Stabilization of the Kinetic Internal Kink Mode by the Sheared Poloidal Flow

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Abstract

The effects of the sheared poloidal flow on the $m = 1$ (poloidal mode number) and $n = 1$ (toroidal mode number) kinetic internal kink mode are simulated by the gyro-reduced MHD code (GRM3D-2F) which is a two-field and two-fluid gyro-reduced MHD model including the effects of electron inertia and the perturbed electron pressure gradients along the magnetic field. GRM3D-2F is based on the moment equations of the nonlinear gyrokinetic Vlasov-Poisson-Ampère system and have exact energy invariances. The results show the stabilization of the kinetic internal kink mode which might be related to the sawtooth stabilization of tokamaks.

1 Introduction

The physics of sawteeth phenomena in tokamaks are still far from complete understanding. The suppression of sawtooth crash, sawtooth crash on the fast time scale, and the physics of q_0(safety factor at the magnetic axis)< 1 after sawtooth crash are some of the examples. It is believed that (collisionless) kinetic effects have the crucial effects on the linear and nonlinear development of $m = 1$ (poloidal mode number) and $n = 1$ (toroidal mode number) kinetic internal kink modes. To study these phenomena, it is inevitable to develop the exteded MHD simulation model, which is the kinetic extension of the conventional MHD model. (Development of exteded MHD simulation model and simulation study of kinetic MHD phenomena in fusion plasmas by using massively parallel computers are one of the main subjects in the NEXT (Numerical EXperiment of Tokamak) Project in JAERI begun from 1996 [1].) We have developed gyrokinetic particle code (GYR3D)[2, 3], gyro-reduced MHD code (GRM3D-2F)[4], and particle-fluid hybrid code (Hybrid3D)[5]. These three codes, which have the exact energy invariances, are based on the nonlinear gyrokinetic Vlasov-Poisson-Ampère system[6] and/or the moment equations of it. It is important to make several codes with different order of physical accuracy and to benchmark those codes for the same physical phenomena.

The nonlinear phenomena of the kinetic $m = 1$ and $n = 1$ internal kink mode are studied by these codes. The fast full reconnection (collisionless magnetic reconnection) followed by the second phase reforming the configuration of $q_0 < 1$ has been observed by the three codes. (This phenomenon was firstly predicted by the simulation by Biskamp et. al.[7].) It is also found the dependence of the growth rates on the collisionless electron skin depth and the ion Larmor radius calculated by the electron temperature is consistent with the prediction of Zakharov et. al.[8] by the parameter runs by GRM3D-2F code. In this paper, stabilization of the $m = 1$ and $n = 1$ kinetic internal kink mode due to the sheared poloidal flow is simulated by GRM3D-2F code. The effects of the pressure gradients and energetic trapped ions are the other candidates of stabilization. The case of stabilization of the collisional internal kink mode by the sheared poloidal flow was studied by Kleva[9]. Here we treat the collisionless case in which kinetic effects of electrons are important. This is the first step to study this subject and the comparison of the results by GRM3D-2F, GYR3D, and Hybrid3D codes will be followed.

The oultine of the article is as follows. The brief summary of the gyro-reduced MHD model is given in Sections 2. The simulation results of the kinetic $m = 1$ and $n = 1$ internal kink mode are shown in Section 3. Concluding remarks and discussion are given in Section 4.

2 Gyro-Reduced MHD Model

We assume a rectangular system with dimensions of L_x, L_y, and L_z. There is a strong and constant magnetic field (toroidal magnetic field), $\boldsymbol{B}_T = B_0\boldsymbol{b}$, where $\boldsymbol{b}$ is the unit vector in the z direction. The compressional component of the longitudinal magnetic field is neglected in the low beta approximation. The periodic boundary condition is assumed in the z direction. The system is bounded by a perfectly conducting wall in the x and y (poloidal) directions.

The moment equations of the gyrokinetic Vlasov equations are used to derive the gyro-reduced MHD model. Because the terminology of "gyro-fluid" usually represents the gyro-Landau model[10, 11], we call our model "gyro-reduced MHD" because it is corresponding to the extention of the Strauss's reduced MHD model[12]. This model is basically the two fluid model; hence, electron inertia as well as the electron pressure gradient along the magnetic field is included in the system of equations.

