Controllability of large bootstrap current fraction plasmas in JT-60U

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Abstract. Controllability of plasmas with a large bootstrap current fraction (f_{BS}) has been investigated in JT-60U. Real time control logic for pressure profile control, through the toroidal rotation control, based on real time calculation of the minimum value of safety factor (q_{min}) using Motional Stark Effect diagnostic has been newly installed to avoid collapses in long sustainment of reversed shear plasmas. By utilizing new real time control, weak reversed shear plasma with f_{BS} ~ 70% is sustained for ~ 8 s. Current profile changes dynamically in accordance with the change in the local pressure gradient at the internal transport barrier (ITB) through rotation control, indicating the strong linkage among the profiles. It is found that the response of pressure and current profiles to off-axis neutral bean current drive (NBCD) seems to be slow compared to the local current diffusion timescale, which can be attributed to the slowing down time of fast ions and the change in beam driven current profile. The change in the loop voltage is found as one of the key factors for control of the radii of ITB and q_{min}. The current profile in strong reversed shear plasma without current hole is largely varied in the core region by electron cyclotron current drive, while the ITB structure is not affected.

1. Introduction

A large fraction of bootstrap current driven by the high beta plasma itself is required for the steady-state tokamak concept to reduce a circulating power for non-inductive current drivers [1]. The scenario for the ITER steady-state operation with Q > 5 have been proposed [2], in which high β_N with the large bootstrap current fraction of f_{BS} ~ 50%. Further large f_{BS} ~75% is required for the concept of steady-state fusion tokamak reactor (SSTR) [1]. A reversed shear plasma is one of the candidates of SSTR, because its current profile is naturally formed with the large f_{BS}. However there is not much research of the large f_{BS} plasmas compared to the other operation scenarios, because the operation regime is limited at high q_{95} (safety factor at the 95% flux surface) in which f_{BS} is enhanced within the attainable beta limit without wall stabilization. Although an internal transport barrier (ITB) contributes to enhance f_{BS}, the profiles of pressure, current and flow should be optimized to keep stability limit and confinement as high as possible because for example local reduction of diffusivity improves confinement while the produced steep pressure gradient at the ITB sometimes causes MHD instability. Since the large f_{BS} strengthens the linkage among these profiles, such plasmas are characterized as self-regulating system. Recent experimental results of ITB research are reviewed in Ref. 3.

In JT-60U, a stationary reversed shear plasma with f_{BS} ~ 75% had been sustained for 7.4 s which is 2.7 times longer than the current diffusion time [4]. Although pressure and current profiles gradually changed in time and seem to become stationary in the latter phase of the discharge, the evaluated loop voltage profile is hollow inside of half minor radius, indicating that the inductive field is still evolving. The evolution of inductive field was found to be largely affected by the change in bootstrap current, indicating strong linkage between pressure and current profiles. This is because the movement of the ITB causes a local change in the bootstrap current density, which generates a local inductive field as a back electro-magnetic-force [5].

Towards the stable sustainment of the large f_{BS} plasmas, active control of the ITB structure is essential because total pressure and current profiles are mostly determined by its structure such as the ITB radius, the ITB strength and its width. In this paper, we discussed about the parameter linkage among the profiles and controllability of the large f_{BS} plasmas.

