Neoclassical Transport Properties in High-Ion-Temperature Hydrogen Plasmas in the Large Helical Device (LHD)

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High ion temperature (T_i) hydrogen plasmas were successfully demonstrated in the LHD in an experimental campaign (FY2006). The power increase of the perpendicular neutral beam injections (NBIs) has mainly contributed to this achievement. T_i exceeded 5 keV at the average plasma density (n_e) of 1.2×10^{19} m^{-3} and also achieved 3 keV at $n_e > 3 \times 10^{19}$ m^{-3}. Neoclassical (NC) analysis was performed for such plasmas. We confirmed that even if T_i or the plasma density became higher, NC transport was remained to a certain value because of the existence of the ambipolar radial electric field (E_r), which was roughly two orders of magnitude smaller for cases not involving the existence of ambipolar E_r. Besides, a T_i and n_e scan of discharge 75235 was also performed to consider the plasma parameter dependence of NC transport. Using these calculations, it is shown that NC ion thermal diffusivities are reduced to a small percentage of NC electron thermal diffusivites even at the fusion reactor relevant parameters such as $n_e \sim 1 \times 10^{20}$ m^{-3} and $T_i \sim T_e \sim 10$ keV.

Keywords: high-ion-temperature, neoclassical transport, radial electric field, GSRAKE code, electron-root

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1. Introduction

High ion temperature (T_i) hydrogen plasmas were successfully demonstrated in the LHD in an experimental campaign (FY2006). T_i exceeded 5 keV at the average plasma density (n_e) of about 1.2×10^{19} m^{-3} and also achieved 3 keV at $n_e > 3 \times 10^{19}$ m^{-3} (See Fig. 1) [1].

It was recognized in the LHD that electron heat transport is predominantly determined by the contribution of the anomalous transport, even in the improved confinement modes of electrons [2]. On the other hand, ion heat transport analysis was only recently initiated in the LHD using the available measured T_i profiles. Thus, a quantitative evaluation of the neoclassical (NC) transport of ions is of vital importance to understand ion heat transport in such high-T_i plasmas in the LHD, because NC ion thermal diffusivity ($\chi_{i,NC}$) were thought to increase due to the ripple transport in helical devices.

It is considered that if a radial electric field (E_r) exists in the plasma, NC ripple transport is reduced to the extent determined by the ambipolar condition, $\Gamma_e = \Gamma_i$, where Γ_e and Γ_i are electron and ion particle fluxes, respectively. Thus, it is important to know how the NC diffusivity of high-T_i plasmas is affected by the E_r quantitatively. For this purpose, NC transport analysis was conducted for high-T_i plasmas, as shown in Fig. 1, by utilizing the GSRAKE code [3]. Systematic parameter-scan calculations were also performed by varying T_i and n_e of a particular shot to investigate the parameter dependence of NC ion diffusivity with regards to the reactor relevant regime. This indicates that NC transport could be kept relatively small even in higher-T_i plasmas in the LHD. In Section 2,

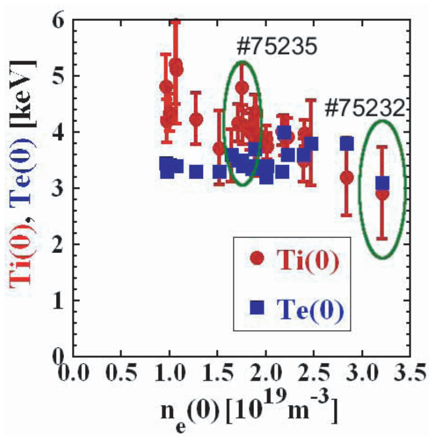

Fig. 1 Ion and electron temperature dependence of the density at the center of the plasma in the high-T_i experiments in the LHD

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the NC transport analysis for the present LHD shots is discussed. Next, the results of the subsequent NC transport analysis in a parameter-scan manner is described in Sec. 3. Finally, a summary is given in Sec. 4.

