Improvement of Plasma Performance Toward Steady-state High-beta Tokamak Operation in JT-60U

S. Takeji and the JT-60 Team

Naka Fusion Research Establishment, Japan Atomic Energy Research Institute
801-1 Mukoyama, Naka-machi, Ibaraki 311-0193, Japan

1. Introduction

High power long pulse DT burning in tokamak plasmas with inductive current drive is now fully supported by the ITER physics bases [1]. However, for the steady state burning tokamak plasma operation with non-inductive current drive, a number of critical issues remain to be investigated and overcome. Recent experiments on Japan Atomic Energy Research Institute Tokamak-60 Upgrade, JT-60U, are focused on establishment of physics basis for realization of integrated plasma performance required for a steady-state tokamak reactor such as SSTR [2]. Two improved confinement modes are intensively studied on JT-60U. One is the high poloidal beta, β_p, mode that has a weak or positive central magnetic shear. The other is the reversed shear mode that has a negative central magnetic shear. Progress in understanding of stability, transport and divertor physics results in improved performance in both modes. Since reversed magnetic shear configuration can be consistent with large bootstrap current fraction [3], the reversed shear mode is considered to have inherent potential for non-inductive steady-state operation without large current drive power. Operation at high beta is essentially important for the steady-sate since the higher beta results in the higher bootstrap current fraction. This paper describes recent progress in reversed shear experiments aiming at the steady-state operation and extended understanding of stability of reversed shear discharges for the high-beta operation.

2. Improvement of Quasi-steady Reversed Shear Discharges

Reversed shear discharges in JT-60U are characterized by the relatively steep negative central magnetic shear with the improved core confinement owing to the internal transport barriers, ITBs, near the null region in the magnetic shear. We calculated a steady-state configuration with non-inductive full current drive with taking typical experimental profiles including the effect of ITB and plasma parameters into account. It was demonstrated numerically that well-aligned large bootstrap current near the ITB prevents the current penetration into the central region and can generate a stable steady-state reversed shear configuration in the experimental situation. Then, we demonstrated the following quasi-steady-state reversed shear discharge similar to the predicted one in the experiment [4]. The discharge is that plasma current, I_p, =0.8MA, toroidal magnetic field, B_T, =3.4T, safety factor at the 95% of the magnetic flux,
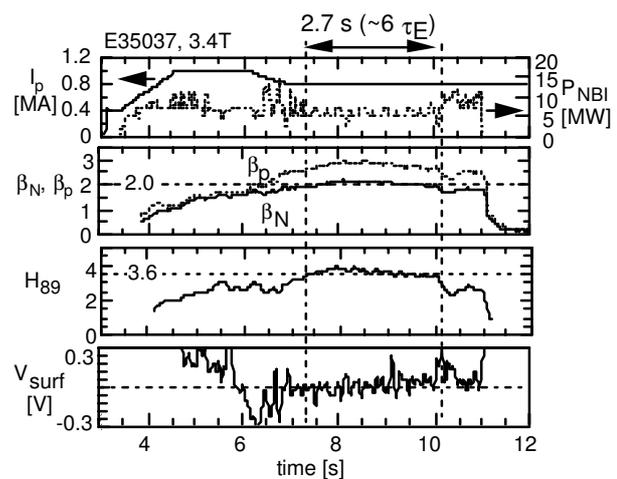

Fig.1 Waveforms of a reversed shear plasma in which high confinement and high bootstrap current fraction were sustained for 2.7 s.

q_{95},~8.5 with the H-mode edge, sustained for 2.7 second with the H-factor, H_{89}~3.6, $H_{H(y,2)}$ ~2. 2 (the energy confinement time = 0.4~0.5s), normalized beta, β_N, ~2.0 and β_p = 2.6~3.0 at the electron density of 65% of the Greenwald density (Fig.1). Large bootstrap current is driven near the ITB and plays a key role to keep the reversed shear configuration. The bootstrap current fraction, f_{BS}, and the beam driven current fraction, f_{BD}, to the total plasma current are f_{BS}~80% and f_{BD}~25%, respectively.

