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journal or publication title	Physics of Plasmas
volume	Vol.18
number	Issue5
page range	056119-1 - 056119-10
year	2011-05-01
URL	http://hdl.handle.net/10655/8932

doi: 10.1063/1.3592675

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Citation: [Phys. Plasmas](#) **18**, 056119 (2011); doi: 10.1063/1.3592675

View online: <http://dx.doi.org/10.1063/1.3592675>

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Effect of pressure-driven MHD instabilities on confinement in reactor-relevant high-beta helical plasmas^{a)}

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(Received 19 November 2010; accepted 27 April 2011; published online 26 May 2011)

Through the experiment data analysis in the large helical device (LHD), the influence of the global MHD instability and the relatively short wave length MHD instabilities driven turbulence on the confinement performance in reactor-relevant high-beta helical plasmas is studied. The comparison of the energy confinement time between just before global MHD instability disappears and after that, and the estimation of the saturated mode structure by the multi-channel soft x-ray measurement enable us to quantitatively estimate the influence of the global interchange type MHD instability with different saturated mode structures on the confinement performance. According to the comparison between thermal conductivities in experiments and those predicted by theoretical transport models, the transport properties in the peripheral region of high beta LHD plasmas are quite similar with anomalous transport model based on an interchange type MHD instability driven turbulence, and that result is supported by the dependence of the density fluctuation with relatively short wave length on beta value. © 2011 American Institute of Physics. [doi:10.1063/1.3592675]

I. INTRODUCTION

The Large Helical Device (LHD)¹ is a heliotron device,² which is a helical type toroidal magnetic plasma confinement system and a probable candidate as the thermonuclear fusion reactor under the steady-state operation because it can confine plasma with only external coils. The heliotron device is characterized as the relatively weak magnetic shear and hill (sometimes magnetic well) in the core and the relatively strong shear and hill in the periphery. The Heliotron-E,^{3,4} the Heliotron-DR,⁵ the ATF,⁶ the CHS,⁷ in addition to the LHD are categorized in the heliotron device. In those devices, the interchange type MHD instabilities are considered to play an important role in the confinement properties due to the magnetic hill. The effects of the interchange type MHD instabilities have been studied well. According to the early researches, the interchange type instabilities induce sawtooth oscillations and internal disruptions,^{8,9} and the instabilities would affect the achieved beta values.^{5,10}

Also in the LHD experiments, we have studied the effects of the interchange type instabilities. In the relatively low-beta discharges, the pressure gradients around the core low-order rational surface are limited, and its upper boundary is consistent with the limitation by the ideal MHD instability.¹¹ And a beta collapse and the recover of the confinement performance are observed in the unfavorable configuration with the fairly high magnetic hill due to the interchange type instability.^{12,13} The collapse resembles the internal disruption phenomena in the Heliotron-E, and the

instabilities radial mode width is predicted quite large according to a linear stability analysis.¹⁴ In the LHD experiment to extend the beta regime to the reactor-relevant high-beta plasmas, the increase of the neutral beam injection (NBI) heating power and/or the optimization of the magnetic configuration enable the production and the maintainment of the 5% volume averaged toroidal beta value for long time with ~ 100 times of the energy confinement time without disruptive phenomena.¹⁵ During the globally stable, long-sustainment phase, the low-order magnetic fluctuations resonated with the peripheral rational surfaces, where the magnetic hill configuration persists even in high-beta regimes, have been observed. On the contrary, the fluctuation resonated with the core surfaces is not observed where the magnetic well is formed in high-beta regimes.¹⁶ The fluctuation level resonated with the peripheral surfaces increases as the beta increases and the magnetic Reynolds number, S , decreases. The experimentally observed dependence on these two parameters is similar to the theoretical prediction by a linear theory of the resistive interchange mode.¹⁷ On the effects of the fluctuations on the confinement, the fine local flattening structures around the peripheral rational surfaces in the temperature profiles are observed together with the low-order fluctuations. Then the fluctuations may cause the degradation of the plasma performance. However, the quantitative influence has not been clear. According to a linear stability analysis, the instabilities radial mode width is predicted fairly narrow.^{14,18} And there is no consistent prediction of the instabilities effects on the confinement based on the non-linear stability analysis with the experiment results. As mentioned above, the radial mode width, which strongly sensitive to S in addition to the shear and the hill parameters, would be the very important key parameter against the

^{a)}Paper DI3 2, Bull. Am. Phys. Soc. **55**, 104 (2010).

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apparent effect of the global MHD instabilities on the plasma confinement like the collapse.¹⁴ However, the effects of the global MHD instabilities with the narrow radial mode width on the confinement performance, which would be very important to predict more accurately the influence of the instability in the helical reactor plasmas, have not been quantitatively identified yet.

