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Radial Electric Field Effects on Experimental and Theoretical Transport Analysis in LHD

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Abstract

Transport analysis code PRE-TOTAL & TOTAL (Toroidal Transport Analysis Linkage) with 3-dimentional equilibrium fitted with experimental values on real coordinate are developed, and has been applied to the Large Helical Device (LHD) experiment. Neoclassical transport analysis on LHD with self-consist ambipolar radial electric field and multi-helicity effects, has been carried out and the rough agreement with experimental data is obtained, especially in the case of outward shifted, high ripple transport. The radial electric field strongly reduces neoclassical ion thermal diffusivity, which is consistent with experimental observations so far. The anomalous transport analysis based on the multi-mode drift-wave model has also been carried out, and the coefficient related to the saturation amplitude is one order smaller than the previous analysis result on the smaller machine Compact Helical System (CHS).

Keywords:

neoclassical ripple transport, radial electric field, transport code, helical system, LHD

1. Introduction

Helical plasma confinement system has a remarkable advantage in confining steady-state high-performance plasmas. Intrinsic features of this concept have been demonstrated successfully in the Large Helical Device (LHD) [1]. Helical system has three-dimensional configuration, which requires elaborate data-fitting method and equilibrium-reconstruction technique for the detailed transport analysis. The three-dimensional equilibrium and one-dimensional radial transport code TOTAL (Toroidal Transport Analysis Linkage) [2,3] was developed and applied to LHD experimental analysis, and has clarified strong gyro-Bohm-like transport properties of LHD plasmas [4,5]. The newly derived confinement scaling laws (New LHD scaling laws) have been used for the extrapolation to the future reactors, and the effectiveness of previous Heliotron reactor designs has been verified [6]. In this paper, theoretical modeling is compared with LHD experimental data, focusing on radial electric field effects on neoclassical transport and taking multi-mode drift-wave turbulent transport into account as anomalous transport models.

2. Equilibrium and Transport Codes Including Radial Electric Field

Transport analysis is required for two purposes; experimental data analysis and theoretical prediction simulation. For both purposes a 3-dimensional

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equilibrium / 1-dimensional transport code TOTAL (Fig. 1) was developed based on the previous predictive HSTR (Helical System Transport) code [2]. By adding experimental data interface code PRE-TOTAL, it has been extended to the experimental data analysis code, and applied to the transient and quasi-steady experimental transport data analyses on LHD [3]. This code is characterized by 3-dimentional self-consistent equilibrium with experimental density and temperature profile data, neoclassical transport including magnetic multiple-helicity and radial electric effects, time-varying NBI deposition profile analysis, bootstrap current effects on equilibrium-transport, and so on. The self-consistent equilibrium has been treated with measured radial profiles by 11-channel FIR laser density measurements [7] and 120-channel YAG Thomson scattering electron temperature measurements [8]. Ion temperature is measured by charge-exchange spectroscopy [9] and the radiation power loss from the plasma was measured by the bolometric measurement [10].

3. Global and Local Confinement Scaling Analysis

The global confinement time of NBI-heated LHD plasmas is defined here by measured plasma kinetic energy and deposited power calculated using the TOTAL code. The global confinement of LHD is 1.5~2.0 times better than the previous scaling laws, and new four "New LHD" scaling laws (dimensional or non-dimensional analyses using only Heliotron-type or all helical devices) are derived [6]. These scaling laws suggested the strong gyro-Bohm like features, which is different from previous scaling laws [11] based on medium-sized devices.

Local transport analysis has also been carried out and the effective thermal diffusivity $\chi_{\rm eff}$ is defined as

$$\chi_{\rm eff} = -\,[Q_{\rm NBI} - {\rm d}W/{\rm d}t] \,/\, [n{\rm d}(T{\rm i}+T{\rm e})/{\rm d}r],$$

