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Effects of Trapped Energetic ions on the 2/1 Tearing Mode and Fishbone-like Mode

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In a tokamak, energetic ions have a strong impact on the triggering and evolution of magnetohydrodynamic (MHD) instabilities, thereby significantly affecting plasma confinement. Trapped energetic ions (TEIs) play a particularly critical role, as they can destabilize and excite various modes. To clarify the respective effects of TEIs on tearing modes (TMs)[1] and fishbone-like modes (FLMs)[2,3], this study offers a systematic investigation by integrating theoretical analysis and numerical simulations. Theoretical results show good agreement with DIII-D[4] and HL-2A[5] experiments, providing analytical expressions that illustrate the essential physical picture.

Analytical modeling identifies two synergistic mechanisms governing deeply TEI-TMs interactions[1]: (1) Adiabatic poloidal pressure anisotropy of deeply TEIs amplifies TM growth through coupling with unfavorable magnetic curvature, and (2) the redistribution of energetic particles due to finite orbit width (FOW) introduces a non-adiabatic correction, partially suppressing this destabilization. For the first time, the perturbed DTEI distribution function incorporating FOW effects is derived. Finally, the modified Mercier criterion, as illustrated in Figure 1(a), demonstrates that TEIs have a net destabilizing effect on TMs. This result aligns with DIII-D experimental observations, as shown in Figure 1(b)[4], where an increase in magnetic island width is observed under TEI injection. Moreover, our analysis not only qualitatively captures these observations but also provides a quantitative analytical expression that explains the fundamental physical mechanism.

Beyond TM dynamics, a new branch of the 2/1 fishbone-like mode is triggered by TEIs when the TM is unstable[2]. An energy-principle-based dispersion relation is derived, incorporating wave-particle resonance and resistive layer physics. When the TEI beta exceeds a critical threshold β_{h0}^{cr}, FLM emerges, as shown in Figure 2(a). As the TEI beta increases, the mode transitions from TM to 2/1 FLM. An analytical expression β_{h0}^{cr} for the FLM excitation threshold is derived, and it shows good consistency with numerical results. Both resistivity and magnetic shear stabilize FLM. These findings provide insights into 2/1 FLM activities observed in HL-2A, as illustrated in Figure 2(b)[5], and make a significant theoretical contribution to the TEI's β_{h0}^{cr} for FLM excitation, which cannot be directly observed due to experimental limitations.

The derived corrections to the TM stability criterion and the excitation threshold required for FLM, both resulting from TEIs, provide valuable insights for the predictive control of MHD instabilities in future fusion devices including ITER. This study provides key insights for real-time MHD control in tokamaks, particularly in scenarios with energetic particle injection. This work is supported by the National Natural Science Foundation of China (NSFC) under Grant No. 12405261.

References

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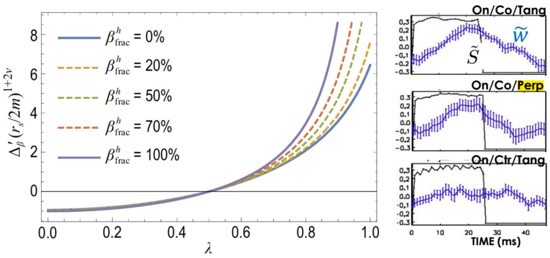
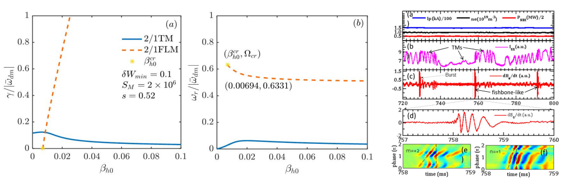


(a) (b)

Figure 1. (a) The impact of different beta fractions of TEIs on the modified stability criterion of the tearing mode. (b) The middle subplot illustrates the weak destabilizing effect of TEIs generated by vertically injected NBI on the magnetic island width in DIII-D.



(a) (b)

Figure 2. (a) Growth rates and real frequencies of TM and FLM as functions of TEI's beta fraction. (b) The 2/1 FLM phenomenon observed in the HL-2A experimental device.