J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

MHD Stability Analysis of IDB Plasma in LHD

Yoshiro NARUSHIMA, Kiyomasa Y. WATANABE, Ryuichi SAKAMOTO,
Ichihiro YAMADA, Kazumichi NARIHARA, Yasuhiro SUZUKI, Satoru SAKAKIBARA,
Satoshi OHDACHI, Hiroshi YAMADA and LHD experimental group

National Institute for Fusion Science 322-6 Oroshi-cho, Toki 509-5292, Japan

Wilfred A. COOPER

Ecole Polytechnique Fédérale de Lausanne (EPFL), Centre de Recherches en Physique des Plasmas Association Euratom-Confédération Suisse, CH-1015 Lausanne, Switzerland

Jacobo VARELA RODRIGUEZ

Universidad Carlos III de Madrid Av. Universidad 30 28911 Leganés (Madrid) España

(Received: 3 September 2008 / Accepted: 16 December 2008)

The characteristics of magnetohydrodynamics (MHD) stability of plasmas with the internal diffusion barrier (IDB) are intensively studied in the Large Helical Device (LHD) experiment. These plasmas are produced by the rapid fueling into the core region with pellet injection. As a result, a high electron pressure due to the large central electron density ($n_e(0)$~10^{21}[m^{-3}]) is attained. A steep pressure gradient appears within the core region and a gentle gradient exists in the peripheral region. In spite of the steep gradient, ideal and resistive MHD modes in the core region are stable. On the other hand, the resistive MHD mode which is investigated with the MHD turbulent transport model becomes unstable in the peripheral region where the pressure gradient is gentle. The formation of such pressure profile with a steep gradient is characterized by a time evolution of an electron density profile after the pellet injection. The electron density within the core region decreases at a slower rate than that of the peripheral region. These theoretical results and experimental observations suggest that the formation of the electron density profile of the IDB plasma is influenced by the resistive MHD mode rather than the ideal MHD mode.

Keywords: Magnetohydrodynamics, Internal diffusion barrier, Large Helical Device,

1. Introduction

The characteristics of magnetohydrodynamics (MHD) stability of plasmas with the internal diffusion barrier (IDB) [1] are intensively studied in the Large Helical Device (LHD) experiment. These plasmas are realized by means of the rapid fueling into the core region with pellet injection. The central electron density ($n_e(0)$) reaches around $n_e(0) \approx 10^{21}$[m^{-3}] just after the pellet injection. After that, the electron density decreases and the electron temperature T_e increases simultaneously. The decreasing rate of $n_e(0)$ is lower than that in the peripheral region. Furthermore, the electron temperature T_e increases with time and the increasing rate of $T_e(0)$ overcomes the decreasing rate of $n_e(0)$. As the result, a steep pressure gradient within the core region and a gentle gradient in the peripheral region are established. The IDB plasmas have been produced in outer-shifted configurations with R^v_{ax} > ~3.7[m], whereas they have not been produced in inner-shifted configurations with R^v_{ax} < ~3.7[m]. Here, R^v_{ax} is the major radius of the pre-set magnetic axis of the vacuum configuration. In the case with R^v_{ax} <(>) 3.75[m], the magnetic axis is shifted inwardly (outwardly) with respect to the geometric center of the last closed flux surface R^v_{lcfs} i.e. R^v_{ax} <(>) R^v_{lcfs} when R^v_{ax} <(>) 3.75[m].

author's e-mail:narusima@LHD.nifs.ac.jp

This paper is organized as follows. The details of equilibrium of IDB and non-IDB plasmas are explained in the following section. In section 3, the MHD stability

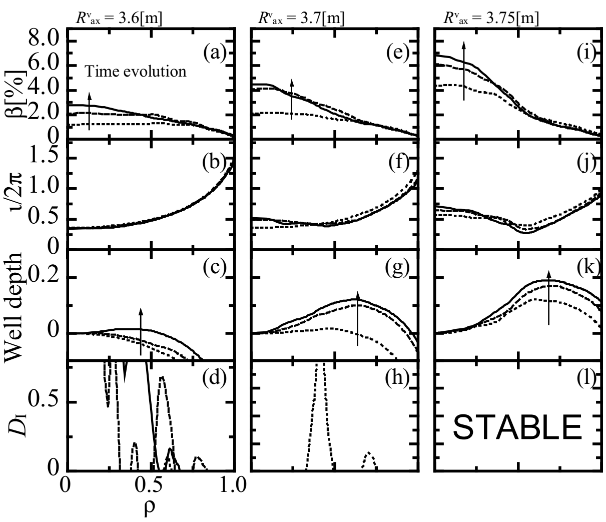

Fig.1 Profiles of β (a, e, i), ι/2π (b, f, j), well-depth (c, g, k), and D_I (d, h, l) in magnetic configurations with the magnetic axis R^v_{ax} = 3.6[m] (left column), 3.7[m] (center column), 3.75[m] (right column) in the time range from maximum $n_e(0)$ (dotted) to maximum β(0) (solid). The dashed lines indicate the time between the maximum $n_e(0)$ and the maximum β(0).

