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Non-equilibrium and extreme state -Heating effect on bulk ions by energetic particle driven geodesic acoustic modes-

非平衡極限 −高エネルギー粒子に駆動される測地線音波のイオン加熱効果−

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Geodesic acoustic modes (GAMs) driven by energetic particles (EPs) have been shown to have several branches. Selection of the branch is determined by the transit frequency and the drift frequency of EPs, which are functions of the energy of EPs. When the eigenfrequency of the GAM is close to the drift frequency of EPs, the poloidal eigenfunction has a sharp peak where the drift velocity has maximum value and the resonance between the wave and EPs is strong. The effective wavenumber parallel to the magnetic field increases due to the sharp peak, which leads to the increase of ion heating effect by Landau damping.

1. Introduction

Importance of geodesic acoustic modes (GAMs) driven by energetic particles (EPs) [1] has been recognized in the study of magnetic confined plasmas. A gyrokinetic simulation has shown that the GAMs driven by EPs couple with turbulence so that it may be possible to control turbulent transport by EPs [2]. GAMs transfer their energy to bulk ions through dissipation such as Landau damping, and the energy channeling from EPs to bulk ions via GAMs has been proposed as GAM channeling [3]. Actually, GAMs driven by EPs have been observed in experiments [4, 5], and several branches of GAMs have been found [5]. Identification of each branch of GAMs driven by EPs is required.

In this study, the eigenmode analysis of GAMs driven by EPs is performed based on the gyrokinetic equation. We show there are several branches of GAMs in the presence of EPs. In accordance with the energy of EPs, the resonance between particles motion and the GAMs changes so that a new branch appears. Here, we show three GAM branches; one of them is studied for the first time. The basic model is described in Sec. 2. The eigenmodes of each branch are shown in Sec. 3. The summary is given in Sec. 4.

2. Model

The plasma configuration under consideration is a high aspect ratio tokamak with a circular cross section. The linearized gyrokinetic equation for the non-adiabatic response of the ion velocity distribution to a GAM oscillation G_ω is governed by

$$\left(\omega + i\omega_t\partial_\theta - \omega_d \sin\theta\right)G_\omega = -\omega\partial_E F_{eq} J_0(k_\perp \mathrm{v}_\perp)\phi_\omega, \quad (1)$$

where ω is the eigenfrequency, ω_t is the transit frequency, ω_d is the drift frequency due to inhomogeneity of the magnetic field. The frequencies are normalized by the typical frequency defined as the ion thermal velocity divided by the major radius. The equilibrium distribution function is denoted by F_{eq}, which consists of bulk component (Maxwell distribution) and EPs component, $J_0(k_\perp \mathrm{v}_\perp)$ is the zero-th order Bessel function, and ϕ_ω is the GAM potential. Here, k is the radial wavenumber normalized by ion gyroradius, θ is the poloidal angle, and q is the safety factor. For the transparency of the analytical treatment, the EP distribution is assumed as a beam distribution. Charge quasi-neutral condition is given as

$$\left\langle J_0 G_\omega \right\rangle = (\tau+1)\phi_\omega - \tau\phi_0, \quad (2)$$

where $\langle \ldots \rangle$ represents velocity integral, τ is the ratio between ion and electron temperature, and ϕ_0 is the poloidal averaged GAM potential. GAM eigenmodes are determined by Eqs. (1) and (2).

3. GAM branches

In this section, GAM branches are shown. Equation (1) has two kinds of poles in accordance with the transit frequency and the drift frequency of EPs. Their frequencies are functions of energy of EPs, so that each branch appears depending on EPs' energy. In the limit of $\omega_h >> \omega_D$, the resonance between the transit motion of EPs and the GAM is realized, and an eigenmode with the frequency close to ω_h is predicted to appear. Here, ω_h is the transit frequency of EPs, and ω_D is the drift frequency of EPs. In the limit of $\omega_D >> \omega_h$, the resonance between drift motion of EPs and the GAM appears, and a branch with $\omega \sim \omega_D$ appears. The characteristics of both branches are explained in the following.

