

Turbulent Transport Reduction in Fusion Plasma - Confirmation of an Optimization Scenario by Five-Dimensional Simulations

Project Representative

Tomo-Hiko Watanabe National Institute for Fusion Science, National Institutes of Natural Sciences

Author

Tomo-Hiko Watanabe National Institute for Fusion Science, National Institutes of Natural Sciences

Turbulent transport in magnetically-confined fusion plasma is investigated by means of kinetic simulations where time-evolutions of the one-body distribution function are numerically solved in the five-dimensional phase-space. It is confirmed by the numerical simulations that the turbulent heat transport in toroidal helical systems can be reduced by self-generated plasma flows (zonal flows) which are enhanced in an optimized configuration of the confinement magnetic field. The obtained results also provide a possible explanation for the transport property found in the Large Helical Device experiments.

Keywords: fusion, plasma, turbulence, transport, simulation

1. Introduction

Magnetically-confined fusion plasma, that is, an ionized gas of hydrogen (or its isotope), involves a variety of fluctuations of density, flow, temperature, and electromagnetic fields which cause the turbulent transport of particles and heat from the core to the edge regions of the toroidal confinement device. The turbulent fluctuations are driven by density and temperature gradients as well as current distribution in the equilibrium profiles. The observed transport levels in the fusion plasma experiments are higher in orders of magnitudes than those expected from the collisional transport theories such as the "classical" and "neoclassical" ones. Then, the turbulent transport is often called "anomalous". The anomalous transport problem has long been studied as one of the central subjects of the magnetic fusion research.

In fusion plasmas with high temperature of several keV, the conventional fluid approximation is not valid, and one needs to employ kinetic descriptions of plasma on the multi-dimensional phase space. For quantitative understandings of the anomalous transport, the gyrokinetic simulations of the toroidal plasma turbulence have been advanced in the last decade, where a kinetic equation of the one-body distribution function defined on the five-dimensional phase-space is solved. Extensive simulation studies revealed that a mean sheared plasma flow generated by the turbulence could effectively regulate the anomalous transport [1]. The self-generated plasma flow perpendicular to the magnetic field and the radial directions is called "zonal flow" in analogy to the strong longitudinal winds in the Jovian atmosphere.

The gyrokinetic simulation with sufficient accuracy demands a lot of computer resources and can be realized only on a tera-flops and tera-bytes scale computers like the Earth Simulator, because of the high-dimensionality of the problem. We have developed the five-dimensional gyrokinetic Vlasov simulation code (GKV code) [2] which has been used for studying the turbulent transport in tokamak and helical fusion devices. The equilibrium configuration of tokamak, such as ITER [3], has toroidal symmetry, while the helical system, such as the Large Helical Device (LHD) [4], is characterized by toroidal asymmetry of the confinement field generated by external coils. In the present study, the plasma turbulent transport in helical systems is investigated by means of the GKV simulations.

In our project of utilizing the Earth Simulator [5] (the project name is "Synergetic simulation study on cross-hierarchy complex physics in high-temperature plasmas"), the GKV simulations of the ion temperature gradient (ITG) turbulence in a tokamak were successfully carried out [6]. In 2006, we also performed the GKV simulations of the electron temperature gradient (ETG) turbulence in a tokamak as well as linear simulations of the ITG instability in helical systems. The first nonlinear GKV simulation of the ITG turbulence in helical systems was done in the fiscal year of 2006-2007, where regulation of ITG turbulent transport by the zonal flow was investigated for the model LHD configurations [7].

In this article we report our recent progress in the GKV simulations of ITG turbulence and zonal flows in helical sys-

tems. It is observed in the inward-shifted configuration of the LHD experiments, where the radial drift motion of helical-ripple-trapped particles is slower, that not only the neoclassical but also the anomalous transport is reduced in spite of the unfavorable instability property [8]. The experimental results seem to be contrary to the conventional idea that the stronger instability drive leads to higher turbulent transport level. On the other hand, our theory of the zonal-flow dynamics in helical systems [9, 10] predicts that optimization of the three-dimensional magnetic configuration for reducing the neoclassical ripple transport can simultaneously enhance the zonal flows which may lower the anomalous transport as well. In our project in the fiscal year of 2007-2008, thus, we examine the effects of the helical confinement field on the ITG turbulent transport for the two cases relevant to the LHD experiments, that is, the inward-shifted and standard configurations.

