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Transition From Ion Root to Electron Root in NBI Heated Plasmas in LHD

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Abstract : Recent Large Helical Device (LHD) experiments revealed that the transition from ion root to electron root occurred for the first in neutral beam heated discharges, where there is no non-thermal electrons exist. The measured values of the radial electric field were found to be in qualitative agreement with those estimated by neoclassical theory. For the configuration with a magnetic axis of 3.75m, where the ion transport loss was comparable to the neoclassical ion loss, a clear reduction of ion thermal diffusivity was observed after the mode transition from ion root to electron root as predicted by neoclassical theory. On the other hand, for the inward shifted configuration (Rax=3.6m), where the neoclassical ion loss is reduced below the anomalous loss, no change in the ion thermal diffusivity was observed.

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1. Introduction

The transition of radial electric field from negative values (ion root) to positive ones (electron root) is theoretically predicted, when the collisionality of plasma becomes low enough in helical plasmas[1]. Associated with the transition from ion root to electron root, a reduction neoclassical transport, especially ion transport, is also expected. However, the transition from ion root to electron root was observed only in plasmas with electron cyclotron heating (ECH), where electron heating is dominant. The ion temperature is much lower than the electron temperature because ions are heated only by the energy exchange between ions and electrons[2-5]. In these experiments, the no improvement of ion transport was observed, because of the lack of direct ion heating. Although the improvement of ion transport namely the reduction of ion thermal diffusivity is expected in the electron root by neoclassical theory, there is no experiment to show the reduction of ion thermal diffusivity due to the transition of ion to electron root. Since the transition from ion root to electron root was observed only in plasmas with ECH, it has been also open to question as to whether the non-thermal electrons driven by ECH are required to achieve the transition. In the Large Helical Device (LHD) the transition from ion root to electron root is observed for the first time in plasmas with neutral beam injection (NBI) heating alone at ta low density of 0.4 – 1.0 x $10^{19}m^{-3}$, where there is non-thermal electrons. Although the more significant improvement of ion transport (rather than the electron transport) is predicted by the neoclassical theory [6], in the temperature range of 1 – 5 keV, there have been no experiments to study the ion transport in the electron root. The ion transport in the electron root is studied in low-density plasma, where the ion transport is decoupled from electron transport.

The Large Helical Device (LHD) [7] is a large Heliotron device (poloidal period number L = 2, and toroidal period number M = 10) with a major radius of 3.6 – 3.75 m, an average minor radius of 0.6 m, magnetic field up to 3 T . The radial electric field (E_r) is derived from the poloidal and toroidal rotation velocity and pressure gradient of Neon impurity measured with charge exchange spectroscopy[8] using a radial force balance. Here the radial electric field is derived from the poloidal and toroidal rotation velocity (v_θ , v_ϕ) and the pressure gradient of Neon impurity is measured with charge exchange spectroscopy at the mid plane in LHD (vertically elongated cross section) using radial force balance equation of $E_r = (en_I Z_I)^{-1}(\partial p_I / \partial r) - (v_\theta B_\phi - v_\phi B_\theta)$, where B_ϕ and B_θ are toroidal and poloidal magnetic field and Z_I, n_I, p_I are ion charge, density and pressure of impurity measured, respectively. The toroidal rotation is damped to less than a few km/s due to the toroidal viscosity, and the effect of diamagnetic drift velocity is also small because of the high ion charge of Neon (Z_I=10). The charge exchange spectroscopy system also gives ion temperature (T_i) profiles. The electron temperature, (T_e) profiles are measured with multi-channel YAG Thomson scattering system[9]. The electron density profiles are measured with an multi-channel FIR laser interferometer[10].

2. Transition from electron root to ion root

The transition from negative electric field to positive electric is observed at the electron densities below 1.0 x 10^{19}m^{-3}. Fig.1 shows the density dependence of the radial electric field near the plasma edge ($\rho = 0.9$) for the configuration with a magnetic axis of 3.75m and that of 3.6m. By shifting the magnetic axis inward, the neoclassical transport is expected to be significantly improved, although the beta limit is expected to be lower in Heliotron configuration[6]. As we discuss later the neoclassical transport loss is predicted to be large enough to exceed the anomalous loss for the configuration with the magnetic axis of 3.75m, while it is relatively small for that of 3.6m. The transition of electron root to ion root is observed at 0.7 x 10^{19}m^{-3} (T_e, = 0.6keVat ρ=0.9) for the plasma with Rax = 3.75m, while it is observed at the lower electron density 0.3 x 10^{19}m^{-3} (T_e = 0.7keVat ρ=0.9) for the plasma with Rax = 3.6m. This is due to the differences in the ratio of edge ion temperature to electron temperature. The ion temperature is 0.5 to 0.9 times of electron temperature at ρ=0.9 for the plasma with R_{ax} = 3.75m, while it is almost the same as the electron temperature for the plasma with R_{ax} = 3.6m. The condition of $T_e > T_i$ causes the transition of ion root to electron root at a higher collisionality in the plasma with a magnetic axis of 3.75m than in the plasma with a magnetic axis of 3.6m.

