Effects of low central fuelling on density and ion temperature profiles in reversed shear plasmas on JT-60U

H Takenaga, S Ide, Y Sakamoto, T Fujita and the JT-60 Team

Japan Atomic Energy Agency, Naka Ibaraki 311-0193, Japan
E-mail: takenaga.hidenobu@jaea.go.jp

Abstract. Effects of low central fuelling on density and ion temperature profiles have been investigated using negative ion based neutral beam injection and electron cyclotron heating (ECH) in reversed shear plasmas on JT-60U. Strong internal transport barrier (ITB) was maintained in density and ion temperature profiles, when central fuelling was decreased by switching positive ion based neutral beam injection to ECH after the strong ITB formation. Similar density and ion temperature ITBs were formed for the low and high central fuelling cases during the plasma current ramp-up phase. Strong correlation between the density gradient and the ion temperature gradient was observed, indicating that particle transport and ion thermal transport are strongly coupled or the density gradient assists the ion temperature ITB formation through suppression of drift wave instabilities such as ion temperature gradient mode. These results support that the density and ion temperature ITBs can be formed under reactor relevant conditions.

1. Introduction

A density profile has large impacts on fusion performance in a fusion reactor. A peaked density profile can produce higher fusion output even with the low edge density. Since operation regime of the edge density is limited below the Greenwald density [1] in tokamak plasmas, a peaked density profile has an advantage for higher fusion output. In addition, a large density gradient can assist formation of the internal transport barrier (ITB) in an ion temperature profile through suppression of drift wave instabilities such as ion temperature gradient (ITG) mode [2]. On the other hand, a peaked density profile raises a concern of impurity accumulation, because neoclassical inward pinch velocity increases with increasing the bulk ion density gradient. Impurity transport analyses in JT-60U advanced tokamak plasmas with ITBs have shown that argon impurities are accumulated inside the ITB, but accumulation level is smaller than the neoclassical prediction [3]. At this impurity accumulation level, argon density profiles yield acceptable radiation profile even with a density ITB in a steady-state tokamak reactor [4]. In JT-60U reversed shear plasmas, high confinement has been achieved with high radiation loss fraction of ~0.9 [5]. In order to optimize fusion performance in a fusion reactor, it is important to understand physical mechanisms responsible for the density profile under reactor relevant conditions, such as low or no central fuelling, electron dominant heating and no Ware pinch velocity.

In ELM H-mode plasmas, tokamak experiments have shown that a density peaking factor increases with decreasing effective collisionality due to anomalous inward pinch driven by drift wave instabilities such as ITG and/or trapped electron mode (TEM) [6, 7]. On the other hand, in advanced scenarios such as reversed shear (RS) plasmas, physics mechanisms for determining the density profile
are not understood well. It is crucial issue for prediction of fusion performance in an advanced steady state tokamak reactor whether a density ITB can be formed with low central fuelling or not. It is expected that the anomalous inward pinch can play less important role in the ITB region, where anomalous transport is reduced by suppressing instabilities. Also, investigation of correlation between a density ITB and an ion temperature ITB is important, because the large density gradient can assist formation of an ion temperature ITB through suppression of ITG. It is crucial issue to understand how large density gradient is necessary for the formation of an ion temperature ITB.

In JT-60U, reversed shear plasmas have been optimized using positive ion based neutral beam injection (P-NBI) [8]. The P-NBI provides high central fuelling, which is different from a reactor relevant condition of low or no central fuelling. JT-60U also has negative ion based neutral beam injection (N-NBI) and electron cyclotron wave heating (ECH), which can provide the reactor relevant condition of low or no central fuelling and electron dominant heating. In this paper, effects of low central fuelling on density and ion temperature profiles were investigated using N-NBI and ECH in reversed shear plasmas on JT-60U.

This article is structured as follows: The NBI and ECH systems are described in section 2. Effects of low central fuelling after the strong ITB formation are discussed in section 3. In section 4, effects of low central fuelling during the ITB formation phase are discussed. In section 5, correlation between a density ITB and an ion temperature ITB during the ITB formation phase are discussed, followed by a summary in section 6.