The quasi-steady state was terminated at t~10 second without obvious MHD activity. What happened at that time was turning-off of a tangential neutral beam in the co-direction. The toroidal rotation profile was changed drastically after that although the net neutral beam power was increased by the perpendicular neutral beam injection instead of the tangential beam. Toroidal rotation can relate to the *ExB* shear stabilization of microscopic turbulence and can affect the property of the internal transport barrier.

This is the first demonstration of a quasi-steady-state reversed shear discharge with non-inductive full current drive with improved confinement. At the point of view of a tokamak reactor, however, operation with lower q regime (q_{95}~4), i.e. higher beta (β_N~3.5) is required while the confinement property is better than the expected one in non-inductive steady-state scenarios of ITER-FEAT. Improvement of β_N is one of the most crucial issues in JT-60U.

3. Stability of Reversed Shear Discharges

Understanding stability of reversed shear discharges is important to improve the attainable β_N value. Stability analysis of JT-60U's reversed shear discharges had been proceeded at the point of view of ideal magnetohydrodynamic (MHD) stability [5-6]. Reversed shear discharges in JT-60U are often terminated in major collapse in the lower beta regime than the ideal stability limit while upper limit of the attainable β_N is in agreement with the no-wall ideal stability limit, β_N^{no-wal}. Resistive MHD instabilities were found to relate to major collapse in the lower beta regime [7].

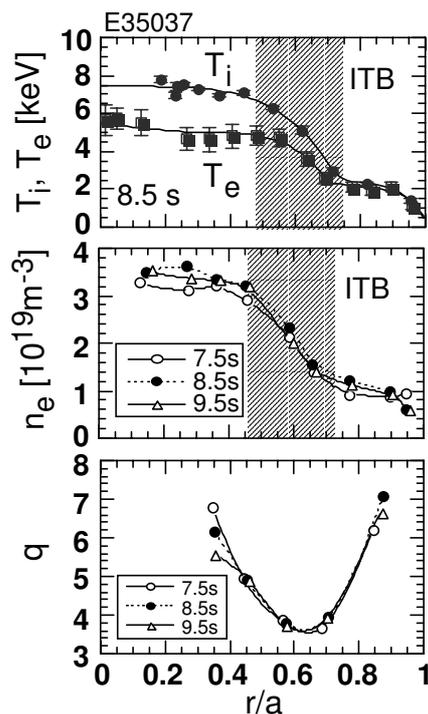Figure 3 shows radial profiles of electron temperature, T_e, q, and T_e perturbations right

Fig.2: Profiles of ion temperature, T_i, electron temperature, T_e, electron density, n_e, and q in the discharge shown in Fig. 1.
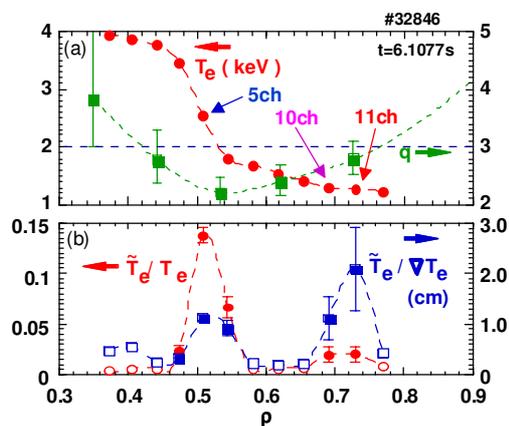

Fig.3: (a) Electron temperature and q profiles, (b) T_e perturbation profiles at a time right before the major collapse. Here, closed squares and circles show channels on which obvious perturbations were observed, and open ones show the channels on which observed perturbations were in the noise level.

before a major collapse at $\beta_N=0.77$ ($\beta_p=0.70$, $q^*=4.85$). Perturbations of T_e with the growth time $\gamma^{-1}\sim 0.5$ms appeared near the steep ∇T_e (4~6ch) with no clear evidence of magnetic islands. Perturbations of $n=1$ tearing mode (the island width ~3cm) were also observed on T_e near the outer $q=3$ surface (10~11ch). These perturbations had the same period for several cycles right before the collapse. The major collapse seems to be caused by a resistive mode of which perturbations can be observed near the steep ∇T_e and the outer $q=3$ surface, or by mode coupling of a resistive mode near the steep ∇T_e with a tearing mode at the outer $q=3$ surface.

