Profile and Shape Control of the Plasmas with Transport Barriers towards the Sustainment of High Integrated Performance in JT-60U

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Abstract

With the main aim of providing physics basis for ITER and the steady-state tokamak reactor, JT-60U has been optimizing the operational concepts and extending discharge regimes toward the sustainment of high integrated performance. In the two advanced operation regimes, the reversed magnetic shear (RS) and the weak magnetic shear (high- β_p) ELMy H modes characterized by both internal (ITB) and edge (ETB) transport barriers, JT-60U has clarified responses of the transport barrier structure to magnetic shear, heating power, momentum, density, etc. Based on these observations, possible parameter linkages and feedback loops in the core and pedestal regimes have been proposed. With the optimization of profile and shape control, both confinement and high β stability have been enhanced and favorable integrated performance has been achieved. Such operational regimes have been extended to the reactor-relevant regime.

Keywords:

internal transport barrier, edge transport barrier, magnetic shear, confinement, MHD stability, integrated performance

1. Introduction

Profile and shape optimization is now widely recognized as the essential research direction in developing the tokamak operation concept towards economically attractive steady state fusion reactors. This is because the radial profiles of temperature, density, pressure, rotation, safety factor, etc. are controllable and their combination changes the fusion performance by more than one order of magnitude. In addition, a highly shaped (elongated and triangular) poloidal cross section enhances high β stability indispensable for compact reactors. Starting from the observation of the H-mode [1] and the formation of a peaked density profile by

pellet injection [2], the fusion society has been recognizing the freedom and restrictions of the profiles related to plasma transport and stability. Among them, observation of spontaneous bifurcations to reduced transport states has opened a new era of confinement physics. Such bifurcations produce transport barriers. The edge transport barrier (ETB) is commonly observed as H-mode, and the internal transport barrier (ITB) is now observed in a number of devices with variety of heating and fueling methods [3-5].

The JT-60U tokamak project has addressed major physical and technological issues in the ITER R&D and in developing commercially attractive steady-state

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reactor concepts such as SSTR [6]. These experimental and demo reactors require simultaneous sustainment of high confinement, high normalized β (β_N), high bootstrap current fraction f_{BS} , full noninductive current drive, high fuel purity, high density, and high radiation fraction (see Fig. 1(a)). In addition to providing physics basis for each individual element, recent JT-60U research has been directed toward the optimization of the operational concepts with the goal of *achieving the high integrated performance, its sustainment in long pulses, and extension to the reactor relevant parameter regimes* [7]. Most of these experiments have been based on the reversed shear (RS) mode [8-11], the high- β_p mode [12-17], and their combination with the H-mode (Fig. 1(b)). This is because these modes are characterized by a flat or a reversed safety factor profile which is naturally expected in a steady-state tokamak reactor with a large fraction of bootstrap current. In particular, the recent JT-60U research program has been focusing on achieving a deeper understanding of the formation and sustainment of the spatial structure of these advanced modes from the view points of energy transport, particle transport and MHD stability. This paper reviews recent observations of the ITB and the ETB characteristics and proposes possible parameter linkages determining their spatial structures. Based on these studies, JT-60U has successfully enhanced the integrated performance in the parameter regime close to the reactor regime by profile and shape controls utilizing variety of heating, current drive, torque input, and particle control capabilities.

Among the world tokamaks, JT-60U has now the largest variety of heating, current drive, momentum

input, and fueling systems which consist of the conventional positive-ion-based neutral beams (P-NBs; co- and counter-tangential and perpendicular), high energy tangential negative-ion-based NBs (N-NBs: 5.7 MW with $402 \text{ keV} \times 1.3\text{s}$), LHRF, ICRF, and ECRF (3 MW torus injection with the four-gyrotron system). This set of actuators enables ion and electron heating, and central and off-axis heating. Furthermore, the profiles of heating, momentum input, and current drive can be controlled independently. As for particle control, the outer pumping slot in the W-shaped divertor opened in 1999 permits both-leg-pumping. In early 2000, the new multiple pellet injector was installed. This system injects 2.1 mm cubic deuterium pellets with a repetition rate of $<10 \text{ Hz}$ and an injection speed of 100–300 m/s for high-field-side (HFS) and 100–1,000 m/s for low-field-side (LFS) injection. The major plasma parameters of the JT-60U high confinement experiments are; plasma current $I_p \leq 3 \text{ MA}$, $B_t(0) \leq 4.2 \text{ T}$, major radius $R = 3.0 \sim 3.5 \text{ m}$, minor radius $a = 0.65 \sim 1.0 \text{ m}$, elongation $\kappa = \kappa_x = 1.3 \sim 1.95$, and triangularity $\delta = \delta_x = -0.08 \sim 0.6$.

This paper uses three measures for confinement improvement; H_{89P} , H_{Hy2} and H_{H-ONL} . The H_{89P} -factor is the total (= thermal + fast ion) confinement improvement factor over the ITER89P L-mode scaling [18]. The H_{Hy2} -factor is the thermal confinement improvement factor over the ITER 98y2 ELMy H mode scaling [19], and the H_{H-ONL} -factor is that over the offset non-linear scaling for ELMy H-mode [20]. We use H_{89P} and H_{Hy2} for evaluation of the global confinement status relative to the standard L-mode and the ELMy H-mode, respectively. The offset non-linear scaling for the ELMy H-mode is given by

$$W_{th}^{ONL} = 0.082 \kappa R a I_p B_t / b^{0.1} + 0.043 R^{1.3} a (I_p n_{19})^{0.6} P_L^{0.4} / b^{0.15}, \quad (1)$$

with $b = B_t R^{1.25}$, where W_{th} is the thermal stored energy, R and a are the major and the minor radii, respectively, I_p is the plasma current, B_t is the toroidal field, n_{19} is the line averaged electron density in the unit of 10^{19} m^{-3} , and P_L is the loss power. This scaling consists of two terms: the first term corresponds to the pedestal part and the other corresponds to the core part (see Fig. 1(b)). We use the H_{H-ONL} -factor in order to evaluate the core and the pedestal thermal confinement status separately.

