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論文の要旨
Summary (Abstract) of doctoral thesis contents

Thermonuclear fusion is a candidate for the steady and sustainable energy source because fusion power is not restricted by weather unlike renewable energy, such as photovoltaic power, and its fuels are abundantly present in seawater. There are two types of thermonuclear fusion reactor: Tokamak is a toroidally symmetric device which has a simpler magnetic coil system. However, large toroidal current in the plasma is required to sustain the magnetohydrodynamic (MHD) equilibrium magnetic field, which confines the plasma. On the other hand, stellarator / heliotron devices do not need the plasma current to make a confinement magnetic field. Instead, they require more complicated helical coil systems than tokamaks.

In a toroidal magnetic plasma, the guiding-center motion of charged particles and Coulomb collisions give rise to a characteristic diffusion process, which is called neoclassical transport. The neoclassical transport in helical plasmas depends strongly on the magnetic geometry and the helical ripples enhance the neoclassical radial particle and energy transport. In the helical plasmas, the turbulence transport and neoclassical transport can be comparable. Furthermore, a self-generated current arises by the neoclassical transport process. This bootstrap current is supposed to be strong enough to affect the MHD equilibrium in the future thermonuclear fusion reactors. In order to optimize the reactor design for smaller neoclassical transport and bootstrap current, and to predict the plasma confinement properties, neoclassical transport simulation is one of the fundamental tools. Unfortunately, there is no exact analytical formula to calculate the bootstrap current in helical plasmas and it is difficult to diagnose it in experimentally. Therefore, a reliable and efficient numerical simulation plays an important role in the study of thermonuclear fusion. The global neoclassical model has been developed in the recent decades. Though it is reliable because of minimum approximations adopted, it requires huge computation resources to solve the drift-kinetic equation in 5-dimensional phase space. The local neoclassical models are fast but their reliability is under the question. The motivation of this work is to verify a new local model (ZOW), which has been proposed recently, so that we can utilize it to estimate the neoclassical transport in a helical reactor.

The thesis consists of two parts as follows. In Part 1, the benchmark of neoclassical radial and parallel flows between the conventional and the new model (ZOW) in LHD, HSX and W7-X is carried out. In Part 2, it demonstrates the effect of the parallel momentum conservation property on the bootstrap current calculation by the benchmarks between the ZOW model and other local neoclassical code, PENTA. Then, these codes are applied for the estimation of the bootstrap current for FFHR-d1

and axisymmetric tokamak.

Part 1

The drift-kinetic models in helical plasmas are benchmarked via the series of neoclassical transport simulations. Here, the drift-kinetic models are the ZOW, ZMD, DKES-like, and global models. The helical magnetic geometries of LHD, W7-X, and HSX devices are employed in the benchmarks. The two-weight delta-f scheme is employed to solve the drift-kinetic equation and to calculate the neoclassical particle flux, energy flux, and parallel flow. The global model solves the drift-kinetic equation in 5-dimensional phase space (3D in position 2D in the velocity space) which solves the exact guiding-center trajectories in the phase space. The local models adopt approximation in the guiding-center trajectories so as to reduce the dimension of the problem from 5 to 4 or 3. The Zero-Orbit-Width (ZOW) model drops the radial component of magnetic drift motion while it maintains the tangential component of the magnetic drift to the flux surface. In the Zero-magnetic-drift (ZMD) and the DKES-like models, the magnetic drift is completely neglected. Furthermore, the kinetic energy is taken as a constant parameter in the DKES-like model. Among the global and local models, only the ZOW model breaks the Liouville's theorem because of the compressible phase-space flow along the approximated guiding-center trajectories. A new delta-f method is adopted which makes the two-weight scheme adaptable to the case in which the phase-space volume is not conserved. In the ZOW model, the variation in the phase-space volume is estimated to bring the $O(\delta^2)$ extra contributions in the particle, parallel momentum, and energy balance equations, where δ is a small ordering parameter in the drift-kinetic theory. The simulation results have demonstrated that the ZOW and ZMD models agree with each other well in the wide range of the radial electric field (E_r). This proves that the $O(\delta^2)$ contributions are indeed negligible in neoclassical transport calculation. Around , the ZMD and DKES-like models show the extremely large neoclassical flux peaks. Owing to the tangential magnetic drift in the ZOW model, the radial flux and parallel flow around $E_r \sim 0$, are much smoothly dependent on E_r and are similar to the global simulation results.

