Achievement of High Fusion Performance in JT-60U Reversed Shear Discharges

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Fusion performance of reversed shear discharges with an L-mode edge has been significantly improved in a thermonuclear dominant regime with up to 2.8 MA of plasma current in the JT-60U tokamak. The core plasma energy is efficiently confined due to the existence of persistent internal transport barriers formed for both ions and electrons at a large minor radius of $r/a \sim 0.7$ near the boundary of the reversed shear region. In an assumed deuterium-tritium fuel, the peak fusion amplification factor defined for transient conditions involving the dW/dt term would be in excess of unity. [S0031-9007(97)04592-4]

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The reversed shear discharges are considered attractive for a steady state operation with a large bootstrap current fraction in tokamak reactors as proposed for SSTR [1] and ITER [2], since it would be possible to match the hollow current profile to a bootstrap current profile in a steady state. While the central magnetic shear in tokamak plasmas is naturally reversed during a sufficiently long discharge duration with a large bootstrap current fraction [3], the forced shear reversal operation by enhancing a skin current effect has become important for establishing a controlled approach to the steady state [4].

In nuclear fusion research, critical conditions in which fusion power produced in plasmas is equal to loss power from the plasmas have been pursued as a crucial milestone ultimately towards the commercial use of thermonuclear fusion energy. In order to determine whether the reversed shear scenario is workable, it is crucially important to demonstrate the fusion-relevant performance, particularly in the thermonuclear fusion regime with the shear reversal operation. So far, however, most of the previous experiments addressing high fusion reactivity in tokamaks have been limited to a hot-ion regime with substantial beam-thermal reactions for deuterium plasmas in TFTR supershot [5], JET hot-ion H mode [6] and JT-60U high-β_p H mode [7], and deuterium-tritium (D-T) plasmas in TFTR supershot [8]. Although fusion performance has been recently enhanced with strong profile and shaping control in deuterium reversed shear plasmas with an H-mode edge in DIII-D [9], the projected D-T fusion power is substantially below the loss power from the plasma. In the present paper, it is shown that fusion performance has been significantly improved in JT-60U for reversed shear discharges with an L-mode edge in a thermonuclear fusion regime, so that the transient fusion amplification factor defined as below would be in excess of unity.

In JT-60U, the experimental campaign of the reversed shear discharges aiming at high fusion amplification factor (Q) has been intensively performed with D beams into D plasmas. The confinement properties for the reversed shear discharges created in JT-60U are characterized by (i) the significant reduction of heat and particle transport for electrons as well as ions around the internal transport barrier (ITB), (ii) a large extension of the enhanced confinement region up to ~70% of the minor radius surrounded by the ITB, and (iii) a comparatively small deviation between ion and electron temperature ($T_i \lesssim 2T_e$) approaching equithermal conditions, as studied for relatively low current discharges with $q_{\min}$ above 3 [10].

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These outstanding features of the plasmas can be very much advantageous to increasing the Q in the thermonuclear fusion regime. The high performance reversed shear regime with an L-mode edge up to the plasma current $I_p = 2.5$ MA [11] has been progressively extended by an increase in I_p up to 3.0 MA at a full field strength of $B_t = 4.3$ T as described hereafter.

A key operational issue to increase the I_p well above 2.5 MA with improved confinement was the suppression of a fast collapse at relatively low β_N around unity resulting in a major disruption when $q_{\min}$ crosses ~ 3. The plasma current, configuration, and beam injection are carefully controlled to achieve an MHD-stable plasma during the current ramp-up phase by tailoring the current and pressure profiles in the presence of the ITB with a significant bootstrap current and then optimizing the confinement. Furthermore, the occurrence of barrier localized modes (BLMs) leading to transient relaxation of the steep pressure gradient in the ITB appears to play an important role in achieving stability across $q_{\min} \sim 3$; the BLM is characterized as a localized MHD-relaxation phenomenon. The similar BLMs were observed in JT-60U high-β_p mode discharges for which the local bootstrap current driven at the ITB plays an essential role in destabilizing low-n modes near the ITB [12].

