KINETIC SIMULATION STUDIES ON MULTI-ION-SPECIES PLASMA TRANSPORT IN HELICAL SYSTEMS

M. Nunami
National Institute for Fusion Science, National Institutes of Natural Sciences
SOKENDAI (The Graduate University for Advanced Studies)
Toki, Japan
Email: nunami.masanori@nifs.ac.jp

M. Nakata, H. Sugama, M. Yokoyama
National Institute for Fusion Science, National Institutes of Natural Sciences
SOKENDAI (The Graduate University for Advanced Studies)
Toki, Japan

M. Sato, S. Toda, and H. Yamaguchi
National Institute for Fusion Science, National Institutes of Natural Sciences
Toki, Japan

Abstract

The comprehensive analyses of kinetic simulations for anomalous and neoclassical transport of steady state multi-ion-species plasmas including impurity ions in helical systems are performed by using gyrokinetic and drift-kinetic approaches. In the multi-species plasmas, there exist multi-transport channels in the particle transport between each particle species. In high ion temperature plasmas heated by neutral beam injection (NBI) with hollow impurity density profiles obtained in the Large Helical Device (LHD), we find that the anomalous particle transport fluxes have various dependences on the temperature and density gradients, and the carbon impurity particle flux remains to be directed inward radially within the wide ranges of the radial gradient profiles of the plasma temperatures and densities. On the other hand, the neoclassical ion fluxes can change due to the generated ambi-polar radial electric field and the external momentum torques by NBI heating. The external torques can cause not only the negative radial electric field, but also the positive radial electric field where the neoclassical carbon flux can be directed outward radially. Furthermore, if the inward-directed current is imposed sufficiently by the co-injected heating beam, the neoclassical carbon particle flux can also be outward-directed. These findings contribute deeper understandings of the hollow profiles in the LHD impurity hole plasmas in terms of fully kinetic framework.

1. INTRODUCTION

To design the fusion reactors, the transport phenomena of plasma particles and heat need to be quantitatively predicted, and numerical simulation approaches based on the kinetic frameworks are powerful for that purpose. Recently, due to the rapid progress of the large-scale simulations using the high-performance computers, it becomes able to validate the kinetic simulation results against the experimental observations for the plasma temperature and density profiles with the experimental errors considered [1]. The understandings of the transport physics of the multi-ion-species plasma are strongly demanded for predicting the performances of the burning plasma in the ITER, future fusion reactors, and also stellarator systems such as the Wendelstein 7-X [2] and the Large Helical Device (LHD) [3]. Our previous linear gyrokinetic analyses for the multi-ion-species plasmas in LHD show that the growth rate of the microinstability strongly depends on the relative densities and temperature profiles of each species [4]. This means that the details of the plasma profiles for each particle species can affect the resultant transport of the multi-ion-species plasmas. In realistic multi-species magnetized plasmas, there should exist impurity ions with high-Z number and heavy masses, and the impurity ions are often accumulated in core regions. The accumulated impurities degrade confinement performance of the plasmas by radiation losses of the heat, reduction of the plasma temperature, etc. On the other hand, in the LHD plasmas heated by neutral beam injection (NBI), we often observe the extremely hollow impurity density profiles called impurity hole. Therefore, the clarification of its generation mechanism is a critical issue for achieving the high-performance of magnetically confined plasmas because the hollow impurity densities may avoid the impurity accumulations. Now, we consider the particle balance relations for the species $s$ in such plasmas,

$$\frac{\partial n_s(\rho)}{\partial t} + \frac{1}{V} \frac{\partial}{\partial \rho} V \left( \Gamma_s^{(\text{NC})} + \Gamma_s^{(\text{NBI})} \right) = S_s,$$  \hspace{1cm} (1)
and the neoclassical contribution of the radial particle flux $\Gamma^{(\text{NC})}_r$ and the anomalous contribution $\Gamma^{(\text{th})}_r$ should be balanced for each species if the system is in the steady state, $\partial n_s/\partial t = 0$, with negligible auxiliary particle sources and sinks, $S_s = 0$. Therefore, the quantitative kinetic calculations of the particle fluxes are significant for transport analyses of the multi-ion-species plasmas.