This paper is arranged as follows: Section 2 treats magnetic shear dependence of the ITB structure. Section 3 deals with the response of the ITB to heating and momentum input. Section 4 introduces the results of

Fig. 1: (a) Integrated performance required for steady state tokamak reactors: high confinement improvement (H-factor), high β_N , high bootstrap current fraction f_{BS} , high noninductive current drive fraction (f_{CD}), high fuel purity, high density normalized to Greenwald density (n_e/n_{GW}) and high radiation fraction normalized to the heating power (P_{rad}/P_{heat}). (b) Schematic pressure profile for the advanced tokamak operational modes with ITB and ETB.

ITB formation with electron heating. Sections 5 and 6 treat the extension of the high confinement regime towards high density and the characteristics of the ELMy H-mode pedestal, respectively. Section 7 proposes possible relationships among parameters determining transport barrier structures. Sections 8 and 9 deal with improved high β stability and the achievement of high integrated performance and extension to the ITER relevant regime. Finally, Sec. 10 summarizes the main results.

2. Magnetic Shear Dependence of the ITB Structure

This section treats the dependence of the ITB characteristics on the magnetic shear profile [3,7,8,12,17,21-23]. In JT-60U, ITBs have been observed over a wide range of the magnetic shear profile. The high- β_p mode is characterized by a weak positive magnetic shear profile, and the RS mode is characterized by a reversed magnetic shear profile. In these modes, inside the ITB radius, both ion and electron thermal diffusivities, χ_i and χ_e , can be reduced. However the improvement is different in structure (Fig. 2). In the case of the high- β_p mode, χ_i and χ_e become as small as the ion neoclassical diffusivity χ_{i-NC} near the axis, but their values stay above ($3\sim 5\times$) χ_{i-NC} at the ITB foot. Therefore, the core pressure gradient ∇p is moderate. On the other hand, in the RS mode, both χ_i and χ_e can drop sharply down to the level of χ_{i-NC} within a narrow (~ 10 cm) layer of the ITB, and the ∇p is strong in the ITB layer. Due to such differences in diffusivity profiles, the weak shear mode (the high- β_p mode) usually has ‘parabolic shape’ temperature profiles inside the ITB foot, while the reversed shear mode has ‘box shape’ profiles [23]. It should be noted that the ‘parabolic type ITB’ sometimes appears in the RS mode in particular with relatively small heating power [24] or with controlled-rotation [25]. The ITB-foot stays at a radius having a weak positive magnetic shear $s < 1$ in the high- β_p mode (the ITB-foot radius also often seems to be trapped at the $q = 2$ or 3 surface) [3,22,26], and stays at a radius with $s \sim 0$ ($\sim q_{min}$) in many of the RS mode discharges [8,21]. In some cases the ITB foot appears outside the q_{min} radius in the RS mode.

In such systems, produced ∇p determines the bootstrap current profile and hence the magnetic shear profile. Then the magnetic shear profile determines the pressure profile. Plasmas of these advanced modes are thus self-regulating systems with strong correlation between the pressure and the current profiles. Therefore,

demonstration of the existence of stable steady-state solutions at high- β_N and high- β_p under full noninductive current drive with a proper combination of externally driven current and self-driven bootstrap current is the critical issue. From this point of view, JT-60U has demonstrated favorable discharges [7,11]: Figure 3 compares the profiles of driven current j , magnetic shear s , safety factor q and ion temperature T_i for a) the weak positive shear case (full noninductive), b) the zero-flat shear case (partially noninductive), and c) the strong reversed shear case (full noninductive). Current profiles were controlled by a) combination of central N-NB and EC current drive (CD) and bootstrap current, b) ohmic and bootstrap currents without NBCD, and c) a combination of broad P-NBCD and large bootstrap current. In all cases, the measured q -profiles or the current profiles in the saturated phase stay near the steady-state solutions calculated by the ACCOME code. By modification of the external current drive profile in a proper combination with the bootstrap current, JT-60U has thus sustained high confinement advanced modes near the steady state current profile solutions from the weak positive to the strong reversed shear configurations.

Based on the JT-60U high β_p mode experience, the ITB is formed in the low shear region; typically $s < 1$ [22,26]. In discharges shown in Figs. 3 a) and b), this criterion was held and wide radii satisfying this

Fig. 2: Difference of profiles of safety factor, ion temperature T_i , electron temperature T_e , electron density n_e and heat diffusivities for a) the high- β_p H-mode (weak positive shear) at high triangularity ≈ 0.47 and b) the reversed shear H-mode.

Fig. 3: Advanced modes with ITBs sustained near the steady-state current profile solutions by active current drive control: a) the weak positive shear (full noninductive: N-NB central CD + P-NB broad CD + bootstrap), b) the flat shear (bootstrap + OH; not full noninductive), c) the strong reversed shear (full noninductive: P-NB broad CD + high bootstrap fraction). a) and b) shows driven current profiles calculated with ACCOME, measured q -profiles in the quasi-steady phase (bold solid lines), calculated steady-state q -profiles (bold hatched lines) and $T_i(r)$ with ITBs. c) shows similar sets of profiles. The measured current profile is compared with the ACCOME calculation in the top column.

condition were sustained. As reported in ref. [3], the ITB-foot radius often coincides with the $q = 2$ or 3 surface. A similar result has been also reported from JET [27]. This, however, cannot apply simply to the conditions of the *initial* formation condition of the ITB in JT-60U, which can occur at an inner region where $q < 2$ and $s < 1$, and then the ITB-foot radius expands and is stagnated near the $q = 2$ surface or $s \sim 1$. In addition, in many of the RS discharges in JT-60U, the ITB is formed in a very early phase of the discharges where $q_{\min} > 4$ [10]. On the other hand, in some discharges having relatively small heating power, the ITB formation location seems to correlate with the $q = 2$ or $q = 3$ surfaces. Also in JT-60/JT-60U discharges with pellet injection into the central region, the strong ITB (observed mainly for density profiles) appeared at the $q = 1$ surface [28]. The low order rational surfaces may play a role in the relaxation of the ITB formation condition.