Moreover, a gradual degradation of the confinement performance is observed as the beta value increases. Figure 1 shows the normalized global energy confinement time by the ISS04 empirical scaling¹⁹ as the function of $\langle\beta\rangle$. Here, the normalized one is defined as an improvement factor, H_{ISS04} , and $\langle\beta\rangle$ is a volume averaged beta value based on the diamagnetic measurements.¹⁸ According to our previous research,²⁰ it looks that the degradation of the global energy confinement time scaling can be explained by taking the renormalization factor induced in the newer empirical global energy confinement scaling (ISS04),¹⁹ which is reflected to the difference of geometrical effects like magnetic configurations except for an averaged rotational transform value (especially difference of magnetic axis positions in LHD), into account. However, according to local thermal transport analysis taking the geometrical effects into account,²⁰ the degradation of the thermal transport property is observed in the peripheral region as the beta increases in LHD. As a probable candidate which can explain the above result, an anomalous transport model based on a pressure driven MHD instability turbulence is considered in LHD.

In this paper, the influence of the global MHD instability and the relatively short wave length MHD instabilities driven turbulence on the confinement performance in the reactor-relevant high-beta helical plasmas is studied. In order to quantitatively evaluate the influence of the global MHD instability on the confinement performance, we compare the energy confinement time between just before global MHD instability disappears and after that, and discuss the relationship between the gradation level of confinement performance and the saturated internal structure of the MHD fluctuation estimated by the multi-channel soft x-ray (SXR) measurement.²¹ Here, we concentrate our attention on the edge

resonant $m=1/n=1$ mode, where m and n are the poloidal and toroidal mode numbers of the MHD instability, respectively, because the $m/n=1/1$ magnetic fluctuations are observed in the almost whole LHD high-beta discharges, their radial mode width is theoretically predicted larger than the pressure driven MHD instabilities with shorter poloidal wave length, the situation of which is favorable to measure the instability's saturated mode structure. And, in order to confirm the effect of the MHD instabilities driven turbulence on the confinement performance, we make a comparative analysis between the experimental thermal conductivities and the theoretically predicted ones based on the resistive interchange MHD instability driven turbulence for the discharges with different geometrical parameters as the magnetic shear and the magnetic curvature and different magnetic Reynolds number because the MHD driven turbulence are predicted strongly sensitive to the above parameters.

II. EXPERIMENTAL ARRANGEMENT AND DATA ANALYSIS

The LHD is a heliotron device with a pair of helical coils and three pairs of poloidal coils. All of the coils are superconducting. The typical configuration parameters of the discharges analyzed in this paper are as follows: the major radius is ~ 3.75 m, the plasma shape in the poloidal cross-section is elliptical, and the length of the major axis is ~ 0.8 m and the minor axis is ~ 1.6 m, the central and the edge values of the rotational transform are ~ 0.4 and ~ 1.5 , respectively, and the magnetic shear is strong in the periphery.²²

In the present study, we will characterize the $m=1/n=1$ mode by three parameters: (1) magnetic fluctuation level at a resonant surface, (2) radial mode width of the local radial displacement (full width at half maximum (FWHM)) evaluated by the SXR fluctuation intensity, and (3) maximum amplitude of the radial displacement by the SXR measurement. The details of the definitions of these three parameters are as follows. The $m=1/n=1$ magnetic fluctuation signals were measured with an array of magnetic probes set on the inner surface of the vacuum vessel. In the present experiment, the $m=1/n=1$ MHD instability is rotating both toroidally and poloidally at a frequency of several kHz. We have defined the magnetic fluctuation level at the resonant magnetic surface, $\iota=1$, as follows. Here ι is the rotational transform. A current sheet was assumed on the $m=1/n=1$ resonant surface and its amplitude was determined such that the magnetic fluctuation amplitude (due to the current sheet) agreed with the experimental value at the inner surface of the vacuum vessel. The magnetic fluctuation amplitude (root-mean-square amplitude) at the resonant surface, b_{11} , was then calculated and normalized to the toroidally averaged magnetic field strength along the magnetic axis [operational magnetic strength], B_0 . The normalized amplitude b_{11}/B_0 is called the magnetic fluctuation level. It should be noted that the current sheet model does not necessarily apply to the pressure-driven interchange mode. However, we will use the current sheet model as a reference model which connects the edge magnetic fluctuation amplitude and saturated internal mode structure, that is, mode amplitude and radial width of the mode.

FIG. 1. The normalized global confinement time by an empirical scaling ISS04 as a function of $\langle\beta\rangle$ for $R_{\text{ax}}^V = 3.6$ m, $A_p = 6.7$ configurations.

