Confinement study on the reactor relevant high beta LHD plasmas

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By improving the heating efficiency of the perpendicular NB injection due to the suppress the Shafranov shift by the pellet injection and the NBI power modulation, in addition to the increment of the parallel NBI power, we had the 5% beta plasma, and we had the 4.8% beta plasma in quasi-steady state with only gas-puffing and parallel NB injection. According to an analysis of the resistive g-mode by using 3 dimensional resistive MHD analyzing code for a typical high beta discharge with 4% beta and 10^6 magnetic Reynolds number, the radial mode width normalized by a plasma minor radius is ~5%. This fact supports that we have never observed disruptive phenomena in the LHD high beta discharges because the predicted MHD instabilities are located at peripheral surfaces with the high magnetic shear and their radial mode structure is quite narrow. According to the transport properties in the high beta discharges, the gradual degradation of the local transport with beta comparing with GB (Gyro-Bohm) model is observed. An anomalous transport model based on a GMT (G-Mode Turbulence) model is fairly consistent with the beta dependence of the experimental thermal transport. 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 magnetic Reynolds number in a reactor is much less by 300~400 times than that in the present LHD high beta discharges.

Keywords: Heliotron, LHD, high beta, MHD stability, Local transport, g-mode turbulence

1. Introduction

A heliotron device is a helical type toroidal magnetic plasma confinement system and a probable candidate as thermonuclear fusion reactor under steady-state operation because it can confine plasma with only external coils and install a well-defined divertor configuration. For an economical fusion reactor, achievement and sustainment of high beta plasma with <β>=5% is necessary. Then, the <β>=5% is a targeted value in the LHD projects from the design phase [1]. It has been considered to have a disadvantage with respect to pressure driven magneto-hydrodynamics (MHD) instabilities because the magnetic hill region exists. In order to predict the behavior of reactor plasma, we have made big effort aimed at achieving <β>=5% by increasing the heating capabilities and optimizing the operational conditions like the configurations, the heating efficiency of NBI and so on. The achieved beta value is increasing yearly as shown in Fig.1. Recently By improving the heating efficiency of the perpendicular NB injection due to the suppress the Shafranov shift by the pellet injection and the NBI power modulation, in addition to the increment of the parallel NBI power, we had the 5% beta plasma, and we had the 4.8% beta plasma in quasi-steady state with only gas-puffing and parallel NB injection. In both cases, we have not observed the disruptive phenomena.

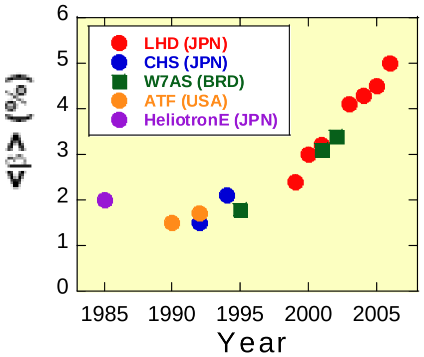

Fig.1 The yearly progress of the achieved beta value in helical devices

In this paper, we make comparative analyses between the observed beta gradient and the prediction of ideal MHD instabilities, and between the experimental thermal conductivity and the prediction based on some theoretical models, such as the Gyro-Reduced-Bohm (GRB) and the resistive g-Mode Turbulence (GMT) in the LHD with different magnetic hill configuration (plasma aspect ratio).

2. Achievement of reactor relevant high beta plasma

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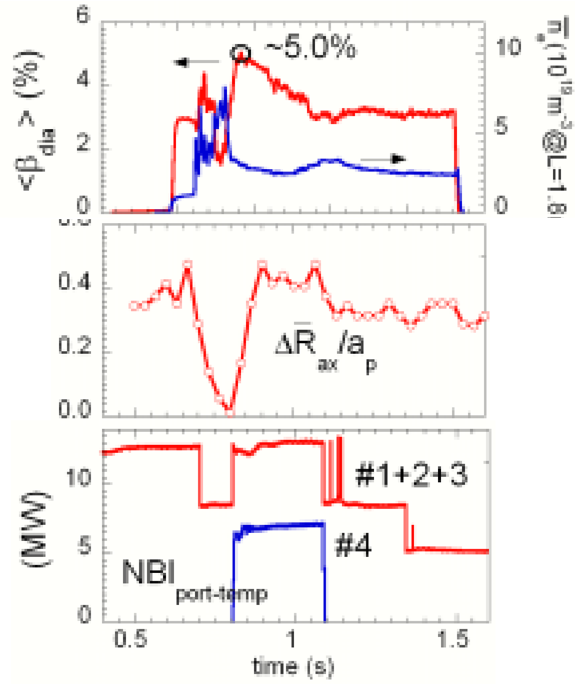

