Effects of Radial Electric Field on Zonal Flows Leading to Turbulent Transport Reduction in Fusion Plasmas

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Turbulent transport in magnetically-confined fusion plasma has been investigated by the use of large-scale gyrokinetic simulations of turbulent transport, where detailed fluctuations of one-body distribution function are directly solved in the five-dimensional phase-space. In fusion plasmas confined by helical magnetic field, an equilibrium-scale radial electric field is formed in association with the neoclassical transport due to binary collisions of particles. Effects of the radial electric field on zonal flows are studied by means of a newly-extended gyrokinetic Vlasov simulation code, GKV. It is found that the poloidal ***E***x***B*** rotation of helically trapped particles enhances the zonal-flow response which may lead to further reduction of the turbulent transport in helical plasmas. The present result supports a new scenario for anomalous transport reduction proposed by a gyrokinetic theory of zonal flows in helical systems.

Keywords: fusion, plasma, turbulence, transport, simulation

1. Introduction

Fusion, space, and astrophysical plasmas generally involve turbulent fluctuations of density, flow, temperature, and electromagnetic fields. In magnetic fusion plasmas, turbulence causes anomalous transport of particles, momentum, and heat, which degrade confinement and may reduce fusion reactions. The plasma turbulence in toroidal fusion devices are driven by density and temperature gradients in the equilibrium profile. Levels of turbulent transport observed in fusion plasma experiments are higher in orders of magnitudes than those expected from the classical and neoclassical theories of collisional transport. The 'anomalous' transport problem has long been one of central subjects in the magnetic fusion research.

For understanding anomalous transport mechanism and predicting transport levels, gyrokinetic simulations of toroidal plasma turbulence have been advanced in the last decade. A kinetic equation of one-body distribution function is numerically solved on the five-dimensional phase-space. Extensive simulation studies revealed that sheared ***E***x***B*** plasma flows spontaneously generated by turbulence could effectively regulate the anomalous ion heat transport [1]. The self-generated shear flow is called 'zonal flow' in analogy to strong longitudinal winds in the Jovian atmosphere.

To accurately simulate the kinetic plasma turbulence, we developed a five-dimensional gyrokinetic Vlasov simulation code (GKV code) [2] which had been used for studying the turbulent transport in tokamak and helical fusion plasmas [2, 3]. The equilibrium configuration of tokamak has a toroidal symmetry, while the helical system, such as the Large Helical Device (LHD) [4], is characterized by an asymmetric equilibrium. In our project of utilizing the Earth Simulator (the project name is "Synergetic simulation study on cross-hierarchy complex physics in high-temperature plasmas"), GKV simulations of ion temperature gradient (ITG) turbulence in a tokamak plasmas were successfully conducted in 2005 [5]. In 2006, we performed GKV simulations of electron temperature gradient (ETG) turbulence in a tokamak configuration and linear simulations of the ITG instability in helical systems. The first nonlinear GKV simulation of the ITG turbulence in helical systems was done in 2006 [5], where regulation of ITG turbulent transport by zonal flows was investigated for the model LHD configurations [3]. In the fiscal year of 2007, the GKV simulations of ITG turbulence and zonal flows in helical systems made further progresses, where reduction of the ITG turbulent transport is discovered with enhanced zonal-flow generation in the neoclassically optimized helical configuration [6]. In Fig. 1 is shown the ITG turbulence and the zonal flows found in the GKV simulation for the inward-shifted LHD plasma. The GKV simulation results obtained in this project agree with the theoretical analysis of the zonal-flow response [7–9]. The inward-shifted plasma of the LHD, thus, should have better confinement than that with the standard magnetic axis position. The GKV simulation result is consistent with the experimental evidences [10].

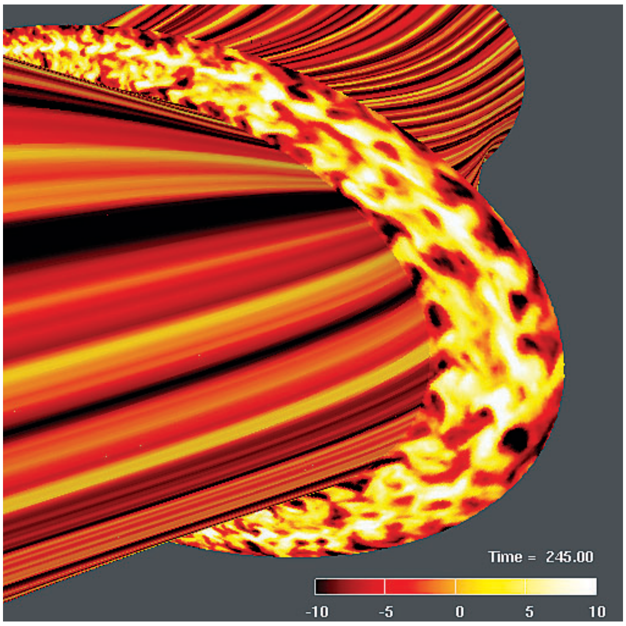

Fig. 1 Snapshot of electrostatic potential found in GKV simulation of inward-shifted LHD plasma. Zonal flows generated in the ion temperature gradient turbulence reduce anomalous ion heat transport.

