Studies of Current Profile Optimization and Influence of Electron Heating towards Advanced Tokamak Operation on JT-60U

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Abstract. Experimental results of studies towards steady state operation of an advanced tokamak on JT-60U are presented. Especially, issues that are related to a current profile and internal transport barriers (ITBs) with emphasis on fusion relevant conditions are discussed. The major results are; 1) High confinement improvement at high normalized density regime which is expected in the ITER steady state operational scenario was obtained in a reversed magnetic shear (RS) plasma under full non inductive current drive (CD). In the discharge, capability of active current profile control was demonstrated. 2) Influence of dominant electron heating on the ITBs was investigated, and it was found that in RS plasmas the confinement improvement by the ITBs could be maintained in the dominant electron heating regime. On the other hand, it was found in positive shear plasmas that the T_i ITB could be degraded by dominant electron heating.

1. Introduction

Toward realization of a steady state (SS) tokamak fusion reactor, it is essential to increase the fraction (f_{bs}) of the bootstrap (BS) current relative to the total plasma current (I_p); a value $f_{bs} \sim 70\%$ is typically required [1]. Formation of an internal transport barrier (ITB) is one effective method of achieving a high f_{bs}. In such a plasma, the current density profile becomes hollow due to off-axis BS current, and the magnetic shear becomes negative in the plasma core region. The JT-60U experiments on reversed (negative) magnetic shear (RS) plasmas have revealed that ITBs can reduce anomalous heat transport dramatically to enable excellent confinement and f_{bs} values, comparable to, or even better than, those expected in future machines [2, 3]. On the other hand, too strong ITB may result in a very hollow current profile, or a deeply reversed safety factor (q) profile. Recently even a current hole has been found in an RS plasma [4, 5] Such a hollow current profile would not be desirable in a reactor, since the orbits of alpha particles might become too large to allow confinement of them in the core region. Moreover collective modes might be destabilized and degrade the alpha particle confinement. Therefore lowering central q with such a strongly localized BS current is one of the critical issues.

On the other hand, study of characteristics of ITBs under fusion plasma relevant conditions , especially on heating method, is also important. In a fusion plasma, main heating source is α particles therefore the heating power is firstly fed to electrons predominantly. However, in many experiments high performance plasmas are obtained by using positive-ion based neutral beam (P-NB) heating. Since the beam acceleration energy (E_B) of a P-NB is usually ranging from several tens of keV to about a hundred keV and the electron temperature (T_e) in a target plasma is in excess of a few keV, heating power is initially absorbed by ions predominantly. Thus the ion temperature (T_i) tends to be higher than

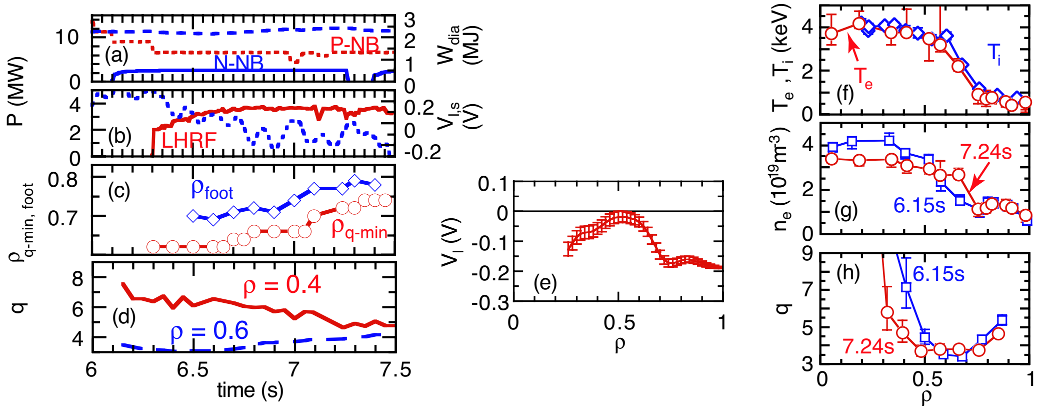

FIG. 1: Waveforms, (a) – (d), and profiles, (e) – (h) of typical parameters in an RS discharge LHCD and N-NBCD are combined to achieve full-CD with good performance (E37964).