1) $\omega_h >> \omega_D$

In this limit, the poloidal side band coupling, which stems from the third term in LHS of Eq. (1), is weak, so that the poloidal eigenfunction is a smooth function of θ. A poloidal mode expansion is suitable. When the poloidal modes up to ± 1 are considered, the dispersion relation can be derived as

$$1 - \frac{\omega_G^2}{\omega^2} + i\Delta_{Landau} - C_h \left[\frac{1}{(\omega - \omega_h)^2} + \frac{1}{(\omega + \omega_h)^2} \right] = 0, \quad (3)$$

where ω_G is the standard GAM frequency defined as $\omega_G = \sqrt{7/4 + \tau^{-1}}$, Δ_{Landau} is the Landau damping term, and C_h is a coefficient that depends on the parameter of EPs and is proportional to the density of EPs. In the absence of EPs ($C_h = 0$), Eq. (3) reproduces the standard GAM branch as $\omega \approx \omega_G - i\omega_G \Delta_{Landau}(\omega_G)/2$. The branch with $\omega \approx \omega_h$ is predicted in the presence of EPs. This branch becomes unstable when $\omega_h < \omega_G$. The detail study of this branch has been analyzed [1, 6].

2) $\omega_D >> \omega_h$

The resonance between the drift motion of EPs and the GAM becomes important in this limit, and the poloidal side band coupling is strong. The poloidal mode expansion cannot be used, so that the eigenfunction is treated as a function of the poloidal angle as in [7]. The dispersion relation is obtained as

$$1 - \frac{\omega_G^2}{\omega^2} + i\Delta'_{Landau} - C_h' \frac{\omega_D}{\left(1 - \omega_D^2 \omega^{-2}\right)^{3/2}} = 0. \quad (4)$$

This dispersion relation also includes the standard GAM branch. In the case of $\omega_D < \omega_G$, only the standard GAM branch exists. When the drift frequency of EPs exceeds the standard GAM frequency $\omega_D > \omega_G$, the standard GAM branch and a branch with $\omega \approx \omega_D$, which is the new one, exist. The eigenfunction of the new branch is shown in Fig. 1. The poloidal eigenfunction has a sharp peak where the drift velocity has maximum value $\theta = \pi/2$, and the resonance between the wave and EPs is strong. The effective wavenumber parallel to the magnetic field, which is evaluated from the poloidal angle derivative, increases due to the sharp peak, and the effect of ion heating through Landau damping becomes large.

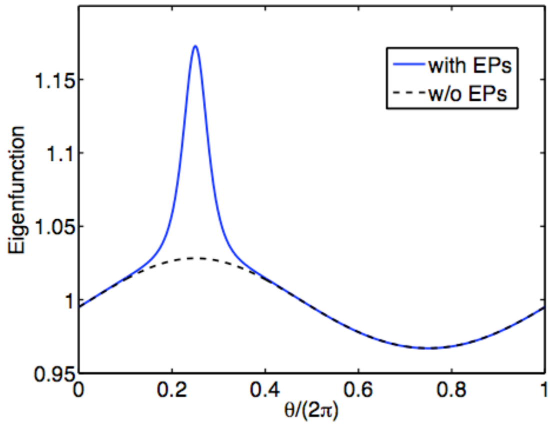

Fig.1. Poloidal eigenfunction with $\omega \approx \omega_D$

4. Summary

GAMs driven by EPs are shown to have several branches in this paper. Ordering of the transit frequency and the drift frequency of EPs is important to determine which branches appear. In the limit of $\omega_h >> \omega_D$, the branch with $\omega \approx \omega_h$ exists in addition to the standard GAM branch. When $\omega_D >> \omega_h$, the new branch with $\omega \approx \omega_D$ is found to exist. Its poloidal eigenfunction has a sharp peak where the drift velocity has maximum value and the resonance between the wave and EPs is strong. The effective wavenumber parallel to the magnetic field increases due to the sharp peak, and the effect of ion heating through Landau damping becomes large.

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