2. Long sustainment of large f_{BS} plasma with real time control

The formation of the reversed shear q profile is usually created by the intense heating to produce the ITB during plasma current ramp-up phase in JT-60U. Then reversed shear q profile gradually changes towards the stationary condition at plasma current flattop phase, where the value of q in core plasma region, including q_{min}, decreases continuously due to the penetration of inductive current. Therefore the value of q_{min} passes through integer values until reaching stationary condition. Then the discharges frequently terminate by disruption when q_{min} goes across the integer values. In order to avoid disruptions, the pressure gradient at the ITB should be decreased when the plasma becomes unstable. It was demonstrated that steep pressure gradient at the ITB could reduce by the control of toroidal rotation profile to avoid disruption at the minimum value of safety factor (q_{min}) ~ integer [4]. Since the timing of q_{min} ~ integer depends on the time evolution of the plasma current profile, it is difficult to adjust the timing of the rotation control as the pre-programmed setting. Figure 1 shows the time evolution of normalized beta (β_N) for similar reversed shear plasmas with large f_{BS}. Collapses and/or disruptions occurred frequently at q_{min} ~ integer. As can be seen in the figure, there are various timings of the encounter with q_{min} ~ 4. These various timings attribute to initial current profile, onset of ITB formation, ITB structure and so on. For example, the early ITB formation delays the penetration of current while the late ITB formation hastens. Therefore one of the issues to avoid collapses is how to set up timing to apply the toroidal rotation control to reduce the pressure gradient at the ITB. In order to establish the pressure profile control at q_{min} ~ integer through the rotation control technique with good reproducibility, feedback control based on real time detection of q profile is required. Recently the real time control system of q profile had been developed [6]. This system calculates q profile in real time including q_{min} and the location of q_{min} using the motional Stark effect (MSE) diagnostic. Therefore the timing of rotation control can be determined in real time using the real time detection of q_{min}. In the new real time control logic, injection of the tangential neutral beam (tang-NB) is controlled. The range of q_{min} and the control period are used to determine the injection timing of tang-NB as setting parameter. For example, ctr-NB is turned off for 0.5 s when the value of the real time detected q_{min} is in the 3.8 to 4.2 ranges.

Typical waveforms of the long sustainment of the reversed shear plasma with large f_{BS} using

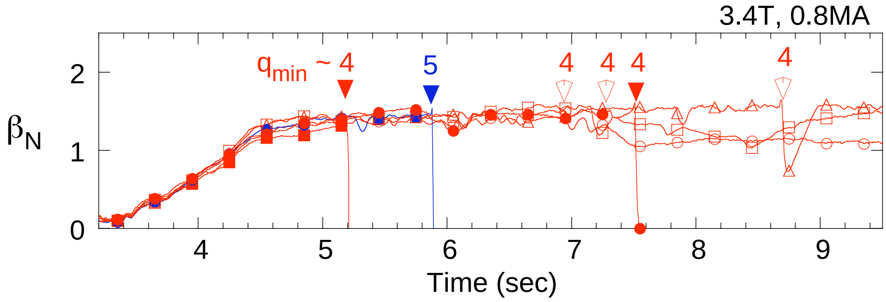

Figure 1. Time evolution of β_N for reversed shear plasmas with large f_{BS}. Open symbols indicate the discharges with collapse. Closed symbols indicate the disrupted discharges.

newly installed real time control logic are shown in figure 2, where $I_p = 0.8$ MA, $B_T = 3.4$ T, $q_{95} \sim 8.5$, $\kappa = 1.6$, $\delta = 0.4$. The co-NB power of ~ 2.6 MW was injected for the non-inductive current drive, and the ctr-NB power of ~ 1.8 MW was injected for the MSE measurement. The ITB was formed during I_p ramp, and the ETB was also formed at t ~ 4.5 s. Using the feedback control of the stored energy by the perpendicular NBs, $\beta_N \sim 1.5$ ($\beta_p \sim 2.1$) was maintained. In this plasma, counter injected NB is turned off for 0.8 s when q_{min} is in the 3.7 to 4.1 ranges as setting. The value of q_{min} decreased in time and was below 4.1 at t ~ 7 s as shown in the figure. Then ctr-NB injection turned off for 0.8 s. During this phase, toroidal rotation started to change towards co-direction, and then electron pressure at the ITB was reduced and recovered as shown in the figure. The behavior of ion temperature was similar to that of electron pressure profile. This short period of reduction of the pressure gradient at the ITB leads to avoidance of collapse at $q_{min} \sim 4$. High confinement of $H_{98} \sim 2.6$ ($HH_{98y2} \sim 1.8$) was obtained in this plasma, and $f_{BS} \sim 70\%$ was sustained for ~ 8 s. In the later 3 s, q profile becomes flat, as shown in figure 2(b), with keeping the good ITB and seems to be almost unchanged. The temporal evolution of the radial profile of the time averaged internal loop voltage is shown in figure 2(c), which is evaluated from the equilibrium reconstruction using MSE measurement [7]. Although the profile of internal loop voltage is flattened in time indicating the plasma approached the stationary condition, more time is required for full relaxation of the internal loop voltage towards steady-state condition. In addition, the electron pressure continues to increase slightly at the core region and then collapse occurs at t ~ 13.3 s. Since the value of q_{min} was just above 3.6, this collapse can be attributed to the evolution of pressure profile.