The rest of this report is organized as follows. The GKV simulation model used for helical systems is given in the next section. Simulation results of the helical ITG instability is described in Section 3. A brief summary is written in the last section.

2. GKV Simulation Model for Helical Systems

The basic formulae for describing the drift wave turbulence in magnetically-confined plasmas are given by the gyrokinetic equations, where time-evolution of the one-body distribution function is described as a nonlinear partial differential equation defined on the five-dimensional phase space. In the gyrokinetics, the finite gyro-radius effect is introduced while the gyro-phase averaging eliminates the fast time-scale phenomena associated with gyro-motions. The nonlinear gyrokinetic equation of the perturbed gyrocenter distribution function δf ,

$$\left[\frac{\partial}{\partial t} + v_{\parallel} \hat{\mathbf{b}} \cdot \nabla + \mathbf{v}_d \cdot \nabla - \mu (\hat{\mathbf{b}} \cdot \nabla \Omega) \frac{\partial}{\partial v_{\parallel}} \right] \delta f + \frac{c}{B_0} \{ \psi, \delta f \} = (\mathbf{v}_* - \mathbf{v}_d - v_{\parallel} \hat{\mathbf{b}}) \cdot \frac{e \nabla \psi}{T} F_M + C(\delta f), \quad (1)$$

is numerically solved in the GKV code. Here, the parallel velocity v_{\parallel} and the magnetic moment μ are chosen as the velocity-space coordinates. Each term on the left-hand-side (l.h.s.) of Eq.(1), except for the time derivative one, represents advection of δf along gyrocenter orbits in the phase space. The background distribution is approximated by the Maxwellian F_M . The last term on the l.h.s. indicates the nonlinear electric ($\mathbf{E} \times \mathbf{B}$) drift term causing the turbulent transport where $\{ , \}$ means the Poisson brackets. Collective motions of ions described by gyrokinetic equation change the fluctuating electric field. The perturbed ion distribution function δf is substituted into the quasi-neutrality condition of space charge (not shown), for calculation of the electro-

static potential fluctuations, where the adiabatic electron response is assumed (except for the zonal flow component).

Effects of the helical confinement field are introduced through variation of the magnetic field strength $|B|$ along the field line, such that

$$B = B_0 \left\{ 1 - \varepsilon_{00}(r) - \varepsilon_l(r) \cos z - \sum_{i=l-1}^{i=l+1} \varepsilon_i(r) \cos[(l - Mq_0)z - M\alpha] \right\}, \quad (2)$$

where $\varepsilon_l(r)$ denotes amplitude of a helical component with the poloidal period number of l . The major helical field of the LHD is given by $L = 2$ and $M = 10$ where L and M mean the poloidal and toroidal period numbers of the confinement field, respectively. The radial and field-aligned coordinates are shown by r and z , respectively. The field-line label is denoted by α . Equation (2) is substituted into the magnetic drift \mathbf{v}_d and the mirror force [the last term in the square brackets on the l.h.s. of Eq.(1)] terms. See Refs. [2] and [7] for more details of the GKV simulation model.

3. GKV Simulations of ITG Turbulence in Helical Systems

In order to investigate effects of helical magnetic configurations on the ITG turbulence and zonal flows, we have performed GKV simulations by utilizing the Earth Simulator. Magnetic configuration models relevant to the LHD experiments with the inward-shifted and standard plasma positions [11] are employed in the GKV code. The frequency and growth rate of the ITG instability obtained from the linear GKV simulations agree with the results of the eigenvalue analysis in a low wavenumber regime. For the experimentally relevant conditions, it has also been confirmed that an initially given zonal flow keeps a higher level for a longer time in the inward-shifted configuration than that in the standard one [11] as predicted by the analytical theory of zonal flows [9, 10]. Here, it is noteworthy that the inward-shifted case is optimized for reducing the neoclassical transport but with more unfavorable stability property than the standard configuration. In the present study, the nonlinear GKV simulation implemented with the specified magnetic field parameters successfully confirms generation of large zonal flows enough to *reduce* the ion heat transport in the inward-shifted plasma [12]. Stationary zonal-flow structures are clearly shown in the present simulation for the helical system with the neoclassical optimization. The obtained results agree with our theoretical prediction, and are consistent with observation of better confinement in the inward-shifted LHD plasma [8].