T_e in these experiments. It is theoretically expected that $T_e/T_i > 1$ is a destabilizing factor to the ion temperature gradient (ITG) micro-instabilities, which is expected to be responsible to the confinement degradation. If the mode is dominant, it would affect formation and sustainment of ITBs under dominant electron heating. Therefore, it is important to investigate confinement improvement in such a condition.

On the JT-60U tokamak, various kinds of heating (H) and current drive (CD) systems are installed and therefore is potentially suitable to investigate improved confinement in electron heating dominant regime; the lower hybrid range of frequencies (LHRF) system is for CD (LHCD) and heating, the electron cyclotron range of frequency (ECRF) system is for CD and direct electron heating without particle fueling and the negative-ion based NB (N-NB) system is for CD and mostly electron heating because of higher E_B (<500 keV) with low fueling. Utilizing these various H/CD systems, issues discussed above have been investigated. In this paper, results of current profile modification and dominant electron heating issues on ITB plasmas are shown.

2. Current Drive and Profile Control in a High Performance RS Plasma

Since the current profile is very important in an RS plasma, control and sustainment of a wide but not deeply hollow current profile with good alignment to the pressure profile are key issues. There would be several aspect in view of current profile optimization in an RS plasma; 1) confinement improvement, 2) reduction of central q, 3) improvement of MHD limits and so on. Here the experimental results on the first and the second issues are discussed. Concerning the first issue, expansion of location ($\rho_{q-\min}$) of the minimum in the q profile ($q_{\min}$) by means of off-axis CD would be effective. The location of the ITB foot location ($\rho_{\rm foot}$) has been reported to be strongly related to the $\rho_{q-\min}$ location, and the confinement of an RS plasma can be scaled with ρ 2 [6]. Considering excellent achievement in many tokamaks [7–10], LHCD should be the most appropriate to apply on this issue. Toward the second issue, approach would be straight forward, that is utilization of central CD. To this purpose, N-NB is a good choice. Although, CD capability in a standard plasma has been proved [11], it should be investigate in such a RS plasma, since higher q in the central region may prevent full capability.

The plasma was operated with $I_p = 0.9$ MA, $B_{t0} = 2.5$ T, $q_{95} = 6.9$, and the working gas was deuterium [12]. Waveforms of typical parameters are plotted in Fig. 1.

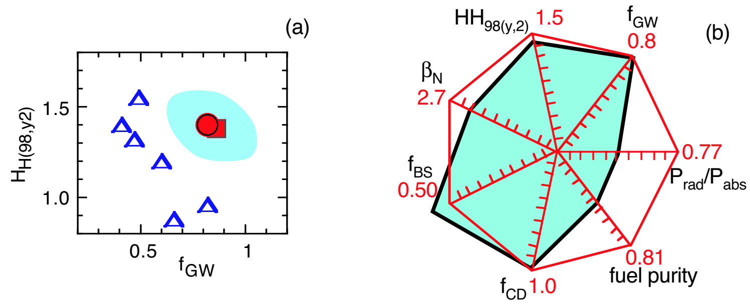

FIG. 2: (a) Plot of $HH_{98(y,2)}$ vs normalized density. Data obtained in this experimental series are shown by closed circle and square. Hatched region indicate ITER SS operational region. Triangles are other data in JT-60U full-CD experiments. (b) Achieved parameter against those required in the ITER SS operation.

