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Enhanced ELMy H-mode performance with reduced toroidal field ripple in JT-60U

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Introduction

By modification of the control systems for the operation, heating and diagnostics, JT-60U has been expanding the advanced tokamak plasma regime with longer time scales than the resistive diffusion time (τ_R) on JT-60U [1]. However, further pursuit of long sustainment of high performance plasmas has been prevented by the loss of fast ions due to the toroidal field ripple from the viewpoint of the available net heating power, heat load to the wall and lower hybrid (LH) wave launcher (Fig. 1(c)), and controllability of the toroidal rotation (V_T) profile due to formation of an inward electric field [2]. As shown in Fig. 1, the ripple amplitude, δ_r, defined as $(B_{max}-B_{min})/(B_{max}+B_{min})$, was varied from δ_r<0.4% to δ_r>2% by changing the plasma configuration. Therefore, ripple induced fast ion losses are severe with large volume plasmas such as LH heated plasmas and wall-stabilized plasmas. In order to reduce the toroidal field ripple, ferritic steel tiles (FSTs), which cover ~10% of the vacuum vessel surface, have been installed inside the JT-60U vacuum vessel on the low field side [3]. Making use of advantages of reduced fast ion losses after installation of FSTs, we have performed to extend the sustainable duration of high β_N plasmas with good confinement close to ITER hybrid operation scenario [4].

Reduction of toroidal field ripple and fast ion losses

The design of FSTs and its location are optimized on the basis of the previous results obtained in JFT-2M [5] and the analysis using Fully Three-Dimensional magnetic field Orbit Following Monte Carlo (F3D-OFMC) code in terms of the reduction of the fast ion losses [6]. Because of space limitation in the vacuum vessel, no FSTs were installed near the outer midplane in some toroidal sections. Since the 18-fold toroidal symmetry of the ripple amplitude was broken, α-parameter, $\alpha \equiv r/NRq\delta$ where r is the minor radius, N is the number of toroidal

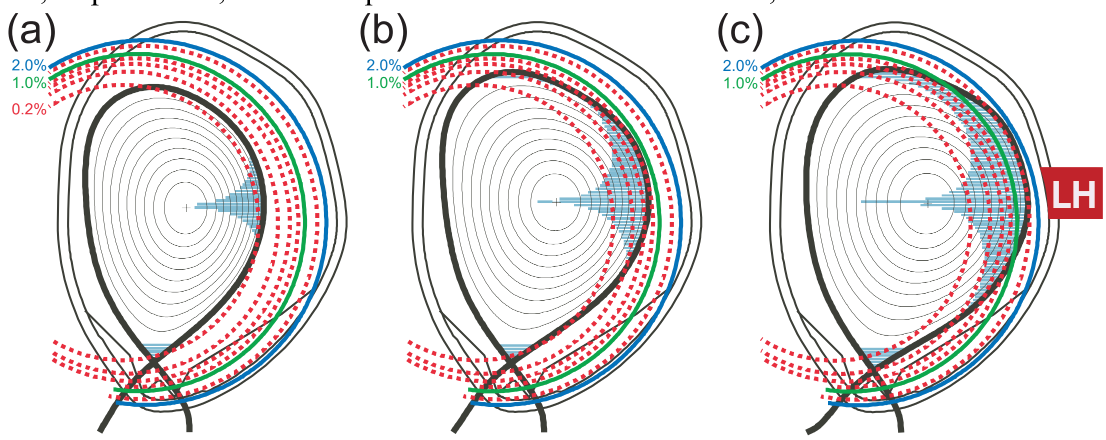

Figure 1. Contour plots of ripple amplitude, δ_r, without FSTs in JT-60U with (a) small (1.04MA/2.71T, V_p~52m^3), (b) medium (1.16MA/2.57T, V_p~65m^3) and (c) large (1.23MA/2.50T, V_p~75m^3) plasma configurations with the position of LH launcher. Ripple well regions are also shown by shaded area. Dotted lines at δ_r < 1% and δ_r > 1% are plotted at every 0.2% and 0.5%, respectively.

symmetry, R is the major radius, q is the safety factor, and δ is the ripple amplitude, is unavailable to determine the ripple well structure. 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 ϕ_s, where $\Delta\phi$ is half of the period of the TF coil installation [6]. Using this definition, figures. 2(a) and 2(b) show a comparison of "quasi" ripple well structure without and with FSTs, respectively.