$$W = (3/2) \int n\,(T{\rm i}+T{\rm e}){\rm d}V,$$

$$T{\rm i}(r) \propto T{\rm e}(r).$$

to avoid the uncertainty of ion temperature. Here, we

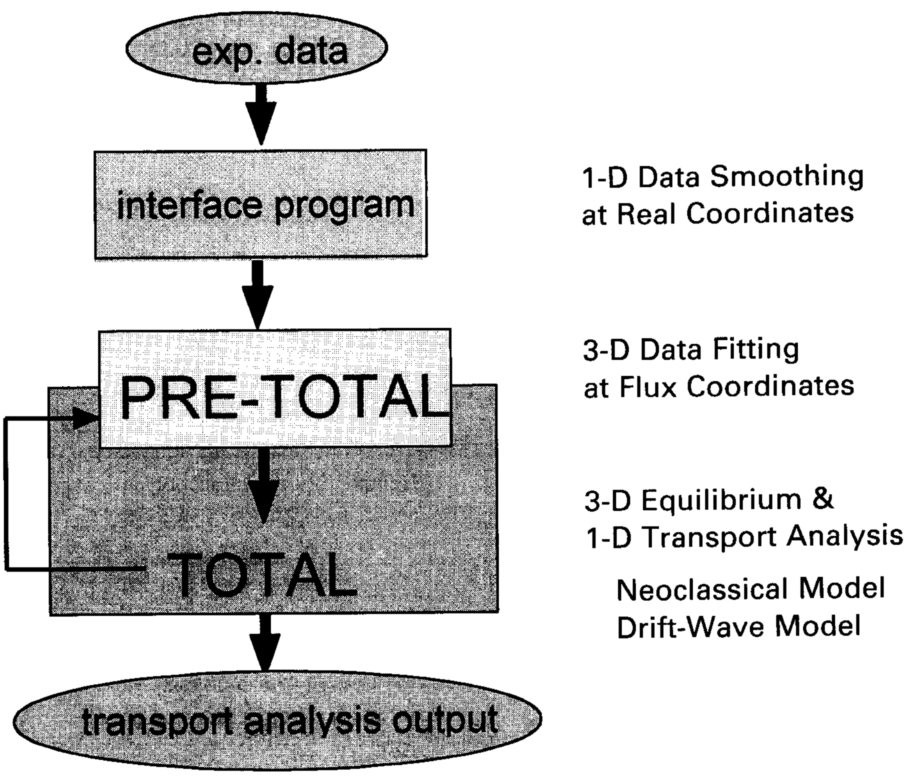

Fig. 1 Flowchart of TOTAL (Toroidal Transport Analysis Linkage) code.

