# Five-Dimensional Gyrokinetic Simulations for Helical Plasmas

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Gyrokinetic simulations for magnetically-confined fusion plasmas are applied to the anomalous transport problem in helical toroidal systems, where fluctuations of the one-body velocity distribution function of ions are calculated in the five-dimensional phase space. The first gyrokinetic-Vlasov simulation of the core-plasma turbulent transport for the Large Helical Device (LHD), which is operated at National Institute for Fusion Science, is carried out by utilizing 192 computational nodes of the Earth Simulator. The obtained simulation results manifest regulation of the turbulent transport by the self-generated zonal flows in helical systems.

**Keywords**: fusion, plasma, turbulence, transport, simulation

## 1. Introduction

With the aim of realizing the controlled nuclear fusion as a possible energy source in the future, research and development of magnetic confinement fusion devices have been extensively promoted in the world. For ignition of fusion reactions, it is necessary to confine gas of hydrogen isotope with high density and temperature for a certain time period. The high-temperature gas exceeding 10 keV is ionized, and called "plasma" which consists of huge numbers of charged particles, ions and electrons. Various types of turbulent fluctuations are spontaneously excited in the plasma confined in a limited space. Then, particles and heat are transported from the core to edge regions of the confinement device, and are finally lost. The transport level associated with plasma fluctuations is higher in orders of magnitudes than that expected from theoretical estimates based on the binary Coulomb collisions of particles. The collisional transport theories are named "classical" or "neoclassical" ones. Contrarily, the observed high-level transport is called "anomalous".

The anomalous transport problem has been one of the central subjects addressed in the long history of the magnetic fusion research. The magnetic field is employed to keep the high-temperature plasma off a wall. Two major types of the magnetic fusion devices are tokamak and helical systems both of which have a donut shape (torus). The confinement field of tokamak devices, such as ITER [1], has rotational symmetry in the toroidal direction. The tokamak magnetic field in the poloidal direction is produced by the plasma current in the toroidal direction. The equilibrium magnetic field in helical systems is toroidally asymmetric, and is mainly supplied by external coils. The world-largest helical system, that is, the Large Helical Device (LHD) [2], has been operated at National Institute for Fusion Science (NIFS). In the present study, the gyrokinetic-Vlasov (GKV) simulations [3] utilizing the Earth Simulator are applied to the anomalous transport phenomena in the LHD experiments.

Magnetically-confined plasmas intrinsically have inhomogeneous profiles of the density and the temperature because of the limited volume of devices. The density and temperature gradients drive various types of plasma instabilities which cause turbulent fluctuations of density, flow, temperature, and electromagnetic fields. Then, the anomalous transport of particles and heat is induced by the plasma turbulence. So far, a lot of theoretical efforts have been devoted to investigation of the anomalous transport, and our knowledge on the transport mechanism has been deepened. The linear properties of plasma instabilities in toroidal confinement systems are clarified in detail. Nevertheless, quantitative understandings of the anomalous transport caused by the plasma turbulence, which involves the nonlinear couplings among different spatio-temporal scales, have not been able to be established by the theoretical approach only.

It is noteworthy in studying the anomalous transport that the conventional fluid approximation can not be valid for the high-temperature plasma in fusion devices with low collision frequencies where the mean-free-paths of particles are much longer than the device size. This makes the theoretical and numerical approaches to the problem quite difficult, because dynamic behaviors of distribution functions in the multi-dimensional phase-space should be fully taken into account.

The gyrokinetic simulation of the toroidal plasma turbulence has been advanced in the last decade, and is currently promoted in the worldwide. One of the advantages of the gyrokinetics is the reduction of the phase-space dimensions that are reduced from six to five by taking average in a phase angle of the gyro-motion of particles (the three-dimensional real-space and the two-dimensional velocity-space). However, it is still a big challenge to directly and accurately simulate fluctuations of the distribution function in the phase space even with tera-flops and tera-bytes scale computers. For studying the anomalous transport, the five-dimensional gyrokinetic-Vlasov simulation (GKV) code [3] has been developed at NIFS, and is implemented with high performance of vector and parallel operations.

