23R3-4

Simulation Research of Toroidal Fusion Plasmas Including Three-Dimensional Effects

3次元効果を含むトロイダル核融合プラズマのシミュレーション研究

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Large-scale computer resources such as the new supercomputer in the IFERC-CSC are highly necessary to conduct simulation researches in toroidal fusion plasmas especially for investigating complicated systems including three-dimensional magnetic field structures. As examples of simulation studies of toroidal plasmas including the three-dimenstional effects, recent results from nonlinear MHD simulation of reversed field pinch plasmas, δf Monte Carlo simulation of neoclassical toroidal viscosity in tokamaks, and gyrokinetic Vlasov simulation of ion temperature gradient turbulence and zonal flows in helical sytems are presented. It is shown that the three-dimensional structures appear ubiquitously in various toroidal systems as critical factors of plasma confinement and their effects need to be extensively pursued.

1. Introduction

In the National Institute for Fusion Science, the Numerical Simulation Research Project is in progress, which promotes comprehensive simulation studies of toroidal magnetic confinement fusion plasmas and aims to realize a helical numerical test reactor as integrated codes for predicting whole plasma behaviors over diverse spatiotemporal scales [1]. Generally, for simulations of helical plasmas such as heliotrons and stellarators, complicated three-dimensional magnetic-field structures require larger numbers of grid points and longer computational time than for the case of tokamaks, and effective utilization of massive parallel computers like the one of the IFERC-CSC is highly desirable. In addition, three-dimensional physical phenomena caused by symmetry breaking have recently been attracting much attention even in researches of tokamaks and reversal field pinches (RFP) which are originally axisymmetric. In this paper, examples of recent simulation studies on such three-dimensional physics are illustrated.

2. Nonlinear MHD Simulation

Recent experiments have shown structural changes of RFP plasmas into self-organized three-dimensional states with helical magnetic configurations, which are now examined as a control method to avoid confinement degradation due to intrinsic tearing mode instabilities [2]. Applying the MHD simulatin code, MHD Infrastructure for Plasma Simulation (MIPS) [3], to the experimental RFP configurations of the RELAX device [2], the mechanisms of formation of helical structures are clarified [4]. Figure 1 shows the nonlinear MHD simulation result, in which helical structures of isopressure surfaces are seen.

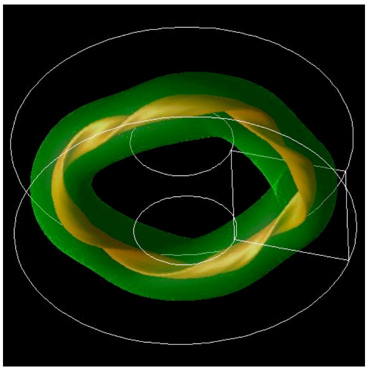

Fig.1. Formation of helical structures in the core region of an RFP plasma obtained from the nonlinear MHD simulation.

3. Simulation of Neoclassical Toroidal Viscosities

The control of the toroidal rotation is an important issue in tokamaks and the International Thermonuclear Experimental Reactor (ITER), in order to improve the stability of the contained plasmas. The significant change of the toroidal rotation can occur when the axisymmetry is broken. The δf Monte Carlo simulation code, FORTEC-3D , which was originally developed to investigate the neoclassical transport processes in helical systems, are applied to the evaluations of neoclassical viscosities (NTVs) in tokamaks with nonaxisymmetric magnetic perturbations [5,6]. As shown in Fig.2, the NTVs calculated from the FORTEC-3D simulation agree well with Park's analytical formula [7] in wide collisionality range except the edge region. Also, a difference between the simulation and analytical results is found in the shape of the peak profile of NTV around the resonant surface. Thus, the direct kinetic simulation using FORTEC-3D can reveal the detailed properties of NTV, which are difficult to treat analytically.

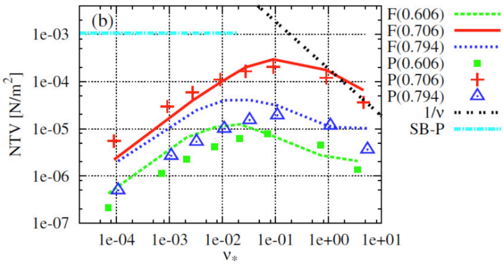

Fig.2. Dependence of the neoclassical toroidal viscosity (NTV) on the normalized collisionality ν_* for several radial positions. The "F" curves are results from the FORTEC-3D simulations and the "P" symbols are from the analytic formula, and the numerals denote the normalized radial position ρ. The "$1/\nu$" and "SB-P" lines represent the values from the asymptotic limit theory for the $1/\nu$ and superbanana-plateau regimes, respectively.

4. Gyrokinetic Simulation

Gyrokinetic simulation is a powerful means to evaluate turbulent transport in magnetically confined plasmas from the first principles. Since the gyrocenter distribution function on the five dimensional phase space is treated, the gyrokinetic simulation requires huge computer resources especially for helical systems. The gyrokinetic Vlasov (GKV) simulation code [8], which employs the local flux tube as a simulation domain, was developed and applied to the investigation of the ITG turbulent transport and zonal flows in helical systems. It was elucidated that, as predicted by the zonal-flow response theory [9], the zonal-flow generation is enhanced and accordingly the ITG turbulent transport is reduced in the neoclassically optimized helical configuration [8]. An extended version of the gyrokinetic Vlasov code (GKV-X) can treat full geometric data of three dimensional MHD equilibria precisely corresponding to the experimental conditions [10]. Simulation results from the GKV-X simulation of the ITG turbulence are successfully compared with experimental results for a high ion temperature plasma in the LHD [11]. Potential contours obtained from the simulation are shown in Fig.3. It is theoretically predicted that, in helical systems, the macroscopic or background radial electric field can enhance generation of zonal flows leading to the further reduction of turbulent transport and the favorable isotope effect of the ion mass [12]. The poloidally global simulations of the ITG turbulence are done by a newly-developed gyrokinetic Vlasov simulation code, from which the increased background electric field is confirmed to strengthen the zonal flow generation [13,14].

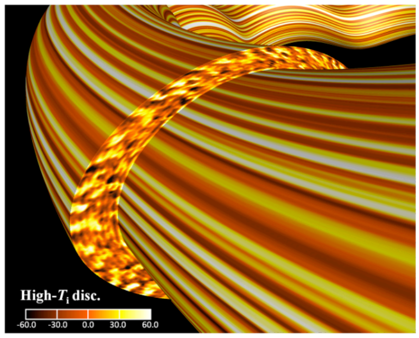

Fig.3. Potential contours in a high *Ti* LHD plasma obtained from the gyrokinetic ITG turbulence simulation using the GKV-X code.

5. Summary

In this paper, recent results from different types (Nonlinear MHD, δf Monte Carlo, and Gyrokinetic Vlasov) of simulations are presented, which investigate effects of three-dimensional magnetic field structures in various types (RFP, tokamak, and helical system) of toroidal plasmas. As seen from these examples, three-dimensional effects critically affect the performance of the magnetic confinement fusion and further simulation studies on them are to be done by maximum utilization of the advanced supercomputers.

Acknowledgments

This work is supported in part by the Japanese Ministry of Education, Culture, Sports, Science, and Technology, Grant Nos. 21560861, 22760660, and 23760810 and in part by the NIFS Collaborative Research Programs, Grant Nos. NIFS10KNTT003, NIFS11KNST017, NIFS11KNXN229, NIFS10KNST006, and NIFS11KNST014.

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