

## Improved Performance in Long-pulse ELMy H-mode Plasmas with Internal Transport Barrier in JT-60U

N. Oyama, A. Isayama, T. Suzuki, Y. Koide, H. Takenaga, S. Ide, T. Nakano, N. Asakura,  
H. Kubo, M. Takechi, Y. Sakamoto, Y. Kamada, H. Urano, M. Yoshida, K. Tsuzuki,  
G. Matsunaga, C. Gormezano and the JT-60 Team

Japan Atomic Energy Agency, Naka, Ibaraki-ken, 311-0193 Japan

e-mail contact of main author: oyama.naoyuki@jaea.go.jp

**Abstract.** After installation of ferritic steel tiles (FSTs), fast ion losses due to toroidal field ripple have been reduced by  $1/2 \sim 1/3$ . The increase in absorbed power at same injection power can reduce the required number of NB units to sustain a given  $\beta_N$ , resulting in a better flexibility of torque input by increasing the available combination of tangential NB units. By making use of these advantages to sustain an internal transport barrier (ITB), the performance of long-pulse ELMy H-mode plasmas was improved in terms of sustained duration time for both high normalized beta ( $\beta_N$ ) and high thermal confinement enhancement factor ( $H_{H98(y,2)}$ ). High  $\beta_N > 2.3$  together with  $H_{H98(y,2)} \sim 1$  was sustained for 23.1s ( $\sim 12\tau_R$ ) at  $q_{95} \sim 3.3$ , which also provide high  $\beta_N \cdot H_{H98(y,2)} \geq 2.2$  and a bootstrap current fraction of 36%-45%.  $\beta_N \cdot H_{H98(y,2)}$  of 2.0 was sustained for 28.6s, which is limited by the maximum injection period of 30s for NBI system. These long-pulse plasmas are possible candidates for ITER hybrid operation scenario. Improved confinement is characterized by the larger thermal components at a given density maintained by smaller heating power than in previous experiments. The strength of the ITB depends on the pedestal temperature, which varies with edge density while keeping constant the pressure (limited by type I ELMs). These long-pulse plasmas indicate that further investigation to establish high performance plasmas longer than  $\tau_w$  with active particle control is essential to establish the operational scenarios for next step devices, where the wall pumping does not work.

### 1. Introduction

Beyond the ITER standard operation with high fusion gain ( $Q$ ) of 10 for  $\sim 400$ s, several advanced tokamak plasma operations have been proposed for ITER to extend the time duration of burning plasma toward steady-state operations. One of these advanced operational modes is the "hybrid scenario" [1, 2], where pulse duration is longer than  $\sim 1000$ s thanks to non-inductive current drive and the subsequent reduced flux consumption providing larger neutron fluence per pulse. It has been developed in many tokamaks [3-6]. One of the key parameter in the "hybrid scenario" is a non-inductive current fraction of larger than  $\sim 50\%$ . Since such a large non-inductive current including the bootstrap current should be kept stationary throughout the discharge, a demonstration of high performance plasma with high bootstrap current much longer than the current diffusion time ( $\tau_R \equiv \mu_0 \langle \sigma \rangle a^2 / 12$  [7]) is important to establish "hybrid scenario" in ITER.

In JT-60U, in order to expand the advanced tokamak (AT) plasma regime with time scales longer than  $\tau_R$ , the control systems for operation, heating and diagnostics have been modified [6]. However, further pursuit of long sustainment of high performance plasmas has been handicapped by the loss of fast ions due to the toroidal field ripple from the viewpoint of the available net heating power and controllability of the toroidal rotation profile due to the formation of an inward electric field [8]. In order to reduce the toroidal field ripple, ferritic steel tiles (FSTs), which cover  $\sim 10\%$  of the vacuum vessel surface, have been installed inside the JT-60U vacuum vessel on the low field side [9]. Making use of advantages of reduced fast ion losses after installation of FSTs, we have extended the sustainable duration of high  $\beta_N$  plasmas with better thermal plasma confinement and larger  $f_{BS}$ . In this paper, we report recent results of long-pulse AT research in JT-60U, which can contribute significantly towards the development of the ITER hybrid operation scenario.

## 2. Advantages of ripple reduction in long-pulse ELMy H-mode plasmas

The design of FSTs and its location are optimized to reduce the fast ion losses using Fully Three-Dimensional magnetic field Orbit Following Monte Carlo (F3D-OFMC) code. The 18-fold toroidal symmetry of the ripple amplitude was broken, because no FSTs were installed near the outer midplane in some toroidal sections due to limitation of space [9]. Here, "quasi" ripple well structure is defined by whether there is a local minimum of the magnetic field within  $\phi_s - \Delta\phi < \phi < \phi_s + \Delta\phi$  at a given toroidal angle  $\phi_s$ , where  $\Delta\phi$  is half of the period of the TF coil installation [10]. Using this definition, figures 1(a) and 1(b) show a comparison of "quasi" ripple well structure without and with FSTs, respectively, based on plasma parameters and configurations in long-pulse ELMy H-mode plasmas at 1.6T. Although Fig. 1(b) is evaluated at a section, where the maximum local ripple exists, ripple well structure becomes small.