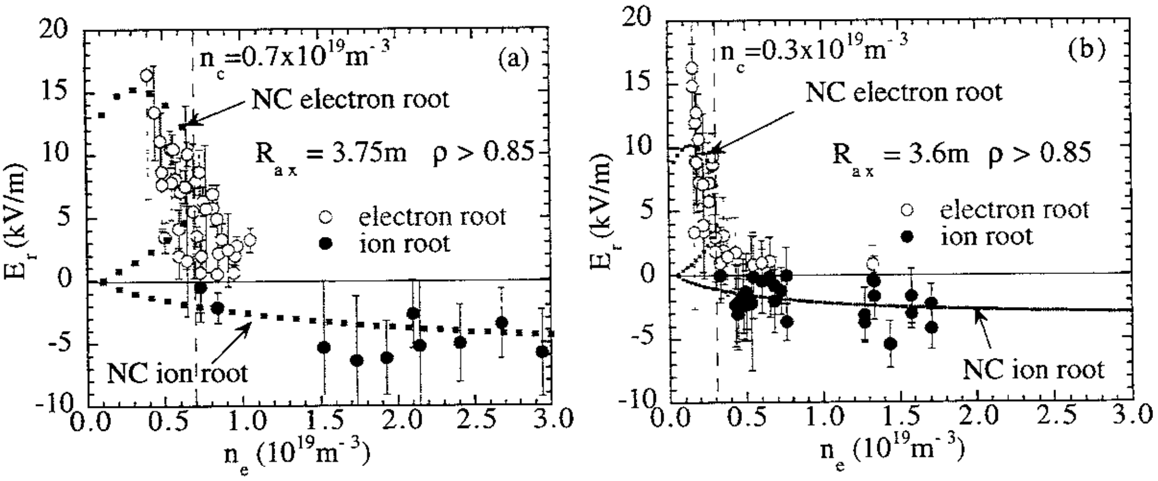

Fig.1 Density dependence of radial electric field at ρ > 0.85 for the plasmas with magnetic axis of 3.75m and 3.6m . The dashed lines in Fig (a) and Fig (b) are neoclassical predictions.

The edge radial electric field sharply increases up to 15 kV/m in the electron root as the electron density is decreased while the absolute values increase gradually up to – 5kV/m in the ion root over a wide range of electron density of 1.0 – 3.0 x10^{19}m^{-3}. The transition from ion root (negative E_r) to electron root (positive E_r) is observed at $\rho > 0.85$ and there is no large radial electric field observed in the plasma core. The behavior of the radial electric field measured can be explained by the neoclassical theory as shown in Fig.1. The absolute values of radial electric field measured in the electron or ion root are the levels predicted by neoclassical theory. The critical electron density required to the transition from electron root to ion root has good agreement with the neoclassical prediction.

3. Radial electric field in the Ion root

The electric field is negative when the electron density is above 1.0 x $10^{19}m^{-3}$ and it becomes more negative as the electron density gradients are increased. The radial electric field in the ion root is typically small and the absolute values are less than 5 kV/m for most discharges (see Fig1). However, a large negative electric field is observed for the discharges with pellet injection.

