18PB-011

Gyrokinetic simulation on energetic-particle-induced geodesic acoustic mode
高速粒子駆動測地線音響モードのジャイロ運動論シミュレーション

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We identify linear dynamics of the energetic-particle-induced geodesic acoustic mode (EGAM) using both eigenmode and initial value analyses based on the gyrokinetic theory. We derive a dispersion relation of the EGAM from the perturbed gyrokinetic equation with energetic particles. Depending on q-value, behavior of the roots can vary. Taking into account of the finite-orbit-width (FOW) effects, we examine variations of the growth rates of the EGAM for various beam intensities. The analyses indicate that the FOW effects are small, within several percent of the growth rates, for experimentally relevant machine sizes. This result is confirmed also in plasma size scan using the full-f gyrokinetic Eulerian code GT5D.

1. Introduction

Understanding of energetic particles physics is of great interest in the burning plasmas. Recent studies have disclosed the existence of energetic-particles-induced modes with n=0, where n is a toroidal mode number. DIII-D experiments have found a mode excitation in the presence of the counter NBI [1]. The mode structure is identical to that of geodesic acoustic mode (GAM) [2], but its frequency is about a half of that of the GAM. Analyses based on a hybrid model including MHD modes and energetic particles [3] have revealed a new GAM-like mode, which has an independent branch from the GAM. The mode is referred to as energetic-particle -induced geodesic acoustic mode (EGAM). So far, the EGAM has been studied with the hybrid model or a local gyrokinetic model [4] without the finite-orbit-width (FOW) effects. However, the FOW effects are essential for estimating the damping rate of GAM [5]. To see its impact on the EGAM, we extend the gyrokinetic theory of EGAM by taking account of the FOW effects.

In this work, we identify linear dynamics of the EGAM, in terms of eigenmode analyses, for a given bump-on-tail particle distributions. A perturbed gyrokinetic equation together with a quasi-neutrality condition closes the system to derive a dispersion relation of the EGAM. We assess the FOW effects of the finite-orbit-width (FOW) on the resonance of EGAM, which is expected to depend on the plasma size, because eigenfunctions of the EGAM typically have global mode structures expanding over the minor radius a. We verify this point by solving the initial value problem of the EGAM, using the full-f gyrokinetic Eulerian code (GT5D) [6].

2. Eigenmode analyses of the EGAM based on the gyrokinetic theory

We use the toroidal coordinates (r, θ, ζ), assuming tokamak plasmas. For a given equilibrium distribution F_0, the linear perturbed gyrokinetic equation for the zonal component with the perpendicular wave number $\boldsymbol{k}_\perp = k_r \nabla r$ is given by [5]

$$\left(\partial_t + v_\parallel \mathbf{b}\cdot\nabla + i\omega_D\right) g_{k_\perp} = -\frac{e}{m}\frac{\partial F_0}{\partial E} J_0 \frac{\partial \phi_{k_\perp}}{\partial t}, \qquad (1)$$

where J_0 is the zeroth-order Bessel function and $E=m_i(v_\parallel^2+2\mu B)/2$ is the particle energy. $\omega_D = v_\parallel \mathbf{b}\cdot\nabla(k_r d_r)$ is the magnetic drift frequency, where $d_r = (q/\omega_{ci})(v_\parallel + v_\perp^2/2v_\parallel)\cos\theta$. We assume radial homogeneity for $F_0(\mathbf{R},\mu,v_\parallel) = F_0(\mu,v_\parallel)$, so that the term proportional to $\partial_r F_0$ is dropped. We also neglect a term of the mirror force.

In reference to Ref. [4], we adopt a bump-on-tail distribution for F_0 as illustrated in Fig.1. An important parameter is a beam intensity n_h, which is defined as the proportion of the number of the energetic particles to that of the bulk ones. By assuming modes with n=0, m=0, ±1, a symmetry in the poloidal modes, and $\omega_D \ll \omega_t (=v_{ti}/qR)$, Eq. (1) together with the quasi-neutrality condition yields a linear dispersion relation,

$$\hat{\omega} + \frac{q^2}{4}\left\{(4\hat{\omega}Z_1^{-1}Z_{2,0}^2 - 4Z_{4,0}) + D_{FOW}\right\} = 0, \qquad (2)$$

where $\hat{\omega} = R_0 q\omega/(\sqrt{2}v_{ti})$, R_0 is the major radius, q is the safety factor, $v_{ti}=(T_i/m_i)^{1/2}$, and Z_1, $Z_{2,0}$, $Z_{4,0}$ are the coefficients related to resonance integrals. D_{FOW} is the contribution from the FOW effects proportional to $(qk_r\rho_i)^2$, where ρ_i is the ion Larmor radius. By assuming $|\mathrm{Im}[\omega]| \ll |\mathrm{Re}[\omega]|$, we keep only the imaginary part of D_{FOW}.

