Dynamics of ion internal transport barrier in LHD heliotron and JT-60U tokamak plasmas

K. Ida 1), Y. Sakamoto 2), M. Yoshinuma 1), H. Takenaga 2), K. Nagaoka 1), N. Oyama 2), M. Osakabe 1), M. Yokoyama 1), H. Funaba 1), N. Tamura 1), K. Tanaka 1), Y. Takeiri 1), K. Ikeda 1), K. Tsumori 1), Y. Oka 1), O. Kaneko 1), K.Itoh 1), S.Inagaki 3), T.Kobuchi 4), A. Isayama 2), T. Suzuki 2), T. Fujita 2), G. Matsunaga 2), K.Shinohara 2), Y. Koide 2), M. Yoshida 2), S. Ide 2), Y. Kamada 2), LHD experimental group and the JT-60 team

1) National Institute for Fusion Science, Oroshi, Toki, Gifu, 509-5292, Japan
2) Japan Atomic Energy Agency, Naka, Ibaraki, 311-0193, Japan
3) Research Institute for Applied Mechanics, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan
4) Department of Quantum Science and Energy Engineering, Tohoku University, Sendai, Miyagi, 980-8679, Japan

e-mail contact of main author: ida@nifs.ac.jp

Abstract. Dynamics of ion internal transport barrier (ITB) formation and impurity transport both in the Large Helical Device (LHD) heliotron and JT-60U tokamak are described. Significant differences between heliotron and tokamak plasmas are observed. The location of the ITB moves outward during the ITB formation regardless of the sign of magnetic shear in JT-60U and the ITB becomes more localized in the plasma with negative magnetic shear. In LHD, the low T_e/T_i ratio (< 1) of the target plasma for the high power heating is found to be necessary condition to achieve the ITB plasma and the ITB location tends to expand outward or inward depending on the condition of the target plasmas. Associated with the formation of ITB, the carbon density tends to be peaked due to inward convection in JT-60U, while the carbon density becomes hollow due to outward convection in LHD. The outward convection observed in LHD contradicts the prediction by neoclassical theory.

1. Introduction

The ITB formation, which is characterized by the abrupt appearance of a steep gradient region (ITB region) of temperature in the interior of the plasma, has been observed both in electron temperature (T_e) and ion temperature (T_i) transport both in LHD and JT-60U plasmas. Although the mechanism of turbulence suppression and the reduction of thermal diffusivity can be explained by the ExB shear, the mechanism determining the magnitude and size of the ITB (magnitude of the maximum T_i gradient and region of steep T_i gradient) is not well understood. Therefore it is important to compare the magnitude and size of the ITB and also the formation characteristics (how the ITB region develops) between the ITB plasma in LHD and the ITB plasma in JT-60U in order to understand ITB physics more comprehensively. Although there are many varieties of the shape of the T_i profiles in the ITB plasma in JT-60U[1] (as discussed in section 2-2), the ITB plasma in LHD is compared with the box-type ITB in JT-60U as a typical ITB plasma with a negative magnetic shear configuration.

2. Formation of the ion internal transport barrier

In LHD, the magnetic field is mainly determined by the external coil current and the rotational transform "iota" (1/q where q is the safety factor) increases toward the plasma edge. Although the sign of the magnetic shear in LHD is the same as the negative magnetic shear in a tokamak, the magnetic field is mainly determined by the external coil current and the rotational transform itself is much larger than that in tokamaks as seen in Fig.1(a). Since the transport and ITB shape are sensitive to the sign of magnetic shear rather than the absolute value of rotational transform[2], the comparison between LHD plasma and JT-60U negative shear plasma would be adequate in spite of the large difference in the absolute value of "iota".