As shown in Fig. 1(a) with Table I, the diamagnetic stored energy, W_{dia}, is increased up to the JT-60U record value of 10.9 MJ with a high neutron emission rate, S_n, of 4.5×10^{16} s^{-1} with $\pm 10\%$ of calibration error at 2.8 MA until the discharge encounters a β limit at $q_{\min} \sim 2$. From Fig. 2, it is clearly found that the internal barrier against ion heat transport is persistently formed inside or near the location of the $q_{\min}$ during the current ramp-up phase. The plasma configuration is transiently changed to enhance off-axis beam deposition from $R_p \sim 3.15$ m to ~ 3.2 m when $q_{\min}$ crosses ~ 3. Then, the plasma is moved inward during $t = 6-7$ s and configured at $R_p \sim 3.1$ m during the current flat top [see Fig. 1(b)] to achieve a central deposition of the D beams and reduce a ripple-induced fast ion loss. The ripple loss power composed of ripple-trapped and banana drift losses is calculated at this timing to be $\sim 12\%$ of the beam injection power (P_{NBI}) using an OFMC (orbit following Monte Carlo) code; note that the ripple loss power is not extracted from the loss power from the plasmas throughout this paper.

The global energy confinement is remarkably improved against the ITER89-P scaling up to H factor $= \tau_E/\tau_E^{\text{ITER89-P}} \sim 3.2$ with an L-mode edge as the I_p is increased [see Fig. 1(a)]. A temporal stagnation against the upward trend of confinement improvement appears from ~ 5 s. Correspondingly, the BLMs occur 5 times during $\sim 4.8-5.2$ s while the T_i gradient becomes steeper at the ITB. After the last BLM, the T_i gradient takes a turn for decaying as seen at 5.6 s in Fig. 2 with a slight decrease in the beam power as the $q_{\min}$ approaches 3, and recovered as seen at 6.4 s with the beam power after it crosses ~ 3. As observed in the course of the experiments, such a confinement stagnation associated with the BLMs might have a favorable effect on the avoidance of the early collapses in addition to the preprogrammed beam power reduction when the $q_{\min}$ crosses ~ 3.