Fig.2 The waveform of the $<\beta_{dia}>$=5.0% plasma. (a) the averaged beta value and the line averaged electron density. (b) the normalized magnetic axis shift. (c) the port-through NBI power.

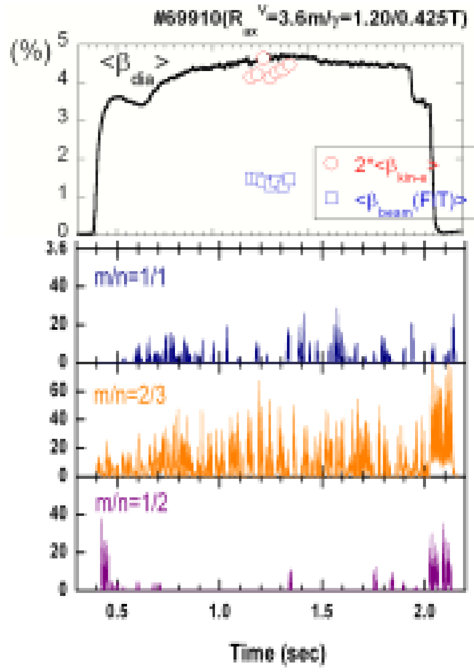

Fig.3 The waveform of the $<\beta_{dia}>$=4.8% plasma. (a) the averaged beta value and the beam component. (b)-(d) the mode amplitude of the magnetic fluctuations.

At first, we briefly mention the progress of the extension of the operational high beta regime up to the experimental campaign before last [2-4]. The heating efficiency of the NB and the MHD stability are the very important key parameters to extend the operational high beta regime. In early high beta operation in LHD, the plasma was heated only with the tangentially injected neutral beam (NB). Because the tangential radius of the NB is located at ~3.65m, the maximum of the heating efficiency is located around R_{ax}=3.6m. As well known, the magnetic axis shifts torus-outwardly as the beta increases. In order to keep the magnetic axis ~3.6m in the high beta regime, the vacuum magnetic (pre-set) configurations with the much torus-inward shifted magnetic axis and/or the high aspect plasma ratio are favorable. On the contrary, the both configurations with the more torus-inward shifted pre-set magnetic axis and the higher aspect plasma ratio are more unfavorable for the property of MHD stability. After optimizing the magnetic axis position and the plasma aspect ratio, we found the R_{ax}=3.6m and A_p=6.6 configuration the most optimum for the high beta operation, and we obtained a $<\beta_{dia}>$=4.5% plasma in F.Y.2005 [4].

