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

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High ion-temperature (Ti) hydrogen plasmas were successfully demonstrated in the experimental campaign (FY2006) in the LHD. The power increase of the perpendicular neutral beam injection has mainly contributed to make this realize. T_i exceeded 5 keV at the average plasma density (n_e) of 1.2 $\times 10^{19}$ m^{-3} and also achieved 3 keV at $n_e > 3 \times 10^{19}$ m^{-3}. The neoclassical (NC) analyses have been performed for such plasmas by utilizing GSRAKE code. We confirmed that even if T_i or the plasma density became higher for any shots, the NC transport is remained to a certain value due to the existence of the ambipolar radial electric field (E_r), which was roughly 2 orders of magnitude smaller for cases without considering the existence of ambipolar E_r.

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

1 Introduction

High ion-temperature (T_i) hydrogen plasmas were successfully demonstrated in the experimental campaign (FY2006) in the LHD. T_i exceeded 5 keV at the average plasma density (n_e) of 1.2 $\times 10^{19}$ m^{-3} and also achieved 3 keV at $n_e > 3 \times 10^{19}$ m^{-3} (See Fig. 1) [1]. In such high ion temperature palasmas, neoclassical transport ion thermal diffusivities ($\chi_{i,NC}$) are thought to be increased due to the ripple transport.

However, It has been considered that if radial electric field (E_r) exists in the plasma, neoclassical transport are reduced to the extent of the smaller electron diffusion which is determined by ambipolar condition, $\Gamma_e = \Gamma_i$, where Γ_e and Γ_i are electron and ion particle flux respectively. And, by utilizing the electron or ion root of the radial electric field, reducing the neoclassical transport has been considered of great importance to improve the plasma confinement for non-axisymmetric helical systems. Thus, it is important to know how the neoclassical diffusivities of high-T_i plasmas are affected by the E_r quantitatively. For this purpose, the neoclassical transport analyses are conducted to some plasmas shown in Fig. 1 by utilizing GSRAKE code [2]. And systematic parameter-scan calculations with varying T_i and n_e have been performed based on these shots to see the parameter dependence of neoclassical ion diffusivity. It is clarified that the neoclassical thermal diffusivities are restrained due to ambipolar E_r. For many cases $E_r < 0$ is predicted, however, electron-root ($E_r > 0$) can appear for cases with low T_i. This indicates that neoclassical transport could be kept relatively small for even in higher T_i plasmas in LHD. In Sec.2, neoclassical transport analyses for LHD shot data are shown. And further neoclassical transport analyses for various plasmas in a parameter-sacn manner are described in Sec.3. Finally, summury is given in Sec.4.

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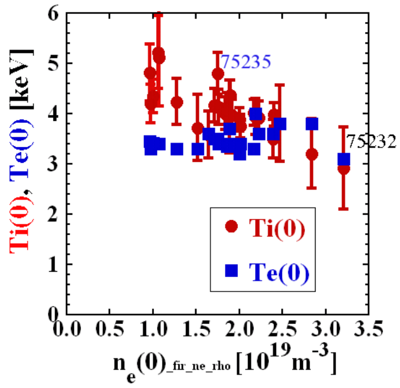

Fig. 1 The ion and electron temperature dependance on the density at the center of the plasma in the High-Ion-Temperature experiments in LHD

2 Neoclassical transport analyses of LHD shot data

Neoclassical transport analyses were performed by utilizing GSRAKE code. GSRAKE code calculates particle and thermal fluxes for ions and electrons, and therefore, ambipolar E_r based on LHD magnetic field config-

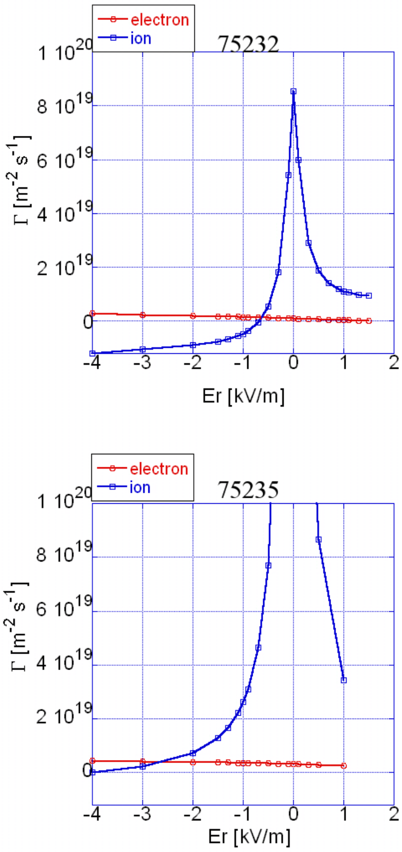

Fig. 2 E_r dependence of Γ_e and Γ_i at $\rho = 0.2$ of shots for 75232 (top) and 75235 (bottom). The intersection provides ambipolar E_r.

