J. Plasma Fusion Res. SERIES, Vol. 4 (2001) 249–252

Active Control of Internal Transport Barrier and Confinement Database in JT-60U Reversed Shear Plasma

SAKAMOTO Yoshiteru*, TAKIZUKA Tomonori, SHIRAI Hiroshi, FUJITA Takaaki, KAMADA Yutaka, IDE Shunsuke, FUKUDA Takeshi and KOIDE Yoshihiko
Naka Fusion Research Establishment, Japan Atomic Energy Research Institute, Naka, Ibaraki, 311-0193, Japan

(Received: 5 December 2000 / Accepted: 27 August 2001)

Abstract

Active control of internal transport barrier (ITB) and confinement properties of plasma with ITB have been studied in reversed shear plasmas. Modifications of the radial electric field (E_r) profile by changing the combination of tangential neutral beams can control the ITB strength, where the contribution to E_r from the toroidal rotation plays an important role. The ITB confinement database of reversed shear plasmas has been constructed. Stored energy is strongly correlated with poloidal magnetic field at the ITB foot.

Keywords:

reversed shear, internal transport barrier, toroidal rotation, radial electric field, energy confinement

1. Introduction

Reversed magnetic shear plasmas have achieved high confinement of both particles and heat owing to the ITB formation [1]. MHD instabilities, however, occurred frequently because of steep pressure gradient, and then the discharges were disrupted. Accordingly active ITB control is one of the most challenging issues in magnetically confined plasmas, especially for the steady state operation, the active control of ITB strength is indispensable from the viewpoints of transport and stability.

For the understanding of plasma confinement and transport properties empirical scalings of confinement have been investigated in L-mode and H-mode plasmas. However confinement scalings for the core-improved plasmas with ITB have not been investigated so far. It is important for the understanding of physics mechanisms of ITB to investigate empirical scalings of the confinement properties.

2. Active Control of Internal Transport Barrier

Possible role of E_r and E_r shear for the ITB formation and sustainment have been discussed and supported results were reported from TFTR [2], DIII-D [3] and JT-60U [4] tokamaks. Pressure gradient and Lorentz force due to the plasma rotation for each ion species balance the E_r in toroidal plasmas, and then it gives

$$E_r = \frac{1}{Z_i e n_i}\frac{dp_i}{dr} + V_\phi B_\theta - V_\theta B_\phi , \qquad (1)$$

where Z_i, e, n_i, p_i, V_ϕ, V_θ, B_θ and B_ϕ are charge number, electronic charge, ion density, ion pressure, toroidal rotation velocity, poloidal rotation velocity, poloidal magnetic field and toroidal magnetic field, respectively. Thus the plasma rotation profile as well as the pressure gradient profile affect the E_r profile. Since the various injection directions of neutral beams (NBs) are

**Corresponding author's e-mail: sakamoty@fusion.naka.jaeri.go.jp*

©2001 by The Japan Society of Plasma Science and Nuclear Fusion Research

simultaneously available in JT-60U, changing the combination of NBs can modify the E_r profile [5].

Figure 1 shows the time evolution of ion temperature (T_i) at each normalized minor radius, where the experimental conditions consisted of the toroidal magnetic field of 3.8T and the plasma current of 1.5MA. The reversed shear plasma with ITB was generated in the standard way by balanced momentum injection (BAL) [1]. The ITB was formed around half the minor radius at t=5.6sec, as shown in Fig. 2(a). After t=5.6sec, the direction of tangential NB switched from BAL to co-momentum injection (CO), as shown in Fig. 1. Injected NB power is about 8MW, which consists of tangential NB power of 4MW and perpendicular NB power of 4MW. Although the T_i profile did not change up to t=5.8sec, the core T_i decreased rapidly in spite of no MHD activities after t=5.8sec. Time scale of the degradation of the core T_i is about 0.3sec, which is comparable to the energy confinement time estimated at t=6.5sec. It is noted that the T_i increased again in the core region after t=6.53sec, as shown in Fig. 1. This phenomenon was also observed in TFTR tokamak [2]. On the other hand, the V_ϕ changed significantly from the notched profile to the monotonic one after the co-momentum injection, as shown in Fig. 2(b). The relation between the pressure gradient at the ITB center and the gradient in V_ϕ is shown in Fig. 3(a). The V_ϕ gradient at the outside notch was estimated by using the measured V_ϕ data at r/a~0.6 and ~0.7, and also the V_ϕ gradient at the inside notch was estimated by the data at r/a~0.5 and ~0.6. Since the co-momentum injection made the toroidal rotation vary from the notched profile to monotonic one, the V_ϕ gradient at the outside notch decreased with keeping the steep pressure gradient up to t=5.8sec. The pressure gradient at the ITB center decreased rapidly when the V_ϕ gradient at the outside