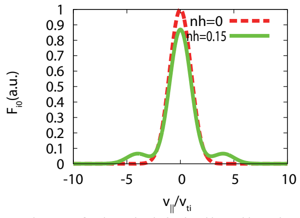

Fig.1 Examples of the initial distributions $F_0(v_{||})$ for a given μ, in cases (a) without beam injection (n_h=0), and (b) with 15% of beam injection to the bulk particles (n_h=0.15).

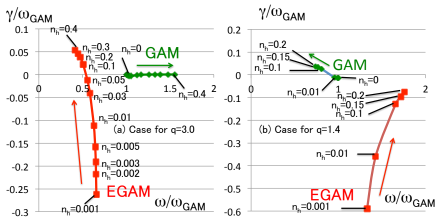

Fig.2 Plots of the GAM (rectangular) and EGAM (diamond) roots for various beam intensities, in (a) q=3.0 and (b) q=1.4 cases. Here, k_r=0 (i.e. no FOW effects) is chosen.

3. Eigenmode analyses of the EGAM with the FOW effects

Solving Eq. (2) with various n_h and q-values, we find possible roots. Without the beam injection we see a single damping mode corresponding to the GAM. We identify a new mode emerging by including the beam injection. We identify the new root as the EGAM.

Behavior of the roots differs, depending on q-values. In the higher q case, as n_h increases, the EGAM root becomes a growing mode, while the GAM root keeps a damping one (See Fig.2(a)). Whereas, for the lower q case, as n_h increases, the GAM root becomes a growing mode, while the EGAM root does not (See Fig.2(b)).

To assess the FOW effects, we examine variation of growth rates of the EGAM for different k_r (See Fig.4), where ρ_i/a=1/150 corresponds to $k_r\rho_i$~π/(a/ρ_i)~0.021, if one assumes global eigenmmodes comparable to the plasma size. Therefore, an impact of the FOW effects on the growth rate is within several percent in reactor relevant plasma sizes.

4. Comparison with simulation results

To verify the findings above, we exploit numerical simulations using GT5D. We solve initial value problems with the initial bump-on-tail distribution given by n_h=0-0.2 and q=1.4, 3.0, and examine the linear growth rate and real frequency. As shown in Fig.3, n_h scan indicates that unstable modes are switched from the EGAM to the GAM depending on q, which dictates a resonance point, and the unstable blanch is consistent with the eigenmode analysis. We also examine the linear growth rate for

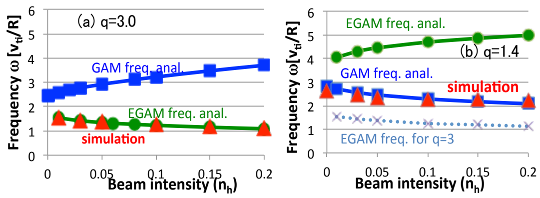

Fig.3 Plots of the real frequencies obtained from eigenmode analyses, corresponding to the GAM (rectangle) and EGAM (circle) and eigenmode analyses (triangle) in case for (a) q=3.0 and (b) q=1.4. In GT5D, a/ρ_i=50 is used.

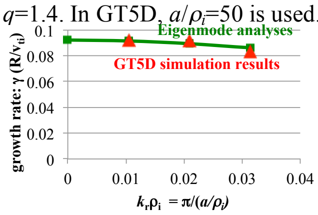

Fig.4 Plots of the growth rates obtained from the GT5D simulations (triangle) and eigenmode analyses (rectangular), for different machine sizes (a/ρ_i=100, 150, 300).

the plasma sizes, a/ρ_i=100, 150, 300. In Fig.4, initial value and eigenmode analyses agree with each other, and both results show negligible FOW effects.

5. Conclusion

We have identified the linear feature of the EGAM, using eigenmode and initial value analyses based on a gyrokinetic model and GT5D simulation. First, we have derived a dispersion relation of the EGAM, with keeping the FOW effects. Second, we have found that the behavior of the roots depends on q. Higher q leads the EGAM excitation, while the lower q leads to the unstable GAM. Third, we have estimated the FOW effects on the EGAM. The FOW effect depends on k_r, thus, the plasma size. However, its impact on the growth rate of the EGAM is limited within several percent for the experimentally relevant parameters, while it may be pronounced in smaller machines. GT5D simulations have verified these findings.

Acknowledgements

This work was supported by the MEXT, Grant for HPCI Strategic Program Field No. 4: Next-Generation Industrial Innovations. The computation in this work was performed on the Helios at the IFERC.

References

[1] R. Nazikian *et al.*, Phys. Rev. Lett. **101**, 185001 (2008).
[2] N. Winsor *et al.*, Phys. Fluids **11**, 2448 (1968).
[3] G.Y. Fu, Phys. Rev. Lett. **101**, 185002 (2008).
[4] D. Zarzoso *et al.*, Phys. Plasmas **19**, 022102 (2012).
[5] H. Sugama and T.-H. Watanabe, Phys. Plasmas **13**, 012501 (2006).
[6] Y. Idomura *et al.*, Nucl. Fusion **48**, 065029 (2009).
[7] E.A. Frieman and L. Chen, Phys. Fluids **25**, 502 (1982).