Sustainment of High Confinement in JT-60U Reversed Shear Plasmas

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Abstract. Experimental results towards long sustainment of JT-60U reversed shear plasmas, where high confinement is achieved owing to strong internal transport barriers (ITBs), are reported. In a high current plasma with an L-mode edge, deuterium-tritium-equivalent fusion power gain, Q_{DT}^{eq} = 0.5 was sustained for 0.8 s (~ energy confinement time) by adjusting plasma beta precisely using feedback control of stored energy. In a high triangularity plasma with an ELMy H-mode edge, the shrinkage of reversed shear region was suppressed and quasi steady sustainment of high confinement was achieved by raising the poloidal beta and enhancing the bootstrap current peaked at the ITB layer. High bootstrap current fraction (~80%) was obtained in a high q regime (q_{95} ~9), which leaded to full non-inductive current drive condition. The normalized beta (β_N) of ~2 and H-factor of H_{89}~3.5 (HH_{98y2}~2.2) were sustained for 2.7 s (~ 6 times energy confinement time).

1. Introduction

In JT-60U reversed shear (RS) plasmas, high confinement (H_{89}<3.5) is obtained owing to formation of internal transport barriers (ITBs) inside the radius of minimum of q, q_{min} [1]. Here H_{89} denotes the confinement enhancement factor over the L-mode scaling [2]. The record value of deuterium-tritium-equivalent fusion power gain, Q_{DT}^{eq} = 1.25 was achieved at the plasma current of 2.6 MA [3]. However, these discharges terminated in a disruptive beta collapse when q_{min} decreased to 2, and hence the high performance was obtained only transiently. In RS plasmas with an ELMy H mode edge, collapses at q_{min} ~2 were suppressed and long sustainment of ITB was realized, but the pressure and current profiles changed continuously and the confinement property was moderate (H_{89}=1.5-2.0) [3]. In this paper, we report on sustainment of high performance in high current RS plasmas and the sustainment of high confinement with stationary profiles in ELMy H mode RS plasmas.

2. Sustainment of High Performance in High Current Regime

The duration of high performance in high current L-mode edge RS plasmas was limited by beta collapses that occurred when q_{min} decreased to 2. Extension of high performance was attempted by controlling the plasma beta in real time using a newly developed feedback control scheme of plasma stored energy (W_{dia}). The evolution of normalized beta (β_N) in high current RS plasmas is plotted in Fig. 1. Here, E31872 is a shot in which Q_{DT}^{eq} = 1.25 was achieved [3]. In this shot, β_N continued to increase after t = 5.8 s or after passing through q_{min} ~3 until the beta collapse occurred when q_{min} became 2 at t = 6.9 s. It was attempted to reduce the beta by using feedback control of W_{dia} in order to suppress collapses at q_{min} ~2. As shown in Fig. 1, collapses were still observed with low β_N of 0.8 though mini-collapses without disruption (denoted by triangles) tended to appear. Even these non-disruptive collapses caused shrinkage of ITB radius and hence high confinement was not obtained afterward. These collapses at q_{min}~2 with low beta seem to be attributed to resistive MHD instabilities [4]. Since passing through q_{min}~2 was found difficult, we intended to enhance the performance as early as possible to extend the high performance duration. In the shot E34292, the reference value of W_{dia} was raised quickly at 5.6 s to increase β_N and to reach high performance earlier after passing through q_{min} ~3 with β_N ~0.7. The reference value of W_{dia} was adjusted to rise as

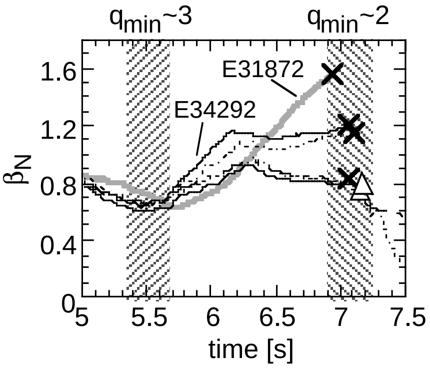


FIG. 1. Evolution of β_N in high I_p reversed shear plasmas (B_t ~ 4.35 T, I_p = 2.4-2.6 MA). Crosses denote disruptive beta collapses while triangles denote non-disruptive collapses.

early as possible without suffering from collapses. Then β_N reached 1.1 at t = 6.1 s and was sustained for 1 s until the beta collapse at t = 7.1 s.