Calculated loss power of fast ions from perpendicular-(perp) NBIs reduces by 1/2~1/3 at 1.6T as shown in Fig. 1(c). Injection angles to the plasma in the toroidal direction for perp-NBIs are not fully at a right angle completely as shown in Fig. 1(d). It is noted that the loss power ratio of perp-NBIs is related to the tilted angle to the plasma current rather than to the beam trajectory (i.e. central heating for upper units and off-axis heating for lower units). Therefore, the selection of perp-NBIs is important to reduce the loss of fast ions.

The reduction of fast ion losses is the dominant effect in long-pulse ELMy H-mode experiments. The increase in absorbed power at same injection power can reduce the required number of NB units to sustain a given  $\beta_N$ , resulting in a better flexibility of torque input by increasing the available combination of tangential NB units. Since lower fast ion losses also reduced the formation of an inward electric field, plasma can now rotate in the same direction as the torque input from tangential NBIs [11].

## 3. Extension of sustained duration of high $\beta_N$ plasmas

Making use of the advantages described in Sec. 2, the duration of high  $\beta_N$  plasmas has been extended close to the hardware limit of heating systems (30s for NBI system) in JT-60U. Figure 2 shows waveforms of a typical high  $\beta_N$  long-pulse plasma with the following parameters,  $I_p=0.9\text{MA}$ ,  $B_T=1.6\text{T}$ ,  $q_{95}\sim 3.3$ ,  $\delta\sim 0.32$  and  $\kappa\sim 1.4$ . Preheating from 2 tangential NBIs with balanced injection was applied during  $I_p$  ramp-up phase and gradually increased up

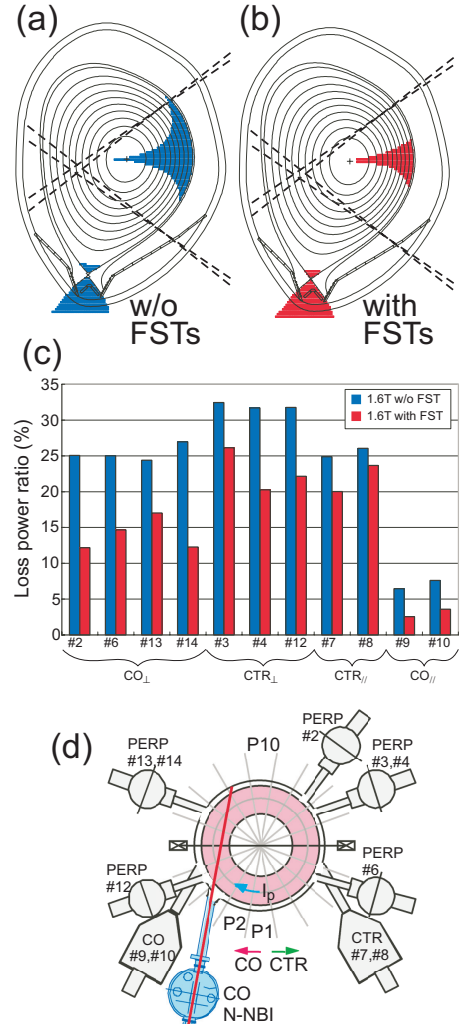


FIG. 1. "quasi" ripple well structure (a) without and (b) with FSTs. The dashed lines show the beam trajectories of two ion sources from one perp-NBI unit. (c) Fast ion losses evaluated with F3D-OFMC code. perp-NBIs of #2, 4, 6, 12, 14 and #3,13 are injected from upper and lower port, respectively. (d) Port arrangement of NBI system (top view).

to 8.1MW as shown in Fig. 2(a). A high confinement plasma ( $H_{H98(y,2)} \sim 1.1$ ) with  $\beta_N \geq 2.4$  was kept up to  $t \sim 22$ s as shown in Fig. 2(b). Destabilization of neoclassical tearing modes (NTMs) was successfully avoided by optimizing the current profile and pressure profile [12] so that a steep pressure gradient is not located at the mode rational surfaces at  $q=1.5$  and 2 as shown in Fig. 3(a). No detectable sawtooth activity was observed in this discharge, which was consistent with the time evolution of  $q$  profile (no  $q=1$  surface or very narrow) as shown in Fig. 2(d). Such optimum  $q$  profile could be sustained much longer than  $\tau_R$  ( $\sim 2$ s) with large  $f_{BS}$  of 36-45%, which is a consequence of the peaked pressure profile as shown in Fig. 3(a). On the other hand, there was an edge fluctuation with  $m/n=3-4/1$  at  $\sim 4$ kHz observed between type I ELMs as shown in Fig. 2(e). Here,  $m$  and  $n$  are poloidal and toroidal mode numbers, respectively. Nevertheless, the existence of edge fluctuations does not affect the plasma confinement, which was similar with and without this mode by changing the edge  $q$  profile with higher  $B_T$ .