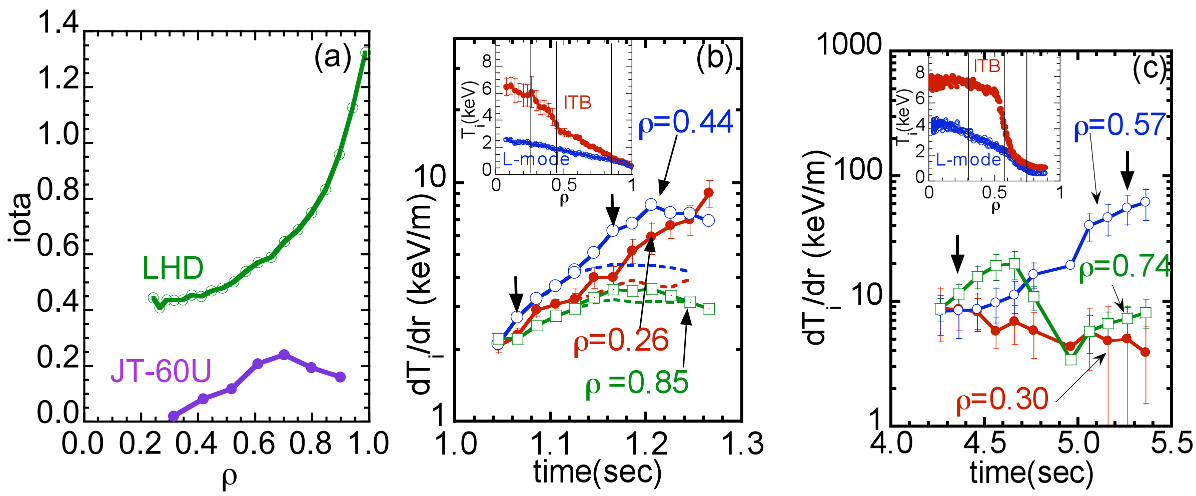

FIG.1 (a) Radial profile of rotational transform "iota" (=1/q) and time evolution of ion temperature (T_i) gradient during the formation of an internal transport barrier (ITB) in (b) the LHD heliotron and (c) the JT-60U tokamak. Radial profiles of T_i in the L-mode and ITB phase (as indicated by arrows in the time evolution of d T_i/dr) are also plotted and lines represent the location of the dT_i/dr traces. The dashed lines in Fig.1(b) are the time evolution of the T_i gradient in L-mode as a reference. The region of steep T_i gradient expands towards the plasma core (ρ =0.44 → 0.26) in LHD, while the region of steep T_i gradient is localized at the half radius (ρ = 0.57) in JT-60U.

2-1. Characteristics of ion transport barrier formation in LHD and JT-60U

The ITB plasma appears after the injection of negative neutral beam injection (N-NBI) with high energy (170-180keV) at t = 0.9s to the relatively low density hydrogen NBI plasma sustained by positive neutral beam injection (P-NBI) with low energy (40keV) in LHD. In JT-60U, the ITB appears associated with the formation of negative magnetic shear by the early NBI during the current rise phase. Significant differences between these plasmas in the characteristics of the ITB formation are observed. As seen in Fig.1(b) the T_i gradients are identical at various radii (ρ = 0.26, 0.44, 0.85). The T_i gradient at ρ = 0.44 gradually increases and that at ρ = 0.26 also increases 0.2sec after the additional heating by N-NBI (at t= 0.9sec). As indicated by the dashed lines, the T_i gradients saturate at a low level when there is no ITB formation. During the formation of the ITB, the increase of the T_i gradient is mild (by a factor of 3) but the ITB region expands towards plasma core and becomes wide in LHD. In contrast, the increase of the T_i gradient is significantly steeper (by one order of magnitude) but the T_i gradient in the core (ρ = 0.30) starts to decrease and the ITB region is localized in the narrow region at the mid point of the plasma minor radius in JT-60U [Fig.1(c)]. The formation of the ITB in the LHD plasma is characterized by the expanding ITB over a wide region of the plasma and that in the JT-60U plasma with negative magnetic shear is a localized ITB at the narrow region of the interior plasma and does not extend to the plasma core where the rotational transform is small. Similar characteristics have been observed in the electron ITB produced by ECH[3].

2-2. Location of the internal transport barrier in the positive and negative shear plasmas in JT-60U

The localization of an ITB characterized by the increase of the temperature gradient within a narrow region often appears in the plasma with a negative magnetic shear (box-shaped ITB) not in the plasma with a positive magnetic shear (parabolic-shaped ITB). The temperature gradient in the ITB plasma with the positive magnetic shear is smaller than that of the negative magnetic shear but the ITB region is relatively wide. It is interesting to compare how the ITB develops in the plasma with positive magnetic shear and with negative magnetic shear. The ion temperature gradients are measured with the modulation charge exchange spectroscopy using a Fourier series expansion technique[4].