A multi-chord measurement of SXR emission intensity I_{SX} was performed using two arrays of silicon PIN photodiodes,²¹ whose vertical sight lines are located in a poloidal cross-section with the vertically elongated plasma shape. The total number of observation chords is 20 for each array, one from torus-outboard side and the other from torus-inboard side. The sampling space is ~ 30 mm on the major radius at the equatorial plane, which corresponds to 7% of the plasma minor radius on the projected equatorial plane in the vertically elongated cross-section. And the spatial resolution of each SXR array is ~ 30 mm due to the aperture of the sightlines. It should be noted that the radial profiles of a radial displacement, ξ_r , of the $m = 1/n = 1$ mode are modelled by the following gaussian function:

$$\xi_r = A \exp\left(\frac{(\rho - \rho_{res})^2}{(\Delta/a_p)^2}\right) \sin(\omega t - (m\theta - n\phi)). \text{ And } \frac{\xi_r}{a_p} \equiv \frac{\delta i_{SX}}{\bar{i}_{SX}/d\rho}. \quad (1)$$

Here A , ρ_{res} , and Δ are the parameters to fit the line-integrated signal, which correspond to the amplitude, the maximum location, and the radial mode width of radial displacement, respectively. ρ , a_p , ω , θ , and ϕ are the normalized minor radius, the plasma minor radius, the fluctuation frequency, the poloidal angle, and the toroidal angle, respectively. And δi_{SX} and $\bar{i}_{SX}$ are the local value of the fluctuation amplitude and DC component of the SXR signal. The DC component of the local SXR signal is evaluated by the Abel inversion methods. Filled symbols in Figs. 2(a) and 2(b) show the typical profiles of the line-integrated DC component and fluctuation of the SXR signals of the $m/n = 1/1$ instability mode for the torus inside array are plotted as the function of the major radius, which corresponds to the crossing point between SXR sightlines and the equatorial plane, respectively. Both signals are normalized by the maximum value of the DC component of the line integrated SXR signals. Figure 2(c) shows the local DC component of the SXR profile evaluated by Abel inversion method (dashed line) and the radial profile of the best fitted radial displacement (solid line) based on Eq. (1). Here, the local DC component of the SXR profile is normalized by its maximum value. The solid lines in Figs. 2(a) and 2(b) correspond to the line integrated value of the Abel inverted SXR DC component and the best fitted radial displacement, respectively. The good agreement between the fitted variable and its integral indicates that we can identify correspondence between the radial width of the mode and the saturated structure of SXR fluctuation profile. It should be noticed that $\sim 15\%$ of the FWHM normalized by the minor radius in the line averaged fluctuation, $\Delta_{1/2}/a_p$, corresponds to $\sim 6\%$ of that in the radial displacement, Δ/a_p .

Estimation of the global confinement property was carried out with the help of ISS04 empirical confinement scaling. As for the plasma β value, the experimental $\langle\beta\rangle$ from the diamagnetic measurement was compared with the β value from the ISS04 scaling value. The similar comparison has also been carried out for the H factor as follows. The H factor was estimated by two steps using ISS04 scaling: one estimated from plasma

FIG. 2. (Color online) Symbols in (a) and (b) are the line-averaged DC component and fluctuation of the SXR signals of the $m/n = 1/1$ instability mode for the torus inside array are plotted as the function of the major radius. (c) Local DC component of SXR profile evaluated by Abel inversion method (dashed line) and radial profile of the best fitted radial displacement (solid line). Lines in (a) and (b) are the line-averaged value of (c).

parameters at a time when the $m = 1/n = 1$ mode is absent at $t = **s$ and the other estimated from instantaneous plasma parameters before or after disappearance of the $m = 1/n = 1$ mode. The ratio $H_{ISS04}/H_{ISS04at**s}$ is used as a measure of the change in confinement properties brought about by the $m = 1/n = 1$ mode.

The experimental thermal conductivity used in Sec. V is the so-called effective one, χ_{eff} , which is evaluated under the assumption that the electron temperature is exactly same with ion temperature, and it is defined as the average of the ion thermal conductivity and the electron thermal conductivity, $\chi_{eff} = (\chi_{ef} + \chi_i)/2$. Here, the χ_{eff} is evaluated by the power balance equation. The all analyzed plasmas are maintained by the tangentially injected NB (neutral beam), the power deposition profiles of which are calculated by a 3-D Monte Carlo simulation code.²³ In this calculation, the powers of the particles which go outside of the last closed flux surface within some rotations in the poloidal direction are treated as the heating power loss. The NBI deposition profiles include the broadening from the birth profiles due to the finite-orbit effect. The electron temperature profiles are measured by Thomson scattering system with more than 100 locations in the radial direction.²⁴ The electron density profiles are measured by the FIR system with 11 sight-lines as the line

integrated values, and the radial profile is estimated by the Abel inversion method.²⁵ Here, we assume the simple plasmas with one species ions and the electrons.