of IDB plasmas are shown by comparison with that of non-IDB plasmas. We discuss the result in section 4, and finally, summarize in section 5.

2. Equilibrium of IDB plasma

Figure 1 shows the time evolution of profiles of equilibrium parameters. In these plasmas, the same size pellets are injected at the same time interval in the beginning phase of the discharge. The beta (β) is calculated by measured n_e and T_e, which is converted into the diamagnetic beta by using the averaged vacuum toroidal magnetic field for the qualitative comparison of the pressure gradient and the diamagnetic beta. The rotational transform $\iota/2\pi$, magnetic well-depth $\{dV(0)/d\Phi - dV(\rho)/d\Phi\}/ dV(0)/d\Phi$ (here, $dV(0)/d\Phi$ and $dV(\rho)/d\Phi$ are the specific volume at magnetic axis and at ρ, respectively), and Mercier index D_I are obtained from the result of VMEC using the measured pressure profile and the current free (I_p = 0) assumption. Three kinds of lines indicate the time when maximum $n_e(0)$ (dotted line), maximum $\beta(0)$ (solid line), and the intermediate between them (dashed line). A clear IDB structure is produced in the configuration with R^v_{ax} = 3.75[m] (Fig.1 right column), in which a steep pressure gradient is maintained in the core region as shown in Fig.1(i). On the other hand, a clear IDB structure does not appear in the configuration with R^v_{ax} = 3.7[m] (Fig.1 middle column), in which a steep pressure gradient does not appear as shown in Fig.1(e).

The R^v_{ax} = 3.6[m] equilibrium case is characterized by monotonically increasing $\iota/2\pi$ (Fig.1(b)), almost magnetic hill (Fig.1(c)) at all times and everywhere, and Mercier unstable (Fig.1(d)). The equilibrium of R^v_{ax} = 3.7[m] case is characterized by almost zero shear in the core region (Fig.1(f)), magnetic well (Fig.1(g)), and Mercier unstable around maximum $n_e(0)$ and Mercier stable around maximum $\beta(0)$ (Fig.1(h)). In the R^v_{ax} = 3.75[m] case, reversed magnetic shear ($d\iota/d\rho < 0$ in Fig.1(j)) and wide ($0 \leq \rho < 0.7$) magnetic well region with deep (~ 0.2) magnetic well depth exist (Fig.1(k)). The Mercier index indicates stability as shown in Fig.1(l).

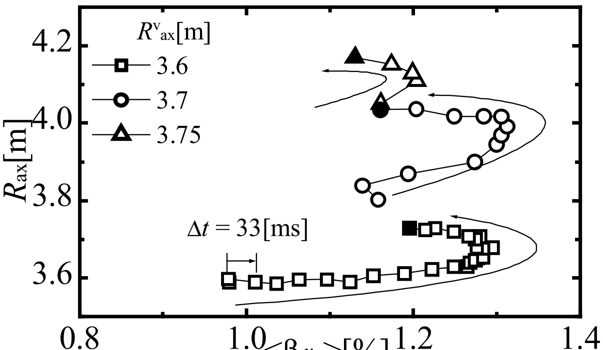

Fig.2 Time trajectories of the magnetic axis positions with symbols of square (R^v_{ax} = 3.6[m]), circle (R^v_{ax} = 3.7 [m]) and triangle (R^v_{ax} = 3.75[m]). The time evolutions reaching maximum $\beta(0)$ (closed symbols) from maximum electron density are plotted.