The development of the ITB plasma can be characterized by the movement of the ITB location (the radii where the plasma has a maximum temperature gradient) and the ITB strength (magnitude of the temperature gradient). Therefore it is interesting to study how the location of the ITB moves (inward or outward) during the ITB formation. As seen in Fig.2, the ITB location moves outward during the formation of the ITB, regardless of the sign of the magnetic shear in JT-60U. There are clear differences in the development of an ITB between the plasma with positive magnetic shear and that with negative magnetic shear. In the plasma with positive magnetic shear, the ITB region tends to expand (Δρ > 0.2) as the ITB location moves outward from ρ = 0.39 to 0.57 and the temperature gradient is somewhat intermediate (~30keV/m). On the other hand, in the plasma with negative magnetic shear, the ITB strengthens (the temperature gradient reaches up to 60keV/m) and becomes more localized at ρ = 0.65 (Δρ < 0.15). In these discharges, the ITB location moves outward from ρ = 0.42 to 0.65, while the minimum q location moves inward from ρ =0.73 to 0.64 during the formation of the ITB. At the beginning of the ITB formation (t =5.0s), the ITB location is far inside of minimum q location. However, at the end of the ITB formation, the ITB location reaches the minimum q location (at ρ = 0.64) and the ITB location tends to keep tracking to the minimum q location afterwards[5]. Therefore if the minimum q location moves inward after the full development of the ITB, the ITB location moves inward associated with the movement of minimum q location.

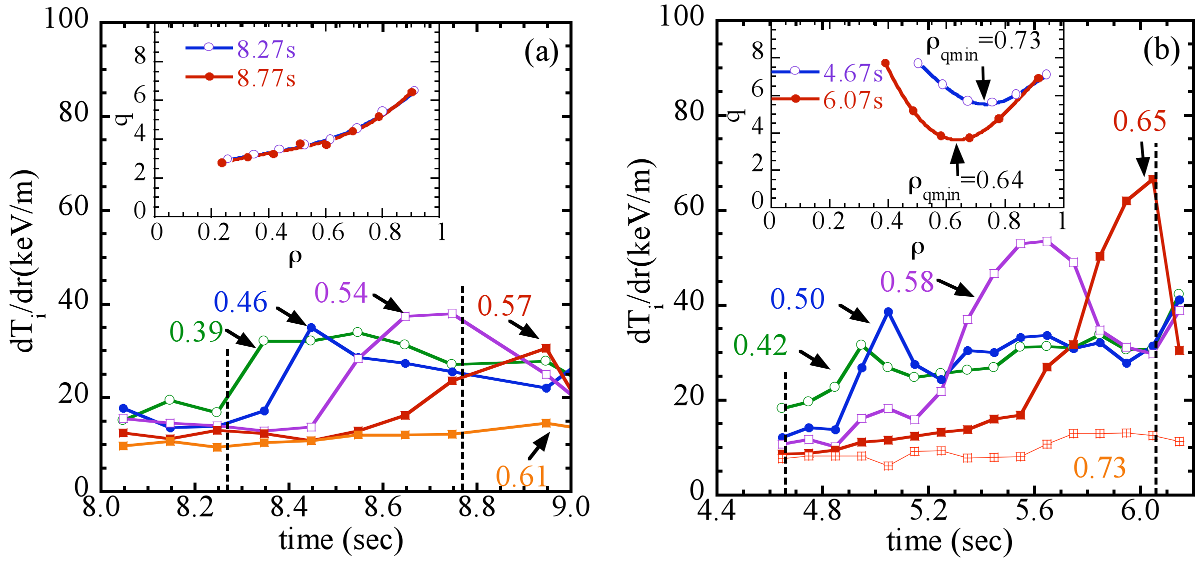

FIG.2 Time evolution of temperature gradients at various normalized radii (evaluated at t = 8.3s in Fig(a) and 5.0s in Fig(b) and indicated in the figures with numbers) during the formation of the ITB with (a) the positive magnetic shear and (b) the negative magnetic shear in JT-60U.