The effects of the tangential magnetic drift is found to be stronger under the following conditions. First, the effect is related to the magnetic geometry and it is more obvious in LHD than W7-X and HSX. In W7-X and HSX, the magnetic configuration is optimized so as to reduce the radial drift of trapped particles. This reduces the magnitude of the particle fluxes at the poloidal resonance which occurs when E_r is small and therefore the poloidal $\mathrm{E} \times \mathrm{B}$ and magnetic drift velocities become comparable. Then, it results in the small gap between the ZMD and the ZOW models in these devices compared to LHD. Second, the effect is obvious in lower collision frequency case. Around $E_r \sim 0$, the tangential magnetic drift helps to avoid the poloidal resonance. Otherwise, the artificially strong $1/\nu$-type neoclassical transport will occur. Third, the ZOW model agrees with the ZMD and DKES-like models in the electron simulations. The significant discrepancies occur only in the ion simulation results. This suggests that the conventional local drift-kinetic models are sufficient for electrons.

It is found that the different treatment of the $E \times B$ drift term is related to the error in the neoclassical transport calculation at large-$|E_r|$. In the DKES-like model, the incompressible-$E \times B$ drift assumption causes the wrong estimation of the neoclassical transport as the poloidal Mach number M_p is larger than 0.4. Due to the mass dependency of $M_{p,a} \propto \sqrt{m_a}$, the parameter window in which the incompressible-$E \times B$ approximation is valid will be narrower for heavier particle species such as impurity ions.

In the practical applications, the neoclassical flux and bootstrap current should be evaluated at the ambipolar condition. The ambipolar-E_r is determined so that the ion radial neoclassical fluxes balances with the electron flux. The ion-root (negative-E_r) usually exists when $T_i \geq T_e$; the electron-root appears in the opposite condition. The strong ion particle flux peak at $E_r \sim 0$ in low-collisionality plasma is an artifact in the ZMD and the DKES-like models. The benchmark result suggests that the threshold of T_e/T_i for the transition from an ion- to an electron-root will be lower in the global and the ZOW models than in the ZMD and the DKES models. Since the neoclassical transport varies drastically if the ambipolar-E_r switches from an ion-root to an electron-root, the tangential magnetic drift in local model plays an important role to investigate the ambipolar-root transition. According to the simulations, the magnetic drift only slightly affects the parallel flow and the bootstrap current evaluation. However, the sign of the parallel flow and bootstrap current may change when the ambipolar-E_r transits from a negative to a positive root. Then, the accurate expectation for the radial flux and the ambipolar-E_r is also important to evaluate bootstrap current in helical plasmas.

In the simulations, steady-state solution of parallel flow is obtained when the parallel momentum balance is satisfied. For the ZOW model, the extra terms from comprehensibility in the phase space and the viscosity appear in the momentum balance equation. However, it is found that these terms do not affect the steady-state solution of the parallel flow. Compared to the radial flux, the magnetic drift does not influence the parallel flow strongly at $E_r \sim 0$, even in the low-collisionality LHD and W7-X cases. On the other hand, the discrepancies of parallel flows at large-M_p appear as clearly as that of the radial flux. The poloidal resonance occurs on the trapped particles in helical magnetic ripples, which cannot contribute to parallel flow. The influence of resonance is transferred to the passing particles via collisions. The parallel flows peak at $E_r = 0$ is much less than the radial flux peaks because it is driven by this indirect mechanism.

