Topic: TH-C/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 tokamkas. Importance of kinetic particle response to such nonaxisymmetry has been continuously emphasized, since the perturbed particle orbit by the nonaxisymmetric magnetic perturbation (NAMP) can drive anisotropic pressures and change neoclassical particle transport and associated kinetic energy. This presentation extends the understanding of neoclassical transport and stability in the perturbed tokamaks throughout a unification of neoclassical toroidal viscosity (NTV) and kinetic potential energy, δW_K.

One of essential results of the NAMP 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 NAMP 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 orbit to closed circuit as shown in Fig. 1, which presents a trapped bounce orbit without ExB and its modification to a closed orbit calculated by Particle Orbit Code for Anisotropic pressures (POCA) code [2]. The BH resonance dominantly contributes to perturbed pressures and NTV torque in the rotating plasmas with NAMP, while random phase-mixing reduces the nonambipolar particle transport in the off-resonance.

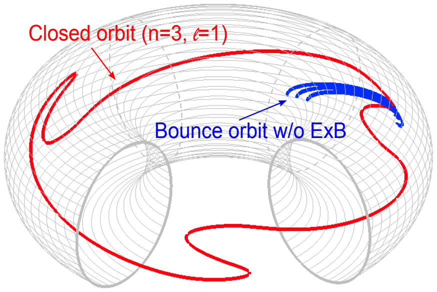

Figure 1. Comparison of bounce orbit without ExB and its modification to closed orbit by BH resonance.

Such driving mechanism of NTV by the BH resonance also plays a very important role on the kinetic stabilization of slowly growing MHD modes such as resistive wall mode (RWM), which is essential to achieve high beta tokamak operation without disruption. Their unified study was enabled by a theoretical progress on 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

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

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.

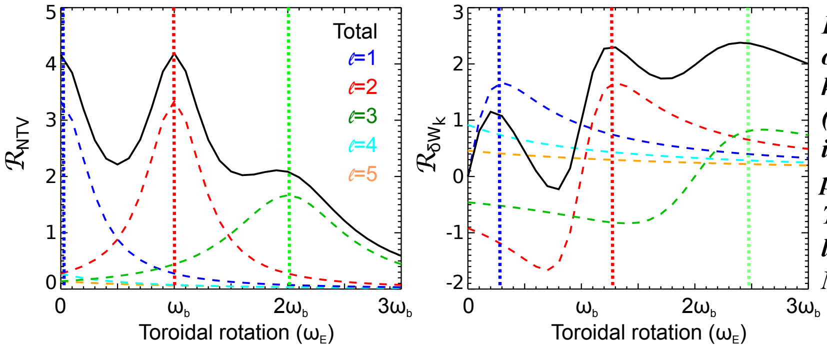

Figure 2. Plot of resonance operator for NTV (left) and kinetic potential energy (right). Vertical broken lines indicate the resonance ω_E for particle's bouncing class ℓ. The resonance ω_E for δW_K is largely shifted from ω_E for NTV.

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 to NTV due to their sub-dominance. For the other part of the kinetic potential energy, however, the dominant contributions are expected from the largely open orbits in the off-resonance. That is, orbits can be even more complicated than expected, thus it may require more precise calculations without the conventional assumptions such as closed orbits or bounce-averaging.

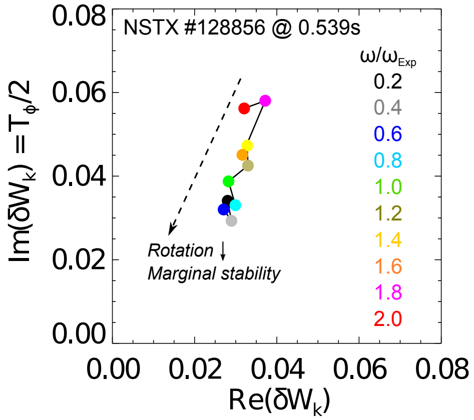

Figure 3. Behavior of NTV and δW_K in the variation of toroidal rotation. Plasma approaches marginal stability as rotation decreases.

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 kinetic potential energy were calculated using the POCA code. A NSTX discharge marginally stable to RMW was analyzed, where insufficient stabilization effect by the kinetic particles was reported [4]. In this discharge, POCA simulations predict consistent behavior of kinetic stability such that plasmas approach marginal stability in the diagonal direction as toroidal rotation decreases, due to the reduced kinetic potential energy by phase-mixing effect of bounce orbits. This is also consistent with a benchmarking study between particle simulation and semi-analytic theory in the Solov'ev equilibrium, indicating the POCA gives smaller kinetic potential energy than the semi-analytic prediction by PENT code [5].

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 provide a unified understanding of the neoclassical particle transport and kinetic energy principle in the tokamaks with nonaxisymmetry.

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