Properties of Internal Transport Barrier Formation in JT-60U

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Abstract. The dependence of the ion thermal diffusivity (χ_i) on the radial electric field (E_r) shear has been investigated in JT-60U plasmas. In positive magnetic shear (PS) plasmas, χ_i in the core region generally increases with the heating power, similar to the L mode at low heating power. However, as a result of the intensive central heating, which is relevant to the enhancement of the E_r shear, a weak internal transport barrier (ITB) is formed, and χ_i in the core region starts to decrease. Corresponding to a further increase of the heating power, a strong ITB is formed and χ_i is reduced substantially. In the case of reversed magnetic shear (RS) plasmas, on the other hand, no power degradation of χ_i is observed in any of the heating regimes. The electron thermal diffusivity (χ_e) is strongly correlated with χ_i in PS and RS plasmas. There exists a threshold in the effective E_r shear to change the state from a weak to a strong ITB. It is found that the threshold of the effective E_r shear in the case of a PS plasma depends on the poloidal magnetic field at the ITB. There are multiple levels of reduced transport in the strong ITB for RS plasmas.

1. Introduction

The ITBs observed in JT-60U [1] can be categorized into two groups, i.e., weak and strong ITBs [2]. The weak ITB has lower diffusivity in the wide core region, compared to L-mode, while the strong ITB exhibits a large reduction in thermal diffusivity in a narrow layer. It is known that the strong ITB often develops into a so-called box-type ITB in RS plasmas. The threshold power (P_{th}) for the ITB formation is one of the critical issues for the application of ITBs to ITER. It is important to investigate the dependence of diffusivity (χ) on the heat flux in the weak and strong ITB plasmas. On the other hand, in order to maintain high stability and high confinement, ITBs have to be actively controlled. Active control of the ITB quality has been demonstrated in JT-60U by changing the toroidal momentum input or heating power, the implication of which was that E_r shear plays an important role [3]. Since the E_r shear is one of the key factors, the dependence of χ on E_r shear is required to develop the ITB control [4]. This type of study leads to a deeper understanding of the mechanism of ITB formation and also helps clarify the source of anomalous transport. To clarify these points, the dependence of χ on heating power and E_r shear has been studied in PS and RS plasmas.

2. Dependence of diffusivity on heat flux in PS and RS plasmas

The threshold power for strong ITB formation was investigated in PS plasmas with the local magnetic shear (s) of around unity [5]. In order to investigate the properties of the ITB formation, including those of weak ITBs, the power of perpendicularly injected neutral beams (P_{NB}) was scanned in a detailed manner for the PS (s<1) and RS plasmas at fixed plasma parameters (B_T=3.7T, I_p=1.3MA, target line averaged n_e=1.0x10^{19}m^{-3}, triangularity of about 0.2, balanced toroidal momentum input). Figure 1 shows the strong ITB formation in a PS plasma. Changes in T_i and T_e profiles were observed simultaneously, accompanying the bipolar transition, which indicated a rapid local drop in χ, and then the strong ITBs were formed. However, χ_i at the ITB is three times as high as the neoclassical level. Figure 2 shows the weak ITB formation in a PS plasma. With increasing heating power, T_i and T_e increased gradually in each radial location, and then the weak ITB appeared in the temperature profiles

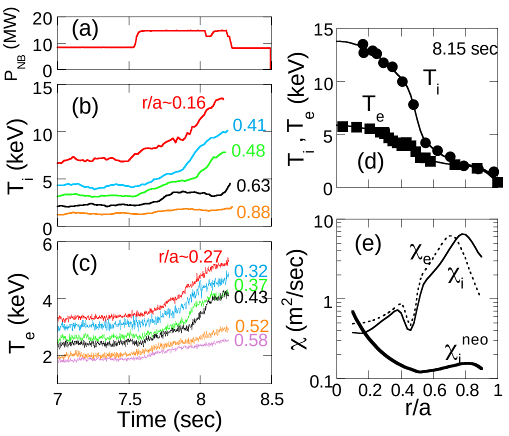

FIG. 1. The strong ITB formation in a PS plasma. (a) Waveform of the injected NB power. Time evolution of (b) T_i and (c) T_e in each radial location. Profiles of (d) T_i (closed circles) and T_e (closed squares), (e) χ_i (solid curve), χ_e (dotted curve) and χ_i^{neo} (bold curve) at t=8.15sec. The strong ITB appeared with a clear transition.