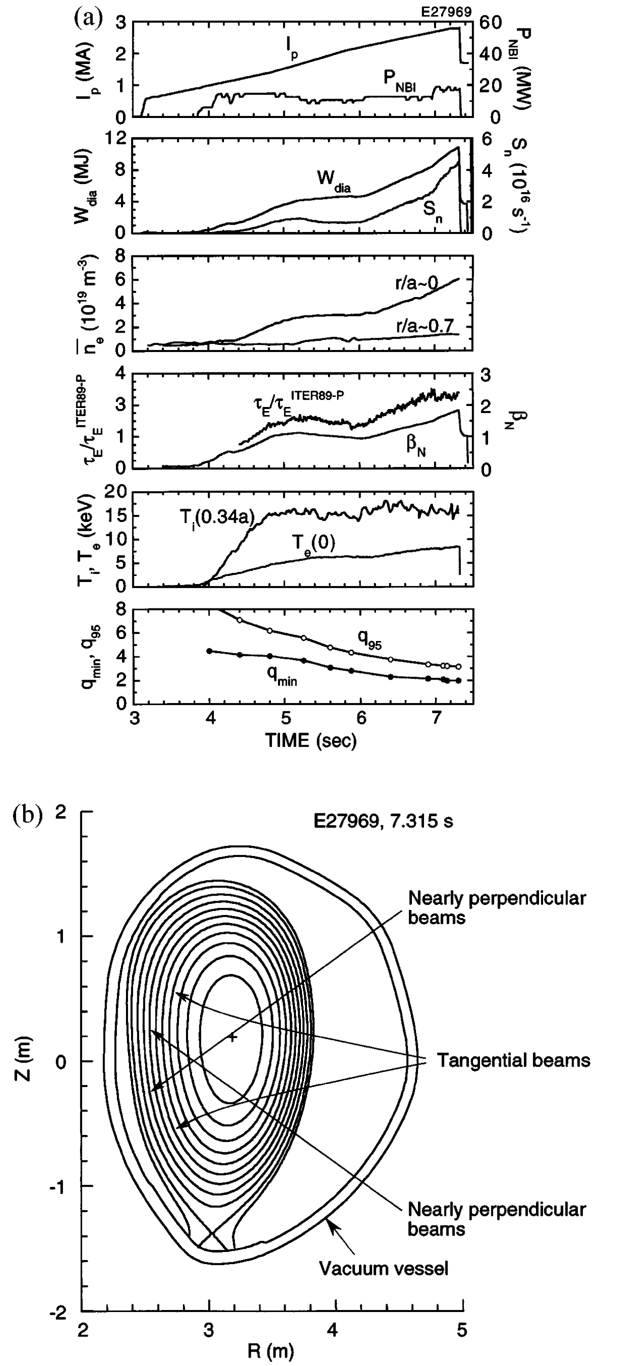

FIG. 1. (a) Discharge wave forms for E27969 with I_p, P_{NBI}, W_{dia}, S_n, central and peripheral $\bar{n}_e$, H factor, normalized beta ($\beta_N = \beta_t a B_t / I_p$), T_i, T_e, and q at 95% flux (q_{95}), and magnetic pitch minimum ($q_{\min}$). (b) The equilibrium configuration reconstructed using the motional Stark effect (MSE) data along with the injection paths of neutral beams.

As shown in Fig. 1(a), a clear separation of the vertically line-averaged electron density signals $\bar{n}_e$ at $r/a \sim 0$ and 0.7 from $t = 4.35$ s is observed suggesting the

TABLE I. Parameters of shot E27969 at $t = 7.315$ s.

$I_p = 2.79$ MA, $B_t = 4.34$ T, $P_{\rm abs} = 16.0$ MW,
$E_{\rm acc} = 81$ kV, $R_p = 3.10$ m, $a = 0.70$ m,
$\kappa = 1.97$, $\delta = 0.065$, $q_{95} = 3.15$, $V_p = 57.5$ m^3,
$W_{\rm dia} = 10.9$ MJ, $S_n = 4.52 \times 10^{16}$ s^{-1},
$dW_{\rm dia}/dt = 6.08$ MW, $T_i(0) = 16.5$ keV, $T_e(0) = 8.4$ keV,
$\overline{n}_e(0) = 6.1 \times 10^{19}$ m^{-3}, $n_e(0) = 9.7 \times 10^{19}$ m^{-3},
$n_D(0) = 4.9 \times 10^{19}$ m^{-3}, $\tau_E = 0.97$ s, $\tau_E/\tau_E^{\rm ITER89\text{-}P} = 3.2$,
$\beta_N^{\rm dia} = 1.88$, $Z_{\rm eff} = 3.49$ (carbon),
$n_D(0)\tau_E T_i(0) = 7.8 \times 10^{20}$ m^{-3} s keV,
Thermonuclear neutron fraction: 0.83, $P_{DT} = 10.7$ MW for $[D]$:$[T] = 50$:50, $P_{DT}/P_{\rm abs} = 0.68$, $Q_{DT}^{\rm eq} = 1.05$

growth of the density gradient at the ITB, which is measured from the CO_2 laser interferometer with a tangential chord and the FIR laser interferometers with two vertical chords at off axis. Although the n_e and T_e measured from electron cyclotron emissions (ECE) keep rising during the current ramp-up phase, the increase in the central T_i is saturated from the early phase of beam heating around 5 s, so that the plasma is approaching an equithermal condition at high density. The n_e, T_i, T_e, and q profiles at 7.15 s are shown in Fig. 3 where the solid line to fit the density profile is deduced from the data on the two interferometer chords at center and off-axis and the Thomson scattering. The existence of the steep gradients simultaneously observed in the n_e, T_i, and T_e profiles just inside the location of the $q_{\rm min}$ suggests that heat and particle transport for both ions and electrons are significantly reduced in the local region.