2. NBI and ECH systems in JT-60U
JT-60U is a large tokamak device with a major radius \((R)\) of \(~3.4\) m and an aspect ratio of \(~4\). The toroidal magnetic field \((B_T)\) is \(~4\) T at maximum and the plasma current \((I_p)\) is limited below 3 MA. Input power up to 25 MW is available from the P-NBI system with beam energy of 85 keV. There are 7 units for perpendicular injection, 2 units for co-tangential injection and 2 units for counter-tangential injection. The Charge Exchange Recombination Spectroscopy (CXRS) measurement system uses 1 perpendicular injection unit and the Mormaltian Stark Effect (MSE) measurement system uses 0.5 or 1 unit of counter-tangential injection unit. For the N-NBI system, input power up to 5-6 MW is available with beam energy of 360-380 keV. The injection direction of N-NBI is co-tangential.

The ECH system with a frequency of 110 GHz also provides an input power of 3 MW by using 4 units of gyrotron. The poloidal injection angle can be scanned by steerable mirrors to change the deposition position. The toroidal injection angle is fixed for 3 units with current drive (CD) mode (+20 degree). It can be changed for 1 unit with co-ECCD mode (+20 degree), counter-ECCD mode (-20 degree) and pure heating mode (0 degree).

3. Effects of low central fuelling after the strong ITB formation
First, effects of low central fuelling and accompanying electron dominant heating on density and ion temperature profiles were investigated after the strong ITB formation using ECH. The central ECH was applied from \(t = 5.6\) s with co-ECCD mode to the RS plasma at \(I_p = 1.3\) MA and \(B_T = 3.7\) T after the strong ITB was formed using P-NBI, as shown in figure 1 [9]. The P-NBI heating power was reduced at \(t = 5.8\) s. In this discharge, \(D_2\) gas-puffing was applied only in the early phase \((t < 4.4\) s). During the low central fuelling phase \((t > 5.8\) s), modulated Helium gas-puffing was applied to estimate helium transport coefficients [10]. The line averaged density \((\bar{n}_e)\) continued to increase without gas-puffing after the P-NBI heating power was decreased. The stored energy also continued to increase and the central electron temperature \((T_e)\) exceeds to the central ion temperature \((T_i)\) under dominant electron heating. The electron heating power was estimated to be higher by a factor of 1.6 than the ion heating power at \(t = 6.5\) s. The high confinement enhancement factor over IPB98(y,2) scaling of 2 was obtained with low central fuelling and central \((T_e/T_i)\) of about 1.3.

Figure 2 shows the density, safety factor \((q)\) and temperature profiles at \(t = 6.5\) s in the discharge shown in figure 1. The strong electron density \((n_e)\) ITB was maintained near the position of minimum safety factor with low central fuelling as shown in figure 2 (a). The strong \(T_i\) and \(T_e\) ITBs
were also maintained as shown in figure 2 (b). The effective electron diffusivity ($D_{\text{eff}}$) defined by considering only diffusion term was smaller in the low central fuelling case than those in the large central fuelling case [3] at the same range of the ion thermal diffusivity ($\chi_i$) as shown in figure 3. The reduction of the central particle fuelling by a factor of 2 was compensated with the reduction of $D_{\text{eff}}$ and the large density gradient was sustained in the ITB region. The value of $D_{\text{eff}}$ is much smaller than the ion neoclassical particle diffusivity, indicating important role of inward convective flux. The outward diffusive flux could be almost balanced with the inward convective flux and small unbalance between these two fluxes corresponds to the flux produced by the central fuelling. Therefore, the central fuelling might have only small effects on the density profile. In the previous studies on effects of low central fuelling and electron heating in JT-60U using ion cyclotron heating (ICH) [11], the density gradient in the ITB region increased with central fuelling together with reduction of effective particle diffusivity. In the discharge shown in figure 1, the effective particle diffusivity did not increase even with low central fuelling as shown in figure 3. Different effects on the density profile between ECH and ICH should be investigated in future.

The helium diffusivity was estimated based on Helium gas-puffing modulation experiments separately from the convective term. Figure 4 shows relation between helium diffusivity and ion thermal diffusivity. Here, the diffusivities were normalized by their neoclassical values, in order to compare how large anomalous transport remains in particle and thermal transport channels. The

Figure 1. Waveforms of the RS plasma with low central fuelling after the strong ITB formation. (a) Plasma current ($I_p$), P-NBI heating power ($P_{\text{NB}}$) and ECH power ($P_{\text{EC}}$). (b) Line averaged electron density ($n_e$), stored energy ($W$) and gas-puffing rates for D$_2$ ($Q_{\text{gas-D2}}$) and He ($Q_{\text{gas-He}}$). (c) Central ion and electron temperatures ($T_i(0)$ and $T_e(0)$).