The plasma was initiated at 3 s with $I_p \sim 0.4$ MA. Then I_p was ramped up to 0.9 MA in 1 s with P-NB heating to form an RS configuration and ITBs as per usual JT-60U RS plasma operation [2]. Up to 6.3 s the stored energy evaluated from the diamagnetics measurement (W_{dia}) was feedback controlled by the P-NB power (P_{P-NB}) so as to obtain and keep a prescribed value of β_N. It should be noted that E_b was ~ 370 keV for the N-NB. After 6.3 s, only pre-programmed P-NB units were used. Injection of N-NB and LHRF started at 6.1 and 6.3 s as shown in Fig.s 1 (a) and (b). The frequency of LHRF was 2 GHz, and two multi-junction launchers were used for the LHRF injection and the spectra were chosen to enhance off-axis LHCD [7,8,13,14]. The surface loop voltage ($V_{\ell,s}$) keeps decreasing and reaches ~ -0.2V as shown in Fig. 1 (b). Temporal evolutions of ρ_{foot} and ρ_{q-min} are plotted in Fig. 1 (c). As shown in the figure, ρ_{q-min} starts increasing after the LHRF injection and ρ_{foot} expands following the movement of ρ_{foot}. It should be noted that in this discharge, the ITB foot rather locates outside the q minimum. In order to assess non-inductive current drive, the loop voltage (V_ℓ) profile inside the plasma was evaluated at around 7 s from the Motional Stark Effect (MSE) measurement [15,16], and is plotted in Fig. 1 (e). The profile is negative. This indicates that the plasma current is fully or even over drive by non-inductive currents. The bootstrap current fraction is evaluated as 62% by the ACCOME code [17]. The profiles of T_e, T_i, n_e and q are shown in Fig. 1 (f) – (h). Owing to the expansion of ρ_{foot}, the temperature and density ITBs build up at very large position.

In Fig. 1 (d) plotted is q at $\rho = 0.4$ and 0.6. The safety factor keeps decreasing at $\rho = 0.4$ and the decrease should be attributed to the central N-NBCD. On the other hand, increase in q at $\rho = 0.6$, near the q_{min} location before external current drive, should be attributed to expansion of q_{min}. As the result, the q profile (Fig. 1 (h)) at 7.24 s looks quite differently from that observed in usual P-NB heated RS plasmas. Actually the q profile at 6.15 s is one of quite a common ones. In the q profile at 7.24 s, lowering q by N-NBCD is quite successful at $\rho > 0.3$. Although the ACCOME code predicts more centrally peaked driven current profile, q near the center looks to stay high. The reason is not clear yet. It might be attributed to a current hole [4]. It remains to be an important issue to investigate intensively. However, lowering q even outside $\rho > 0.3$ would help together with the expansion of the ITB. Even if the high energy ion orbit expands due to high q they might stay well inside very flat profile inside the ITB. It also should be noted that decrease in q or rather flattening of the q profile is clearly highlighted because of off-axis CD by LHRF. Central intensive CD would simply make $\rho_{q_{min}}$ shrinking to lose RS area.

It should be noted that this plasma is very interesting from a view point of performance. The confinement improvement factors relative to ELMy H-mode scaling ($HH_{98(y,2)}$) and to L-mode scaling (H_{89P}) [18] were ~ 2.2 and ~ 3.5. This good confinement was sustained for 2.7 s (six times the energy confinement time (τ_E)). Furthermore, the line averaged