urations, using T_i and T_e (T_e is the electron temperature) and the plasma density profiles. At first, I chose the shot 75235 (at 1.35 sec) and 75232 (at 1.35 sec) from the high-ion-temperature experiments. While the ion temperature of 75235 is 4.8 keV at the density of $\sim 1.8\times10^{19}\mathrm{m}^{-3}$, that of 75232 is $\sim$ 3 keV at $\sim 3.2\times10^{19}\mathrm{m}^{-3}$. T_i of 75232 is comparable to T_e, T_i of 75235 is higher than T_e. Neoclassical transport calculations are carried out for these two shots. Γ_i and Γ_e at $\rho = 0.2$ for 75235 and 75232 are shown in Fig. 2. Here, ρ is normalized minor radius. Ambipolar E_r are shown in Fig. 3(a) for 75235 and 75232 respectively. Fig. 3(b) shows the ion-ion collisionalities $\nu_{i,p}$, normalized by the value at the platue-banana boundary. From Fig. 3(a) and (b), it is recognized that these plasmas are in $1/\nu$ regime in which neoclassical diffusion steeply increases in proportion to ν^{-1} when $E_r = 0$. In fact, as seen in Fig. 2, Γ_i becomes extremely large near $E_r = 0$. Then, ion thermal diffusivities devided by $T_i^{1.5}$ (Gyro-Bohm factor), $\chi_{i,NC}/T_i^{1.5}$, are shown in Fig. 3(c) where $\chi_{i,NC}/T_i^{1.5}$ at $E_r = 0$ is also shown for reference. The diffusivities are obviously reduced to almost the same magnitude (about 2-3 orders of magnitude smaller than that for $E_r = 0$), in spite of about 2 times higher T_i in 75235 than that in 75232. It is clearly indicates that ion diffusivity does not increase as T_i is increased due to the presence of predicted ambipolar E_r.

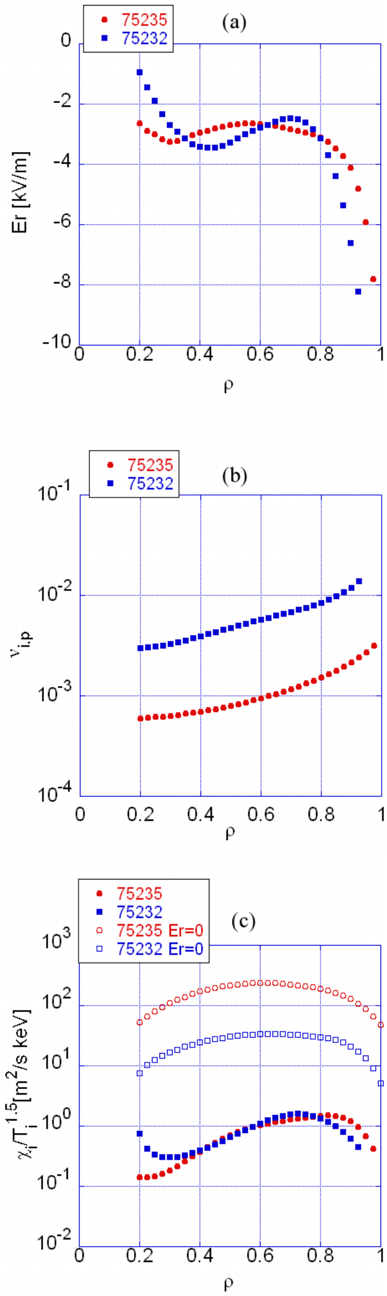

Fig. 3 Radial profiles of (a) ambipolar E_r, (b) ion collisionality with and (c) thermal diffusivities with or without E_r are shown for 75235 and 75232 respectively.

3 Temperature and density scan calculations

Then, in order to investigate the dependence of neoclassical transport on plasma parameters, such as T_i and

n, have been performede based on 75235 and 75232. T_i and n of 75235 and 75232 are widely varied as shown in Fig. 4. $T_i(0)$ of 75235 ($\sim$ 4.8 keV) is multiplied by 0.3, 0.5 and 2, $n(0)$ of 75235 ($\sim$ 1.8 $\times 10^{19}\mathrm{m}^{-3}$) is multiplied by 2, 5, 10, respectively. And then, $T_i(0)$ of 75232 ($\sim$ 3 keV) is multiplied by 0.5, 2, 4, n of 75232 ($\sim$ 3.2 $\times 10^{19}\mathrm{m}^{-3}$) is multiplied by 0.5, 3, 5, respectively. In these calculations, I assumed that magnetic configuration equilibrium is fixed for simplicity, although T_i and n are varied.