2. Neoclassical Transport Analysis of High-T_i LHD Plasmas

NC transport analysis was performed by utilizing the GSRAKE code. The GSRAKE code can calculate NC particle and thermal fluxes for ions and electrons, and therefore, ambipolar E_r from T_i and T_e (T_e is the electron temperature) and n_e profiles based on the information of LHD magnetic field configurations. Discharges 75235 (at 1.35 s) and 75232 (at 1.35 s) from the high-T_i experiments are examined. The T_i of discharge 75235 is 4.8 keV at $n_e \sim 1.8 \times 10^{19}\ \mathrm{m}^{-3}$ and that of discharge 75232 is ~ 3 keV at $n_e \sim 3.2 \times 10^{19}\ \mathrm{m}^{-3}$ (see Fig. 1). While T_i of discharge 75232 is comparable to T_e, T_i of discharge 75235 is higher than T_e. The heating scenario for discharge 75235 is shown in Fig. 2(a). The low-energy (~40 keV) perpendicular neutral beam (NBI4A and NBI4B) was injected along with the ion cyclotron range of frequency (ICRF) from t = 0.5 s (just after electron cyclotron heating (ECH) turn-off), with superposition of high-energy (~180 keV) tangential NBI (NBI1-3) from t = 1.1 s. NBI4 consists of four ion sources with two independently operatable power supplies (4A and 4B). This flexibility is utilized to modulate one of the power supplies (in this case, 4B) to modulate the injection for obtaining the background signals for T_i measurement. Maximum T_i was observed at t = 1.35 s (as shown in Fig. 2(b)), where the all four neutral beams were injected. It is noted that although the NBI3 pulse was unintentionally turned off at 1.3 s, the heating effect can be considered to be maintained up to 1.35 s by considering the slowing-down time of injected particles. T_i, T_e and n_e of discharge 75235 at 1.35 s are also shown in Fig. 2(b). T_i, T_e and n_e are measured by charge exchange recombination spectroscopy (CXS), Thomson scattering system and FIR interferometer, respectively.

Calculated NC Γ_i and Γ_e at ρ = 0.2 for discharge 75235 and 75232 are shown in Fig. 3 as a function of E_r. Here, ρ is the normalized minor radius. It is shown that Γ_i steeply increases around E_r = 0. However, it is known that realizable particle flux is determined by the ambipolar condition, $\Gamma_i = \Gamma_e$. Therefore, Γ_i is reduced to the lower level of Γ_e, because Γ_e does not change so much depending on E_r in these cases. Ambipolar E_r is shown in Fig. 4 (a). Figure 4 (b) shows $\nu_{i,p}$, the ion-ion collisional-

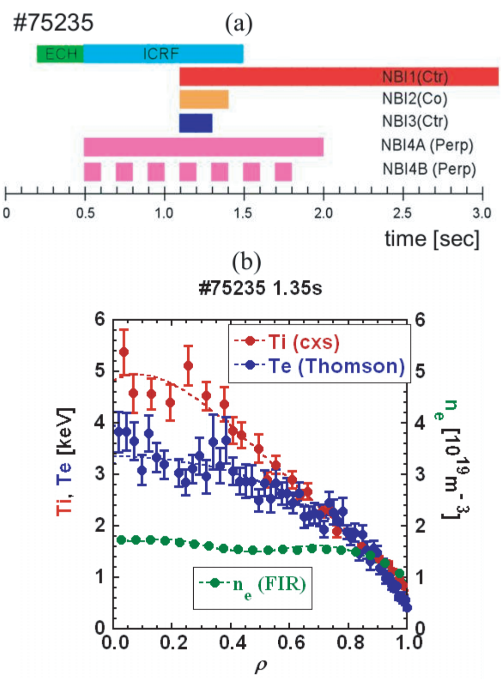

Fig. 2 (a) Heating scenario of discharge 75235. (b) Measured plasma parameters of discharge 75235 are shown. In this experiment, T_i, T_e and n_e are measured by CXS, a Thomson scattering system, and FIR interferometer, respectively.

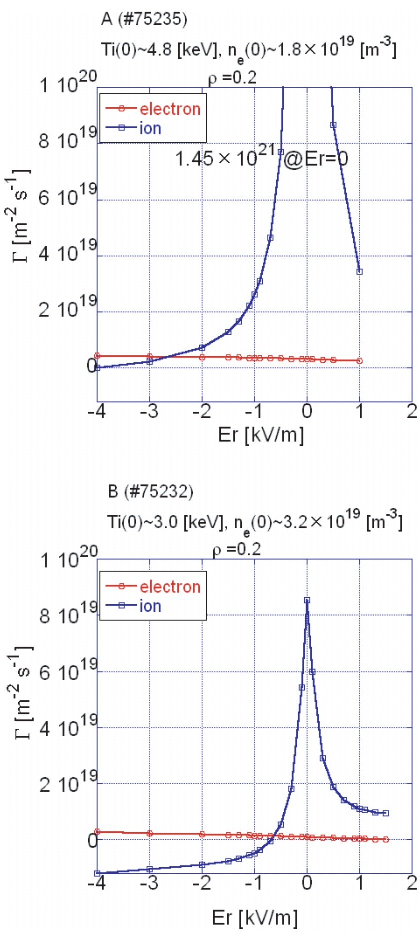

Fig. 3 E_r dependence of Γ_i and Γ_e at ρ = 0.2 of shots case A (#75235, upper) and case B (#75232, lower). The intersection of Γ_i and Γ_e provides ambipolar E_r.