Stability analysis was done for the discharge discussed in Fig.3. Figure 4 shows eigenfunctions of the marginally stable ideal modes calculated by the MARG2D code [8] in the free boundary condition. The stability parameter of tearing modes, Δ', is positive (destabilizing) only at the outer $q=3$ surface ($\Delta'_{3,out}>0$). The stability parameter of double tearing modes, $\Delta(0)$, which is evaluated by taking coupling between two mode rational surfaces into account is negative (negative value means destabilizing) only at the $q=3$ surface. It is found that these stability parameters become to be more destabilizing in higher β and become to be stabilizing in the fixed boundary condition. This result suggests that a stable external kink ($m=5$) mode which appears significantly in higher beta and in the free boundary condition can destabilize tearing modes at the outer $q=3$ surface and double tearing modes at the $q=3$ surface. In other words, tearing modes can be stable if the conducting wall is close enough to the plasma surface.

Figure 5 shows the number of major collapses versus a safety factor at the plasma surface, q^* ($\sim q_{95}$) in reversed shear discharges in JT-60U. We found a tendency that major collapses occur near q^*

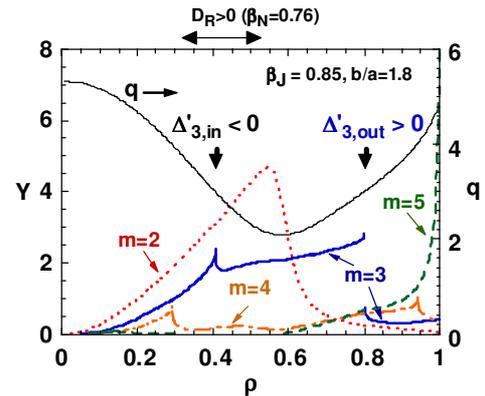*Fig.4: Eigenfunctions of m=2~5 (n=1) modes calculated by the MARG2D code in the free boundary condition (d/a=1.8). A q-profile employed in the analysis is also shown. Here, $\beta_N=1.11$ and $q_{95}\sim4.87$.*

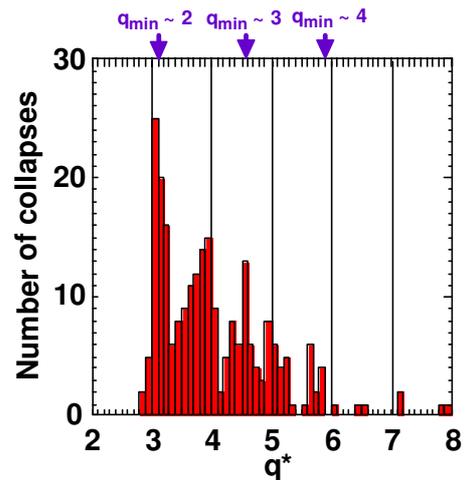*Fig.5: The number of collapses versus q^*. Indicated q_{min} values are corresponding to that in typical discharges.*

=3,4 and 5 as well as near the minimum safety factor, q_{min}, =2,3 and 4. Since significant number of collapses with resistive precursor such as that mentioned in Fig.3 are included here, Fig.5 suggests that external kink modes (or the particular condition that $q^* \sim$ integer) are important not only for ideal modes but also for resistive modes.

These numerical results are not in contradiction with the experimental observations and the impact of a stable external kink mode on tearing modes is in agreement with the experimental evidence shown in Fig.5. Thus, double tearing modes can be plausible instabilities for major collapse in the beta regime lower than the ideal stability limit. Possibility of mode coupling between the resistive interchange mode which can be destabilized near the steep ∇T_e ($D_R>0$) and the tearing mode at the $q=3$ surface is in analysis.