Waveforms of E34292 are shown in Fig. 2. The large radius (~0.65) of q_{min}, ρ_{qmin} and hence the large ITB radius were sustained by I_p-ramp as shown in Fig. 2 (f) though q_{min} continued to decrease. The feedback control of W_{dia} was started at t = 4.0 s and continued until the end of the discharge. In Fig. 2 (b), the reference value of W_{dia} and the measured valued of W_{dia} are shown by a dashed line and a solid line, respectively. It is found that W_{dia} was controlled precisely according to the reference value. W_{dia} was ramped up from 4 s to 4.8 s to form an ITB with a large radius, was kept constant to suppress collapses at q_{min} ~3, was raised after t = 5.6 s and was kept constant after that. The H-factor and Q_{DT}^{eq} increased with β_N and Q_{DT}^{eq} = 0.5 was reached at t = 6.25 s and sustained until t = 7.05 s. The duration was 0.8 s or nearly equal to the energy confinement time, τ_E (τ_E = 0.8-0.9 s). During this period, β_N =1.1-1.2, H_{89} =2.5-2.7, HH_{98y2} ~1.4, $T_i(0)$ =12-14 keV, $n_D(0)\tau_E T_i(0)$ ~4x10^{20} m^{-3}•keV•s were sustained at B_t =4.35 T, I_p = 2.4 MA, q_{95} = 3.4, κ(elongation) = 1.84 and δ(triangularity) = 0.05; HH_{98y2} is the enhancement factor of thermal confinement to the ELMy H-mode scaling (ITER Physics Basis 98(y,2) [5]). Here and throughout this paper, the fast ion loss due to toroidal field ripple or charge exchange with neutrals is not subtracted from the heating power for the estimation of τ_E, H_{89} and HH_{98y2}. The value of Q_{DT}^{eq} is the highest one sustained quasi-stationary for τ_E in JT-60U.