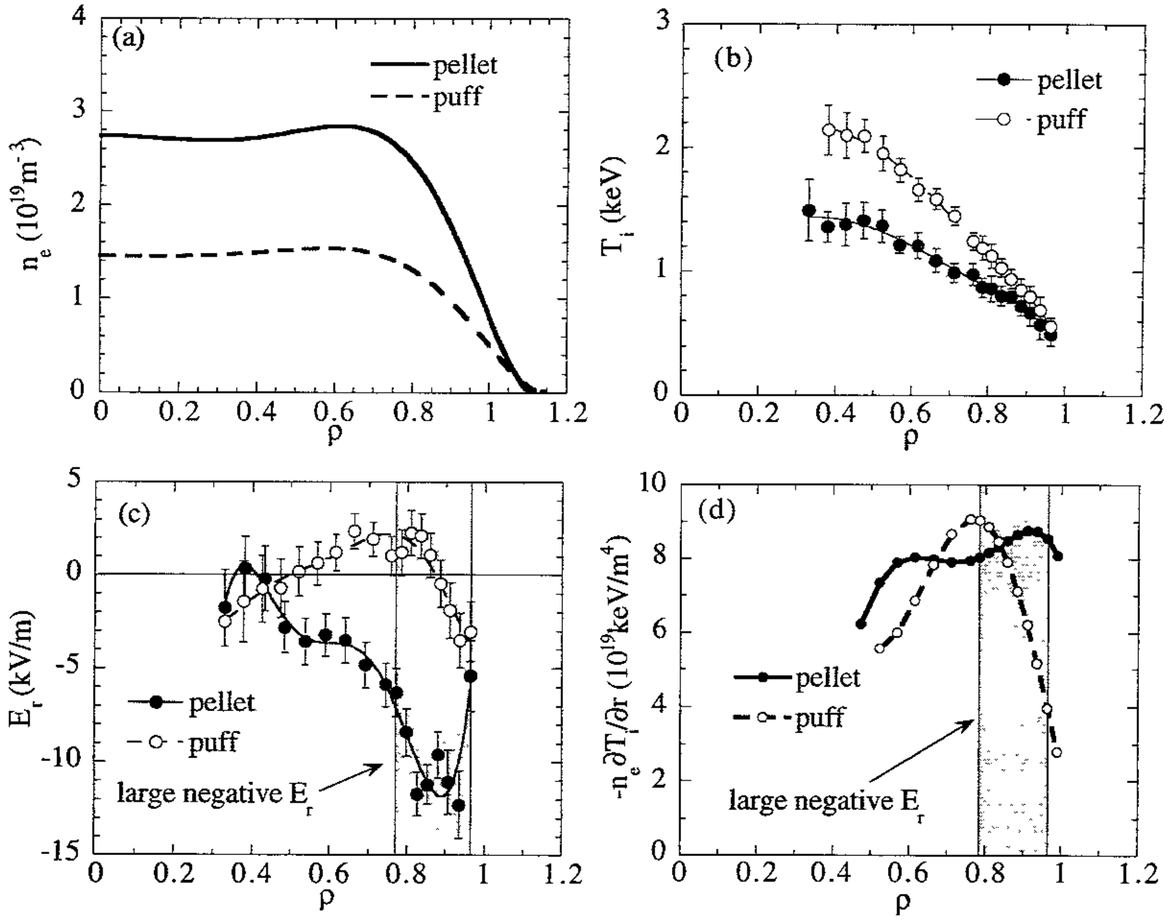

Fig.2 Radial profiles of (a) electron density and (b) ion temperature (c) radial electric field and (d) gradient of ion temperature for the discharges with pellet injection and gas puff for the discharges heated by NBI with the magnetic axis of 3.6m and the magnetic field of 2.75T.

By injecting the ice pellet , where the 1 % Neon is doped for the purpose of diagnostic of charge exchange spectroscopy, the electron density is increased to 3 x $10^{19}m^{-3}$ as shown in Fig.2. The central ion temperature is lower for the discharge with pellet injection because of the higher density, however, the ion temperature gradient near the plasma edge ($\rho > 0.85$) with pellet injection is comparable to that without pellet injection even at higher electron density. This data suggests the improvement of ion transport near the edge with pellet injection. The negative electric field extends to the plasma core range of ρ =0.6, where a sharp density gradient is sustained by the pellet injection. The absolute values of negative electric field reach 10 kV/m at ρ = 0.8 – 0.9 for the discharge with pellet injection. As shown in Fig.2(d) the gradient of ion temperature multiplied by electron density is high even at the plasma edge for the discharge with pellet injection, while it started to decrease toward the edge for the plasma without pellet injection. The improvement of ion transport is observed only near the plasma edge ($\rho > 0.8$), where the large negative electric field is observed.