In this work, the transport fluxes of the multi-ion-species LHD plasmas with impurity hole structure are evaluated by fully kinetic simulations for the anomalous and neoclassical contributions, where the stationary conditions for each particle species should be satisfied by the total particle transport fluxes including the both contributions.

2. SIMULATION MODELS

In this paper, we employ the gyrokinetic local flux-tube turbulence code GKV [5, 6] for the analyses of anomalous transport, and the local drift-kinetic simulation code DKES/PENTA [7] for neoclassical transport analyses. The GKV has been extended to treat multi-species plasmas including precise collision operator [8, 9], for the analyses of the turbulent transport phenomena in the LHD plasmas. In the GKV code, the time evolution of the wavenumber-space representation of electromagnetic gyrokinetic equation,

$$
\left( \frac{\partial}{\partial t} + v_i b \cdot \nabla + i \omega_{\text{pe}} - \frac{\mu b \cdot \nabla B}{m_s} \frac{\partial}{\partial v_i} \right) h_{sk,\perp} - \frac{c}{B} \sum_s b \cdot (k'_{\perp} \times k''_{\perp}) \delta \psi_{k'_{\perp}} h_{sk',\perp} = \frac{e_s F_{\text{MS}}}{T_s} \left( \frac{\partial}{\partial t} + i \omega_{\text{xte}} \right) \delta \psi_{k_{\perp}} + C_s(h_{sk,\perp}),
$$

is solved for the perturbed gyrocenter distribution function of species $s$, $h_{sk,\perp}$. Collisional effects are introduced in terms of a linearized model collision operator $C_s$, where a simplified Lenard-Bernstein model is applied in order to perform the numerical scans for wide-parameter regimes in this work. The potential fluctuations are calculated by the Poisson and Ampère equations.

On the other hand, in the neoclassical simulations, we employ the PENTA code which can treat the mono-energetic transport coefficients to account for momentum conservation for calculation of radial electric field satisfying the ambipolar condition, $\Sigma_{s \neq e} Z_s \Gamma_s = \Gamma_e$. Here, $Z_s$ is the charge number of the ion species $s$. The PENTA code employs Sugama-Nishimura method [10] for deriving the viscous stress tensor in terms of transport coefficients which are calculated by DKES code [11]. If we estimate the neoclassical particle fluxes in the presence of the external momentum torques by the NBI heating, we have to include a source term $F_{\text{beam}}$ in the parallel momentum balance equation for each particle species,

$$
\langle B \cdot (\nabla \times \pi) \rangle - ne \langle B E_\parallel \rangle = \langle B E_{\text{dy}} \rangle + \langle B F_{\text{beam}} \rangle.
$$

Using both codes, we carry out the kinetic simulations for the turbulent and neoclassical transport in the LHD impurity hole plasma which is same as the plasma discussed in previous our works [12, 13].

3. KINETIC SIMULATION RESULTS

3.1. Anomalous simulation results

In many gyrokinetic simulations, it was found that the turbulent transport fluxes have strong sensitivity to plasma profiles, i.e. the radial gradients of the temperature and densities [1, 14, 15]. Within the observation errors or certain ranges of the plasma profiles, the gyrokinetic simulations can reproduce the experimental transport fluxes, so called flux-matching. Therefore, as far as the simulations or models for the turbulent transport are employed, we have to discuss the turbulent transport phenomena within the experimentally allowable ranges or certain wide ranges of the plasma profile gradients in terms of a concrete way for quantitative simulations and analyses.