Color contours of the electrostatic potential ϕ in the steady ITG turbulence are plotted in Fig. 1, where the collision frequency is negligibly smaller than the linear ITG

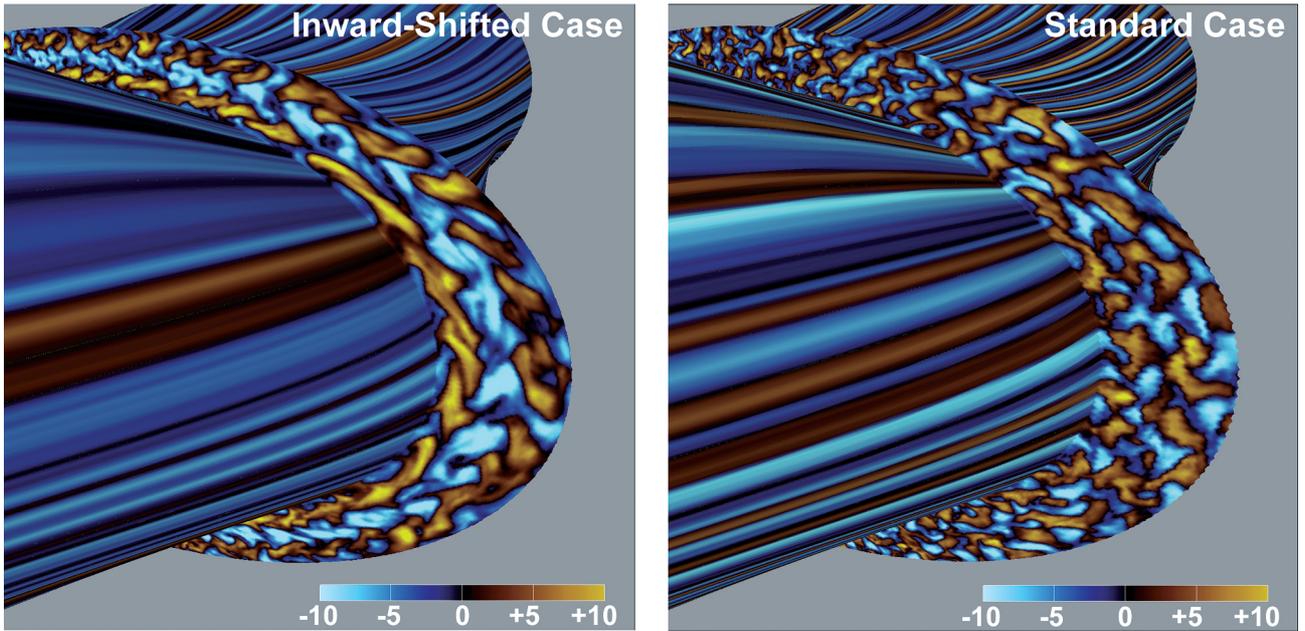


Fig. 1 Color contours of the electrostatic potential ϕ of the zonal flow and the ion temperature gradient (ITG) turbulence obtained by the GKV simulation for inward-shifted (left) and standard (right) model configurations of the Large Helical Device (LHD). Normalization is chosen as $e\phi L_n/T_e\rho_i$.

mode growth rates. The ballooning-type mode structure of the ITG instability observed in the linear growth phase is destroyed in the latter turbulent state by the self-generated zonal flows. For the inward-shifted configuration shown in Fig. 1 (left), we see clear structures of poloidal $\mathbf{E} \times \mathbf{B}$ zonal flows in the potential profile mapped on the poloidal cross section, while more isotropic $\mathbf{E} \times \mathbf{B}$ vortices are observed in the standard case [see Fig. 1 (right)]. This larger zonal-flow generation in the inward-shifted case agrees with results from the linear analysis of the zonal-flow response [9, 10, 11] which predicts a larger zonal-flow response to a given source in neoclassically optimized helical configurations

such as the inward-shifted one.

