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Dimensionless Transport Analysis on Plasma Radial Profiles in LHD

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Abstract

For the confinement data analysis of Large Helical Device (LHD), the PRE-TOTAL code is developed for the Toroidal Transport Analysis Code TOTAL. Several new scaling laws are derived using LHD data and medium helical system data, mainly based on dimensionless regression analysis. The global confinement is strongly gyro-Bohm-like. Using same database, the radial profile of diffusion coefficients are obtained, and it is found that the local transport in the core is weakly gyro-Bohm-like, and near the boundary it is strongly gyro-Bohm-like. The global confinement feature is consistent with edge-region transport coefficient. These new scaling laws can be used for the design of future helical reactors

1. Introduction

Helical confinement systems have the great advantage of sustaining steady-state fusion plasmas by external helical magnetic field without plasma current disruptions. These merits of helical concept have recently been demonstrated in the Large Helical Device [1]. In order to realize high-performance steady-state plasmas in the future reactor, the core and edge transport phenomena should be clarified. Especially, reactor system designs strongly depend on plasma energy confinement scaling. Therefore, precise and reliable scaling laws of plasma confinement time are required. In this paper, recent LHD experimental results are analyzed, and new several confinement scaling laws are derived

2. Transport Data Analysis Code

For precise predictive simulation and experimental data analysis on LHD, a 3-dimensional equilibrium / 1-dimensional transport code TOTAL (Toroidal Transport Analysis Linkage, Fig.1) with PRE-TOTAL code for experimental data interface has been developed as an extension of previous HSTR code [2]. This code is characterized by including the self-consistent equilibrium with experimental data, magnetic multiple-helicity effect and radial electric field effects on neoclassical transport, time-varying NBI deposition profile, bootstrap current effects on equilibrium-transport, and so on [3]. In the analysis of experimental transport coefficient, time-dependent neutral-beam power deposition profile and slowing down calculation are carried out based on experimentally obtained density and temperature profiles. Using these data, impurity transport dynamics is estimated.

