Beta and Magnetic Configuration Dependence of Local Transport in the LHD Plasmas

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In high beta plasmas on heliotron devices, the magnetic configuration changes as a result of the beta increment. Especially, the position of the magnetic axis is largely shifted outward. On the other hand, it is reported that the global confinement of low beta plasmas on LHD strongly depends on the magnetic configuration properties such as the magnetic axis position. In this paper, the influence of the change of the magnetic configuration on the local transport is studied in low beta plasmas at first. Next, the dependence of the local transport characteristics in high beta plasmas on the position of the magnetic flux surface are compared with those in the low beta plasmas. The local transport in the peripheral region of high beta plasmas is found to be more correlated with beta than the position of the magnetic flux surface, while the local transport in the core region has almost similar characteristics in the low beta plasmas. These results suggest that the local transport at the peripheral region in high beta plasmas on LHD is strongly affected by the anomalous transport caused by the increment in the magnitude or the gradient of beta.

Keywords: high beta, magnetic configuration, local transport, International Stellarator/Heliotron scaling

1. Introduction

The plasmas with the volume averaged beta, $\langle\beta\rangle$, value of close to 5 % have been obtained on the Large Helical Device (LHD) [1]. Transport analysis of such high beta plasmas are made in this paper.

Transport study of helical plasmas has been mainly done for low beta plasmas up to now. The activity of the International Stellarator/Heliotron Scaling (ISHS) has intensively progressed. Scaling laws of the energy confinement time for helical plasmas have been proposed by this activity (ISS95 : International Stellarator Scaling 1995) [2], ISS04 : International Stellarator Scaling 2004) [3]). According to the ISS04 scaling, the global confinement property depends on the magnetic configurations as a factor. The factor is introduced as the renormalization factor. This renormalization factor strongly depends on the magnetic axis position in vacuum or the ellipticity of the outermost magnetic flux surface in the case of LHD, although the causes have not been clarified.

Recently, as the results of the transport analysis of high beta plasmas with more than 1 % of $\langle\beta\rangle$, it is found that the transport property is degraded in high beta plasmas compared with the gyro-reduced Bohm (GRB) model or the ISS95 scaling. On the other hand, the magnetic flux surfaces are shifted outside with the increment in beta due to the Shafranov shift. The purpose of the analysis in this paper is to clarify that the confinement degradation with β increment observed on LHD is caused by the change of magnetic configuration by the increment in β or it is directly caused by the increment in β or $\nabla\beta$.

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The energy confinement time by the ISS04 scaling, τ_E^{ISS04}, is expressed as follows:

$$\tau_E^{ISS04} = 0.134 \cdot a^{2.28} R^{0.64} P^{-0.61} \overline{n}_e^{\,0.54} B^{0.84} \iota\!\!\!-_{2/3}^{0.41}, \quad (1)$$

where $a, R, P, \overline{n}_e, B$ and $\iota\!\!\!-_{2/3}$ are the minor radius, the major radius, the absorbed power, the line average electron density, the volume averaged strength of the magnetic field, the rotational transform, $\iota\!\!\!- = \iota/2\pi$ at the normalized average minor radius, $\rho = 2/3$, respectively. The advance from the previous ISS95 scaling to ISS04 is that the strong effect depending on the devices or the magnetic configurations is included although the dependence on the plasma parameters are similar. This effect is expressed as the renormalizaton factor, f_{ren}, which represents the dependence on the device or the magnetic configuration. In the case of LHD, this f_{ren} is strongly dependent on the position of the magnetic axis in vacuum, R_{ax}^{vac}, and the shape of the outermost magnetic flux surface. In ref. [3], the dependence of f_{ren} on the R_{ax}^{vac} is analyzed in detail and the derived f_{ren} values are shown in table 1. This f_{ren} is denoted as f_{ren}^{ISS04} hereafter. The f_{ren}^{ISS04} values are evaluated in the low beta discharges. For LHD, the beta values of the plasmas are in the range of $\langle\beta^{dia}\rangle \leq 1.5$ %.