3.1.1. Temperature gradient dependences

While the micro-instability analyses for the LHD impurity hole plasma which consists of four species (e, H, He, and C) indicate that the ion temperature gradient (ITG) mode is a dominant instability mode [12, 16], the nonlinear gyrokinetic turbulence simulations are performed by the GKV code to evaluate the turbulent transport.
Here, to reduce the computational costs, we employed the model LHD configuration with limited numbers of field components from the equilibrium obtained by VMEC code [17], where the model configuration does not affect main features of the transport. Figure 1 shows the dependences of the turbulent heat transport fluxes for all four species on electron and ion temperature gradient lengths. Here, the turbulent particle fluxes satisfy the ambi-polar condition at each gradient. All ion heat fluxes rapidly increase with increasing the ion temperature gradient, which is a typical character of the ITG-driven turbulent transport. Although the electron heat flux also depends on the electron temperature gradient, every heat flux has similar dependences on the temperature gradient lengths. On the other hand, in the case of particle transport fluxes shown in Fig. 2, quite different temperature gradient dependences of the particle fluxes are found among different particle species. Furthermore, the impurity carbon particle flux remains negative (radially inward-directed) within 50% changes of the ion and electron temperature gradients from their nominal values.

3.1.2. Density gradient dependences

Particle fluxes are affected by not only the temperature gradients but also the density gradient lengths for several particle species. Here, as same as Sec. 3.1.1, the density gradient length dependences of turbulent particle fluxes are evaluated by the nonlinear gyrokinetic simulations. Figure 3 represents the simulation results for the density gradient length dependences of turbulent particle fluxes for each species. In the figure, we can see different multi-transport channel from the heat fluxes, i.e., although the density gradients of bulk ions (H, and He) have little impacts on the turbulent particle fluxes, the density gradients of electron and carbon ions strongly affect the turbulent particle fluxes of electron and hydrogen. However, the carbon particle flux cannot be outward-directed unless the impurity hole structure is disappeared, i.e. the carbon density profile becomes to be peaked. Therefore, based at least on the results from the temperature and density gradient dependences obtained in Sec. 3.1.1 and 3.1.2, if the system is in the steady state with negligible auxiliary particle sources or sinks, the neoclassical carbon particle flux should be expected to be outward directed against the inward turbulent flux.

FIG. 1. Temperature gradient length dependences of turbulent heat fluxes $Q_{(trb)}$ (color contours) for (a) electron, (b) hydrogen, (c) helium, and (d) carbon, where $L_{te} = (-d\ln T_e/dr)^3$ and $L_{ti} = (-d\ln T_i/dr)^3$ are the temperature gradient length of electron and ions, respectively. And $L_{te0}$ and $L_{ti0}$ represent the nominal temperature gradient lengths for electron and ions, respectively. Each fluxes are evaluated at $r/a = 0.6$ and normalized by the arbitrary unit.
FIG. 2. Temperature gradient length dependences of turbulent particle fluxes $\Gamma_{(trb)}^{(s)}$ (color contours) for (a) electron, (b) hydrogen, (c) helium, and (d) carbon, where $L_{te} = (-d\ln T_e/dr)^{-1}$ and $L_{ti} = (-d\ln T_i/dr)^{-1}$ are temperature gradient length of electron and ions, respectively. And $L_{te0}$ and $L_{ti0}$ represent the nominal temperature gradient lengths for electron and ions, respectively. Each fluxes are evaluated at $r/a = 0.6$ and normalized by the arbitrary unit.

FIG. 3. Turbulent particle fluxes $\Gamma_{(trb)}^{(s)}$ for changing (a) electron density gradient, (b) hydrogen density gradient, (c) helium density gradient, and (d) carbon density gradient, where $L_{ns} = (-d\ln(n_s)/dr)^{-1}$ is the density gradient length of s-species. And $L_{ns0}$ represent the nominal density gradient lengths for s-species. Here, each fluxes are evaluated at $r/a = 0.6$ and normalized by the arbitrary unit.
3.2. Neoclassical Contributions

In order to evaluate the neoclassical contributions in the LHD impurity hole plasma transport, we use the DKES/PENTA code, and we employ the plasma profiles which are same as the nominal profiles used in our work [12]. In the previous neoclassical analyses in the plasma, it was found that there is the negative radial electric field, so called ion-root which is expected in almost LHD plasmas, and electron and bulk ions (H and He) have outward directed particle fluxes. Although the neoclassical particle flux of carbon impurity is extremely small, the direction is radially inward which is inconsistent with above expectation against the negative anomalous particle flux discussed in Sec. 3.1. However, the neoclassical particle fluxes can be changed by various effects such as the changes of the radial electric field, the external momentum torques by NBI heating, and the potential variations on the flux-surfaces [18]. In recent work [19], the effects of the potential variations are expected to be not small in the LHD case with the impurity hole structure, but the carbon impurity particle flux changes to opposite direction against the above expectation.