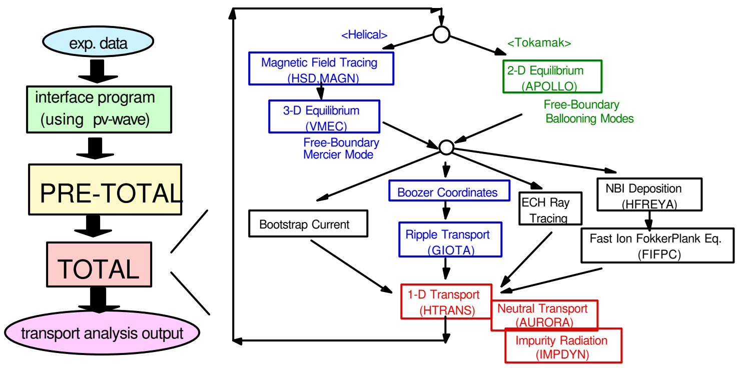

Fig.1 Flow Chart of PRE-TOTAL and TOTAL codes

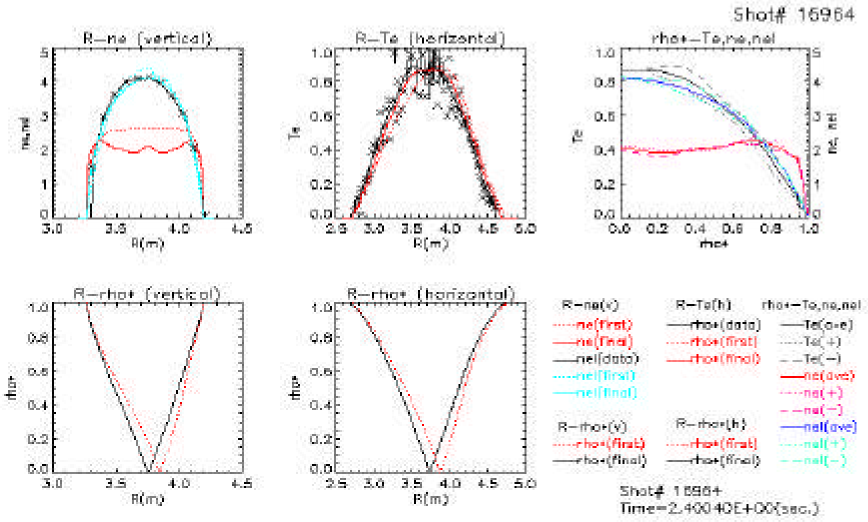

Fig.2 Output of PRE-TOTAL code

In the part of the experimental data analysis, the self-consistent equilibrium (Fig.2) has been treated with measured radial profiles by 11-channel FIR laser density measurement [4] and 120-channel YAG Thomson scattering electron temperature measurement. Dimensionless analysis based on Kadomtevs constraints [5] is also used in the log-linear regression analysis of experimental data. Here, we adopted special method to add dimensional constraints. To clarify the relationship between global and local transport, we used same experimental database to evaluate the both global and local transport based on kinetic pressure instead of diamagnetic energy. The ion temperature is not routinely measured and we assumed the same temperature profile as electron temperature. The global kinetic pressure obtained using this assumption is slightly (~10%) lower than the diamagnetic energy obtained by the magnetic measurement. Here it should be noted that MHD equilibria are calculated iteratively and self-consistently.

3. Transport Data Analysis for NBI Discharges

(1) Global Transport Analysis

NBI-heated LHD hydrogen plasmas on LHD are analyzed by comparing with neoclassical ripple transport as well as anomalous transport (empirical or drift turbulence theory). Time-dependent high-energy beam component and bootstrap current effects are also included in this experimental analysis. The confinement time is defined by measured plasma energy and deposited power calculated in the TOTAL code. Here, we used plasma kinetic energy obtained by the TOTAL code assuming that ion temperature is equal to electron temperature. This assumption was

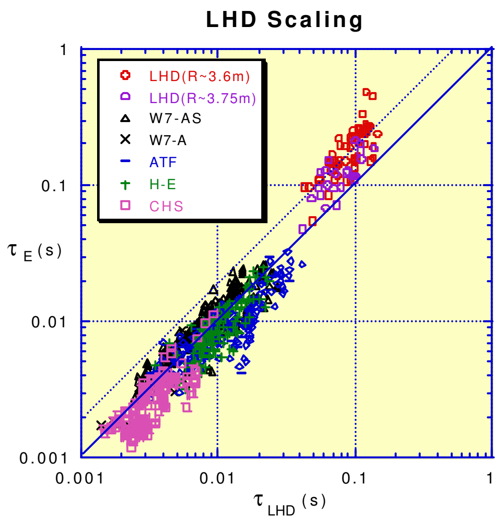

Fig.3 Experimental confinement time vs. LHD scaling law

confirmed in several typical discharges.

There are four conventional global confinement scaling laws for helical systems: LHD scaling (LHD)[6], gyro-reduced Bohm scaling (GRB)[7], Lackner-Gotardi scaling (LG) [8] and International Stellarator Scaling (ISS95) [9],

$$\tau_{LHD} = 0.17 P^{-0.58} \bar{n}_e^{0.69} B^{0.84} R^{0.75} a^2 , \quad (1)$$

$$\tau_{GRB} = 0.25 P^{-0.6} \bar{n}_e^{0.6} B^{0.8} R^{0.6} a^{2.4} , \quad (2)$$

$$\tau_{LG} = 0.17 P^{-0.6} \bar{n}_e^{0.6} B^{0.8} R a^2 \iota_{2/3}^{0.4} , \quad (3)$$

$$\tau_{ISS95} = 0.26 P^{-0.59} \bar{n}_e^{0.51} B^{0.83} R^{0.65} a^{2.21} \iota_{2/3}^{0.4} . \quad (4)$$

Units used here are $\tau_E(s)$, $P(MW)$, $\bar{n}_e(10^{20} m^{-3})$, $B(T)$, $R(m)$, $a(m)$, respectively. These are mainly based on medium-sized helical experiments. In LHD, ~ 1.5 times higher confinement time than the ISS95 scaling is obtained which corresponds to ~ 2 times of the LHD scaling value (Fig.3).

Newly obtained global confinement scaling laws (New LHD scaling) by regression analysis are as follows:

$$\tau_{NLHD\#1} = 0.263 P^{-0.58} \bar{n}_e^{0.51} B^{1.01} R^{0.64} a^{2.59} ,$$

$$\tau_{NLHD\#2} = 0.115 P^{-0.64} \bar{n}_e^{0.54} B^{0.85} R^{1.02} a^{2.09} .$$

The former (Fig.4) is based on experimental data from heliotron-type devices, and the latter based on those from all helical devices including previous experimental data set [9]. In this analysis we confirmed that the magnetic rotational transform does not play a statistic role, then we neglected this term.

