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Effect of parallel heat flux in the ion gyroviscous tensor on tearing instability in extended magnetohydrodynamic model

拡張MHDモデルにおけるテアリング不安定性に対するジャイロ粘性テンソル中の磁力線方向の熱流束の効果

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The effect of parallel heat flux in the gyroviscous tensor on the tearing mode instability in the extended magnetohydrodynamic (MHD) model is investigated. The linear eigenmode equations for the tearing mode instability including the perturbed parallel heat flux in the gyroviscous tensor are derived from the fluid moment equations with simplification by taking only first order diamagnetic terms in the MHD ordering and are numerically solved.

1. Introduction

Finite Larmor radius effects on MHD instabilities such as the tearing mode instability have been studied by using two-fluid magnetohydrodynamic (MHD) models with ion gyroviscous tensor. However, the conventional two-fluid models are valid for collisional plasmas. In the fluid moment equations for low collisionality plasmas, the parallel heat flux that arises in the gyroviscous force due to the non-Maxwellian part of the velocity distribution function cannot be neglected [1,2]. We investigate the effect of parallel heat flux in the gyroviscous tensor on the tearing mode instability in the extended MHD model. We derive the linear eigenmode equations for the tearing mode instability including the perturbed parallel heat flux in the gyroviscous tensor. The eigenmode equations are numerically solved.

2. Gyroviscous Force

In order to implement the effects of the parallel heat flux in the gyroviscous force into the analysis of the tearing mode instability, we simplify the gyroviscous force in Ref [2] by taking only the first-order terms in the MHD ordering,

$$v \sim v_{th}, \quad v_d \sim \delta v_{th}, \quad \delta \ll 1, \quad p_{e\|} = p_{e\perp}.$$

The resulting gyrociscous force is written in the following form,

$$\nabla \cdot \Pi_i^{gv} = \sum_{N=1}^{5} \left(\nabla \cdot \Pi_i^{gvN} \right) \ ,$$

$$\begin{aligned}
\nabla \cdot \Pi_i^{gv1} \simeq & -m_i n \mathbf{v}_{*i} \cdot \nabla \mathbf{v} - \nabla \chi_v \\
& -\nabla \times \left\{ \frac{m_i p_{i\perp}}{eB} \left\{ \left(\mathbf{b} \cdot \nabla \right) \mathbf{v} \right. \right. \\
& \left. \left. + \frac{1}{2} \left\{ \nabla \cdot \mathbf{v} - 3 \mathbf{b} \cdot \left[\left(\mathbf{b} \cdot \nabla \right) \mathbf{v} \right] \right\} \mathbf{b} \right\} \right\} \\
& + \left(\mathbf{B} \cdot \nabla \right) \left\{ \frac{m_i p_{i\perp}}{eB^2} \mathbf{b} \times \left[3 \left(\mathbf{b} \cdot \nabla \right) \mathbf{v} + \mathbf{b} \times \boldsymbol{\omega} \right] \right. \\
& \left. + \frac{\chi_v}{B} \mathbf{b} \right\},
\end{aligned}$$

$$\begin{aligned}
\nabla \cdot \Pi_i^{gv2} \simeq & \frac{m_i}{e} \left[\nabla \times \left(\frac{\mathbf{b}}{B} \right) \right] \cdot \nabla \left(q_{iT\|} \mathbf{b} \right) - \nabla \chi_q \\
& -\nabla \times \left\{ \frac{m_i}{eB} \left\{ \left(\mathbf{b} \cdot \nabla \right) \left(q_{iT\|} \mathbf{b} \right) \right. \right. \\
& \left. \left. + \frac{1}{2} \left\{ \nabla \cdot \left(q_{iT\|} \mathbf{b} \right) - 3 \mathbf{b} \cdot \left[\left(\mathbf{b} \cdot \nabla \right) \left(q_{iT\|} \mathbf{b} \right) \right] \right\} \mathbf{b} \right\} \right\} \\
& + \left(\mathbf{B} \cdot \nabla \right) \left\{ \frac{m_i}{eB^2} \boldsymbol{b} \times \left[3 \left(\mathbf{b} \cdot \nabla \right) \left(q_{iT\|} \mathbf{b} \right) \right. \right. \\
& \left. \left. + \mathbf{b} \times \left(\nabla \times \left(q_{iT\|} \mathbf{b} \right) \right) \right] + \frac{\chi_q}{B} \mathbf{b} \right\},
\end{aligned}$$

