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Hybrid kinetic-MHD simulations of the fishbone instability with JOREK

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Energetic particles will play a central role in future burning plasma experiments, and their confinement is an important aspect for a fusion reactor. Understanding the effects of energetic particles (EPs) is essential, as they can strongly interact with the main plasma and drive magnetohydrodynamic (MHD) instabilities. One notable example is the fishbone instability, which arises from an internal kink mode with n=1 resonance to the precessional frequency of EPs.

To investigate wave-particle interaction phenomena in tokamaks, numerical simulations serve as a major research tool. This contribution focuses on applications and developments of the nonlinear extended MHD code JOREK [1], which includes a kinetic module specifically for energetic particles. In the present hybrid kinetic-MHD model implemented in JOREK, the EPs are simulated using the particle-in-cell technique, while the bulk plasma is treated as a fluid by solving the equations of MHD. A full-f formulation for the kinetic particles and an anisotropic pressure coupling scheme to the fluid are used.

The kinetic particle module was applied to study toroidal Alfvén eigenmodes (TAE) and was successfully validated in the linear regime [2]. The current setup is now being used to investigate the fishbone instability both in the linear and in the nonlinear regime. Initial linear simulations demonstrate good agreement with a benchmark case using the M3D-C1-K code which is explained in [3].

Furthermore, a new hybrid kinetic-MHD model is currently under development for JOREK. It aims at treating also the thermal ions kinetically and only describing the electrons as fluid. The new model is based on the standard drift model. The ion density, parallel velocity and pressure are determined through projections from the kinetic particles, while the electron pressure and the MHD velocity are calculated using fluid equations. The new model is under development in JOREK and we present the key concepts and the present state in this contribution.

[1] M. Hoelzl et al. "The JOREK non-linear extended MHD code and applications to large-scale instabilities and their control in magnetically confined fusion plasmas". In: Nuclear Fusion 61.6 (May 2021), p. 065001. doi: 10.1088/1741-4326/abf99f. url: https://dx.doi.org/10.1088/1741-4326/abf99f.

[2] T. J. Bogaarts et al. "Development and application of a hybrid MHD-kinetic model in JOREK". In: Physics of Plasmas 29.12 (2022), p. 122501. doi: 10.1063/5.0119435. eprint: https://doi.org/10.1063/5.0119435. url: https://doi.org/10.1063/5.0119435.

[3] C. Liu et al. "Hybrid simulation of energetic particles interacting with magnetohydrodynamics using a slow manifold algorithm and GPU acceleration". In: Computer Physics Communications, 275 (2022), p. 108313, url: https://doi.org/10.1016/j.cpc.2022.108313

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