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Kinetic-MHD simulation of nonlinear interaction between Alfvén instabilities and energetic particles

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Studying the nonlinear interaction between MHD activities and energetic particles using first-principles numerical simulations is an important and challenging task. Recently, a new kinetic code, M3D-C1-K, has been developed to address this issue. The code utilizes a slow-manifold Boris algorithm to push particles, which provides excellent conservation properties for particle momentum. It is also very computationally efficient, using GPUs to accelerate the particles pushing, which can exhibit up to 11 times speedup compared to CPUs. Both drift-kinetic and gyro-kinetic schemes for δf calculations and both pressure coupling and current coupling schemes for MHD-kinetic interaction have been implemented. Several linear benchmarks, including fishbones, TAEs and RSAEs, have been conducted, and good agreement with other codes has been obtained.

Using M3D-C1-K, we can do self-consistent nonlinear simulation to study the excitation and saturation of Alfven instabilities with energetic particles. We first focus on the nonlinearity in the particle kinetic equation, and study the frequency chirping of reversed shear Alfvén eigenmodes after saturation. For RSAE, we find that the mode frequency chirps both upward and downward, with the chirping rate depending on the MHD dissipation. The up-chirping and down-chirping modes can have different mode structures, which shift in the opposite radial directions. The chirping result agrees well with the Berk-Breizman theory [1] for cases with damping rate about one half of mode growth rate, but deviates from the theory for some other cases.

We further study the fluid nonlinearity including mode-mode coupling. For this task, we develop a quasilinear method in M3D-C1-K to accelerate the MHD simulation and keep the nonlinear physics. We find that after including the fluid nonlinearity, the mode saturation level become smaller compared to the simulation result without only particle nonlinearity, which agrees with previous simulation work [2]. The mode-mode coupling can lead to generation of zonal flows, the direction of which is determined by the motion of resonant particles. After the zonal flow develops, the Alfvén mode can either get damped or exhibit frequency chirping, depending on the parity of the zonal flow.

This simulation provides a consistent model to understand the nonlinear behavior of Alfvén modes in tokamak geometry and supports studies of energetic particle confinement.

References

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[2] Y. Chen, G.Y. Fu, C. Collins, S. Taimourzadeh, and S.E. Parker, Phys. Plasmas **25**, 032304 (2018)

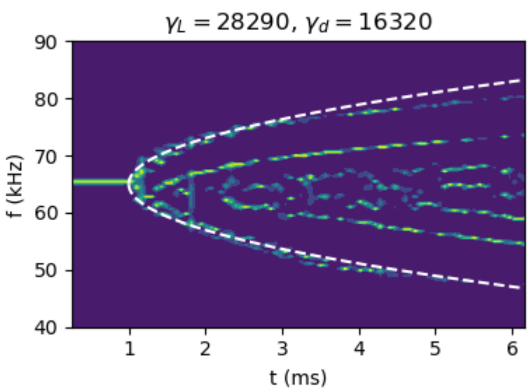

Figure 1. Frequency chirping of RSAE after saturation due to MHD dissipation

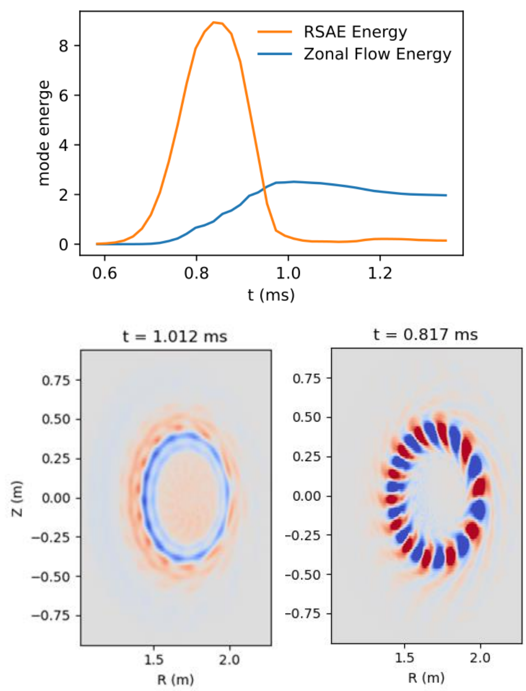

Figure 2. Nonlinear simulation of RSAE saturation and energy transfer to zonal flow