Figure 2. (a) electron density (circles) and safety factor (squares) profiles and (b) electron (circles) and ion (squares) temperature profiles under low central fuelling and dominant electron heating at $t = 6.5$ s in the discharge shown in figure 1.
helium diffusivity is similar to or even higher than those with high central fuelling at the same $\chi_i/\chi_{i,NC}$ range. The convection velocity in the low central fuelling case is slightly negative (inward), however, its level is smaller than those in the high central fuelling case. The systematic helium transport study under the low central fuelling and the electron dominant heating is necessary in future.

The effects of low central fuelling on argon (Ar) accumulation were investigated in the similar discharge [3]. The central soft X-ray signal continued to increase after switch to the low central fuelling. The profile of the total Ar density summed over all ionization states was estimated using an impurity transport code, where the transport coefficient is determined by fitting the calculated soft x-ray profile to the measurement. The Ar radiation coefficient was taken from the ADAS database [12] considering the JT-60U diagnostic setup. The Ar density estimated from the soft X-ray intensity profile was more peaked by a factor of about 4 than the $n_e$ profile as shown in figure 5. Here, 4 times larger diffusivity than the neoclassical value and the neoclassical inward pinch velocity were used in the ITB region, which suggests that the Ar accumulation is weaker than the neoclassical prediction. In the weak shear plasma, the flattening of the density profile was observed with the central ECH and the Ar accumulation was drastically reduced [3]. However, in the RS plasma, the strong $n_e$ ITB was kept

Figure 3. Relation between the effective electron diffusivity and the ion thermal diffusivity. Circles and square show the data in the high and low central fuelling cases, respectively.

Figure 4. Relation between helium diffusivity and ion thermal diffusivity normalized by their neoclassical transport values. Circles and square show the data in the high and low central fuelling cases, respectively.

Figure 5. Electron density profile (circles) normalized at $r/a = 0$ and Ar density profile (solid line) adjusted to electron density outside the ITB.
and Ar was still accumulated inside the ITB even with the central ECH.

4. Effects of low central fuelling during the ITB formation phase

Next, effects of low central fuelling and electron dominant heating on $n_e$ and $T_i$ profiles were investigated during the ITB formation phase at $I_p = 1$ MA and $B_t = 3.7$ T. In the low central fuelling case, ECH ($\sim 2.5$ MW), N-NBI ($\sim 4.6$ MW) and P-NBI ($\sim 3.3$ MW) were injected during $I_p$ ramp-up phase as shown in figure 6 (a). The P-NBI injection included 1 unit of perpendicular beam and half unit of counter-tangential beam for diagnostics of CXRS and MSE. In the high central fuelling case, only P-NBI ($\sim 10.4$ MW) was injected during $I_p$ ramp-up phase as shown in figure 6 (b). In this case, 4 units of perpendicular beam and half unit of counter-tangential beam were used. The central fuelling rate was estimated to be $3.9 \times 10^{20}$/s in the low central fuelling case, which includes $3.2 \times 10^{20}$/s from P-NBI and $6.6 \times 10^{19}$/s from N-NBI. On the other hand, the central fuelling rate was estimated to be $1.0 \times 10^{21}$/s in the high central fuelling case. Central fuelling was smaller by a factor of 2.5 in the low central fuelling case than that in the high central fuelling case. In these discharges, density feedback control was applied during $I_p$ ramp-up phase. The gas-puffing rate was higher in the low central fuelling case than that in the high central fuelling case. However, difference is not large compared with difference of the central fuelling rate. In the low central fuelling case, $n_e$ and $T_i$ at $r/a = 0.4$ continued to increase, while those at $r/a = 0.6$ stayed constant after $t = 4.2-4.4$ s, indicating the $n_e$ and $T_i$ ITB formation. The increasing rate for a number of electrons inside the separatrix ($dN_e/dt$) was

