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Multi-scale simulations of electron- and ion-scale turbulence in magnetic fusion plasma

核融合プラズマにおける電子／イオン系乱流のマルチスケールシミュレーション

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In magnetic fusion plasma researches, plasma turbulence at ion and electron scales has often been treated separately by assuming their scale-separation. The gyrokinetic simulation code GKV, which is highly optimized for the K computer by developing the efficient MPI process mapping and computation-communication overlap techniques, allows direct numerical simulations of the multi-scale plasma turbulence. It is demonstrated that the cross-scale interactions exist even with real ion-to-electron mass ratio, where ion and electron scales are well separated by a factor of the square root of mass ratio.

1. Introduction

The understanding of the plasma turbulence is strongly promoted by theoretical and numerical studies based on gyrokinetics [1]. Most of the previous gyrokinetic simulations of plasma turbulence treat ion-scale turbulence (a typical wave length ~ the ion Larmor radius ρ_{ti} and a frequency ~ the ion transit frequency v_{ti}/R) and electron-scale turbulence (a typical wave length ~ the electron Larmor radius ρ_{te} and a frequency ~ the electron transit frequency v_{te}/R) separately, by assuming their scale-separation. However, since the assumption is not trivial, it should be clarified whether the cross-scale interactions between ion- and electron-scale turbulence exist or not. Such an analysis resolving both of ion and electron scales requires huge computations, and therefore we had to wait the appearance of the extreme-scale supercomputer such as the K computer.

The GKV code is one of major gyrokinetic simulation codes in fusion community, and its physics capability is extended along with the development of simulation models and of high performance computers: ion-scale turbulence in a simple circular torus tokamak plasma on the Plasma Simulator (1.4TFLOPS, at NIFS) in 2006 [2], ion-scale turbulence simulations in a complex non-axisymmetric LHD plasma on the Earth Simulator (40TFLOPS, at JAMSTEC) in 2008 [3], and ion-scale turbulence simulations with rapid electron motions on the Helios (1.2PFLOPS, at IFERC-CSC) in 2013 [4]. For now, in 2014 the Japanese fastest supercomputer K (10PFLOPS, at RIKEN) enables multi-scale simulations fully resolving ion and electron scales [5]. By means of the direct numerical simulations, we analyze the dynamics of the multi-scale plasma turbulence, which reveal the existence of the cross-scale interactions.

2. Optimizations of the GKV code on the K computer

The GKV code solves nonlinear time evolution of perturbed distribution functions of ions and electrons with electromagnetic fluctuations. In the numerical point of views, the code is regarded as a computational fluid dynamics application in the 5D phase space (3D configuration space and 2D velocity space). The 2D dynamics perpendicular to the confinement magnetic field is calculated by the spectral method using parallel 2D FFTs, and the other 3D dynamics are calculated by the finite difference methods. The computations are parallelized by using the OpenMP/MPI hybrid parallelization. Multi-dimensional domain decomposition introduces various inter-node communications: data transpose for parallel FFTs, point-to-point communications for finite differences, and reduction communications for charge and current density evaluations (integrations over the velocity space and particle species). Since multi-scale plasma turbulence simulations demand high computational performance and memory requirements, which can be attained by extreme scale parallelization over 100k cores, the reduction of the inter-node communication cost and improvement of the strong scaling is of critical importance.

The K computer is a distributed memory super-

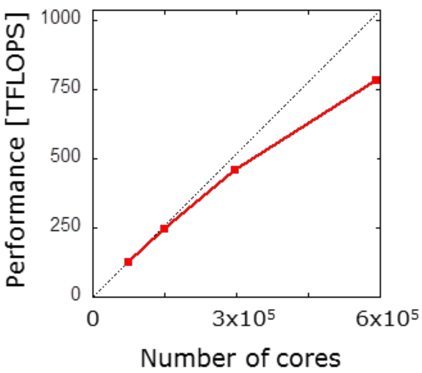

Fig. 1 Strong scaling of multi-scale plasma turbulence simulation with ~6×10^{11}grids on the K computer.

computer, which consists of 82,944 computation nodes (2 GHz, 16 GFlops/core, Memory-BW 8 GB/s/core, 8 cores/node) connected by Torus fusion (Tofu) interconnect (6D mesh/torus topology, Interconnect-BW 5 GB/s × 4, Multi-way simultaneous communications: 4 sends + 4 receives). To minimize the communication cost of the GKV code on the K computer, we develop the segmented rank mapping on the Tofu network which is designed so that the various inter-node communications are preformed locally and independently on a 3D torus network [6]. In addition, we implement the pipelined overlaps of computations and communications for spectral and finite difference calculations. Thanks to these optimizations, the computational performance of the GKV code is significantly improved, which shows excellent strong scaling up to ~600k cores with the high parallelization rate ~99.99994% as plotted in Fig. 1.

4. Multi-scale turbulence simulations

Using the highly-optimized code, we first analyzed multi-scale plasma turbulence simulations resolving from electron to ion scales with real ion-to-electron mass ratio and β value. As shown in Fig. 2, at first high-growth-rate electron temperature gradient modes appear and create radially elongated eddies, streamers (a). After that, ion temperature gradient modes slowly grow up and become dominant at the steady state (b). At the same time, electron-scale streamers are suppressed by the ion-scale turbulent eddies. Thus, the results demonstrate the existence of the cross-scale interactions between electron- and ion-scale turbulence even with the real mass ratio, where electron and ion scales are well separated by a factor of the square root of mass ratio. The analysis

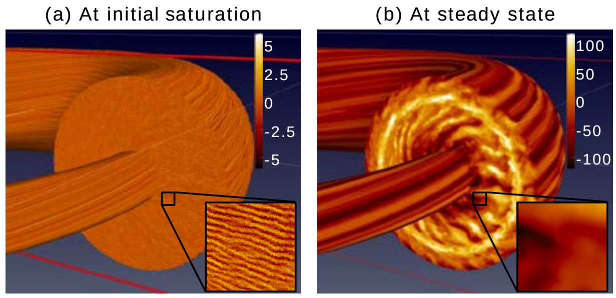

Fig. 2 Snapshots of electrostatic potentials in multi-scale simulations.

with the real β value shows that electromagnetic perturbations stabilize ion temperature gradient modes and changes the multi-scale interactions.

5. Summary

Gyrokinetic simulations promote the understanding of the plasma turbulence along with the development of high performance computing. Optimizations of the GKV code on the K computer (segmented process mapping and pipelined computation-communication overlaps) significantly improve the computational performance of the GKV code. The highly-optimized code allows multi-scale plasma turbulence simulations in magnetic fusion plasma. It reveals the existence of the multi-scale interactions between electron- and ion-scale turbulence.

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References

[1] X. Garbet, Y. Idomura, L. Villard, and T.-H. Watanabe: Nucl. Fusion **50** (2010) 043002.

[2] T.-H. Watanabe, and H. Sugama: Nucl. Fusion **46** (2006) 24.

[3] T.-H. Watanabe, H. Sugama, and S. Ferrando-Margalet: Phys. Rev. Lett. **100** (2008) 195002.

[4] S. Maeyama et al.: Comput. Phys. Commun. **184** (2013) 2462.

[5] S. Maeyama et al.: *Proc. 25th IAEA FEC*, St. Petersburg, 2014, TH/1-1.

[6] S. Maeyama et al.: *Int. Conf. High Perform. Comput. Network. Storage and Analysis (SC13)*, Denver, 2014.