The main purpose of this study is to distinguish the causes of the gradual confinement degradation with beta from following two effects: (1) the change of magnetic configuration by the increment in beta, (2) beta value or the gradient of beta. The global transport study is made taking the change of the magnetic configuration by the increment in beta into account. Then, analysis of the dependence of the local transport properties on magnetic configuration or the beta value is made.

Device	R_{ax}^{vac} [m]	$R_{geo}^{vac}(2/3)$ [m]	f_{ren}^{ISS04}
LHD	3.60	3.643	0.93 ± 0.15
LHD	3.75	3.740	0.67 ± 0.06
LHD	3.90	3.849	0.48 ± 0.05

Table 1. Relation among the positions of the magnetic axis in vacuum, R_{ax}^{vac}, the geometric center of the $\rho = 2/3$ magnetic surface in vacuum, $R_{geo}^{vac}(2/3)$ and f_{ren}^{ISS04} in the ISS04 scaling for three magnetic configurations on LHD [3] .

This paper consists of the following sections. In section 2, the method of transport analysis are described. The dependence of the local transport on the magnetic configuration in the low beta regime is investigated in Section 3. In Section 4, the relation between the local transport coefficients and the change of the geometric center position of the magnetic flux surface by increment in beta is shown. Then, its effect on the confinement degradation in the high beta region is discussed and a summary is provided in Section 5.

2. Experimental setup and the method of transport analysis

LHD is a heliotron type device with the poloidal period number $l = 2$ and the toroidal period number $m = 10$. The major radius position of the magnetic axis in vacuum, $R_{ax}^{vac} = 3.5 \sim 4.1$ m and the average minor radius $a \simeq 0.6$ m. The magnetic field strength at the toroidally averaged magnetic axis in vacuum, B_0, is up to almost 3 T.

The value of the volume average beta, $\langle\beta^{dia}\rangle$, is derived from the diamagnetic measurement [4]. The profiles of electron temperature, T_e, are measured by the Thomson scattering with YAG lasers. The power deposition profiles of NBI are calculated by a three-dimensional Monte Carlo simulation code [5]. These NBI deposition profiles, which are used in the local transport analysis, include the broadening from the birth profiles of NBI by the finite orbit effect. Here, the magnitude of the ionized power of NBI in the calculation is set to be equal to the experimentally estimated NBI absorbed power, which is the port through power minus the shine through power and contains about 10 % error [6] .

The thermal transport coefficients of electrons and ions, χ_e^{exp} and χ_i^{exp}, respectively are evaluated by using one-dimensional transport code for helical plasmas, PROCTR [7] . Here, $T_i = T_e$ and $n_i = f n_e$, are assumed, where f is determined by the following relation in order to make the kinetic stored energy become equal to the measured stored energy.

$$W_p^{dia} = \int \frac{3}{2}(1+f)\, n_e T_e dV, \tag{2}$$

where the integral is the volume integral. In this paper, the local transport is analyzed based on the measurements of T_e and n_e. By the assumption of $T_i = T_e$, the equipartition power between electrons and ions , $P_{ei} = 0$ is assumed. Therefore, behaviour of the effective transport coefficients which are evaluated by

$$\chi^{eff} = (\chi_e^{exp} + f\chi_i^{exp})/(1+f) \tag{3}$$

is studied.

3. Dependence of the local transport on the magnetic configuration in the low beta regime

In this section, the dependence of local transport on magnetic configurations is investigated in the low beta region first in order to clarify the causes of the degradation of the local transport property in the high beta region.

The dependence of the local transport coefficients on the magnetic configuration, which is represented by the geometric center of the magnetic flux surface in this paper, are investigated at some minor radius positions in the low beta plasmas. In order to evaluate this dependence, the renormalization factor for local transport coefficients, $g_{ren\chi}$, is introduced. And the reference local transport coefficient, χ^{ISS04}, based on the global confinement scaling of ISS04, is used in this analysis.