ity normalized by the value at the plateau-Pfirsch Schlüter boundary. Because $\nu_{i,p} < 1$, as shown in Fig. 4 (b), it is recognized that these plasmas are in the $1/\nu$ regime, in which NC diffusivity steeply increases in proportion to ν^{-1} if $E_r = 0$. In fact, as seen in Fig. 3, Γ_i becomes extremely large near $E_r = 0$. Further, ion thermal diffusivity divided by $T_i^{1.5}$ (gyro-Bohm factor), $\chi_{i,NC}/T_i^{1.5}$, is shown in Fig. 4 (c), $\chi_{i,NC}/T_i^{1.5}$ at $E_r = 0$ is also shown for reference. The diffusivities are obviously reduced to almost the same magnitude (about two to three orders of magnitude smaller than that for $E_r = 0$), even though T_i in discharge 75235 was about twice that in discharge 75232. It clearly indicates that NC ion diffusivity does not increase as T_i is increased because of the presence of predicted ambipolar E_r. Thus, it can be considered that the NC ripple transport can be adequately suppressed in these high-T_i plasmas.

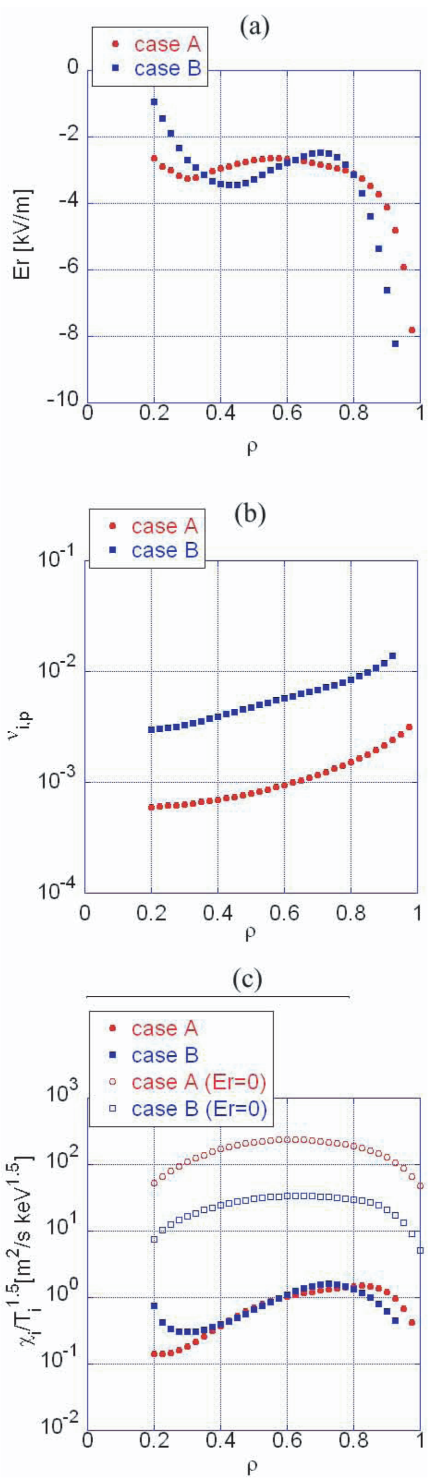

Fig. 4 Radial profiles of (a) ambipolar E_r, (b) ion collisionality, and (c) thermal diffusivities with or without E_r are shown for discharge 75235 (case A) and discharge 75232 (case B), respectively, where $T_A = 4.8$ keV, $n_A = 1.8 \times 10^{19}$ m^{-3}, $T_B = 3.0$ keV, and $n_B = 3.2 \times 10^{19}$ m^{-3}.

3. Temperature and Density Scan Calculations

Next, in order to investigate the NC transport properties with regard to reactor relevant parameter regime, parameter-scan calculations were performed for discharge 75235. T_i and n_e are widely varied, as shown in Fig. 5 for discharge 75235 while maintaining their profile shapes. $T_i(0)$ of 75235 (~4.8 keV) is multiplied by 2, and $n_e(0)$ of discharge 75235 (~1.8×10^{19} m^{-3}) is multiplied by 2, 5, and 6. In these calculations, it is assumed that the magnetic configuration equilibrium is fixed same as that for discharge 75235 for simplicity. It is known that NC diffusion tends to increase in the LHD as the plasma beta increases [4]. Thus, it should be noted that the following results of NC calculations provide under-estimated values.