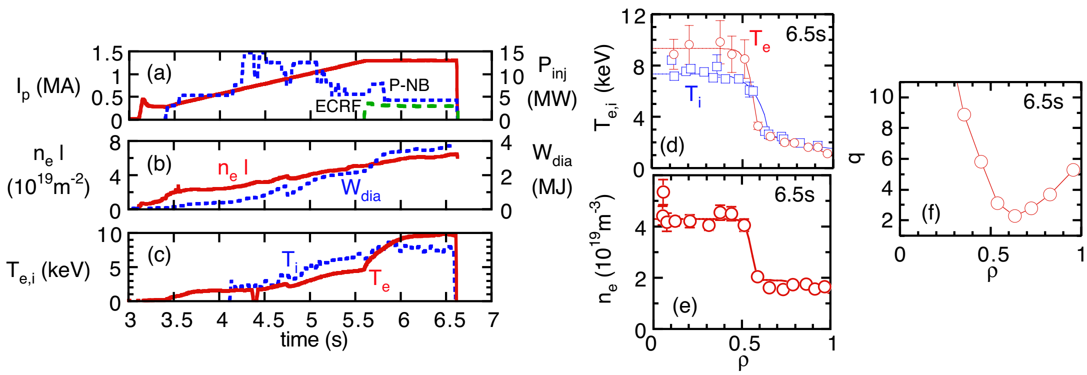

FIG. 3: Waveforms, (a) – (c), and profiles, (d) – (f) of typical parameters in an RS discharge with dominant electron heating (E41738).

density normalized to the Greenwald density [19] reached 0.8 in this experiment. As shown in Fig. 2 (a), this is a good advance from the past JT-60U steady state experiments. The typical parameters achieved in the plasma is plotted against those required in the ITER steady state operational scenario. As is shown in the figure, the achievement is quite successful in core confinement and CD, while more efforts should be required for particle and heat handling.

3. ITB under Dominant Electron Heating

Characteristics of ITBs under dominant electron heating have been investigated by changing a ratio of fed power to electrons (P_e) to that to ions (P_i), or $T_\mathrm{e}/T_\mathrm{i}$, utilizing the LHRF, the ECRF and both the P- and N-NB systems on JT-60U [20, 21]. Very recent improvement of the JT-60U ECRF system [16] enables us to extend the region of electron heating experiment with higher P-NB power therefore with stronger ITBs. In the series of the experiments shown here electron heating is done by ECRF mainly. In order to assess high confinement at dominant electron heating regime, ECRF power is injected in addition to the positive NB power or substituting some NB power to raise the electron heating fractional power further. However, P-NB power can not be lowered too much since ITB becomes weakened and shrink in such cases. Although the ECRF power has been increased, it is not enough in some cases.

3.1. ITB in a Reversed Magnetic Shear Plasma

In this subsection, results obtained in RS plasmas are shown. Waveforms of a discharge with high electron heating fraction are shown in Fig. 3. During the I_p ramp-up, P-NB power was injected to form the RS configuration and the T_e, T_i and n_e ITBs. The injection of ECRF, about 3 MW in the discharge, started at the I_p flat-top. Up to the ECRF injection, discharge scenario is the same as usual P-NB heated RS discharge. The P-NB power was feedback controlled in order to achieve certain performance. After 5.8 s, the NB-power was fixed. As shown in the figure, the stored energy keeps increasing. As shown in the figure, due to the electron heating by ECRF the core T_e quickly increased and exceeded the core T_i. The core T_i rather decreased slightly due to step down of the P-NB power. Both electron and ion temperatures look saturated before disruption. The profiles of T_e, T_i, n_e and q at 6.5 s, just before the disruption, are shown in Fig. 3 (d) - (f). As shown in the figure, strong ITBs are confirmed in the T_e, T_i and n_e profiles. In the q profile, the q minimum is close to two. The disruption should be attributed to that the q minimum is approaching or crossing two as usual P-NB RS discharges, but not to the electron heating. At 6.5 s, the $HH_{98(\mathrm{y},2)}$ factor is evaluated as 2.0. The $HH_{98(\mathrm{y},2)}$ factor is evaluated in the RS plasmas in this electron heating experiments. The $HH_{98(\mathrm{y},2)}$ factor is compared to that obtained in usual P-NB heated RS plasmas and plotted against a ratio $T_\mathrm{e}/T_\mathrm{i}$ in Fig. 4. Here the temperatures are evaluated at the center, since the profile inside the ITB is usually very flat in high confinement RS plasmas. As shown in the figure, the $HH_{98(\mathrm{y},2)}$ factor obtained in the electron heating experiments (shown by open circles) is comparable to that obtained in P-NB heated RS plasmas (shown by ope squares). It should be noted that in the electron heating series data are taken with $I_\mathrm{p} \sim 1.3$ MA, while in the P-NB cases I_p is mainly in 0.8 - 1. MA and one 1.3 MA data is included.