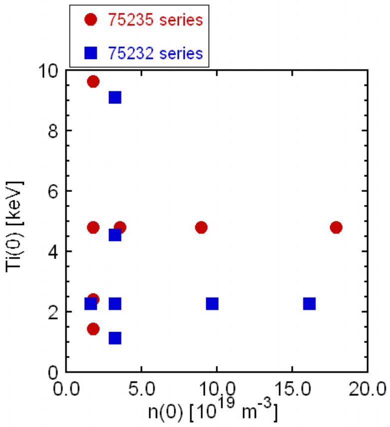

Fig. 4 Range of n and T_i scan calculations based on 75232 and 75235.

The results of parameter scan calculations are summurized in Fig. 5, where $\chi_i/T_i^{1.5}$ is shown for n-scan calculations and χ_i for T_i-scan calculations is shown. χ_i for T_i-scan and $\chi_i/T_i^{1.5}$ for n-scan are reduced to alomost the same extent in all cases. The collisionalities are all in $1/\nu$ regime. In Figs. 5(a) and (b) (n-scan), it is recognized that the neoclassical ion thermal diffusivity at $E_r = 0$ increses as n (thus collisionality) decreased. However, it reduces to almost the same lavel in the presence of ambipolar E_r regardless of the n-value. It is also the case for T_i-scan calculations. As expected, the incease of T_i (thus the decrease of collisionality) makes χ_i larger and lager for cases with $E_r = 0$ as shown in Figs. 5(c) and (d). However, it is reduced to almost the same level in the presence of ambipolar E_r. This fact indicates that the neoclassical χ_i will not increase even for higher-T_i (ranging of 10keV) cases in LHD, due to the presence of ambipolar E_r.

It is interesting to note that, in 75235-T_i scan, not only the ion root but also the electron root is predicted to exist at peripheral region of the plasmas when T_i is decreased (case of 0.3, 0.5 in Fig. 5(d)). It is considered that since the absolute value of electron root is larger than that of ion root, χ_i can be reduced more effectively. The electron root

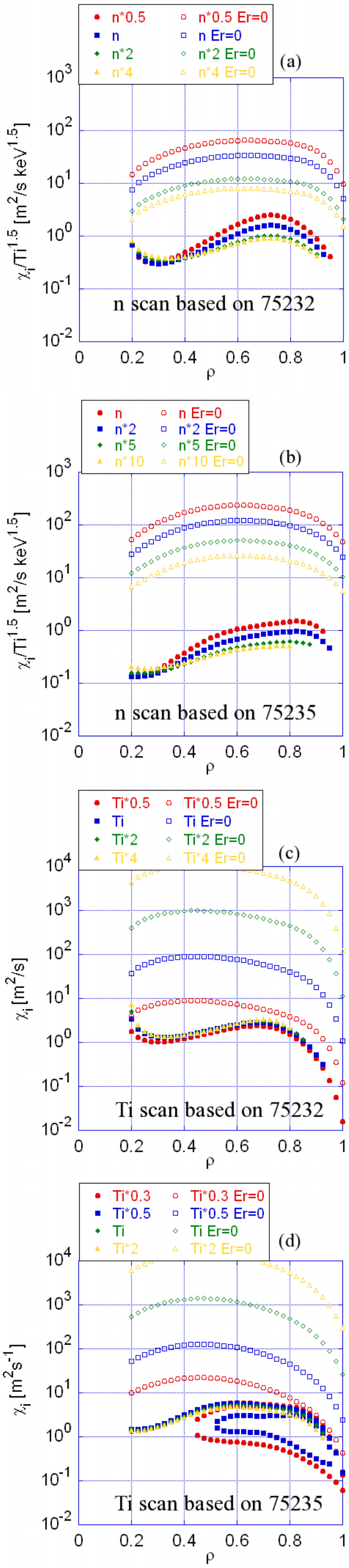

Fig. 5 neoclassical $\chi_i/T_i^{1.5}$ for n scan based on 75232 (a) and 75235 (b), and neoclassical χ_i for T_i scan based on 75232 (c) and 75235 (d) can appear for the case of 0.5 times $T_i(0)$ ($\sim$ 2.4 keV) of 75235 (Fig. 5(d)), but the case of 75232 (Fig. 5(c)), although T_i is almost the same. It should be noted here that T_e has been fixed (T_e is about 3.1 and 3.5 keV for 75232 and 75235, respectively, as shown in Fig. 1). Higher ratio of T_e/T_i for 75235 might help to make the electron root appear.

4 Summury

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

It is clearly demonstrated that ion thermal diffusivity avoids to be increased even with higher-T_i cases due to the predicted ambipolar E_r. It is also the case even for a range of $T_i \sim 10$ keV, which is clalified by parameter scan calculations. This is favorable fact for further increase of T_i in LHD by avoiding the ripple transport nature.

The possibility of the electron-root scenario for high-T_i plasmas is also pointed out by parameter scan calculations. This is interesting topic to be investigated.

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[2] C.D.Beidler *et al.*, Plasma Phys. Control. Fusion. **37** 463 (1995).