In this work, it is found that the tangential magnetic drift does not only decrease the magnitude of the particle flux peak but also change the value of E_r at which the peak appears. Since it is found that the amount of the shift is proportional to the magnetic drift velocity, or T_i, it is anticipated that the radial ion flux peak in the global and ZOW models will tend to appear much more negative-E_r side in FFHR-d1 helical reactor than that in LHD. This will affect the prediction of the ion-root E_r Therefore, the importance of the tangential magnetic drift effect becomes significant to evaluate the neoclassical transport especially in the ion-root condition of high-temperature fusion reactor.

This work demonstrates the advantage of the ZOW model as follows. (1) It is able to mitigate the unphysical behavior in the radial neoclassical flux around $E_r \sim 0$, (2) the compressibility of $\mathrm{E} \times \mathrm{B}$ flow is retained, and (3) it also improves the reliability of the bootstrap current evaluation in helical plasmas compared to the conventional local models, i.e., ZMD and DKES. It also reduces the computation cost compared to the global model.

Part 2

The importance of the parallel momentum conservation on the bootstrap current evaluation in nonaxisymmetric systems is demonstrated by the benchmarks among the local drift-kinetic equation solvers, i.e., the ZOW model and two other codes : DKES and PENTA. The verification and application are carried out in a FFHR-d1 helical DEMO reactor case. In the previous studies, the ZOW model considered the momentum conservation in the like-species collision operator but did not treat the correct momentum transfer among the particle species. In the present study, the collision term is improved to include the ion parallel mean flow effect on the electron-ion parallel friction. In DKES, collision term is approximated by the pitch-angle-scattering operator, which does not ensure the momentum balance. PENTA code employs the Sugama-Nishimura method to amend the DKES result so that it satisfies the correct momentum balance in the collisions. The ZOW and PENTA models agree well each other on the calculations of the bootstrap current. The DKES results without the parallel momentum conservation deviates significantly from those from the ZOW and PENTA models. It is also verified that the ZOW with the improved electron collision term and PENTA both satisfies the intrinsic ambipolarity in axisymmetric tokamak, i. e., the ion and electron radial flux are equal for any value of E_r and the bootstrap current is independent of E_r. The intrinsic ambipolarity can be reproduced only if the parallel momentum is conserved in the collision operator.

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It is well-known that the pitch-angle scattering operator has enough accuracy to evaluate the radial neoclassical fluxes in helical plasmas. In the present study, however, it is clearly demonstrated that the pitch-angle scattering operator is insufficient for the bootstrap current calculation in helical plasmas. The present study shows that both the momentum conservation in the like-species collision and the friction on the electrons are the important physics to estimate the bootstrap current correctly. The electron-ion collision operator in the ZOW model drift-kinetic equation is improved in order to treat the correct friction force on the electrons with the ions which have finite parallel mean flow. This work is also the first report of the benchmark between the ZOW and PENTA for bootstrap current calculations. Using a FFHR-d1 operation parameters, it is demonstrated that the bootstrap current evaluated by PENTA agrees with the one by the ZOW model with the improved electron-ion collision operator. These two codes will serve to improve the accuracy of the bootstrap current calculation in general helical plasmas. In the application for FFHR-d1, it is found that the magnitude of the bootstrap current becomes the order of MA, which may affect the MHD equilibrium. However, it demonstrates that the bootstrap current is drastically reduced by choosing a more collisional operation scenario.