3.2.1. Impacts of external momentum torque

The neoclassical particle fluxes can be affected by the external torque by NBI heating and the ambi-polar radial electric filed [20, 21]. Indeed, in the LHD experiment, the density profiles are changed when there exist NBI heating, the hollow density profiles are more generated in the case of co-directed NBI heating, and the impurity transport can change through the coupling between the radial electric field and toroidal flows [22]. In order to evaluate the neoclassical particle fluxes in the presence of the external torques by the NBI heating, we include a source term $F_{\text{beam}}$ in Eq. (3) for each particle species. The nominal external torque profiles employed here are obtained from the experimental results of the input power and the ratio of the densities between each particle species. Here, we analyze the cases of the external torques by counter-injected and co-injected NBI with the range of $-5F_{\text{beam}}^{(\text{nom.})} < F_{\text{beam}} < 5F_{\text{beam}}^{(\text{nom.})}$. Here, $F_{\text{beam}}^{(\text{nom.})}$ is the nominal value of the external torque, and the negative or positive sign represent the counter- or co-directions of the injected beam, respectively. Figure 4 shows the simulation results of the dependences of the neoclassical particle fluxes of electron and total ions on the radial electric field with the external momentum torques at core region, $\rho = r/a = 0.4$. For changing external momentum sources, the roots of ambi-polar condition are varying with changing particle transport fluxes, and the ambi-polar radial electric field is moderated from counter-injected to co-injected NBI cases.

![FIG. 4. Dependence of neoclassical particle fluxes of electron $\Gamma_e$ (red curves) and total ions $\sum_{\text{ion}} Z_i \Gamma_i$ (blue curves) to radial electric field with external momentum torques at $\rho = r/a = 0.4$. Dotted, dashed, sold, two-dot dashed, and dot dashed curves represent $F_{\text{beam}} = -5F_{\text{beam}}^{(\text{nom.})}$, $F_{\text{beam}}^{(\text{nom.})}$, 0, $F_{\text{beam}}^{(\text{nom.})}$, and $5F_{\text{beam}}^{(\text{nom.})}$, respectively. $F_{\text{beam}}^{(\text{nom.})}$ is the nominal value of the external torque. Green points represent the roots of ambi-polar conditions for each case.](image)

Due to the moderated radial electric field, the electron particle flux and the main ion (H) particle flux increase. On the other hand, the helium particle flux does not change and the carbon particle flux decreases, because the dependences of the particle fluxes on the radial electric field are quite different between each particle species. Figure 5 shows the PENTA results of the radial profiles of the ambi-polar radial electric field and the neoclassical particle fluxes of each species with co-injected and counter-injected NBI torques. In the counter-injected case, the electron flux and the main ion flux slightly decreases, and the carbon flux increases to positive...
For the co-injected case, on the contrary, the electron and the main ion flux increase, and the carbon particle flux decreases and becomes to be more inward directed. Therefore, even if there is the external momentum source by co-injected NBI heating which moderates the electric field, the changes of the particle fluxes are not large including the carbon ion, and the direction of the carbon flux does not change.

However, the electric field can be changed further by the external momentum sources. In Fig. 4, if the external sources by co-injected NBI increases, there are not only the ion-root with negative ambi-polar radial electric field, but also the electron-root with positive radial electric filed. Figure 6 shows the radial profiles of the ambi-polar radial electric filed and the neoclassical particle fluxes of each species in the case of the electron-root with the external momentum torque by co-injected NBI heating. In the electron-root case, the particle fluxes of each species can be changed and the impurity carbon particle flux can be radially outward directed in not only the outer region but also in the inner radial region where strong hollow density profile is generated. If such outward-directed carbon flux exists, there may be a possibility of existence of the neoclassical particle flux of the impurity which can be balanced with the negative turbulent particle flux obtained from gyrokinetic simulations.