4. Reduction of ion thermal diffusitiy in the electron root

Figure 3 shows the radial profiles of electron density and temperature and ion temperature and radial electric field. The density profiles in LHD are flat or slightly hollow. The temperature shows an edge pedestal [11] at $\rho > 0.9$ but there is no clear edge pedestal in the ion temperature profiles. As demonstrated in Fig.3, at the transition regime from ion root to electron root, the ion temperature increases associated with the transition as the electron density is decreased, while there is no significant change of electron temperature for the plasma with Rax = 3.75m. On the other hand, the ion temperature slightly decreases as the electron density is decreased for the plasma with $R_{ax} = 3.6$m, regardless of the transition. As shown in Fig.3(d), the radial electric field near the edge changes from negative value (ion root) to positive values (electron root) as the electron density is decreased. The measured radial electric field is compared with that predicted by neoclassical theory. The radial electric field is calculated with the balance of neoclassical ion flux and electron flux using measured electron density, electron temperature and ion temperature profiles[12]. The radial electric field calculated with neoclassical theory in the electron root becomes larger towards the plasma edge as shown in Fig.3(d), which shows qualitative agreement with the measured E_r.

The increase of ion temperature gradient is most significant at $\rho > 0.6$, where the transition from ion root to electron root occurs. The ion temperature gradient increases towards the plasma edge up to 7 keV/m in the electron root, while it is only 2 keV/m in the ion root. It should be noted that the temperature gradient in the ion root in LHD is comparable to that in the L mode (2 – 3 keV/m) and the temperature gradient in the electron root is close to the level observed in the in H-mode discharges (5 – 25 keV/m) and in D-IIID[13]. As shown in Fig. 3 (e), the ion temperature gradient multiplied by electron density in the electron root is twice of that in the ion root, which suggests the improvement of ion transport in the electron root. The transport analysis shows that the ion diffusivity at $\rho = 0.85$ is reduced from 5.5 m^2/s to 2 m^2/s (more than factor of two) associated with the transition from ion root to electron root as shown in Fig.3(f). The beam power deposition profiles are calculated with a three-dimensional Monte Carlo simulation code [14] including orbit loss and charge exchange loss. The reduction of ion thermal diffusivity predicted by neoclassical theory is much larger than that observed. This fact suggests that the anomalous transport is of the order of $2m^2/s$ at the plasma edge. The gradient of radial electric field (Er shear) is 120 kV/m^2 at $\rho = 0.9$ in the electron root and it is not large enough to suppress the anomalous transport. The Er shear required to suppress the fluctuations and to improve electron transport is 350 kV/ m^2 in CHS[4]. Therefore larger E_r shear is expected to be necessary to suppress the fluctuations and improve anomalous transport in the electron root plasma in LHD.