The beam ion distribution can be considered approximately in a steady state due to the short slowing down time. Using a TOPICS (tokamak prediction and interpretation code system) code with the Stix's steady state solution to evaluate the slowing down profile of fast ions, the D-D fusion neutron emission profile is calculated using the plasma conditions as shown in Fig. 4 where the $Z_{\rm eff}$ value is inferred from matching the kinetic analysis of S_n to the measured value assuming carbon as a dominant impurity. Since the measured $Z_{\rm eff}$ by visible bremsstrahlung appears to be slightly lower than the inferred $Z_{\rm eff}$ value, both TOPICS and TRANSP [13] code calculations would overpredict the neutron rate if the measured value is used. The calculated thermonuclear fusion fraction reaches 83% of the total neutron emission rate with 93% thermal stored energy of the total stored energy. This is a clear evidence for the production of the conditions sufficiently in the thermonuclear fusion regime with a large fraction of thermonuclear neutrons.

The TOPICS code analysis can simulate plasmas which could have been produced in an assumed D-T fuel. Simply considering the full D beams with the experimental beam energy into a 50:50 D-T mixture of plasmas, the output power from the shot E27969 would reach 10.7 MW

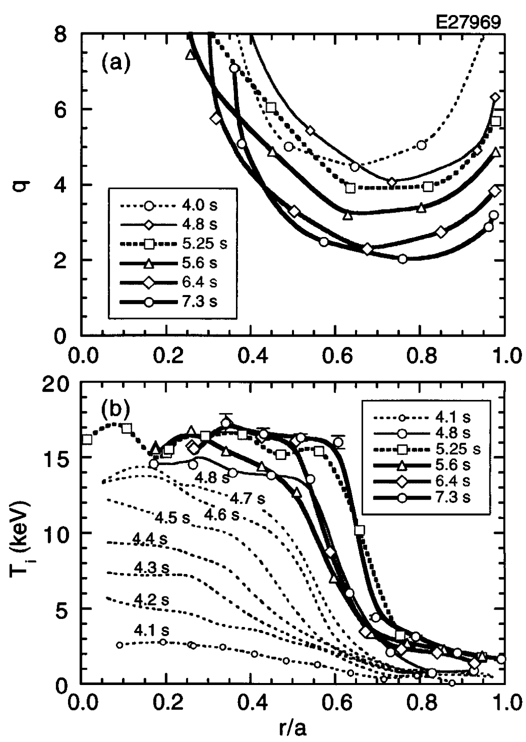

FIG. 2. Evolution of the safety factor (q) and T_i profiles for E27969, which are measured from the MSE spectroscopy and the charge exchange recombination spectroscopy, respectively.

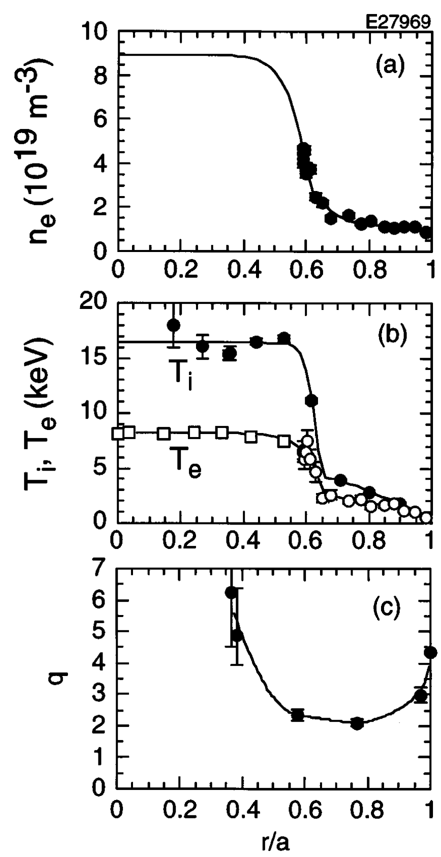

FIG. 3. n_e, T_i, T_e, and q profiles at $t = 7.15$ s in which the T_e is measured by Thomson scattering (open circles) and ECE (open squares).