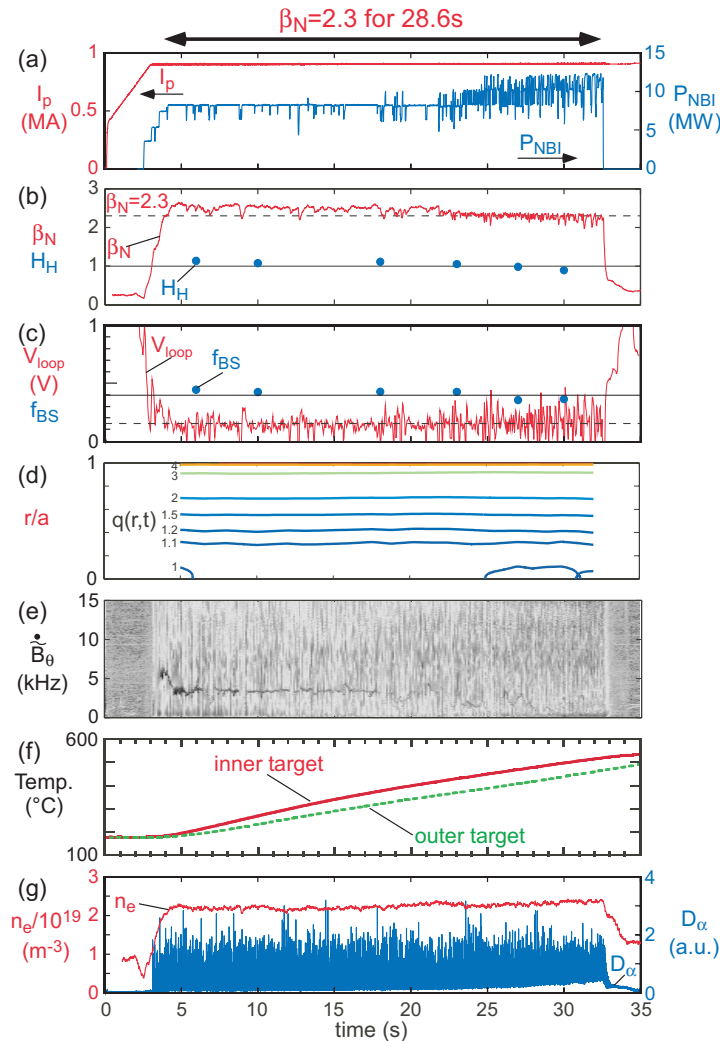


FIG. 2. Waveforms of a typical high  $\beta_N$  long-pulse plasma (E45436), (a) plasma current and heating power, (b) normalized beta,  $\beta_N$ , and confinement enhancement factor,  $H_{H98(y,2)}$ , (c) loop voltage and fraction of bootstrap current (d) safety factor,  $q$ , profile, (e) frequency spectrum of magnetic fluctuation (f) wall temperature at both inner and outer divertor target plates and (g) line-averaged density and divertor  $D_\alpha$  intensity. Dashed line in (b) and (c) indicate  $\beta_N=2.3$  and  $V_{loop}=0.15$ V, respectively. Solid line in (b) and (c) indicate  $H_H=1$  and  $f_{BS}=0.4$ , respectively.