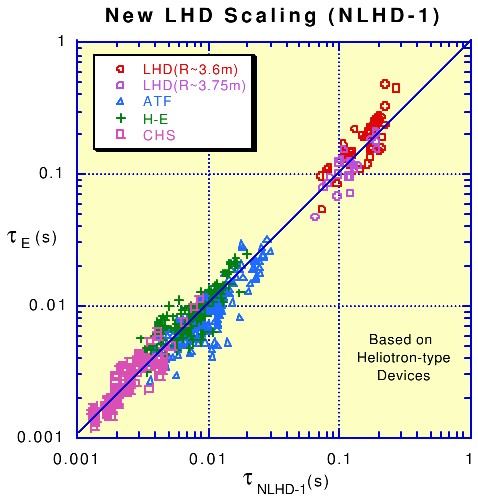

Fig.4 Experimental confinement time vs. New LHD scaling law #1.

The regression analysis is also applied to dimensionless values using normalized gyro-radius ρ_*, collisionality ν_{0*} and beta value. Here we used special analysis to keep Kadomtev s constraint.

$$\tau_{NLHD-D\#1} = 0.269 P^{-0.59} \bar{n}_e^{0.52} B^{1.06} R^{0.64} a^{2.58} \sim B^{-1} \rho_*^{-3.61} \nu_{0*}^{-0.17}$$

$$\tau_{NLHD-D\#2} = 0.115 P^{-0.64} \bar{n}_e^{0.54} B^{1.03} R^{1.04} a^{2.08} \sim B^{-1} \rho_*^{-3.41} \nu_{0*}^{-0.08} \beta^{-0.22}$$

Again, #1 scaling is based on only heliotron-type devices, and #2 is obtained from all database. These global scaling laws suggested the strong gyro-Bohm like features, which is different from previous conventional scaling laws (weakly gyo-Bohm like) based on only medium-sized devices.

(2) Local Transport Analysis

Local transport analysis has been carried out using 120 channel YAG Thomson electron profiles and FIR electron density profiles. Ion density and temperature profiles are assumed to be equal to those of electron, which is confirmed in some medium typical discharges. The NBI power deposition is calculated by TOTAL code , and effective thermal diffusivity χ_{eff} is defined as

$$\chi_{eff} = - (Q_{NBI}+Q_{RF}+Q_{OH} - dW/dt)/(2.5ndT/dr)$$

to avoid the uncertainty of ion temperature. Here, we use the following dimensionally normalized scaling:

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

The exponents of each parameter are obtained as a function of normalized minor radius by regression analysis as shown in Fig.5. Here, plasma radius is expanded to include stochastic magnetic surfaces.

It is found that the radial distribution is weak gyro-Bohm in the core and strong gyro-Bohm near the boundary. This seems to be related to the edge pedestal of electron temperature [10,11]. These analyses suggested that the multi-mode transport feature of LHD plasma should be considered. The global confinement feature is qualitatively consistent with strong gyro-Bohm-like local transport coefficient near the edge region.

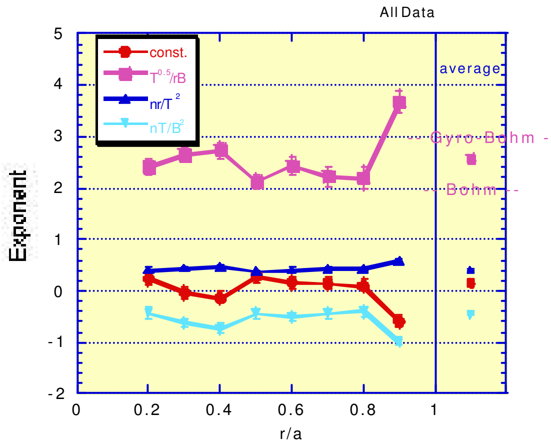

Fig. 5 Exponents of dimensionless $\chi_E / (Br^2)$ scaling vs. normalized minor radius.

4. Summary

The future prospect of helical confinement concepts should be confirmed by the demonstration of good plasma confinement in the present experiments. For the precise analysis of this confinement analysis, the Toroidal Transport Analysis Code TOTAL couple with PRE-TOTAL code has been developed and applied to LHD plasmas. Global confinement is strongly gyro-Bohm-like. It is found that the radial distribution is weakly gyro-Bohm-like in the core and strongly gyro-Bohm-like near the boundary. The global confinement feature is consistent with edge-region transport coefficient.

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