III. CHARACTERISTICS OF THE MARGINAL STABLE DISCHARGE FOR GLOBAL MHD INSTABILITY

In order to identify the direct effect of the global MHD instability on the confinement performance, we study the confinement properties of marginally stable discharges. An example of waveforms in a discharge where the edge resonant $m = 1/n = 1$ mode appears and disappears are shown in Fig. 3. We obtain this type of discharge by inducing an impurity gas-puffing and the changing magnetic configuration. These procedures lead to the changing the magnetic Reynolds number, the pressure gradient, the magnetic shear, and the magnetic hill height around the resonant surface. Then, we obtain the marginal unstable discharges for global MHD instability with even around beta equal about 1% and almost same level of magnetic fluctuation amplitude with 5% volume averaged beta discharges. In such discharges, the $m = 1/n = 1$ magnetic fluctuation appears, or excited fluctuation disappears, in a single discharge. The magnetic fluctuation behaviour is an indication that the discharge is marginally stable or unstable to the $m = 1/n = 1$ mode, and the change in plasma performance associated with appearance or disappearance can be regarded as a direct effect of the mode. The internal structure of the saturated mode is studied with SXR fluctuation intensity profile and electron temperature profile by Thomson scattering. Figure 3(a) shows the time evolutions of the $\langle\beta\rangle$, the line averaged electron density and the NBI port-through power. The beta value is obtained from the diamagnetic measurement. Figure 3(b) shows time evolution of the coherence of the magnetic fluctuation as a function of the frequency. The white region corresponds to the existence of the coherent modes. Before $t = 1.9$ s, the strong coherent modes are observed in ~ 1.7 kHz, ~ 3.5 kHz, ~ 5 kHz, and so on, which correspond to

FIG. 3. (Color online) An example of a LHD discharge analyzed in the present study. The magnetic fluctuation due to low-order $m = 1/n = 1$ peripheral MHD mode disappears during the discharge, the disappearance being accompanied by the recovery of confinement properties.

$m/n = 1/1, 2/2, 3/3, \dots$ according to the mode analysis with the magnetic probe arrays. Here, it should be noted that the power spectrum of $m/n = 1/1$ mode is much larger by one order than those of the other modes. The abrupt increase (recovery) of $\langle\beta\rangle$ is observed when the coherent magnetic fluctuations disappear at $t \sim 1.9$ s. The dashed line corresponds to the predicted beta value to keep the same confinement property based on the ISS04 scaling as that before the MHD activity disappears. From Fig. 3(a), the plasma confinement property is degraded by 5% in the plasma stored energy due to the existence of the coherent magnetic fluctuation.

From the above effect of the MHD fluctuation on the plasma confinement property, it is essential to obtain the relationship between the internal structure of the saturated mode and its effect on plasma confinement. The saturated mode structure before the disappearance of the $m = 1/n = 1$ magnetic fluctuation is obtained from the SXR fluctuation. Figure 4(a) shows the major radial profiles of the rotational transform and the fluctuation amplitude of the line integrated SXR emission intensity just before the disappearance of the $1/1$ mode shown in Fig. 3, which corresponds to the filled symbols in Fig. 2(b). Figure 4(b) shows the phase difference profile, indicating that the fluctuation is odd in poloidal mode number and that the phase does not change in the region where the amplitude of SXR fluctuation large. The latter is similar to the characteristic of the linearly predicted interchange instability which produces no current sheet on the resonant surface. From this line integrated SXR fluctuation profile, we can define the line-integrated mode width $\Delta_{1/2}$ as the FWHM from the torus-inboard profile. As described in Sec. II, in this case, the radial mode width of the local radial displacement normalized to a_p is $\sim 6\%$, which is quite narrower than the normalized line-integrated mode width $\Delta_{1/2}$. The maximum amplitude of the radial displacement normalized by the plasma minor radius is $\sim 4\%$ as shown in Fig. 2(c).

FIG. 4. (Color online) Major radial profiles of the rotational transform and SXR amplitude (a) and phase (b) coherent with the $m = 1/n = 1$ magnetic fluctuation at $t = 1.8$ s in Fig. 3.

IV. INTERNAL STRUCTURE OF GLOBAL MHD INSTABILITY AND ITS EFFECTS ON CONFINEMENT

We will describe the dependence of plasma performance on magnetic fluctuation and SXR fluctuation, and discuss what parameters of SXR fluctuation amplitude is a good index to characterize the improvement or degradation of the plasma performance.