The gyro-reduced MHD model comprises of the equations for the electrostatic potential ϕ and the z component of the vector potential A_z:

$$\frac{d}{dt}(\nabla_\perp^2\phi) = -v_A^2\, \boldsymbol{b}^* \cdot \nabla(\nabla_\perp^2 A_z)\,, \tag{1}$$

$$\frac{\partial}{\partial t}A_z = -\boldsymbol{b}^* \cdot \nabla\phi + d_e^2\,\frac{d}{dt}(\nabla_\perp^2 A_z) + \rho_s^2\,\boldsymbol{b}^* \cdot \nabla(\nabla_\perp^2\phi)\,, \tag{2}$$

where $v_A = c\,\omega_{ci}/\omega_{pi}$ (c is the speed of light in vacuum, ω_{ci} and ω_{pi} are the ion cyclotron and plasma angular frequencies, respectively) is the Alfvén velocity, $d_e = c/\omega_{pe}$ (ω_{pe} is the electron plasma angular frequency) is the collisionless electron skin depth, $\rho_s = \sqrt{T_e/m_i}/\omega_{ci}$ (m_i is the ion mass, T_e is the electron temperature) is the ion Larmor radius calculated by the electron temperature, $\boldsymbol{b}^*$ is the unit vector of the magnetic field,

$$\boldsymbol{b}^* = \boldsymbol{b} + \frac{\nabla A_z \times \boldsymbol{b}}{B_0}\,, \tag{3}$$

and d/dt is the convective derivative defined by

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \frac{\boldsymbol{b} \times \nabla \phi}{B_0} \cdot \nabla \,. \tag{4}$$

Eq.(1) represents the vortex equation while generalized Ohm's law in the direction parallel to the magnetic field is described by Eq.(2).

In order to derive Eq.(2), we replaced the pressure term, p_e, in the electron moment equation by assuming $p_e = n_e T_e$ and $T_e =$ constant (isothermal model);

$$\nabla p_e = T_e \nabla n_e = \frac{\epsilon_0}{e} \frac{\omega_{pi}^2}{\omega_{ci}^2} \nabla (\nabla_\perp^2 \phi) \,, \tag{5}$$

where gyrokinetic Poisson equation is used in the second equality by assuming $\delta n_i = 0$ which is consistent to assume $U_i = 0$ (U_i is the ion fluid velocity parallel to the magnetic field) in the 0-th order moment equation (continuity equation) of ions.

3 Simulation Results

The system is filled with a plasma with uniform equilibrium density and temperature. The equilibrium profile of A_z is chosen to be

$$A_z(x,y) = \frac{2 L_x L_y B_0}{\pi q_0 L_z} \sin \frac{\pi x}{L_x} \sin \frac{\pi y}{L_y} \tag{6}$$

where q_0 is the safety factor at the magnetic axis [12]. The q profile corresponding to the above A_z is given by

$$q(x,y) = \frac{2}{\pi} q_0 K(\sin\psi), \quad \cos\psi = \sin \frac{\pi x}{L_x} \sin \frac{\pi y}{L_y} \tag{7}$$

where K is the elliptic integral of the first kind. The q-value increases monotonically from the axis to the wall where q is infinite. The central q value (safety factor) of $q_0 = 0.85$ is selected for the equilibrium.

The sheared poloidal flow is generated by the $E \times B$ drift due to the radial electric field corresponding to the equilibrium electrostatic potential profile,

$$\phi(x,y) = \phi_0 \left\{ \sin \frac{\pi x}{L_x} \sin \frac{\pi y}{L_y} \right\}^4 \,, \tag{8}$$

and the toroidal magnetic field. Althogh the rigid rotation of the mode does not affect the mode structure, the difference of the poloidal angular velocity of the mode tends to break the mode structure of the internal kink mode and have the stabilizing effects. The simulation results of the linear version of the GRM3D-2F code, which includes only $n = \pm 1$ modes as well as the equilibrium $n = 0$ mode, have verified these effects; stabilization of the mode is observed as ϕ_0 increases. The mode structure around the $q = 1$ surface changes drastically in the radial direction when there is a poloidal shear flow. So the finer mesh is required to resolve the mode structure.

4 Conclusions and Discussion

The effects of the sheared poloidal flow on the $m = 1$ and $n = 1$ kinetic internal kink mode are simulated by the GRM3D-2F code which is a two-field and two-fluid gyro-reduced MHD code including the effects of electron inertia and the perturbed electron pressure gradients along the magnetic field. The linear stabilization of the kinetic internal kink mode is observed by the linear version of the GRM3D-2F code. The nonlinear simulation focusing on the nonlinearly stable and unstable cases will be done by the nonlinear version of GRM3D-2F code. Also the comparison of the simulation results by GRM3D-2F, GYR3D, and Hybrid3D codes will be reported in the near future.

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