7th Asia-Pacific Conference on Plasma Physics, 12-17 Nov, 2023 at Port Messe Nagoya

Kinetic-magnetohydrodynamic hybrid simulation study of energetic-particle driven off-axis fishbone instability in tokamak plasmas

Hanzheng Li[1,2], Yasushi Todo[1,2], Hao Wang[2] ,Jialei Wang[2] ,Malik Idouakass[2]
[1] Department of Complexity Science and Engineering, The University of Tokyo
[2] National Institute for Fusion Science, National Institutes of Natural Sciences
e-mail (speaker):li.hanzheng@nifs.ac.jp

Off-axis fishbone mode (OFM), also known as energetic-particle-driven wall mode (EWM), is a magnetohydrodynamic (MHD) instability primarily driven by energetic particles (EPs). This instability has been observed in various tokamak plasmas such as JT-60U [1] and DIII-D [2], where the central safety factor (q) exceeds unity. OFMs are destabilized by precessional drift motion of trapped EPs, and their frequency decreases after the mode amplitude reaches saturation. These characteristics are similar with classical fishbones with q = 1. However, OFMs are localized near the q = 2 magnetic flux surface, whereas classical fishbones reside within the q = 1 surface. OFMs play a crucial role in fusion research as they redistribute EPs, destabilizing resistive wall modes (RWMs) and edge localized modes (ELMs) [3].

Firstly, we investigated the linear growth of Off-axis fishbone mode (OFM), destabilized by trapped energetic ions [4]. The MHD equilibria were constructed using the Grad-Shafranov equation based on experimental data from DIII-D [2]. The spatial profile of OFM primarily consists of the m/n = 2/1 mode inside the q = 2 magnetic flux surface, while the m/n = 3/1 mode dominates outside this surface. The spatial profile of OFM exhibits a strongly shearing shape on the poloidal plane, indicating the nonperturbative effect of the interaction with energetic ions. The precession drift resonance is the primary resonance between energetic particles and OFM.

Next, we focus on the nonlinear evolution of OFM. We examined the energetic ion distribution function in (P_φ, E) space. We demonstrated that the gradient of the distribution function along the constant E' line, where E' represents a combination of energy and toroidal canonical momentum conserved during the wave-particle interaction, drives or stabilizes the instability. In the nonlinear phase, the distribution function flattens along the constant E' line, resulting in the saturation of the instability.

Finally, in the experimental observations conducted in JT-60U and DIII-D devices, both the magnetic probe signals and δT_e -ECE signals exhibit significant waveform distortion, characterized by non-sinusoidal oscillations. Analysis of toroidal array data reveals that this waveform distortion is associated with higher-n harmonics. We expanded our previous simulations [4] to capture this phenomenon by incorporating higher-n harmonics in the MHD fluid model. Notably, for the first time, the simulation successfully reproduced the waveform distortion in both magnetic and temperature fluctuations [5], as illustrated in Figure 1. We found two types of waveform distortion, rising distortion and falling distortion, depending on the phase relationship between the n=1 OFM and n=2 harmonics and the relative amplitude of the n=2 harmonics to the n=1 OFM.

References

[1] G. Matsunaga *et al*, Phys.Rev.Lett.103,045001(2009)
[2] M. Okabayashi *et al*, Phys. Plasmas 18,056112(2011)
[3] G. Matsunaga *et al*, Nucl. Fusion 53,123022(2013)
[4] H. Li *et al*, Nucl. Fusion 62, 026013 (2022)
[5] H. Li *et al*, Nucl. Fusion 63, 086012 (2023)

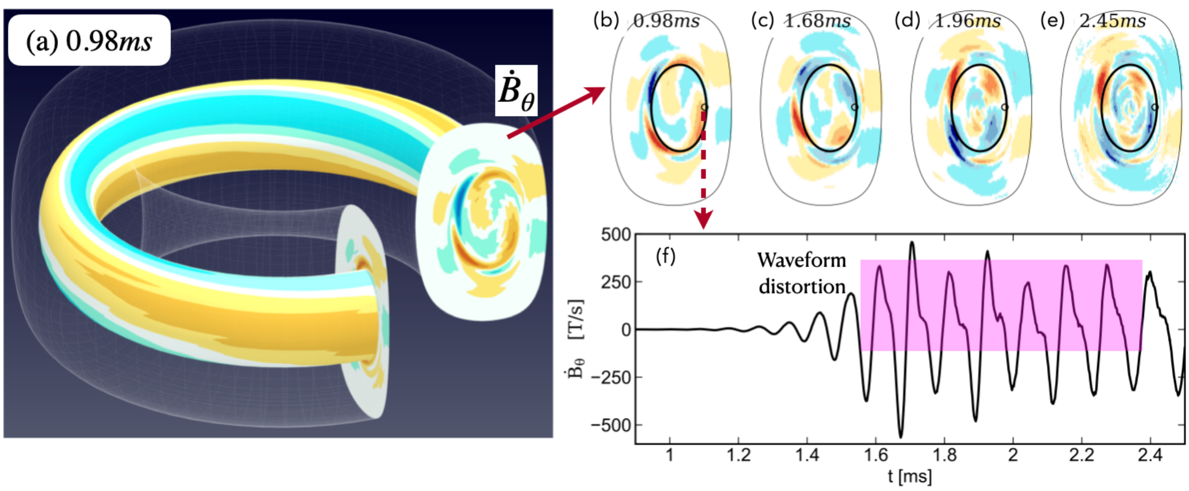

Figure 1: (a) The 3D plot illustrating the off-axis fishbone instability during the linear stage. (b)-(e) Snapshots depicting the poloidal structure of $\dot{B}_\theta$ at four different time points. (f) The signal of $\dot{B}_\theta$ measured from the q=2 surface at the outboard midplane reveals waveform distortion (magenta region).