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Transport Analysis of Quasi Steady State Operations in LHD

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Abstract

For the confinement analysis of toroidal plasmas, the Toroidal Transport Analysis Code "TOTAL" is developed and applied to LHD plasmas for steady-state and transient transport analysis. The global confinement time obtained in the LHD experiment is ~2 times higher than the LHD scaling, and ~1.5 times higher than the ISS-95 scaling. The 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. Moreover, around n = 1/m = 1 or 2 island surface, Bohm-like dependence is suggested. The global confinement feature is consistent with edge-region transport coefficient. Slow Relaxation behavior called "Breathing" is also analyzed based on time-dependent equilibrium-transport without plasma current by means of time-dependent neutral beam heating analyses. This simulates the radial profile of impurity radiation and clarified the role of metal impurities.

Keywords:

plasma transport, confinement scaling, slow relaxation oscillation, impurity radiation, LHD

1. Introduction

Helical confinement systems have inherent merits of sustaining steady-state fusion plasmas by external helical magnetic field without plasma current disruptions. These advantages of helical concept have recently been demonstrated in the Large Helical Device [1] by NBI-heated quasi-stationary plasma operations with ~ 1 keV plasma temperature and ~ 80 second duration.

In order to realize steady-state plasmas in the future reactor, the physics of core transport relaxation coupled with equilibrium and impurity dynamics should be clarified. The slow relaxation oscillation called "breathing" has been recently found in the LHD experiments and is now under investigation of its impurity dynamics.

Reactor plasma designs strongly depend on plasma energy confinement scaling. Therefore, precise and reliable scaling laws of plasma confinement time are required. For the extrapolation of the present data to the future steady-state reactors, the following items should be clarified by the theory and experiments:

(1) Reactor designs strongly depend on plasma energy confinement τ_E. How much enhancement factor is required in the reactor design? In the LHD-type reactor, doubled improved confinement time is assumed based on the LHD scaling. Is it really achievable?

(2) Global τ_E scaling is useful for direct projection to reactors. Some scaling laws are not dimensionally correct. It might be necessary to keep Kadomtsev's constraints locally. However, is this necessary even in global confinement scaling?

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(3) Global τ_E scaling cannot often explain radial profile of transport coefficient. For example, as well known, the simple gyro-reduced Bohm formula is often inconsistent with radial profile of transport coefficient.

(4) Radial profile estimation is crucial for accurate projection of alpha heating plasma behavior in the reactor. To clarify time-dependent plasma dynamics in the reactor core, elaborate simulation studies are required.

(5) Clarification of transport physics is required. Especially, multi-mode modeling and non-local transport feature should be taken into account by comparing LHD experimental data with theoretical and empirical models.

In this paper, by taking above-stated issues into account the recent LHD experimental results are analyzed by the newly developed transport code TOTAL [2,3].

2. Transport Data Analysis Code Development

Transport analysis is carried out for two purposes, experimental data analysis and theoretical prediction simulation. As for transport data analysis of Tokamak plasmas, the TRANSP code in PPPL, the TOPICS code in JAERI, and the ASTRA code in Kurchatov Institute were developed as a time-dependent 2-dimensional equilibrium / 1-dimensional experimental transport data analysis code, so-called 1.5-D data analysis code. In the case of helical systems, 2.0-D code is required. The time-dependent PROCTR code was developed in Oak Ridge National Laboratory. The helical version of ASTRA code has been also used in the reactor projection.

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) was developed as a predictive simulation code by modifying the previous HSTR code [2]. Recently by adding experimental data interface code PRE-TOTAL, it has been extended to the experimental data analysis code, and applied to the transient and steady-state experimental transport data analyses on LHD [3]. Different from other experimental analysis codes, self-consistent equilibrium with experimental profile data, magnetic multiple-helicity effect and radial electric effects on neoclassical transport, time-varying NBI deposition profile, bootstrap current effects on equilibrium-transport, and so on are included. This TOTAL code can also be applied to tokamak plasma simulations [3].

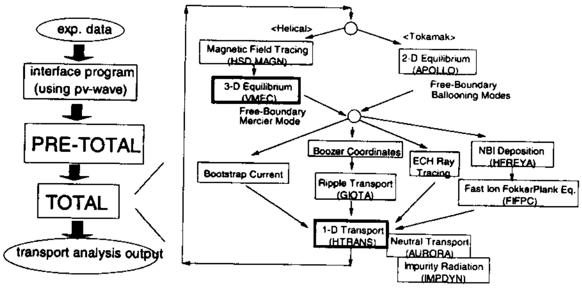

Fig. 1 Flow Chart of PRE-TOTAL and TOTAL codes.

