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Prospects of Hybrid Simulation of Energetic Particles and Magnetohydrodynamics in Fusion Burning Plasmas
核燃焼プラズマにおける高エネルギー粒子・MHD連結シミュレーションの展望

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A hybrid simulation model for energetic particles and magetohydrodynamics is presented with simulation results and performance scaling on number of CPU cores. Prospects for petascale and super-petascale hybrid simulations of energetic alpha particles and Alfvén eigenmodes in burning plasmas are discussed.

1. Introduction

In fusion burning plasmas of magnetic confinement devices like ITER, alpha particles are born from the deuterium-tritium interaction. The born energy of alpha particle is 3.5 MeV and the speed is comparable or faster than the Alfvén velocity of the core plasma. Alfvén eigenmodes, which transport and redistribute energetic particles, can be destabilized by the energetic alpha particles through resonant interaction. The redistribution and losses of energetic alpha particles leads to a deterioration of the fusion device performance, because the energetic alpha particles are expected to heat the fuel plasma for the self-sustained operation. Then, the interaction between energetic particles and Alfvén eigenmodes is a crucial issue for burning plasmas. Many experiments have been devoted to investigate this issue substituting the fast particles generated by neutral beam injection or ICRF (ion cyclotron range of frequency) heating for energetic alpha particles.

Nonlinear simulations are needed to predict the evolution of Alfvén eigenmodes and the transport of energetic alpha particles. In this talk, a hybrid simulation model for energetic particles and magetohydrodynamics (MHD) is presented with simulation results and performance scaling on number of CPU cores.

2. Physics Model

MEGA is a hybrid simulation code for energetic particles and MHD [1-3]. In MEGA code, the bulk plasma is described by the nonlinear MHD equations and the energetic ions are simulated with the δf particle method. The MHD equations with the energetic-ion effects are given by

$$\frac{\partial \rho}{\partial t} = -\nabla\cdot(\rho\mathbf{v}) + \nu_{\mathrm{n}}\Delta(\rho - \rho_{\mathrm{eq}}), \tag{1}$$

$$\rho\frac{\partial}{\partial t}\mathbf{v} = -\rho\vec{\omega}\times\mathbf{v} - \rho\nabla(\frac{\mathrm{v}^2}{2}) - \nabla p + (\mathbf{j} - \mathbf{j}'_h)\times\mathbf{B} + \frac{4}{3}\nabla(\nu\rho\nabla\cdot\mathbf{v}) - \nabla\times(\nu\rho\vec{\omega}), \tag{2}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}, \tag{3}$$

$$\frac{\partial p}{\partial t} = -\nabla\cdot(p\mathbf{v}) - (\gamma-1)p\nabla\cdot\mathbf{v} + (\gamma-1)[\nu\rho\omega^2 + \frac{4}{3}\nu\rho(\nabla\cdot\mathbf{v})^2 + \eta\mathbf{j}\cdot(\mathbf{j}-\mathbf{j}_{\mathrm{eq}})] + \nu_{\mathrm{n}}\Delta(p - p_{\mathrm{eq}}), \tag{4}$$

$$\mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta(\mathbf{j} - \mathbf{j}_{\mathrm{eq}}), \tag{5}$$

$$\mathbf{j} = \frac{1}{\mu_0}\nabla\times\mathbf{B}, \tag{6}$$

$$\vec{\omega} = \nabla\times\mathbf{v}, \tag{7}$$

where μ_0 is the vacuum magnetic permeability, γ is the adiabatic constant, ν and ν_{n} are artificial viscosity and diffusion coefficients chosen to maintain numerical stability and all the other quantities are conventional. The subscript “eq” represents the equilibrium variables. The energetic ion contribution is included in the MHD momentum equation [Eq. (2)] as the energetic ion current density $\mathbf{j}'_h$. The energetic ion current density $\mathbf{j}'_h$ in Eq. (2) includes the contributions from parallel velocity, magnetic curvature and gradient drifts, and magnetization current. The $\mathbf{E}\times\mathbf{B}$ drift disappears in $\mathbf{j}'_h$ due to the quasi-neutrality [1]. We see that electromagnetic field is given by the standard MHD description. This model is accurate under the condition that the energetic ion density is much less than the bulk plasma density. The MHD equations are solved using a fourth order (in both space and time) finite difference scheme.