The energy confinement time by ISS04, τ_E^{ISS04}, is expressed as follows by using the non-dimensional parameters, such as the normalized Larmor radius (ρ^*), ν_b^*, β, A_p and $\iota_{2/3}$.

$$\tau_E^{ISS04} = C_\tau \cdot \tau_{Bohm} \cdot \rho^{*-0.79}\beta^{-0.19}\nu_b^{*0.00}A_p^{0.07}\iota_{2/3}^{1.06}, \tag{4}$$

where τ_{Bohm} is the global confinement time based on the Bohm type scaling and C_τ is a constant. Then, a modeled transport coefficient, χ^{ISS04}, which has the same non-dimensional parameter dependence as ISS04 is introduced in order to use as a reference for the local transport coefficient:

$$\chi^{ISS04} = C_\chi \cdot \chi^{Bohm} \cdot \rho^{*0.79}\beta^{0.19}\nu_b^{*0.00}A_p^{-0.07}\iota_{2/3}^{-1.06}. \tag{5}$$

Here, C_χ is determined to make the average of χ^{eff}/χ^{ISS04} become unity in the low beta region ($\langle\beta^{dia}\rangle < 1\%$) in the data set of $R_{ax}^{vac} = 3.60$ m (Table 2) .

ρ	C_χ
0.5	0.104
0.7	0.133
0.9	0.294

Table 2. The normalized average minor radius, ρ, and the coefficient in χ^{ISS04} expression, C_χ .

Therefore, the magnitude of χ^{eff}/χ^{ISS04} represents the ratio of the normalized transport coefficients to the value in the configuration of R_{ax}^{vac} = 3.6 m at each minor radius position. The ratio χ^{eff}/χ^{ISS04} increases as R_{ax}^{vac} moves torus-outward. This tendency of the local transport coefficients seems to agree qualitatively with the global confinement property. Then, the average value of the experimental results is defined as the renormalization factor for the local transport coefficients, $g_{ren\chi}$, at this local position. The factor $g_{ren\chi}$ is derived for various magnetic configurations and radial positions. The relation between $g_{ren\chi}$ and the geometric center position of each magnetic flux surface, $R_{geo}(\rho)$, in vacuum is shown in Fig. 1. The symbols ○ , ◇ and △ correspond to the values at $\rho = 0.9, 0.7$ and 0.5, respectively. The data in $R_{geo}(\rho) = 3.6 \sim 3.7$ m, $R_{geo}(\rho) = 3.7 \sim 3.8$ m and $R_{geo}(\rho) = 3.8 \sim 3.9$ m are for the configurations of R_{ax}^{vac} = 3.60 m, R_{ax}^{vac} = 3.75 m and R_{ax}^{vac} = 3.90 m, respectively.

As the geometric center of the magnetic flux surface is shifted torus outward, $g_{ren\chi}$ increases at any minor radius positions. Moreover, it is found that the dependence of $g_{ren\chi}$ on the geometric center position of the magnetic surface is almost same at different minor radial positions.

The closed circles (●) in Fig. 1 represent the renormalization factor for transport coefficients which is derived from the global scaling ISS04, $g_{ren\chi}^{ISS04}$. This $g_{ren\chi}^{ISS04}$ is related with the global f_{ren} and it is compared with the renormalization factor for the local transport coefficients, $g_{ren\chi}$. The parameter $g_{ren\chi}^{ISS04}$ is is derived by normalizing $f_{ren}^{-1/(\alpha_P+1)}$ with the value at R_{ax}^{vac} = 3.60 m as the following,

$$g_{ren\chi}^{ISS04} \equiv f_{ren}^{-1/(\alpha_P+1)} / f_{ren}^{-1/(\alpha_P+1)}(R_{ax}^{vac} = 3.6\,\mathrm{m}), \qquad (6)$$

where α_P is one of the scaling coefficients when a global scaling law is expressed as

$$\tau_E = f_{ren} n^{\alpha_n} P^{\alpha_P} B^{\alpha_B} a^{\alpha_a} R^{\alpha_R}, \qquad (7)$$

where n is the density and $\alpha_n, \alpha_P, \alpha_B, \alpha_a$ and α_R are exponents for each parameter. In the case of ISS04, α_P = −0.61. The values of $g_{ren\chi}^{ISS04}$ at the R_{ax}^{vac} = 3.60, 3.75 and 3.90 m configurations are shown in Table 3.