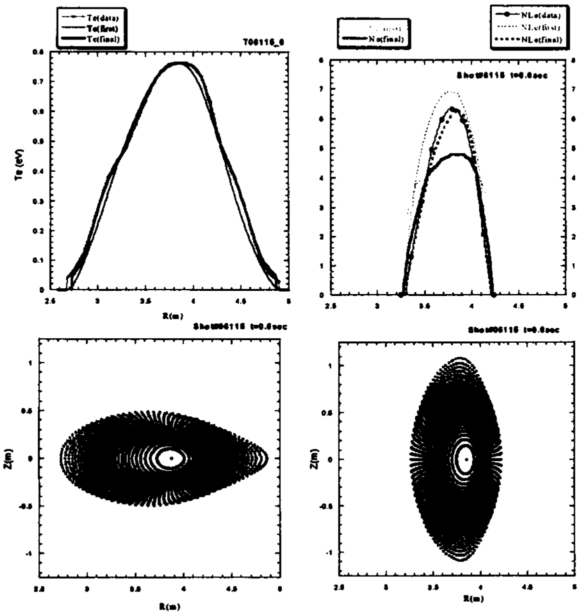

Fig. 2 Output of PRE-TOTAL code.

In the predictive simulation part of this code several transport models are adopted: empirical models (LHD, GRB, LG, ISS95, NEW, etc.), neo-classical model (plateau, 1/ν regime, $\nu^{1/2}$ regime), and turbulence theories (universal drift wave, DTEM, CTEM, η_i mode, electro-magnetic DW, Fluid Turbulence and so on).

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 measurements and 120-channel YAG Thomson scattering electron temperature measurements. Dimensional analysis based on Kadomtev's constraints is also used in the regression analysis of experimental data.

3. Steady-State Transport Analysis for NBI Discharges

(1) Global transport analysis

NBI-heated LHD 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 confirmed in several typical discharges.

There are four global confinement scaling laws used for helical systems: LHD scaling (LHD) [4], gyro-reduced Bohm scaling (GRB) [5], Lackner-Gotardi scaling (LG) [6] and International Stellarator Scaling (ISS95) [7],

$$\tau_{LHD}=0.17\,P^{-0.58}\,\overline{n}_e^{\,0.69}\,B^{0.84}\,R^{0.75}\,a^{2}\,, \tag{1}$$

$$\tau_{GRB}=0.25\,P^{-0.6}\,\overline{n}_e^{\,0.6}\,B^{0.8}\,R^{0.6}\,a^{2.4}\,, \tag{2}$$

$$\tau_{LG}=0.17\,P^{-0.6}\,\overline{n}_e^{\,0.6}\,B^{0.8}\,Ra^{2}\,\iota\!\!-_{2/3}^{\,0.4}\,, \tag{3}$$

$$\tau_{ISS95}=0.26\,P^{-0.59}\,\overline{n}_e^{\,0.51}\,B^{0.83}\,R^{0.65}\,a^{2.21}\,\iota\!\!-_{2/3}^{\,0.4}\,, \tag{4}$$

Units used here are $\tau_E(s)$, $P(MW)$, $\overline{n}_e(10^{20}\ \mathrm{m}^{-3})$, $B(T)$, $R(m)$, $a(m)$, 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).

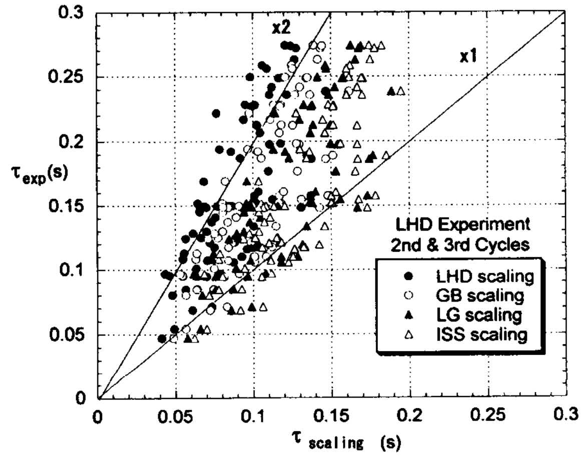

Fig. 3 Experimental confinement time of LHD vs. various confinement scaling laws.