Calculated loss power of fast ion for perpendicular-(PERP) NBIs reduces by 1/2~1/3 at 2T as shown in Fig. 2(c). The reduction in fast ion losses was also confirmed with reduction of the heat load to the first wall measured with an IR-camera. Injection angles to the plasma in the toroidal direction for PERP-NBIs are not a right angle completely as shown in Fig. 2(d). It is noted that the loss power ratio of PERP-NBIs is related to the tilted angle to the plasma current rather than the beam trajectory (i.e. central heating for upper units and off-axis heating for lower units). Since the magnetic field produced by FSTs is saturated at 1.78T at usual baking temperature of 423K above an external vacuum magnetic field of ~0.6T, the magnetic field produced by FSTs is almost constant at B_T>1T. This means that the effect of ripple reduction at higher magnetic field becomes smaller and ripple amplitude can be varied at a fixed plasma configuration by changing the external magnetic field strength [6]. Even in the higher magnetic field of 3.2T with the plasma configuration shown by Fig. 2, loss power ratio is smaller with FSTs by ~10% than that without FSTs.

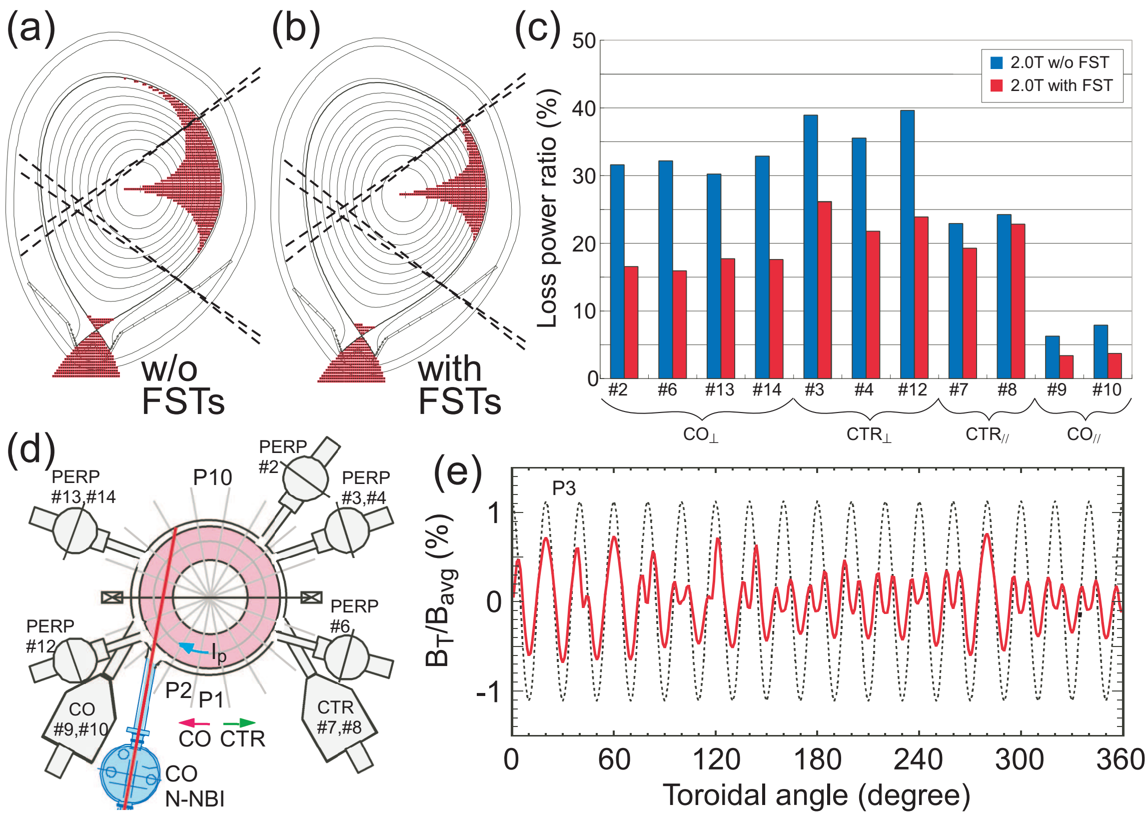

Figure 2. "quasi" ripple well structure (a) without and (b) with FSTs around P3 section, where the maximum local ripple exists (see. (e)). The dashed lines show the beam trajectories of PERP-NBIs. (c) Fast ion losses evaluated with F3D-OFMC code. PERP-NBIs of #2, 4, 6, 12, 14 and #3,13 are injected from upper and lower port, respectively. (d) Port arrangement of NBI system. (e) Toroidal variation of the calculated toroidal magnetic field strength at R = 4.3m and Z = 0.2m. The dotted curve shows the data with TF coils alone and the solid curve shows the data with FSTs. All figures are evaluated in the plasma with 1.08MA and 2.0T.