Spatio-temporal profiles of the zonal flows are shown in Fig. 2, where one can clearly find the steady zonal flow component in the inward-shifted case. In contrast, the zonal flow potential in the standard configuration involves more oscillatory components. Peak amplitude of the time-averaged (from $t = 60$ to $250 L_n/v_n$) zonal-flow potential $e\langle\phi\rangle L_n/T_e\rho_i = 4.5$ for the inward-shifted plasma is about six times larger than the largest amplitude of $e\langle\phi\rangle L_n/T_e\rho_i = 0.72$ for the standard case. This remarkable enhancement of the zonal-flow generation in the inward-shifted case leads to the turbulent transport reduction. Although the linear ITG insta-

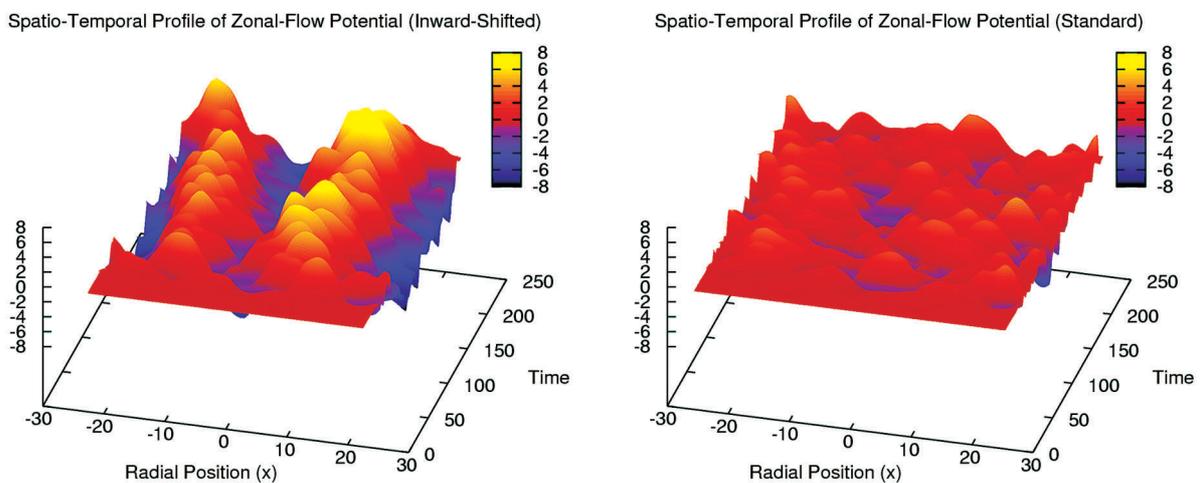


Fig. 2 Perspective plots of the spatio-temporal profiles of the electrostatic potential ϕ of the zonal flow obtained by the GKV simulation for inward-shifted (left) and standard (right) model configurations of the Large Helical Device (LHD). Normalization is chosen as $e\phi L_n/T_e\rho_i$.

bility grows slightly faster and causes the higher peak value of the ion heat diffusivity χ_i for the inward-shifted configuration than for the standard case, the time-averaged ion thermal diffusivity $\chi_i = 1.27\rho_i^2 v_{ti}/L_n$ in the saturated ITG turbulence for the former case is about 30% smaller than that of $\chi_i = 1.78\rho_i^2 v_{ti}/L_n$ for the latter one. The evident transport reduction in the inward-shifted case is attributed to the enhanced zonal flows in the optimized helical configurations for decreasing neoclassical ripple transport.

4. Summary

In our project of utilizing the Earth Simulator (the project name is "Synergetic simulation study on cross-hierarchy complex physics in high-temperature plasmas"), the following activities are advanced during the fiscal year of 2007–2008.

