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Transport Barrier Analysis of LHD Plasmas in Comparison with Neoclassical Models

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Abstract

In the local Electron Cyclotron Heating (ECH) experiments, high electron temperature plasmas have been obtained in Compact Helical System (CHS), and recently in the Large Helical Device (LHD). The internal transport barrier (ITB) with strong positive radial electric field has been experimentally observed in CHS, which reduces neo-classical ripple transport and anomalous transport losses. The same physics pictures are expected in LHD high temperature plasmas. Several ion temperature profiles are assumed for analyzing LHD experimental data, and it is found that the experimentally obtained electron thermal transport coefficients seem to roughly agree with neoclassical ripple transport outside the ITB region. However, around ITB region, about ten times higher than the neoclassical coefficients with strong ambipolar electric field prediction are obtained. The anomalous transport losses might be dominant and be reduced by this strong electric field shear around the ITB region.

Keywords:

internal transport barrier, radial electric field, neoclassical confinement, transport code simulation, helical system, LHD

1. Introduction

In the helical plasma confinement systems, the neoclassical ripple transport is supposed to be serious in the high temperature reactor regime. The strong electric field can be utilized for improving the plasma confinement in addition to the transport optimization by changing magnetic field configurations. High central electron temperature plasmas with positive electric potential have been obtained in the centrally focused Electron Cyclotron Heating (ECH) experiment of the Compact Helical System (CHS) [1]. The formation of this internal transport barrier (ITB) is correlated with the reduction of density fluctuation and the shear of electric field. In CHS it was found that the ITB is related to neoclassical positive electric field in the low-density regime [1]. Recently in the Large Helical Device (LHD) we have obtained a ten keV electron temperature plasma using centrally focused Gaussian beam at the fundamental and second harmonic resonances [2]. The threshold on the appearance of ITB in LHD is related to the plasma density and the heating power.

Here, LHD transport analyses using experimentally obtained radial profiles are described focusing on neoclassical transports with radial electric field effects. The ion temperature profile effects on electron confinement are also clarified.

2. Transport Barrier Formation in LHD

In the fifth campaign of the LHD experiment, the hot electron temperature operations have been performed using ~ 1 MW ECH heating power [2].

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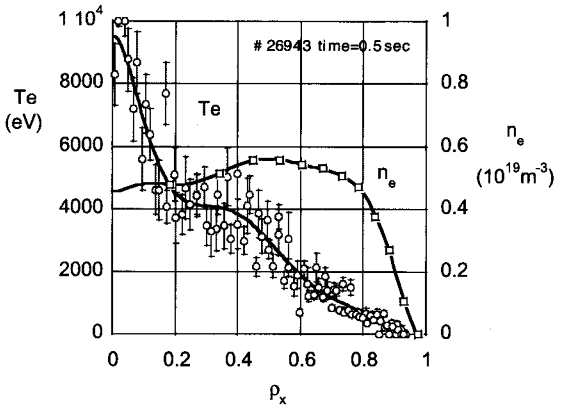

Fig. 1 Experimental profiles of electron temperature and density obtained in LHD.

Figure 1 shows the electron temperature and density profile measured by 200-channel YAG Thomson scattering system [3] and 11-channel FIR interferometer [4]. The density profile was obtained by the Abel inversion method with 3-dimentional self-consistent equilibrium calculated by using extended radial magnetic coordinates ρ_x to treat with ergodic regions in the PRE-TOTAL code. The radial coordinate normalized by plasma surface boundary, $\rho_p \equiv \rho_x/1.1$, is also utilized. The central ion temperature is measured by the crystal spectrometer measurement, and the plasma equilibrium is calculated by assuming ion temperature profile. In this discharge the positions of estimated rational surfaces are ρ_x = 0.4 (m=2/n=1) and ρ_x = 0.8 (m=1/n=1).

In order to identify the existence of the internal transport barrier (ITB), it is necessary to calculate the thermal diffusivity and to clarify which is a dominant effect to produce ITB, the heating deposition profile effect or plasma transport improvement effect. In tokamaks, the box-type temperature profile often can be seen in reversed-shear tokamaks and the parabola-type ITB is obtained in the normal shear operations. In LHD sharp peaked electron temperature profiles are obtained, which is related to central heating scheme but not due to the direct effects of strong central power deposition. For clarifying this point and comparing with neoclassical predictions, we have carried out 3D equilibrium/1D transport data analysis using TOTAL code [5].