R_{ax}^{vac} [m]	$R_{geo}^{vac}(2/3)$ [m]	f_{ren}^{ISS04}	$g_{ren\chi}^{ISS04}$
3.60	3.643	0.93	1.00
3.75	3.740	0.67	2.33
3.90	3.849	0.48	5.48

Table 3. f_{ren}^{ISS04} and $g_{ren\chi}^{ISS04}$ for three magnetic configurations on LHD.

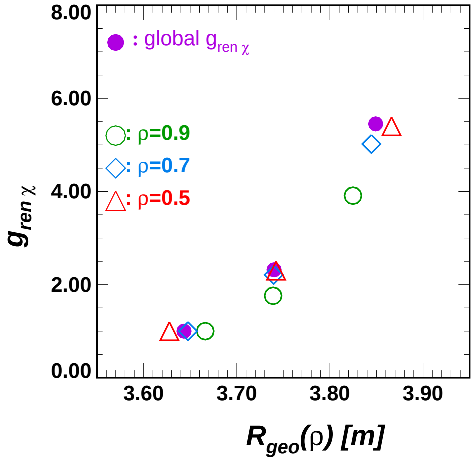

Fig. 1 Dependence of $g_{ren\chi}$ on the geometric center position of the vacuum magnetic flux surface, $R_{geo}(\rho)$. fren chi.

It should be noted that an assumed spatially uniform thermal transport coefficient, $\langle\chi\rangle$, in the R_{ax}^{vac} = 3.90 m configuration is about 5 times larger than that in the R_{ax}^{vac} = 3.60 m configuration when it is evaluated based on ISS04. The values of $g_{ren\chi}^{ISS04}$ almost agree with the values of $g_{ren\chi}$ which are evaluated from the local transport analysis from the results in Fig. 1. Here, as the flux surface corresponding to $g_{ren\chi}^{ISS04}$, the $\rho = 2/3$ surface is chosen because it is assumed that $R_{geo}(2/3)$ represents the property of a magnetic configuration.

4. Local transport property in the high beta regime and its dependence on the magnetic configuration

In Fig. 2, the dependence of χ^{eff}/χ^{ISS04} on $R_{geo}(\rho)$ in the high beta regime are compared with the dependence of χ^{eff}/χ^{ISS04} on $R_{geo}(\rho)$ in the low beta regime with various magnetic axis positions. Figs. 2, (a) (b) and (c) show the results for $\rho = 0.5, 0.7$ and 0.9, respectively. The closed circles (●) represent the relation between χ^{eff}/χ^{ISS04} and $R_{geo}(\rho)$. At the all positions of $\rho = 0.5, 0.7$ and 0.9, the magnitude of χ^{eff}/χ^{ISS04} increases with the torus outward shift of $R_{geo}(\rho)$ of the each magnetic flux. The dependence of increment in the ratio χ^{eff}/χ^{ISS04} on $R_{geo}(\rho)$ is steeper at the larger ρ position. One reason of this is that the magnitude of the shift of $R_{geo}(\rho)$ is smaller at larger ρ. At $\rho = 0.9$, an abrupt increment in χ^{eff}/χ^{ISS04} is found around $R_{geo}(\rho) \simeq 3.70$ m, where $\langle\beta^{dia}\rangle$ is about $1.0 \sim 2.5$ %. The symbols of △, ◇ and ○ in Fig. 2, are the same as in Fig. 1, respectively. They represent the dependence of the normalized thermal transport coefficients on the geometric center position of the magnetic flux surfaces which is evaluated from the local transport analysis.