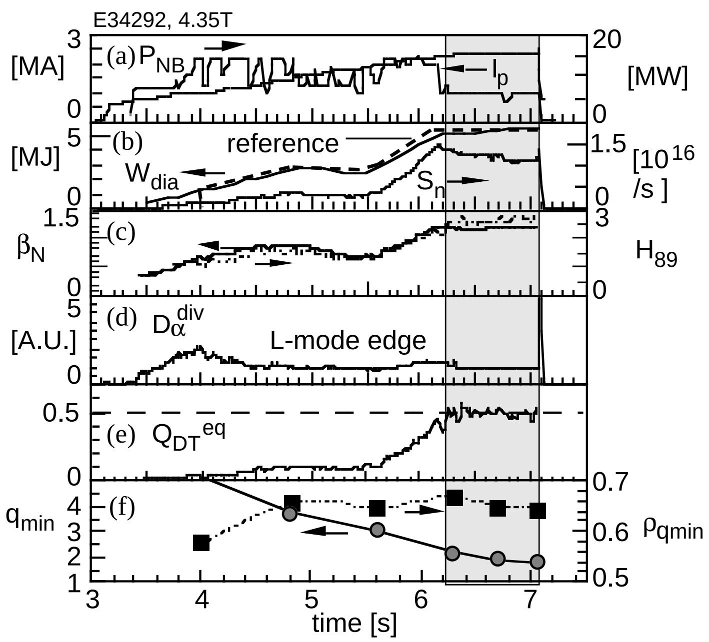


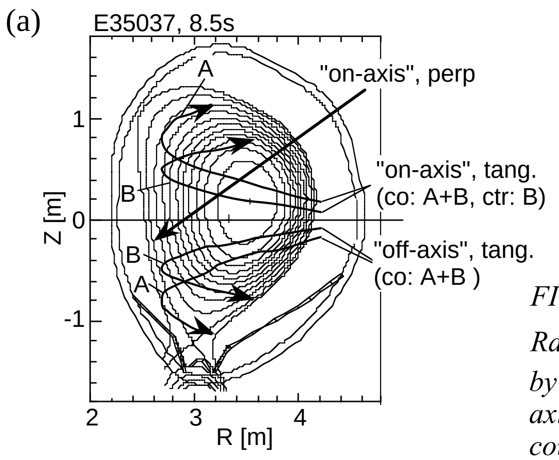
FIG. 2. Waveforms of a RS discharge in which Q_{DT}^{eq}~0.5 was sustained for 0.8 s. From the top, (a) plasma current (I_p) and NBI power (P_{NB}), (b) reference value (dashed line) and measured value (solid line) of stored energy (W_{dia}) and neutron emission rate (S_n), (c) β_N (solid line) and H_{89} (dotted line), (d) deuterium recycling emission at the divertor, (e) Q_{DT}^{eq}, (f) q_{min} and normalized radius of q_{min} (ρ_{qmin}).

3. Quasi-steady Reversed Shear Plasma with Large Bootstrap Current Fraction

In RS plasmas with an ELMy H-mode edge, collapses at q_{min} ~2 were suppressed and long sustainment of ITB was obtained [3]. However, the radius of q_{min} and hence the radius of ITB continued to shrink during I_p flat-top according to the penetration of inductive current, which resulted in confinement degradation. RS plasmas with ITB were sustained by using lower hybrid current drive (β_N~0.9, β_p~0.5-0.7) in Tore-Supra [6] and in JT-60U [7]. The bootstrap current fraction was estimated ~23% in the JT-60U case [7]. For steady state operation of tokamak reactors, higher beta and higher bootstrap current fraction (>~70%) are necessary to reduce the circulating power for non-inductive current drive [8]. Therefore we intended to realize RS plasmas with high bootstrap current fraction, typically larger than 70%, and to sustain current and pressure profiles stationarily.

The pressure and current profiles are strongly linked to each other in RS plasmas with large bootstrap current fraction. The profiles achieved in a steady state are determined by the dependence of transport coefficient on the magnetic shear. Two major issues have to be solved for steady sustainment of this kind of plasma. The first issue is the MHD stability of resultant pressure and current profiles since we have a small room to change the relationship between the pressure profile and the current profile. The other large issue is whether the current and pressure profiles are kept stationarily or not. If the ITB is formed well inside the radius of q_{min}, the location of q_{min} and ITB will continue to move inward. If the ITB is formed near or outside of the radius of q_{min}, the location of q_{min} and ITB will continue move outward. If we are lucky, they will stay stationarily. Of course, we will be able to keep the MHD stability and sustain the location of q_{min} and ITB stationarily by using local non-inductive current drive, but the power for that current drive should be small in fusion reactors.

To realize high bootstrap current fraction, RS plasmas with an ELMy H-mode edge and with high triangularity (δ ~0.4) in a high q regime (q_{95} =7.5-9) were optimized. A typical configuration is shown in Fig. 3 (a) together with NB lines used in this experiment. Here, B_t is 3.4 T, I_p is 0.8 MA, κ is 1.56, δ is 0.43 and q_{95} ~9. A high q_{95} regime was chosen to enhance β_p and the bootstrap current fraction within the beta limit typically imposed by β_N<2 in JT-60U RS plasmas [3]. A high value of δ was employed to obtain high β_N [9]. In previous RS plasmas with an ELMy H-mode edge [3], δ was less than 0.3. Two units of co-directional to I_p tangential beam are employed for the NB current drive. Injected NB power was 2-2.2 MW per unit and the beam energy was ~85 keV. Since off-axis current drive helps to sustain a RS profile together with the bootstrap current, the magnetic axis of the plasma was elevated so that the lower tangential beam lines pass through ρ~0.5 while the upper beam lines pass near



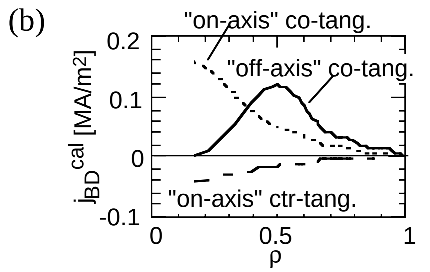


FIG. 3. (a) Plasma configuration and beam lines. (b) Radial profiles of beam driven current j_{BD}^{cal} density by "on-axis" co-tangential unit (dashed line), "off-axis" co-tangential unit (solid line) and "on-axis" counter-tangential unit (chain-dashed line).

the magnetic axis (ρ~0.1). The former is denoted by "off-axis" while the latter by "on-axis" in Fig. 3 (a). Examples of profiles of calculated beam driven current by tangential units are shown in Fig. 3 (b). The beam driven current by "off-axis" units has its peak around ρ~0.5. In a low I_p regime of 0.8 MA, the driven current by "off-axis" units, typically 100-120 kA, is supposed to be effective.