2-3. Formation of internal transport barrier and the ITB location in LHD

A high ion temperature plasma (~7keV) is obtained with a relatively high heating power (P_{abs} = 12 – 16MW) by both P-NBI and N-NBI with a low electron density of 0.9 – 1.3 x $10^{19}m^{-3}$. In general, both the turbulent and neoclassical flux of the ion heat transport are sensitive to the ratio of the electron temperature to the ion temperature, T_e/T_i, and the ion thermal diffusivity is expected to increase as the T_e/T_i ratio significantly exceeds unity. Therefore it is important to keep the T_e/T_i ratio close to or below unity at the onset of the high power NBI to achieve high ion temperature. There are two approaches to achieve the high ion temperature plasma by keeping the T_e/T_i ratio to a low level in LHD. One is pellet injection during the N-NBI phase and the other is only P-NBI before the start of high power heating.

Figure 3 shows the time evolution of temperature gradients in the discharges with different T_e/T_i ratios at the onset of ITB formation and with similar heating power, density and the density peaking factor (a ratio of central electron density to the line-averaged electron density). The only significant difference is in how the target plasma (t < 0.9s) for the high power heating (P_{nbi} = 11-13 MW t > 0.9s) is produced; by N-NBI, or N-NBI+pellet injection or P-NBI. No ITB formation is observed in the discharge where the target plasma for the high power heating is produced by N-NBI (6MW) where the T_e/T_i ratio is high (~1.8) because the N-NBI contributes more to electron heating. In the discharge with pellet injection, the T_e/T_i ratio drops to 1 by the decrease of the equi-partition time between ions and electrons before the onset of high power NBI and the ITB formation is observed during the decay phase of the electron density. In the discharge where the target plasma is produced by only P-NBI (5.5MW), the T_e/T_i ratio is low (~0.8), because the P-NBI contributes to the ion heating more than N-NBI because of the low beam energy . In the discharges with the target plasma produced by P-NBI, a clear ITB formation is observed after the onset of high power NBI.

These experiments clearly show that the ITB formation is sensitive to the T_e/T_i ratio. This is because the temperature gradient stays much below the threshold for the transition to the ITB plasma when the T_e/T_i ratio is significantly larger than unity. Therefore the low T_e/T_i ratio (< 1) is a necessary condition for the ITB formation in LHD. It should be noted that the degradation of transport due to the high T_e (and higher T_e/T_i ratio) is much larger than the increase of deposition power to ions due to the increase of T_e. There are differences in the time evolustion of the ITB location between the N-NBI+pellet target plasma and P-NBI target plasma. In the discharge with the N-NBI + pellet injection, the ITB first appearas near the plasma center and the ITB location moves outward. This is in contrast to the discharge with P-NBI where the ITB appears at the half plasma minor radius (ρ = 0.46) and the ITB location moves inward during the ITB formation.