4. Wall Stabilization of High-beta Discharges

Discharges with the plasma volume, V_p, larger than $70m^3$, which corresponds to $d/a<1.3$ (d: wall radius, a: plasma minor radius), resulted in the improved beta limit of $\beta_N>2.4$ while the no-wall ideal stability limit was $\beta_N^{no-wall} \sim 2.2$ in the typical discharge with $l_i\sim0.7$. The beta limit exceeded an empirical beta limit scaling $\beta_N \sim 4l_i$ in the discharges of $V_p>70m^3$. The weak dependence of β_N on l_i may be due to the limited heating power by neutral beam injections. An $n=1$ magnetic perturbation with $\gamma^{-1}\sim15ms$ which may corresponds to the time constant of the JT-60U wall, τ_w, was observed together with T_e perturbations corresponding to a rotating $n=1$ mode at $f\sim20Hz$ ($\sim1/2\pi\tau_w$). These MHD perturbations can be attributed to the resistive wall mode. The plasma rotation velocity was ~4kHz in the counter direction at the peripheral region. No clear degradation of the rotation velocity was observed before appearance of the resistive wall mode.
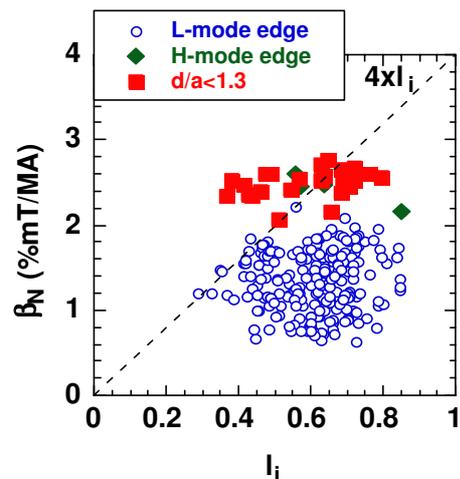

Fig.6: Dependence of the beta limit on the internal inductance, l_i, determined by the external magnetic measurement.

5. Summary

Recent experiments on JT-60U have been focused on optimization of integrated plasma performance toward steady-state high-beta tokamak operation. A quasi-steady state reversed shear discharge with full non-inductive current driven was demonstrated with large bootstrap current fraction ($f_{BS}\sim80\%$) and high confinement ($H_{89}=3.6$). In order to realize such a discharge in the reactor relevant regime, improvement of β_N is one of the most crucial issues. Understanding of stability of reversed shear discharges was extended in the wide beta regime. Resistive modes such as the double tearing mode is a plausible causal instability limiting the stable reversed shear plasma operation. The attainable β_N is limited at the ideal stability limit without the wall when the plasma surface is far from the wall ($d/a>1.5$). Both of resistive and ideal modes can be stabilized by the wall and relatively higher beta was obtained with a plasma shape close enough to the wall (typically, $d/a<1.3$). Further trial will be done to improve the attainable beta by optimizing the operation scenario.

Experimental study of control of internal transport barrier by means of toroidal momentum input, that is considered to be a possible control method even in burning plasmas, is in progress for optimization of pressure and current profiles.

References

[1] ITER Physics Basis Editors, *et al*., Nucl. Fusion **39** (1999) 2137.
[2] M. Kikuchi, Plasma Phys. Controlled Fusion **30** (1993) 39.
[3] T. Ozeki, *et al*., in *Plasma Physics and Controlled Nuclear Fusion Research*, Würzburg, 1992 (IAEA, Vienna, 1993), Vol.2 p187.
[4] T. Fujita, et al., to be published in J. Plasma and Fusion Research.
[5] Y. Ishii, et al., Plamsa Phys. Control. Fusion **40** (1998) 1067.
[6] J. Manickam, et al., Nucl. Fusion **39** (1999) 1819.
[7] S. Takeji, et al., to be published in J. Plasma and Fusion Research (Japanese).
[8] S. Tokuda, T. Watanabe, Phys. Plasmas **6** (1999) 3012.