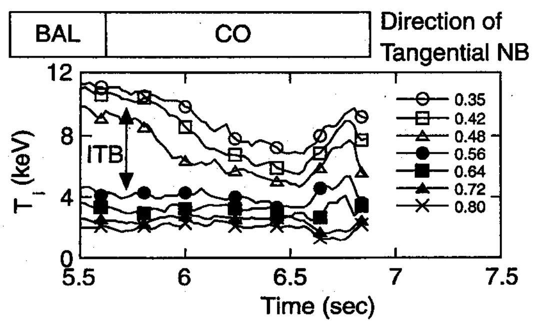

Fig. 1 Time evolution of T_i at each normalized minor radius for a direction of tangential NB.

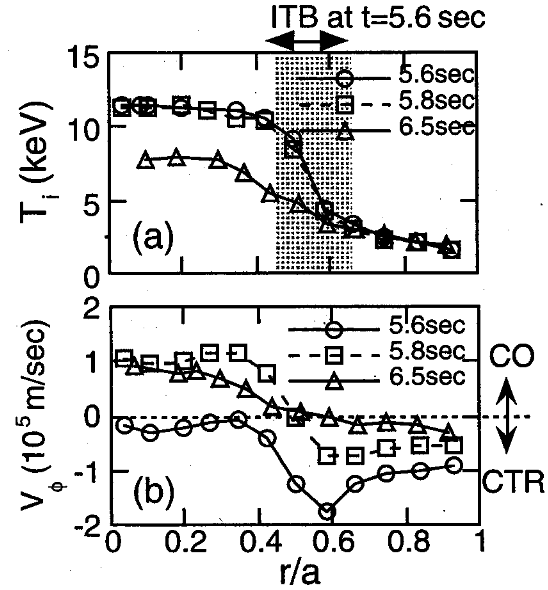

Fig. 2 Time evolution of (a) T_i profiles and (b) V_ϕ profiles at the end of BAL injection phase (t=5.6sec), right before the degradation of ITB (t=5.8sec) and after the degradation of ITB (t=6.5sec).

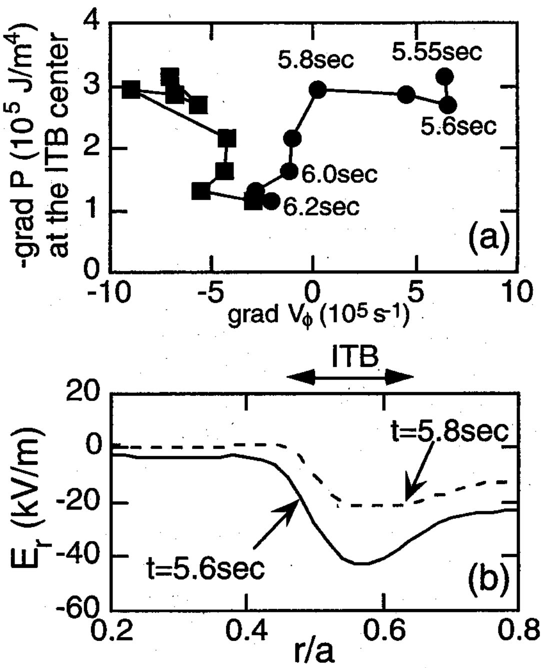

Fig. 3 (a) Relation between the pressure gradient at the ITB center and the gradient in V_ϕ. Closed circles denote the V_ϕ gradient at the outside notch, and closed squares denote the V_ϕ gradient at the inside notch. (b) E_r profiles at the end of BAL phase (t=5.6sec) and right before the degradation of ITB (t=5.8sec).

notch became about zero, as shown in Fig. 3(a). This relation suggests the causality of the ITB degradation and V_ϕ gradient. Figure 3(b) shows the E_r profiles at the end of BAL phase (t=5.6sec) and right before the degradation of the ITB (t=5.8sec). The procedure to estimate the E_r profile is described in Ref. [6]. The E_r and its gradient became smaller by the co-momentum injection, especially in the outer half region of the ITB, where the contribution to E_r from toroidal rotation is mainly changed as described above. Therefore it is conceivable that the modification of the E_r profile through the change of V_ϕ profile can control the ITB strength.