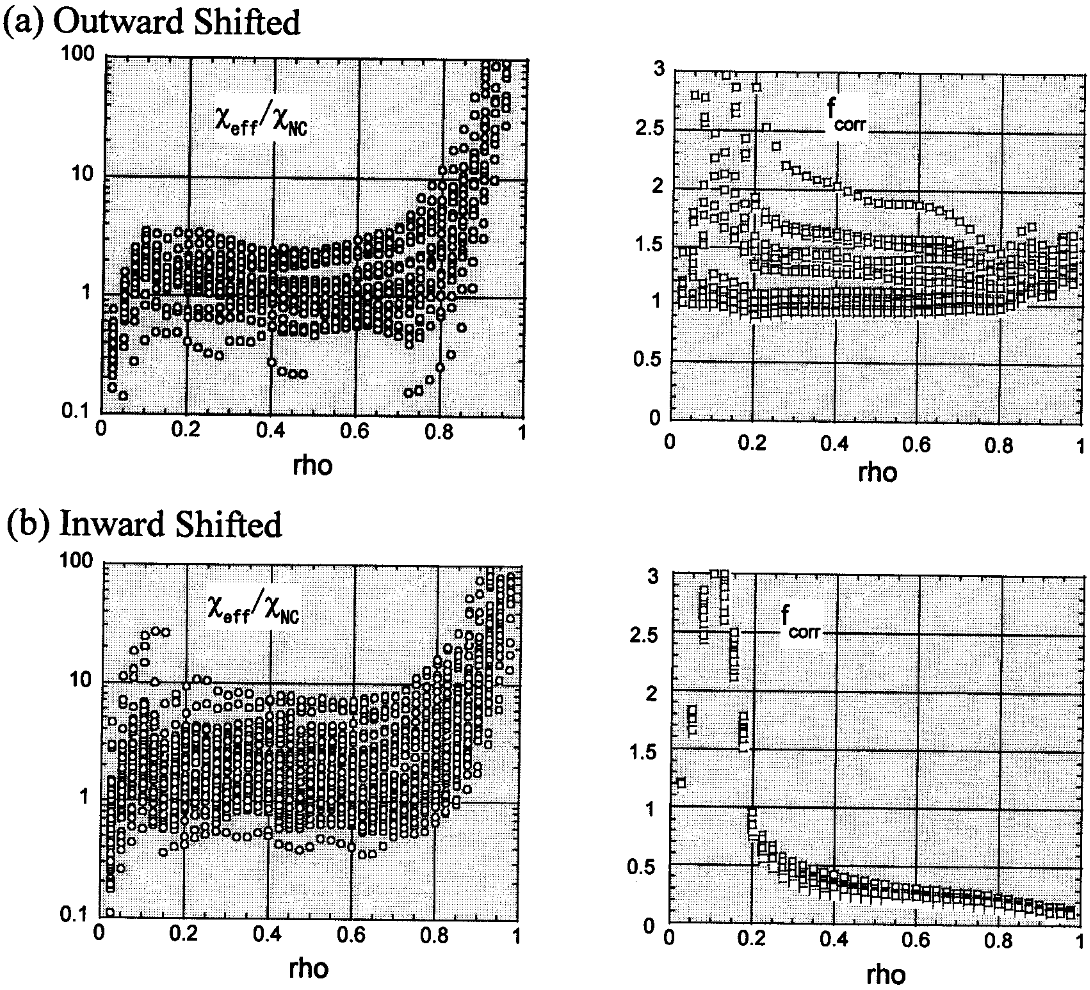

Fig. 2 Comparisons with neoclassical transport and experimental values for a variety of LHD discharges. (a) Outward-shifted case ($R > 3.7$ m) and (b) Inward-shifted case ($R < 3.7$ m). The values f_{corr} is correction factor of multi-helicity effect on thermal diffusivity normalized by single helicity one. Here, rho = 1 corresponds to plasma radius a = 0.69 cm (case a) and 0.68 cm (case b).

use the following dimensionally normalized scaling:

$$\chi_E/(Ba^2) \sim 10^{c}\rho_*^{\,c_\rho}\nu_{0*}^{\,c_\nu}\beta^{c_\beta},$$

Here, B, a, ρ_*, ν_{0*} and β are magnetic field strength, plasma minor radius, normalized gyro-radius, collisionality parameter and plasma beta value, respectively. The exponents of each parameter are obtained as a function of normalized minor radius rho by regression analysis. It is found that the radial distribution is weak gyro-Bohm-like in the core and strong gyro-Bohm-like near the boundary. The global confinement feature is qualitatively consistent with strong gyro-Bohm-like local transport coefficient near the edge region [5,6]. More elaborate analysis will be required to clarify this physics in the future.

4. Neoclassical Transport Analysis

Figure 2 shows a set of the diffusivities normalized by the neoclassical values for more than 50 discharges. The effective thermal diffusivity is same order of magnitude of effective neoclassical transport with the assumption of $Ti = Te$, especially agrees with them in the case of outward shifted case ($R > 3.7$ m) as shown in Fig. 2(a). On the contrary, experimentally obtained thermal diffusivity is several times higher on average than the predicted neoclassical value (Fig. 2(b)). Here, the correction factors f_{corr} of multi-helicity effect on thermal diffusivity normalized by single helicity case are shown in the right-hand side. This multi-helicity