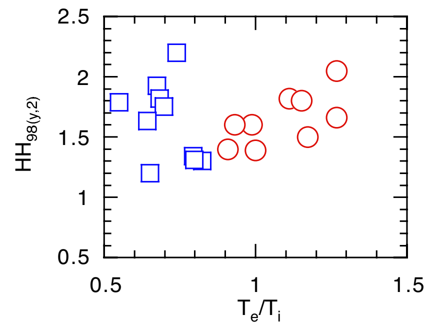

FIG. 4: The $HH_{98(\mathrm{y},2)}$ factor plotted against a ration $T_\mathrm{e}/T_\mathrm{i}$, that taken in the electron heating experiments is shown with open circles and that obtained in usual P-NB heated plasma is shown with open squares.

In the results shown above, fraction of the electron heating power is changed after the ITBs are developed. Another issue in the electron heating is to investigate influence of the electron heating onto the ITB formation phase. Formation of T_e ITB with electron heating dominant have been widely reported. Formation of T_i ITB would be of interest and important. In order to assess T_i ITB formation under dominant electron heating, ECRF was injected from very early phase in an RS discharge. The experiment was carried out in a hydrogen plasma with hydrogen NB. The waveforms of typical parameters are plotted in Fig. 5. The ECRF injection starts at 3.4 s almost the same timing as the NB injection starts. As shown in Fig. 5 (c), T_e stays higher than T_i in the core region through out the discharge. The T_e profile at 3.6 s is shown in Fig. 5 (d) and the T_e ITB is found to be formed already. The T_i profiles (Fig. 5 (e)) at 3.9 and 4.1 s suggest that the T_i ITB is not formed before 3.9 s. The q profiles at each timing are shown in Fig. 5 (f). It should be noted that at 5.1 s, although 8.5 MW of P-NB is injected the absorbed power is about 5.5 MW with $P_\mathrm{EC} \sim 3$ MW, the ration $P_\mathrm{e}/P_\mathrm{i}$ is about 0.9.

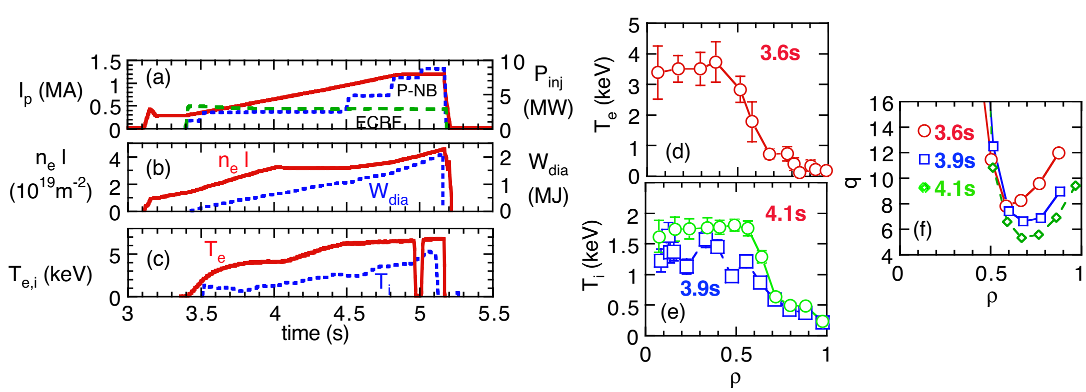

FIG. 5: Waveforms, (a) – (c), and profiles, (d) – (f) of an RS discharge with dominant electron heating from very early phase (E40735).

