氏　　　　名	松岡　清吉
学位（専攻分野）	博士　(理学)
学 位 記 番 号	総研大甲第 1412 号
学位授与の日付	平成２３年３月２４日
学位授与の要件	物理科学研究科　核融合科学専攻 学位規則第６条第１項該当
学 位 論 文 題 目	Effects of Finite Orbit Width on Neoclassical Transport in High-Temperature Helical Plasmas
論 文 審 査 委 員	主　　査　　教授　　洲鎌　英雄 准教授　横山　雅之 教授　　武藤　敬 教授　　福山　淳　京都大学 准教授　北島　純男　東北大学

論文内容の要旨

Improving confinement of the particle and energy transport is an important task to realize a nuclear fusion reactor in toroidal magnetic devices and a great effort has been devoted theoretically and experimentally to achieve this aim. Neoclassical (NC) transport theory has been studied in detail, since it describes a diffusive transport phenomenon caused by particle collisional interactions in a torus configuration, and thus, determines a irreducible minimum transport level depending on the magnetic geometry. In helical/stellarator devices which have the three-dimensional magnetic structure, neoclassical transport has a character of increasing with $T_{\mathrm{a}}^{7/2}$ in low collisionality regime, where T_{a} is the temperature of species $\mathrm{a} = \mathrm{e}, \mathrm{i}$. In addition to this, the radial electric field (E_{r}), which in general reduce both neoclassical and anomalous transport, is determined by the ambipolar condition of neoclassical particle transport in helical devices.

The plasmas of $T_{\mathrm{i}} > 5$ keV are successfully obtained in the recent LHD experiments. Neoclassical transport analyses are performed for such plasmas. We confirm that when T_{i} increases, the NC transport flux is reduced by two orders of magnitude compared to that without E_{r} due to the existence of the ambipolar radial electric field. The parameter survey calculations on T_{i} and n_{e} are also carried out to consider the NC transport flux dependence on the plasma parameter. With these calculations, it is shown that NC ion thermal diffusivity is reduced to small level as that of electron even for plasmas with the fusion reactor relevant parameter if $T_{\mathrm{e}} \simeq T_{\mathrm{i}}$ is numerically retained. It is found that the radial electric field in high T_{i} plasmas with high T_{e} has a significant impact on the reduction of the NC transport. This fact provides us the opportunity to reconsider the NC transport more rigorously in high T_{e} plasmas.

Neoclassical transport in an asymmetric magnetic field has been estimated and calculated by using numerical simulations based on *local* assumptions, which neglect the particle drift, or the deviation from a certain magnetic surface. Although it has been pointed out that the finite orbit width effect for ions plays an important role in neoclassical transport theory in recent studies, it has been considered that such conventional local assumptions have been valid for electrons. This is because the deviation from the magnetic surface on which the electron is located initially has been considered to be small enough. On the other hand, very high T_{e} plasmas exceeding $T_{\mathrm{e}} \simeq 20$ keV at the plasma core region followed by electron internal transport barrier formation of the steep T_{e} gradient have been achieved in recent experiments in LHD. These plasmas are called Core Electron-Root Confinement, CERC, since they are accompanied by the formation of the strong positive radial electric field, or the electron root. The high electron temperature makes helically-trapped electrons drift away from the initial magnetic surface. As a result, local assumptions of the neoclassical transport may be broken even for electrons in CERC plasmas.

This effect of electron drift, however, has not been considered seriously so far and it is quite unclear whether the local treatment is valid or not. In this thesis, the electron finite orbit width effect on neoclassical transport is investigated in detail by using non-local δf Monte Carlo simulation code, FORTEC-3D, which is newly extended to apply to electrons in this work. It is found that the electron finite drift makes qualitative difference between the local treatment and the non-local treatment in neoclassical transport calculations.

This thesis is organized as follows. First, we performed NC transport analysis based on the local treatment for high $T_{\rm i}$ plasmas. With these calculations, the electron-root $E_{\rm r}$ is obtained in high $T_{\rm i}$ plasmas numerically considering $T_{\rm e}$ is high at the same time. This suggests that the non-local electron drift plays an important role in the $E_{\rm r}$ formation.

Second, FORTEC-3D, which solves the drift kinetic equation without the local assumptions is newly extended to apply to electrons including electron-ion collisions. Precise benchmark calculations are carried out with DCOM/NNW and GSRAKE code, which are both widely used local neoclassical transport simulation codes. By numerical calculations, it is found that the electron ∇B and curvature drifts change the particle and energy flux due to the particle poloidal precession and collisionless detrapping process in high $T_{\rm e}$ and the low collisionality regime, while results in low $T_{\rm e}$ and high collisionality regime reproduce the similar transport dependence on $E_{\rm r}$ obtained by DCOM/NNW and GSRAKE. The changes of NC transport in the low collisionality regime appear as the reduction of the peak value and/or shift of peak position in flux dependence on the radial electric field. Non-local effect is confirmed by fully taking the particle drift and its orbit into account in neoclassical transport calculations by FORTEC-3D.