The calculated collisionalities are in the $1/\nu$ regime for all cases. χ_i (or $\chi_i/T_i^{1.5}$) in this regime increases steeply as ν is decreased in the absence of E_r. However, from the results of parameter-scan calculations, it is clarified that χ_i (or $\chi_i/T_i^{1.5}$) is reduced to almost the same level in all cases with the ambipolar E_r taken into account. For example, the results of n_e scan of discharge 75235 are shown in Fig. 6, including (a) the ambipolar E_r and (b) $\chi_i/T_i^{1.5}$. In these cases, T_e is not changed; that is, $T_e(0) \sim 3.8$ keV. Therefore, this result indicates that the NC ion thermal diffusiv-

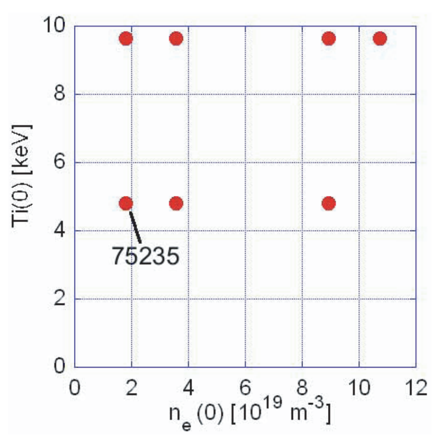

Fig. 5 Range of n_e and T_i scan calculations for discharge 75235.

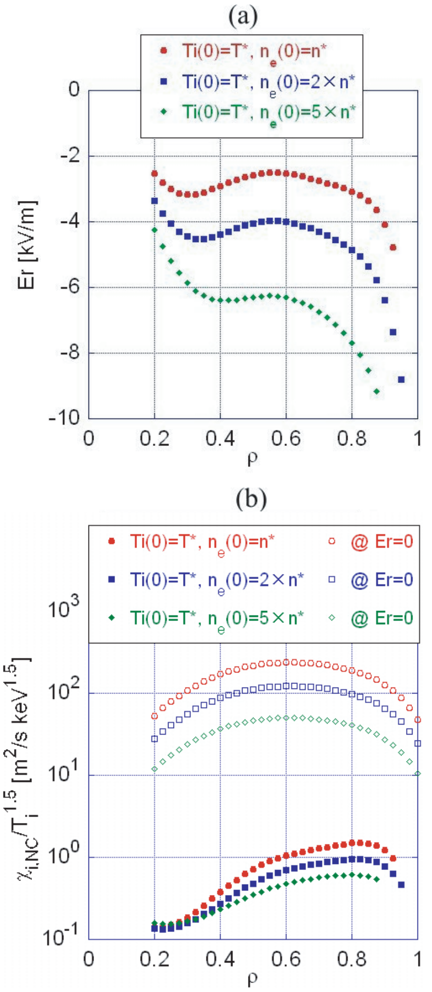

Fig. 6 Results of NC transport analysis. (a) E_r and (b) $\chi_i/T_i^{1.5}$ for n_e scan of discharge 75235, where $T^* = 4.8$ keV and $n^* = 1.8 \times 10^{19}$ m^{-3}. T_e is not changed so as to allow comparison with T_i.

ity at $E_r = 0$ increases as n_e (thus collisionality) decreases; however, it is reduced to almost the same level in the presence of ambipolar E_r regardless of the n_e value. This is also the case for T_i-scan calculations. As expected, the increase in T_i (thus the decrease in collisionality) makes χ_i larger for cases with $E_r = 0$. However, it is reduced to almost the same level in the presence of ambipolar E_r. This fact indicates that the NC χ_i does not increase even for high-T_i (ranging up to 10 keV) cases in the LHD, because of the presence of ambipolar E_r.