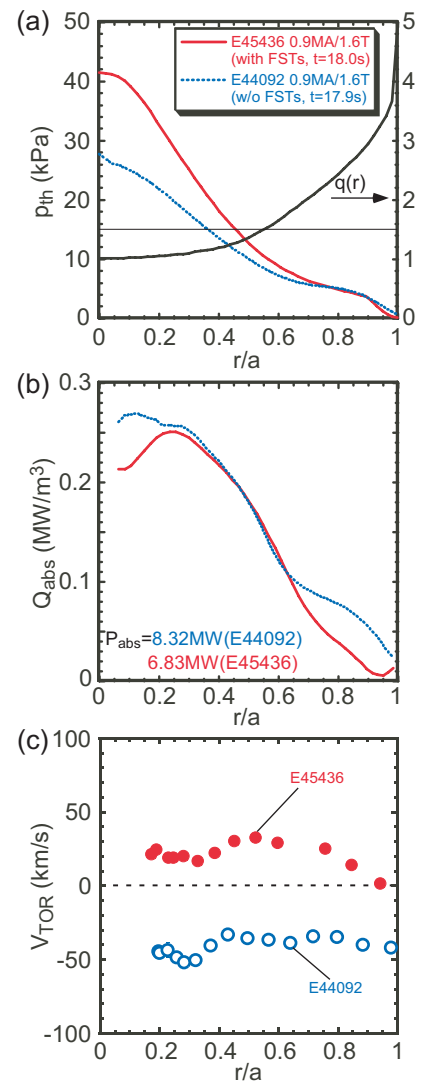


FIG. 3. Comparison of (a) thermal pressure profiles, (b) power deposition profile and (c) toroidal rotation profile in high  $\beta_N$  ( $>2.3$ ), long-pulse plasma without FSTs (E44092 at 17.9s) and with FSTs (E45436 at 18.0s). Safety factor profile for E45436 is also shown in (a).

Because of the long duration of NB heating in these discharges, the surface temperature at the divertor targets continuously increased from  $\sim 180^\circ\text{C}$  to  $\sim 500^\circ\text{C}$  as shown in Fig. 2(f). The increase in wall temperature may increase the recycling level in the latter phase ( $t > 23\text{s}$ ), as shown in Fig. 2(g), due to the reduced net pumping speed by the first wall [13]. During this phase, the core temperature, also in the ITB region, decreases with the reduction of edge temperature as the edge density increased, due to the core-pedestal interplay as discussed in a later section. After switching from central heating to off-axis heating of perp-NBI at  $t = 22.7\text{s}$  because of the limitation of available NB units, the power deposition profile became broader. Owing to these reasons, the same ITB performance could not be sustained in the latter phase ( $t > \sim 23\text{s}$ ). However, the constant stored energy feedback system increased the NB heating power to keep the stored energy at  $\beta_N > 2.3$  throughout the discharge (28.6s). Then, the sustained duration of high  $\beta_N$  plasmas has been extended up, close to the limitation of the NB injection pulse length (30s) as shown in Fig. 4.

In the previous long-pulse ELMy H-mode experiments shown by open symbols in Fig. 4, the sustained duration of high  $\beta_N$  plasmas was limited by the maximum duration of the available power, mainly limited by 6 perp-NBIs for 10s injection. In E44092 without FSTs, for example, average loss power of fast ions was 21.5% of injected power, while only 13.7% of injected power was lost in E45436 with FSTs. Moreover, plasma confinement property in E45436 was much better than E44092 as discussed in the next section. Then, we could reduce the number of NB units from 6-7 units (4 tangential NBIs plus some perp-NBIs and/or N-NBI) to 4.5-6.5 units (3.5 tangential NBIs plus one or two perp-NBIs) to sustain  $\beta_N > 2.3$  resulting in longer sustained duration time without any modification of the heating system.

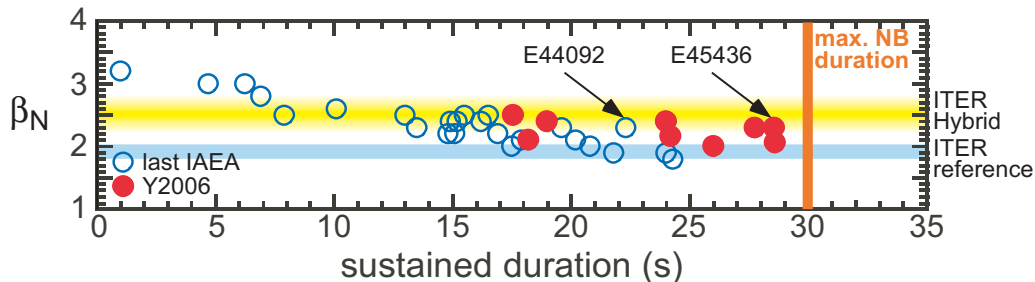


FIG. 4. Sustained duration of high  $\beta_N$  plasmas.

#### 4. Improved thermal confinement in long-pulse plasma with high $\beta_N$

In addition to the extension of the sustained time duration of  $\beta_N = 2.3$  for 6.3s as shown in Fig. 4, thermal confinement was much improved after installation of FSTs. Figure 3 shows the comparison of pressure profile, power deposition profile and toroidal rotation profile between two plasmas with same  $\beta_N$ , E44092 without FSTs and E45436 with FSTs. The ITB was formed in both plasmas with similar location of ITB foot. Nevertheless, the ITB performance was quite different with similar pedestal pressure. It is noted that the deposited power inside the ITB region was similar for the two plasmas. Higher pressure profile sustained by smaller heating power as shown in Fig. 3(b) provides higher  $H_{H98(y,2)}$  of 1.1 in E45436 with FSTs as compared to 0.73 in E44092 without FSTs.

