Local Transport Property of Reactor-Relevant High-Beta Plasmas on LHD

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Abstract. The high-beta plasmas up to 5 % of the volume-averaged beta are obtained on the Large Helical Device (LHD) in the magnetic configuration with the aspect ratio, $A_\mathrm{p} = 6.6$. The property of such high-beta plasmas are evaluated by the local transport analysis with referring the property of the International Stellarator Scaling 2004 (ISS04) and comparing the plasmas with the standard $A_\mathrm{p} = 5.8$. The effects of the changes of the magnetic configuration by the increment in beta is considered in this evaluation. The dependence of the local transport in the peripheral region is correlated more with beta itself than the magnetic configuration effect in both A_p cases, whereas the core transport appears to be correlated more with the configuration effect. The transport degradation at the high-beta region becomes small in the $A_\mathrm{p} = 6.6$ configuration.

1. Introduction

High beta plasmas of more than 5 % of the volume averaged beta ($\langle\beta\rangle$), which are required for an economic fusion reactor of helical type, were obtained in the Large Helical Device (LHD). Such high-beta plasmas are produced in a magnetic configuration with the optimal aspect ratio $A_\mathrm{p} = 6.6$ [1], while the usual A_p value is 5.8 in the low-beta plasmas on LHD. The magnitude of the Shafranov shift in the configuration with $A_\mathrm{p} = 6.6$ is smaller than that in the $A_\mathrm{p} = 5.8$ configuration. In the higher A_p configurations, the NBI heating efficiency in the high-beta region is improved, while the magnetic shear becomes small. These are some of the reasons that the high-beta plasmas were obtained in the configuration with $A_\mathrm{p} = 6.6$.

The previous analysis for the global confinement and the local transport of the high-beta plasmas on LHD was made for the configuration of $A_\mathrm{p} = 5.8$, since the global confinement property in low-beta plasmas in this configuration has been investigated in detail. From those results, no degradation seems to appear on the global confinement property, which is compared with the International Stellarator Scaling 2004 (ISS04 [2]), in the $A_\mathrm{p} = 5.8$ configuration when effects of the change of the plasma volume or the magnetic configuration by the Shafranov shift due to the increment in beta are considered [3]. In order to confirm the possibility of extrapolation of this global confinement property on LHD to reactor plasmas, it is studied whether the local transport property is preserved in the high beta region. It is found that the local transport property of the $A_\mathrm{p} = 5.8$ plasmas in the low-beta region is almost coincides with the property which is predicted

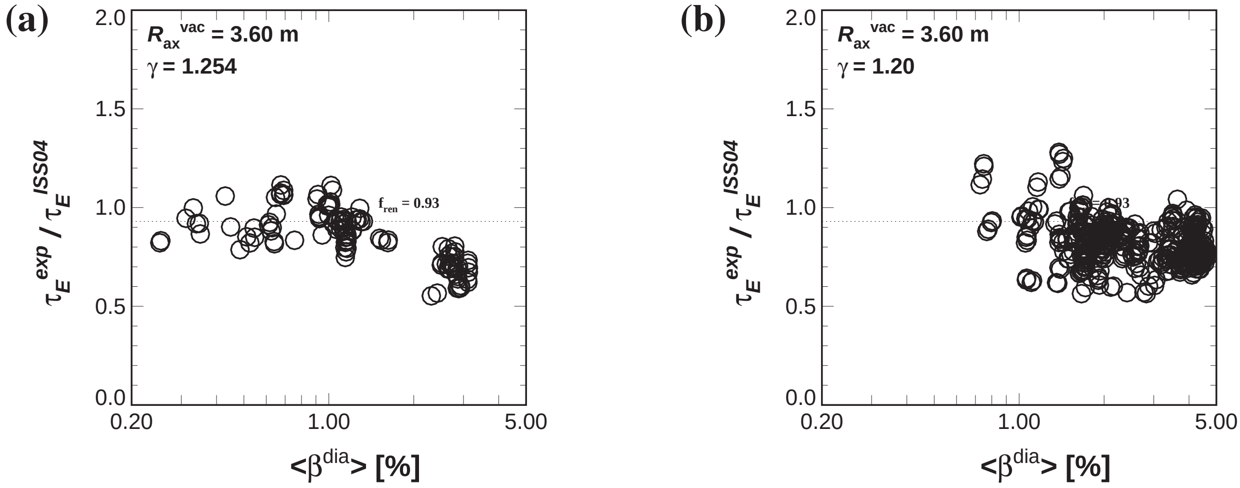

FIG. 1. Beta dependence of the ratio of the energy confinement time $\tau_{\mathrm{E}}^{\mathrm{exp}}$ and the ISS04 scaling value $\tau_{\mathrm{E}}^{\mathrm{ISS04}}$ in the (a) $A_{\mathrm{p}} = 5.8$ and (b) $A_{\mathrm{p}} = 6.6$ configurations.