Waveforms of a typical discharge are shown in Fig. 4 (a). The initial overshooting of I_p was meant to reduce q_{min} rapidly to an expected steady-state value and to form strong ITBs safely below the beta limit. The ITB was formed during the I_p ramp and β_N ~ β_p ~1.5 was obtained during the first flat-top (1 MA). After that I_p was ramped down to reach I_p = 0.8 MA at t = 6.9 s, which caused the increase in β_N and β_p. The feedback control of plasma stored energy was employed in this discharge. During t = 7.3-10 s the measured value of stored energy exceeded the reference value and only pre-programmed NB units were injected. Then, τ_E =0.4-0.5 s, β_N =1.9-2.2, β_p =2.6-3.2 and H_{89} =3.3-3.8 were sustained for 2.7 s (~6τ_E). The thermal component of plasma stored energy was 80-82% and HH_{98y2} was 2.1~2.3. These values (H_{89} ~3.5, HH_{98y2} ~2.2) are the highest ones sustained quasi-stationarily in JT-60U. The high confinement period was terminated at t = 10 s when "off-axis" co-tangential NB turned off and perpendicular NBs were injected instead 0.1 s later to sustain the stored energy. The shrinkage of ITB radius was observed at t = 10 s, which might be caused by the rapid change of toroidal rotation.

Profiles of T_i and T_e at t =7.5 s and those of n_e and q at t = 7.5, 8.5, 9.5 s are shown in Fig. 4 (b). We can see that n_e and q profiles were sustained almost stationarily (q_{min}~3.6, ρ_{qmin}~0.65, ρ_{foot} ~0.7) for t= 7.5-9.5 s. Here ρ_{foot} denotes the normalized radius of outside edge of steep