Some part of this improvement of the ITB performance shown in Fig. 3(a) comes from the difference in the pedestal density and temperature as discussed in the next section. But, even when we compare the temperature profiles at the same pedestal density, ITB strength was different (especially for the  $T_e$ -ITB). Figure 5(a) shows the density dependence of  $H_{H98(y,2)}$  with and without FSTs. Higher  $H_{H98(y,2)}$  can be obtained in all density region. The reason why

plasmas with smaller  $H_{H98(y,2)}$  can achieve similar  $\beta_N$  to those with FSTs is shown in Fig. 5(b). In the previous experiments without FSTs, the stored energy of the beam component was higher than the thermal component. On the other hand, higher thermal component than the beam component was obtained at the similar  $\beta_N$ , resulting in a better thermal confinement.

Therefore, we could expand the operation regime toward higher  $\beta_N \cdot H_{H98(y,2)}$ , which is a measure of fusion performance, for longer duration as shown in Fig. 6. In the discharge shown in Fig. 2, high  $\beta_N \cdot H_{H98(y,2)} \geq 2.2$  was sustained for 23.1s, which corresponds to  $> \sim 12\tau_R$ , with bootstrap current fraction of 36%-45%. Since these plasmas were operated in lower  $q_{95} \sim 3.3$ , a figure of merit for Q, so-called G-factor ( $\beta_N \cdot H_{H98(y,2)} / q_{95}^2$ ), has exceeded the value for ITER reference scenario of 0.2 as shown in Fig. 6. Considering these plasma parameters, these discharges are possible candidates for ITER hybrid operation.

Most of the improved confinement was attributed to the improved ITB performance as can be seen in Fig. 3(a). In order to check the effect of better ITB performance on the edge stability, a relation between the pedestal  $\beta_p$ ,  $\beta_{p,ped}$ , and the total  $\beta_p$  (a measure of Shafranov shift) is compared with the previous JT-60U database [14] in Fig. 5(c). Since the achieved  $\beta_N$  was similar in both long-pulse plasmas with similar  $q_{95}$ , achieved  $\beta_p$  was also similar. The fact that both long-pulse plasmas with (E45436) and without (E44092) FSTs achieved similar  $\beta_{p,ped}$  indicates that the edge stability seemed to be similar.

As shown in Fig. 3(c), a larger co-toroidal rotation was observed with net co-torque input with FSTs. The effect of different toroidal rotation profile on the ITB performance was also investigated by changing the combination of tangential and perp-NBIs. As a result, we found that the reducing co-toroidal rotation has degraded performance of  $T_e$ -ITB. Moreover, when we set the similar core toroidal rotation profile to the previous experiments

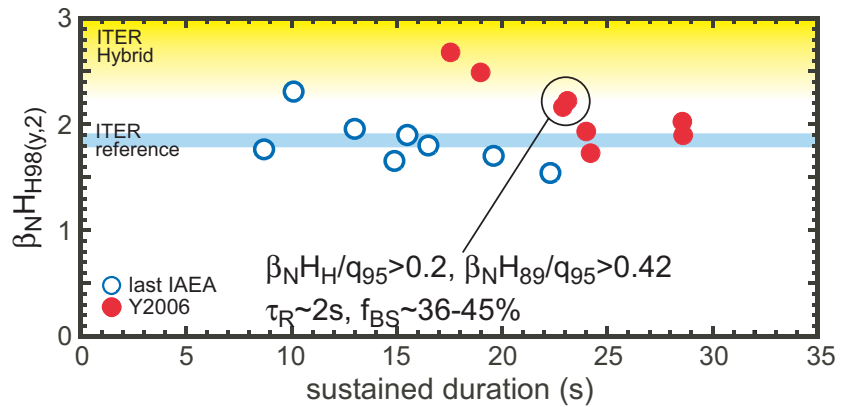


FIG. 6. Sustained duration of  $\beta_N \cdot H_{H98(y,2)}$ .