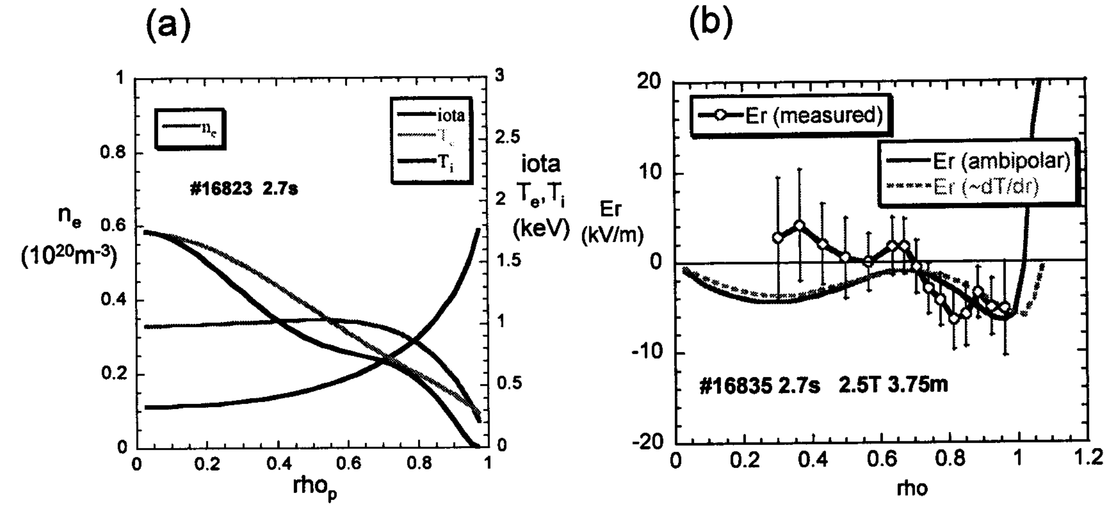

Fig. 3 (a) Density and temperature profiles and (b) experimental and theoretical radial electric field strength.

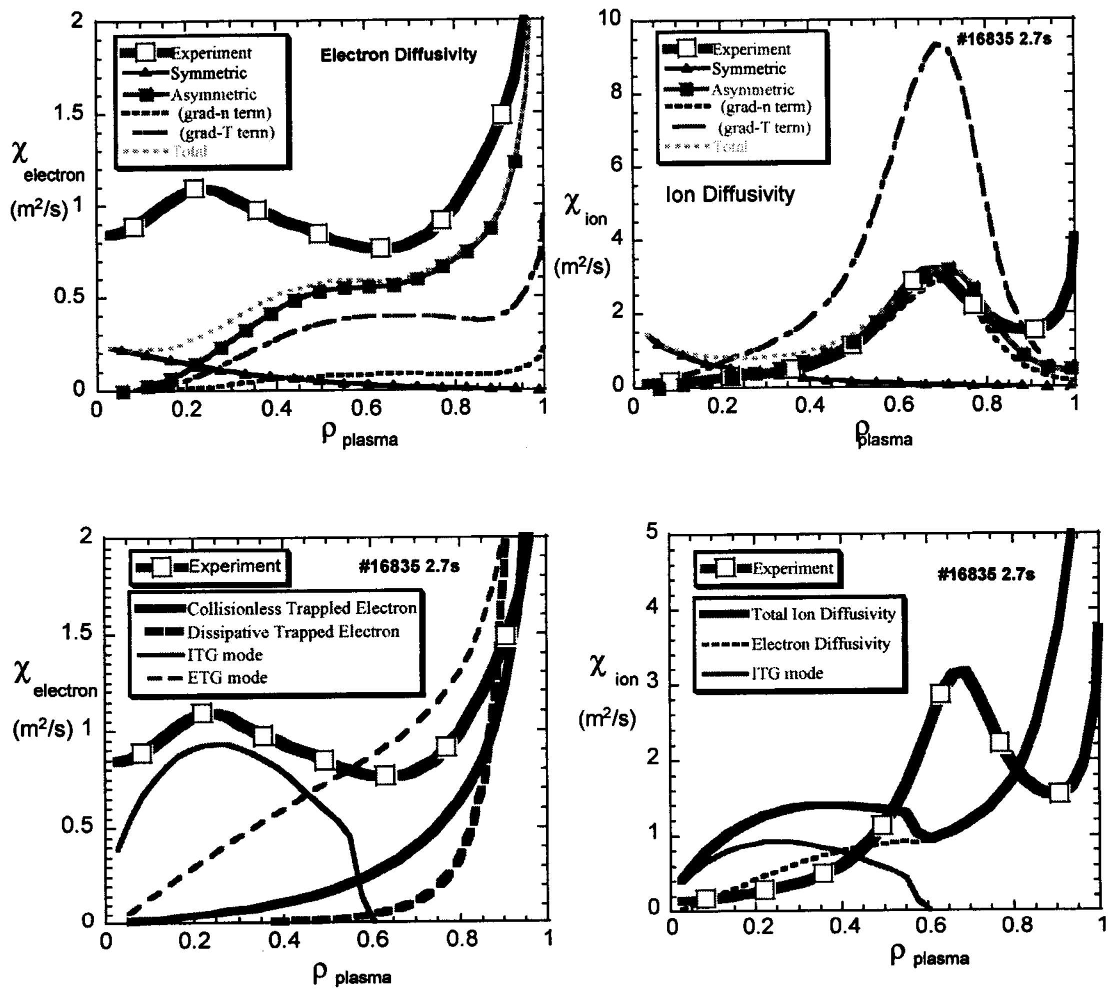

Fig. 4 Evaluation of neoclassical transport (upper) and multimode drift wave transport (lower) compared with experimental values. Left and right figures correspond to electron and ion diffusivities.