Another clear difference between the weak positive and the reversed shear profiles appears in the reduction

of electron thermal diffusivity. In H-mode, both χ_i and χ_e are generally reduced. In turn, for ITBs, the deeply reversed magnetic shear mode shows strong reduction in χ_e [8], while the weak magnetic shear mode often shows weaker or little reduction in χ_e . In some of the high- β_p mode discharges, χ_e does not seem to change across the ITB [22]. In the high β_p H mode, however, a drop of χ_e across the ITB tends to be clearly observed (see Fig. 2(a)) at high triangularity [17]. These observations may suggest that, in the weak shear mode, the turbulent transport is not determined by a single instability, and if the dominant one is suppressed, the residual second instability governs the anomalous transport. In the strongly reversed shear mode, in turn, the second instability is stable and if the first instability is suppressed the diffusivity jumps easily down to the neoclassical level.

As discussed above, JT-60U has studied the advanced mode operation over a wide range of the current profile. Recently, equilibrium with nearly zero toroidal current in the central region, the “current hole”,

Fig. 4: ‘Current hole’ observed in the reversed shear discharge: current density profile with nearly zero toroidal current in the central region ($< 0.4a$) and temperature profiles.

was observed for the first time to persist stably for several seconds in the JT-60U RS plasmas [29]. This indicates the possible lack of necessity of the central toroidal current, which has been believed necessary in tokamaks. The radius of the current hole expanded up to 40% of the plasma minor radius (Fig. 4). The current hole was formed not by a simple delay of inductive current in a large sized plasma but by a negatively induced toroidal electric field through the increase of off-axis bootstrap current.

In the strongly reversed shear discharges, flat profiles with a ‘shoulder structure’ are often observed in the core region in density and temperature profiles (see Fig. 4 for example). Since such profiles have never been observed in the high- β_p mode plasmas, this structure seems to be due to a small poloidal field or large negative magnetic shear. One can imagine that the neoclassical diffusivity increases in the core regime of the strong reversed shear plasmas, and that the enhanced transport results in this flatness. However, in this case, the expected diffusivity profile increases smoothly toward the axis and the sudden increase in diffusivity profile (see $r/a \sim 0.5$ in Fig. 2(b)) cannot be explained. Another candidate is the large orbit of high temperature thermal ions at a small poloidal field. Although in some cases the radial location of the ITB-shoulder seems to coincide with the ion orbit width, there are many exceptions. On the other hand, the lower limit of the

ITB width (between the ‘shoulder’ and the ‘foot’) is proportional to the ion poloidal gyroradius evaluated at the center of the ITB width [25].

3. Response of ITB to Heating and Momentum Input

Based on the experimental and theoretical research progress in the world, it is now widely believed that E_r or its gradient is the fundamental element for the formation of transport barriers [4]. The radial electric field E_r is determined for the plasma species I by

$$E_r = \nabla p_I / (Z_I e n_I) + V_{I\phi} B_\theta - V_{I\theta} B_\phi,$$

where p is the pressure, Z is the charge number, e is the electric charge, V_ϕ is the toroidal velocity, V_θ is the poloidal velocity, B_θ is the poloidal magnetic field, and B_ϕ is the toroidal magnetic field. Among several approaches, the hypothesis of $\mathbf{E} \times \mathbf{B}$ flow shear suppression / decorrelation of turbulence has been widely applied to both the core and the edge transport bifurcation. In many experiments, the formation and subsequent growth of transport barriers, at least for the ion transport, seem to be well explained by this framework [4]. The characteristic rate for shearing turbulence is given by

$$\omega_{E \times B} = (RB_\theta/B) (\partial/\partial r)(E_r/(RB_\theta)).$$

In the widely adopted treatment, the turbulence is completely quenched when $\omega_{E \times B} > \gamma_{\text{lin}}^{\text{max}}$, where $\gamma_{\text{lin}}^{\text{max}}$ is the maximum linear growth rate of the dominant instability calculated without $\omega_{E \times B}$ [30]. Although a more complete nonlinear treatment is needed, this approach has been found to work well in many cases including H mode, VH mode, high- l_i mode, and ERS/NCS modes [31]. From TFTR [32] and DIII-D [33], it has been reported that the reduced transport and $\omega_{E \times B} > \gamma_{\text{lin}}^{\text{max}}$ correlates well for spatial distribution and temporal evolution, and that the density fluctuation decreases at the same location and time. In JT-60U, the ‘box type’ ITB has strong E_r shear inside the ITB layer and the estimated $\omega_{E \times B}$ becomes almost the same as $\gamma_{\text{lin}}^{\text{max}}$. On the other hand, in the ‘parabolic type’ ITB, the E_r shear is not so strong [23].

In addition to the $\mathbf{E} \times \mathbf{B}$ flow shear, other stabilization mechanisms are to be considered, for example magnetic shear (both small and strongly positive), Shafranov shift at a low magnetic shear, density gradient, etc. [34]. It should be noted that these stabilizing mechanisms are not independent to each other. As for the sources driving turbulence, it may be

natural to consider multiple types of microinstabilities rather than a single instability [5,35]. The complicated feature here is that a stabilizing term is at the same time a driving term of transport. Figure 5 schematically shows recent approaches to control levels of turbulence and $E \times B$ flow shear. Although ion and electron channels are linked together to some extent, they can be independent. (This figure also includes a mechanism of the self-regulation of turbulence: A recent nonlinear gyrokinetic simulation of microturbulence shows that the zonal flows are generated spontaneously and which regulate the turbulence [36]).

In order to maintain high stability and to control energy and particle confinement, the diffusivity profiles (height, width, and location of transport barriers) have to be actively controlled. Figure 6 shows a schematic dependence of diffusivity on the stabilizing effects. If the diffusivity dependence is like that in a), with only a jump, it is difficult to control the depth of diffusivity at the transport barrier without help by MHD instabilities like ELMs. If the dependence is more gradual such as b), it is easier to control the level of diffusivity.

Recent JT-60U experiments illuminate this important issue. The previous section showed that the level of diffusivity in the ITB layer can be changed by controlling the magnetic shear profiles from strongly reversed to weakly positive configurations. Another method to control the ITB structure is toroidal torque injection. In the JT-60U reversed magnetic shear regime, active ITB control based on radial electric field shear stabilization has been performed by toroidal momentum injection in different directions [25,37]. Figure 7 compares three cases with different toroidal rotation profiles produced by co-tangential NB injection, balanced injection, and counter-tangential injection. In the case of balanced injection, χ_i decreases quickly

down to the level of χ_{i-NC} and a steep temperature gradient is produced. Whereas in the cases of co- and counter-injection, the ITB becomes moderate. From this experiment, it can be concluded that there are at least some stages of improved transport.