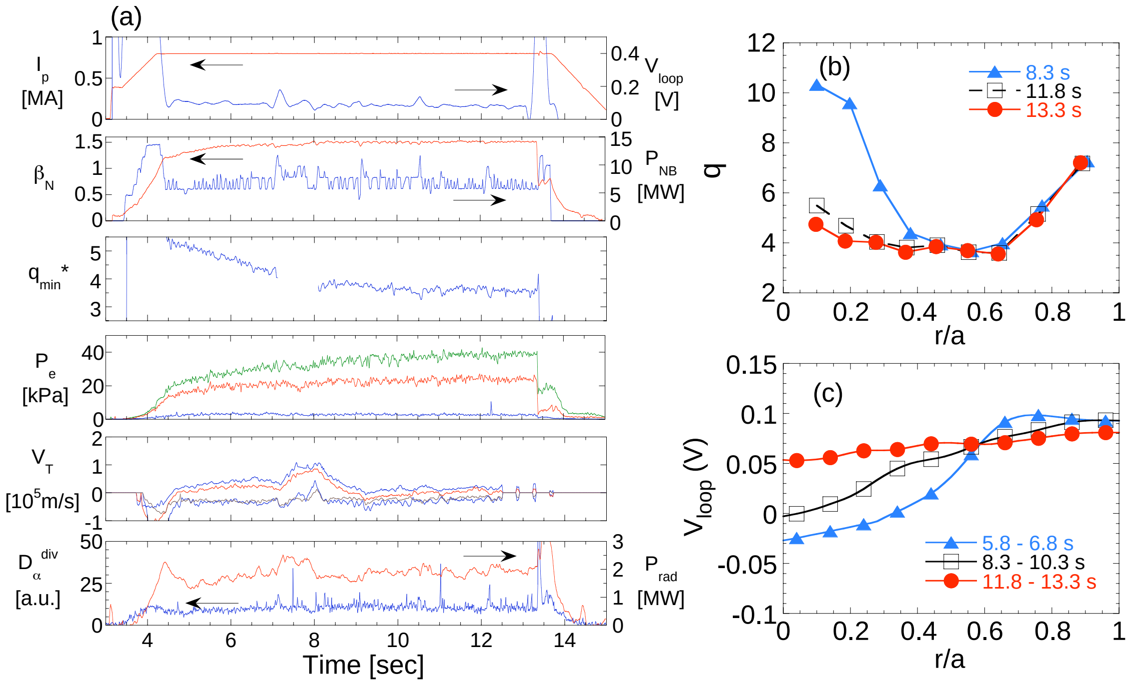

Figure 2. Typical discharge of long sustainment of reversed shear plasma with large fBS using newly installed real time control logic. (a) Waveforms of the discharge. (b) Temporal evolution of q profile. (c) Temporal evolution of inductive field profile.