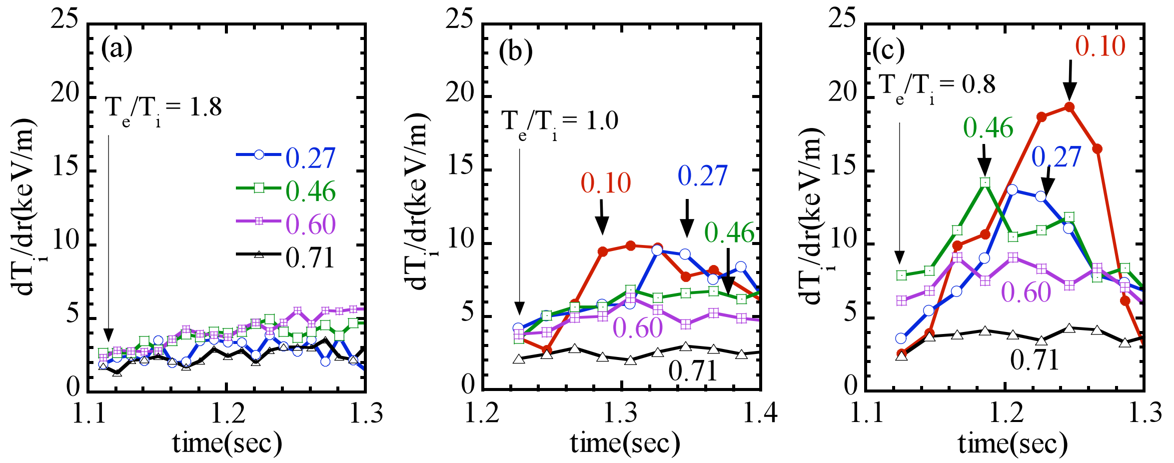

FIG.3 Time evolution of temperature gradients at various normalized radii during the formation of an ITB for the target plasma with a T_e/T_i ratio of (a) 1.8 (N-NBI), (b) 1.0 (N-NBI+pellet) and (c) 0.8 (P-NBI) in LHD. The heating power of P-NBI and N-NBI and the line averaged electron density and peaking parameter of the density profiles are (a)$P_{P\text{-}NBI}$ = 5.0MW, $P_{N\text{-}NBI}$ = 7.7MW, $n_e(0)$ = $0.9 \times 10^{19} m^{-3}$, $n_e(0)/\langle n_e \rangle$ = 1.27 (b) $P_{P\text{-}NBI}$ = 5.5MW, $P_{N\text{-}NBI}$ = 5.8MW, $n_e(0)$ = $1.1 \times 10^{19} m^{-3}$, $n_e(0)/\langle n_e \rangle$ = 1.39 (c) $P_{P\text{-}NBI}$ = 5.8MW, $P_{N\text{-}NBI}$ = 6.5MW, $n_e(0)$ = $1.3 \times 10^{19} m^{-3}$, $n_e(0)/\langle n_e \rangle$ = 1.26.

3. Impurity transport

Simultaneous achievement of high T_i and low concentration of impurity is crucial for the high fusion triple product, because impurities cause dilution of fueling particles. Since the particle diffusion in the plasma with an ITB is relatively low because of the suppression of turbulence, the sign of the convection, which appears as an off-diagonal term of the transport matrix, becomes important in the ITB plasma. Sign differences of convection of impurity transport are observed in LHD and JT-60U ITB plasmas.

3-1 Carbon density profile during the formation of an an ITB in LHD and JT-60U

The radial profiles of carbon density are evaluated from the radial profiles of the intensity of the charge exchange line CVI and the beam attenuation calculation based on the measured density and temperature profiles. As seen in Fig.4(a), the carbon density, n_C, profile changes its shape from a peaked profile to a hollow profile due to an outward convection in the wide region of ρ = 0.25–0.65 and the radial profile of carbon becomes hollow during the ITB phase in LHD. It is interesting that the electron density profiles are almost unchanged regardless of the significant change in the impurity profiles. The radial profile of carbon becomes more hollow as the ion temperature gradient is increased and when the T_i gradient is steep, an extremely hollow carbon profile "impurity hole" is observed. In contrast in JT-60U, the carbon density tends to increase due to inward convection and low diffusion in the narrow region of ρ = 0.35–0.6 and the radial profiles become more peaked in the ITB phase as seen in Fig.4(b). The electron density profile is also peaked associated with the formation of the ITB.