from the global confinement scaling of ISS04. From the results of the local transport analysis in the wide range of beta, the local transport property, which is evaluated by referring to ISS04, is preserved or improved in the core region, while it is degraded in the peripheral region in the $A_{\mathrm{p}} = 5.8$ configuration.

This study is intended to clarify the local transport property of low- and high-beta plasmas with $A_p = 6.6$. This paper consists of the following sections. Global confinement property of high-beta LHD plasmas with $A_p = 6.6$ is investigated by referring the ISS04 scaling in Section 2. In Section 3, the characteristics of local transport with $A_p = 6.6$ in the low-beta region is shown. The reference transport coefficient χ^{ISS04} and a renormalization factor for the local transport $g_{\mathrm{ren}\chi}$ are used. Then in Section 4, the effect of the change of magnetic flux surface in high beta plasmas is evaluated in the $A_p = 5.8$ and 6.6 configurations. A summary is provided in Section 5.

2. Global Confinement Property in the $A_{\mathrm{p}} = 6.6$ Configuration on LHD

The LHD is a heliotron-type device with the poloidal period number $l = 2$ and the toroidal period number $m = 10$. The major radius of the magnetic axis in the vacuum $R_{\mathrm{ax}}^{\mathrm{vac}} = 3.5 \sim 4.1\,\mathrm{m}$ and the average minor radius $a \simeq 0.6\,\mathrm{m}$. High-beta plasmas were produced by the high-power neutral beam injection (NBI) heating of more than 10 MW of injected power and in the condition of low magnetic field strength B ($\leq 0.5\,\mathrm{T}$). The discharges in low B were started by NBI heating only.

The parameters for the magnetic configuration of LHD are as follows: $R_{\mathrm{ax}}^{\mathrm{vac}}$ is the major radius position of the magnetic axis in vacuum, which is controlled by the vertical magnetic field produced by the poloidal coils. The parameter B_{q} is the canceling ratio of the quadrupole component of the helical magnetic field, which is related with the ellipticity of the shape of the poloidal cross section averaged in the toroidal direction. $B_{\mathrm{q}} = 100\,\%$ corresponds to almost unity ellipticity. The data in this study are obtained in the configuration of $B_{\mathrm{q}} = 100\,\%$. One more parameter γ is the pitch parameter of the helical coils [4], which corresponds to the plasma aspect ratio A_{p}. For example, the standard γ value of 1.254 corresponds to $A_{\mathrm{p}} = 5.8$. The maximum $\langle\beta^{\mathrm{dia}}\rangle$ value more than $5\,\%$ was obtained in the $\gamma = 1.20$ configuration, while the maximum $\langle\beta^{\mathrm{dia}}\rangle$ in the plasmas with