effect on neoclassical transport cannot be neglected in the LHD configurations. Almost all data in this figure are in the ion-root negative-electric-field regime. The radial electric field has been measured by the charge-exchange spectroscopy [9] as shown in Fig. 3, which shows rough agreement between experimental value and theoretical values. Here, electric field is nearly zero around rho ~ 0.6, which is related to ion temperature gradient. In this figure, a simple estimation of electric field potential proportional to plasma temperature is also shown by broken line in addition to self-consistent ambipolar electric field (solid line).

The typical electron and ion diffusivities derived with measured electron and ion temperature profiles are plotted in Fig. 4 (upper figures) in the case of R = 3.75 m, B = 2.5 T. Symmetric and asymmetric (∇n and ∇T) parts of neoclassical transport coefficients using self-consistent ambipolar electric field are shown in this figure. The experimental electron thermal diffusivity is greater than the neoclassical value (upper left figure), however ion diffusivity roughly agrees with neoclassical value (upper right) in this typical case of R = 3.75 m. More detailed analyses including experimental errors are required to get final conclusions.

5. Multi-mode Anomalous Transport Analysis

In addition to neoclassical model, theoretical multi-mode turbulence models (universal drift wave, dissipative trapped electron mode, collisionless trapped electron mode, η_i mode, η_e mode, Fluid Turbulence and so on) are evaluated. The transport coefficients used here are described in ref. [2]. The lower part of Fig. 4 shows that the drift wave turbulence model roughly agrees with measured electron thermal diffusivity (lower left), and neoclassical model agrees with ion diffusivities (upper right). Here, it should be noted that the coefficient fitted to LHD data, which is related to the mode saturation amplitude, is one order of magnitude smaller than the previous analysis of the smaller device Compact Helical System (CHS) [2].

6. Summary

In order to clarify the physics of helical plasma confinement, the experimental and theoretical comparisons on the Large Helical Device (LHD) have been performed, and we came to the following conclusions focusing on radial electric field:

(1) We developed 2.0-D transport analysis code PRE-TOTAL & TOTAL (Toroidal Transport Analysis Linkage) with 3-dimentional equilibrium fitted with experimental value on real coordinate, and has been applied to the LHD experiment. The effectiveness of this code has been verified.

(2) Neoclassical transport analysis on LHD with self-consist ambipolar radial electric field and multi-helicity effects, has been carried out, and the rough agreement with experimental data is obtained, especially in the case of the R = 3.75 m case.

(3) The electric field strongly reduces neoclassical ion thermal conductivity, which is consistent with experimental observations so far.

(4) The anomalous transport analysis based on the multi-mode drift-wave model has been carried out, and the coefficient related to the saturation amplitude is one order smaller than the previous analysis on the smaller machine Compact Helical System (CHS).

References

[1] M. Fujiwara *et al.*, *IAEA Fusion Energy Conference* (Sorrento, 2000) OV1/4.

[2] K. Yamazaki and T. Amano, Nucl. Fusion **32**, 633 (1992).

[3] K. Yamazaki *et al.*, J. Plasma Fusion Res. SERIES **2**, 125 (1999).

[4] K. Yamazaki *et al.*, *Proc. 26th EPS Conference* (Maastrich, 1999) P3.107.

[5] H. Yamada *et al.*, *IAEA Fusion Energy Conference* (Sorrento, 2000) OV1/4.

[6] K. Yamazaki *et al.*, *IAEA Fusion Energy Conference* (Sorrento, 2000) FP2/12.

[7] K. Kawahata *et al.*, Rev. Sci. Instrum. **70**, 1, p.707 (1999); K. Tanaka *et al.*, *Proc. 26th EPS Conference* (Maastricht, 1999) P3.101.

[8] K. Narihara *et al.*, *IAEA Fusion Energy Conference* (Sorrento, 2000) EXP5/28.

[9] K. Ida *et al.*, *IAEA Fusion Energy Conference* (Sorrento, 2000) EX9/4.

[10] B. Peterson *et al.*, *IAEA Fusion Energy Conference* (Sorrento, 2000) EXP5/27.

[11] U. Stroth *et al.*, Nucl. Fusion **36**, 1063 (1996).