In Fig. 5, three different discharges are shown to see the dependence of confinement degradation evaluated from the time evolution of the normalized H_{ISS04} factor. In Fig. 5(a), where the magnetic fluctuation level is $\sim 0.008\%$, the appearance of the $m = 1/n = 1$ mode at $t = 2.69$ s does not cause any degradation of the H factor. When the magnetic fluctuation level is $\sim 0.04\%$, as shown in Fig. 5(b), the H factor is degraded by $\sim 5\%$ as the mode appears. In this case, the total magnetic field intensity B_0 is 1.375 T, lower than the case in Fig. 5(a) with B_0 of 1.75 T. And $\langle \beta \rangle$ in Fig. 5(b) is 0.5%, lower than the case in Fig. 5(a) with $\langle \beta \rangle \sim 1\%$. In Fig. 5(c), the $m = 1/n = 1$ mode brings the further degradation, up to 10%. In this case, the magnetic fluctuation level is almost the same as in Fig. 5(b), but with lower B_0 of 0.9 T and higher $\langle \beta \rangle \sim 1\%$. In Fig. 6, the radial profiles of the line-integrated SXR fluctuation amplitude are shown in the three cases in Fig. 5. Here, it should be noted the fluctuation amplitude are normalized by the maximum of the DC component of the line

FIG. 5. (Color online) Time evolution of the $m = 1/n = 1$ magnetic fluctuation level normalized by operational magnetic field strength B_0 and the confinement performance based on the ISS04 empirical global energy confinement time scaling.

FIG. 6. (Color online) Line averaged SXR fluctuation profiles normalized by the DC maximum of the line averaged SXR signals for various operational magnetic field strength B_0 .

integrated SXR signal. The operational magnetic field strength, B_0 is chosen as a parameter to distinguish discharges in this figure. In all cases, the line-integrated mode widths $\Delta_{1/2}$ are almost same. On the contrary, as the maximum of the normalized fluctuation amplitude intensities are larger, the degradation levels of the confinement performance are larger. Next, we evaluate the saturated instability mode structures with the mode width and the mode amplitude as shown in Sec. II. In the case of $B_0 = 0.9$ T, the normalized mode width is $\sim 6\%$ and the maximum intensity of the normalized radial displacement is $\sim 4\%$. Figure 7 shows the summary of the relationships between the saturated internal mode structures as characterized by the mode width and the amplitude maximum of the radial displacement. Figure 7 suggests that amplitude maximum of saturated radial displacement is strongly related with degradation level of confinement performance due to the low- n instability. The $m = 1/n = 1$ mode amplitude is a good index to characterize the effect of the mode on the degree of confinement degradation.

Here we discuss how the internal electron temperature profile changes when the confinement property is degraded. In Fig. 8, we compare the radial profiles of decrement in electron temperature caused by the presence of the $m = 1/n = 1$ mode

FIG. 7. (Color online) Degradation level of confinement performance based on the ISS04 empirical scaling versus amplitude maximum and mode width of radial displacement.

FIG. 8. (Color online) Radial profile of decrement in electron temperature associated with the presence of the $1/1$ mode.

in the case of $B_0 = 0.9$ T. In this case the $m = 1/n = 1$ mode with the amplitude maximum of the radial displacement normalized by the plasma minor radius of $\sim 6\%$ and the magnetic fluctuation level of 0.04% disappears at $t = 1.9$ s. The time averaged electron temperature profiles well before the disappearance ($t = 1.8$ – 1.87 s) are compared with the profile just after the disappearance ($t = 1.9$ s) of the $m = 1/n = 1$ mode, and the differences by the electron temperature without the $m/n = 1/1$ instability are plotted. The result shows that the decrease in electron temperature is restricted to the peripheral region where the $m = 1/n = 1$ mode amplitude has substantial value, and the decrease in the hot core region is not observed. Then, for the $m = 1/n = 1$ instability, the amplitude maximum of radial displacement of less than 4% , the instability does not have influence in the hot core region.

V. EFFECT OF THE PRESSURE DRIVEN MHD INSTABILITY DRIVEN TURBULENCE ON THE TRANSPORT

As shown in Sec. I, a gradual degradation of global confinement performance is observed as the beta value increases in LHD. Here we focus the study of the peripheral thermal transport property because it affects a large effect on the global energy confinement. Figure 9 shows the dependence of the normalized thermal conductivity, $\chi_{\text{eff}}/\chi_{\text{GB}}$, by the Gyro-Bohm (GB) model in the peripheral region on the beta value for the $A_p = 6.2$ configuration, the achieved highest beta value in which is 4.5% . It should be noted that the GB model has the similar property of ISS04 empirical confinement scaling,¹⁹ and it is proportional to β^0 . In the low-beta

FIG. 9. Normalized thermal conductivities at $\rho = 0.9$ on the beta value in the $A_p = 6.2$ configurations. χ_{GB} denotes the gyro-Bohm model.

regime, the $\chi_{\text{eff}}/\chi_{\text{GB}}$ is insensitive to the beta value as shown in Fig. 9. In the high-beta regime, $\chi_{\text{eff}}/\chi_{\text{GB}}$ looks proportional to β^1 .²⁶ The thin solid line in Fig. 9 denotes the β^1 dependence.

