Topic: TH-S

Kinetic stability modification of resistive wall mode in tokamaks by drift-kinetic orbit effects

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Toroidal nonaxisymmetry, which can be either internally generated by magnetohydrodynamic (MHD) activity or turbulence, or externally applied by nonaxisymmetric coils, can substantially modify global stability and performance of tokamaks. The importance of the kinetic particle response to such nonaxisymmetry has been continuously emphasized, since perturbed particle orbits due to nonaxisymmetric magnetic perturbations can drive anisotropic pressures and change neoclassical particle transport and the associated kinetic energy. This presentation extends the understanding of neoclassical transport and stability in perturbed tokamaks through a unification of neoclassical toroidal viscosity (NTV) and kinetic potential energy, δW_K.

One of essential results of nonaxisymmetric magnetic perturbations is the NTV torque, which is driven by net radial drift of particles across flux surfaces due to the non-uniformity of magnetic field strength along the field lines. The complicated interaction between drift-kinetic orbits and nonaxisymmetric magnetic perturbations can be elucidated by accurately tracking the guiding-center particle motions [1]. Resonance of perturbed orbits with toroidal ExB rotation, called the bounce-harmonic (BH) resonance, changes trapped bounce orbits to closed circuits as shown in Fig. 1, which presents a trapped bounce orbit without ExB and its modification to a closed orbit calculated by the Particle Orbit Code for Anisotropic pressures (POCA) [2]. The BH resonance dominantly contributes to perturbed pressures and NTV torque in the rotating plasmas with nonaxisymmetric magnetic perturbations, while random phase-mixing reduces the nonambipolar particle transport for off-resonance particles.

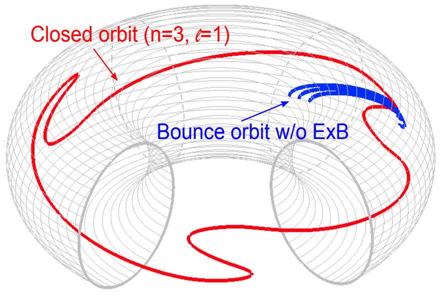

Figure 1. Comparison of bounce orbit without ExB and its modification to closed orbit by BH resonance.

Such driving mechanism of NTV by the BH resonance also plays a very important role in the kinetic stabilization of slowly growing MHD modes such as the resistive wall mode (RWM), which is essential to achieve high beta tokamak operation without disruption. Their unified study was enabled by a theoretical demonstration of the equivalence of NTV and kinetic potential energy [3]; the imaginary part of NTV is identical to the real part of kinetic potential energy. It was shown that NTV and kinetic potential energy are identical in formalism but only differ in the resonance operator, $\mathcal{R}$, due to a phase shift, as

$$\mathcal{R}_{NTV} = \frac{n^2\nu}{\left[l\omega_b - n\left(\omega_E+\omega_B\right)\right]^2+\nu^2} \qquad \mathcal{R}_{\delta W_K} = \frac{n\left[n\left(\omega_E+\omega_B\right)-l\omega_b\right]}{\left[l\omega_b - n\left(\omega_E+\omega_B\right)\right]^2+\nu^2}.$$

Here ω_E, ω_b, ω_B, and ν are the frequencies of ExB, bounce motion, magnetic precession, and collision, respectively, n is the toroidal mode number, and ℓ represents the bouncing class of particles. The phase shift results in the change of resonance frequency condition as shown in Fig. 2, where $\omega_E \neq \ell\omega_b$ for kinetic potential energy while $\omega_E \sim \ell\omega_b$ for NTV.