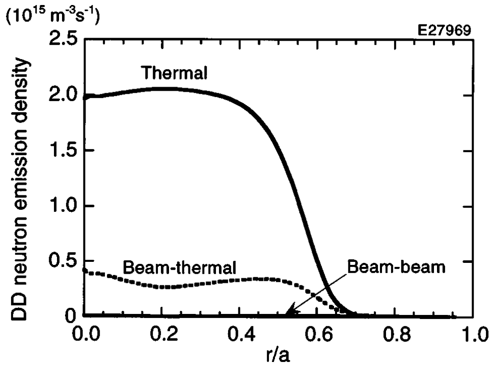

FIG. 4. Calculated profiles of *D-D* neutron emission density at $t = 7.315$ s for E27969 showing the thermal, beam-thermal, and beam-beam components.

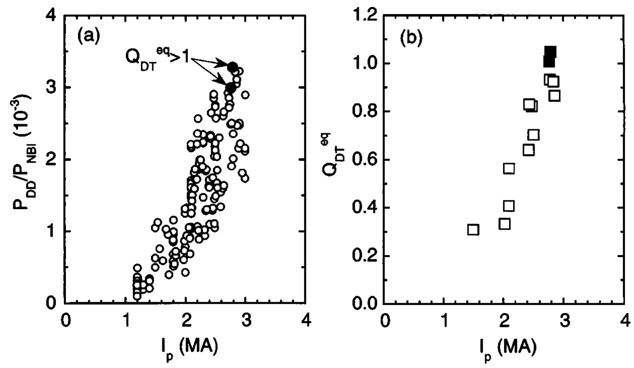

FIG. 5. (a) Ratio of the *D-D* fusion power to P_{NBI} with H factor above 1.5 and (b) Q_{DT}^{eq} for typical high performance discharges as a function of I_p for the reversed shear discharges. Closed symbols indicate the discharges achieving Q_{DT}^{eq} in excess of unity.

(83% from the thermal reactions) with the D-T power ratio to D-D power of $P_{DT}/P_{DD} = 202$. The validity for the results is cross-checked using the TOPICS code with a Fokker-Planck solver and the TRANSP code with a Monte Carlo method. Good agreement is obtained with confidence among these analyses for both D-D analysis and D-T simulation in which sufficient α thermalization is also confirmed in the TRANSP code analysis.

A simple ratio of the fusion power to the actual beam absorption power, P_{DT}/P_{abs} would be 0.68. For the transient plasmas as discussed here, the Q can be defined to the loss power from the plasmas subtracting the dW/dt term instead of the beam power only. Previously, such a definition of Q was given as follows [14]: the Q is defined as $Q = Q_{\mathrm{thermal}} + Q_{\mathrm{beam}}$, where Q_{beam} is simply the ratio of fusion power from beam-thermal and beam-beam interactions to beam power deposited in the plasma, and Q_{thermal} is the ratio of fusion power from thermal processes to the input power (P_{in}^*) which would be required to maintain the plasma in steady state, i.e., $P_{\mathrm{in}}^* = P_{\mathrm{in}} - dW/dt - P_\alpha$ where P_{in} is the observed input power in an actual discharge (including any α-particle power) and P_α is the α-particle power calculated for a simulated discharge, but not actually included in the simulation. Following this definition, the equivalent Q in the D-T fuel assumed as above, Q_{DT}^{eq}, would reach 1.05 with a high fusion triple product of $n_D(0)\tau_E T_i(0) = 7.8 \times 10^{20}$ m^{-3} s keV. The uncertainty of the Q_{DT}^{eq} value is $\pm 10\%$ as it dominantly derives from the neutron calibration error.