In our project of utilizing the Earth Simulator [4] (the project name is "Synergetic simulation study on cross-hierarchy complex physics in high-temperature plasmas"), we succeeded in the GKV simulations of the ion temperature gradient (ITG) instability in a tokamak system, where the statistically steady state of the turbulence with zonal flows is clearly demonstrated [5]. In 2005-2006, we also carried out 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. Our gyrokinetic simulation project in the fiscal year of 2006-2007 is, then, focused on the ITG turbulent transport in helical systems.

In this article is reported our recent progress in the gyrokinetic-Vlasov simulations of plasma turbulence. We extended the nonlinear GKV code to helical systems while introducing helical components of the equilibrium magnetic field. Then, effects of helical-ripple-trapped particles are incorporated, which is essential to considering the zonal-flow dynamics in helical systems [6]. 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 short summary is written in the last section.

## 2. Simulation Model for Helical Systems

In the GKV simulations of toroidal plasma turbulence, the nonlinear gyrokinetic equation of the perturbed gyro-center distribution function $\delta f$ is numerically solved as a partial differential equation in the five-dimensional phase space, such that

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

Here, the parallel velocity $v_{\parallel}$ and the magnetic moment $\mu$ 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 $\delta f$ associated with particle motions 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 (**E**x**B**) drift term causing the turbulent transport where { , } means the Poisson brackets.

Effects of the helical field are introduced through spatial variations of the magnetic field strength $|B|$, such that

$$B = B_0\Big\{1 - \varepsilon_{00}(r) - \varepsilon_t(r)\cos z - \sum_{l=L-1}^{l=L+1}\varepsilon_l(r)\cos\big[(l - Mq_0)z - M\alpha\big]\Big\}, \tag{2}$$

where $\varepsilon_l(r)$ denotes amplitude of a helical component with the poloidal periodicity of $l$. The major helical field component of the LHD is given by $L$=2 and $M$=10 where $L$ and $M$ mean the poloidal and toroidal periodicities, respectively. The radial and field-aligned coordinates are shown by $r$ and $z$, respectively. The field-line label is denoted by $\alpha$. 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. The safety factor of the confinement field is represented by $q_0$.

The perturbed distribution function for ions, $\delta f$, is used to calculate the electrostatic potential fluctuations $\Psi$ by the charge neutrality condition, where the electron response is assumed to be adiabatic. Thus, collective motions of ions and electrons change the fluctuating electric field. The finite gyro-radius effect is retained in the gyrokinetic equations, while the fast time-scale phenomena associated with gyro-motions are eliminated by taking the gyro-phase average.

We calculate the nonlinear **E**x**B** term by means of the spectral method. The GKV code is designed so that the Fast Fourier Transform (FFT) operations are efficiently performed on a single computational node of the Earth Simulator. The fourth-order finite-difference methods are employed for the first and second derivative terms in the $z$, $v_{\parallel}$, and $\mu$ directions. The GKV code is implemented with the hybrid parallelization technique of MPI and the automatic one, and highly optimized both for the vector and parallel operations. The peak performance of about 5 T flops is achieved by using 192 nodes of the Earth Simulator. See Refs. [3], [4] and [7] for more details of the GKV simulation model.

## 3. GKV Simulations of ITG Turbulence in Helical Systems

The magnetic field configuration of helical systems has more degrees of freedom in the equilibrium profile than that in tokamaks with the toroidal symmetry. The central position of the poloidal cross-section (that is, the magnetic axis) of the LHD can be shifted by changing the electric currents in the external coils. As the magnetic axis is shifted inward, magnitudes of the helical sideband components are increased so that the radial drift velocity of the helical-ripple-trapped particles is decreased. It leads to improvement of the neoclassical transport in the inward-shifted configuration. At the same time, however, the inward-shift of the axis enhances the unfavorable magnetic curvature that degrades stability of the pressure-driven modes such as the toroidal ITG mode. Thus, it has attracted many researchers' attention that, in the LHD experiments, not only the neoclassical but also the anomalous transport is reduced in the inward-shifted configurations [8].