### 3.2.2. Direct perpendicular contribution of injected beam

The neoclassical particle fluxes and the ambi-polar radial electric filed can be affected by the external torque by NBI heating as discussed in Sec. 3.2.1. The carbon flux tends to be directed inward radially with the nominal expected radial electric field in the ion-root, and this is inconsistent with the expectation from the gyrokinetic
turbulence simulations that the inward turbulent carbon particle flux should be balanced with the outward directed neoclassical carbon particle flux. However, the inward directed radial particle flux $\Gamma_b$ produced by additional effects, e.g., the perpendicular contributions to the total ion particle flux from the co-injected beam which is one of the missing effects in the past neoclassical analyses, may change the ami-polar radial electric filed and each neoclassical ion particle flux. Indeed, even in the case of negative radial electric field, the neoclassical carbon flux becomes to be positive as shown in Fig. 7(b), if the inward directed radial particle flux $\Gamma_b$ exceeds a certain level that the ami-polar radial electric filed is up-shifted within the allowable ranges of typical observation errors as shown in Fig. 7(a). However, based on the numerical analyses of the trajectory of the fast neutrals injected from the beam by using HFREYA code [23], the magnitudes of the directed radial particle flux from the co-injected beam are not enough to generate the outward carbon particle flux. Therefore, we need to analyze more additional effects, e.g., the global estimates which can also cause weakening of the neoclassical ion fluxes and the ami-polar radial electric field from the results of the local DKES calculations.

\[ E_r^{(\text{nom})} = \pm 2 \text{kV/m} \]

**FIG. 7.** Radial profiles of (a) changes of the ami-polar $E_r$ (red curve) from the nominal values (black curve) due to the imposed $\Gamma_b$, and (b) neoclassical carbon particle flux. The dotted curves represent allowable ranges of $E_r$ and $\Gamma_b^{(\text{neo})}$ within the typical observation errorbars of $E_r^{(\text{nom})} = \pm 2 \text{kV/m}$.

4. SUMMARY

In this work, the first comprehensive analyses of kinetic simulations for the anomalous and neoclassical transport of the multi-ion-species plasma in helical systems are carried out. While there exist quite various transport channels in the LHD impurity hole plasmas, it is newly found in this work that the turbulent carbon particle flux remains radially inward-directed within widely changes of the temperature gradients and the density gradients of each particle species. On the other hand, the neoclassical carbon flux can be changed by the external momentum torques, where the co-injected NBI causes the possibilities of the electron-root with positive ami-polar radial electric field and outward directed neoclassical impurity particle flux. Although the carbon particle flux can be outward-directed even in the negative radial electric field if the sufficient additional inward-directed current, the perpendicular contributions from the co-injected NBI heating is not enough to cover the effects to explain the outward-directed carbon particle flux. The global treatment is very important for the neoclassical analyses, since the global neoclassical estimates can give substantial weakening of the neoclassical ion fluxes near $E_r = 0$ [24], which may bring on the outward directed neoclassical impurity particle flux.
ACKNOWLEDGEMENTS

The authors would like to thank the LHD experiment group. This work was supported in part by the Japanese Ministry of Education, Culture, Sports, Science and Technology, Grant (Nos. 26820398, 16K06941, 17K14899, and 18H01202), by National Institute for Fusion Science (NIFS) Collaborative Research Program (KNTT043, KNTT045 and KNST095), and by the FLAGSHIP2020, MEXT within the priority study 6. The results were obtained by using the K computer at the RIKEN Advanced Institute for Computational Science (Proposal number: hp120138, hp170260, hp180200, and hp180083), JFRS-1 at International Fusion Energy Research Center (Project code: KML3D, GKVISo and GT5DSTL), and “Plasma Simulator” at NIFS.

REFERENCES