In last experimental campaign in F.Y.2006, we finely study the heating efficiency of perpendicular NBI in the high beta discharges to use it more effectively for the extension of the operational high beta regime than ever before. According to a calculation, the heating efficiency of perpendicular NBI is much more sensitive to the magnetic axis position of the configurations than that of the tangential NBI. It suddenly decreases as the magnetic axis shift torus- outwardly because most of the ionized NB is trapped helically. Up to last experimental campaign, the contribution of the perpendicular NBI to the beta value was very small in the high beta discharges where the large magnetic axis shift was observed. In the high beta and low-density discharges, the beam component of the pressure is fairly large [2]. Then, it is expected that, just after the pellet injection, the beam pressure suddenly decreases, and that the magnetic axis shift decreases. Moreover, the reduction of the NBI power leads to the reduction of the magnetic axis shift due to beta. In order to control the magnetic axis position before perpendicular NB injection, we apply the pellet injection and a short break down of the tangential NBI. Due to the suppress the Shafranov shift by the pellet injection and the NBI power modulation and the addition to the perpendicular NBI power, we transiently had the 5.0% beta plasma, where plasma with more than 90% of maximum $<\beta_{dia}>$, $<\beta_{dia}>_{max}$, is maintained for a short time, ~10τ_E. Here $<\beta_{dia}>$ is the volume averaged beta value [2] and τ_E is the energy confinement time based on the diamagnetic measurement. Figure 2 shows the waveform of the $<\beta_{dia}>$=5.0% plasma. In Fig.2(a), the averaged beta value and the line averaged electron density are shown, the normalized magnetic axis shift in Fig.2(b), and the port-through NBI power in Fig.2(c), where #1+2+3 corresponds to the sum of the tangentially NB injected power and #4 to the perpendicularly NB injected power. The pellets are injected during t=0.6-0.8s. Before the pellets inject, the normalized shift of the magnetic axis exceeded 40%. During pellet injections and a NBI line break down for 0.1s, the shift of the magnetic axis approaches to zero. The perpendicular NB injection starts just after all pellet injections. After the last pellet injection, the electron density suddenly decreases and the beta value increases and reaches the maximum value of the beta, when the shift of the magnetic axis is more than 40% of the minor radius. After the beta maximum it decreases gradually. It should be noted that according to the comparison the discharges with and without perpendicular NBI, the contribution of the perpendicular NBI to the beta value is ~10% of the total beta value.

Figure 3 shows the waveform of the $<\beta_{dia}>$=4.8% plasma, which corresponds to the maximum beta value without pellet injection and the perpendicular NBI. The extension of the beta range is mainly due to the increment of the tangential NBI power comparing with the experimental campaign before last. In Fig.3(a), the averaged beta value and the beam component of the stored energy are shown, the magnetic fluctuations in Fig.3(b)-(d). The high beta plasma with $<\beta_{dia}> > 0.9\mathrm{x}<\beta_{dia}>_{max}$ is maintained for more than 80 times of τ_E (in quasi-steady). And the MHD activities corresponding to the peripheral rational surfaces are observed and its levels are not so large. The above properties are almost same with those in the

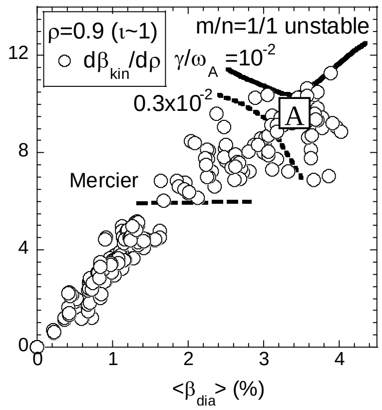

Fig.4 The peripheral beta gradients as the function of $<\beta_{dia}>$ in A_p=6.2 configuration. The contours of the growth rate of the low-n ideal MHD unstable modes are over plotted.

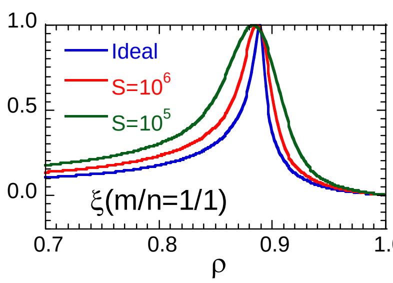

Fig.5 The radial mode structure of the global mode (m/n=1/1) for the plasma of 'A' in Fig.4 taking the resistivity into account by FAR3D. .

$<\beta_{dia}>$=4.5% plasma [2-4].

3. Effect of global MHD mode on high beta confinement

According to the analysis of the MHD equilibrium properties in the high beta configuration, the stability in the core region is improved as the beta increases. On the contrary, the stability in the peripheral region becomes worse as the beta increases. This characteristics is consistent with the fact shown in the previous section that only the MHD activities corresponding to the peripheral rational surfaces are observed in the LHD high beta plasmas. In this section, the effect of the global MHD mode resonating with the peripheral surface like m/n=1/1 (m and n are the poloidal and toroidal mode numbers, respectively) on the confinement is studied.