In similar experiments, we have shown that the profiles of the E_r shear in the strong ITB layer initially produced by balanced injection weakened after

Fig. 5: Approaches for suppression mechanisms of turbulent transport based on $E \times B$ flow shear and control parameters.

Fig. 6: Behavior of diffusivity against the stabilization effects to be clarified; a) sudden jump down to neoclassical level or b) gradual decrease.

Fig. 7: Control of the ITB structure by toroidal rotation profile modification; Co-, Counter- and Balanced injection of the tangential beams (Reversed Shear, $I_p = 1.5$ MA, $B_t = 3.8$ T, $P_{NBinj} = 8$ MW (perpendicular = 4 MW + tangential = 4 MW)).

switching the NB injection from balanced to co-injection [25]. When the ITB started to weaken, E_r shear decreases only in the outer half region inside the ITB layer due to compensation of the ∇p contribution by the toroidal rotation contribution. After this time, in the whole ITB layer (not only in its outer half region), the ion temperature gradient decreased. This observation

Fig. 8: Response of ion heat diffusivity to absorbed NB heating power at various radial locations (weak shear). Up to 2–3 MW, χ_i over the whole radii increases with P_{NB}^{abs} . Then χ_i inside $r = 0.6a$ starts to decrease by formation of ‘parabolic’ ITB. Above 6 MW, further large reduction of χ_i is observed at $r = 0.4a$. (Reduction of χ_i at $r = 0.86a$ above 4 MW is due to L-H transition at the edge.)

suggests semi-global (not local) dynamics of the ITB.

In order to clarify the dependence of ITB formation and structure on heating power, we have conducted a NB injection power scan [24]. Figure 8 shows result for the weak magnetic shear discharges at fixed I_p and B_t . Up to P_{NB}^{abs} (absorbed NB heating power) = 2–3 MW, χ_i over the whole radii increases with P_{NB}^{abs} . This is the nature of the L-mode transport. Then χ_i inside $r = 0.6a$ starts to decrease due to the formation of ITB. In this regime, the produced ITB shape is typically parabolic. Interestingly, above 6 MW, a further deep reduction of χ_i is observed at $r = 0.5a$ and at this location a much steeper ITB is formed. (Reduction of χ_i at $r = 0.86a$ above 4 MW is due to L-H transition at the edge.) This observation suggests that χ_i is continuously controllable in the ‘parabolic type ITB’ regime and the jump in χ_i occurs from the parabolic type ITB to the box type ITB.

In the ‘box type’ regime, sometimes a ‘double jump of ITB’ is observed [24]. Figure 9 shows the evolution of ion temperature at various radii and its profile in a RS discharge. Before $t = 4.9$ s, the box type ITB has been already formed (see Fig. 9(b)). Then, at $t \sim 4.9$ and $t \sim 5.5$ s (see Fig. 9(a)), a sudden increase in T_i is observed twice (see traces of $r/a = 0.44$ and 0.53). The reason or condition of such a double jump has not yet been clarified, but this observation suggests the existence of multiple stages (or structures) of transport in the box type ITB regime. In JT-60U we have observed a so called ‘ITB event’ [38] which is characterized by abrupt and spatially wide (covers 30%

Fig. 9: ‘Double jump of ITB’: (a) Evolution of NB power and ion temperature T_i at various radii and (b) T_i profiles in a strong reversed shear discharge. Before $t = 4.9$ s, the box type ITB has been already formed. Then, at $t \sim 4.9$ and $t \sim 5.5$ s, sudden increase in T_i is observed twice at $r/a = 0.44a$ and $0.53a$. ($B_t = 4T$, during I_p ramp up).

Fig. 10: High electron temperature achieved in a reversed shear discharge produced with off axis LHCD and EC central heating (1.2 MA, 3.6T, $q_{95} = 6.2$): (a) Time evolution of electron temperature at the center $T_e(0)$ and at $r/a = 0.5$ $T_e(0.5)$, EC power, LH power and plasma current I_p . (b) Profiles of T_e at two timings shown by arrows in (a).

Fig. 11: (a) H_{89P} vs. n_e/n_{GW} for various discharge regimes at $I_p = 0.9 - 1.2$ MA: low δ (0.15-0.2) ELMy H-mode (thin open circles), high δ (0.45-0.55) H-mode (black closed circles), high δ (0.45-0.55) high- β_p ELMy H-mode with NB fueling alone (gray circles) and with pellet injection (indicated by +Pellet), Ar injected ELMy H-mode (squares), and reversed shear mode produced with LHCD and NB heating (bold open circles). (b) Electron and ion temperature profiles for the LHCD+NB reversed shear discharge with $H_{Hy2} = 1.4$ under full non-inductive condition. The two big circles at $n_e/n_{GW} \sim 0.7$ corresponds to a pellet injected discharge and a reference gas fuelled discharge shown later in Fig. 15.

of minor radius) variations of both electron and ion heat diffusivities $\delta\chi_{e,i}$ for parabolic ITBs in both RS and weak shear plasmas. This event also suggests the semi-global radial structure of ITB dynamics. The ‘ITB event’ has been also observed for strong ITBs in RS plasmas. In this case, profiles of $\delta\chi_{e,i}$ are localized near the ITB-foot radius with a narrower width.