As shown in Fig.1(e) and Fig.1(i), the difference of pressure gradient is remarkable though the difference between R^v_{ax} = 3.7 and 3.75[m] is only five centimeters and each <β_{dia}> are almost same (<β_{dia}> = 1.16[%] (3.7[m]), <β_{dia}> = 1.13[%] (3.75[m]). However, the difference of the positions of magnetic axis becomes 0.13[m] when the $\beta(0)$ is maximum, namely, the axis positions shift to the R_{ax} = 4.04[m] (R^v_{ax} = 3.7) and 4.17[m] (R^v_{ax} = 3.75), as shown by closed symbols in Fig.2. Figure 3 shows the relationship between central diamagnetic beta $\beta(0)$ and averaged diamagnetic beta <β_{dia}> within the time range from maximum $n_e(0)$ to maximum $\beta(0)$. In all configurations, the maximum $\beta(0)$ is achieved in the decreasing phase of <β_{dia}>. The peakedness ($\beta(0)$/<β_{dia}>) shows the tendency to increase with R_{ax}. The peakedness attains $\beta(0)$/<β_{dia}> = 6.1 in the IDB plasma obtained in the configuration with R^v_{ax} = 3.75[m].

3. MHD stability of IDB plasma

Since the steep pressure gradient is realized around the core region where the rational surface of $\iota/2\pi$ = 0.5 is located in the IDB plasma, we pay attention to the local ideal MHD mode at that surface (D_I at $\iota/2\pi$ = 0.5) and the global ideal MHD mode with m/n = 2/1 (here, m/n means the poloidal/toroidal Fourier mode number). From the result of the 3-D low-n ideal MHD analysis [2], the global mode with m/n = 2/1 appears only in the configuration of R^v_{ax} = 3.6[m] at <β_{dia}> = 1.2 ~ 1.3[%] ($\beta(0)$ = 2.1 ~ 2.8[%]) indicated by closed squares in Fig.3. Its growth rate (γ/ω_A) and the normalized full width at half maximum (FWHM) of the mode width (δ/a) are γ/ω_A = 1.1 ~ 1.9×10^{-2} and δ/a = 0.08 ~ 0.11, respectively. The maximum γ/ω_A and δ/a appear in the equilibrium with maximum $\beta(0)$ of 2.8[%].

Figure 4 shows the relationship between the pressure gradient $d\beta/d\rho$ at $\iota/2\pi$ = 0.5 surface and the $\beta(0)$. The experimental data are indicated by some symbols with

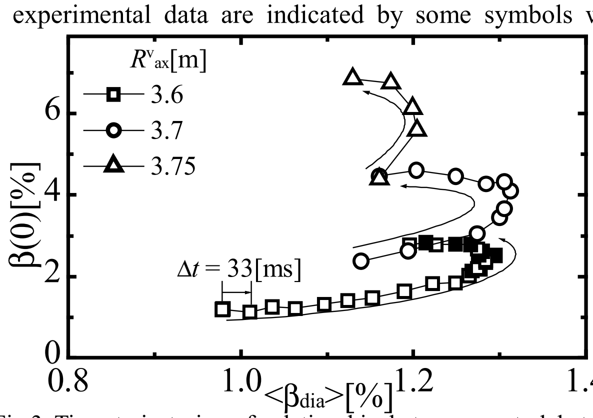

Fig.3 Time trajectories of relationship between central beta $\beta_{dia}(0)$ and averaged diamagnetic beta <β_{dia}> with symbols of square (R^v_{ax} = 3.6[m]), circle (R^v_{ax} = 3.7 [m]) and triangle (R^v_{ax} = 3.75[m]). The time evolutions reaching maximum $\beta(0)$ from maximum electron density are plotted. Closed squares indicate the global mode with m/n = 2/1 unstable.

circle (at normal magnetic shear $d\iota/d\rho > 0$) and square (at reversed magnetic shear $d\iota/d\rho < 0$). Solid lines indicate the Mercier indexes obtained from equilibrium reference with some kinds of modeled pressure profiles. The Mercier unstable region decreases with R^{v}_{ax} and eventually disappears for R^{v}_{ax} = 3.75[m]. In the case of R^{v}_{ax} = 3.6[m], experimental data exist in the Mercier unstable region. The global mode with $m/n = 2/1$ appears around ($\beta(0)$, $d\beta/d\rho$) = (2.0 ~ 3.2[%], 0.9 ~ 3.8[%]) indicated by closed circles in Fig.4(a). In the case of R^{v}_{ax} = 3.7[m], the maximum value of the Mercier index is less than $D_I = 0.13$. The experimental data seem to move temporally along the line of $D_I = 0$ as shown in Fig.4 (b). In the case of R^{v}_{ax} = 3.75[m] (Fig.4 (c)), the local MHD mode becomes stable. The pressure gradient increases with $\beta(0)$ and the maximum pressure gradient attains to $d\beta/d\rho$ = 14.3[%]. In configurations of R^{v}_{ax} = 3.6 and 3.7[m] cases, the pressure gradient might suppress the development of the local ideal MHD mode (Fig.4(a)(b)). In these configurations, the IDB plasmas have not been produced. In the IDB plasma, on the other hand, the pressure gradient seems to increase without restriction with respect to the local ideal MHD mode (Fig.4 (c)).