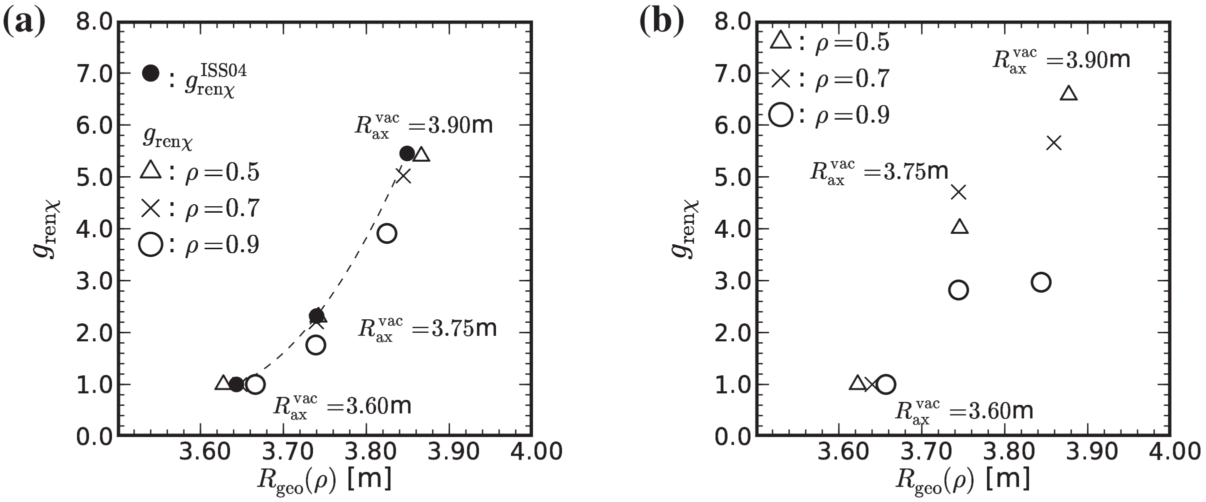

FIG. 2. Dependence of the renormalization factor for the local transport coefficients, $g_{\mathrm{ren}\chi}$, on the major radius of the geometric center position of the magnetic flux surface, $R_{\mathrm{geo}}(\rho)$, in the (a) $A_{\mathrm{p}} = 5.8$ and (b) $A_{\mathrm{p}} = 6.6$ configurations.

$\gamma = 1.254$ is almost $3.2\,\%$.

The global confinement property of low-beta LHD plasmas are expressed by the ISS04 scaling which has a renormalization factor, $f^{\mathrm{ISS04}}_{\mathrm{ren}}$, in order to include the difference of the devices or the effects of the magnetic configurations. The energy confinement time by ISS04, which was derived mainly from the data of low-beta plasmas for LHD, is expressed as follows: $\tau^{\mathrm{ISS04}}_{\mathrm{E}} = 0.134 \cdot a^{2.28} R^{0.64} P^{-0.61} \overline{n}_{\mathrm{e}}^{\,0.54} B^{0.84} \iota^{0.41}_{2/3}$, where $a, R, P, \overline{n}_{\mathrm{e}}, B$ and $\iota_{2/3}$ are the effective minor plasma radius, the major radius, the heating power, the line-averaged electron density, the volume-averaged magnetic field and the rotational transform at the normalized minor radius $\rho = 2/3$, respectively. The experimentally derived energy confinement time $\tau^{\mathrm{exp}}_{\mathrm{E}}$ should be compared with the scaling value $f^{\mathrm{ISS04}}_{\mathrm{ren}} \tau^{\mathrm{ISS04}}_{\mathrm{E}}$. The factor $f^{\mathrm{ISS04}}_{\mathrm{ren}}$ for LHD is derived only for the configurations with $A_p = 5.8$. Figure 1 shows the beta dependence of the ratio of the energy confinement time $\tau^{\mathrm{exp}}_{\mathrm{E}}$ and the ISS04 scaling value $\tau^{\mathrm{ISS04}}_{\mathrm{E}}$ in the (a) $A_{\mathrm{p}} = 5.8$ and (b) $A_{\mathrm{p}} = 6.6$ configurations. The $f^{\mathrm{ISS04}}_{\mathrm{ren}}$ value for $R^{\mathrm{vac}}_{\mathrm{ax}} = 3.60\,\mathrm{m}$ and $A_{\mathrm{p}} = 5.8$ is 0.93. In Fig. 1 (a), $\tau^{\mathrm{exp}}_{\mathrm{E}} / \tau^{\mathrm{ISS04}}_{\mathrm{E}}$ seems to degrade in the range of $\langle\beta\rangle > 1\,\%$. However, in order to include the effects of change of the magnetic configuration on the global confinement, when a new renormalization factor, which is derived by interpolating $f^{\mathrm{ISS04}}_{\mathrm{ren}}$ for the geometric center position of the magnetic flux surface and denoted by $f^{\mathrm{int}}_{\mathrm{ren}}$, is used in evaluating the scaling value $f^{\mathrm{int}}_{\mathrm{ren}} \tau^{\mathrm{ISS04}}_{\mathrm{E}}$, the global confinement seems to show a similar property as the ISS04 scaling in the wide beta range. In Fig. 1 (b), the $\tau^{\mathrm{exp}}_{\mathrm{E}} / \tau^{\mathrm{ISS04}}_{\mathrm{E}}$ values in $\langle\beta\rangle < 1\,\%$ are around unity. Although $\tau^{\mathrm{exp}}_{\mathrm{E}} / \tau^{\mathrm{ISS04}}_{\mathrm{E}}$ becomes around 0.8 in the region of $\langle\beta\rangle > 2\,\%$, it does not seem to degrade with the beta increment.