$$\nabla\cdot\Pi_i^{gv3}\simeq\nabla\times\left\{\mathbf{B}\times\left[\frac{m_i}{eB^2}\left(2\boldsymbol{q}_{iB\parallel}-3\boldsymbol{q}_{iT\parallel}\right)\boldsymbol{\kappa}\right.\right.$$
$$\left.\left.+2\left(\frac{p_{i\parallel}-p_{i\perp}}{B}\right)\left(\mathbf{B}\cdot\nabla\right)\mathbf{v}\right]\right\}$$
$$+\left(\mathbf{B}\cdot\nabla\right)\left[\frac{2m_i}{eB^2}\left(2\boldsymbol{q}_{iB\parallel}-3\boldsymbol{q}_{iT\parallel}\right)\boldsymbol{\kappa}\right.$$
$$\left.+2\left(\frac{p_{i\parallel}-p_{i\perp}}{B}\right)\left(\mathbf{B}\cdot\nabla\right)\mathbf{v}\right],$$
$$\nabla\cdot\Pi_i^{gv4}\simeq\nabla\cdot\Pi_i^{gv5}\simeq 0.$$

3. Liniearized Equations

We consider following equilibrium in the slab geometry,

$$\mathbf{v}_0=0,$$
$$\mathbf{B}_0=\left[0,B_{0y}\left(x\right),B_{0z}\left(x\right)\right],$$
$$n_0=n_0\left(x\right).$$

The equilibrium pressure is isotropic. The equilibrium satisfies the force balance

$$\frac{d}{dx}\left[\frac{1}{2\mu_0}\left(B_{0y}^2+B_{0z}^2\right)+p_{i0}+p_{e0}\right]=0$$

The two-fluid MHD equations are linearized by assuming the following perturbation,

$$f_1=f_1\left(x\right)\exp\left[-i\left(\omega t-ky\right)\right].$$

The linearized equations of motion are

$$-in_0\omega v_{1x}=-B_{0z}B_{1z}'-B_{0z}'B_{1z}$$
$$-\frac{i}{k}\left(B_{0y}B_{1x}''+B_{0y}'B_{1x}'\right)$$
$$+ikB_{0y}B_{1x}-p_{i\perp1}'-p_{e1}'$$
$$-\lambda_i\left(\nabla\cdot\Pi_i^{gv}\right)_{1x}$$
$$-in_0\omega v_{1y}=-ikB_{0z}B_{1z}+B_{0y}'B_{1x}$$
$$-\frac{ik}{B_0^2}\left(B_{0y}^2p_{i\parallel1}+B_{0z}^2p_{i\perp1}\right)$$
$$-ikp_{e1}-\lambda_i\left(\nabla\cdot\Pi_i^{gv}\right)_{1y}$$
$$-in_0\omega v_{1z}=ikB_{0y}B_{1z}+B_{0z}'B_{1x}$$
$$-\frac{ikB_{0y}B_{0z}}{B_0^2}\left(p_{i\parallel1}-p_{i\perp1}\right)$$
$$-\lambda_i\left(\nabla\cdot\Pi_i^{gv}\right)_{1z}$$

We substitute the linearized form of the gyroviscous force in Sec. 2 into the above equations of motion. In the linearized form,

$$\left(\nabla\cdot\Pi_i^{gv3}\right)_1=0.$$

The effects of the parallel heat flux appear in

$$\left(\nabla\cdot\Pi_i^{gv2}\right)_1$$

We examine the influences of this term on the tearing mode instability by solving the linear eigenmode equations numerically.

References

[1] J. J. Ramos, Phys. Plasmas **12**, 052102 (2005).
[2] J. J. Ramos, Phys. Plasmas **12**, 112301 (2005).