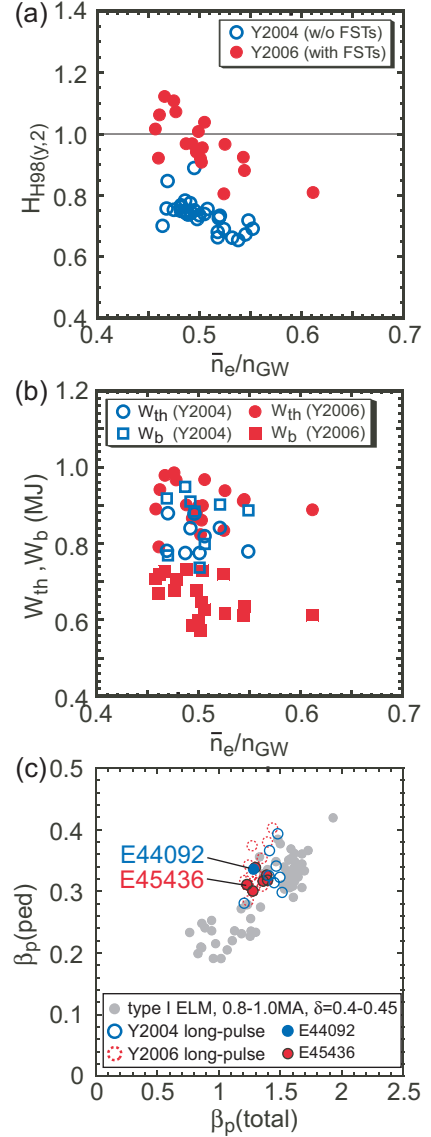


FIG. 5. Comparison of density dependence of (a) thermal confinement enhancement factor and (b) thermal and beam stored energy components. (c) relation between pedestal and total  $\beta_p$ . Type I ELM data shown by gray symbols indicate both with and without ITB.

without FSTs, achieved  $T_e$  profile became also similar. The better quality of  $T_e$ -ITB obtained with FSTs also gives some contribution to the improved performance of these long-pulse plasmas with high  $\beta_N$ .

### 5. Importance of particle control on ITB performance

The performance of these long-pulse plasmas degraded as the density and the recycling became higher in the latter phase as described in the previous section. It is important to understand the mechanism of the confinement degradation for the further investigations of long-pulse AT tokamak operation.

Figure 7(a) shows the pedestal operational regime in ion and electron including the time evolution of  $n_i$ - $T_i$  trace for E45436. Selected timing of six points plotted in Fig. 7(a) correspond to the timing of  $H_{H98(y,2)}$  analysis in Fig. 2(b). In E45436, the pedestal  $T_i$  started to decrease at  $t \sim 23$ s. It is noted that the pedestal pressure for both ion and electron in these long-pulse plasmas were limited at  $\sim 2$ kPa by type I ELMs. Then, the pedestal temperature has to vary to keep constant the pedestal pressure. In other words, the pedestal temperature has decreased when the pedestal density was increasing, similar to the usual type I ELMy H-mode plasmas without an ITB [15].

Pedestal temperature is quite important as a boundary condition for the core plasma in the ELMy H-mode plasmas due to the stiff-profile [15] nature of the temperature profile. Figures 7(b) and (c) show the time evolutions of pedestal  $T_i$  measured at  $r/a=0.86$  versus core  $T_i$  and  $T_i$  at the ITB foot measured at  $r/a=0.53$  versus  $T_i$  inside the ITB, respectively. These data were obtained in two long-pulse discharges in a low recycling case (E45436) and a high recycling case (E45570) as shown in Fig. 8. The  $T_i$  measured at  $r/a=0.77$  between the pedestal top and the ITB foot (Fig. 3(a)) was clearly stiff as shown by inverse triangles in Fig. 7(b). However, the  $T_i$  inside the ITB including the ITB foot does not show the linear relation, but the offset-linear relation with a change of pedestal  $T_i$  (solid line in Fig. 7(b)). On the other hand, a linear relation was clearly found in Fig. 7(c) showing that core  $T_i$  inside the ITB increased with the  $T_i$  at the ITB foot. Therefore, reduction of pedestal temperature can also degrade the ITB performance.

The degradation of the ITB due to the increase in the edge density was severer in the  $T_i$ -ITB, because the relation between the edge density and the edge temperature for ions was stronger than that for electrons as shown in Fig. 7(a). These results indicate that the performance of plasmas with an ITB strongly depends on the pedestal condition.