In the case of outer-shifted configurations, a core density collapse (CDC) after the formation of the IDB has been observed [3]. Typical profiles of n_e and β are plotted in Fig.5 in the case of R^{v}_{ax} = 3.85[m]. The n_e in the core (R = 3.7 ~ 4.3[m]) suddenly drops (Fig.5(a)) whereas the T_e is sustained during the CDC. Consequently, the β in the core region also decreases as shown in Fig.5(b). The equilibrium just before the CDC shows a steep pressure gradient (Fig.6(a)), reversed $\iota/2\pi$ (Fig.6(b)), deep magnetic well depth (Fig.6(c)), and Mercier stable (Fig.6(d)). Profiles of 5 shots are plotted in same style without distinction to show reproducibility. The global ideal MHD mode is also stable to the $n = 1$ mode family with $m < 31$. Therefore, it is thought that the ideal MHD cannot explain the CDC phenomena and the other mechanisms may cause the CDC.

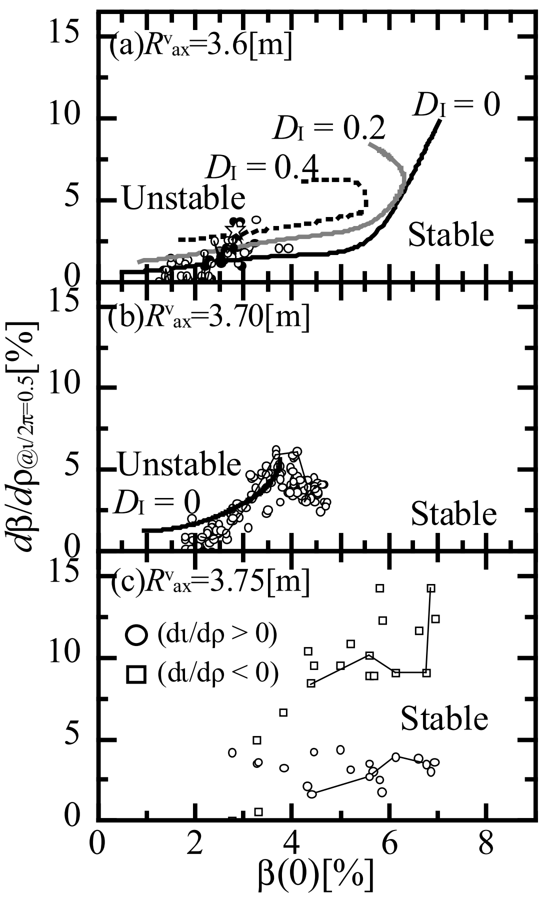

Fig.4 $\beta(0)$ vs. $d\beta/d\rho$ space at magnetic axis positions of (a) 3.6[m], (b) 3.75[m] and (c) 3.75[m], respectively. The Mercier index of D_I = 0, 0.2, and 0.4 are shown by black, gray, and dotted lines, respectively. Symbols of circle (at $d\iota/d\rho > 0$) and square (at $d\iota/d\rho < 0$) indicate experimental data. Thin line connecting symbols indicates time trajectory of one shot.

4 Discussion

The ideal MHD stability of IDB Plasma was analyzed. These results show that the IDB plasma is stable to the ideal mode in the whole plasma region. In the IDB plasma, the pressure gradient seems to increase