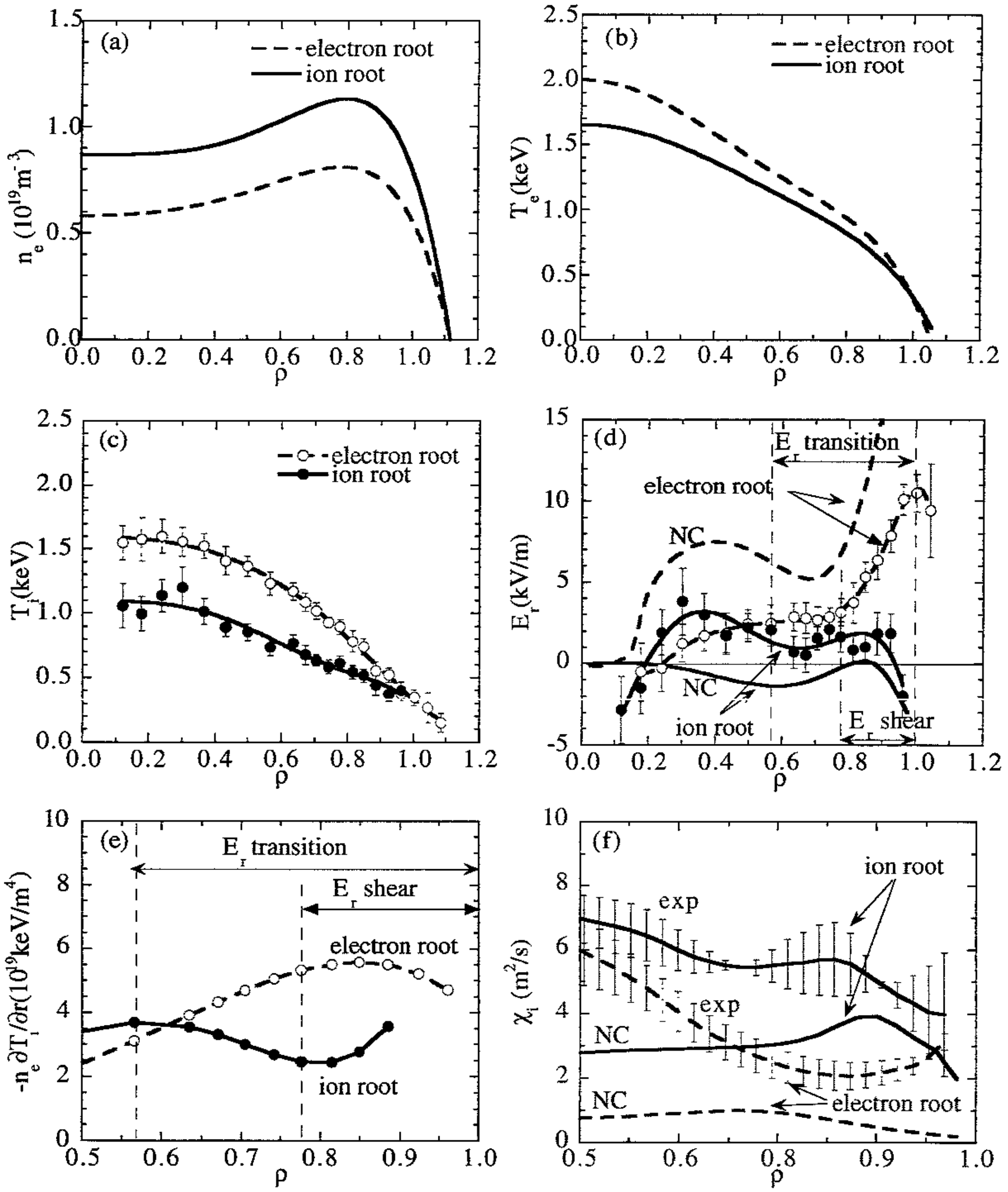

Fig.3 Radial profiles of (a) electron density, (b) electron temperature, (c) ion temperature (d) radial electric field, (e) ion temperature gradient, (f) ion thermal diffusivity for the electron root (closed circles) and ion root (open circles) plasmas. The dashed lines in Fig (d) and Fig (f) are neoclassical predictions.

Figure 4 shows the relation between ion thermal diffusivity and radial electric field near the plasma edge (ρ ~ 0.9) at the density of transition regime ($n_e(0.9) = 0.4 - 1.2 \times 10^{19}\mathrm{m}^{-3}$ for $R_{ax} = 3.75$m and $n_e(0.9) = 0.2 - 0.5 \times 10^{19}\mathrm{m}^{-3}$ for R_{ax}=3.6m). The neoclassical ion thermal diffusivity for the given radial electric field is also calculated. The neoclassical ion thermal diffusivity becomes maximum at zero radial electric field and decreases as the radial electric field increases both for negative and positive Er. Since the absolute values of radial electric field in the electron root are much large than that in the ion root, larger reduction of ion thermal diffusivity is expected in the neoclassical theory. In experiment, in the density regime of transition from ion to electron root, the absolute values of radial electric field in the ion root are only 1 -3 kV/m, while they increase sharply up to 10 kV/m in the electron root.