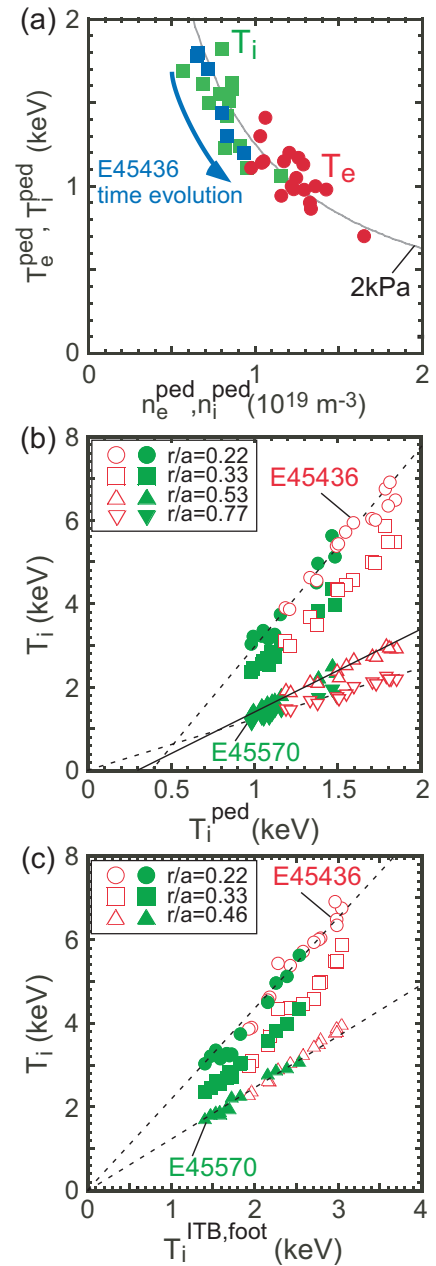


FIG. 7. Pedestal operational space in  $n_i$ - $T_i$  and  $n_e$ - $T_e$ .  $n_i$  was evaluated assuming that carbon is the only impurity. All data are taken with FSTs. Time evolution and its relation between (b) pedestal  $T_i$  and core  $T_i$  and (c)  $T_i$  at ITB foot and core  $T_i$ .

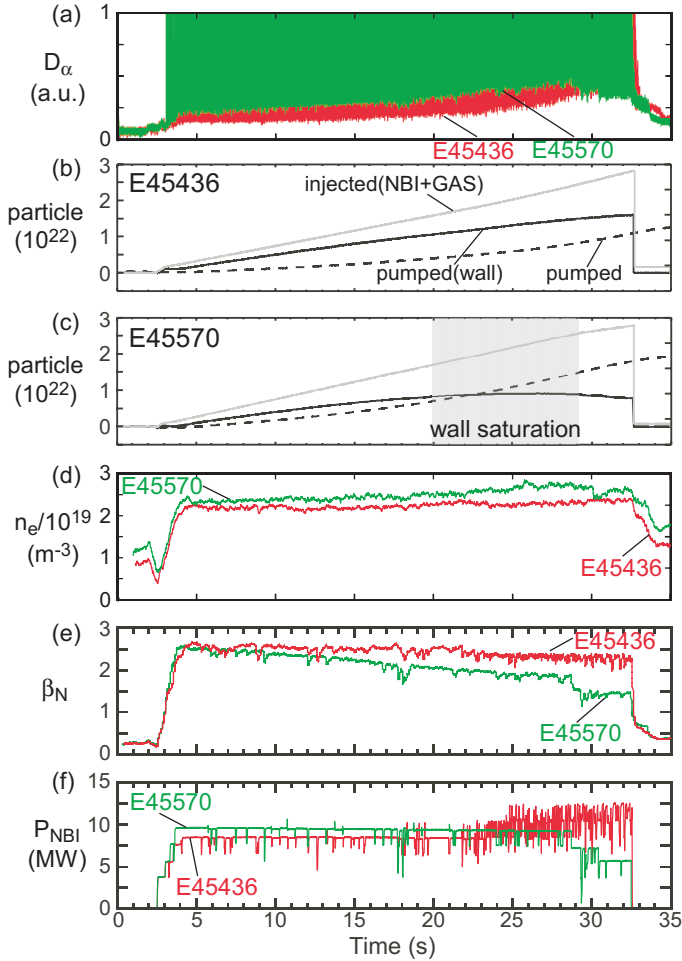


FIG. 8. Comparison of waveforms between low recycling case (E45436) and high recycling case (E45570). (a) divertor  $D_\alpha$  intensity. (b), (c) particle balance for low and high recycling cases, respectively. (d) line-averaged density. (e) normalized beta,  $\beta_N$ . (f) heating power.

Because of the higher edge density in such wall condition with high recycling, good ITB cannot be formed in the early phase of the discharge even if the heating power increased to keep the same power deposition profile inside the ITB. This situation can be found in Figs. 7(b) and (c) as the different highest temperature,  $\sim 7\text{keV}$  in E45436 and  $< 6\text{keV}$  in E45570 at  $r/a \sim 0.22$ .

When the recycling level was high, such as in E45570, higher NB power cannot help to keep the high  $\beta_N$  plasma for long time, because higher NB power provides faster increase in divertor recycling due to larger fueling into the torus and larger heat flux to the wall, as shown in Fig. 8. Achieved  $\beta_N$  could be raised only in the initial phase by higher beam component. But, the plasma confinement was degrading faster than in a low power discharge due to the faster increase in the edge density as observed in Figs. 8(e), 7(b) and 7(c). Therefore, enough pumping capability to control the edge density is essential for keeping the long-pulse plasmas stationary longer than the time scale of wall saturation ( $\tau_w$ ). In JT-60U, however, the divertor pumping is effective only in high density plasmas with high divertor pressure under optimum configuration, where both divertor legs located close to divertor slot [16]. Therefore, wall conditioning is the only way to obtain enough pumping capability in these long-pulse experiments on JT-60U. These results indicate that further investigation to establish high performance plasmas longer than  $\tau_w$  with active particle control is quite important to establish

Therefore, it is very important to control the edge density to keep the high performance plasmas with an ITB, especially in a long-pulse plasma operation.

