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On the energetic particle-induced geodesic acoustic modes with finite-orbit-width effects

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Geodesic acoustic modes (GAMs) are well-established waves in tokamaks. [1] They can be significantly influenced by energetic particles (EPs), giving rise to energetic particle-induced geodesic acoustic modes (EGAMs). EGAMs exhibit an unstable branch with a positive growth rate and a lower frequency than that of conventional GAMs. [2]

This study presents an analytical investigation of EGAMs within a gyro-kinetic model, incorporating finite-orbit-width (FOW) effects up to the second order. We begin by deriving a general dispersion relation applicable to arbitrary EP distributions. Subsequently, by modeling EPs with the standard slowing-down beam distribution, we derive exact expressions and find the second-order FOW effects introduce two kinds of additional resonances: one at $qR\omega = v_{||}$ and the other at $qR\omega/2 = v_{||}$. Here, q is the safety factor, R is the major radius of tokamaks, ω is the EGAM frequency, and $v_{||}$ is the EP parallel velocity with respect to the magnetic field.

Utilizing these exact expressions, we investigate the influence of second-order FOW effects on unstable EGAMs by numerically calculating the EGAM dispersion relation, as illustrated in figures 1(a) and 1(b). Our findings reveal that second-order FOW effects have minimal impact on the original unstable EGAM branch, denoted as low frequency branch (LFB). However, these effects introduce a new unstable EGAM branch, denoted as the high frequency branch (HFB). The frequency of the HFB is significantly higher than that of GAMs and exceeds the EP transit frequency, which provides a potential explanation for LHD observations [3]. The instability of the HFB is driven by inverse Landau damping, originating from the EP-wave resonance at $qR\omega/2 = v_{||}$, which is an additional resonance introduced by second-order FOW effects. Furthermore, we observe that increasing the EP concentration, as depicted in figures 1(c) and 1(d), leads to a higher frequency and growth rate for the HFB. In contrast, as the EP concentration increases, the LFB frequency declines, and its growth rate first increases and subsequently decreases.

Overall, our investigation underscores the significance of second-order FOW effects in the analysis of EGAM instability. These effects give rise to a novel unstable EGAM branch through the EP-wave resonance at $qR\omega/2 = v_{||}$, characterized by a considerably higher frequency than conventional GAMs.

References

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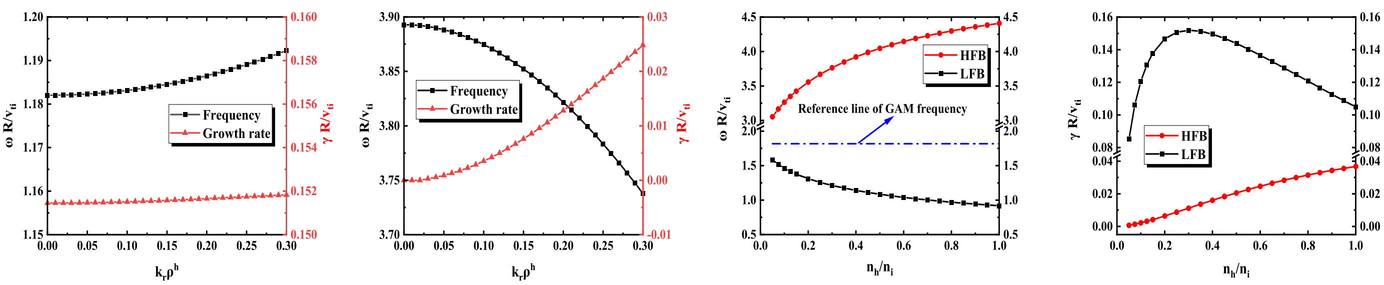

(a) Low frequency branch (LFB) (b) High frequency branch (HFB) (c) Frequency (d) Growth rate

Figure 1. The dependence of frequency ω and growth rate γ of two branches on $k_r\rho^h$ and n_h/n_i. Here, k_r is the radial wavenumber, $n_h(n_i)$ is the EP (bulk ion) density, $\rho^h = \sqrt{2E_0(1-\Lambda)/m_h}/\omega_c^h$ represents the FOW effects, E_0 is the injection energy of EPs, Λ is the normalized injection pitch angle, m_h is the EP mass, and ω_c^h is the EP gyro-frequency. Parameters are adopted according to Ref. [3-4] as follows: $T_e = T_i = 4\text{keV}, E_0 = 170\text{keV}, \Lambda = 0.3, q = 2; n_h/n_i = 1/3$ in (a, b); $k_r\rho^h = 0.2$ in (c, d).