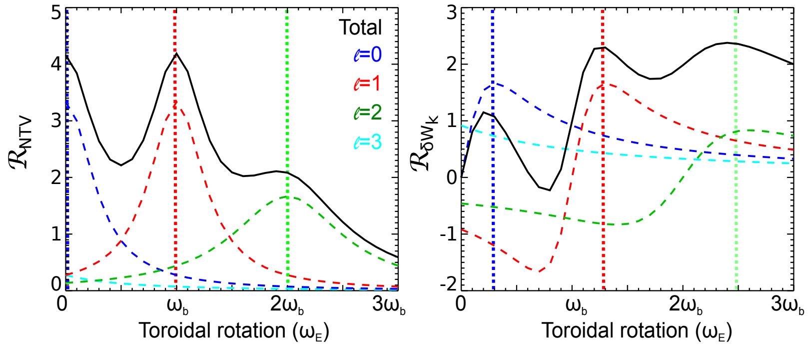

Figure 2. Plot of resonance operator for NTV (left) and kinetic potential energy (right). Vertical broken lines indicate the resonance ω_E for particle's bouncing class ℓ. The resonance ω_E for δW_K is largely shifted from ω_E for NTV.

It should be noted that semi-analytic integration of the resonance operator in NTV and kinetic stability theories is based on the closed orbit assumption, and this means the accuracy of the subsequent theoretical results may be not highly guaranteed when orbits are not closed. This possible inaccuracy of the semi-analytic theory with open orbits might be acceptable in NTV calculations due to the sub-dominance of open orbits. For the real part of the kinetic potential energy, however, a large contribution is expected to come from open orbit particles that are not in rotational resonance. That is, orbits can be even more complicated than expected, thus more precise calculations may be required without conventional assumptions such as closed orbits or bounce-averaging.

The drift-kinetic particle simulation can be a useful tool to improve kinetic potential energy and RWM analysis. A possible improvement of stability analysis with particle simulation is presented in Fig. 3, where the NTV torque and the real part of the kinetic potential energy were calculated using the POCA code. A NSTX discharge marginally stable to the RMW was analyzed, where the kinetic stabilization effect was previously calculated to be too large to explain the experimental marginal stability [4]. In this discharge, POCA simulations predict that plasmas approach marginal stability as toroidal rotation decreases, due to the reduced kinetic potential energy from the phase-mixing effect of bounce orbits. A benchmarking study between particle simulation and semi-analytic theory in an analytical Solov'ev equilibrium indicated that POCA gives smaller kinetic potential energy than the semi-analytic prediction by the PENT code [5], which could help explain previous over-predictions of stability.

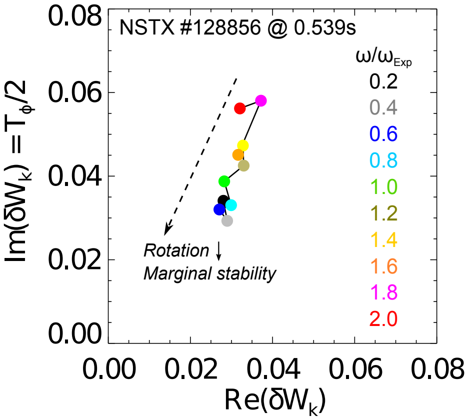

Figure 3. Behavior of NTV and δW_K in the variation of toroidal rotation. Plasma approaches marginal stability as rotation decreases.

This presentation will further show benchmarking studies of NTV and kinetic potential energy between POCA, PENT, MISK, and MARS-K codes. Analysis on the kinetic stability modification of RWM in NSTX using the particle simulation will be discussed with focus on the role of realistic perturbed orbit dynamics. This study will extend understanding of the neoclassical particle transport and kinetic energy principle in tokamaks with nonaxisymmetry.

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[1] K. Kim et al., Phys. Plasmas 19, 082503 (2012)
[2] K. Kim et al., Phys. Rev. Lett. 110, 185004 (2013)
[3] J.-K. Park, Phys. Plasmas 18, 110702 (2011)
[4] J.W. Berkery et al., Phys. Rev. Lett. 104, 035003 (2010)
[5] N.C. Logan et al., Phys. Plasmas 20, 122507 (2013)