19aE-1

Progress of Turbulent Transport Studies on Toroidal Plasmas via Gyrokinetic Simulation

ジャイロ運動論的シミュレーションによるトーラスプラズマ乱流輸送研究の進展

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Recent progress of gyrokinetic Vlasov simulations of turbulent transport in magnetic confinement fusion plasmas is reported, focusing on multiple scale interactions of turbulence and zonal flows. Gyrokinetic simulations of the kinetic ballooning mode instability and the ion/electron temperature gradient and the trapped electron mode turbulence are realized with the real mass ratio of protons and electrons. Continuous efforts also are devoted to applications to transport analysis for tokamak and helical plasma experiments, and construction of the first principle based transport model.

1. Introduction

Gyrokinetic simulation of plasma turbulence has been developed as an indispensable research tool for understanding the anomalous transport observed in magnetic fusion experiments. Using the gyrokinetic Vlasov simulation code, GKV/GKV-X, we have investigated the zonal flow enhancement in an optimized helical configuration and the ion heat transport reduction by the ion scale turbulence. Application to the Large Helical Device (LHD) experiments was also successfully carried out by introduction of the confinement field structure reconstructed from the experimental data. For comprehension of turbulent transport in magnetic fusion plasmas, however, one needs to overcome a difficulty of multiple scales intrinsic to the magnetized fusion plasmas.

The gyrokinetic simulation of electromagnetic ion temperature gradient (ITG) turbulence in the helical plasmas demands a fine time resolution (with respect to the ion drift frequency) so as to resolve the fast parallel electron motion passing through helical ripples. Also, in simulations of the trapped electron mode (TEM), one must take account of influences by turbulent fluctuations in the adjacent wavenumber regimes, such as the ITG and electron temperature gradient (ETG) modes. In short, the multi-scale turbulence in multi-species plasmas may interact with each other directly or indirectly via zonal flows.

2. Recent progress in GKV simulations

For studying the multiple scale problems related to the plasma turbulent transport, we have continuously extended the physics model and the numerical method of the GKV code, introducing high performance computing techniques. The obtained results are summarized as follows: (a) the first gyrokinetic simulation of the electromagnetic ITG and the kinetic ballooning mode (KBM) turbulence in a non-axisymmetric torus [1-3], (b) discovery of ETG turbulence regulation through a cross-scale interaction with TEM via zonal flows [2], (c) realization of multi-scale gyrokinetic simulation of ITG/TEM/ETG turbulence with the real ion-to-electron mass ratio [5], (d) amplification of zonal flow response to a turbulent source due to an equilibrium-scale radial electric field in helical systems [6], (e) development of a novel numerical simulation method for local turbulence with a long parallel correlation length [7].

As a highlight of the recent results, a color contour of the KBM fluctuations in LHD plasma is presented in Fig. 1, where a nonlinear interaction of unstable modes with finite radial wavenumbers plays a key role in saturation of the KBM instability growth [1-3]. This is contrast to the zonal flow dominant state of the ITG turbulence, and the KBM growth is expected in an LHD discharge with a high-β value and high ion temperature.

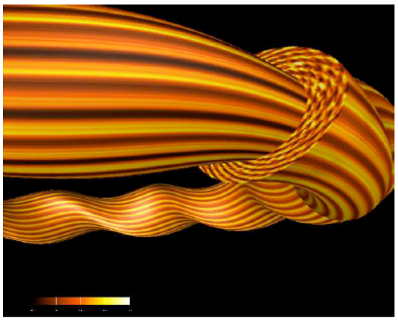

Figure 1: Color contour of electrostatic potential fluctuations in a saturated state of the KBM instability growth in LHD plasma [3].

In the course of GKV simulations, the entropy balance relation is carefully checked as a verification test of numerical soundness. It is also utilized as a powerful analysis tool of plasma turbulence, where the triad interactions of turbulence and zonal flows are quantitatively evaluated by the entropy transfer function [8-10].

The GKV simulations with the helical [11] and tokamak [12] configurations reconstructed form the experimental data are also extended to the ITG/TEM turbulence with kinetic electrons, and are employed for transport studies of the LHD and JT-60U experiments. The GKV simulation data has also been utilized for construction of the anomalous ion heat transport model for the LHD experiments [13-16]. The first principle based transport model is compared with the GKV-X simulations in Figure 2, showing a good agreement with the nonlinear simulation result.

Continuous and elaborate efforts have been devoted to further extensions of the GKV code, such as multiple ion species and their collisions with different temperatures, towards quantitative predictions of turbulent transport properties in future experiments.

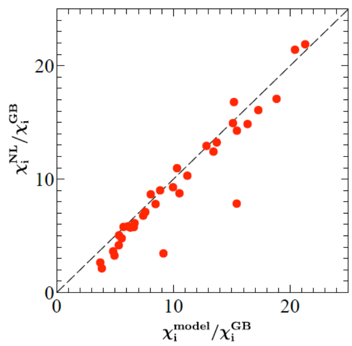

Figure 2: Comparison of the ion heat diffusivity model (χ_i^{model}) with nonlinear simulation results (χ_i^{NL}) [15].

Acknowledgments

This work was supported in part by JSPS KAKENHI (Grant Numbers 23561003 and 24561030), in part by HPCI Strategic Program Field No. 4, and by use of Plasma Simulator under the collaborative research with National Institute for Fusion Science (14KNST065, 14KNST067, 14KNTT026, and 14KNTT027), Helios at International Fusion Energy Research Center, and the K computer at RIKEN (hp140044 and hp140227).

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