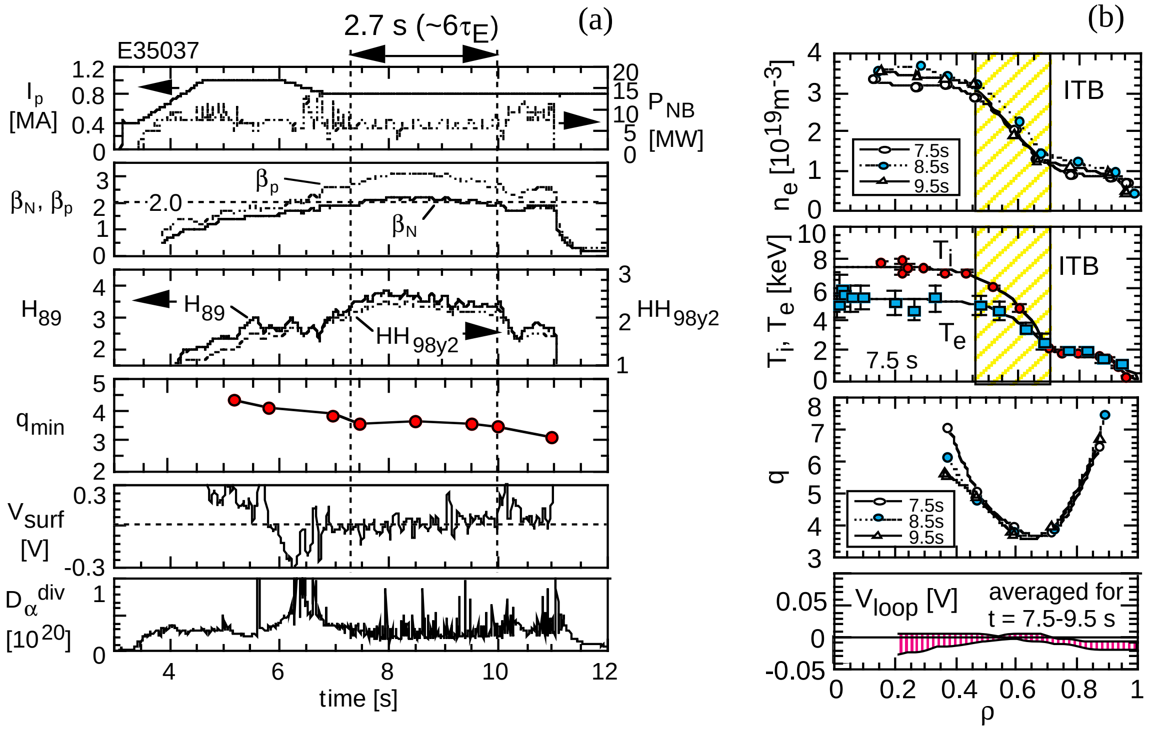


FIG. 4. (a) Waveforms and (b) profiles of a RS plasma in which high confinement and high bootstrap current fraction were sustained for 2.7 s. In (a) from the top, plasma current (I_p) and NBI power (P_{NBI}), β_p (dotted line) and β_N (solid line), H_{89} and HH_{98y2}, q_{min}, surface loop voltage V_{surf} deuterium recycling emission at the divertor. In (b), from the top, n_e profiles at 7.5, 8.5, 9.5 s, T_i and T_e profiles at 7.5 s, q profiles at 7.5, 8.5, 9.5 s and loop voltage profile averaged during 7.5-9.5 s.

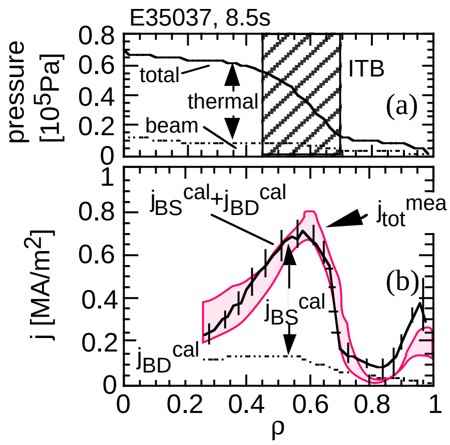


FIG. 5. (a) pressure profiles and (b) current profiles in E35037, t=8.5s. In (a), the beam pressure and the total pressure are shown by a dashed line and a solid line, respectively. In (b), calculated profiles of beam driven current and the sum of beam driven current and bootstrap current are shown by a dashed line and a solid line, respectively. The profile of measured current density is shown by a shaded area.

gradient in n_e [1]. The profile of loop voltage, $V_{loop}(\rho)$, averaged during t = 7.5-9.5 s, which was evaluated using equilibrium reconstruction [10], is also shown in the bottom of Fig. 4 (b). Since the surface voltage was slightly negative during t = 7.5-9.5 s as shown in Fig. 4 (a) and the q profile stayed constant, $V_{loop}(\rho)$ was almost flat and slightly negative in the greater part of the plasma volume, which implies the full non-inductive current drive was achieved.

The radial profile of measured total current density, j_{tot}^{mes} and that of calculated non-inductive current density $j_{BS}^{cal} + j_{BD}^{cal}$ are shown in Fig. 5 (b). The beam driven current density j_{BD}^{cal} was evaluated using ACCOME code [11]. The profile of j_{BS}^{cal} has its peak around ρ~0.6 because of the large pressure gradient at the ITB layer as shown in Fig. 5 (a). For the calculation of fast ion pressure and beam driven current, ripple-induced loss and charge-exchange loss of fast ions were subtracted from injected beam power. The loss due to ripple and charge-exchange is estimated to be ~20% of ionized beams using OFMC code [12]. We can see that the profile of measured current density and that of calculated non-inductive current density agree to each other well especially around ρ~0.6. This indicates that the inductive current was small and that the current profile was determined mainly by the bootstrap current peaked at the ITB layer. The fraction of bootstrap current was 80-88% during t=7.5-11 s in E35037. The amount of beam driven current was evaluated to be ~0.20 MA or 25% of I_p during t= 7-10 s. The sum of bootstrap current and beam drive current exceeds the total plasma current for t= 7.5-10 s, which supports the achievement of the full non-inductive current drive.