Figure 4 shows the thermal beta gradients at the m/n=1/1 rational surface (ρ~0.9) as faction of $<\beta_{dia}>$ in the A_p=6.2 configuration, where the achieved $<\beta_{dia}>_{max}$ is

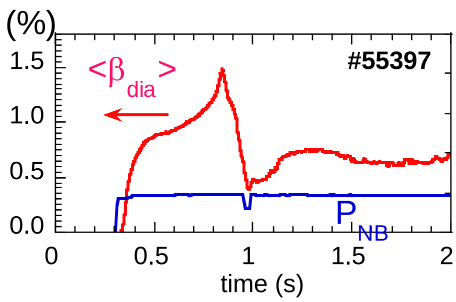

Fig.6 The evolution of the beta value and the NBI port-through power in A_p=8.3 configuration.

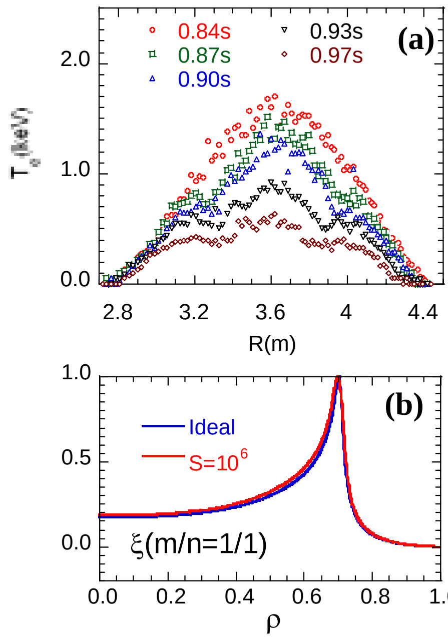

Fig.7 (a) The evolution of the electron temperature in collapse. (b) The radial mode structure of the global mode (m/n=1/1) at the just before collapse calculated by FAR3D. .

4.1% [2]. In Fig.4, the contours of the growth rate of the low-n ideal MHD unstable modes by terpsichore code [5] are superposed. It should be noted that the gradients are estimated as the averaged value for $\Delta\rho$=0.1. Around Mercier unstable region, the gradients slightly changes, but the strong reduction of the gradients are not observed in the region where the ideal global mode is predicted unstable. According to the analysis of the dependence the amplitude of magnetic fluctuation on the magnetic Reynolds number, S around $<\beta_{dia}>$~3%, it scales $S^{-0.69}$ [3]. This fact supports that the observed magnetic fluctuation in the high beta plasmas is due to the resistive interchange instability (g-mode) because the mode width estimated by a simple model, $w \sim \sqrt{\tilde{b}_\theta / B_t}$, is consistent with the theoretically predicted linear mode width of the g-mode. Figure 5 shows the mode structure of the g-mode calculated by FAR3D code [6] for the plasma presented by the 'A' in Fig.4. For the plasma consistent with the experimental S, ~10^6, the mode width is expected narrow, ~5% of the plasma minor radius. This fact supports that we have never observed disruptive phenomena in the LHD high beta discharges because the predicted MHD instabilities are located at peripheral surfaces with the high magnetic shear and their radial mode structure is quite narrow. It is noticed that, in the LHD high beta plasmas, the mode width of the resistive mode is a little bit larger than that of the ideal mode.

In order to confirm the above statement, we study the comparative analysis between the theoretical predicted mode structure and the electron temperature profile in the high aspect configuration, A_p=8.3, which is expected the much more unstable than the A_p=6.2 due the low magnetic shear and the high magnetic hill, there the achieved $<\beta_{dia}>_{max}$ is 2.6% and the collapse phenomena are observed shown in Fig.6, where the beta drops suddenly at t~0.85s. Figure 7(a) shows the evolution of the electron temperature profiles just before collapse and after it. The electron temperature at the core region significantly decreases due to the collapse. Figure 7(b) shows the linear mode structure predicted by FAR3D code. In this case the mode width is more than 10% of the minor radius and the amplitude of the mode at center is fairly large, which is much larger than that in Fig.5. It supports that the radial mode width is the very important key parameter against the apparent effect of the global MHD instabilities on the plasma confinement like the collapse. The identification of the threshold value should be investigated more.