Extension of pulse duration of high β_N ELMy H-mode plasma

The reduction of toroidal field ripple increases absorbed heating power as shown in Fig. 2(c). The increase in the absorbed power at the same injection power can reduce the required number of NB units to sustain a given β_N, resulting in better flexibility of torque input by increasing the available combination of tangential NB units. The reduction of fast ion losses also reduced formation of an inward electric field, which may induced a CTR-toroidal rotation [7]. Because of these advantages, we have extended the sustainable duration of high β_N plasmas as shown in Fig. 3.

Figure 3(a)-(c) show the waveforms of a typical high β_N long-pulse plasma (I_p=0.9MA, B_T=1.58T, q_{95}~3.3). A high confinement plasma ($H_{98(y,2)}$~1.1) with β_N≥2.4 was kept up to t~22s as shown in Fig. 3(b). Because of the low central magnetic shear with q_0~1 as shown in Fig. 3(d), pressure gradient at q=1.5 and 2 was enough small to avoid neoclassical tearing modes throughout the discharge. Because of the long duration of the NB heating, the surface temperature at the divertor targets increased with time (from ~180°C to >500°C in E45436), which may change the recycling level in the latter phase (t>~15s). Since the edge density also increased in this phase, the edge temperature decreased with keeping pedestal pressure almost constant. In spite of the constant pedestal pressure, the core temperature including ITB region decreased with the reduction of edge temperature as the edge density increased. After switching from central heating to off-axis heating of PERP-NBI at t=22.7s due to 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>~23s). However, the constant stored energy feedback system increased the NB heating power to keep the stored energy at β_N>2.3 through the discharge. Then, the sustained duration was extended up to the limitation of the NB injection pulse length (30s) as shown in Fig. 4(a).

In these plasmas, the H-mode confinement was improved at a given line-averaged density because of the increase in the thermal stored energy as shown in Fig. 3(d). A larger