3. Model of Transport Analysis

The steady-state transport equations solved here are as follows:

$$\frac{3}{2}\frac{\partial}{\partial\rho}\left(n_e T_e\right) = -\frac{1}{V'}\frac{\partial}{\partial\rho}(V'Q_e) + P_{in\_e}(\rho) = 0$$

$$\frac{3}{2}\frac{\partial}{\partial\rho}\left(n_e T_i\right) = -\frac{1}{V'}\frac{\partial}{\partial\rho}(V'Q_i) + P_{in\_i}(\rho) = 0\,. \quad (1)$$

The heat flux is a summation of neoclassical symmetric term Q_{sym} (Hazeltine-Hinton (HH) formulus for electron and Chang-Hinton (CH) formulus for ion), neoclassical ripple term Q_{rip} and anomalous transport term Q_{anom}:

$$Q_k \equiv Q_{sym\_k} + Q_{rip\_k} + Q_{anom\_k} \quad (k = e, i) \qquad (2)$$

Here, the effective ripple diffusivities, χ_{ripple_e} and χ_{ripple_i}, are defined as

$$\begin{aligned} Q_{rip\_k} &= -\chi_{1\_k}\left[T_k\left\langle(\nabla\rho)^2\right\rangle\frac{\partial n_e}{\partial\rho} - n_e E_\rho\right] \\ &\quad - \chi_{2\_k} n_e\left\langle(\nabla\rho)^2\right\rangle\frac{\partial T_k}{\partial\rho} \\ &\equiv -\chi_{ripple\_k} n_e\left\langle(\nabla\rho)^2\right\rangle\frac{\partial T_k}{\partial\rho} \quad (k = e, i) \end{aligned} \qquad (3)$$

with neoclassical ripple coefficients χ_1 and χ_2. The helical magnetic field harmonics and self-consistent radial electric field effects are included [5]. The total neo-classical transport coefficients are obtained by

$$\begin{aligned} \chi_{nc\_e} &\equiv \chi_{HH\_e} + \chi_{ripple\_e} \\ \chi_{nc\_i} &\equiv \chi_{CH\_i} + \chi_{ripple\_i}\,. \end{aligned} \qquad (4)$$

These values are compared with the following effective experimental transport coefficients $\chi_{\exp}$,

$$\begin{aligned} \chi_{\exp\_e} &\equiv -\frac{Q_{in\_e}}{n_e\left\langle(\nabla\rho)^2\right\rangle\frac{\partial T_e}{\partial\rho}} \\ \chi_{\exp\_i} &\equiv -\frac{Q_{in\_i}}{n_e\left\langle(\nabla\rho)^2\right\rangle\frac{\partial T_i}{\partial\rho}}\,. \end{aligned} \qquad (5)$$

The ECH power deposition is modeled by the following power localization to the central region with the width of ρ_{wid}=0.1:

$$P_{ECH}(\rho) \propto \frac{1}{\exp\left[\{\rho/\rho_{wid}\}^4\right]}\,, \qquad (6)$$

which roughly agrees with the results of the ray-tracing analysis.

The high electron temperature can be expected in the case of centrally focused ECH experiment. Related to the ITB shot of Fig. 1, the following five cases have been analyzed; (1) full simulation with empirical and neoclassical transport models without using experimental profile data, (2) experimental density profile is used, (3) experimental density (n_e) and electron temperature (T_e) profiles are used, (4) experimental density and temperature profiles are used and ion temperature (T_i) profile with experimental central value is assumed, and (5) drift wave model full simulation. We found that the electron temperature critically depend on ECH central power deposition profile and electron density profile. In this paper, the data analysis with experimental n_e and T_e data and the modeled T_i profile (case (4)) is focused as shown in the next chapter. Other simulation results will be reported somewhere in the future.