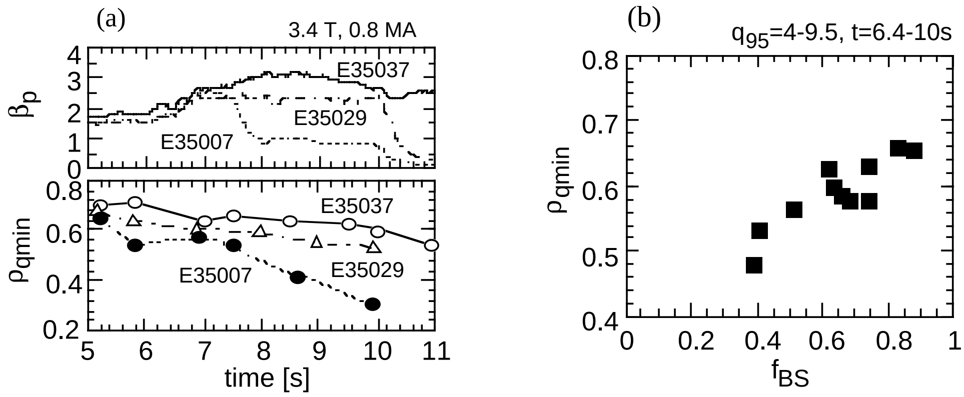


FIG. 6. (a) Time evolution of poloidal beta (top) and normalized radius of q_{min} (bottom) in E35037 (solid line) E35029 (dash-dotted line) and E35007 (dashed line). In E35007, the ITB disappeared at t ~7.5 s due to decrease of NB power. (b) Normalized radius of q_{min} (ρ_{qmin}) as a function of bootstrap current fraction (f_{BS}) in various RS plasmas (I_p=0.8-1.5MA, q_{95}=4-9.5) at a later phase (t= 6.4-10s).

The sustainment of large ρ_{qmin} was attained only in high β_p discharges. In Fig. 6 (a), time evolution of ρ_{qmin} was compared in three discharges. In E35007, the ITB disappeared at t ~7.5 s due to the decrease of heating power. Then, β_p dropped and the position of q_{min} moved quickly inward. In E35029, the ITB was sustained with lower β_p than that in E35037 then ρ_{qmin} was also sustained at a smaller value of ~0.55 In Fig. 6 (b), ρ_{qmin} is plotted against bootstrap current fraction at a later phase in various RS discharges with a similar configuration. Large ρ_{qmin} was sustained for larger bootstrap current fraction. These clearly indicate the role of bootstrap current for preventing the shrinkage of ρ_{qmin} and for sustainment of current profile.

Now we return to the two issues presented in the early part of this section. Since the current profile was already relaxed to that determined by the bootstrap current and similar β_N to lower f_{BS} RS plasmas was achieved, we find that the high f_{BS} does not degrade the MHD stability of RS seriously. For the stationary sustainment, we have shown that the profiles did not change within 2 s, which suggests the existence of steady state solution, but we need to extend the duration further to address the evolution in a longer time scale.

4. Sustainment of High Beta and High Confinement

The outstanding confinement performance achieved in the discharge described in the previous section (E35037) is attributed to the large ITB radius [1] as shown in Fig. 4 (b) in addition to the high edge stability due to high δ. In Fig. 7, HH_{98y2} is plotted against bootstrap current fraction (f_{BS}) for same discharges as used in Fig. 6 (b). It is seen that HH_{98y2} increases with f_{BS}. This tendency seems to be caused by the fact that ρ_{qmin} increases with f_{BS} as shown in Fig. 6 (b) since high confinement is obtained with large ρ_{qmin} as shown in Fig. 7 (b). Hence, it is confirmed that the high confinement can be sustained in RS plasmas if ρ_{qmin} can be sustained by some non-inductive (bootstrap or external) current drive.

The low I_p (0.8MA) and high q operation (q_{95}~9) in E35037 was necessary to sustain large ρ_{qmin} in steady sate with available co-tangential beam power (~2.2 MW) for off-axis current drive and with attainable beta in the present JT-60U RS experiments. With more off-axis NBCD power, we would obtain stationary high confinement RS plasmas in a lower q regime.