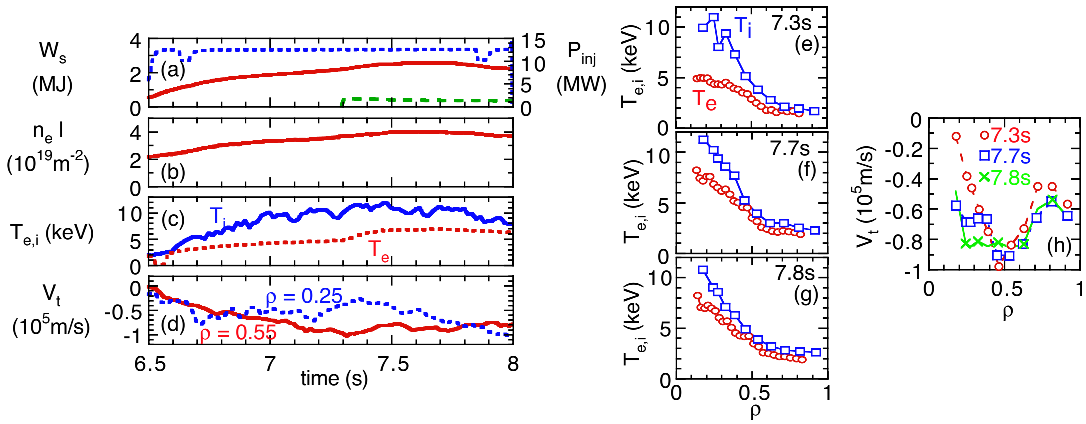

FIG. 6: Waveforms, (a) – (d) of typical parameters in an PS discharge with dominant electron heating (E41760). Also profiles of T_e, T_i and V_t are shown at 7.3, 7.7 and 7.8 s in (e) – (h).

The power fed to electrons by NB is not small due to faster thermal speed of hydrogen compared to that of deuterium of the same energy. It should be noted that at 5.1 s the $HH_{98(y,2)}$ factor is evaluated as 1.2. These results suggest that in an RS plasma formation and sustainment is not seriously affected under dominant electron heating. Quantitative study is left for future issue.

3.2. ITB in a Positive Magnetic Shear Plasma

Electron heating experiments have also been carried out on ITBs in positive shear plasmas. Here positive shear ITB is referred to ITBs similar to those observed in high β_p discharges in JT-60U. They are formed at positive magnetic shear region in a plasma. However, in order to make T_e/T_i is closer to unity P_{NB} is limited to modest level compared to that used in high performance high β_p discharges. Since in high β_p like discharges, T_i tends to developed more than T_e. Also it should be noted that the target plasma are of L-mode edge plasmas due to lower input power and higher B_t for ECRF resonance in this experiments. Waveforms of a typical discharge is shown in Fig. 6. Injection of NB starts at 6.5 s to form ITBs. In the plasma q is monotonously decreasing towards the plasma center and near unity at the center. The formation of the ITB is rather slow in the discharge compared to that in higher performance high β_p plasmas, due to limited P_{NB}. The ITB seems to be formed at around 7.2 s. Profiles of T_e and T_i at 7.3, 7.7 and 7.8 s are shown in Fig. 6 (e) – (g). As shown in the figure, a clear ITB structure is observed in both the T_i and T_e profiles at 7.3 s. At 7.7 s, the T_i ITB looks eve clearer. Due to the electron heating by ECRF, T_e is approaching to T_i as shown in the waveforms and the profiles. However at 7.8 s, the T_i profile becomes smooth at the location ($\rho \sim 0.4 - 0.5$)

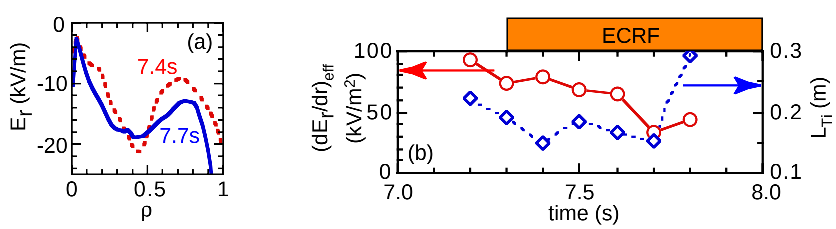

FIG. 7: (a) Profile of E_r evaluated at 7.4 and 7.7 s in E41760. (b) Temporal change of $(dE_r/dr)_{eff}$ and the minimum scale length of the T_i profile.