The gyrokinetic theory on zonal flows in helical systems suggests further enhancement of zonal flows and resultant transport reduction, when the equilibrium radial electric field produces the poloidal ***E*x*B*** rotation of helical-ripple-trapped particles with reducing their radial displacements [11, 12]. In our project in 2008, we have numerically investigated the zonal-flow response in case with the radial electric field. The GKV code is newly extended so as to include the poloidally rotating ***E*x*B*** drift particles [13]. This article reports the new GKV simulation results showing enhancement of the zonal-flow response by the equilibrium radial electric field in helical plasma confinement.

The rest of this report is organized as follows. The gyrokinetic theory of zonal flows with the equilibrium radial electric field is briefly reviewed in section 2. The GKV simulation model and results are shown in section 3. A short summary is given in the last section.

2. Theoretical Analysis of Zonal-Flow Response with Radial Electric Field

In our previous studies, we did not take account of the equilibrium radial electric field E_{r0} which is spontaneously generated in helical systems due to the neoclassical particle transport. Enhancement of zonal flows and resultant transport reduction are theoretically expected [12] when E_{r0} causes poloidal ***E*x*B*** rotation of helically-trapped particles with reduced radial displacements [11]. Here, we assume a uniform E_{r0} which gives only the Doppler shift of real frequencies for the ITG modes. If the equilibrium is symmetric for the field-line label α, it plays no role in response of zonal flows. However, the explicit α-dependence of the confinement field causes α-dependence of the perturbed gyrocenter distribution function δf through the magnetic drift.

For the helical configuration with a single-helicity component, we have derived the response kernel of zonal flows in the long time limit [12],

$$K_{Er} = \left[1 + G + \frac{15}{8\pi}\sqrt{2\varepsilon_h}\left(\frac{\varepsilon_t\, v_{ti}}{r\omega_\theta}\right)^2 \left(1 + \frac{T_e}{T_i}\right)\right]^{-1} \qquad (1)$$

where the shielding term due to radial drift motions of the helical-ripple-trapped particles is inversely proportional to the square of E_{r0} with $\omega_\theta = -\,cE_{r0} / rB_0$. As E_{r0} increases, the response kernel K_{Er} increases and approaches $1/(1+G)$ where G represents ratio of the neoclassical polarization due to toroidally trapped ions to the classical polarization. The theoretical analysis, thus, shows enhancement of the zonal-flow response under the equilibrium radial electric field.

3. GKV Simulation of Zonal-Flow Response with Radial Electric Field

The above theoretical prediction for the effect of equilibrium radial electric field on zonal-flow response is examined by a newly-extended GKV simulation [13], where the ***E*x*B*** drift term should generally be kept in the gyrokinetic equation, as discussed in the previous section. The new GKV simulation model and results are described in this section.

3.1 Simulation Model

In the present study, we solve the gyrokinetic equation modified for investigating the collisionless damping of zonal flows with E_{r0} in the helical configuration,

$$\left[\frac{\partial}{\partial t} + v_\parallel \hat{\mathbf{b}} \cdot \nabla + i\mathbf{k}_r \cdot \mathbf{v}_d - \mu\left(\hat{\mathbf{b}} \cdot \nabla \Omega\right)\frac{\partial}{\partial v_\parallel} + \omega_\theta \frac{\partial}{\partial \alpha}\right]\delta f =$$
$$- i\mathbf{k}_r \cdot \mathbf{v}_d \frac{e\langle \boldsymbol{\Psi} \rangle}{T_i} F_M \qquad (2)$$

where the field-aligned coordinates of $x = r - r_0$, $y = r_0[\theta - \zeta/q]$, and $z = \zeta$, are used with the field-line label $\alpha = \theta - \zeta/q$. We choose α so that $\mathbf{B} = \nabla\Psi_t \times \nabla\alpha$, where Ψ_t denotes the toroidal flux. The new GKV simulation model is a poloidally global one including the ***E*x*B*** rotation of helically trapped particles, while the local flux-tube model around a single field line were employed in our model for the ITG/ETG turbulence. The equilibrium electric field is introduced as the fifth term on the left-hand-side of Eq. (2). We define the zonal-flow component by the flux-surface-averaged electrostatic potential <ϕ>, so as to decouple unstable ITG modes and zonal flows. The electrostatic potential is given by the quasi-neutrality condition. For simplicity, we assume the hot electron limit of

$T_i/T_e = 0$, and hence, no density perturbation arises in the quasi-neutral limit.

Variation of the magnetic field strength $|B|$ along the field line is modeled as,

$$B = B_0\left\{1 - \varepsilon_{00}(r) - \varepsilon_t(r)\cos z - \sum_{l=L-1}^{l=L+1} \varepsilon_l(r)\cos\left[l\alpha + (l/q - M\zeta)\right]\right\}, \tag{3}$$

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 $L = 2$ and $M = 10$ where L and M mean the poloidal and toroidal period numbers of the confinement field, respectively.