As the transport model proportional to β^1 , the MHD driven turbulence model is known. Here as a MHD driven turbulence model, we introduce the anomalous transport model based on the resistive interchange turbulence (g-mode turbulence, GMT) proposed by Carreras and Diamond.¹⁷ The thermal conductivity of the GMT model are written as the following:

$$\chi_{\text{GMTe}} \propto \left(\frac{q}{s}\right)^{\frac{7}{3}} (\kappa_n R_0)^{\frac{4}{3}} \frac{a_{\text{eff}}}{R_0} \left(\frac{\beta R_0}{L_p}\right)^{\frac{4}{3}} S^{-\frac{2}{3}} v_{Te} a_{\text{eff}} \quad (2)$$

or

$$\chi_{\text{GMTe}} \propto G_{\text{GMTe}} \beta^1 \nu_{p*}^{0.67} \rho_*^{0.33} \chi_B. \quad (3)$$

Here, G_{GMTe} is defined as a geometric factor, which increases with the bad curvature and decreases the magnetic shear, and χ_B is the thermal conductivity of Bohm model. In the peripheral region of heliotron devices as LHD, the resistive interchange is always unstable due to the magnetic hill configuration.

In order to study the GMT on the confinement properties in high-beta LHD plasmas, we analyze the confinement property in 2 configurations with different magnetic hill height and compare between the experimental thermal conductivities and those predicted by the GMT model. Figure 10 shows the beta dependence of the geometric factor, G_{GMTe} , in Eq. (3) for the $A_p = 6.2$ and 8.3 configurations. In the wide range of the beta regime, the level of the G_{GMTe} in $A_p = 8.3$ is larger by ~ 2 times than that in $A_p = 6.2$ dominantly due to the large level of the magnetic curvature. Figure 11 shows the dependence of the normalized thermal conductivity, $\chi_{\text{eff}}/\chi_{\text{GB}}$, by the GB model in the peripheral region on the beta value for the $A_p = 8.3$ configuration. For $A_p = 8.3$ configuration discharges, the data points with $\langle \beta \rangle < 1\%$ are a few, and the normalized thermal conductivity by GB model increases in the whole beta

FIG. 10. (Color online) Dependence of geometric factor of GMT anomalous transport model on $\langle \beta \rangle$ for the $A_p = 6.3$ and 8.2 configurations.

FIG. 11. Normalized thermal conductivities at $\rho=0.9$ on the beta value in the $A_p=6.2$ configurations. χ_{GB} denotes the gyro-Bohm model.

region as the beta increases. Here the thin solid line denotes the β^1 dependence.

Now we compare between the experimental thermal conductivities and an anomalous transport model based on the GMT.¹⁷ Figure 12 shows the experimental thermal conductivities normalized by the GMT model, $\chi_{\text{eff}}/\chi_{\text{GMTe}}$, as a function of $\langle\beta\rangle$. Here, we focus on the peripheral region, $\rho=0.9$. Figures 12(a) and 12(b) correspond to the $A_p=6.2$ and 8.3 configurations, respectively. And the thin lines denote the β^0 dependence. In Fig. 12(a), $\chi_{\text{eff}}/\chi_{\text{GMTe}}$ in the beta range of $\langle\beta\rangle < 1\%$ is quit large, which occurs because there the effect of the GMT is quite small. In the beta range of $\langle\beta\rangle > 1\%$, the beta dependence of the χ_{eff} looks consistent with the GMT model. As shown in Fig. 12(b), the beta dependence of the χ_{eff} looks also consistent with the GMT

FIG. 12. The normalized thermal conductivities at $\rho=0.9$ on the beta value. (a) and (b) correspond to the $A_p=6.2$ and 8.3 configurations, respectively. χ_{GMTe} denotes a g-mode turbulence model.