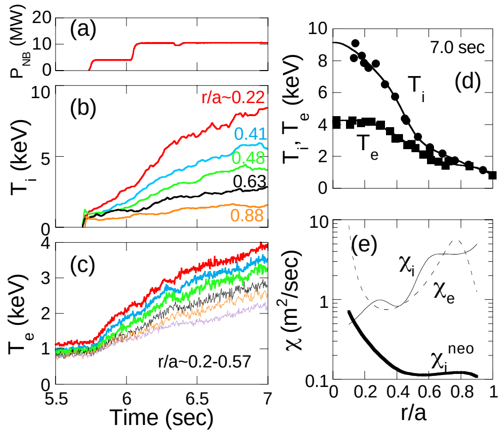

FIG. 2. The weak ITB formation in a PS plasma. (a) Waveform of the injected NB power. Time evolution of (b) T_i and (c) T_e in each radial location. Profiles of (d) T_i (closed circles) and T_e (closed squares), (e) χ_i (solid curve), χ_e (dotted curve) and χ_i^{neo} (bold curve) at t=7.0sec. The weak ITB appeared without a clear transition.

without a clear transition. The reduced transport level of the weak ITB is higher by a factor of 10 than the neoclassical level.

The dependence of χ on heat flux in PS plasmas is shown in Fig. 3. Below an absorbed P_{NB} (P_{NB}^{abs}) of 2MW, the increment of the ion temperature gradient ($-\nabla T_i$) at r/a~0.46 is very small with increasing ion heat flux (Q_i) divided by ion density (n_i), as shown in Fig. 3(c), and χ_i increases with heating power. This indicates the L-mode transport without an ITB. Indeed, the confinement enhancement factor over the L-mode scaling in this case was around unity. In the range of P_{NB}^{abs}=3-5MW, the increasing rate of Q_i/n_i against $-\nabla T_i$ is slightly reduced, which is indicative of the weak ITB formation. In the case of P_{NB}^{abs}~8MW, further reduction of χ_i is observed at the formation of the strong ITB. The relation between Q_i/n_i and $-\nabla T_i$ at the strong ITB formation is interpreted as a bifurcation in transport. On the other hand, the increasing rate of Q_i/n_i in the outer region (r/a~0.7) stays large in the L-mode state. It should be noted that the dependence of χ_e on heat flux is similar to that of χ_i, as shown in Fig. 3(b), suggesting a strong correlation between electron and ion transport. Figure 4 shows the dependence of χ

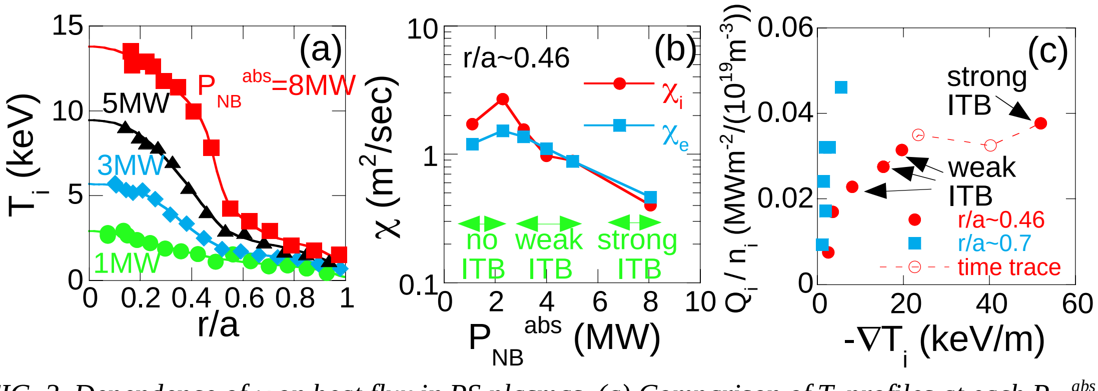

FIG. 3. Dependence of χ on heat flux in PS plasmas. (a) Comparison of T_i profiles at each P_{NB}^{abs}. (b) χ_i and χ_e as a function of P_{NB}^{abs}. With increasing heating power, the transport properties change from no ITB to the weak ITB and to the strong ITB. (c) Relation between ion heat flux divided by ion density and ion temperature gradient indicates a bifurcation in transport.