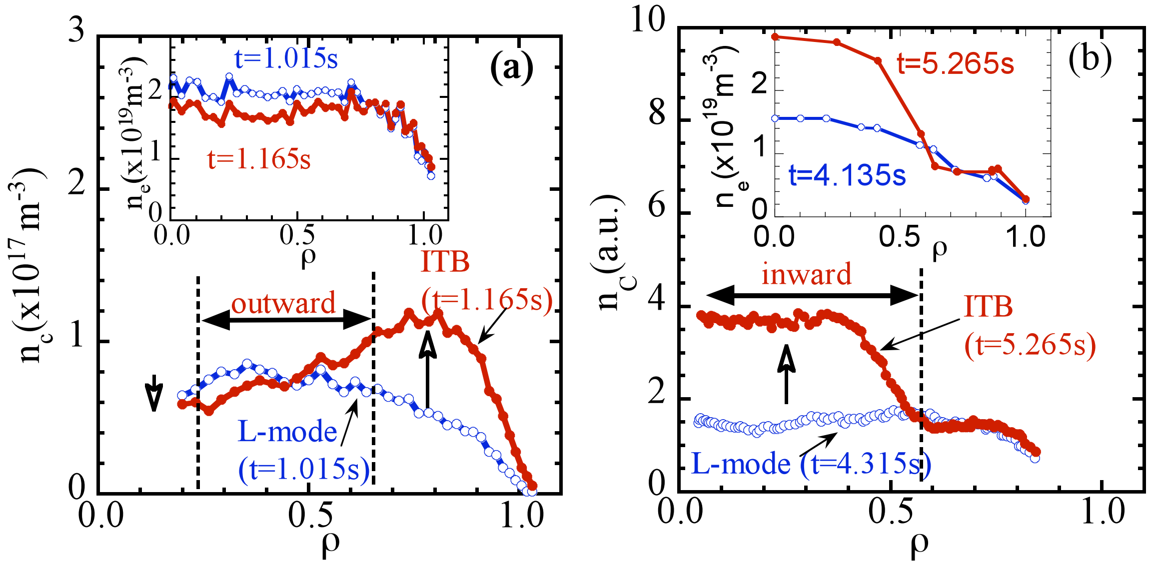

FIG.4 Radial profiles of electron density and carbon density (n_C) in the L-mode phase and ITB phase in (a) LHD and (b) JT-60U plasmas. Associated with the formation of an ITB, a strong outward convection leads the n_C profile to be hollow in the LHD plasma, while a strong inward convection is observed in the ITB region of the JT-60U plasma.

3-2. **Impurity transport analysis**

The diffusion coefficient and the convective velocity can be evaluated from the time evolution of carbon profiles assuming the diffusion and the convection velocity are constant in time after the formation of the ITB. This analysis requires a significant change in density gradients to evaluate the diffusion coefficient accurately. Therefore the diffusion coefficients can not be evaluated in the region where the density gradient and its changes in time are small especially such as in the core region of JT-60U plasma in Fig4(b). In this analysis, the diffusion coefficient is evaluated at half of the plasma minor radius, where the change in density gradient is maximum. For simplicity the diffusion coefficient is assumed to be constant in space and the radial profile of the convection velocity are evaluated both in LHD and JT-60U ITB plasmas to discuss the sign of the convection (inward or outward). The diffusion coefficient in the JT-60U plasma is $0.04 m^2/s$ and smaller than that in LHD ($0.39 m^2/s$) by an order of magnitude. This is consistent with the fact that the change in the carbon profile is relatively slow (~0.9sec) compared with the fast change in LHD (~0.15sec). The convection velocity in the LHD plasma is 0.5m/s (outward) and peaked at ρ = 0.65, while the convection velocity in JT-60U plasma is -0.2m/s (inward) and peaked at ρ = 0.45. The sign difference in the convection velocity between LHD and JT-60U is interesting because there are clear reductions of ion heat transport observed in both plasmas.