3. Local Transport Property at Low-Beta Region in the $A_{\mathrm{p}} = 6.6$ Configuration

In this section, local transport property of low-beta plasmas are shown. The local transport coefficients are derived by using a transport code for helical plasmas PROCTR [5] based on the power balance in the steady state. The deposition profiles of the NBI power are calculated by a threedimensional Monte Carlo simulation code [6]. At first, the non-dimensional-parameter (ρ^*, β, ν^* : normalized gyro radius, beta and normalized collisionality, respectively) dependence of the experimentally evaluated transport coefficient $\chi^{\rm eff}$ in the low beta plasmas at $\rho = 0.5, 0.7$ and 0.9 is compared with that of ISS04. For this comparison, a reference transport coefficient, $\chi^{\rm ISS04}$, which has the same non-dimensional parameter dependence as the ISS04 scaling is introduced and $\chi^{\rm eff}$ is normalized by $\chi^{\rm ISS04}$ [3]. As the renormalization factor $f_{\rm ren}^{\rm ISS04}$ for the global confinement, a new renormalization factor for the local transport coefficients, $g_{{\rm ren}\chi}$, which represents the dependence of the local transport coefficients on the magnetic configurations, is introduced. This $g_{{\rm ren}\chi}$, represents the effects of the magnetic configurations on the local transport. Since the magnetic configurations are changed in the high-beta plasmas from the vacuum configuration, this $g_{{\rm ren}\chi}$ is used as a reference parameter in order to evaluate the effects of beta increment itself separately from the change of the magnetic configuration in Section 4. The factor $g_{{\rm ren}\chi}$ is derived by averaging the experimentally evaluated $\chi^{\rm eff}$ in low-beta plasmas at several minor radius, ρ, positions with different magnetic configurations of the various $R_{\rm ax}^{\rm vac}$ positions or $A_{\rm p}$.

Figure 2 shows the dependence of the renormalization factor for the local transport coefficients, $g_{{\rm ren}\chi}$, on the major radius of the geometric center position of the magnetic flux surface, $R_{\rm geo}(\rho)$, in the (a) $A_{\rm p} = 5.8$ and (b) $A_{\rm p} = 6.6$ configurations. The local $g_{{\rm ren}\chi}$ values are obtained for $R_{\rm ax}^{\rm vac} = 3.60, 3.75$ and $3.90\,{\rm m}$. The beta region of the plasmas which are used for Fig. 2 is $\langle\beta\rangle < 1.5\,\%$. As the geometric center of the magnetic flux surface is shifted torus-outward, $g_{{\rm ren}\chi}$ increases at all minor radial positions. In Fig. 2 (a), the factor $g_{{\rm ren}\chi}$ depends strongly on each $R_{\rm geo}(\rho)$ at each $\rho = 0.5, 0.7$ and 0.9. These relations almost coincide with the relation between $R_{\rm geo}(\rho)$ and $g_{{\rm ren}\chi}^{\rm ISS04}$ (●) which is derived from $f_{\rm ren}^{\rm ISS04}$ in the ISS04 scaling (The definitions of the parameters are listed in Table 1). This result shows that the local transport in the low beta region also has the similar property as ISS04. In Fig. 2 (b), the dependence on $R_{\rm geo}(\rho)$ at $\rho = 0.9$ differs from those at $\rho = 0.5$ and 0.7 especially at $R_{\rm ax}^{\rm vac} = 3.90\,{\rm m}$. However, since the shift of $R_{\rm geo}(\rho)$ at $\rho = 0.9$ in the $A_{\rm p} = 6.6$ configuration is not large, the influence of $g_{{\rm ren}\chi}$ value in the range of $R_{\rm geo}(\rho) > 3.75\,{\rm m}$ on the evaluation at the high-beta region is small.

parameter	definition
$f_{\rm ren}^{\rm ISS04}$	renormalization fator in ISS04
$f_{\rm ren}^{\rm int}$	derived by interpolating $f_{\rm ren}^{\rm ISS04}$
$g_{{\rm ren}\chi}$	renormalization fator for local transport coefficients
$g_{{\rm ren}\chi}^{\rm ISS04}$	renormalization fator for local transport coefficients derived from $f_{\rm ren}^{\rm ISS04}$
$g_{{\rm ren}\chi}^{\rm int}$	derived by interpolating $g_{{\rm ren}\chi}$
$\chi^{\rm eff}$	experimentally evaluated local transport coefficient χ
$\chi^{\rm ISS04}$	reference χ which has the same non-dimensional parameter dependence as ISS04

Table I Definitions of the renormalization factors and transport coefficients.