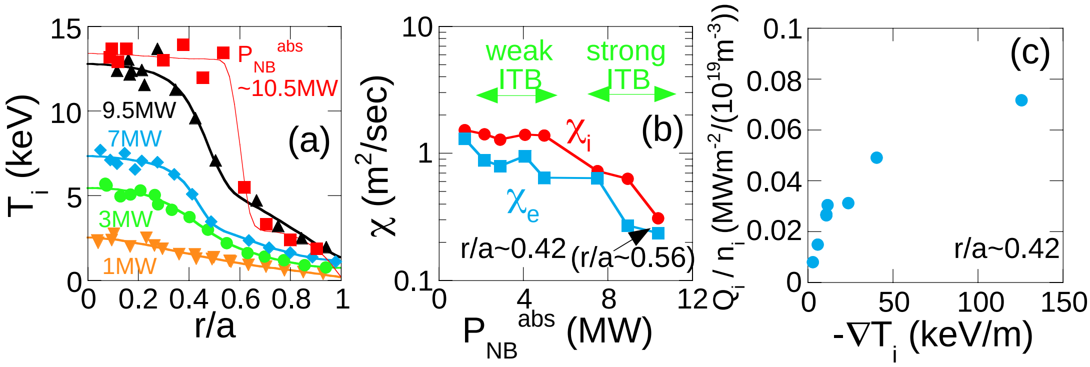

FIG. 4. Dependence of χ on heat flux in RS plasmas. (a) Comparison of T_i profiles at each P_{NB}^{abs}. (b) χ_i and χ_e as a function of P_{NB}^{abs}. No L-mode phase, where χ increases with heating power, was observed, suggesting the absence of a threshold power. (c) Relation between ion heat flux divided by ion density and ion temperature gradient.

on heat flux in RS plasmas. Below a P_{NB}^{abs} of ~5MW, χ_i stays constant with increasing heating power. In the range of P_{NB}^{abs}>7.5MW, χ_i starts to decrease when the strong ITB is formed. It is noteworthy that no power degradation in χ_i is observed for RS plasmas, suggesting the absence of a P_{th} for the weak ITB formation in RS plasmas.

In order to investigate the condition of T_e-ITB formation in the absence of T_i-ITB, the power of ECH was scanned in the range P_{ECH}=0.6-3MW in PS and RS plasmas under the condition of B_T=3.7T, I_p=1MA, and line averaged n_e~0.75×10^{19}m^{-3}. Changes in the scale length of T_e show the absence of a P_{th} for ECH with RS, while an ITB is difficult to form without T_i-ITB with PS. These results indicate that magnetic shear might play a significant role in the T_e-ITB formation.

3. Dependence of diffusivity on the E_r shear

Figure 5 shows profiles of T_i, the E_r shear (dE_r/dr) and χ_i in a PS plasma with a strong ITB (P_{NB}^{abs}~8MW). The strong E_r shear formed near the ITB layer, where a large reduction in χ_i was observed. It is seen that the ITB layer is located between the positions of the maximum and the minimum values of the E_r shear. The E_r shear becomes zero around the minimum of χ_i. In the balanced toroidal momentum injection experiment, the E_r profile has a local minimum at around half the minor radius, where the sign of the E_r shear changes. Moreover, the experiments on the toroidal momentum input [3] indicate that a reduction in the maximum and/or the minimum values of E_r shear leads to degradation of the ITB. These effects indicate the non-locality in the relation between the E_r shear and the reduction of transport. Actually, abrupt variation of the diffusivity around the ITB (ITB event) was observed over a wide interval (30% of the minor radius) [6]. By considering the non-locality, we define the effective E_r shear near the ITB as

