9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Development of the Gyrokinetic-MHD Hybrid Code cuGMEC and Its Nonlinear Simulations of Alpha Particle-driven Alfvén Eigenmodes in ITER

Shiyang Liu[1], Peiyou Jiang[2], Pengfei Liu[3], Guoyong Fu[1]
[1] Institute for Fusion Theory and Simulation, School of Physics, Zhejiang University, Hangzhou 310058, People's Republic of China
[2] Max Planck Institute for Plasma Physics, 85748 Garching, Germany
[3] Institute of Physics, Chinese Academy of Sciences, Beijing 100190, People's Republic of China
e-mail (speaker): s.y.liu@zju.edu.cn

We report the development of cuGMEC, a high-performance GPU-accelerated gyrokinetic-MHD hybrid code implemented in CUDA C++, along with its nonlinear simulation results for the ITER steady-state scenario (#131041). In cuGMEC, electrons are treated as a fluid, energetic particles (EPs) and thermal ions are described by gyrokinetic equations solved via the Particle-in-Cell (PIC) method. Compared to the CPU version [1][2], additional equations and terms are integrated, and all nonlinear terms are implemented to make the physics more self-consistent. Spatial and temporal discretization uses five-point central differencing and fourth-order Runge-Kutta methods. A field-aligned coordinate is used to enhance grid resolution, while a shifted metric coordinate and staggered grid are employed to improve numerical stability. The hybrid model is verified through benchmarks against theories and other codes. Several optimizations are applied to both MHD and PIC components. Testing on NVIDIA A800 GPUs shows favorable scaling and acceleration. Specifically, the computational speed of a single A800 GPU is equivalent to that of 25 Intel Xeon Gold 6348 CPUs (700 cores).

For ITER simulations, we first scan toroidal mode numbers, obtaining growth rates and frequencies in good agreement with GTC results [3]. Then we conduct fully nonlinear simulations with multiple toroidal mode numbers (0 to 36). The figures below show the mode evolution of the potential and the mode structure, and the alpha particles density profile at the nonlinear stage. Simulating 20,000 steps (0.3 ms) takes only 8.6 hours on 16 A800 GPUs, using 10 million grid points, 3.6 billion particles, and 4 points for gyro-average operation. During the linear phase, the modes with n~30 exhibit the highest growth rate and saturate first. However, in the nonlinear phase, lower-n modes are excited and ultimately dominate in amplitude. By t=0.3ms, the alpha particle distribution function shows significant flattening. More details on nonlinear ITER simulations will be presentd.

References
[1] P. Y. Jiang et al., Phys. Plasmas 31, 073904 (2024).
[2] Z. Y. Liu et al., Phys. Plasmas 31, 073905 (2024).
[3] Z. Lin et al., 49th EPS Conference on Plasma Physics. European Physical Society, 2023.

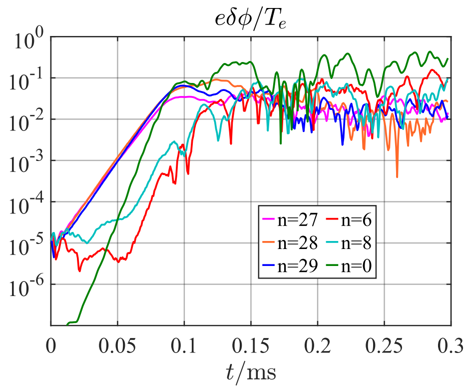

Figure 1. Selected mode evolution of the potential.

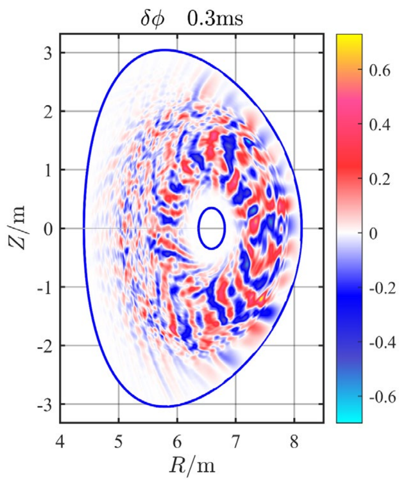

Figure 2. 2D Mode structure at 0.3 ms.

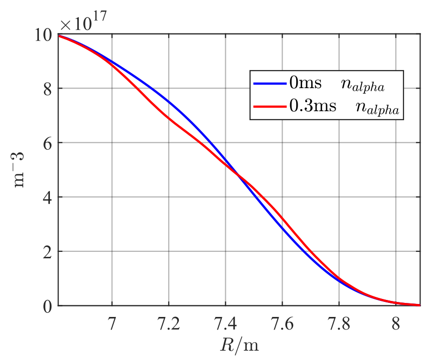

Figure 3. Alpha particles density profile.