The remarkable progress in fusion performance can be attributed to a stable increase in the I_p maintaining a vast reversed shear region extended up to $r/a \sim 0.7$–0.8 and controlling the beam deposition profile during the current ramp-up as shown in Fig. 5. The further increase in the I_p up to 3 MA with a 10% larger plasma volume degrades the fusion performance probably due to some enhancement of the ripple loss and off-axis beam deposition. So far, no high performance discharges have been attained with $q_{\min}$ below $\sim$2 in the campaign. When the $q_{\min}$ closely approaches 2, the discharges around 2.8 MA tend to be disruptively terminated by a fast beta collapse at $\beta_N \sim 2$ with the low q of $q_{95} \sim 3$. From the ERATO-J [15] code analysis, the observed β limits are found to be close to the ideal stability limits for low-n kink-ballooning modes. At the β limit for E27969, ECE measurements with a fast sampling time of 5 μs actually show that the collapse develops from the ITB region and grows with a very fast time scale of the order of 10 μs [16].

In conclusion, the fusion performance has been so improved with the plasma current for reversed shear discharges with an L-mode edge in a thermonuclear fusion regime that the fusion amplification factor is in excess of unity; this represents the achievement of equivalent plasma conditions for breakeven under the present definition of Q_{DT}. Since there is an intrinsic link between pressure and current profile evolutions through the bootstrap current, the control of pressure profile under the persistent transport barrier formation is found to be very much significant as well as that of the current profile for the steady state operation scenarios.

There have been continuous efforts of engineering and technical staffs in JT-60U and collaborative work. In particular, the TFTR group in the Princeton Plasma Physics Laboratory has remotely participated in this campaign and made the TRANSP code analysis for cross validation. The continued support and encouragement of Dr. M. Yoshikawa have enabled the fulfillment of this task.

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[1] T. Ozeki *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research, Wurzburg, 1992* (IAEA, Vienna, 1993), Vol. 2, p. 187.

[2] D. Boucher *et al.*, in *Plasma Physics and Controlled Nuclear Fusion Research, Montreal, 1996* (IAEA, Vienna, 1997).
[3] S. Ishida *et al.*, Phys. Rev. Lett. **68**, 1531 (1992).
[4] F. Kazarian *et al.*, in *Proceedings of the 21st EPS Conference on Controlled Fusion and Plasma Physics, Montpellier* (European Physical Society, Geneva, 1994), Vol. 18B, Pt. III, p. 1058.
[5] J. D. Strackan *et al.*, Phys. Rev. Lett. **58**, 1004 (1987).
[6] JET Team, Nucl. Fusion **32**, 187 (1992).
[7] S. Ishida *et al.*, in Ref. [2].
[8] J. D. Strachan *et al.*, Phys. Rev. Lett. **72**, 3526 (1994).
[9] E. A. Lazarus *et al.*, Phys. Rev. Lett. **77**, 2714 (1996).
[10] T. Fujita *et al.*, Phys. Rev. Lett. **78**, 2377 (1997); K. Itami *et al.*, Phys. Rev. Lett. **78**, 1267 (1997).
[11] T. Fujita *et al.*, in Ref. [2].
[12] S. Takeji *et al.*, Phys. Plasmas (to be published).
[13] R. J. Goldston *et al.*, J. Comput. Phys. **43**, 61 (1981).
[14] JET TEAM, in Ref. [1], Vol. 1, p. 99.
[15] S. Tokuda *et al.*, JAERI Report No. JAERI-M 9899, 1982.
[16] S. Ishida *et al.*, in Proceedings of the 24th EPS Conference on Controlled Fusion and Plasma Physics, Berhitesgaden (European Physical Society, Geneva, to be published).