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

$$\tau_{NLHD\#1}=0.263\,P^{-0.58}\,\overline{n}_e^{\,0.51}\,B^{1.01}\,R^{0.64}\,a^{2.59}\,,$$
$$\tau_{NLHD\#2}=0.115\,P^{-0.64}\,\overline{n}_e^{\,0.54}\,B^{0.85}\,R^{1.02}\,a^{2.09}\,.$$

The former is based on experimental data from heliotron-type devices, and the latter based on those from all helical devices including previous experimental data set [7]. In this analysis we confirmed that the magnetic rotational transform does not play a statistic role, then we neglected this term.

The regression analysis is also applied to dimensionless values using normalized gyro-radius ρ_*, collisionality ν_{0*} and beta value.

$$\tau_{NLHD-D\#1}=0.269\,P^{-0.59}\,\overline{n}_e^{\,0.52}\,B^{1.06}\,R^{0.64}\,a^{2.58}$$
$$\sim B^{-1}\,\rho_*^{-3.61}\,\nu_{0*}^{-0.17}$$
$$\tau_{NLHD-D\#2}=0.115\,P^{-0.64}\,\overline{n}_e^{\,0.54}\,B^{1.03}\,R^{1.04}\,a^{2.08}$$
$$\sim B^{-1}\,\rho_*^{-3.41}\,\nu_{0*}^{-0.08}\,\beta^{-0.22}$$

These scaling laws suggested the strong gyro-Bohm like features, which is different from previous scaling laws based on 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

$$\chi_{\mathit{eff}}=-\,(\,Q_{NBI}+Q_{RF}+Q_{OH}-\mathrm{d}W/\,\mathrm{d}t\,)/(2.5n\,\mathrm{d}T/\,\mathrm{d}r)$$

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

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

The exponents of each parameter are obtained as a function of normalized minor radius by regression analysis as shown in Fig. 4.

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 [8,9]. Moreover, around n = 1/m = 2 and n = 1/m = 1 island surfaces (r/a ~ 0.50 and 0.85), Bohm-like dependence is suggested, different from edge region (r/a > 0.9). Here the plasma radius a is defined using extended coordinate including stochastic

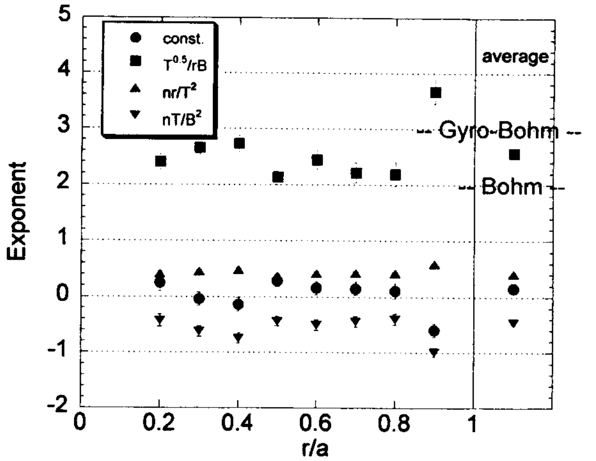

Fig. 4 Exponents of dimensionless $\chi_E/(Br^2)$ scaling vs. normalized minor radius.

magnetic surfaces. These analyses suggested the multi-mode transport feature of LHD plasma. The global confinement feature is qualitatively consistent with strong gyro-Bohm-like local transport coefficient near the edge region.

4. Time-Dependent Impurity Transport Analysis

Recently a new slow relaxation phenomenon called "Breathing" was found in a quasi-steady state operation in LHD [2]. Using this TOTAL code, this "Breathing" relaxation phenomenon is also analyzed to clarify its time-dependent characteristics.

The impurity dynamics is calculated using measured electron temperature and electron density. The initial total impurity density was assumed by the percentage of main plasma density. Here the recycling rates of all impurity ions are assumed to be unity. In this analysis, carbon, oxygen, and iron densities are assumed as 1%, 1% and 0.2%, respectively. Their initial profiles are determined by the coronal equilibrium model, and the time-variation of each charge-state impurity ions is dynamically solved by the rate equation of each charge-state and the diffusion equation with the transport coefficient D of 1 m^2/s and without the inward flow (v = 0 m/s).