4. Transport properties of high beta plasmas

As shown in Fig.4, the strong reduction of the beta gradients is not observed in the high beta plasma. However, a gradual degradation of global confinement performance is observed as the beta value increases as shown in ref.[2]. Here we focus the study of the peripheral transport property because it affects a large effect on the global confinement. Figure 8 shows the dependence of the normalized thermal conductivity, χ_{eff}/χ_{GB}, by the GB (Gyro-Bohm) model in the peripheral region on the beta value for the A_p=6.2 configuration. It should be noted that the GB model has the similar property of ISS95 confinement scaling [7], and it is proportional to β^0. In the low beta regime, the χ_{eff}/χ_{GB} is insensitive to the beta value. In the high beta regime, χ_{eff}/χ_{GB} looks proportional to β^1 [8].

As the transport model proportional to β^1, the MHD driven turbulence model is known. Here as a MHD driven turbulence model, we introduce an anomalous transport model based on the resistive interchange turbulence (g-mode turbulence, GMT) proposed by Careras et al. [9]. The thermal conductivity of the GMT model are written as the following,

$$\chi_{GMTe} \propto G_{GMTe}\ \beta^1\ \nu_*^{0.67}\ \rho_*^{0.33} \chi_B .$$

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 heliotron devices as LHD, the g-mode is always unstable due to the magnetic hill in the peripheral region.

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 with the experimental data the local transport analysis for the 2 configurations with the different magnetic hill height. Figure 9 shows the thermal conductivities normalized by the GMT model, χ_{GMTe}, as a function of $<\beta_{dia}>$. Here we focus on the peripheral region, ρ=0.9. (a) and (b) in Fig.9 correspond to the A_p=6.2 and 8.3 configurations, respectively. The amplitude of the bad curvature in A_p=8.3 is larger than that in A_p=6.2, that is, G_{GMTe} is larger by twice. In Fig.9(a), χ_{eff}/χ_{GMTe} in the beta range of $<\beta_{dia}>$ < 1% is quit large, which occurs because there the effect of the GMT is quite small. In the beta range of $<\beta_{dia}>$ >1%, the

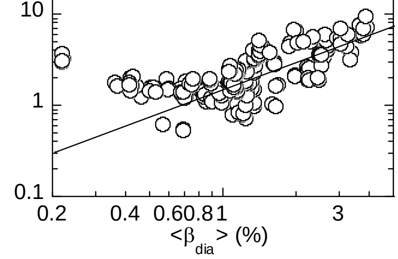

Fig.8 The normalized thermal conductivities at ρ =0.9 on the beta value in the A_p=6.2 configurations. χ_{GB} denotes the gyro-Bohm model.

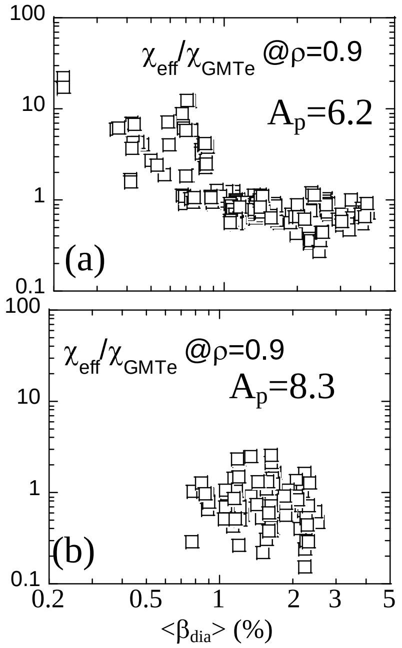

Fig.9 The normalized thermal conductivities at ρ =0.9 on the beta value. (a) and (b) correspond to the A_p=6.2 and 8.3 configurations, respectively. χ_{GMTe} denotes a g-mode turbulence model.

beta dependence of the χ_{eff} looks consistent with the GMT model. As shown in Fig.9(b), the beta dependence of the χ_{eff} looks also consistent with the GMT model in the higher magnetic hill configuration though the dispersion of χ_{eff}/χ_{GMTe} is fairly large. It should be noted that at the same $<\beta_{dia}>$ (~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 g-mode turbulence.