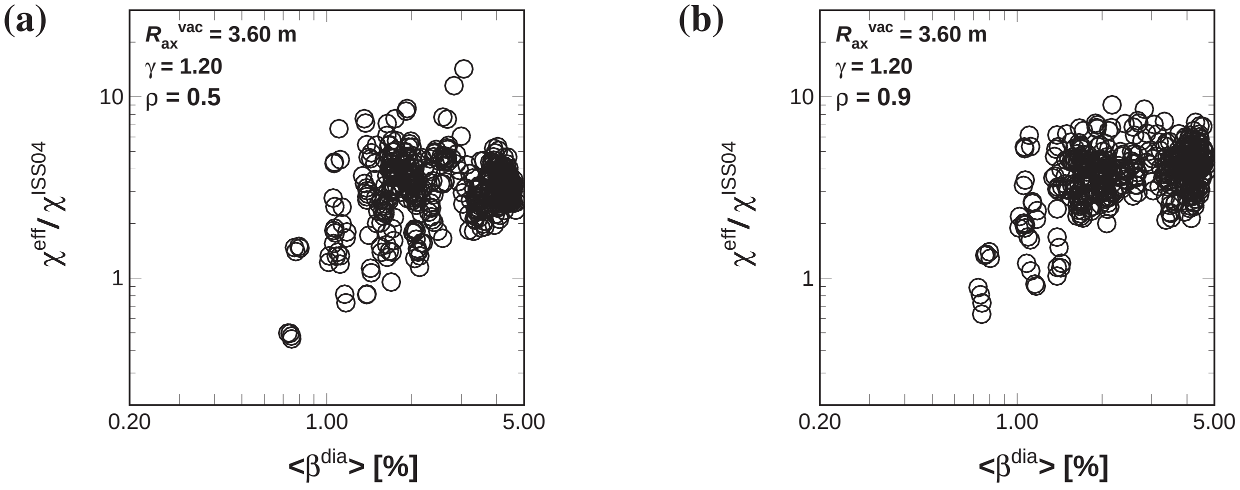

FIG. 3. Beta dependence of the normalized local transport coefficients at (a) $\rho = 0.5$ and (b) $\rho = 0.9$.

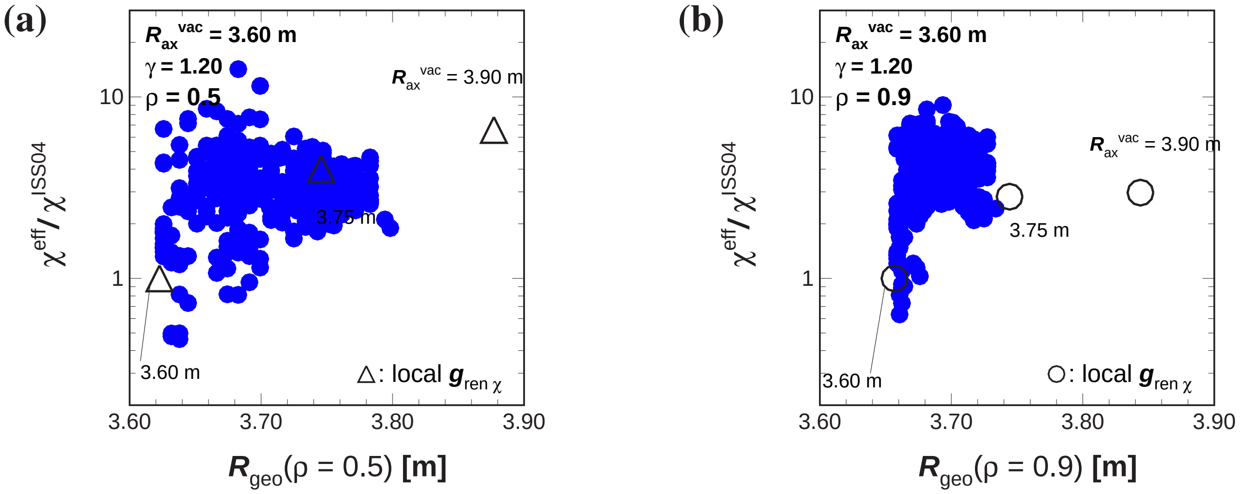

FIG. 4. Dependence of the normalized local transport coefficients on the major radius of the geometric center position of the magnetic flux surface at (a) $\rho = 0.5$ and (b) $\rho = 0.9$.