3. Stored Energy Scaling on Reversed Shear Plasmas with ITB

Confinement properties of reversed shear plasmas were investigated under the discharge conditions of B_T=4T, $0.03<\delta<0.1$, $1.7<\kappa<2.0$, $3.08<R<3.18$, $0.5<\rho_{foot}<0.75$, nearly balanced momentum injection, L-mode edge and NB heating. Here B_T, δ, κ, R and ρ_{foot} are toroidal magnetic field, triangularity, elongation, major radius and the radius of the ITB foot, respectively. The large ITB radius and L-mode edge plasmas reduced the contribution for the stored energy (W_{dia}) from outside of ITB. For this study, we use a limited data set of deuterium plasmas heated by NB. Under above discharge condition, 40 time slices over 13 discharges were selected from our database that consists of 150 time slices over 60 discharges including the various B_T and the various plasma configurations. The parameter regions of this data set are in the ranges of the plasma current I_p=1.1–2.6MA, of the line averaged electron density n_e=2.0–6.6×10^{19}m^{-3}, and of the NB power P_{NB}=6–19MW. As shown in Fig. 4(a), it is found that W_{dia} is strongly correlated with I_p. The scatter come mostly from the variation of ρ_{foot} as shown in Fig. 4(b), where I_p is fixed around 2MA. As shown in Fig. 4(c), it is mentioned that W_{dia} seem to almost independent of the loss power (P_L=P_{tot}–dW_{dia}/dt), where P_{tot} is the total heating power. Therefore the confinement property should be characterized by the local parameter such as poloidal magnetic field at ρ_{foot}, which is written by

$$B_p^{foot} \sim \frac{\rho_{foot}}{R} B_T \frac{q_{eff}}{q_{foot}} \frac{RI_p}{a^2 B_T}. \quad (2)$$

where a, q_{eff} and q_{foot} are the minor radius, the effective safety factor and the safety factor at the ITB foot, respectively. Figure 5(a) shows W_{dia} versus B_p^{foot} in the different P_L. The stored energy was strongly correlated

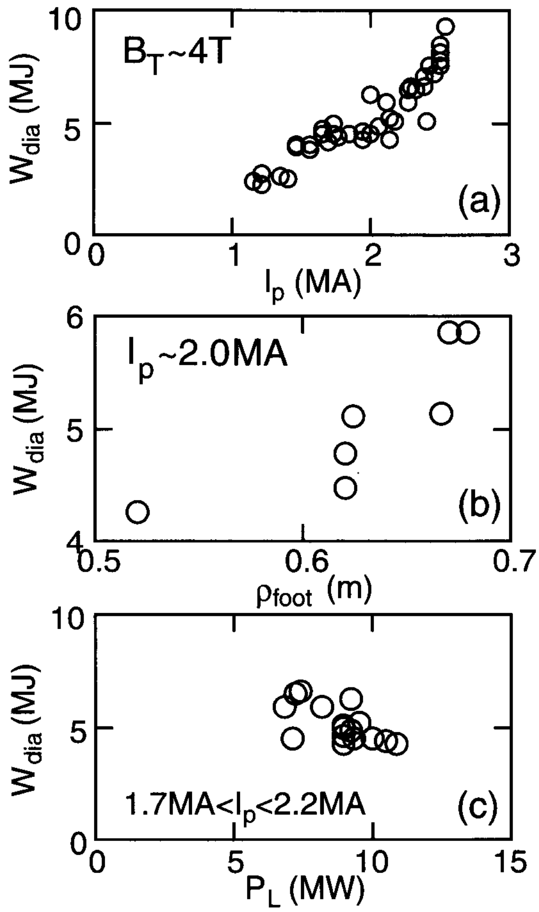

Fig. 4 Dependence of W_{dia} on (a) I_p, (b) ρ_{foot} and (c) P_L.

with B_p^{foot} rather than I_p, and it is proportional to $(B_p^{foot})^{1.5}$. As a result, the W_{dia} scaling for reversed shear plasmas was obtained as

$$W_{dia} \propto \left(B_p^{foot}\right)^{1.5} \quad (3)$$

(in MJ and T). The RMSE for this (Eq. (3)) fit, which is shown in Fig. 5(b), is 9.15%. In JT-60U reversed shear plasmas, the ITB width (Δ_{ITB}) becomes narrower with the evolution of the ITB and the lower boundary of the ITB width is proportional to the ion poloidal gyroradius at the ITB center (ρ_{pi}^{ITB}) [5]. This indicates that the transport property at the ITB layer can be characterized by the ratio of Δ_{ITB} to ρ_{pi}^{ITB}. We consider the dependence of this ratio, and then the W_{dia} scaling for reversed shear plasmas was rewritten by

$$W_{dia} = 27.1 \times \left(B_p^{foot}\right)^{1.5} \times \left(\Delta_{ITB} / \rho_{pi}^{ITB}\right)^{-0.25} \quad (4)$$