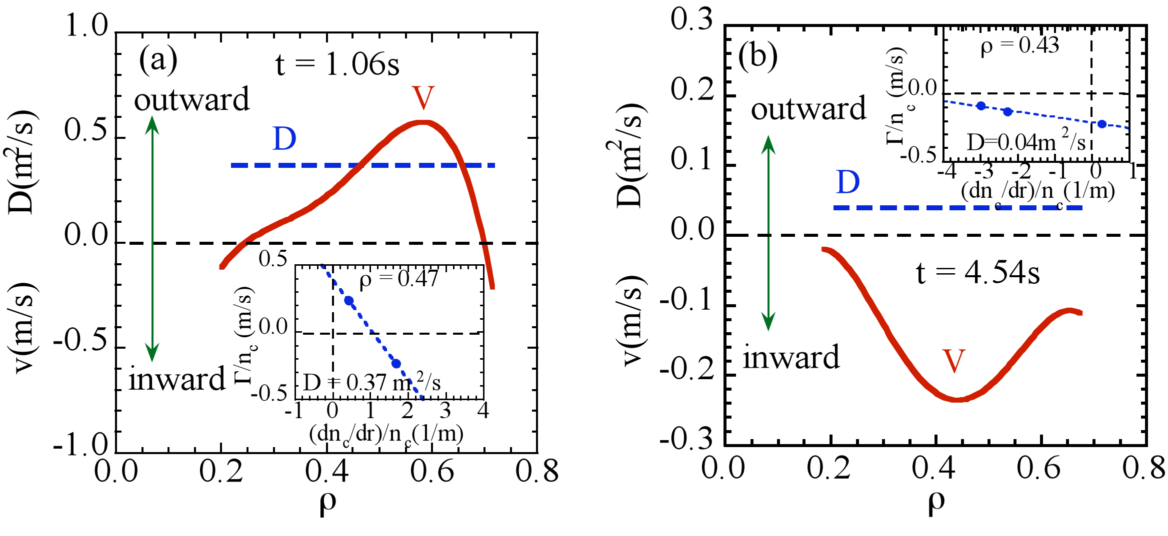

FIG.5 Radial profiles of diffusion coefficient and convection velocity for the ITB plasma in (a) LHD and (b) JT-60U. The relations between the normalized radial flux and normalized density gradient are also plotted.

The inward convection in JT-60U is predicted by neoclassical impurity transport because of the large density gradient[6]. However in neoclassical theory of helical plasmas[7], the inward convection due to the negative electric field always overcomes the outward convection due to the ion temperature gradient (temperature screening effect [8]) in this plasma, because T_i is larger than T_e by a factor of two at the end of the formation of the ITB. The prediction by the neoclassical contradicts to that the outward convection is observed in experiment in LHD. The diffusion coefficient predicted by the neoclassical theory based on measured the density temperature profiles is $0.09 m^2/s$ at $\rho = 0.5$ and is much smaller than the experimental value. The convection velocity is predicted to be -0.13m/s at $\rho = 0.5$ which contradicts the observation in LHD. These results suggest the existence of anomalous diffusion and convection driven by turbulence in LHD.

4. Discussion and Summary

The candidates for mechanisms causing the differences in the ITB formation dynamics between these two devices are the difference in the radial structure of turbulence and the contributions of neoclassical transport (significant in LHD but negligible in JT-60U). Although the steady state profile of the ITB plasma can be explained by the turbulence suppression by the radial electric field shear, it is not well understood how the ITB region develops in the L-mode region because of the complex mechanism of radial electric field generation in the plasma. The experimental results on the differences in the development of the ITB between LHD and JT-60U would give useful information to develop a comprehensive ITB theory which can cover both helical and tokamak ITBs. The sign differences in the convection of the impurity transport in the ITB plasmas can not be explained by neoclassical theory (it fails to explain the “impurity hole” observed in LHD) and would be due to the different turbulence structures driving the radial flux of particles. The outward convection of the impurity transport in the ITB plasma is considered to be beneficial for future fusion relevant plasmas.

Acknowledgement

The authors would like to thank to the technical staff in LHD and JT-60U for their support of these experiments. This work is partly supported by a Grant-in-aid for Scientific research (15206106) and the Grant-in-Aid for Specially-Promoted Research (18206094) of MEXT Japan. This work is also partly supported by NIFS05LUBB510.

References

[1] SAKAMOTO, Y., et al., Nucl. Fusion, 44 (2004) 876.
[2] FUJITA, T, Plasma Phys. Contol. Fusion 46 (2004) A35.
[3] IDA, K., et al., Plasma Phys. Control. Fusion 46 (2004) A45.
[4] IDA, K., et al., Rev. Sci. Instrum. 79 (2008) 053506
[5] SAKAMOTO, Y., et. al., Nucl. Fusion 41 (2001) 865.
[6] TAKENAGA, H., et. al., Nucl. Fusion 43 (2003) 1235.
[7] YOKOYAMA, M., et. al., Phys. Plasmas 15 (2008) 056111
[8] WADE, M.R, et. al., Phys. Rev. Lett. 84 (2000) 282.