- (1) The gyrokinetic Vlasov simulation code (GKV code) extended to helical systems are performed on 256 nodes of the Earth Simulator with high performance.
- (2) The GKV simulation of the ion temperature gradient turbulence and zonal flows for the helical systems confirms the optimization scenario for reducing the anomalous transport, and gives a possible explanation for the improved confinement found in the inward-shifted plasma of the Large Helical Device (LHD).
- (3) Parallelization and optimization of an energetic-particle simulation code, MEGA, are completed, and the code is ready for running on the Earth Simulator.

As described in the above, the simulation result for the inward-shifted configuration of the LHD manifests generation of large-amplitude stationary zonal-flow structures leading to significant turbulent-transport reduction, which was not so obviously shown in our previous simulations using simpler model configurations [7]. The newly obtained result confirms the optimization scenario of the anomalous transport in helical systems [9, 10], such that, reduction of the neoclassical ripple transport can simultaneously improve the turbulent transport with enhancing zonal-flow generation. It also gives a possible explanation to the confinement improvement observed in the LHD experiments of inward plasma shift [8]. The main contributions made in the present study have been reported in detail in Ref. [12]. Extension of the GKV simulation is planned for the study in 2008 in order to investigate how the radial electric field driven by the neoclassical ripple transport influences the zonal flow and the turbulent transport.

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核融合プラズマの乱流輸送低減-5次元シミュレーションによる最適化シナリオの検証

プロジェクト責任者

渡邊 智彦 自然科学研究機構 核融合科学研究所

著者

渡邊 智彦 自然科学研究機構 核融合科学研究所

1. 目的と計画

磁気核融合プラズマ閉じ込め研究において、熱及び粒子の輸送機構の理解と予測、さらにその制御は、核融合条件を達成・維持し、高い炉心プラズマ性能を実現するための重要な課題である。閉じ込めプラズマに付随する密度・温度勾配により電磁場変動をともなう乱流揺動が励起され、粒子間クーロン衝突に起因する拡散よりも桁違いに大きな輸送、いわゆる「異常輸送」が引き起こされる。こうしたプラズマ乱流を、5次元位相空間中の分布関数揺動のレベルからシミュレーションすることによってはじめて、核融合プラズマの異常輸送現象の実相を明らかにすることができると期待される。これまでに、核融合プラズマにおける輸送機構の解明、輸送レベルの予測とその低減に関わる研究に寄与することを目指して、高精度ジャイロ運動論的シミュレーション・コードの開発とそれらを用いた解析を行ってきた。

平成19年度は、特にヘリカル型閉じ込め装置への応用を中心として、以下の項目について、地球シミュレータ研究プロジェクトを進めた。

- ① プラズマ乱流輸送特性のヘリカル磁場配位依存性の解明
 - a) 輸送改善をもたらす平均流(ゾーナルフロー)の磁場配位依存性の検証
 - b) 磁場配位最適化による乱流抑制と輸送低減の研究
- ② 高速粒子の運動と背景プラズマの電磁的相互作用を自己無撞着に求めるハイブリッド・コードの地球シミュレータへの実装と、ヘリカル型配位における高速粒子輸送のシミュレーション研究

2. 今年度得られた成果

- ① 地球シミュレータ256ノードを利用して、ジャイロ運動論的ヴラソフ・シミュレーションコード(GKVコード)によるヘリカル系プラズマの大規模なシミュレーションを実行した。
- ② イオン温度勾配乱流のジャイロ運動論的ヴラソフ・シミュレーションにより、磁気軸位置を内寄せにしたヘリカル磁場配位において強いゾーナルフローが励起され、熱輸送が低減されることを世界で初めて実証した。この結果は、理論的に予測された輸送低減の最適化シナリオを検証するとともに、大型ヘリカル装置実験の結果に対する物理的理解を与えている。
- ③ 高速粒子-背景プラズマ相互作用を自己無撞着に求めるハイブリッド・コード(MEGA)を地球シミュレータに移植し、シミュレーションの実行を開始した。これまでに16ノード利用で高い効率を達成し、今後研究を進める準備を整えた。

キーワード: 核融合, プラズマ, 乱流, 輸送, シミュレーション