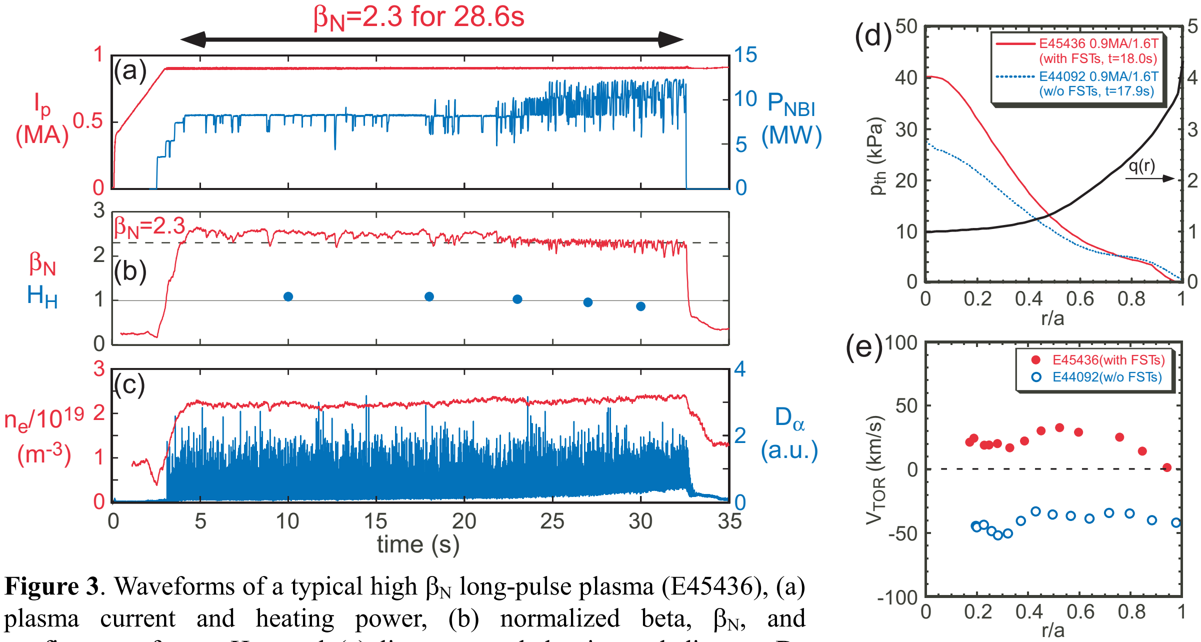

Figure 3. Waveforms of a typical high β_N long-pulse plasma (E45436), (a) plasma current and heating power, (b) normalized beta, β_N, and confinement factor, H_{98}, and (c) line-averaged density and divertor D_α intensity. (d), (e) Comparison of thermal pressure profiles and toroidal rotation profile in high β_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 (d).

CO-toroidal rotation in E45436 as shown in Fig. 3(e) which may relate with the improved core confinement can be obtained with net CO-torque input. The larger thermal stored energy was due to the peaked pressure with the internal transport barrier (ITB) in the core region (r/a<0.6), although the power deposition profile in this region was similar. Therefore, we could expand the operation regime toward higher $\beta_N \cdot H_{98(y,2)}$ for longer duration as shown in Fig. 4(b). In the discharge shown in Fig. 3, high $\beta_N \cdot H_{98(y,2)} \geq 2.2$ was sustained for 23.1s, which corresponds to >~12τ_R with bootstrap current fraction of 33%~39%.

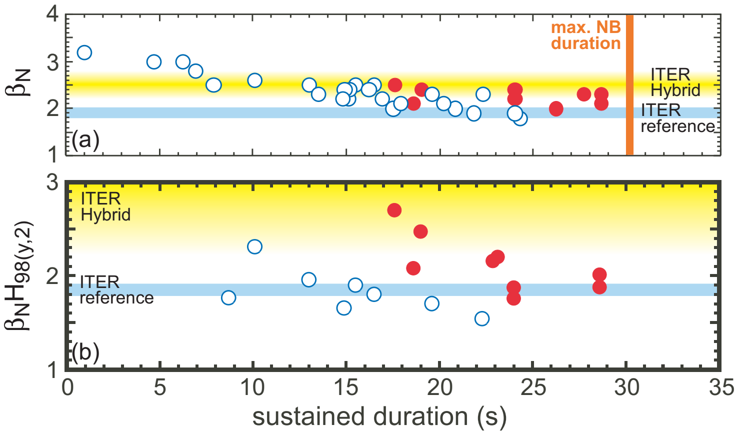

Figure 4. Sustained duration of (a) normalized beta, β_N, and $\beta_N \cdot H_{98}$. Solid and open symbols show the data in long-pulse plasma with and without FSTs, respectively.

Because of the reduction of thermal energy components due to an increase in the edge density and recycling, $H_{98(y,2)}$ decreased from 1.0 (t=23s) to 0.87 (t=30s) as indicated in Fig. 3(b). The degradation of ITB with increasing the density and recycling was also observed in the previous discharges without FSTs [8]. The density and recycling seemed to increase earlier in the higher heating power case. Therefore, it has been recognized that the controllability of the edge density and recycling level in relation to the wall temperature as well as an effective pumping is quite important to keep the ITB performance in the long-pulse plasma operation.

Summary

In order to reduce the loss of fast ions, FSTs have been installed inside vacuum vessel on JT-60U. Evaluation with F3D-OFMC shows the reduction of fast ion losses by 1/2~1/3 for PERP-NBIs at 2T. The reduction of the heat load to the first wall due to the reduction of fast ion losses was confirmed experimentally. The reduction of fast ion losses provided better flexibility of torque input by increasing available combination of tangential NB injectors at given absorbed power. Larger CO-toroidal rotation, which may relate with the improved core confinement, can be obtained with CO-torque input. Because of these changes after installation of FSTs, sustained duration of β_N=2.3 (higher than ITER standard operation) has been extended to 28.6s, where smaller heating power could keep peaked pressure profile without large MHD modes. The improved core confinement provided high $\beta_N \cdot H_{98(y,2)} > 2.2$ sustained for 23.1s (~12τ_R) at q_{95}~3.3. These long-pulse plasmas can be considered as a candidate for ITER hybrid operation scenario.

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