4. Local Transport Property at High-Beta Region in the $A_{\mathrm{p}} = 5.8$ and 6.6 Configurations

From the viewpoint of the local transport, although the global confinement has the similar property of ISS04 in the high-beta region, it is needed to compare the parameter dependence of the local transport property with ISS04 for the extrapolation to the high-beta reactor plasmas.

Figure 3 shows the beta dependences of the normalized local transport coefficients $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ at (a) $\rho = 0.5$ and (b) $\rho = 0.9$ in the $A_{\mathrm{p}} = 6.6$ configuration. The maximum $\langle\beta\rangle$ is about $5\,\%$ in this magnetic configuration. The value of χ^{ISS04} is determined so that the average of $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ in the low-beta region of $\langle\beta\rangle < 1\,\%$ becomes unity. The ratio $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ increases in the range of $\langle\beta\rangle < 2\,\%$ in both $\rho = 0.5$ and 0.9. In the range of $\langle\beta\rangle > 2\,\%$, the increment of $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ with beta is small in $A_{\mathrm{p}} = 6.6$, while $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ increased with beta in $A_{\mathrm{p}} = 5.8$ [3].

The dependences of $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ on $R_{\mathrm{geo}}(\rho)$ with $A_{\mathrm{p}} = 6.6$ at (a) $\rho = 0.5$ and (b) $\rho = 0.9$ are shown in Fig. 4. The closed circles (blue ●) represent the relation between $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ and $R_{\mathrm{geo}}(\rho)$ of the data which are sown in Fig. 3. In this figure, the dependence of $\chi^{\mathrm{eff}}/\chi^{\mathrm{ISS04}}$ on $R_{\mathrm{geo}}(\rho)$ in

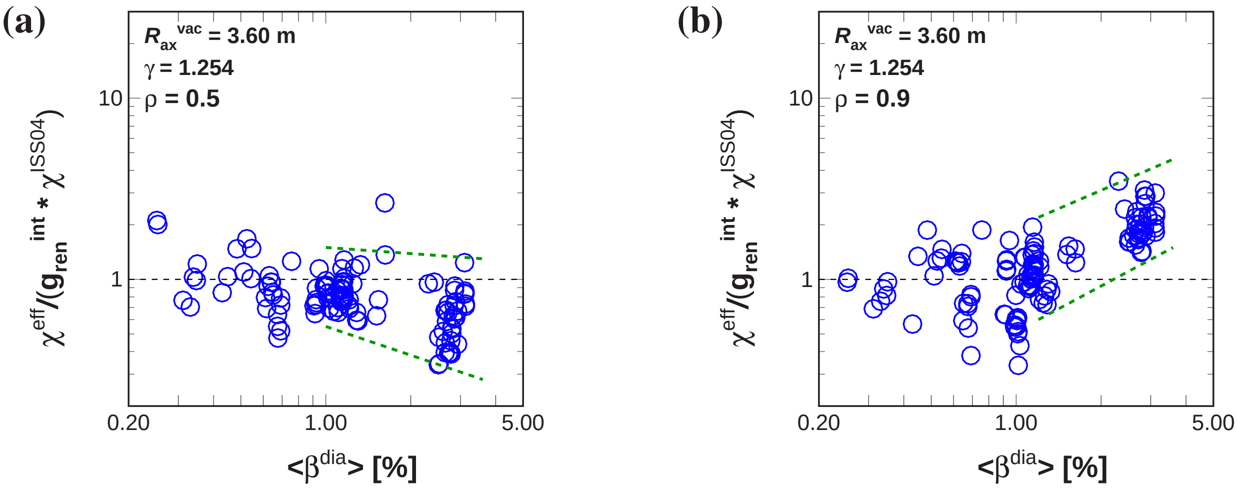

FIG. 5. *Beta dependence of the normalized local transport coefficient in the* $A_\mathrm{p} = 5.8$ *configuration at (a)* $\rho = 0.5$ *and (b)* $\rho = 0.9$*. The effect of the change of the magnetic configuration is included.*

