SIII-4

高エネルギー粒子駆動型不安定性のシミュレーション研究
Simulation Study of Energetic Particle Driven Instabilities

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Energetic particle driven instabilities (e.g. Alfvén eigenmodes) are one of the most important issues for the ITER plasmas because they lead to energetic alpha particle redistribution and losses. Computer simulation is expected to predict the stability of Alfvén eigenmodes and the associated energetic particle transport for ITER operation scenarios. In a Lighthouse Project of the IFERC-CSC Supercomputer Helios, this issue has been investigated using MEGA that is a hybrid simulation code for energetic particles and magnetohydrodynamics (MHD). In this paper, we will present the results of MEGA code [1] for performance benchmark test on Helios, Alfvén eigenmode stability and energetic particle transport in ITER steady operation scenario, and nonlinear MHD effects on Alfvén eigenmode evolution and bursts. We will discuss the future work on the energetic particle driven instabilities.

I. Performance benchmark test of MEGA code on Helios

The computational performance of MEGA code was investigated using Helios. The numbers of grid points and computational particles are (256, 256, 512) for (R, φ, z) coordinates and 34 million, respectively. Figure 1 shows the computational performance vs. number of nodes on Helios. We see an excellent strong scaling up to 512 nodes with 8192 CPU cores.

II. Alfvén eigenmode stability and energetic particle transport in an ITER steady state operation scenario

Stability of Alfvén eigenmodes and the associated transport of energetic alpha particles

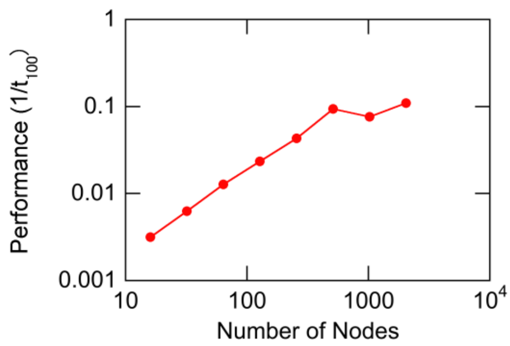

Fig. 1 Strong scaling of MEGA code vs. number of nodes on Helios.

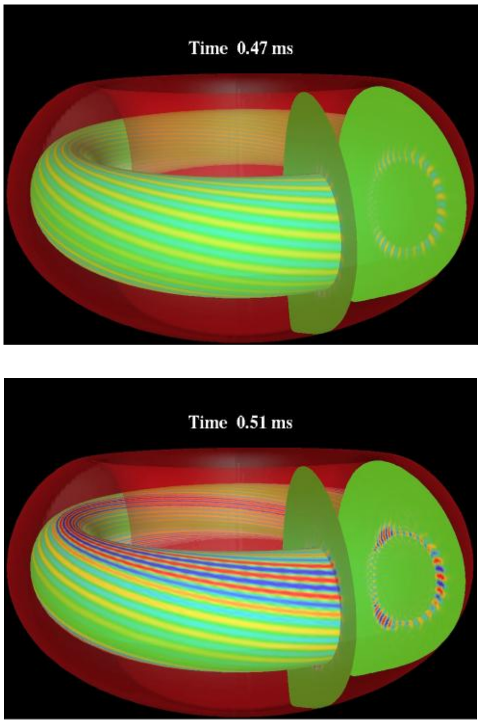

Fig. 2 Spatial profiles of TAE modes in the linearly growing phase (top) and in the saturation phase (bottom).

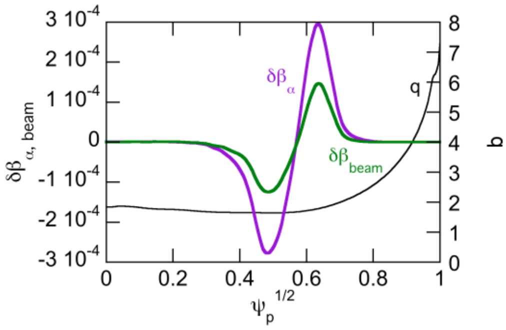

Fig. 3 Beta value perturbations for energetic alpha particles and beam deuterium particles, and safety factor profile.

and beam deuterium particles were investigated for an ITER steady state operation scenario using MEGA code. The equilibrium data provided on the ITER web site is used for the simulation. The specific parameters are major radius 6.2m, minor radius 2m, and total plasma current 9MA. The particle simulation method is applied to both alpha particles and beam deuterium particles. The finite Larmor radius effects are taken into account for both the species.

It was found that toroidal Alfvén eigenmodes (TAE modes) with toroidal mode number from 12 to 22 are unstable and the saturation level of the magnetic fluctuation is 0.2% normalized by the toroidal field. Figure 2 shows the spatial profiles of the TAE modes in the linearly growing phase and the saturation phase. Figure 3 shows the beta value perturbations for alpha and beam deuterium particles. Slight redistributions take place for alpha and beam deuterium particles with beta value perturbations 0.03% and 0.01%, respectively.

III. Nonlinear MHD effects on Alfvén eigenmode evolution

We have recently investigated nonlinear MHD effects on Alfvén eigenmode evolution using MEGA code [2, 3]. In addition to fully nonlinear code, a linear-MHD code was used for comparison. The only nonlinearity in that linear code is from the energetic-particle dynamics. No significant difference was found in the results of the two codes for low saturation levels, $\delta B/B \sim 10^{-3}$. In contrast, when the TAE saturation level predicted by the linear code is $\delta B/B \sim 10^{-2}$, the saturation amplitude in the fully nonlinear simulation was reduced by a factor of 2 due to the generation of zonal (*n=0*) and higher-*n* modes. This reduction is attributed to the increased dissipation arising from the nonlinearly generated modes. The fully nonlinear simulations also show that geodesic acoustic mode is excited by the MHD nonlinearity after the TAE mode saturation.

MEGA code has been extended to simulate recurrent bursts of Alfvén eigenmodes by implementing the energetic-particle source, collisions and losses [4]. The Alfvén eigenmode bursts with synchronization of multiple modes and beam ion losses at each burst are successfully simulated with nonlinear MHD effects for the physics condition similar to a reduced simulation for a TFTR experiment. It is demonstrated with a comparison between nonlinear MHD and linear MHD simulation results that the nonlinear MHD effects significantly reduce both the saturation amplitude of the Alfvén eigenmodes and the beam ion losses. The Alfvén eigenmode bursts take place for higher dissipation coefficients with roughly 10% drop in stored beam energy and the maximum amplitude of the dominant magnetic fluctuation harmonic $\delta B_{m/n}/B \sim 5\times10^{-3}$ at the mode peak location inside the plasma. Quadratic dependence of beam ion loss rate on magnetic fluctuation amplitude is found for the bursting evolution in the nonlinear MHD simulation. The beam ion pressure profiles are similar among the different dissipation coefficients.

These results on nonlinear MHD effects indicate the coupling of Alfvén eigenmode and zonal structures, and suggest the beam ion profiles might reach close to a marginally stability state in the self-consistent evolution. An important development of Alfvén eigenmode simulation using Helios will be an extension of the simulation model with kinetic thermal ions and electrons.

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[2] Y. Todo *et al.*, Nucl. Fusion **50**, 084016 (2010).
[3] Y. Todo *et al.*, Nucl. Fusion **52**, 094018 (2012).
[4] Y. Todo *et al.*, Nucl. Fusion **52**, 033003 (2012).