Further, T_e is modified to match T_i (i.e., $T_i \sim T_e$), and the same scan calculation is performed. It is interesting to note that not only the ion root but also the electron root is predicted (see Figs. 7(a) and (b)). The predicted χ_i is further reduced to a smaller level with the electron root than that with the ion root. In Fig. 7(a), it is also indicated that the electron root does not appear for higher n_e cases. Then, for the $2T_i$ cases of discharge 75235, further n-scan calculations were performed. The results are shown in Figs. 7(b) and (c). Figure 7(b) indicates that the electron root appears

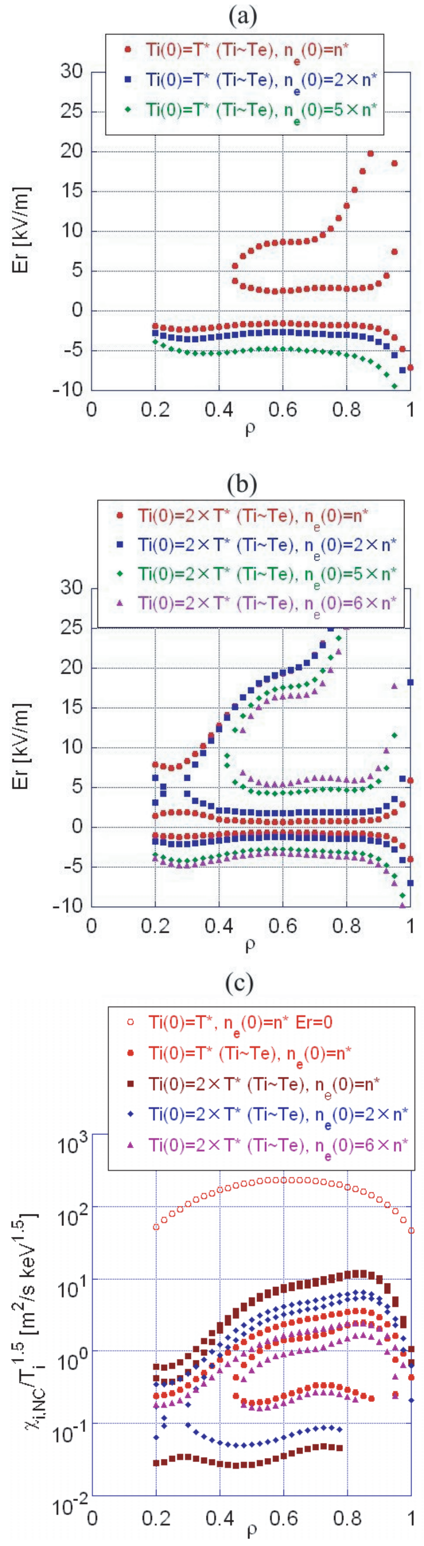

Fig. 7 (a) E_r for n scan calculations for discharge 75235 in the same n range as in Fig. 6. In this case, T_e is set to be comparable to T_i. (b) E_r for n scan calculations with a T_i value twice that of discharge 75235, and (c) $\chi_i/T_i^{1.5}$ (NC) for some cases shown in (a) and (b). In these figures, $T^* = 4.8$ keV and $n^* = 1.8 \times 10^{19}$ m^{-3}.

for the higher n_e of the $2T_i$ cases of discharge 75235. In addition, as shown in Fig. 7(c), $\chi_i/T_i^{1.5}$ for all cases is reduced to a small level compared with the case of $E_r = 0$ of discharge 75235. In these figures, two to three points are shown for each case at the same radii. From top to bottom in Figs. 7(a) and (b), each point corresponds to the value with electron root, unstable root, and ion root. On the other hand, in Fig. 7(c), each point corresponds to the value with ion root, unstable root, and electron root from top to bottom. From Fig. 7(c), it is also seen that $\chi_i/T_i^{1.5}$ with electron root is reduced more than that with ion root. It is considered that χ_i can be reduced more effectively since the absolute value of the electron root E_r is larger than that of ion root E_r.

4. Summary

In this paper, NC transport properties (especially for ions) are reported for the high-T_i hydrogen plasmas achieved in the LHD.

It is clearly demonstrated that NC ion thermal diffusivity is not easily increased even at high-T_i cases due to the predicted ambipolar E_r. It is also the case for $T_i \sim 10$ keV, which is clarified by parameter-scan calculations. This is favorable for further increase in T_i in the LHD by avoiding the appearance of the NC ripple transport.

It is also indicated that NC ion diffusion can be reduced more effectively with the electron root in high-T_i ($T_e \sim T_i$) plasmas. As seen in Fig. 5, the calculated parameter range reaches the level of $T_i \sim T_e \sim 10$ keV and $n_e \sim 10^{20}\ \mathrm{m}^{-3}$, which are relevant to a fusion reactor. Thus, it seems favorable to further explore the electron root scenario for producing high-T_i plasmas with regard to a reactor relevant regime.

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