Third, the extended FORTEC-3D for electrons is applied to a CERC plasma obtained in the LHD experiment. Such non-local electron transport analysis for the LHD experimental discharge is performed for the first time in this study. The radial electric field is analyzed in two ways: (1) the electron particle flux is calculated by FORTEC-3D with the fixed radial electric field for given plasma profiles and the steady state radial electric field is determined so as to satisfy the ambipolar condition of the electron particle flux obtained by FORTEC-3D and the ion particle flux by DCOM/NNW. (2) Time evolution of the radial electric field is followed as an initial value problem with given plasma profiles using ion-particle-flux-radial-electric-field table made by DCOM/NNW. The ambipolar radial electric field is obtained as its steady state solution. This separate procedure for electron and ion is adopted in order to reduce the calculational burden since simultaneously calculating the NC transport for both species waste too much computational resources. It is shown that the resultant $E_{\rm r}$ differs from that obtained by DCOM/NNW in the core region, while it agrees with ion-root $E_{\rm r}$ evaluated by DCOM/NNW in the edge region.

In this study, the importance of the electron finite orbit width effect in determining the neoclassical transport flux and its influence on the radial electric formation in high temperature helical plasmas is investigated by directly the the drift kinetic equation including the finite orbit width effect of electrons. With this approach, we provide a sufficient and reasonable basis on how the electron drift affects the neoclassical transport and the resultant radial electric field. This enables one to analyze the neoclassical transport property with a desirable accuracy, and thus, leads ones to obtain more detailed physical insight to the plasma physics involving the transport and the radial electric field.

博士論文の審査結果の要旨

ヘリカルプラズマでは、理論的見地から、低衝突周波数領域での拡散(リップル拡散)増大が予測され、高性能ヘリカルプラズマ研究の進展の上で懸念される課題の一つとなっている。本学位論文は、核融合科学研究所の大型ヘリカル装置(LHD)における高温プラズマを対象とした新古典輸送解析を行い、さらなる高イオン温度化への実験シナリオ提案を行うとともに、従来考慮されていなかった電子の有限軌道幅効果を正確に取り入れられるように新古典輸送シミュレーションコードを改良し、高電子温度プラズマに適用することにより、新古典輸送および電場に対する電子ドリフト軌道の有限軌道幅効果を初めて明らかにしたものである。

新古典輸送コード GSRAKE を用いた解析によって、高イオン温度 LHD プラズマでは、新古典拡散束の両極性条件から、実験結果と一致する負電場(イオンルート)が予測されること、その電場の存在によってリップル拡散が大幅に低減されていることを明らかにした。さらに、炉心条件をも想定した密度・温度領域に対する解析を行い、イオン温度の上昇に伴うイオンルートの促進、及び、電子温度の上昇に伴って正電場(電子ルート)が現れうることで、炉心プラズマへの温度上昇の過程で新古典イオン熱拡散の増大を抑え続けることが可能であることを、現存の実験データからの展望として定量的に示した。

今後の LHD 実験において電子温度の上昇も重要であるとの結果、及び、昨今の LHD 実験で進展著しい電子温度領域の拡大に着目して、新たに δf モンテカルロコード FORTEC-3D の改良を行い、電子の有限軌道幅効果を取り入れた初めての新古典輸送・径電場形成シミュレーションを実行した。GSRAKE のような従来の新古典輸送コードは、軌道幅が小さな極限を考える「局所近似」に基づいているが、Core Electron-Root Confinement (CERC)のような高電子温度・低衝突周波数領域では、電子ドリフト軌道幅が大きく、局所近似の妥当性が問題となる。そこで、FORTEC-3D を電子の新古典輸送解析に適用するために、電子-イオン間ピッチ角散乱衝突項を新たに組み込んだ。有限軌道幅効果の小さな低電子温度プラズマに対して、局所近似に基づく新古典輸送コードと FORTEC-3D とのベンチマークテストを行い、良い一致が得られることを確認した。さらに、高電子温度条件において FORTEC-3D と局所コードによるシミュレーション結果の比較を行い、有限軌道幅効果によって、1)小さな電場では電子輸送が低下すること、2)両極性条件から決定される電場は、より正の大きな値に変化すること等を明らかにした。このように、改良したシミュレーションコードの妥当性を検証した上で LHD の CERC プラズマに適用した結果、中心部において、有限軌道幅効果により従来の計算結果よりも実験結果に近いピークした正電場分布が得られることを示した。

以上の研究成果は、今後の LHD プラズマ高イオン温度化に向けた径電場の役割を明確にするとともに、高電子温度プラズマにおける高精度シミュレーションによって、粒子・熱輸送や径電場形成の解析・予測に大いに貢献するものと考えられる。よって、本審査委員会は、本論文が博士学位論文として十分価値があるものであると判定した。