4. ITB Formation with Electron Heating

The advanced operation modes in JT-60U were developed originally in the ion heating dominant regime with the 80–90 keV NB heating and T_i being much higher than T_e . In order to prove the applicability of the advanced operation modes to fusion reactors, the critical issue is the demonstration of high confinement at $T_i \sim T_e$. This is because the α -particle heating in reactors is electron heating. In addition, equipartition between ions and electrons is strong in high density reactor plasmas. For current drive, a higher T_e is more beneficial. The anomalous electron transport may be governed by a much shorter wavelength turbulence and/or a much larger growth rate turbulence than ion transport. JT-60U has now the favorable capability of electron heating with high energy N-NB, ECRF, LHRF, and ICRF minority heating. Utilizing these capabilities, JT-60U has extended the high confinement regimes with ITB. In both high β_p ELMy H-mode and RS ELMy H-mode, $H_{89PL} = 2.5\text{--}3.5$ ($H_{Hy2} \sim 1.2\text{--}2.2$) has been successfully demonstrated at $T_e \sim T_i$ [7,39]. More recently, JT-60U has demonstrated high values of electron temperature up to 26 keV inside the ITB. Figure 10 shows time evolution and profiles of T_e in RS discharges produced by off-axis LHCD with central EC heating.

5. Extension of High Confinement Regime towards High Density

In order to achieve high fusion gain and to maintain high radiation fraction for protection of the divertor first wall, high density operation, $\bar{n}_e \sim 0.8 - 1.2 n_{GW}$, is required in ITER and demo reactors, where n_{GW} is Greenwald density [40].

Figure 11 summarizes various JT-60U discharge regimes on the H_{89P} and $\bar{n}_e/n_{GW}$. The highest normalized density with high confinement has been achieved by the RS discharges produced by LHCD (+ NB injection) [41]. In this regime, $H_{89P} > 2$ has been achieved at a very high value of $\bar{n}_e \sim 1.15 n_{GW}$. In addition, at $\bar{n}_e \sim 0.85 n_{GW}$, full non-inductive discharge has been achieved with $H_{Hy2} = 1.4$ and $T_e \sim T_i$ (see Fig. 11(b)). In such RS discharges, high density is sustained inside the ITB.

On the other hand, in the standard (without ITB) H-mode and the high β_p H-mode regimes, the pedestal density of the H-mode edge becomes the critical condition. In Fig. 11(a), in the standard (without ITBs) ELMy H-mode regime, the density limit at $H_{89PL} > 2$ is $\sim 0.35 n_{GW}$ for low triangularity $\delta = 0.15\text{--}0.2$ and $\sim 0.45 n_{GW}$ for high $\delta = 0.45\text{--}0.55$. With increasing δ , the achievable density with $H_{89P} > 2$ increases [16]. In the high- β_p ELMy H-mode regime, $H_{89P} > 2$ is achievable up to $0.6 n_{GW}$ with NB fueling alone. However, if a strong gas puff is applied for a further increase in density, H_{89P} decreases with increasing density. In order to extend the density range, JT-60U has employed multiple pellet injection into the high β_p ELMy H-mode discharges, and the density range with $H_{89P} > 2$ has been extended to $0.7 n_{GW}$ [7]. Another approach towards high density is Ar injection into high triangularity H-mode. In this regime, $H_{89P} \sim 1.7$ ($H_{Hy2} \sim 1$) has been achieved up to $\bar{n}_e \sim 0.8 n_{GW}$ [42,43]. Such improvements achieved by high- δ , Ar-injection, and pellet injection are all related to the high pedestal temperature discussed in the next section.

6. Characteristics of ELMy H-mode Pedestal

The pedestal structure is characterized by the ‘width’ and ‘gradient’ of the pedestal layer. Figure 12 shows the evolution of the ion temperature profile in the pedestal regime of a type I ELMy high β_p H-mode discharge [44]. In the type I ELMy regime, the pedestal pressure gradient is limited by ELMs and the limit is consistent with the stability boundary of the medium n

Fig. 12: Time evolution of the pedestal ion temperature profile: $t = 6.15$ s (circles), 6.3 s (crosses), 6.5 s (triangles) and 8.8 s (squares). In this discharge, NB heating was started at $t = 6.0$ s. (Type I ELMy high β_p H-mode E32358, $I_p = 1$ MA, $B_t = 2.1$ T).

(toroidal mode number) peeling mode and/or high n ballooning mode [45]. In addition, a detailed density fluctuation study has clarified that the type I ELM crash is highly localized poloidally at the low field side [46]. In the JT-60U ELMy H-mode, the pedestal width Δ_{ped} observed in ion temperature profiles is 2–3 times larger than that in the ELM-free phase [44,47]. At high triangularity, Δ_{ped} reaches 8–15 cm (9–16% of the minor radius) at the plasma current of 1 MA. The width Δ_{ped} scales linearly with the poloidal gyro radius of thermal ions ρ_{pi} at a fixed peripheral safety factor q_{95} ($\Delta_{\text{ped}} \sim 3-4\rho_{\text{pi}}$, $q_{95} = 3-4$), and has a weak dependence on q_{95} ; $\Delta_{\text{ped}} \sim 5\rho_{\text{pi}} q_{95}^{-0.3}$ [44]. Thus, in the type I ELMy H-mode, the pedestal pressure is limited by ELMs and, under this limitation, pedestal temperature decreases with increasing pedestal density. In addition, once pedestal temperature decreases, Δ_{ped} shrinks and pedestal pressure decreases further. This relationship is one of the key factors in the confinement degradation at high density shown in Fig. 11. From here, this section discusses more

detailed results regarding this important issue.

For the low triangularity H-mode discharges shown in Figure 11, we have evaluated energy confinement enhancement over the offset non-linear scaling for ELMy H-modes [20]. Figure 13(a) shows confinement improvement factors over the offset nonlinear scaling (given by eq. (1) in Sec. 1) for both the pedestal and the core parts, and the total enhancement factor. It should be emphasized that the total confinement degradation with increasing density is due to the degradation in the core region and not in the pedestal region. In the type I ELMy discharges in JT-60U, the pedestal pressure stays roughly constant ($n_{\text{ped}} T_{\text{ped}} \sim \text{const.}$) for fixed I_p , B_t and plasma shape. Therefore, pedestal temperature decreases with increasing pedestal density. As seen in Fig. 13(b), the core enhancement factor decreases with decreasing pedestal temperature when $T_{i\text{-ped}} \lesssim 2$ keV [48,49]. This dependence suggests the stiffness of core profiles [50] in the JT-60U high density H-mode [51]. In practice, as shown in Figs. 13(c) and (d), ‘profile shapes’ for n_e , T_e

Fig. 13: (a & b) Density and pedestal ion temperature dependences of confinement enhancement factors $H_{\text{H-ONL}}$, (c) relationship between line averaged and central electron density, (d) relationship between pedestal and central T_e and T_i . (type I ELMy H-mode at low triangularity = 0.15–0.2, $q_{95} = 2.9-3.0$, $I_p = 1.8 \text{ MA}$, $B_t = 3.0 \text{ T}$)

and T_i are almost stiff.