4. Experimental Data Analysis in Comparison with Neoclassical Theory

In order to get electron and ion transport coefficients, the parabolic T_i profile with experimental central value T_{i0} is assumed.

$$T = T_{i0}(1-\rho^{2l})^m \ .$$

Three cases were analyzed; (1) reference parabolic case (l=1,m=2), (2) flat case (l=2,m=2), and (3) peaked case (l=1,m=4). We obtained experimental transport coefficients denoted as "Exp" as shown in Fig. 2 in the case of reference-T_i profile. The neoclassical value (NC) is a summation of axi-symmetric coefficient (NC(HH) for electroin or NC(CH) for ion) and ripple transport coefficient (NC(ripple)). The transport coefficient with zero ambipolar potential is also plotted as "NC(E=0)". The experimental transport coefficient near ITB (ρ_p ~ 0.2) obtained here seem to be one order of magnitude higher than the neoclassical value (HH plus ripple transport for electron, CH plus ripple transport for ion). The strong positive radial electric field ("electron root") in the center has been predicted by the analysis. The negative electric field region ("ion root") is obtained outside the central region (ρ_p > 0.4). The radial profile shape of zero-potential transport coefficient does not fit the experimental value for both electron and ion. The reduc-

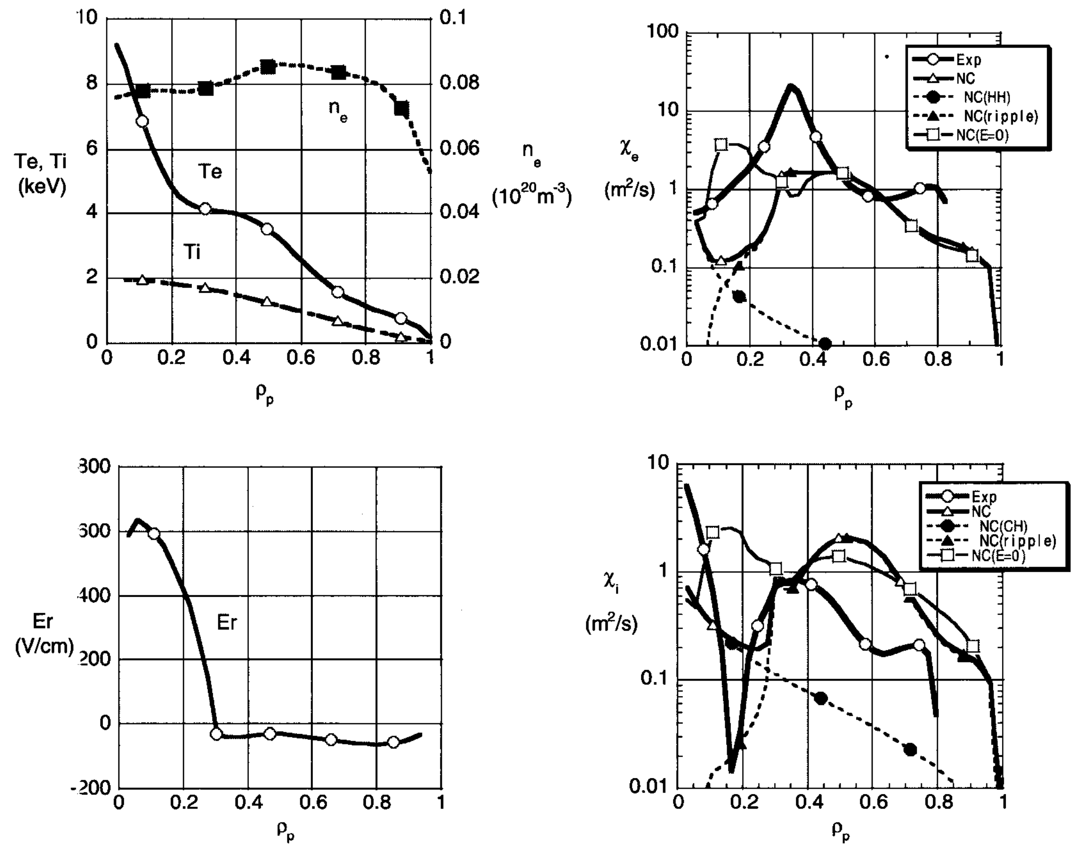

Fig. 2 Transport analysis using experimental n_e and T_e profiles and assumed parabolic ion temperature T_i profile. The radial electric field E_r, electron diffusivities χ_e and ion diffusivities χ_i are shown.