3. Controllability of large f_{BS} plasmas by external controls

Large f_{BS} plasmas are characterized as self-regulating system in which profiles of pressure, current and flow are strongly linked through ITB structure. Therefore control of ITB structure is essential for such plasmas. In this section, controllability of the ITB plasmas with large f_{BS} is discussed using the plasmas described in section 2.

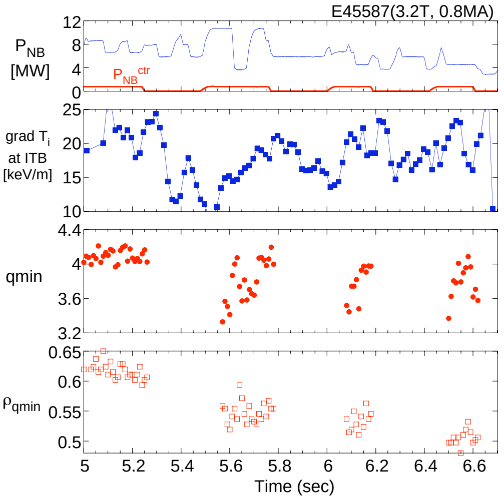

Figure 3. Temporal evolution of (a) neutral beam power, (b) gradient of ion temperature at ITB, (c) q_{min} in real time detection and (d) ρ_{qmin} in real time detection during ITB control through rotation.

3.1 Response of pressure and current profile to rotation control

The bootstrap current density should be changed during the pressure profile control through toroidal rotation, which changes the total current density profile. This effect becomes as remarkable as f_{BS} is large. The value of q_{min} decreases with decreases in pressure gradient through the reduction of the off-axis bootstrap current density. On the other hand, the value of q_{min} increases with increases in pressure gradient. Since a local change in the bootstrap current density generates a local inductive field (a toroidal electric field) as a back electromagnetic force, the evolution of total current density profile has some delay compared to the change in the bootstrap current density. Figure 3 shows the temporal evolutions of ion temperature gradient at the ITB, q_{min} and ρ_{qmin}, where degradation and recovery of ITB are repeated three times by repetitive rotation control. This indicates strong linkage between rotation and pressure profiles. Although the total current profile could not be measured during the rotation control phase due to the no injection of diagnostic NB for MSE, in addition, the increase in q_{min} was quickly observed just after the recovery of ion temperature gradient. The change in ρ_{qmin} tends to be similar to that in q_{min}. This indicates strong linkage between pressure and current profiles. These observations suggest that very sensitive and quick controls are required for stable sustainement of the reversed shear plasma with large f_{BS}.

3.2 Response of pressure and current profile to off-axis NBCD

Off-axis non-inductive driven currents, by the NB injection, and by the radio-frequency electromagnetic waves, are required for long sustainment of the reverse shear plasmas with large f_{BS}. In the stationary reversed shear plasmas with full non-inductive current drive condition, the large bootstrap current and the off-axis beam driven current sustained the reversed shear q profile and hollow current profile [4,8]. Towards active control of current profile, we investigate the response of current and pressure profiles under the strong linkage to off-axis neutral beam current drive (off-axis NBCD). Off-axis co-NB was turned off for 1 s during no stationary phase, where q_{min} and ρ_{qmin} continued to decrease, in the discharge shown in figure 4. The values of q_{min} and ρ_{qmin} continued to decrease after off-axis co-NB was turned off. After off-axis co-NB was re-injected, the decrease in ρ_{qmin} was suppressed, and then ρ_{qmin} was started to expand from 0.56 to 0.62 as shown in figure 4(b). The locations of ITBs were also expanded as shown in figure 4(c). The beam driven current of off-axis NB is 15% of total plasma current. The profiles of total current density, bootstrap current and beam driven current are shown in figure 4(d). The beam current is mainly driven around ITB region or near ρ_{qmin}, which acts the value of q_{min} and its location. It is noted that the changes in current and pressure profile were delayed for ~ 0.4 s from off-axis NB injection, and the evolution of ρ_{qmin} seems to be slow. This delay time is comparable to the slowing down time of fast ions