3. Results

Many energetic particle driven instabilities in tokamak and helical plasmas have been investigated using MEGA code. These include 1) nonlinear MHD effects on Alfvén eigenmode instability and bursts [4, 5], 2) energetic particle transport by reversed shear Alfvén eigenmode [6], 3) nonlinear evolution of energetic particle modes in JT-60U [7, 8], 4) energetic particle driven geodesic acoustic mode in LHD [9]. A toroidal Alfvén eigenmode in an LHD plasma simulated using MEGA code is shown in Fig. 1.

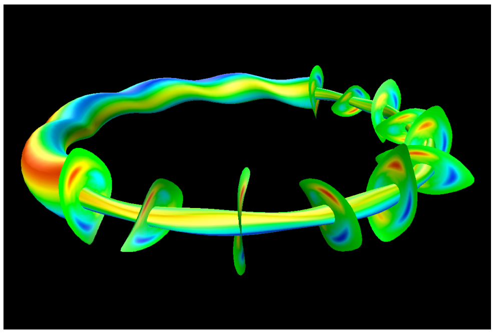

Fig.1. Toroidal electric field of a toroidal Alfvén eigenmode in LHD plasma.

4. Performance Scaling

The strong scaling and the weak scaling of MEGA code were investigated on the Plasma Simulator (HITACHI SR16000, 77TF) at National Institute for Fusion Science. The Plasma Simulator consists of 4096 CPU cores distributed on 128 nodes. The computational performance for different numbers of CPU cores were investigated for 1024^3 grid points and the same number of particles. The result is shown in Fig. 1. We see an excellent strong scaling. The weak scaling is also excellent over two orders of numbers of CPU cores.

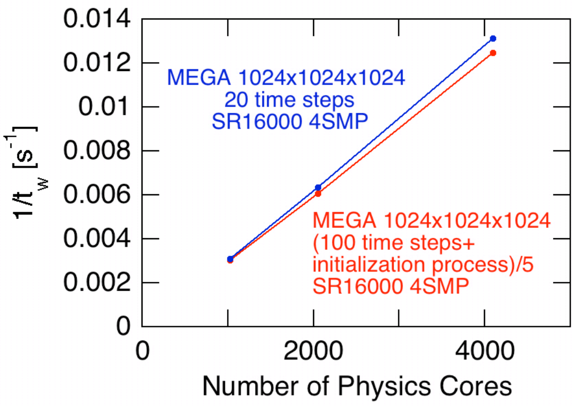

Fig.2. Strong scaling of MEGA code on Plasma Simulator (HIACHI SR16000). Vertical axis is in proportion to computational performance.

5. Future Prospects

For petascale computers we can expect good performance of MEGA code using ~1024^3 grid points. As the weak scaling is always good, we can expect reasonable performance also for computers faster than petaflops if we adopt larger numbers of grid points and particles. However, MHD model is no longer valid for the larger number of grid points because the grid size will be smaller than the ion gyro radius. Then, to exploit computer performance faster than petaflops, we should realize strong scaling with MHD model or utilize the surplus computer power for extended physics models.

Let us discuss on what is the critical physical issue for the prediction of Alfvén eigenmode stability and energetic alpha particle transport in burning plasmas. Realistic geometry is quite important for Alfvén eigenmode stability. MEGA code is ready to simulate using realistic equilibrium data produced with HINT, MEUDAS, and EFIT codes. Another key element is the kinetic effects of bulk ions and electrons. A substantial part of Alfvén eigenmode damping rate arises from radiative damping that involves bulk ion finite Larmor radius effects and electron Landau damping. Then, extensions of the MHD model or the adoption of the gyrokinetic plasma model to include the kinetic effects are required for more accurate prediction.

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