} \sqrt{\frac{\epsilon}{2\pi}} \frac{d \ln p_i}{dr}
\]

\[
\eta_1 = n \Gamma \left( \frac{5}{2} \right) 4K (\kappa_{\text{res}}) \kappa_{\text{res}}^2 (1 - \kappa_{\text{res}}^2) |a_n^2 + \beta_n^2|
\]

\( \kappa_{\text{res}} \simeq 0.83 \)
No resonant structure in global simulations.

Velocity space structures of non-axisymmetric part of $f$ are successfully verified.

- Non resonant structures along the boundary (barely-trapped) region.
- Rather complicated structures are observed.
- Especially, a clear large scale structure appears in trapped region.
- Complicated structures survive for smaller $\delta B \approx 0.05\% \rightarrow$ determined by unperturbed orbit.
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Absence of resonance results from the large finite orbit width of barely-trapped (resonant) particles.

- Banana width $\Delta_b/a_0 = 0.17$ for $v/v_{th} = \sqrt{2}$; variation of $q = 1.2 - 1.59$.
- Barely-trapped particle feel the perturbation only for a fraction of the bounce period.
  - Perturbation becomes less effective.
- Bounce-average of $dr/dt$ significantly decreases as $m$ increases.

Barely-trapped particle orbits with contour plot of $(b \times \nabla B_1) \cdot \nabla r$

mass (banana-width) dependency of $\langle dr/dt \rangle_{bc}$
FOW generates finite-\(l\) mode, causes phase-mixing.

\(\delta n\) sampled along the bounce motion

- Non-zero (finite) mode structure appears along the bounce motion.
- Finite-\(l\) along the bounce motion causes the phase-mixing as;
  \[
  \partial_t \delta f_l + il\omega_{bc} \delta f_l = 0
  \]
- Phase mixing generates fine scale structures in lower \(\nu_b^*\).
- Makes NTV smaller in lower \(\nu_b^*\).
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Full-f gyrokinetic simulations for 3D field

GT5D+VMEC
- Solves gyrokinetic equation.
- Global full-f model.
- VMEC equilibrium for 3D field.
- Eulerian approach.
  - Conservative Morinishi scheme.
- Radial electric field solver.
  - Ambipolar condition of neoclassical transport.
- Neoclassical benchmark has been initiated.

Benchmark case parameters
- LHD inward shifted configuration with $R_{ax} = 3.6$ m and $B_{ax} = 3.0$ T.
- $a_0 = 0.63$ m.
- $T_{i,ax} = 0.91$ keV, and $n_{e,ax} = 3.5 \times 10^{18}$ m$^{-3}$. 
(Preliminary) NC Benchmarks w/ and w/o Er

- NC particle flux of GT5D+VMEC shows fairly good agreement with FORTEC-3D.
- $1/\nu$-regime; $\nu_b^* \approx 0.15$ @ $\rho \approx 0.51$.
- (bottom) $E_r$ is determined according to the ambipolar condition of $\Gamma$. 

![Graph of NC particle flux for GT5D and FORTEC-3D](image1)

![Graph of $E_r$ for GT5D and FORTEC-3D](image2)
Summary

FOW effect on NTV in Superbanana-Plateau regime

- NTV of GT5D well reproduces the $\nu$-dependency of NTV and velocity space structure of FORTEC-3D simulations.

- Large banana width of the unperturbed orbit plays a key role in NTV physics.
  1. Radial drift caused by perturbation significantly decreases. $\rightarrow$ Smaller NTV.
  2. Finite-l mode along the bounce motion causes the phase mixing $\rightarrow$ $\nu$-dependency.

GT5D+VMEC

- Global full-f gyrokinetic simulation code for 3D geometries.

- Equilibrium from VMEC is incorporated into GT5D via the newly developed interface.

- First neoclassical benchmarks w/ and w/o Er show good agreements with FORTEC-3D.