At high triangularity δ , because of improved stability against ELMs, the edge pressure is higher than that in low δ discharges [16,52], and thus the pedestal temperature is higher at a given pedestal density. The relationship between T_{i-ped} and H_{H-ONL} for the high- δ H-mode (without ITB) is almost the same as that of the low- δ H-mode. The core profile shape is also similar to those of the low- δ H-mode discharges [53].

In ELMy H-mode discharges with Ar injection (1.2 MA, 2.5 T, $q_{95} = 3.4$, $\delta = 0.36$), $H_{Hy2} \sim 0.9$ has been obtained with a high radiation loss power fraction ($\sim 80\%$) at $n_e/n_{GW} \sim 0.7$ [42]. The H_{Hy2} -factor is $\sim 50\%$ higher than that without Ar injection (Fig. 14(a)). The main reason for the high confinement achieved by Ar injection again seems to be due to the higher edge temperature than without Ar at the same density (Fig. 14(b)). (The pedestal pressure is similar to that of without Ar cases because of lower ion density due to

dilution.) The H_{Hy2} factor increases with increasing T_{i-ped} , and the core profile shape is also similar as shown in Fig. 14(c). The data points follow this same tendency over the wide range of Ar-fractions. The core diffusivity decreases, that is, the H_{Hy2} factor increases with increasing T_{i-ped} (Fig. 14(d)) [53].

With the high field side multiple pellet injection into high triangularity high β_p type I ELMy H-mode discharges, JT-60U has extended the density range with a favorable confinement [7,54]. Figure 15 compares the two discharges at $I_p = 1$ MA and $0.7 n_{GW}$ shown in Fig. 11 highlighted by large bold circles; one (E37413) with pellet injection and the other (E32398) with gas fueling. In the pellet injected discharge, the H_{89P} -factor stays almost constant even with increasing density. In this case, $H_{Hy2} = 1.05$ together with $\beta_N = 2.2$ and $f_{BS} \sim 60\%$ was achieved. On the other hand, the H_{89P} -factor decreases with density in the gas-fueled discharge. The pellet case retains a clear ITB structure and the density

Fig. 14: (a) H_{Hy2} factor vs. $\bar{n}_e/n_{GW}$, (b) pedestal T_i vs. line averaged electron density, (c) relationship between pedestal and central T_i , and (d) dependence of core effective diffusivity on pedestal ion temperature. (Ar injected and deuterium only ELMy H-mode at $\delta = 0.36$, $q_{95} = 3.4$, $I_p = 1.2$ MA, $B_t = 2.5$ T)

Fig. 15: (a) and (b): Time evolution of the two discharges at $I_p = 1$ MA and $0.7 n_{GW}$ shown by double circles in Fig. 11; one (E37413) with pellet injection and the other (E32398) with gas fueling. (c) Radial profiles of T_i for E37413 (pellet) and E32398 (gas fueled). (d) n_{e-ped} vs. T_{e-ped} for ELMy discharges at 1 MA and $\delta = 0.44-0.48$ (open circles: standard ELMy H-mode, small closed circles: type I ELMy high β_p H-mode and pellet injected discharges.). Time evolutions of E37413 ($t = 3.5$ s – 7 s) and E32398 ($t = 6.5$ s – 11 s) are shown by bold lines.

profile is peaked. However, more important here is the difference seen in the pedestal region. These two discharges have similar edge n_e (at $r/a \sim 0.9$); however, the pellet case has a remarkably high edge T_i and T_e and the pedestal width is wider (Fig. 15(c)). Figure 15(d) (treating discharges at 1 MA and $\delta = 0.44-0.48$) shows that the pedestal pressure ($\sim n_{e-ped} \times T_{e-ped}$) stays roughly constant for the standard ELMy H-mode with type I ELMs (open circles). While in the high β_p ELMy H-mode (small closed circles), the pedestal pressure can be higher than that of the standard H-mode. In the pellet injected cases, the pedestal pressure increases gradually (see the time evolution of E37413), and reaches high values. On the other hand, in the gas-fueled case (E32398), T_{e-ped} decreases with increasing n_{e-ped} . The pedestal temperature in E37413 is higher than that in

E32398 by more than a factor of 2.

The enhanced pedestal pressure for the high β_p mode including the pellet discharges is due to improved edge stability enhanced by high β_p values: Figure 16 shows dependence of the pedestal parameters on the total β_p values. Figure 16(a) shows that the pedestal β_p , β_p^{PED} , increases with increasing total β_p at high $\delta \sim 0.44-0.48$ (circles), where β_p^{PED} is the ratio of pedestal pressure to the surface poloidal magnetic field. The two discharges E37413 and E32398 follow this relationship. This relationship between β_p^{PED} and the total β_p seems to be independent of the existence of the ITBs (open symbols: without ITB, closed symbols: with ITB). On the other hand, β_p^{PED} is almost constant at low δ (squares). The pedestal pressure is sustained by both the pedestal width and the pedestal pressure gradient. Figure

Fig. 16: Dependence (a) of the pedestal β_p (β_p^{PED}), (b) the normalized pedestal width to the scaling ($\Delta_{\text{ped}}/\rho_{\text{pi}}q_{95}^{-0.3}$) and (c) the edge α -parameter on the total β_p for the type I ELMy discharges at 1MA: circles: high $\delta = 0.44 - 0.48$, squares: low $\delta = 0.14 - 0.2$, open: without ITB, closed: with ITB, gray circles: evolution of E32358, small circles connected with lines: evolution of E37413.

