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Nonlinear excitation of energetic particle-induced geodesic acoustic mode via resonance overlap with Alfvén instability in CFQS

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Energetic particle-induced geodesic acoustic modes (EGAMs) are critical for energetic particle (EP) transport and bulk plasma heating in magnetic confinement fusion devices. Recent studies[1,2] on the ASDEX Upgrade tokamak reported that EGAMs can be nonlinearly excited through resonance overlap with Alfvén instabilities. Using the MEGA code[3], we observe a similar phenomenon in the Chinese First Quasi-axisymmetric Stellarator (CFQS), which is a tokamak-like stellarator and has a magnetic field periodicity of $N_{FP} = 2$[4].

Prior CFQS simulations[5] have identified EP-driven instabilities, including $m/n = 3/1$ and $m/n = 5/2$ modes. We extend the previous investigation[5] by varying the neutral beam injection pitch angle Λ_0. We find that EGAMs can be excited in the nonlinear phase when $0.3 < \Lambda_0 < 0.6$. In the linear phase, the dominant Alfvén instability is identified as an energetic particle mode (EPM) with $m/n = 6/2$ for v_r and about 100 kHz linear frequency ($\omega/2\pi$). In the nonlinear phase, the dominant mode is the EGAM with $m/n = 0/0$ for v_θ and about 70kHz frequency. In Figure 1(a-b), frequency spectra clearly reveal the sequential emergence of these two modes.

Figure 1(c-d) presents a resonance analysis performed on the 200 and 2000 particles with the largest δf (perturbed distribution) values. The dominant resonance conditions for the EPM and EGAM are $\omega_{\mathrm{EPM}} = 4\omega_\phi - 9\omega_\theta$ and $\omega_{\mathrm{EGAM}} = \omega_\theta$, respectively. For the EGAM, the subdominant resonance condition is $\omega_{\mathrm{EGAM}} = 4\omega_\phi - 9\omega_\theta$.

The evolution of δf in energy E and pitch angle Λ phase space reveals that, as the linear phase approaches its end, hole-clump structure of δf gradually forms in pitch angle and energy space. Then, due to the EPM frequency chirping in the nonlinear phase, the clump gradually moves towards and eventually overlaps with the EGAM resonant region, thus triggering the EGAM excitation. This nonlinear excitation mechanism is resonance overlap, which is further supported by an analysis of the total distribution function $f(E,\mu)$ at a fixed magnetic moment $\mu = \mu_0$. Due to the EPM activity in linear and nonlinear phases, f becomes steeper in the EGAM resonant region, enabling the EGAM to extract energy from the modified distribution. As the EGAM is subsequently excited and its amplitude increases, f in these regions (initially steepened by the EPM) is gradually flattened. These phase-space observations provide strong evidence that the nonlinear excitation of the EGAM is enabled by resonance overlap with the Alfvén instability (EPM).

References

[1] P. Lauber *et al*, In: 27th IAEA Fusion Energy Conference Proceedings (2018)
[2] H. Wang *et al*, Sci. Rep. **15**, 1130 (2025)
[3] Y. Todo and T. Sato, Phys. Plasmas **5**, 1321 (1998)
[4] A. Shimizu *et al* Plasma Fusion Res. **13** 3403123 (2018)
[5] H. Wang *et al*, Nucl. Fusion **62**, 106010 (2022)

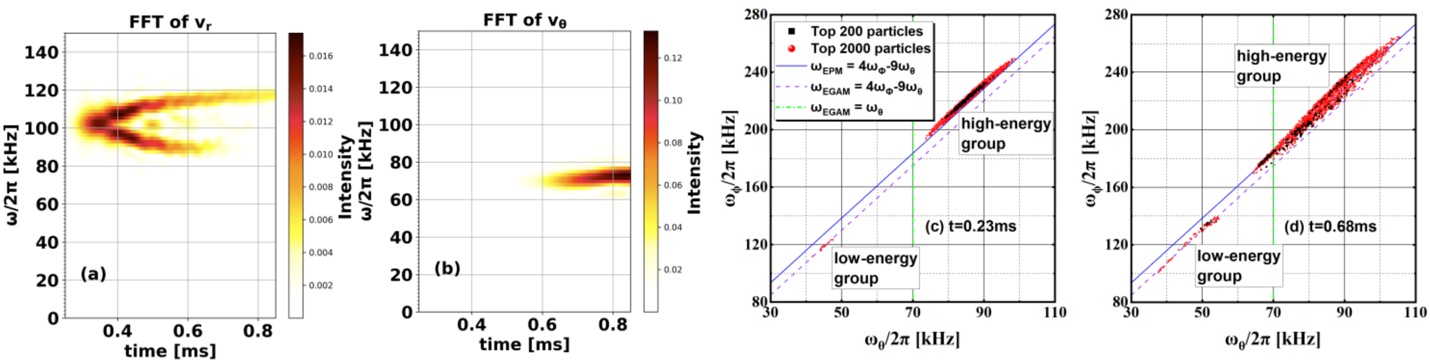

Figure 1. (a-b): The frequency spectra of v_r and v_θ from MEGA simulation with $\Lambda_0 = 0.4$. The linear stage ends at $t \approx 0.4$ms, after which the EPM splits into two branches with upward and downward chirping. (c-d): The relationship between particle frequencies $\omega_\phi/2\pi$ (frequency of toroidal motion) and $\omega_\theta/2\pi$ (frequency of poloidal motion) for top 200 and top 2000 particles with the largest δf values in linear stage ($t = 0.23$ms) and nonlinear stage ($t = 0.68$ms). Although the EGAM is not dominant during the linear stage, it briefly appears and disappears within a short time window, resulting in some particles being located along the EGAM resonance line in panel (c).