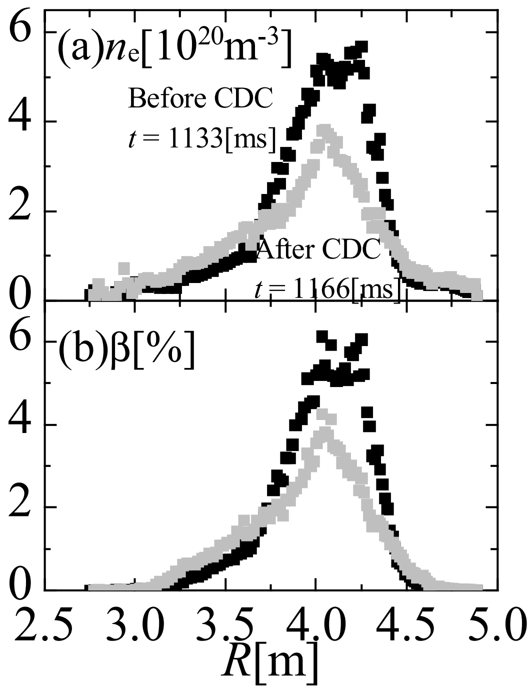

Fig.5 Profiles of (a) electron density and (b) beta at before (black) and after (gray) core density collapse.

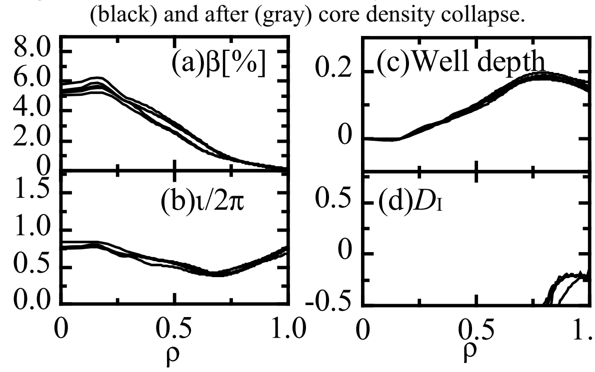

Fig.6 Profiles of (a) β, (b) $\iota/2\pi$, (c) well-depth, and (d) D_I just before core density collapse. Profiles of 5 shots are plotted in same style without distinction to show reproducibility.

without restriction imposed by the local ideal MHD mode. It is thought that the establishment of the steep pressure gradient in the core region of the IDB plasma is not affected by the ideal MHD mode. The possibility of the effect of the resistive MHD on the formation of the IDB plasma is discussed here. The time evolution of the electron density profile after the pellet injection is examined closely. The time evolution of the electron density profile is shown in Fig.7. The remarkable decrease is seen in the peripheral region. The profile of the decreasing rate of the electron density γ_{ne} ($\equiv -(dn_e/dt)/n_e$) is shown in Fig.8. The γ_{ne} is less than 1[1/s] in the core region ($\rho \leq 0.5$) and $\gamma_{ne} \cong 4$[1/s] at peripheral region ($\rho \geq 0.7$).

Next, the effect of the resistive MHD instability mode is discussed. Here, the transport via the resistive

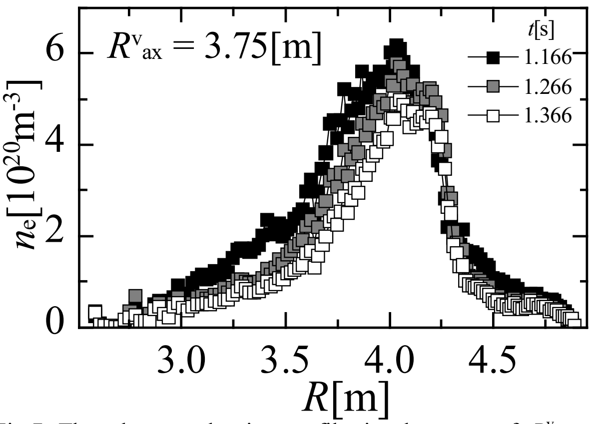

Fig.7 The electron density profile in the case of R^v_{ax} = 3.75[m]. The symbol colors indicate the time evolution from black to white at intervals of 100[ms].

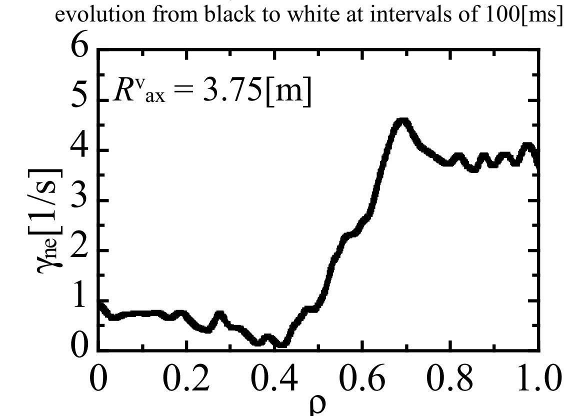

Fig.8 Profile of the decreasing rate of electron density γ_{ne} in the case of R^v_{ax} = 3.75[m].