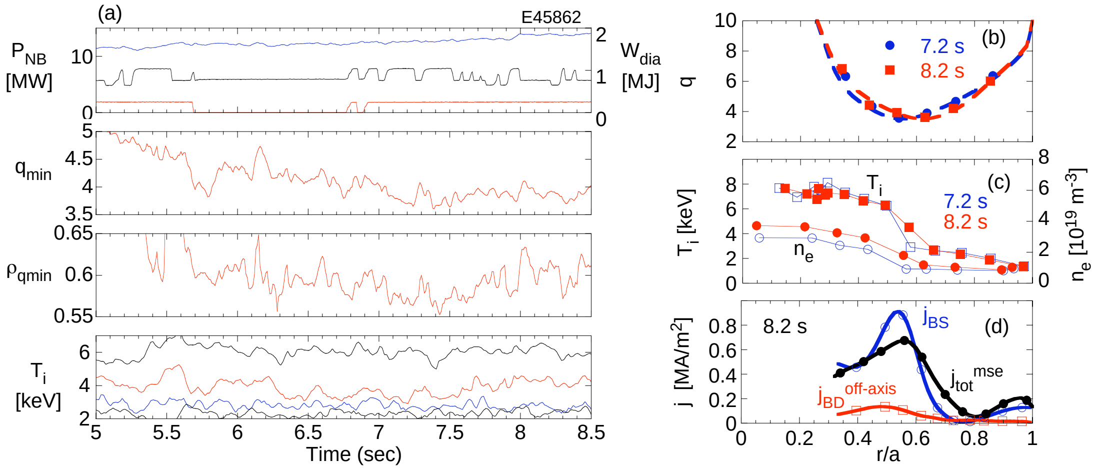

Figure 4. Response of off-axis NBCD to reversed shear plasma with large f_{BS}. (a) Time evolution of neutral beam power, stored energy, q_{min}, ρ_{qmin}, ion temperature in each radial location. Profiles of (b) safety factor at t = 7.2, 8.2 s, (b) ion temperature and electron density at t = 7.2, 8.2 s, (c) measured total current density, off-axis beam driven current and bootstrap current at t = 8.2 s.

form NB. Furthermore the beam driven current profile should be changed due to the change in ITB radius, which leads to change the beam deposition profile. Therefore the response of current profile to off-axis NBCD is affected by the slowing down time of fast ions and the change in pressure profile under the strong linkage.

3.3 Response of pressure and current profile to the change in loop voltage

Inductive current (Ohmic current) can be considered one of the ways for current profile control. The ITB radius could actively shrink with keeping the ITB strength by plasma current ramp down. Figure 5(a) shows the change in q profile of the plasma with $f_{BS} \sim$ 60% during plasma current ramp down. Here plasma current was reduced from 1MA to 0.9MA in 0.6s, which causes the reduction of loop voltage. As the result, the ρ_{qmin} shifts inward and the ITB foot (ρ_{foot}) follows in the wake of ρ_{qmin} as shown in figure 5(b). Since the ITB strength was kept during I_p ramp down, this movement of ρ_{qmin} is not attributed to the bootstrap current. The reason for this movement might be attributed to the reduction of current near the ITB foot due to change in loop voltage.

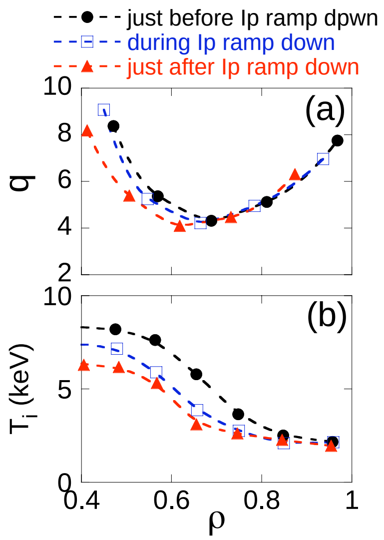

Figure 5. Changes in (a) q profile and (b) ion temperature profile during plasma current ramp down.