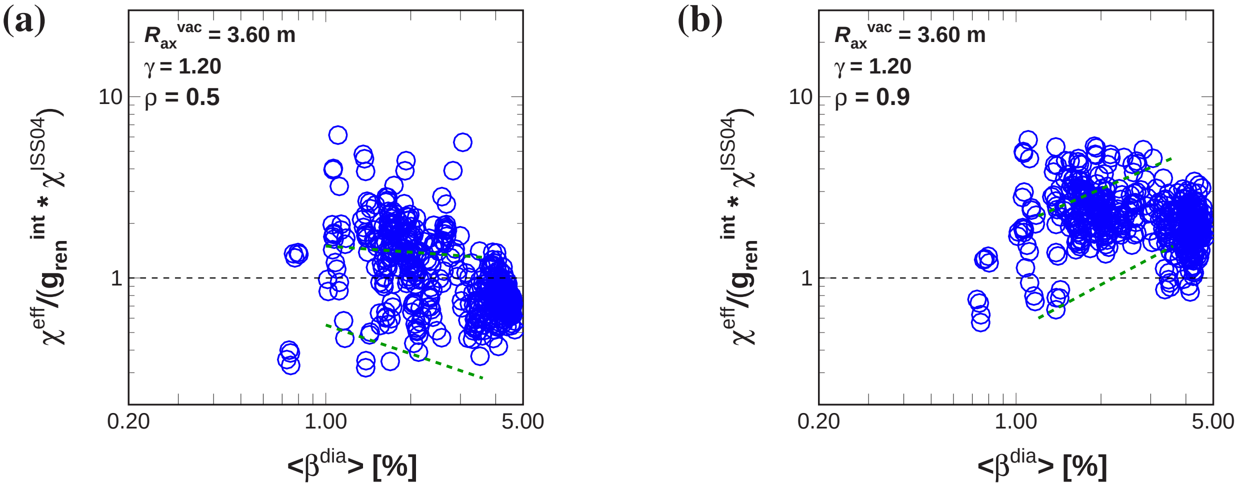

FIG. 6. *Beta dependence of the normalized local transport coefficient in the* $A_\mathrm{p} = 6.6$ *configuration at (a)* $\rho = 0.5$ *and (b)* $\rho = 0.9$*. The effect of the change of the magnetic configuration is included.*

the high-beta regime is compared with the dependence of $\chi^\mathrm{eff}/\chi^\mathrm{ISS04}$ on $R_\mathrm{geo}(\rho)$ in the low-beta regime because it is defined that the magnitude of $g_{\mathrm{ren}\chi}$ at $R_\mathrm{ax}^\mathrm{vac} = 3.60\,\mathrm{m}$ is 1. Although $R_\mathrm{geo}(\rho)$ depends on the pressure profile of the plasma, the data at the larger $R_\mathrm{geo}(\rho)$ position have higher β values in general. The symbols △, and ○ in Fig. 4 are the same as in Fig. 2. 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 in the low-beta regime.

In order to evaluate the degradation in the local transport which is caused from reasons other than the change of the magnetic configuration, a new factor $g_{\mathrm{ren}\chi}^\mathrm{int}$ is introduced, which is derived by interpolating $g_{\mathrm{ren}\chi}$ at each ρ in Fig. 2. Figures 5 and 6 show the beta dependences of the normalized local transport coefficient $\chi^\mathrm{eff}/\chi^\mathrm{ISS04}$ in the $A_\mathrm{p} = 5.8$ and 6.6 configurations at (a) $\rho = 0.5$ and (b) $\rho = 0.9$, respectively. The effects of the change of the magnetic configurations on the local transport coefficients in the high beta region are represented by $g^{\mathrm{int}}_{\mathrm{ren}\chi}$. Therefore, the effects of the beta increment or the increment in gradient beta are appear in $\chi^{\mathrm{eff}}/(g^{\mathrm{int}}_{\mathrm{ren}\chi}\chi^{\mathrm{ISS04}})$. Figure 5 shows the results in the configuration of $A_{\mathrm{p}} = 5.8$. The outlines of the data region more than $1\,\%$ of $\langle\beta\rangle$ in the configuration of $A_{\mathrm{p}} = 5.8$ are shown by the green dashed lines in Figs 5 (a) and (b). In Fig. 5 (b), as $\chi^{\mathrm{eff}}/(g^{\mathrm{int}}_{\mathrm{ren}\chi}\chi^{\mathrm{ISS04}})$ becomes large with the increment in $\langle\beta\rangle$, transport degradation due to effects other than the change of the magnetic configuration exists at $\rho = 0.9$. The degradation of the local transport with the increment in $\langle\beta^{\mathrm{dia}}\rangle$ seems to be comparable with or slightly smaller than the degradation by the torus-outward shift of the magnetic flux surface at $\rho = 0.5$.

