Recent progress and future prospects of kinetic-magnetohydrodynamic hybrid simulations using the MEGA code

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The MEGA code was originally developed as a kinetic-magnetohydrodynamic (MHD) hybrid simulation code to analyze the interaction between energetic ions and MHD instabilities. It was extensively applied to the analysis of energetic ion-driven instabilities, and its high reliability has been well established through benchmarks with other simulation codes and comparisons with experimental results. In recent years, the MEGA code has been extended to treat not only energetic ions but also thermal ions kinetically.[1] This extension has enabled simulations to capture the energy transfer process from energetic ions to thermal ions.[2] Furthermore, the inclusion of kinetic thermal ion effects has improved the accuracy of simulations not only for energetic ion-driven instabilities but also for pressure-driven instabilities.[3]

A notable example is the reproduction of high-beta plasma sustainment observed in Large Helical Device (LHD) experiments. In the LHD, it has been experimentally demonstrated that plasmas with a volume-averaged beta value of approximately 5% can be stably maintained. However, MHD simulations based on single-fluid models have shown strong instability under such high-beta conditions, failing to reproduce the experimental results. By contrast, kinetic-MHD hybrid simulations using the MEGA code, incorporating the kinetic effects of thermal ions, revealed that ions trapped in the helical ripple can suppress the slowly growing pressure-driven instabilities (Fig. 1). As a result, the high-beta state was successfully sustained in the simulation, consistent with experimental observations. These results indicate that the kinetic effects of thermal ions play a crucial role in stabilizing slowly growing pressure-driven instabilities. Similar behavior has also been observed in tokamak plasmas, where, although the suppression mechanism differs, kinetic thermal ion effects significantly reduce the saturation level of resistive infernal modes.[4]

Recent applications of the MEGA code include successful nonlinear simulations reproducing nonlinearly excited EGAMs observed in ASDEX-Upgrade.[5] In addition, by incorporating ICRF heating effects into the simulation, the excitation of shear Alfvén waves (SAWs) by ICRF power in LHD was predicted and later experimentally confirmed.[6] Furthermore, simulations analyzing experiments in LHD involving multiple energetic ion species revealed that the presence of multiple species leads to additional destabilization of Alfvén eigenmodes, resulting in increased losses of both energetic protons and energetic deuterons.[7] These simulation results showed good agreement with experimental observations and have contributed to a deeper understanding of the underlying physics.

Thus far, the MEGA code has been primarily applied to the analysis of macroscopic instabilities, such as energetic ion-driven and pressure-driven instabilities. However, it is increasingly important to also account for the influence of microscopic instabilities. Toward this goal, ongoing efforts are being made to extend MEGA's applicability to turbulence driven by microinstabilities. Benchmark tests have been conducted against the GT5D code for the linear growth rate of ion temperature gradient (ITG) modes, showing good agreement.[8] These results suggest that the MEGA code has the potential to simulate not only macroscopic instabilities but also microturbulent phenomena. Future work will include verification in nonlinear regimes and aim to realize multi-scale simulations that incorporate interactions among macroscopic instabilities, microturbulence, and zonal flows generated by them.

In this talk, we will present recent developments of the MEGA code, its applications, and future prospects.

References
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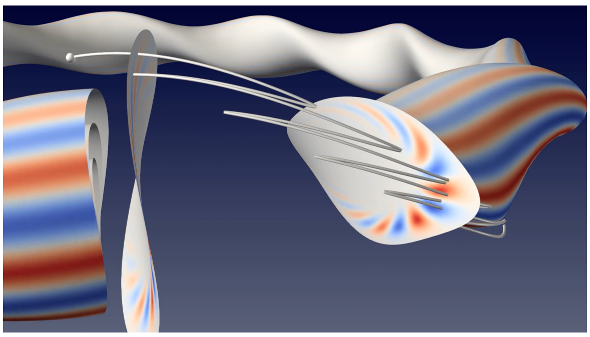

Figure 1. Electron pressure perturbation of a pressure driven MHD instability and the orbit of a thermal ion trapped in the helical ripple in an LHD plasma simulated using the MEGA code.