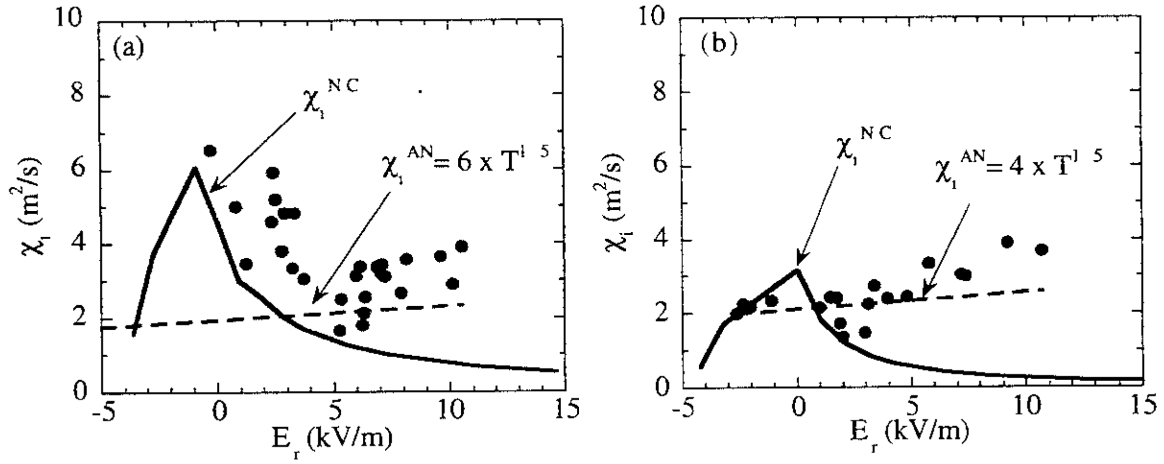

Fig 4. Ion thermal diffusivity as a function of radial electric field at $\rho = 0.92$ for the plasmas with magnetic axis of (a)3.75m and (b)3.6m. The solid lines are prediction by neoclassical theory, while the dahsed lines are anomalous levels using a dtemperature dependence of $T^{1.5}$

The reduction of ion thermal diffusivity sharply decreases as the positive electric field increases after the transition from ion root to electron root in the plasma with R_{ax} = 3.75m, which qualitatively agrees with the prediction from neoclassical theory. Once the neoclassical ion diffusivity decreases below the anomalous levels (~ 2 m^2/s), there is no reduction of ion thermal diffusivity observed. On the other hand, the reduction of ion thermal diffusivity associated with the transition from ion root to electron root is not observed in the plasma with R_{ax} = 3.6m, where the neoclassical ion diffusivity is lower. The ion thermal diffusivity slightly increases as the radial electric field is increased after the neoclassical ion thermal diffusivity decreases below the anomalous levels (~ 2 m^2/s). This is because the temperature slightly increases as the radial electric field becomes more positive in the electron root. We assume the ion thermal diffusivity has the temperature dependence of $\chi_i \propto T^{1.5}$, where $T = (T_e + T_i)/2$, based on the LHD scaling for the glocal energy confinement time ($\tau_E \propto P^{-0.6}$, where P is absobed power) [15]. The anomalous ion thermal diffusivities is scaled as $\chi_i \propto T^{1.5}$ in order to compare the anomalous levels for those two configurations that have differenct temperature. As shown in Fig.4, the levels of anomalous ion thermal diffusivity required to explain the ion thermal diffusivity measured, are 6 x $T^{1.5}$ m^2/s, where T is in the unit of keV, for the plasma with R_{ax} = 3.75m B=1.5T and 4 x $T^{1.5}$m^2/s for the plasma with R_{ax} = 3.6m B=2.5T. The coefficient of anomalous ion thermal diffusivities are determined by the best fit of $T^{1.5}$ curves to the experimental anomalous values, that are given by subtracting neocalsical values from measured ion thermal diffusivities, in the range of radial electric field from 2 kV/m to 11 kV/m, where the neoclassical transport is less dominant than the anomalous transport. The coefficient for the plasma with R_{ax} = 3.6m B=2.5T is smaller than that for the plasma with R_{ax} = 3.75m B=1.5T, which is because the ion transport is improved by the higher magnetic field and the inward shift of magnetic axis.

5. Discussions

The reduction of ion thermal diffusivity in the electron root observed in LHD support the validity of the concept for the stellarator configuration, where the helical ripple loss is suppressed by the radial electric field even in the low collisionality regime. The anomalous transport near the edge is comparable or even smaller than that observed in L-mode plasmas ($\chi_i = 3 - 10\ m^2/s$) in tokamaks[16]. In order to suppress the anomalous transport, the E_r shear (not just E_r) should be produced similar to that in the transport barrier in tokamak plasmas.

The neoclassical prediction used in this paper is based on the conventional ambipolarity condition of the local particle fluxes, that do not include the fluxes due to viscosity or high energy particles. Since the plasma is sustained only by the NBI heating, there is no non-thermal electrons. However, high energy ions in the direction parallel to the magnetic field exist in the plasma. In general, the high energy ions contributes to the bipolar ion loss and tends to prevent the transition from ion root to electron root. In experiment, the transition is observed at the electron density, where the simple neoclassical theory predict. This fact suggests that the ripple loss of high energy ions in LHD is too small to affect the radial electric field.

In order to make a definite comparison of radial electric field and ion thermal diffusivity between the measurements and neoclassical theory, the Monte Carlo technique[17], which would be the appropriate approach to solve the Fokker-Planck equation, should be applied. In this paper the prediction by neoclassical theory is given as a reference to explain the experimental results and the definite comparison between the measurements and theory is out of scope of this paper.

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