It has widely been believed that radially-sheard mean plasma flows driven by the Reynolds stress in the ITG turbulence regulate the anomalous transport. Thus, generation and damping mechanisms of the shear flow, which is called the zonal flow, have intensively been studied in the last decade. We analytically derived the response function of the zonal flow in helical systems [6]. Validity of the theory is confirmed by the linear GKV simulations of collisionless damping of the zonal flow [9]. The theoretical analysis shows that optimization of the three-dimensional magnetic configuration of helical systems for reducing the neoclassical ripple transport, e.g. the inward-shifted configuration of the LHD, can simultaneously leads to enhancement of the zonal flow response, which may lower the anomalous transport as well.

The experimental and theoretical results summarized above strongly motivate us to extend the GKV code to helical systems. The first GKV simulation of the ITG turbulent transport in helical systems is successfully carried out in August, 2006, by utilizing 192 computational nodes of the Earth Simulator. A whole picture of a helical system of $L$=2 and $M$=10 like the LHD is plotted in Fig. 1, where the innermost toroidal magnetic flux surface in the simulation domain is colored according to amplitude of potential perturbations resulted from the GKV simulation of the ITG turbulence. On the helically-twisted toroidal flux surface, one can see fine striation patterns along field lines which have larger amplitudes on the outside of the torus, that is, the ballooning type mode structure.

Magnified snapshots of the turbulent potential perturbations at $t$=37.5, 75.0, and 112.5 $L_n/v_t$ are shown in Fig. 2 (from the left to the rigt), where an elliptic poloidal plane is also plotted. Here, only the main helical component ($l$=2) of the confinement field is included in the simulation model (single-helicity case). In the linear growth phase of the toroidal ITG instability, one finds the ballooning type mode structure with radially elongated potential patterns (left). In the nonlinear phase of the instability, the self-generated zonal flows destroy the mode structure. Then, the statistically steady ITG turbulence is observed with the mean ion heat transport (middle and right).

Accuracy of the present simulation is verified by the entropy balance calculation, where the square integral of the perturbed distribution function $\delta f$, the potential energy, the ion heat transport flux, and the collisional dissipation are examined [5]. The non-Maxwellian nature of $\delta f$, which is properly reproduced in our GKV simulations, substantiates the limitation of the conventional fluid model for the high-temperature plasma turbulence. Thus, the five-dimensional gyrokinetic-Vlasov simulation dealing with the fluctuating distribution function, which is realized by using the Earth Simulator, is necessary for reliable evaluation of the anom-

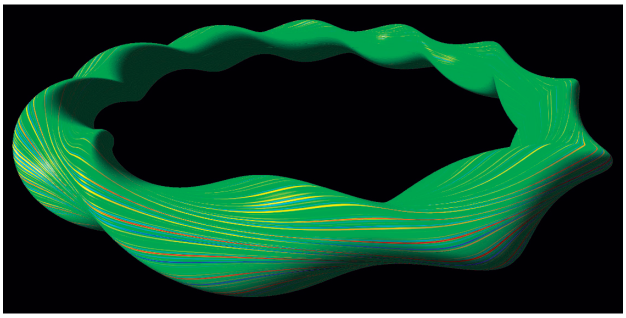

Fig. 1 A whole picture of a helical system of $L$=2 and $M$=10, where the innermost toroidal magnetic surface is plotted. Here, $L$ and $M$ denote the poloidal and toroidal periodicities of the major helical component of the confinement field. Red and blue colors represent positive and negative electrostatic potential perturbations of the ion temperature gradient mode resulted from the GKV simulation.