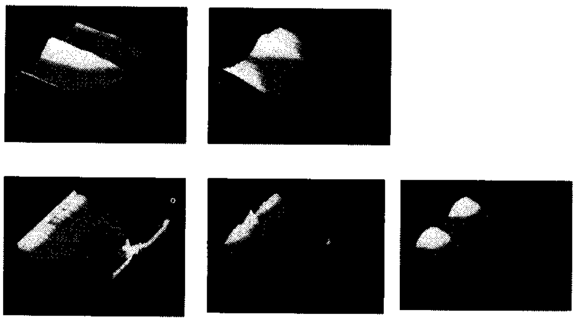

Fig. 5 Transport analysis on LHD plasma.
Upper raw: experimental data (n_e and T_e)
Lower raw: analyzed output (E_r, P_{rad} and Z_{eff})

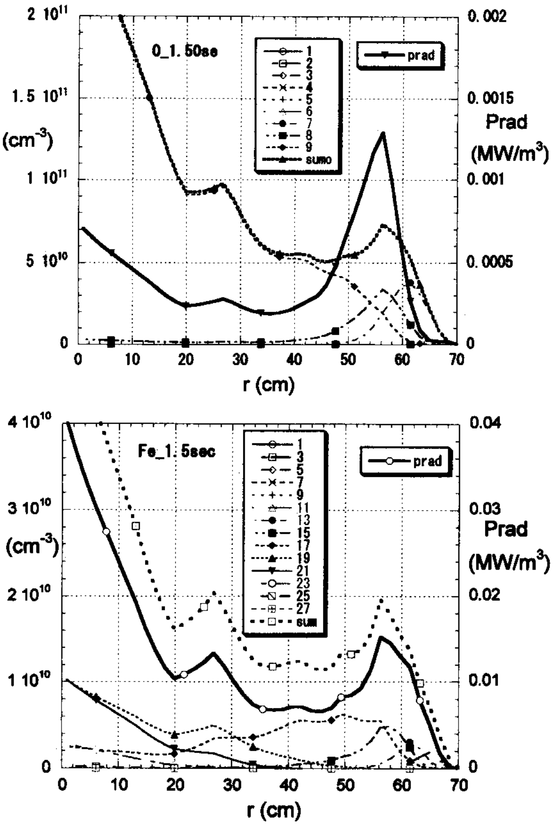

Fig. 6 Radial profile of impurities.
Top: Oxygen impurity porfile and its radiation
Bottom: Iron impurity profile and its radation

Figure 5 shows the breathing oscillation of measure profiles and calculated radial electric field, radiation power and effective Z values. Typical radial profiles of impurity ions are shown in Fig. 6. The 1% light impurity does not explain the core radiation power loss, because the total radiation power is one order of magnitude smaller than the experimental bolometric measurement, and the calculated radiation power is mainly localized near the edge, which does not fit the experimental evidence. The role of high Z impurity ions such as 0.2% iron is suggested for core radiation power loss. The detailed analysis and its simulation analysis will be presented somewhere in the future.

5. 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" has been developed and applied to LHD plasmas for steady-state and transient transport analysis and extrapolation to the reactor regime.

The global confinement obtained in LHD is ~2 times higher than LHD scaling, and ~1.5 times higher than ISS-95 scaling. 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. Moreover, around n = 1/m = 1 or 2 island surfaces, Bohm-like dependence is suggested. The global confinement feature is consistent with edge-region transport coefficient.

Slow Relaxation behavior called "Breathing" has been analyzed based on time-dependent equilibrium-transport without plasma current by means of time-dependent neutral beam heating analyses. Time-dependent impurity behaviors are also analyzed, and clarified the metal impurity roles.

As a future plan of transport analysis, the following items should be clarified:

(1) Global scaling: The present analysis is still preliminary, and a wide variety of database (higher beta, lower collisionality, and so on) is required.

(2) Local scaling: Radiation effect and two fluid (electron & ion) effect should be included in the local transport analysis. Island, pedestal effects etc. are also clarified.

(3) Future projection: Full simulation using LHD-based empirical transport coefficients should be done for LHD upgrade experiments and future reactors.

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