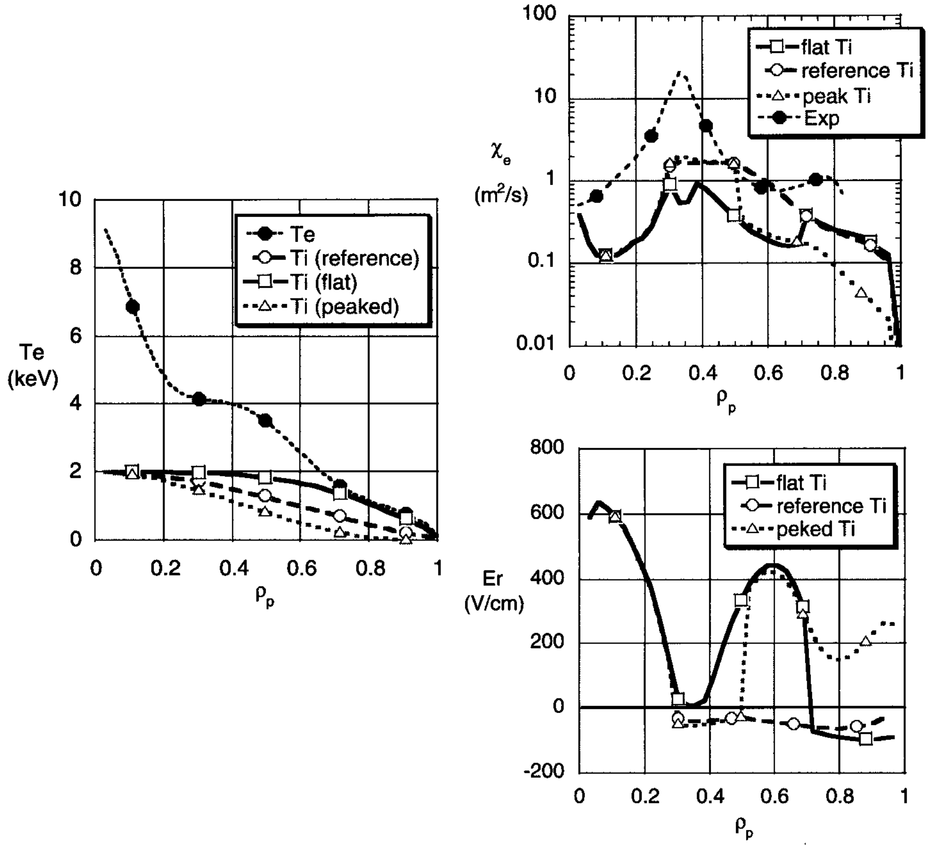

Fig. 3 Effect of ion temperature T_i profile on electron diffusivities χ_e and radial electric field E_r. The reference T_i profile is parabolic.

tion in thermal electron diffusivity is obtained by adding radial electric field effects in the neoclassical analysis, but the absolute transport value is one order of magnitude less than the experimental value. The anomalous loss might be dominant near the central and ITB region. Outside ITB ($\rho_p \sim 0.5$) the transport coefficient is on the same level of the neoclassical value, but the transport is also anomalous near the plasma surface ($\rho_p \sim 0.8$).

The effect of ion temperature profile on the electron diffusivity is shown in Fig. 3. The change in ion temperature profile gives rise to the change in the production of positive electric field. The central region ($\rho_p < 0.3$) is always in the "electron root" regime and its transport coefficient does not strongly depend on the ion temperature profile. The experimental transport coefficient near ITB is one order of magnitude higher than the neoclassical value. On the other hand, outside the central region ($\rho_p > 0.4$) the strong positive electric field has been obtained in flat and peaked T_i cases, and the neoclassical transport coefficients are reduced by this electric field. The edge transport also cannot be explained by the neoclassical vales.

More detailed analysis should be carried out by comparing with experimental radial electric potential and ion temperature profiles which will be obtained in the near future experiment.

5. Summary and Discussion

Several experimental data analyses have been carried out for high electron temperature discharges in LHD electron cyclotron heating experiments, and came to the following conclusions;

(1) The thermal diffusivities of the hot electron temperature discharges in LHD have been obtained and compared with the neoclassical values.

(2) The prediction of radial electric field production by the neoclassical theory strongly depends on the assumed ion temperature profile. However, the central region is not sensitive to the ion temperature profile.

(3) Experimentally obtained transport coefficients roughly agree with neoclassical values at normalized radius $\rho_p \sim 0.5$, however around $\rho_p \sim$ 0.2 (ITB region) they are several or ten times

higher than the neoclassical vale. The anomalous transport might be dominant around here and be reduced by the strong electric field shear.

More precise analyses should be continued for LHD in comparison with CHS, using additional future experimental data such as electric potential profile, ion temperature profile, density and power scan data, and so on. The anomalous transport model simulation with strong electric field shear will be given somewhere in the future.

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