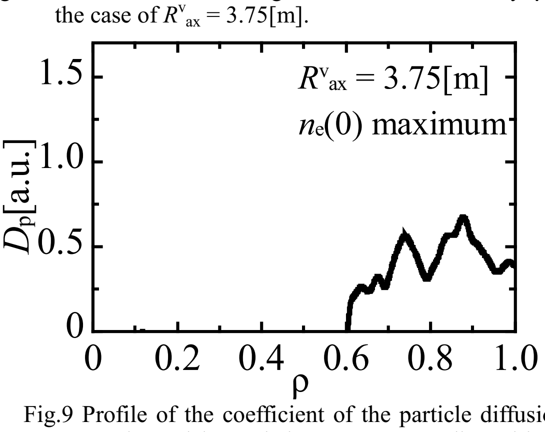

Fig.9 Profile of the coefficient of the particle diffusion estimated by resistive pressure gradient driven turbulence model.

pressure gradient driven turbulence is discussed as the effect of the resistive MHD instability. We pay attention to the time evolution after the time when the density reaches the maximum value. The characteristic time is few-hundreds milliseconds, and it is greatly different from the characteristic MHD time of few microseconds. Here, we investigate not the direct effect of MHD but the influence of MHD through the diffusion process. The coefficient of the particle diffusion driven by the turbulence D_p is defined by the differential of the specific volume (V''), Reynolds number (S), and the pressure gradient ($d\beta/d\rho$) as follows [4-5].

$$D_p \propto \frac{V''}{S}\frac{d\beta}{d\rho}\left(\rho\frac{d\iota}{d\rho}\right)^{-2} \qquad (1)$$

Here, the differential of the specific volume V'' is used instead of κ_n to estimate the coefficient of the particle diffusion D_p. The profile of D_p in the IDB plasma at maximum $n_e(0)$ is shown in Fig.9. The D_p is negative within the core region of $\rho < 0.6$ and finite in the peripheral region of $\rho > 0.6$. This suggests that the peripheral region becomes resistive MHD unstable whereas the core region is stable to both ideal and resistive MHD modes. That is, the IDB plasma is produced via the process that the electron density within the core region decreases at a slower rate than that of the peripheral region. It is suggested that the formation of the IDB plasma is affected by the resistive MHD mode correlated with the transport via the pressure gradient driven turbulence in the peripheral region. The result of the study about resistive MHD mode is shown as the collateral evidence. The resistive MHD study is being continued to clarify physics of formation of IDB plasmas.

5. Summary

The MHD stability of IDB Plasma is analyzed. The IDB plasmas have been produced in outer-shifted configurations with $R^v_{ax} > \sim$3.7[m], whereas they have not been produced in inner-shifted configurations with $R^v_{ax} < \sim$3.7[m]. The IDB plasma is not affected by the ideal MHD stability whereas the pressure gradient seems to be suppressed by the ideal local MHD mode in the case of non-IDB plasma. In the case of R^v_{ax} = 3.85[m], the CDC after the formation of the IDB has been observed, in which the ideal MHD mode is stable. It is thought that the ideal MHD cannot explain the CDC phenomena and the other mechanisms may cause the CDC. The formation of the IDB plasma with a steep pressure gradient is characterized by a time evolution of the electron density profile in the time range from $n_e(0)$ maximum to β maximum. The remarkable decrease is seen in the peripheral region. The coefficient of the particle diffusion by the resistive pressure gradient driven turbulence is positive in the peripheral region. These theoretical results and experimental observations suggest that the formation of the electron density profile of the IDB plasma is influenced by the resistive MHD mode rather than the ideal MHD mode in the peripheral region.

Acknowledgements

This study was supported by a Grant-in-Aid for Scientific Research (A)(No.17206094) from the Ministry of Education, Culture, Sports, Science and Technology of Japan. This work was supported by NIFS under Contract No.NIFS08ULPP535

References

[1] N. Ohyabu et al Phys. Rev. Lett. **97**, 055002(2006)
[2] W.A. Cooper Plas. Phys. Control. Fusion **34**, 1011 (1992)
[3] H. Yamada et al. Plas. Phys. Cont. Fus. **49** B487 (2007)
[4] B.A. Carreras et al. Phys. Fluids **30**, 1388(1987)
[5] B.A. Carreras et al. Phys. Fluids **B1**, 1011(1989)