$$(dE_r/dr)_{eff} = (|(dE_r/dr)_{max}| + |(dE_r/dr)_{min}|)/2.$$

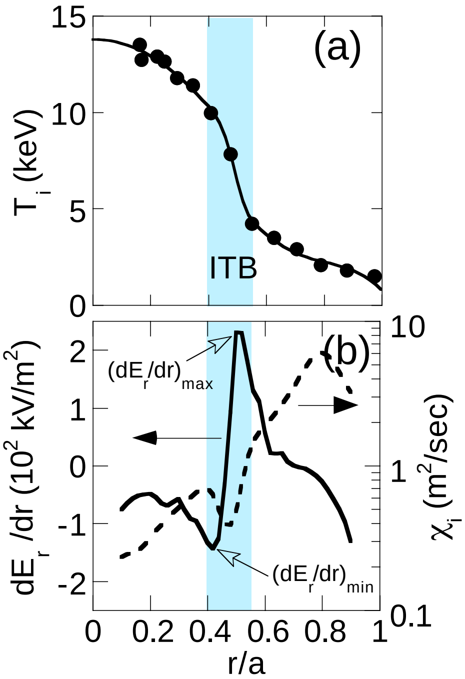

FIG. 5. Non-locality in the relation between E_r shear and χ_i. (a) T_i profile in the strong ITB. (b) Profiles of E_r shear (solid curve) and χ_i (dotted curve).

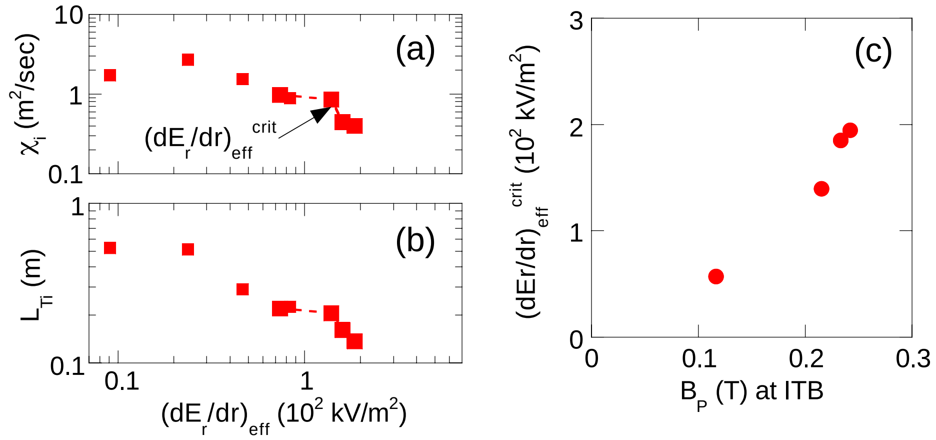

FIG. 6. (a) χ_i and (b) L_{Ti} as a function of the effective E_r shear for PS plasmas. The dotted line indicates the time trace. There exists a critical $(dE_r/dr)_{eff}$ to change the state from a weak to a strong ITB. (c) The critical $(dE_r/dr)_{eff}$ depends on the poloidal magnetic field at the ITB.

The dependences of χ_i and the scale length of T_i (L_{Ti}) on $(dE_r/dr)_{eff}$ in PS plasmas are shown in Figs. 6(a) and (b). The same cases shown in the previous figures are plotted. The value of χ_i increased with $(dE_r/dr)_{eff}$ for the cases with no ITB, whereas χ_i decreased for the data with weak and strong ITBs. There exists a critical value of $(dE_r/dr)_{eff}$ to change the state from a weak to a strong ITB. The value of L_{Ti} was constant for the cases with no ITB, and gradually decreased with increases in $(dE_r/dr)_{eff}$ for the cases with a weak ITB. A drop in L_{Ti} was observed at the strong ITB formation. The possible physical processes involved in the formation of weak and strong ITBs are considered as follows. The E_r shear increased with an increase in heating power due to the increase in the pressure gradient. The core confinement was improved, which corresponded to the formation of a weak ITB. Once the plasma state changes in acquiring the weak ITB, the E_r shear is enhanced by an increase in the heating power, and χ_i is gradually decreased. The growth of a weak ITB due to the gradual reduction in χ_i leads to an increase in the E_r shear. The transport properties change according to the transition from a weak to a strong ITB when the E_r shear exceeded the critical value. It is found that the critical value of $(dE_r/dr)_{eff}$ correlates with the poloidal magnetic field (B_p) at the ITB as shown in Fig. 6(c).