![Figure 6. Waveforms of RS plasmas with (a) low and (b) high central fuelling during the ITB formation phase. First panel: plasma current, heating powers from P-NBI, N-NBI and ECH. Second panel: gas-puffing rate. Third panel: electron density. Fourth panel: electron temperature. Bottom panel: ion temperature. In the third, fourth and bottom panels, thick and thin lines show the data at $r/a = 0.4$ and 0.6, respectively.](image)
estimated to be $1.1 \times 10^{20}$/s for the low central fuelling case and to be $2.0 \times 10^{20}$/s for the high central fuelling rate. The central fuelling rate was larger by a factor of 4.5 than $dN_e/dt$ for both cases. In the high central fuelling case, the formation of the $n_e$ and $T_i$ ITBs seems to occur earlier. However, the time evolutions of $n_e$ and $T_i$ were similar to those in the low central fuelling cases, while the time evolution of $T_e$ was quite different for two cases. Note that electron heating was dominant in the low central fuelling case. In the low central fuelling case, the $T_e$ ITB was formed independently from the $n_e$ and $T_i$ ITBs.

Figure 7 shows profiles of $n_e$, $T_i$, $q$, $T_e$ and toroidal rotation velocity ($V_t$) at $t = 5.2$ s in the discharges shown in figure 6. It can be seen from figure 7 (a) that the density ITB can be formed even in the low central fuelling case. The effects of low central fuelling on the density ITB seems to be small, because $n_e$ and $T_i$ ITBs were similar in the region of $r/a = 0.4-0.6$ for the low and high central fuelling cases. In the low central fuelling case, wide current hole (CH) was produced due to higher $T_e$ as shown in figure 7 (c). In the central region ($r/a \leq 0.4$), the $T_i$ profile was flat in the low central fuelling case due to CH. On the other hand, the $T_i$ profile was peaked in the high central fuelling case. The $T_e$ profile was quite different for two cases due to the electron dominant heating in the low central fuelling case. The fluctuation dominating electron thermal transport could be different from that dominating density and ion thermal transport. Also, the toroidal rotation was different for two cases as shown in figure 7 (e). The counter $V_t$ was larger in the high central fuelling case due to fast ion loss induced by the toroidal field ripple in the edge region. The notch structure was observed in the low central fuelling case. These results indicated that the central fuelling does not strongly affect the $n_e$ and $T_i$ ITB formation. The penetration of the recycling neutrals is very shallow [13] and the neutrals do not reach ITB region. Therefore, the edge particle source does not play important role for the ITB formation. This result suggests that a ratio of convection velocity and particle diffusivity does not strongly depends on $q$, $T_e$ and $V_t$, although it is necessary to investigate the effects of different $q$ and $V_t$ profiles on the $n_e$ and $T_i$ ITBs more carefully.

5. Relation between density ITB and ion temperature ITB during the ITB formation phase
Finally, relation between $n_e$ and $T_i$ ITBs was investigated during the ITB formation phase. Here, two RS discharges with low central fuelling at $I_p = 1$ MA and $B_T = 3.7$ T shown in figure 8 were referred.
In the discharge shown in figure 8 (a), \( n_e \) was first increased by gas-puffing and then gas-puffing was stopped at \( t = 4.4 \) s. After gas-puffing was stopped, particle flux could be produced in the core region due to decrease in the edge density, resulting increase in the \( n_e \) gradient. The particle flux could give a similar effect to the central fuelling. In the other discharge shown in figure 8 (b), \( n_e \) was further increased by gas-puffing to get optimum density for the L-H transition and then gas-puffing was gradually decreased. The increase in the edge \( n_e \) induced by the L-H transition could decrease the \( n_e \) gradient in the ITB region.

In the discharge where gas-puffing was stopped at \( t \sim 4.4 \) s, the \( n_e \) and \( T_i \) ITBs were formed just after the gas-puffing stop as shown in figure 8 (a). The edge \( n_e \) decreased just after gas-puffing was stopped, while the central \( n_e \) continued to increase, resulting formation of the \( n_e \) ITB. At the same time, the central \( T_i \) largely increased, although the edge \( T_i \) stayed constant. The \( n_e \) and \( T_i \) profiles at \( t = 5.4 \) s were similar to the profiles shown in figure 7. In the discharge shown in figure 8 (b), the L-H transition occurred at around \( t = 5 \) s and ELMs appeared. After the L-H transition, the edge \( n_e \) increased and the \( n_e \) gradient decreased. In this phase, increase in the central \( T_i \) seems to be prevented. By decreasing the gas-puffing rate, the central \( T_i \) restarted to increase together with increase in the \( n_e \) gradient. These results indicated that the \( T_i \) ITB was changed when the \( n_e \) ITB was modified by gas-puffing and L-H transition.