In addition turning off the negative ion-based NB (N-NB) injection as shown in figure 6 can expand the ITB radius. This plasma has $f_{BS} \sim$ 60% and the N-NB driven current fraction of ~30%. The ρ_{qmin} shifts outward after N-NB turning off, and then the ITB radius was expanded. It should be noted that the loop voltage increases rapidly during N-NB turning off, which is attributed to the reduction of the N-NB driven current of ~ 50%, which is estimated from the slowing down time of fast ions. Therefore this change in q profile might be attributed to both the reduction of N-NB driven current inside the ITB and the increase in the Ohmic current outside the ITB. It

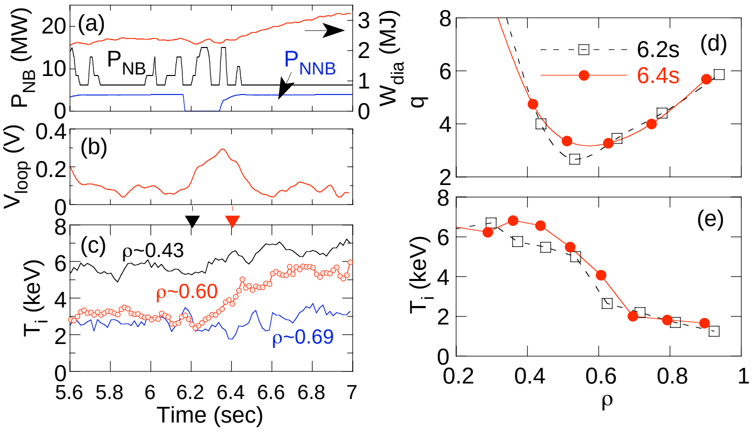

Figure 6. (a) Waveforms of neutral beam power (P_{NB}) and negative-ion based neutral beam power (P_{NNB}) and stored energy (W_{dia}). Time evolution of (b) surface loop voltage and (c) ion temperature in each radial location. Temporal evolution of profiles of (d) safety factor and (e) ion temperature.

should be noted that the movement of ITB radius did not go back to the previous state after the N-NB turning off or the plasma current ramp down due to large f_{BS}, suggesting the self-regulating nature.

3.4 Response pressure and current profile to ECCD

The electron cyclotron current drive (ECCD) is one of actuators for control of the current profile, which can drive the current locally. Towards active control of current profile, we investigate the response of current and pressure profiles under the strong linkage to ECCD. In the case of strong reversed shear plasma with current hole, ECCD did not change the current inside current hole [9]. In the experiment, B_T = 3.4 T and I_p = 0.8 MA, the electron cyclotron wave was injected near the ITB shoulder (just inside ITB layer) in the reversed shear plasma without current hole. The current profile (q profile) was quickly varied after EC injection as shown in figure 7(a), where q at r/a ~ 0.18 decreased from ~ 8 to ~ 4 within 0.3 s, and then the