On the other hand, the results in the $A_{\mathrm{p}} = 6.6$ configuration are shown in Fig. 6. The green dashed lines in Figs 6 (a) and (b) are the same as those in Fig. 5 (a) and (b), respectively. Figure 6 (b) shows that the degradation of the local transport is larger than the effect of the change of the configuration in the $\langle\beta\rangle > 1\,\%$ region at $\rho = 0.9$. However, it is different from the case of $A_{\mathrm{p}} = 5.8$ that the ratio $\chi^{\mathrm{eff}}/(g^{\mathrm{int}}_{\mathrm{ren}\chi}\chi^{\mathrm{ISS04}})$ seems to decrease in $\langle\beta\rangle > 2\,\%$. As shown in Fig. 6 (a), $\chi^{\mathrm{eff}}/(g^{\mathrm{int}}_{\mathrm{ren}\chi}\chi^{\mathrm{ISS04}})$ also seems to be improved in the $\langle\beta\rangle > 2\,\%$ region at $\rho = 0.5$ in $A_{\mathrm{p}} = 6.6$.

5. Discussion and Summary

The local transport coefficients of high beta plasmas in the magnetic configuration with $R^{\mathrm{vac}}_{\mathrm{ax}} = 3.60\,\mathrm{m}$ and $A_p = 6.6$, where the maximum $\langle\beta\rangle$ was obtained on LHD, are evaluated. The renormalization factor for the local transport $g_{\mathrm{ren}\chi}$ are derived from the low-beta plasmas at $R^{\mathrm{vac}}_{\mathrm{ax}} = 3.60, 3.75$ and $3.90\,\mathrm{m}$ with $A_{\mathrm{p}} = 6.6$. As the geometric center of the magnetic flux surface is shifted torus-outward, $g_{\mathrm{ren}\chi}$ increases at all minor radial positions. However, the dependence on $R_{\mathrm{geo}}(\rho)$ at $\rho = 0.9$ differs from those at $\rho = 0.5$ and 0.7 especially at $R^{\mathrm{vac}}_{\mathrm{ax}} = 3.90\,\mathrm{m}$.

The increment in the local transport at $\rho = 0.9$ seems to be larger than the effect of the change of magnetic configuration in the $\langle\beta\rangle > 1\,\%$ region with $A_p = 6.6$. This is similar to the results in the $A_p = 5.8$ case. However, the ratio $\chi^{\mathrm{eff}}/(g^{\mathrm{int}}_{\mathrm{ren}\chi}\chi^{\mathrm{ISS04}})$ seems to decrease in $\langle\beta\rangle > 2\,\%$. As the shift of the geometric center of the magnetic flux surface of $\rho = 0.9$ is small, more detailed dependences of $g_{\mathrm{ren}\chi}$ on $R^{\mathrm{vac}}_{\mathrm{ax}}$ in low-beta region is needed.

In the high beta regime with $A_p = 5.8$, the beta dependence of the transport coefficients at the peripheral region is similar to the calculated transport coefficients by the resistive pressure-gradient driven turbulence (resistive g-mode) [7]. This predicted transport by resistive g-mode becomes small when the magnetic Reynolds number S is large. This is one possible cause of the difference in the local transport at the peripheral region between $A_p = 5.8$ and 6.6. Moreover, since the parameter S is mainly related with the magnetic field strength and the temperature, it is considered that the influence of this degradation in high-beta regime will be small in high temperature plasmas relevant to fusion reactors.

Acknowledgement

The authors thank Prof. A. Komori for his continuous encouragement. This work has been supported at NIFS by NIFS10ULHH016.

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