From the viewpoint of the particle control in JT-60U, the condition of first wall as a pumping is quite important to obtain high performance plasmas. Even in such a long-pulse discharge, most of the injected particles were pumped out not by the divertor pumping but by the wall as shown in Fig. 8(b), when the wall inventory was small enough before the discharge. However, pumping speed of the wall became smaller in the latter phase of the discharge as the wall temperature increased with time, and then the divertor recycling and edge density slightly increased as described in the previous section. When we repeated this kind of long-pulse discharges, such low recycling condition could not be kept any longer, and then finally the number of particles absorbed by the wall was effectively saturated during the discharge as shown in Fig. 8(c).

the operational scenarios for ITER and DEMO, where the wall pumping does not work.

## 6. Summary

After the installation of FSTs in JT-60U, fast ion losses due to toroidal field ripple have been reduced by 1/2~1/3 at 1.6T. The increase in the absorbed power at the same injection power can reduce the required number of NB units to sustain a given  $\beta_N$ , resulting in better flexibility of torque input by increasing the available combination of tangential NB units. Making use of these advantages to sustain good ITB, sustained duration of  $\beta_N=2.3$  has been extended to 28.6s. In this plasma, smaller heating power could keep peaked pressure profile without NTMs and detectable sawteeth throughout the discharge. The improved core confinement provided high  $\beta_N \cdot H_{98(y,2)} > 2.2$  with bootstrap current fraction of 36%-45% sustained for 23.1s ( $\sim 12\tau_R$ ) at  $q_{95} \sim 3.3$ , which gives high G-factor (larger than 0.2). These long-pulse plasmas are possible candidates for the ITER hybrid operation scenario. These long-pulse plasmas revealed the mechanism of ITB degradation due to the pedestal and core interplay. As the edge temperature decreased by increasing the edge density due to higher recycling, core  $T_i$  including inside ITB region degraded. It is now recognized that the controllability of the edge density and recycling level is quite important to keep the ITB performance in the long-pulse plasmas. Therefore, further investigation to establish high performance plasmas longer than  $\tau_w$  with active particle control is essential to establish the operational scenarios for next step devices such as ITER and DEMO.

## Acknowledgement

The authors acknowledge the members of the Japan Atomic Energy Agency who have contributed to the JT-60U projects. The authors are grateful to Dr. M. Kikuchi for continuous encouragement and support. This research was partly supported by the Grant-in-Aid for Scientific Research (S) 17106013 and for Young Scientists (A) 18686076, Japan Society for the Promotion of Science.

## References

- [1] Green B. J. 2003 *Phys. Plasma Phys. Control. Fusion* **45** 687.
- [2] Sips A. C. C. 2005 *Phys. Plasma Phys. Control. Fusion* **47** A19.
- [3] Wade M. R. *et al.* 2005 *Nucl. Fusion* **45** 407.
- [4] Staebler A. *et al.* 2005 *Nucl. Fusion* **45** 617.
- [5] Joffrin E. *et al.* 2005 *Nucl. Fusion* **45** 626.
- [6] Ide S. and the JT-60 Team 2005 *Nucl. Fusion* **45** S48.
- [7] Mikkelsen D. R. 1989 *Phys. Fluids B* **1** 333.
- [8] Koide Y. *et al.* 1993 *Plasma Phys. Control. Nucl. Fusion Research* **1** 777.
- [9] Sakurai S. *et al.* 2006 "Reduction of toroidal magnetic field ripple with ferritic steel armors in JT-60U", submitted to *J. Nucl. Mater.*
- [10] Shinohara K. *et al.* 2006 *Plasma Fusion Res.* **1** 007.
- [11] Yoshida M. *et al.* 2006 "Effects of ripple loss of fast ions on toroidal rotation in JT-60U", submitted to *Phys. Plasma Phys. Control. Fusion*.
- [12] Isayama A. *et al.* 2003 *Nucl. Fusion* **43** 1272.
- [13] Nakano T. *et al.*, 2006 "Particle control under wall saturation in long-pulse high-density H-mode plasmas of JT-60U", submitted to *J. Nucl. Mater.*
- [14] Kamada Y. *et al.* 2006 *Phys. Plasma Phys. Control. Fusion* **48** A419.
- [15] Urano H. *et al.* 2002 *Nucl. Fusion* **42** 76.
- [16] Kubo H. *et al.* 2006 Proc. 21st Int. Conf. on Fusion Energy 2006 (Chengdu, 2006) (Vienna: IAEA) CD-ROM file EX/P4-11.