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Analysis of JT-60U experiment by extended kinetic-MHD model

拡張された運動論的MHDモデルによるJT-60U実験解析

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The kinetic-magnetohydrodynamic (MHD) model is extended to include toroidal rotation effect self-consistently. The first extension is due to generalization of the guiding-center Lagrangian to include rotation. The second extension stems from rotational modification to an equilibrium distribution function. These extensions lead to generalization of energy exchange between MHD modes and particles' motion. Numerical analysis indicates that although the conventional kinetic-MHD model shows that unstable region exists in large toroidal rotation regime, such unstable region vanishes in the extended kinetic-MHD model.

1. Introduction

The kinetic-magnetohydrodynamic (MHD) model is a theoretical framework to describe the dynamics whose characteristics cannot be captured by the ideal MHD. The kinetic-MHD model investigates particles' motion effect on MHD dynamics by consolidating particles' effect into the total pressure tensor. Recently, thermal particles' precession effect on resistive wall modes (RWMs) gains more momentum, since the kinetic-MHD model has revealed that slow rotation comparable with particles' drift motion leads to kinetic damping of RWMs [1]. In this paper, we exclusively focus on the RWM stability since onset of RWMs limits achievable beta value in advanced tokamaks.

The JT-60U experiment clearly shows that the loss of toroidal rotation shear at a rational surface $q = 2$ leads to destabilization of RWM [2]. This experiment motivated us to extend the kinetic-MHD model to include toroidal rotation effect self-consistently, since the conventional model [3] employs the formulation without rotation.

2. Structure of conventional kinetic-MHD model

The final goal of the kinetic-MHD model is to compute energy exchange between MHD modes and particles' motion. This quantity is denoted by δW_k, which is invoked in dispersion relation. Since RWMs have small growth rate and real frequency, the dispersion relation reads [1]

$$-i(\omega_r + i\gamma)\tau_w = -\frac{\delta W_\infty + \delta W_k}{\delta W_b + \delta W_k}, \qquad (1)$$

where ω_r (γ) is the real frequency (growth rate) of the RWM , τ_w is the wall decay time, and δW_∞ and δW_b are fluid potential energies with a wall at infinity and at $r = b$ respectively (r is a well-define radial coordinate). Since δW_∞ and δW_b are real, the RWM stability is strongly affected by δW_k that has an imaginary part due to kinetic resonance. Hence, accurate estimate of δW_k is essential for the kinetic-MHD model. In the conventional kinetic-MHD model, δW_k is schematically written as [1,3]

$$\delta W_k \propto \sum_l \int \left|Y_l^0\right|^2 \lambda_l \, dr dE_k d\Lambda, \qquad (2)$$

where l is the Fourier harmonic index of bounce motion, Y_l^0 is a bounce-averaged Fourier component of an oscillating part of the perturbed conventional guiding-center Lagrangian $L_0^{(1)}$, E_k is the kinetic energy, and Λ is the pitch angle variable. The resonance fraction λ_l yields the imaginary part in the conventional kinetic-MHD model. The resonance fraction can be schematically written as $\lambda_l = L_l f$ where L_l is a differential operator.

3. Extension of the kinetic-MHD model

The first extension is due to the rotational modification to the perturbed guiding-center Lagrangian as $L^{(1)} = L_0^{(1)} + L_1^{(1)} + L_2^{(1)}$ where $L_1^{(1)}$ and $L_2^{(1)}$ are the perturbed guiding-center Lagrangians related to Coriolis and centrifugal acceleration, respectively [4]. The second extension stems from the equilibrium distribution function. In the conventional kinetic-MHD model, the equilibrium distribution function is assumed to be non-shifted Maxwellian, which leads to the standard resonance fraction λ_{l0}. In the extended kinetic-MHD model, the equilibrium distribution function modified by rotation [5] is employed $f_i \propto e^{M_i \Omega^2 \langle R^2 \rangle / 2T_i}$, where Ω is the toroidal rotation frequency, $\langle R^2 \rangle$ is the magnetic-flux average of the squared R coordinate, and T_i is the ion temperature. This brings about the generalized resonance fraction as $\lambda_l = \lambda_{l0} + \lambda_{l1}$ where $\lambda_{l1} \propto \Omega d\Omega / d\psi$ depends on the toroidal rotation shear since the operator L_l contains the derivative $\partial / \partial \psi$.

These extensions leads to the generalized δW_k as $\delta W_k = \sum_{j=0}^{3} \delta W_{kj}$, where terms $\propto Y_l^1 \lambda_{l1}$ and $Y_l^2 \lambda_{l1}$ are neglected due to their smallness. In addition to the conventional term $\delta W_{k0} \propto |Y_l^0|^2 \lambda_{l0}$, we obtain new terms, the Coriolis term $\delta W_{k1} \propto Y_l^{0*} Y_l^1 \lambda_{l0}$, the centrifugal term $\delta W_{k2} \propto Y_l^{0*} Y_l^2 \lambda_{l0}$, and the rotation shear term $\delta W_{k3} \propto |Y_l^0|^2 \lambda_{l1}$. When there exists no rotation, we get $Y_l^1 = Y_l^2 = 0$ and $\lambda_{l1} = 0$, i.e., $\delta W_{k1} = \delta W_{k2} = \delta W_{k3} = 0$, hence we obtain the conventional result (2). These additional terms are overlooked in the conventional model.

4. Numerical analysis of JT-60U like equilibrium

Since computation of δW_k requires the fluid displacement, we utilize the MINERVA/RWMaC [6], which solves the RWM dynamics in tokamak geometry. We employ a JT-60U like equilibrium from experimental data, which revealed that loss of rotation shear leads to RWM destabilization [2]. In this paper, we focus on rotation shear effect at $q = 2$ by setting the rotation frequency $\Omega = 30 krad/s$ at $q = 2$ based on the dispersion relation (1). We plot the growth rates of RWMs as functions of rotation shear based on the conventional and extended kinetic-MHD model in Figure 1. Figure 1 indicates that increased rotation shear leads to RWM stabilization for both conventional and extended kinetic-MHD models.

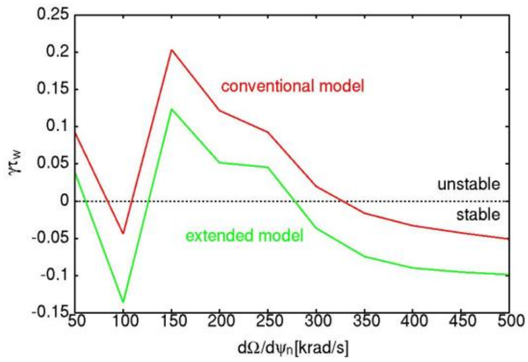

Figure 1. RWM growth rates as functions of rotation shear for the conventional and extended models.

These tendencies are consistent with experiments. Also, we note that the RWM growth rates by the extended kinetic-MHD model is much smaller than the conventional ones. Resultantly, the marginal rotation shear of the extended kinetic-MHD model is smaller than the conventional one. This fact indicates that more accurate estimate of δW_k by the extended kinetic-MHD model is essential for estimating RWM stability in the rotating tokamaks. The detailed analysis on both models will be presented in the conference.

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