16(b) shows that the pedestal width normalized by the scaling is almost constant, $\Delta_{\text{ped}} \sim \rho_{\text{pi}} q_{95}^{-0.3}$ [44]. Including the pellet cases, the data follow this scaling. Figure 16(c) shows that, at high δ , the edge α -parameter (normalized pedestal pressure gradient) limit increases with total β_p . On the other hand, at low δ , it is almost constant at a low value. This observation shows that the pedestal stability in the type I ELMy regime is improved with high δ and high β_p . In Fig. 16(c), time evolutions of E37413 (pellet) and E32358 (NB fueling only [44], see also Fig. 12) are shown again by small circles connected with lines and gray circles, respectively. These two evolutions show the almost linear dependence of α on β_p in each discharge. But the slopes are different, which may be due to difference in edge magnetic shear or edge current density. This β_p -dependence of α may be due to an increasing Shafranov shift or radially increasing field line pitch at the low field side. According to ref. [44], at high δ , the pedestal temperature and the pedestal pressure increases gradually with a slow time constant of $\sim 2-3$ sec ($\sim 10 \times \tau_E$) which is comparable with the edge current diffusion time over the pedestal layer. In this case, the total β_p and α also increased simultaneously (see the gray circles in Figs. 16(a)&(c) which show time evolution of the representative discharge E32358 from $t = 6.3$ s with $\beta_p \sim$

1.2 to $t = 9.5$ s with $\beta_p \sim 1.7$). Although we have not clarified the role of edge current density systematically, the stability analyses [45] show that the edge current is critically important for the edge stability. Based on these observations and analyses, stability of the type I ELMy edge seems to be determined by δ , total β_p , and edge current driven mainly by the bootstrap current.

7. Relationships among Parameters Determining Transport Barrier Structures

This section proposes possible correlations among pedestal and core parameters based on the observations in JT-60U. The right hand side of Fig. 17 treats parameter linkages in the core region determining the ITB structure discussed in early sections in this paper. The linkage among current, pressure, and rotation profiles becomes stronger with increasing β . In the reactor with a high fusion gain, the externally injected power is less than 20% of the total heating power. In the steady-state with a high bootstrap fraction, the externally driven current fraction is about 20–30%. The reactor plasma should be controlled such small fractions of heating and current drive.

The left hand side of Fig. 17 treats the pedestal regime. For a steep pedestal pressure gradient, high δ , high β_p and edge magnetic shear control are required.

The effects of the edge magnetic shear on the edge turbulence suppression (thus on the pedestal width) have not been clarified in JT-60U. The steep ∇p enhances pedestal pressure. The high pedestal pressure allows a high pedestal temperature at a given pedestal density. The high pedestal temperature widens the pedestal width (ρ_{pi} dependence) [5]. The wide pedestal width enhances the pedestal pressure and the pedestal temperature. High pedestal temperature improves the core confinement in the standard ELMy H-mode. In turn, for the H-mode with an ITB, it has not been clarified whether the high edge temperature helps the ITB formation. However, at least for the high β_p mode, the high δ plasmas seem to have relatively lower threshold heating power for ITB formation with a clear electron temperature internal barrier. And then, if the core confinement (or β_p) is improved due to ITB formation and evolution, the pedestal stability is improved. According again to ref. [44], the time constant required for this positive feedback cycle seems to be ~ 2 sec ($10 \times \tau_E$) in the JT-60U operation regime at $I_p = 1$ MA. It may be necessary to fit the time constant of density rise to this cycle. In practice, in the pellet injected discharge E37413, the slow density rise over 3 sec is successful. On the other

hand, a strong gas puff decreases the pedestal temperature which may force the plasma to follow the negative feedback loop shown in Fig. 17.

8. Improved High β Stability

The high confinement modes treated above are characterized by a large pressure gradient at transport barriers and the location of the ITB is related to magnetic shear. Therefore, current and pressure profile control is essential for the optimization of MHD stability.

It is well known that achievable β_N increases almost linearly with internal inductance l_i [31], in other words, with peaking of the current density profile or increasing the magnetic shear. However, in the advanced tokamak operation regime with a large fraction of bootstrap current, the resultant current profile tends to be flat in the steady-state. In order to compensate for such a disadvantage, optimization of the pressure profile and shape control becomes essentially important. The dependence of β_N on the peaking factor of $p(r)$, $p(0)/\langle p \rangle$, has been systematically studied including the high- β_p mode, the high- β_p H-mode, and H-mode [16]. As shown in Fig. 18(a), a medium value of

Fig. 17: Possible parameter correlations (feedback loops) in pedestal and core regimes.

$p(0)/\langle p \rangle$ is optimum. At a larger peakedness, the achievable β_N is limited by the β_p -collapse (the ideal kink-ballooning mode) [14]. At a smaller peakedness, β_N is limited by giant ELMs. The edge stability is improved by increasing triangularity, and the achievable β_N becomes higher than that of low triangularity. Because of the enhanced β -limit and improved H-mode confinement, high triangularity allows simultaneous

achievement of high β_N and high H_{9p} -factors as shown in Fig. 18(b).

In the high β_p ELMy H-mode regime, low- n neoclassical tearing modes NTMs [55,56] ($(m,n)=(3,2)$ or $(2,1)$) degrade sustainable β_N [16,17,57]. A simple scaling of the mode onset condition is given by $\beta_N/\rho_i(\text{toroidal})^* \sim v_e^{*0.36}$ [58]. However, even at small values of $\rho_i(\text{toroidal})^*$ and v_e^* , NTM-free high β_N

Fig. 18: (a) Achievable β_N as a function of peakedness of total pressure (open: limited by giant ELMs, closed: limited by β_p -collapses, circles: triangularity $\delta \sim 0.34$ with $I_p = 1.5-1.8$ MA/ $B_t = 3.1-3.6$ T, triangles: $\delta \sim 0.08$ with $I_p = 2-2.7$ MA/ $B_t = 4.2-4.4$ T). Achievable β_N increases with increasing δ mainly because of the improved edge stability. (high- β_p mode, high- β_p H-mode and H-mode (b) Simultaneous achievement of β_N and H_{9p} -factor improved with increasing triangularity.

Fig. 19: (a) Comparison of two discharges with almost the same safety factor profiles. One is unstable against NTM and the other is stable. The stable discharge was sustained with reduction of ∇p at the $q = 2$ surface. (b) Profiles of EC driven local current (J_{CD}) on the $m/n = 3/2$ island and bootstrap current (J_{BS}) in a discharge where $3/2$ NTM was completely suppressed by ECCD ($\beta_N \sim 1$).