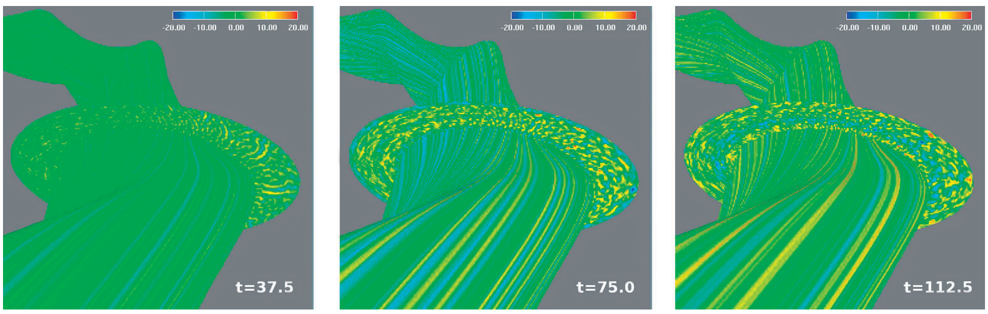


Fig. 2 Snapshots of the electrostatic potential perturbations at $t$=37.5 $L_n/v_t$ (left), 75.0 $L_n/v_t$ (middle), and 112.5 $L_n/v_t$ (right) obtained by the GKV simulation of ITG turbulence in a helical system with $L$=2 and $M$=10 like the LHD. The equilibrium magnetic field is given by a single-helicity model configuration.

alous transport in fusion plasmas.

The gyrokinetic simulations of the ITG turbulence for the standard and inward-shifted model configurations of the LHD are also carried out by introducing the multi-helicity components of the confinement field. The nonlinear GKV simulations show that the ion heat transport in the inward shifted model, which has the larger linear growth rates of the ITG instability, is observed in a level comparable to the standard case [7]. This is attributed to the stronger zonal flows generated in the inward-shifted model configuration. Numerical simulations using more detailed equilibrium parameters to reproduce the LHD experimental conditions have also been started, and will be reported afterwards.

## 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 in the fiscal year of 2006–2007.

(1) The fist gyrokinetic simulation of nonlinear saturation of the tokamak electron-temperature-gradient turbulence is successfully carried out for the standard parameter set of the Cyclone DIII-D base case [10] with the adiabatic ion response.

(2) The gyrokinetic-Vlasov simulation code (GKV code) is extended to helical systems while achieving the high computation speed (about 5 T flops on 192 nodes of the Earth Simulator).

(3) The first gyrokinetic simulation of the ion temperature gradient turbulence in helical systems is performed on the Earth Simulator by means of the GKV code. Effects of the helical-ripple-trapped particles on the zonal flow and the turbulent transport are investigated for model configurations of the Large Helical Device.

(4) Parallelization and optimization of a kinetic simulation code for the high-energy particle transport are advanced.

Through the present Earth Simulator project, the gyrokinetic-Vlasov simulations of the plasma turbulence and the zonal flows in toroidal fusion systems are established with physical reality, where time-evolutions of the one-body distribution function are accurately solved in the five-dimensional phase-space.

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# ヘリカル系プラズマの5次元ジャイロ運動論的シミュレーション


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## 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要素となっている。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18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) トカマク型閉じ込め磁場配位での電子温度勾配(ETG)乱流輸送のシミュレーション

(2) イオン温度勾配(ITG)乱流輸送解析のためのシミュレーション・コード(5次元ジャイロ運動論的ヴラソフ・シミュレーション・コード)のヘリカル型磁場配位への拡張と地球シミュレータへの最適化

(3) 大型ヘリカル装置(LHD)磁場配位でのITG乱流輸送のシミュレーション

(4) 高エネルギー粒子輸送シミュレーション・コードの地球シミュレータへの移植

## 2. 今年度得られた成果

今年度の地球シミュレータ利用により、以下にまとめた成果が得られた。

(1) 標準的なパラメター下でのETG不安定性の非線形飽和と乱流遷移のシミュレーションに世界ではじめて成功した。これにより、同等な条件下でETGとITG乱流輸送の比較研究が可能になり、電子輸送のより強い異常性が明らかとなった。

(2) 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)を、従来のトカマク型配位からヘリカル型へと拡張すると同時に、従来と同様の高い実行性能を達成した(192ノード使用で実行性能約5Tflops)。

(3) 世界にさきがけて、ヘリカル型磁場配位におけるITG乱流輸送のシミュレーションに成功した。大型ヘリカル装置(LHD)を例に、乱流による平均流生成や乱流輸送に対し、ヘリカル磁場が与える影響を調べた。

(4) LHDを対象とした高エネルギー粒子輸送シミュレーション・コードの地球シミュレータへの移植に向けて、並列化およびコードの最適化を進めた。

キーワード：核融合, プラズマ, 乱流, 輸送, シミュレーション