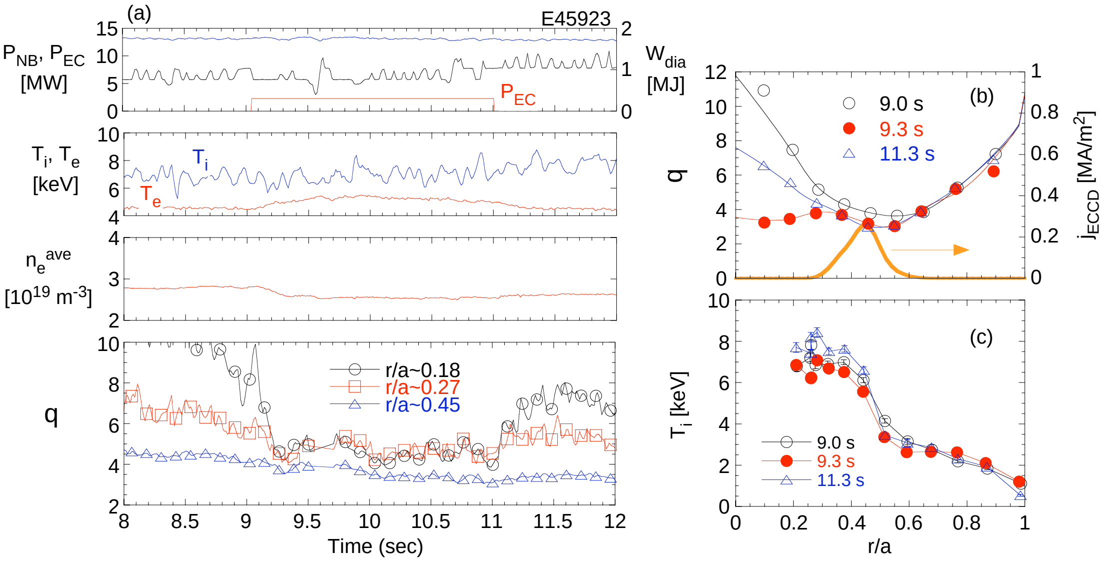

Figure 7. (a) Waveforms of the discharge with off-axis EC injection to the reversed shear plasma with large f_{BS}. (b) temporal evolutions of (a) q profile and EC driven current profile at t = 9.3 s, (c) ion temperature.

reversed shear q profile became the flat shear in the core region as shown in figure 7(b). The flat shear q profile was sustained during EC injection and the q in the core region increased again after EC was stopped. Here EC power of ~ 2.3MW was injected near 43% of minor radius, and EC driven current of 0.1MA (12.5% of total current) was estimated. The large change in q profile near the center in spite of off-axis ECCD might be attributed to poor confinement near the core region in the case of box-type ITB [10]. Although electron density decreased slightly after EC injection as shown in the figure 7(a), good ITBs were remained during q profile changed from the reversed shear to flat shear, indicating the magnetic shear in the core region, where transport is not improved, do not affect the transport at the ITB.

4. Summary

Response and controllability of plasmas with the large f_{BS} was investigated. The longer sustainment of reversed shear plasma with the large f_{BS} with good reproducibility is necessary to investigate those. For that purpose, real time control logic for pressure profile control through toroidal rotation based on real time calculation of q_{min} using MSE diagnostics was newly installed. By utilizing this new real time control, the pressure profile could be controlled with good reproducibility just before q_{min} ~ integer in which collapse and/or disruption occurred frequently. As the result weak reversed shear plasma with f_{BS} ~70% was sustained for ~ 8 s, but it could not reach to steady-state condition. Even so, the responses of the plasma with large f_{BS} to external controls are investigated in such plasmas. As for the response of pressure and current profile to rotation control, dynamic change in current profile, which corresponded to change in pressure profile through rotation control, was observed, indicating the strong linkage among the profiles. The timescale for change in the current profile seems to be local current diffusion time ~ 0.1 s. On the other hand, response of pressure and current profiles to off-axis NBCD seems to be slow compared to local current diffusion timescale. This can be attributed to the slowing down time of fast ions, which shoulders beam driven current, and the change in the beam driven current profile due to the change in pressure profile, which causes change of beam deposition profile. The change in the loop voltage can act the current and pressure profiles near the ITB. The movement of ITB by change of the loop voltage did not go back to the previous state, suggesting the self-regulating nature. The current profile was largely varied in the core region by ECCD, while pressure profile was not affected. Since the development of the large f_{BS} plasmas is required towards a steady-state fusion reactor, we should continue to study the controllability of large f_{BS} plasmas with strong linkage among profiles with different timescales.

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