model in the higher magnetic hill configuration though the dispersion of $\chi_{\text{eff}}/\chi_{\text{GMTe}}$ is fairly large. Figure 13 shows that the dependence of the normalized beta gradient and the magnetic Reynolds number on $\langle\beta\rangle$ in the $A_p=6.2$ and the $A_p=8.3$ configurations. Here the plotted data is exact same with those in Figs. 9, 11, and 12. Both the beta gradient and the Reynolds number are the key parameters in the GMT models shown in Eq. (2). The magnetic Reynolds number in the $A_p=8.3$ configuration discharges are much lower by one order than that in $A_p=6.2$ for the same beta value. On the contrary, the beta gradients in the both cases at the same beta are almost same. The difference of the magnetic Reynolds number between the $A_p=6.2$ and 8.3 configuration discharges leads to the big difference of the absolute value of the anomalous thermal conductivity based on the GMT. Nonetheless, the experimental thermal conductivities are quite consistent with the theoretical one in both different magnetic configurations and the plasma parameters. Here it should be noted that at the same $\langle\beta\rangle$ ($\sim 2\%$), the χ_{eff} in $A_p=8.3$ is larger by 6–7 times than that in $A_p=6.2$, and that the magnetic Reynolds number, S ($\sim \beta^{0.5} \nu_*^{-1} \rho_*^{-2}$), in $A_p=8.3$ is smaller by ~ 10 times than that in $A_p=6.2$. The above facts support the probability that the peripheral thermal transport in the reactor-relevant high-beta plasma in LHD is governed by the GMT.

Another collateral evidence of the probability of the GMT model is the correlation between the beta dependence of the density fluctuation with relatively long wave length (“long” means the comparing with “micro-turbulence.” When it is compared with “global MHD instabilities,” it is “short.”) and the normalized thermal conductivity at the peripheral region by GB model. Figure 14 shows the beta dependence of the line integrated density fluctuation level with relatively long wavelength, $\lambda > 30$ mm ($m < 100$) and low frequency (< 30 kHz) for the $A_p=6.2$ configuration discharges on $\langle\beta\rangle$. Here, the line integrated density fluctuation is measured by the FIR system. The amplitude of the density

FIG. 13. (Color online) Dependence of magnetic Reynolds number, S , and beta gradient, $R_{\text{eff}} d\beta/dr$ as the function of $\langle\beta\rangle$ for $A_p=6.3$ and 8.2 configurations.

FIG. 14. The beta dependence of line integrated density fluctuation with the relatively long wave length measured by FIR.

fluctuation is quite small in the low-beta regime with $\langle\beta\rangle < 1\%$ and it suddenly increases with the beta value in the beta range of $\langle\beta\rangle > 1\%$. This behaviour looks synchronized with that of $\chi_{\text{eff}}/\chi_{\text{GB}}$ as shown in Fig. 9. And according to Ref. 27, the probable poloidal mode number of the turbulence is >10 in the turbulence, which is consistent with the observation of the density fluctuation. This result would support that the thermal transport in the peripheral region of the LHD high-beta plasma is governed by the GMT as the additional collateral evidence.

Finally, we consider the effect of the GMT on the confinement in reactor-relevant plasmas. Figure 15 shows the contours of the thermal conductivity based on the GMT model in S - $R_0 d\beta/dr$ space. The thermal conductivity becomes large with the decrease of S and increase of $R_0 d\beta/dr$. Especially in high-beta regime, the decrease of S leads to significant increase of the thermal conductivity. The operation range of S - $R_0 d\beta/dr$ for the data of Fig. 9 is also shown in Fig. 15. In LHD, the operational beta range is extended by decreasing the operational magnetic field strength. Then in LHD high-beta operation, S is small, which leads to the prediction of large thermal conductivity. Here we shall consider a fusion reactor.²⁸ Its geometrical factor on

FIG. 15. The predicted thermal conductivity by the GMT model in S - $d\beta/d\rho$ diagram with the experimental data.

the GMT model, such as magnetic shear and magnetic curvature, and the normalized beta gradient are almost same with those in present LHD high-beta operations. On the other hand, the magnetic Reynolds number would be much larger by 300–400 times than that in the present LHD high-beta operations because the magnetic field strength would be larger by around 10 times and the device size would be larger by ~ 3 times than the present LHD. When S is 300–400 times larger comparing with present LHD high-beta operation, the predicted thermal conductivity would be $\sim 1 \text{ m}^2/\text{s}$. For a fusion reactor with LHD like configuration, the anomalous transport based on the GMT is still important, but it would not be strong obstacle for the production of the high performance plasmas.

VI. CONCLUSION AND DISCUSSION

Any disruptive phenomena due to MHD instabilities is not observed, and only toroidally and poloidally rotating low-order peripheral resonant instabilities are frequently observed in the reactor-relevant high-beta LHD discharges. At the same time, the fine flattening structures in the temperature profiles on the corresponding resonant magnetic surfaces are also measured. It is very important to make clear the influence of them on the confinement performance for the design of the helical type reactor. Up to now, the influence has not been made clear, because in the typical LHD high-beta operation, we have not measured the internal structures of the instabilities due to some technical reasons such as for ECE cut-off density is too low to measure the signal due to its low operating magnetic field, and for SXR, the density of the impurity is too low to emit enough.