3.2 Simulation Results

The new GKV simulations of the collisionless damping of zonal flows are conducted for the model configuration with a single-helicity component of $L = 2$ and $M = 10$. The y and z coordinates are discretized by 128 and 1536 grid points, respectively. The two-dimensional velocity-space is represented by (256, 48) mesh points. The y-derivative is calculated in the Fourier space.

Numerical simulations of the zonal-flow response are performed for ω_θ / (v_{ti}/R_0) = 0, 5/12, 5/6, and 5/4, respectively. Time-histories of the flux-surface average of zonal-flow potential is plotted in Fig. 2 for different ω_θ. For larger ω_θ, the first minimum value of the potential before $t = 2\ v_{ti}/R_0$ increases. After the initial damping of the geodesic acoustic mode (GAM) ($t > 6\ v_{ti}/R_0$), the zonal-flow potential starts to oscillate. The oscillation period becomes shorter for larger ω_θ, and is slightly shorter than the poloidal rotation period of ExB drift particles. In a long time limit, averaged amplitude of the zonal-flow potentials is remarkably enhanced by the equilibrium radial electric field. The time-averaged residual zonal-flow level for ω_θ / (v_{ti}/R_0) = 5/4 is about 2.5 times higher than that for ω_θ / (v_{ti}/R_0) = 0. This conclusion is consistent to the theoretical prediction. The present GKV simulation results, thus, support the zonal-flow enhancement due to the equilibrium radial electric field.

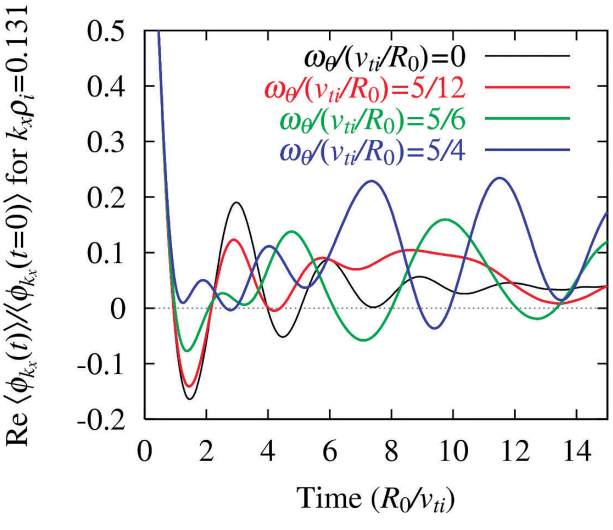

Fig. 2 Time-histories of zonal-flow potentials averaged on a flux surface for cases with equilibrium radial electric field. Poloidal rotation frequency of helical-trapped particles are changed as ω_θ / (v_{ti}/R_0) = 0, 5/12, 5/6, and 5/4, respectively.

4. Summary

To investigate effects of equilibrium radial electric field on the zonal flow, we have performed gyrokinetic Vlasov simulations by utilizing the Earth Simulator. Recent theoretical analysis [12] predicts enhancement of zonal flows under equilibrium radial electric fields which produce poloidal ***E***x***B*** rotation of helical-ripple-trapped particles with decreased radial displacements. Enhancement of the zonal-flow response in case with the radial electric field is found by the use of the newly-extended GKV simulation code which is implemented with the poloidal rotation of ***E***x***B*** drift particles. Thus, the anomalous transport is expected to be more effectively reduced by the equilibrium radial electric fields. The present study clarifies that a coupling of the neoclassical and turbulent transport mechanisms through zonal flows exists in helical systems, which should be important for investigating the confinement improvement in helical systems.

Acknowledgements

This work is supported in part by grants-in-aid of the Ministry of Education, Culture, Sports, Science and Technology (No. 17360445), and in part by the National Institute for Fusion Science (NIFS) Collaborative Research Program (NIFS08KTAL06, NIFS08KNXN145, and NIFS08KDAD008).

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核融合プラズマの乱流輸送低減をもたらす帯状流への径電場効果

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本プロジェクトでは、磁場閉じ込め核融合プラズマにおける異常輸送現象の実相を明らかにし、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的として、高温プラズマ乱流を多次元位相空間内の分布関数変動のレベルから直接扱う大規模ジャイロ運動論的シミュレーションを進めてきた。

ヘリカル型磁場閉じ込めプラズマにおいては、粒子間衝突に起因した新古典輸送により平衡配位スケールをもつトーラス小半径方向の電場が生じる。平成20年度は、この平衡径電場がつくる大規模なプラズマ流が局所的にシアを持つ帯状流（ゾーナルフロー）生成に与える影響について、新たに拡張した5次元ジャイロ運動論的シミュレーション・コードを用いて研究を進めた。乱流輸送抑制に効果をもつゾーナルフローが、径電場の存在下でより効率的に生成され得ることが確認された。これは、最近導かれた理論予測とも整合する結果であり、「ヘリカル系プラズマの新古典輸送に関わる平衡径電場が、ゾーナルフローを介して異常輸送低減を導く」という新しい閉じ込め改善シナリオを指示するものである。

キーワード：核融合, プラズマ, 乱流, 輸送, シミュレーション