Fig. 20: (a) Discharge shape with triangularity = 0.6. (b) Progress of β_N value sustainable sufficiently longer than the energy confinement time ($> 5\tau_E$) in the low q_{95} (< 4) regime.

Fig. 21: (a) Long (7.4 s) sustainment of high β_N value (2.7). (type I ELMing high- β_p H-mode at $q_{95} = 3$). The high β_N duration is limited by hardware capability. (b) β_N and sustained duration obtained in JT-60U so far.

discharges can be sustained by the reduction of pressure gradient at the rational surfaces. Figure 19(a) compares two discharges with almost the same safety factor profiles. The stable discharge was sustained with reduction of ∇p at the $q=2$ surface. In a medium β_N (~ 1) regime, complete suppression of the neoclassical tearing mode has been demonstrated by local ECCD (1.6 MW) applied at the mode resonant surface. In this case, the required EC-driven current density was $\sim$ twice as high as the locally driven bootstrap current density [58].

JT-60U has recently improved its capability of high triangularity operations, which allows us to produce higher triangularity at a given plasma current (for example $\delta = 0.6$ at $I_p = 1\text{MA}$) or to sustain a medium δ for longer period ($\delta = 0.45$ for 8–9 sec). This improvement has enhanced JT-60U high β_N performance (Fig. 20): At $\delta = 0.6$ with the optimum pressure profile

mentioned above, the β_N -value sustainable sufficiently longer than the energy confinement time ($> 5\tau_E$) has been increased up to 3.05 in the low q_{95} (< 4) regime without NTM. In addition, at $\delta \sim 0.45$, the sustainment time of $\beta_N = 2.7$ has been elongated to 7.4 s, which is determined by the hardware limitations (Fig. 21). In this case, $m/n = 3/2$ NTM was destabilized but the mode amplitude was saturated. Another benefit of the high δ shape is the achievement of Grassy ELMy discharges [59] with small peak heat and particle load onto the divertor plates. One of the urgent issues for ITER is the achievement of the small ELMy discharges in the low safety factor ($q_{95} < 4$) regime. With the new high $\delta (= 0.6)$ shape, grassy ELMy discharges have been successfully expanded to the low q regime of $q_{95} = 3.7$.

9. Achievement of High Integrated Performance and Extension to the ITER-Relevant Regime

As mentioned in Sec.1, the most important research goal of JT-60U is the achievement and sustainment of high integrated performance (Fig. 1(a)) and its extension to the ITER-relevant parameter regime. Based on the understanding of the structure and parameter linkages in the advanced operation modes discussed in the previous sections, we have demonstrated favorable integrated performance both in the RS H-mode [11] and the high- β_p H-mode ([7] and recent discharge at $I_p = 1.8$ MA/ $B_t =$

4 T) under full non-inductive current drive. The integrated performances of representative discharges are shown in Figs. 22(a) and (b). The full scale for each axis represents one of the ITER steady-state operation design examples. Figure 22(c) shows the achieved full non-inductive discharge regime on the v_e^* (collisionality) – ρ_{pi}^* (normalized poloidal gyroradius) plane. Since the behavior of the key physical processes, such as stability, transport, and bootstrap current, are determined by these non-dimensional parameters, it is necessary to demonstrate the required performances at sufficiently low values of v_e^* and ρ_{pi}^* close to the reactor

Fig. 22: Achieved integrated performance in a full non-inductive discharges with high integrated performances. The full scale for each axis represents one of the ITER steady-state operation design examples. (a) reversed shear ELMy H-mode at $I_p = 0.8$ MA and $q_{95} = 9.3$ and (b) high- β_p H-mode discharges at $I_p = 1.0, 1.5$ and 1.8 MA, $q_{95} = 4-5$. (c) Operation regime of full noninductive CD at high β_N approaching the ITER regime in terms of normalized poloidal gyroradius ρ_{pi}^* and collisionality v_e^* .

operational regimes. The JT-60U high- β_N full noninductive CD regime has accessed $v_e^* \sim 0.01\text{--}0.02$ and $\rho_{pi}^* \sim 0.06$. These values are close to those for the ITER steady-state reference design; $v_e^* \sim v_e^{*ITER}$ and $\rho_{pi}^* \sim 3 \rho_{pi}^{*ITER}$.

As seen in Fig. 22(a), the RS H mode has fairly high values of H_{Hy2} and f_{BS} , in addition, density and radiation fractions are also favorable. The remaining issues are relatively small β_N and insufficient fuel purity. In the high β_p H-mode regime, the discharges satisfy the requirements for H_{Hy2} , f_{BS} and f_{CD} . However, for higher density and radiation power, in particular, further improvement is needed.

10. Summary

With the main aim of providing physics basis for ITER and the steady-state tokamak reactor, JT-60U has been optimizing the operational concepts and extending discharge regimes toward the sustainment of high integrated performance, that is, simultaneous sustainment of high confinement, high normalized β (β_N), high bootstrap current fraction f_{BS} , full noninductive current drive, high fuel purity, high density, and high radiation fraction. In the two advanced operation regimes, the reversed magnetic shear (RS) and the weak magnetic shear (high- β_p) ELMy H modes characterized by both internal (ITB) and edge (ETB) transport barriers, JT-60U has clarified the responses of the transport barrier structure to magnetic shear, heating power, momentum, density, etc. The ITB structure and evolution (levels of χ_i and χ_e , ITB-foot location, shoulder structure, transitions etc.) change with magnetic shear. As an extreme case of the RS configuration, an equilibrium with nearly zero toroidal current in the central region, the "current hole", was observed for the first time to persist stably for several seconds. In the type I ELMy phase, ∇p is enhanced with increasing δ and β_p , and the ETB width is proportional to ρ_{pi} . With increasing T_{i-ped} (or T_{e-ped}), the core confinement improves when the profile stiffness exists. Based on these observations, a possible parameter linkage and feedback loops in the core and pedestal regimes are proposed. With the optimization of profile and shape control, both transport and high β stability has been enhanced and favorable integrated performance has been achieved. Such operational modes have been extended to the reactor-relevant regime with small values of collisionality and normalized gyroradius.

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