The dependences of χ_i and L_{Ti} on $(dE_r/dr)_{eff}$ in RS plasmas are shown in Figs. 7(a) and (b). In the weak ITB plasmas, χ_i stays constant and L_{Ti} slightly decreases with an increase of $(dE_r/dr)_{eff}$. The first drop in χ_i and L_{Ti} was observed at $(dE_r/dr)_{eff}$~70kV/m^2, which is smaller than that in the case of a PS plasma. The second drop in χ_i and L_{Ti} is observed at a larger value of $(dE_r/dr)_{eff}$, when χ_i is reduced to the neoclassical level. Discontinuous evolution of the strong ITB was sometimes observed in high performance RS discharges as shown in Fig. 8. In this discharge, the transition for strong ITB formation occurred at t=4.2sec, and then a box-type ITB was already formed by t=4.9sec. Rapid increases of T_i and T_e inside the ITB layer was observed at t=4.9sec and t=5.5sec. These results suggest that there are

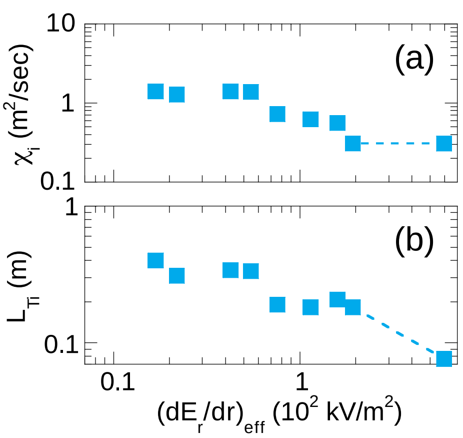

FIG. 7. (a) χ_i and (b) L_{Ti} as a function of the effective E_r shear for RS plasmas. The dotted line indicates the time trace

multiple levels of reduced transport in the strong ITB in the RS plasma. Comparison between the results shown in this paper and the local linear analysis [7] of microinstabilities is future work.

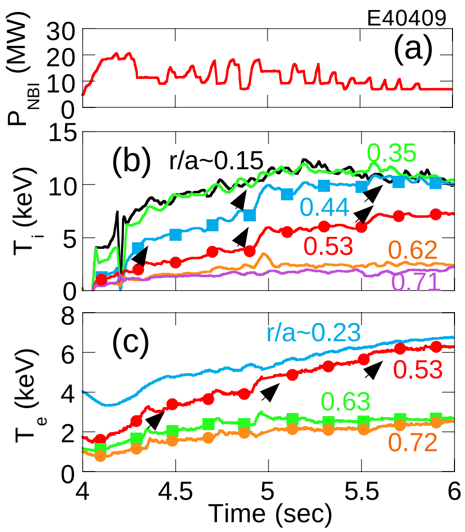

FIG. 8. (a) Waveform of the NB power. Discontinuous evolution of (b) T_i and (b) T_e at each radial location.

4. Summary and discussion

In order to address the P_{th} and control of ITBs, the dependence of χ_i on the E_r shear was investigated in JT-60U experiments with a dedicate scan of the NB heating power. In PS plasmas, χ_i in the core region generally increases with the heating power, similar to the L mode at low heating power. However, as a result of the intensive central heating, which is relevant to the enhancement of the E_r shear, a weak ITB is formed, and χ_i in the core region starts to decrease. Corresponding to a further increase of the heating power, a strong ITB is formed and χ_i is reduced substantially. In RS plasmas, however, no power degradation of χ_i is observed, suggesting absence of a P_{th} for the weak ITB formation. The T_e-ITB strongly correlates with the T_i-ITB in PS and RS plasmas. Furthermore, the results of the T_e-ITB formation experiment performed using EC heating in the absence of a T_i-ITB indicate that magnetic shear may be very influential for the T_e-ITB formation. On the other hand, E_r shear is one of the key factors for the T_i-ITB formation. In weak ITB plasmas, χ_i decreases gradually with increasing E_r shear for both PS and RS plasmas. There exists a critical value of $(dE_r/dr)_{eff}$ to change the state from a weak to a strong ITB. It is found that the critical value of $(dE_r/dr)_{eff}$ in PS plasmas correlates with B_p at the ITB. There are multiple levels of reduced transport in the strong ITB for RS plasmas.

As for the P_{th}, it is difficult to define the P_{th} for a weak ITB due to the absence of a clear transition, particularly since the P_{th} for RS is very small, suggesting the absence of a P_{th}. On the other hand, the P_{th} for a strong ITB is defined unambiguously both for PS and RS. As for the controllability of the ITB quality, a weak ITB is favorable for continuous control, while a strong ITB seems to be unfavorable due to the rapid drop in χ. Since there are multiple levels of reduced transport in the strong ITB for RS, however, the plasma can move between several levels discontinuously.

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