(in MJ, T and m). The RMSE for this (Eq. (4)) fit,

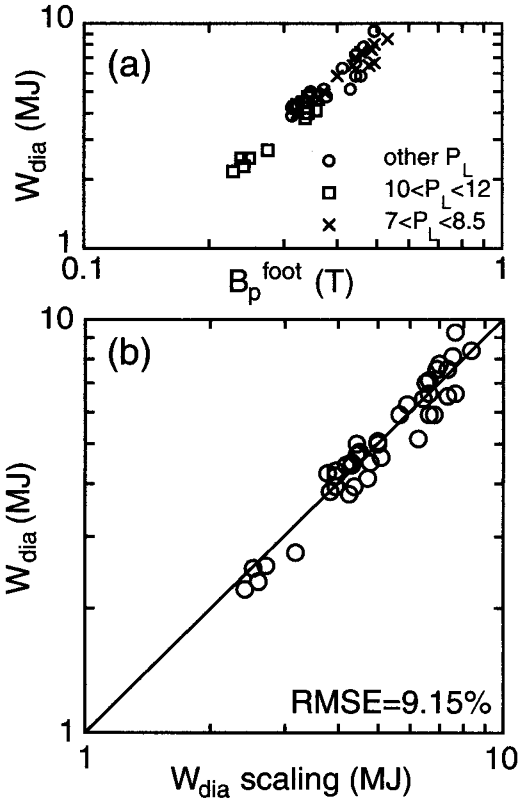

Fig. 5 (a) Dependence of W_{dia} on B_p^{foot} in different P_L (MW). (b) Comparison of experimental data of W_{dia} with the scaling expression in Eq. (3).

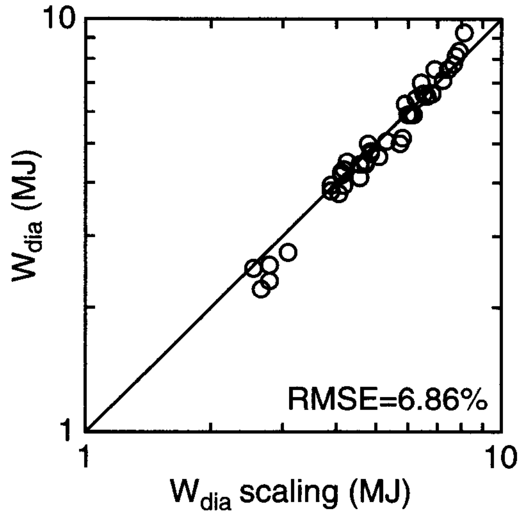

Fig. 6 Comparison of experimental data of W_{dia} with the scaling expression in Eq. (4).

which is shown in Fig. 6, is 6.86%. This scaling indicates that confinement property of reversed shear plasma with the ITB is characterized by the local parameter at the ITB, and W_{dia} is almost independent of the heating power in this scaling expression. It should be mentioned that ρ_{foot} and Δ_{ITB} are also independent of the heating power [1,5]. Physics mechanism of this confinement property is the future work.

4. Summary

Active control of the ITB based on the modification of E_r profile was performed by changing the toroidal momentum injection directions, where the contribution to the E_r from V_ϕ plays an important role. Furthermore the ITB confinement database of reversed shear plasmas was constructed. The scaling of stored energy indicates that the confinement property is characterized by the local parameter at the ITB and the stored energy is almost independent of the heating power.

References

[1] T. Fujita *et al.*, Nucl. Fusion **38**, 207 (1998).
[2] E.J. Synakowski *et al.*, Phys. Rev. Lett. **78**, 2972 (1997).
[3] C.M. Greenfield *et al.*, Phys. Plasmas **7**, 1959 (2000).
[4] H. Shirai *et al.*, Nucl. Fusion **39**, 1713 (1999).
[5] Y. Sakamoto *et al.*, Nucl. Fusion **41**, 865 (2001).
[6] H. Shirai *et al.*, Plasma Phys. Control. Fusion **42**, A109 (2000).