Nonlinear dynamics of toroidal *Alfvén eigenmodes* driven by trapped energetic particles

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The nonlinear dynamics of toroidal Alfvén eigenmodes (TAEs) driven unstable by resonant interactions with trapped energetic particles and, to a lesser extent, with nonstandard copassing particles are investigated using simulations performed with the HMGC code (Hybrid Magnetohydrodynamic Gyrokinetic Code) [1]. The study focuses on a low-shear magnetic equilibrium representative of the ITPA (International Tokamak Physics Activity) benchmark [2]. The nonlinear mode-particle interactions are analyzed using the Hamiltonian-mapping approach, where resonant phase-space structures are sampled by a large number of test particles evolving in the self-consistently computed perturbed fields.

Multiple precession-bounce resonances contribute to the TAE destabilization, leading to the formation of closed-trajectory islands in the (phase, radius) space around each resonance location, as can be seen from the figure below. As the mode amplitude grows, these islands expand and eventually merge, resulting in global density mixing. This process causes a sudden reduction in the power transfer between the mode and energetic particles, acting as the primary saturation mechanism at high energetic-particle densities.

The saturation amplitude exhibits a scaling slightly weaker than linear with the mode growth rate, akin to the radial-decoupling scaling reported in previous studies [3,4]. This behavior arises because the extent of density mixing at saturation is constrained by the effective mode structure, which remains largely unaffected by the growth rate. At lower energetic-particle densities, localized density mixing around individual resonances becomes the dominant saturation mechanism, leading to a transition to a stronger scaling, similar to the resonance-detuning regime discussed in the literature.

This work has been recently published in Physics of Plasmas [5].

References

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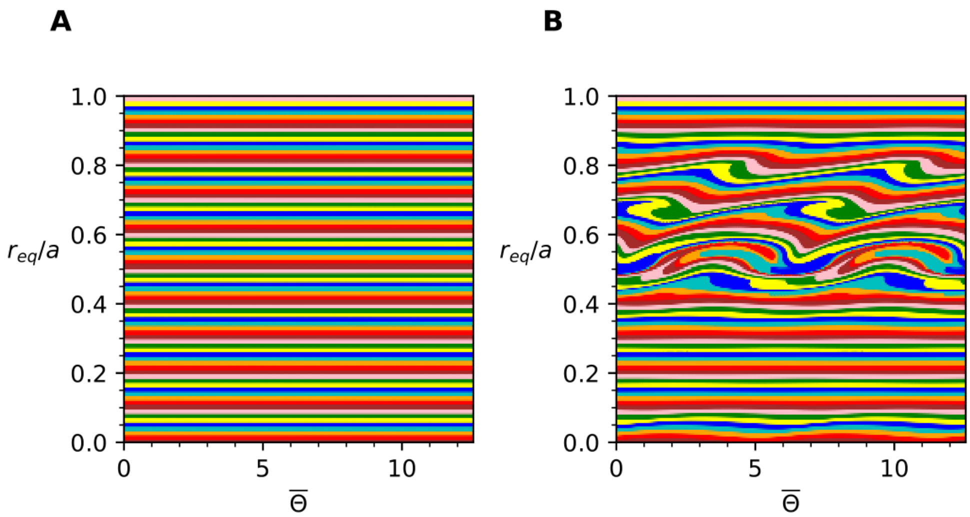

Figure 1. (**A**) Markers representing test particles in the $(\overline{\Theta}, r_{eq})$ plane during the linear phase. (**B**) The same markers during the nonlinear phase. Each marker is colored according to its initial r_{eq} value. To improve readability, a twin marker is also drawn at $\overline{\Theta} + 2\pi$ with the same r_{eq} value. The right frame highlights the formation of several islands around the different resonances.