Gyrokinetic simulation of helical plasmas with field-line-label dependence

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Outline

- Introduction
- Zonal-flow response in tokamak and helical systems with no $E_r$ ($E_r$: equilibrium-scale radial electric field)
- Zonal flow response in helical systems with $E_r$
  - Radial wavenumber dependence of ZF response
  - Mach number dependence of ZF response
- ITG mode simulations for helical systems with $E_r$
- Summary
Zonal flow response in helical configurations
Effect of Helical Field on Zonal Flow

\[ B = B_0 \left[ 1 - \varepsilon \cos \theta - \varepsilon_t \cos(L \theta - M \zeta) \right] \]

- Radial drift motion of helical-ripple-trapped particles leads to additional shielding effect of zonal flow.

Classification of particle orbits in helical system

\[ \langle v_{dr} \rangle_b \]
Zonal-Flow Enhancement in LHD Configuration

- Reduction of helical-ripple-trapped particle’s drift improving the neoclassical transport also enhances the zonal-flow response with small shielding due to helical-ripple trapped particles.
- Higher ZF response is found for the inward-shifted LHD configuration.

Ferrando, Sugama & Watanabe, PoP 2007
Watanabe, Sugama & Ferrando, PRL 2008
Stronger zonal flows generated in inward-shifted configuration lower the ITG turbulent transport

GKV simulation results for the I.-S. and Standard cases (Watanabe, Sugama, & Ferrando., PRL 2008)
Zonal flow response in helical systems with $E_r$
Effects of Equilibrium-Scale $E_r$ on Zonal-Flow Response

- Equilibrium-scale $E_r$ field generates an $E_xB$ component of the drift velocity.
- The poloidal $E_xB$ rotation with reduced radial displacement $\Delta E$ will decrease the shielding of zonal-flow potential and increase its response!

(Mynick & Boozer, PoP 2007)
Zonal Flow Responses

- Zonal flow response in tokamak (Rosenbluth-Hinton)

\[ K \equiv \frac{\langle \phi_{k_x}(t = \infty) \rangle}{\langle \phi_{k_x}(t = 0) \rangle} = \frac{1}{1 + G} \approx \frac{1}{1 + 1.6q^2/\epsilon^{1/2}} \]

- In case with no radial electric field \((E_r=0)\)

\[ K_L(t) \equiv \frac{1 - (2/\pi)(2\epsilon_H)^{1/2}\{1 - g_{i1}(t, \theta)\}}{1 + G + \mathcal{E}(t)/(n_0\langle k_{\perp}^2 a_i^2 \rangle)} \]

- Long-time response of zonal flow in case with \(E_r\)

\[ \phi(t) = \frac{\phi(0)}{1 + G_p + G_i + M_p^{-2}(G_{hi} + G_h)(1 + T_e/T_i)} \]

\[ M_p = \left| \omega_\theta \frac{R_0 q}{v_{ri}} \right|, \quad \omega_\theta = -\frac{cE_r}{r_0 B_0} \]

Sugama, Watanabe & Ferrando, PFR 2008; Sugama & Watanabe, PoP 2009
GK Equation for ZFs with $E_r$

- **Field-line label $\alpha$ dependence of $|B|$**

\[
B = B_0 \left[ 1 - \varepsilon_i(r) \cos(\alpha + i\zeta/2\pi) - \sum_l \varepsilon_l(r) \cos(l\alpha + (l/2\pi - M\zeta)) \right]
\]

- **Gyrokinetic equation for zonal flows with $E_r$**

\[
\begin{aligned}
\frac{\partial}{\partial t} + v_{i\parallel} \hat{b} \cdot \nabla + ik_r \cdot v_d - \mu (\hat{b} \cdot \nabla \Omega) \frac{\partial}{\partial v_{i\parallel}} + \omega_\theta \frac{\partial}{\partial \alpha} \delta f &= -ik_r \cdot v_d \frac{e<\psi>}{T_i} F_M \\
\end{aligned}
\]

- **Even if the zonal-flow potential is independent of $\alpha$, $\alpha$-dependence of $\delta f$ appears through $v_d$ term etc.**

- **Symmetry of $E_r$ => - $E_r$ & $\alpha$ => - $\alpha$ is kept.**

\[\alpha = \theta - \zeta/q\]

\[\omega_\theta = -cE_r/r_0B_0\]

\[\text{α-dependence}\]
GKV Simulation of ZF Enhancement by Equilibrium-Scale $E_r$

- Single helicity model
  $\varepsilon_h = \varepsilon_t = 0.1$ and $\varepsilon_- = \varepsilon_+ = 0$

- Inward-shifted LHD model
  $\varepsilon_h = \varepsilon_t = 0.1$, $\varepsilon_- / \varepsilon_t = -0.8$, and $\varepsilon_+ / \varepsilon_t = -0.2$
**$k_r$-dependence of Residual Zonal-Flow Levels**

- The residual level with small $k_r$ vanishes for $M_p = 0$, but remains finite for non-zero $M_p$.
- Stronger enhancement of the ZF response by $E_r$ for the inward-shifted case.
$M_p$-Dependence of ZF Response

- Residual ZF amplitude increases with the poloidal Mach number, $M_p$, in agreement with the theoretical estimate.

- $M_p$ increases with the ion mass for the same $E_r$ and $T_i$.
  - Neoclassical transport analysis predicts almost the same $E_r$ and $T_i$ for H and D discharges.

Isotope effect on ZF response
ITG mode simulations for helical systems with $\alpha$-dependence and $E_r$
Linear GK simulations of ITG modes in helical systems with $\alpha$-depend.

- The field-line-label dependence is incorporated into terms related to $k_r v_d$ and $\Omega_i$ in the GKV code.

- Linear growth rates measured at different time (before and after the mode coupling appears through $\alpha$)
- Radial electric field does not much influence the linear ITG growth.
Summary

- Zonal-flow response in helical system is increased by slowing the radial drift of trapped particles or by imposing the equilibrium-scale $E_r$.
- Shielding effect of helical-ripple-trapped particles is improved by helical field optimization as well as $E_r$.
  - New GKV simulations confirm enhancement of zonal-flow response by $E_r$.
- The results suggests stronger ZF in the inward-shifted configuration with $E_r$ for heavier ion mass.
- ITG mode simulations for helical systems with the field-line-label dependence have been tried.
- Nonlinear simulation with $E_r$ is currently in progress.