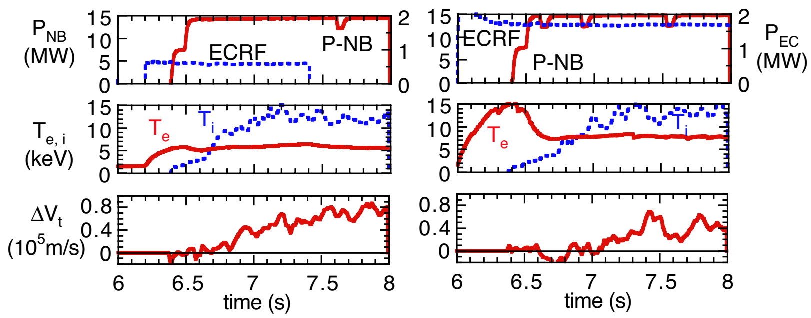

FIG. 8: Comparison between two discharged with different ECRF power to investigate influence of electron heating on the formation of the ITB. (a) Lower ECRF power, ∼ 0.6 MW (E41674). (b) Higher ECRF power, ∼ 1.5 MW (E41696).

where clear ITB was observed at earlier timing. The scale length of the $T_{\rm i}$ profile ($L_{\rm Ti} = T_{\rm i}/({\rm d}T_{\rm i}/{\rm d}r)$) changes from about 15 cm at 7.7 s to 29 cm at 7.8 s (Fig. 7 (b)). These results indicate that the $T_{\rm i}$ ITB is lost between 7.7 and 7.8 s. It should be noted that the $T_{\rm e}$ profile also looks smoother at 7.8 s and the $T_{\rm e}$ scale length also becomes doubled, that means the $T_{\rm e}$ ITB is lost as well. Waveforms of the toroidal rotation of carbon species ($V_{\rm t}$) at $\rho \sim 0.25$ and 0.55 are plotted in Fig. 6 (d). The profile of $V_{\rm t}$ is shown for 7.3, 7.7 and 7.8 s in Fig. 6 (h). As shown in the profile, the difference of $V_{\rm t}$ between these two location can be representative of gradient of the $V_{\rm t}$ profile around the ITB location inside the bottom of the notched $V_{\rm t}$ structure. The profile of the radial electric field ($E_{\rm r}$) is determined as, $E_{\rm r} = \frac{1}{eZ_{\rm i}n_{\rm i}}\nabla p_{\rm i} + V_{\rm t,i}B_{\rm p} - V_{\rm p,i}B_{\rm t}$, here e is an electron charge, $Z_{\rm i}$, $n_{\rm i}$, $p_{\rm i}$, $V_{\rm t,i}$, $V_{\rm p,i}$ are charge number, density and pressure, toroidal and poloidal rotational velocities of an ion species and $B_{\rm p}$ and $B_{\rm t}$ are the poloidal and toroidal magnetic fields. The $E_{\rm r}$ profiles at 7.4 and 7.7 s are shown in Fig. 7 (a) they have a notched structure which is more steeply notched when the ITB is clearer. In the JT-60U ITB experiments, it is found that the shear of the $E_{\rm r}$ profile is a key for formation and sustainment of the $T_{\rm i}$ ITB [22]. Level, or strength, of the shear can be represented by a parameter $(|(dE_{\rm r}/dr)_{\rm max}| + |(dE_{\rm r}/dr)_{\rm min}|)/2$ which is denoted as $(dE_{\rm r}/dr)_{\rm eff}$ in this paper. That roughly indicates how sharply or deeply the $E_{\rm r}$ profile is digged. Change of $(dE_{\rm r}/dr)_{\rm eff}$ is plotted in Fig. 7 (b). As shown in the figure, $(dE_{\rm r}/dr)_{\rm eff}$ continues to decrease during ECRF injection and reached to the same level as that without the ITB, while $L_{\rm Ti}$ stays small until 7.7 s. The results indicate that the ECRF injection influences the structure of $E_{\rm r}$.