According to the analysis of the beta dependence of the density fluctuation with relatively long wavelength, le>30mm for the A_p =6.2 configuration, the amplitude of the fluctuation is quite small in the low beta regime with $<\beta_{dia}> < 1\%$ and it suddenly increases with beta value in the beta range of $<\beta_{dia}> >1\%$. This behavior looks synchronized with Fig.8. And according to ref.[10], the probable poloidal mode number of the turbulence is ~10, which is consistent with the observation of the density fluctuation. This result would be another collateral evidence for the effect of the g-mode turbulence on the LHD high beta plasma.

Next we consider the effect of the g-mode turbulence on the confinement in reactor relevant plasmas. Figure 10 shows a contour 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 range, decrease of S leads to significant increase of the thermal conductivity. In Fig.10, the operation rage of S-$R_0 d\beta/dr$ for the data of Fig.9(a) is also shown in Fig.10. In LHD, the decreasing the operational magnetic field strength extends the operational beta range. 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. Its geometrical factor on 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 [11]. When S is 300~400 times larger comparing with present LHD high beta operation, the predicted thermal conductivity would be ~1m^2/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.

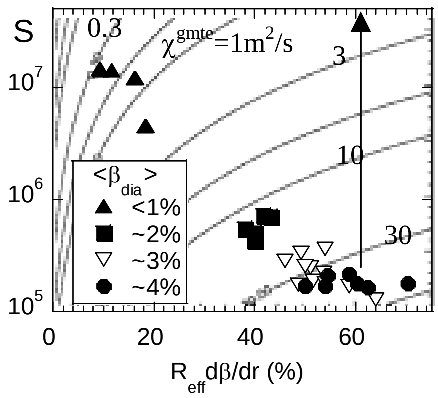

Fig.10 The predicted thermal conductivity by a t model in S-dβ/dρ diagram with the experimental data.

5. Summary

By improving the heating efficiency of the perpendicular NB injection due to the suppress the Shafranov shift by the pellet injection and the NBI power modulation, in addition to the increment of the parallel NBI power, we had the 5% beta plasma, and we had the 4.8% beta plasma in quasi-steady state with only gas-puffing and parallel NB injection, where the duration time with $<\beta_{dia}>/<\beta_{max}> > 90\%$ is longer than $100\tau_E$.

The characteristics of the high beta plasmas with β~5% is as the followings;

1. As MHD activities of global modes, only the modes resonated with peripheral rational surfaces are observed.
2. The apparent pressure-flattening region is not observed according to the electron pressure profile measurements.
3. According to linear global MHD stability analyses

taking resistivity effect into account, the global mode resonated with peripheral rational surfaces is predicted unstable, but its radial mode width is ~5% of the plasma minor radius.

From results of the comparative analyses between achieved pressure gradients and linear MHD numerical analyses for the high beta and the high aspect configurations, it is supported that the radial mode width is the very important key parameter against the apparent effect of the global MHD instabilities on the plasma confinement like the collapse.

From the comparative analyses between experimentally obtained thermal conductivities and some theoretically predictions in high beta plasmas, there is possibility that a theoretical model based on g-mode turbulence (GMT) explains the beta dependence of the peripheral thermal conductivity in high beta plasmas. This fact is supported by the similar analyses against other configuration and the beta dependence of the observed density fluctuation amplitude with relatively long wavelength.

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 S value, and the S value of a reactor is much larger by 300~400 times than that in the present LHD high beta discharges.

Acknowledgments

We special thank the LHD technical staff for their great effort of LHD operation and maintenance. We are grateful to Dr. A.Cooper for permitting use of the terpsichore code, to Drs. S.P.Hirshman and P.Merkel for the VMEC code, to late Prof. T.Hayashi for the HINT code and to Dr. Y.Nakamura for KMAG and KSPDIAG codes. We acknowledge continuous encouragement by Prof. O.Motojima. This work is supported by NIFS under Contract No. NIFS06ULHH519.

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