Numerical Investigation of Fishbone Phase-space Nonlinear Dynamics

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Understanding the dynamics of Energetic Particles (EPs) is essential for optimizing the performance of fusion devices. EPs serve as the primary energy carriers in fusion, and their loss caused by transport from the core to the edge of the device leads to a significant reduction in efficiency. One of the key phenomena driving this transport is the fishbone instability.
The fishbone instability [1, 2, 3] is a kinetic instability caused by the destabilization of a mode due to an EP gradient. This process modifies the gradient, thereby inducing EP transport.
In this work, we present our numerical study of the fishbone instability's characteristics using a simplified 2D phase-space model [4]. The model couples a reduced MagnetoHydroDynamic (MHD) framework in cylindrical geometry, describing the thermal plasma, with a kinetic description of the trapped energetic particles. This study builds on the reduced MHD code AMON [5], developed at the PIIM laboratory, to which we have added a gyro- and bounce-averaged Vlasov equation for the energetic particles.
We investigate the resonant interaction between particles and fields, which drives the nonlinear evolution of the EP gradient self-consistently with the mode, ultimately leading to frequency chirping. Both adiabatic and nonadiabatic frequency chirping [6] are observed and analyzed as key mechanisms behind EP transport. Within this nonlinear framework, we examine the radial particle flux to estimate EP losses due to the fishbone instability. Finally,we analyse our numerical results in the context of experimental data measured in JET and MAST.

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