The degradation of the local transport with the increment in $\langle \beta^{dia} \rangle$ seems to be comparable with the degradation by the torus outward shift of the magnetic flux surface at $\rho = 0.7$. Moreover, The degradation at $\rho = 0.5$ seems to be comparable with or slightly smaller than the degradation by the torus outward shift. On the other hand, at the peripheral region of $\rho = 0.9$, it is observed that the degradation of the local transport is larger than that predicted from the torus outward shift of the magnetic flux surface. This results shows that some effects which are caused directly by the beta value or the gradient of beta may exist at the peripheral region.

5. Summary

The following results are obtained by comparing the dependence of the local transport coefficients on beta values and the geometric center positions of the magnetic flux surfaces with the above relations between the local transport coefficients and the geometric center positions of the magnetic flux surfaces in the low beta region . The degradation of the local transport with the increment in $\langle \beta \rangle$ seems to be comparable with or slightly smaller than the degradation by the torus outward shift of the magnetic flux surface at $\rho = 0.7$ or 0.5. On the other hand, at the peripheral region of $\rho = 0.9$, degradation of transport coefficients which is larger than those predicted from the torus outward shift is observed. It is considered that some effects which are directly caused by the beta value or the gradient of beta may exist.

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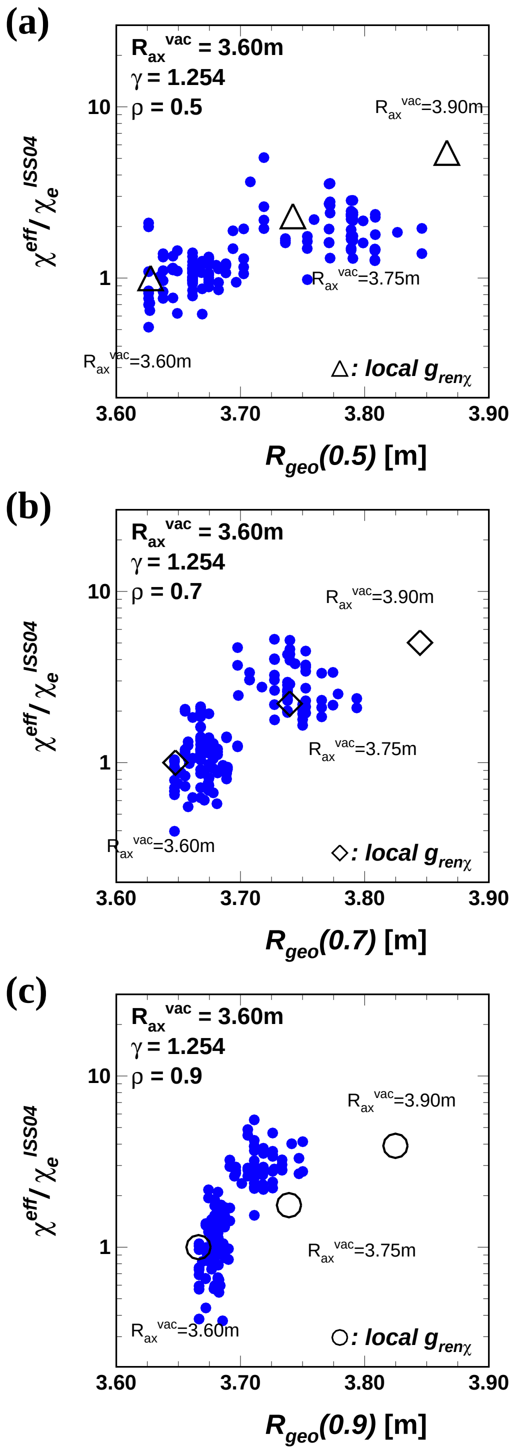

Fig. 2 Dependence of the local transport coefficients χ^{eff}/χ^{ISS04} on $R_{geo}(\rho)$. (a) $\rho = 0.5$, (b) $\rho = 0.7$ and (c) $\rho = 0.9$.