In this paper, the experimental studies have been carried out to quantitatively evaluate the effect of the $m=1/n=1$ peripheral instability on the plasma confinement performance using the LHD discharges which are marginally stable or unstable to the $m=1/n=1$ instability, in the range of magnetic fluctuation level up to 0.04%. We obtain this type of discharges by inducing an impurity gas-puffing and changing magnetic configuration. These procedure leads to the changing the magnetic Reynolds number, the pressure gradient, the magnetic shear, and the magnetic hill height around the resonant surface. Then we obtain the marginal unstable discharges for the global MHD instability with even around the beta equal about 1% and almost same level of the magnetic fluctuation amplitude with 5% volume averaged beta discharges. The degradation of the confinement performance is caused by the decreased edge electron temperature where the resonant surface of the mode exists. We can make the following quantitative evaluation of the influence in terms the magnetic fluctuation level and the radial displacement. The rotating $m=1/n=1$ mode magnetic fluctuation level of 0.04%, the amplitude maximum of the radial displacement normalized by the plasma minor radius of $\sim 4\%$, and its mode width of $\sim 6\%$ brings about 10% degradation of confinement performance characterized by the global confinement time normalized by the ISS04 empirical scaling. It was found that the amplitude maximum of the radial displacement estimated by SXR fluctuation profile in the

equatorial plane is a good index to characterize the influence of the global interchange type of MHD instability on the confinement performance.

In LHD high-beta discharges, the gradual degradation of the global energy confinement time normalized by an empirical scaling ISS95 is observed. It is also very important to make clear the degradation mechanism for the design of the helical type reactor. From the comparative analyses between experimentally obtained thermal conductivities and some theoretical predictions in the high-beta plasmas, there is possibility that a theoretical model based on a resistive interchange type MHD instability driven turbulence (GMT) explains the beta dependence of the peripheral thermal conductivity in the high-beta plasmas. This fact is supported by the similar analyses against other configurations and the wide range of the magnetic Reynolds number discharges, and the beta dependence of the observed density fluctuation amplitude with relatively long wavelength. The GMT model predicts the thermal conductivity scales to the first power of the beta value. However, for a fusion reactor with LHD like configuration, the anomalous transport based on the GMT is still important, but it would not be strong obstacle for the production of the high performance plasmas. Because the anomalous transport based on the GMT strongly depends on the magnetic Reynolds number, and the value of a reactor is estimated much larger by 300–400 times than that in the present LHD high-beta discharges.

According to the development researches of the reactor-relevant high-beta discharges in heliotron plasmas through the LHD experiment studies, two approaches to make high-beta plasmas are proposed.²⁹ One is the standard averaged-high-beta scenario, which is characterized as that the peakedness of the pressure profile, $\beta_0/\langle\beta\rangle$, is ~ 2 , and we consider in this paper. Here the subscript 0 denotes the center value. In this scenario, the 5% volume averaged beta discharges are necessary for the economical fusion reactor. In the LHD experiments, the high-beta discharges are achieved in an optimized configuration with the relatively high rotational transform and magnetic shear, the configuration of which is characterized as the small Shafranov shift, the strong magnetic shear, and the magnetic hill in the periphery. According to a linear theoretical prediction, the FWHM of the most unstable mode is about 5% of the plasma minor radius.^{14,18} The optimized configuration has the low-order rational surfaces in peripheral region with the magnetic hill region. Then, the study of the interchange type MHD instabilities effect on the plasma confinement is important as shown in this paper, which would be useful for the development of the modeling on the non-linear effects of the interchange MHD instabilities on the confinement.^{30,31}

The other approach to make high-beta plasmas is the high-central-beta scenario based on so-called “SDC(super dense core)” plasmas. It is characterized as the much peaked pressure profile ($\beta_0/\langle\beta\rangle > \sim 3$) and the large Shafranov shift, which is favorable to the particle supply by the ice pellet injection and the particle confinement in the core.³² In the high-central-beta scenario, the rotational transform is less than unity and the magnetic well exists in the periphery, and the interchange type instability is not considered crucial.

However, in the middle-central-beta discharges, a collapse phenomena is observed. The collapse is called the CDC (central density collapse) and reduces the central beta value by 30%–50%, but the collapse has not been observed in the reactor relevant high-central-beta discharges.²⁹ A candidate of the driving mechanism is the ballooning MHD instability, but it is still unclear.³³ In the high-central-beta scenario, the study of the MHD instability effect on the confinement is out of the scope of the present paper, and one of our future subjects.

ACKNOWLEDGMENTS

The authors are grateful to the LHD operation group for their technical support. This work is supported by the budget NIFS07KOA022 and NIFS10ULPP022 of the National Institute for Fusion Science.

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