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博士論文審査結果の要旨

Summary of the results of the doctoral thesis screening

大型ヘリカル装置(LHD)や、設計中のヘリカル型核融合炉 FFHR-d1 など、ヘリカル型のトーラスプラズマ閉じ込め装置において、荷電粒子の案内中心のドリフト運動とクーロン衝突に起因する新古典輸送が、閉じ込め性能を左右する重要な役割を持つ。また、将来の核融合炉では、新古典輸送現象の一つであるブートストラップ電流が閉じ込め磁場に影響を与えるほど大きくなる可能性があり、その定量的な予測が必須である。新古典輸送計算には、第一原理により忠実なグローバルモデルと、幾つかの仮定を用いた様々な局所近似モデルがある。近似モデルは計算コストを大幅に抑えられるが、その定量的予測精度ついては詳しく調べられてこなかった。出願者の博士論文は二部構成になっており、まず第一部で、グローバルモデルと局所近似モデルによる新古典輸送計算の両方が可能な FORTEC-3D コードを用いたシミュレーションを実行し、各モデルの計算結果を比較し、その精度の詳細な検証を行った。また、第二部では、従来の近似モデルとの比較により精度を向上させた局所近似モデルを応用して、FFHR-d1 の設計において重要な要素となるブートストラップ電流の定量的評価に初めて成功した。

第一部、3 章では、案内中心ドリフト運動に使われる三つの局所近似モデルの違いが説明され、4 章では、ドリフト運動論方程式の速度空間積分から得られる、粒子、エネルギー、運動量バランス方程式にどのような違いが各モデルの間に現れるかが調べられた。新しい局所近似モデルである Zero- Orbit-Width (ZOW)モデルは、トーラス小半径方向のドリフトの効果のみを落としたモデルであり、他の局所近似に比べグローバルモデルに近いが、位相空間中の軌道に沿った保体積性(Liouville の定理)を満たさないため上記のバランス方程式に余剰の項が現れるという固有の問題があることが明確に示された。5 章ではドリフト運動論方程式を数値的に解く手法が説明され、6 章では LHD 配位や HSX、W7-X 等他のヘリカル装置における新古典輸送のシミュレーションがなされ、モデル間の詳細な比較が行われた。重要な発見として、局所近似モデルにおいて ZOW モデルのみに残された磁気面接線方向の磁気ドリフト項が、径電場 Er による E×B ドリフトと同程度になる Er ~ 0 近傍において径方向の新古典輸送を抑える働きがあることが示された。この傾向は LHD 配位において著しく、グローバルモデルでも見られるが、従来の局所近似では再現できず、特にプラズマの衝突周波数が小さい場合に顕著な差を生むことが明らかにされた。一方径電場が大きくなると、E×B 回転の非圧縮近似を使っていた従来のモデルによる新古典輸送の評価では誤差が増大することが示され、圧縮性 E×B 回転が扱える ZOW モデルの有効性が示された。また、磁気面接線方向の磁気ドリフト項は、磁力線方向のプラズマ流やブートストラップ電流にはほとんど影響しないこと、また ZOW の問題点である Liouville の定理が成り立たないことによる誤差は、計算結果にほとんど影響しないことが、方程式に含まれる余剰項のオーダー評価やシミュレーション結果から確認された。

第二部では ZOW モデルが FFHR-d1 の自己点火シナリオの条件下におけるブートストラップ電流の評価に応用された。まず 9 章で、新たに電子-イオン間摩擦力にイオンの有限な平均流速の効果を組み込むコード改良について説明がなされた。10 章では、衝突項の運動量

バランスを正しく扱える他の局所近似コード PENTA とのベンチマークテストが行われ、同種粒子種衝突の運動量保存性と､電子-イオン間摩擦力の両方を正しく評価することで正確にブートストラップ電流が評価できることが証明された。FFHR-d1 の自己点火シナリオでのブートストラップ電流は平衡磁場に影響を与える程大きくなる可能性が示されたが、プラズマの衝突周波数を上げることでその影響が抑えられることも定量的に明らかにされ、今後の核融合炉設計研究活動に重要な指針を与えた。

以上のように、本論文は、多様な新古典輸送計算法の精度が、どのように、磁場配位・径電場や衝突周波数等の条件に依存するかを解明し、局所近似モデルの信頼性を向上させるとともに、核融合炉設計研究への応用により、その有用性を証明した重要な研究成果であると認められる。よって本論文の内容は博士学位（学術）の授与に十分値すると判断した。