Influence of electron heating on the ITB formation was also investigated. In the experiment, $P_{\rm EC}$ was injected prior to the NB injection. Furthermore $P_{\rm EC}$ was scanned with the same $P_{\rm NB}$. The waveforms of typical quantities are shown in Fig. 8. Again $I_{\rm p}$ is 1 MA. Difference of $V_{\rm t}$ between near the bottom of the notch and $\rho \sim 0.3$ ($\Delta V_{\rm t}$) is shown in the figure as a measure of the gradient of the $V_{\rm t}$ profile. As shown in the figure, $\Delta V_{\rm t}$ starts increasing at about 6.8 s for lower $P_{\rm EC}$ case and 7.3 s for higher $P_{\rm EC}$ cases respectively. In the higher $P_{\rm EC}$ case, slow growth of the ITB might have started earlier. Rapid increase in $\Delta V_{\rm t}$ can be related to the formation of the $T_{\rm i}$ ITB. It seems that increasing $P_{\rm EC}$ delays the formation of ITB. As shown in the figure, temperature at the $\Delta V_{\rm t}$ increase is different in both electrons and ions, higher for larger $P_{\rm EC}$. However, a ratio of $\langle T_{\rm e}\rangle_{\rm core}$ to $\langle T_{\rm i}\rangle_{\rm core}$, where $\langle\rangle_{\rm core}$ means volume average from the plasma center to the ITB foot,is almost the same value at the $\Delta V_{\rm t}$ increase in two discharges. The ratio evaluated in E41674 at 6.9 s is 0.60 and that taken from E41696 at 7.3 s is 0.62. This may suggest that influence of electron heating can be related not only to the $E_{\rm r}$ structure, as descried above, but also to the ratio between electron and ion temperatures. However, due to lack of both central heating NB and ECRF powers, scanned range is not wide enough. Further detailed investigation would be required for deeper understanding. Concerning the study of positive shear ITBs, more ECRF and on-axis P-NB power would be necessary. On axis P-NB helps to develop $E_{\rm r}$ structure more, and more ECRF power enable high $T_{\rm e}$ at such intense ion heating regime.

4. Summary

Results of studies towards steady state operation of an advanced tokamak accompanied by ITBs concerning fusion relevant conditions on JT-60U are shown. High confinement improvement at high normalized density regime which is expected in the ITER steady state operational scenario was obtained in a reversed magnetic shear (RS) plasma under full non inductive CD. It was demonstrated that off-axis LHCD could extend $\rho_{\rm q-min}$ and $\rho_{\rm foot}$ as the result. It was also indicated that n axis-N-NBCD could contribute to lower q in the RS region. Influence of dominant electron heating on the ITB was investigated. It was found that in RS plasmas the confinement improvement by the ITBs could be maintained indifferent to the heating method. High enough $HH_{98({\rm y},2)}$ factor of 2.0, which is comparable to that obtained in the dominant ion heating region, was obtained in the dominant electron heating region. On the other hand, it was found that the $T_{\rm i}$ ITB could be degraded by dominant electron heating in positive shear plasmas. Electron heating would seem to influence the $E_{\rm r}$ structure at the PS ITB.

Acknowledgement

The authors would like to acknowledge all the members of Japan Atomic Energy Research Institute who have contributed to the JT-60U project.

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