Figure 9 shows relation between the \( n_e \) gradient and the \( T_i \) gradient around half the minor radius.

**Figure 8.** Waveforms of plasma current \( (I_p) \) and heating powers from ECH, N-NBI and P-NBI (first panel), line averaged electron density \( (\bar{n}_e) \) and gas-puffing rate \( (Q_{gas}) \) (second panel), electron densities (third panel) and ion temperatures (bottom panel). In the discharge shown in (a), gas-puffing was stopped at \( t = 4.4 \) s. In the discharge shown in (b), gas-puffing continued after \( t = 4.4 \) s and was gradually decreased.
The $T_i$ gradient increased with the $n_e$ gradient in these plasmas. The relation between the $n_e$ gradient and the $T_i$ gradient has been reported in [3], where the $n_e$ gradient and the $T_i$ gradient are correlated in the small value region ($-\nabla n_e/n_e$ and $-\nabla T_i/T_i < -5$). In the higher $T_i$ gradient region ($-\nabla T_i/T_i > -5$), the $n_e$ gradient was almost constant. The data points plotted in figure 9 are selected from this small region where the $n_e$ gradient and $T_i$ gradient are correlated. This correlation indicated that particle transport and ion heat transport might decrease simultaneously or the $n_e$ ITB might assist the formation of the $T_i$ ITB. In the latter case, there might be time delay of the increase in the $T_i$ gradient from the increase in the $n_e$ gradient, however it was not obvious from figure 9. In order to understand the causality, fast measurements are important. Recently, fast CXRS measurement was introduced in JT-60U. This measurement can provide precious information to understand the causality for the relation between $n_e$ and $T_i$ ITBs.

6. Summary
Effects of low central fuelling on the $n_e$ and $T_i$ ITBs were investigated in the RS plasmas on JT-60U. Strong $n_e$ and $T_i$ ITBs were maintained, when central fuelling was decreased after the strong ITB formation. Similar $n_e$ and $T_i$ ITBs were formed for the low and high central fuelling cases. An anomalous inward pinch could be still important with suppressed instabilities. Possibility for the formation of the strong $n_e$ and $T_i$ ITBs with ion thermal transport reduced to the neoclassical level and role of anomalous inward pinch in such strong ITB region are future issues. The $T_i$ gradient increased with the $n_e$ gradient, but their causality was not well understood yet. These results indicated that central fuelling does not largely affect the $n_e$ and $T_i$ profiles. Thus, it seems that the peaked density profiles with the ITB maybe possible in a fusion reactor.

References
[1] Greenwald M 2002 Plasma Phys. Control. Fusion 44 R27
[2] Rewoldt G and Tang W M 1990 Phys. Fluids B 2 318
[3] Takenaga H et al. 2003 Nucl. Fusion 43 1235
[4] Takenaga H, Kubo H, Kamada Y, Miura Y, Kishimoto Y and Ozeki T 2006 Fusion Sci. Tech. 50 503
[5] Takenaga H et al. 2005 Nucl. Fusion 45 1618
[6] Angioni C, Peeters A G, Pereverzev G V, Ryter F, Tardini G and ASDEX Upgrade Team 2003 Phys. Rev. Lett. 90 205003
[7] Weisen H et al 2005 Nucl. Fusion 45 L1
[8] Takenaga H and the JT-60 Team 2007 Nucl. Fusion 47 S563
[9] Ide S, Suzuki T, Sakamoto Y, Takenaga H, Fujita T, Oyama N, Isayama A, Koide Y, Kamada Y and the JT-60 Team 2004 Nucl. Fusion 44 87
[10] Takenaga H et al. 1999 Nucl. Fusion 39 1917
[11] Iwase M, Koide Y, Tobita K, Moriyama S, Takenaga H, Fujita T, Shirai H, Kusama Y, Kramer G J and Kimura H 1999 Plasma Phys. Control. Fusion 41 1189
[12] Summers H P 1994 JET-IR 06 JET Joint Undertaking Culham
[13] Nakashima Y, Higashizono Y, Kawano H, Takenaga H, Asakura N, Oyama N, Kamada Y and Yatsu K submitted to Journal of Physics: Conference Series