§1. Simulation of Global MHD Phenomena by the Gyrokinetic PIC Code

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The simulation model, which can treat global magnetohydrodynamic (MHD) phenomena in the present-day and future high temperature large tokamaks like ITER (International Thermonuclear Experimental Reactor), is necessary to extend the operational parameter range of experiments. Such model must have an ability to simulate extended (or kinetic) MHD phenomena because a lot of phenomena observed in experiments seem beyond explanation by conventional MHD model. To study these phenomena, we developed GpicMHD code [1], which is a PIC (Particle In Cell) code based on the electro-magnetic gyrokinetic theory. Although GpicMHD is free from 'closure' problem, which is encountered in the fluid-type MHD code, GpicMHD inevitably requires the utilization of huge computer resources because PIC code must follow huge number of particle orbits.

A present version of GpicMHD assumes a lowest order tokamak model in cylindrical geometry. The toroidal version will be developed in the near future. There are two versions of GpicMHD. One is a 2-D code assuming a single helicity. The other is a 3-D code, which can treat a multi-helicity case. While 2-D version is mainly used to develop and test new algorithms, 3-D version based on the conventional gyrokinetic algorithm is used to test the parallelization performance on the existing massive-parallel computers.

[I] Development of new algorithm

In order to apply GpicMHD to higher beta and larger scale tokamak simulation, a new algorithm is proposed [2]. In the new algorithm, the electrostatic potential, ϕ, and the longitudinal component of the vector potential, A_z, are obtained using the vortex equation and the generalized Ohm's law along the magnetic field, respectively.

$$\frac{\partial}{\partial t}\nabla_\perp^2\phi = -v_A^2\boldsymbol{b}^*\cdot\nabla\left(\nabla_\perp^2 A_z\right) - \frac{\boldsymbol{b}\times\nabla\phi}{B_0}\cdot\nabla\left(\nabla_\perp^2\phi\right)$$

$$\frac{\partial}{\partial t}\nabla_\perp^2 A_z = \mu_0 e^2\left(\frac{n_e}{m_e}+\frac{n_i}{m_i}\right)\left(\frac{\partial A_z}{\partial t}+\boldsymbol{b}^*\cdot\nabla\phi\right) - \frac{\boldsymbol{b}\times\nabla\phi}{B_0}\cdot\nabla\left(\nabla_\perp^2 A_z\right)$$
$$-\mu_0 e\boldsymbol{b}^*\cdot\nabla\int v^2 f_e dp + \mu_0 e\boldsymbol{b}^*\cdot\nabla\int v^2 f_i dp$$

Both equations are derived exactly from the gyrokinetic Vlasov, Poisson, and Ampere system without approximation. The gyrokinetic Poisson equation and the Ampere's law, which are used in the conventional gyrokinetic PIC code, are employed but only for estimating initial ϕ and A_z. Although gyrokinetic particles are advanced in time as in the conventional gyrokinetic code with δf-scheme, particle information is mainly used to estimate second order moments (pressure terms) in the Ohm's law. In other words, the lower order moment equations are closed by the particle information (particle closure or complete closure). The simulation of $m = 1/n = 1$ (m: poloidal mode number, n: toroidal mode number) kinetic internal kink mode by using the new version of GpicMHD revealed the following facts: (1) Linear growth rates and mode profiles are compared with results of Gyro-Reduced-MHD code: both results coincide very well. (2) Energy conservation is excellent. (3) Noise level due to particle discreteness is quite low. (4) There are no limits for the higher beta ($\rho_s/d_e = v_{te}/v_A > 1$) and large scale ($d_e/a << 1$) simulations. Here ρ_s, d_e, v_{te}, and v_A are ion sound Larmor radius, electron collisionless skin depth, electron thermal velocity, and Alfven velocity, respectively.

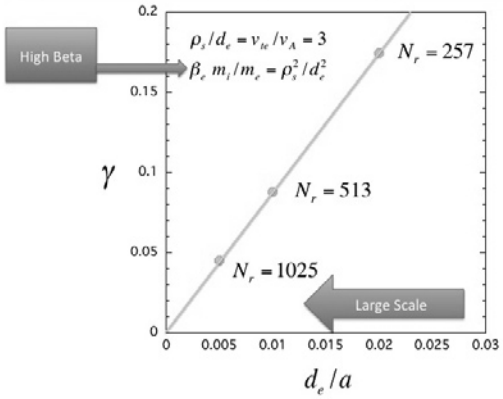

Fig.1 Growth rate versus collisionless electron skin depth

[II] Parallelization performance

Assuming utilization of high performance massive-parallel computer of 10 peta-flops in the near future, parallelization performance of GpicMHD on the present computer is tested for SR16000 ("plasma simulator" in NIFS), which is a scalar SMP cluster system consisting of 8192 logical cores (128 nodes consisting of 64 logical cores: one physical core is equivalent to two logical cores). The test parameters are meshes of N_r=129, N_θ=128, N_z= 128, 8192000000 particles, and 1000 time steps. The version of one-dimensional (1-D) domain decomposition in z direction using 64 domains, 128 copies, and 2 threads (auto-parallelization for threads and MPI for processes), showed 2.4 T-flops using total cores. Measurement of the weak scaling showed no clear saturation as the number of cores increased. In order to implement the good scaling in the future machine with more cores, the version of 2-D domain decomposition in r and z, was developed. To equate the load of particle pushing and charge assignment, the radial direction is non-uniformly decomposed. The case with 64 domains in z, 16 domains in r, 4 copies, and 2 threads showed 1.4 T-flops using total cores. It is expected that for the realistic parameters of several thousands of radial meshes, the version of 2-D domain decomposition will show good performance.

1) Naitou, H. et al.: J. Plasma Fusion Res. SERIES **8** (2009) 1158
2) Naitou, H. et al.: Bull. APS 51th Annual Meeting of DPS **54** (2009) 35