Though stationary sustainment of q profile is not expected in a lower q regime at present, q values (q_{min} and/or q_{95}) are supposed to affect the MHD stability significantly in RS plasmas and hence lower q operation was attempted to address this issue. Figure 8 shows an example of RS plasma in a lower q regime (3.7T, 1.35 MA, q_{95} ~5). Here, H_{89} ~2 (HH_{98y2} ~1.2) and β_N ~1.6 were sustained for 3 s though the q_{min} continued to decrease gradually. The q_{min} passed through q = 3 successfully with β_N~1.5 and was located between q = 2 and q = 3 for the

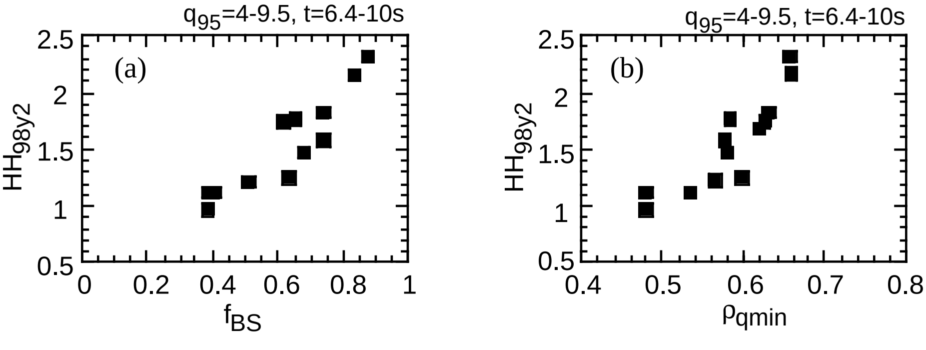


FIG. 7. HH factor (HH_{98y2}) as a function of (a) bootstrap current fraction, f_{BS} and (b) normalized radius of q_{min}, ρ_{qmin}.

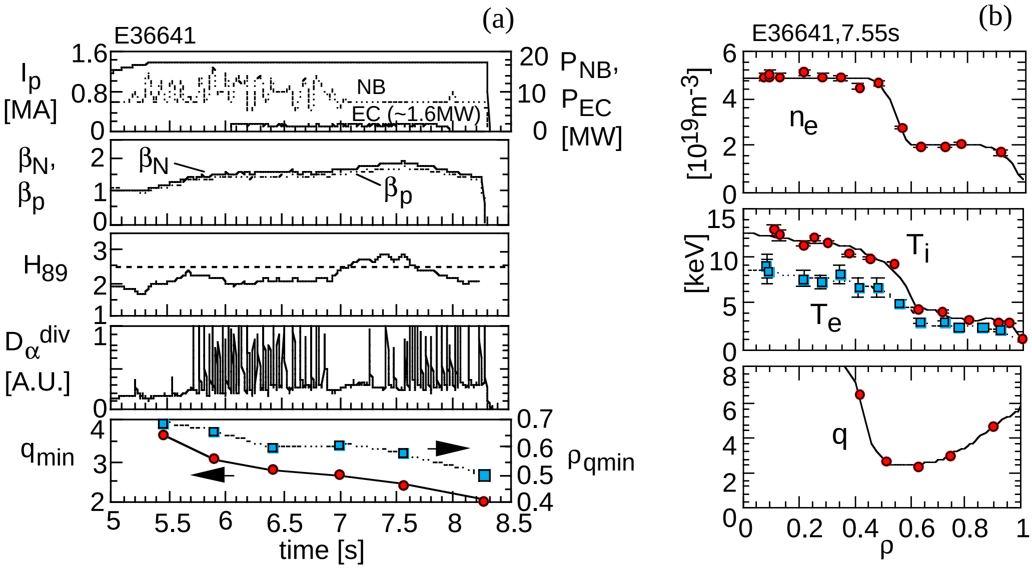


FIG. 8. (a) Waveforms and (b) profiles of a reversed shear discharge where high confinement was obtained at q_{95}~5 and q_{min}~2.5 (3.7T, 1.35MA). In (a), from the top, plasma current (I_p), NBI power (P_{NB}) and EC power (P_{EC}), measured (solid line) and reference (dashed line) values of stored energy (W_{dia}), β_N (solid line) and β_p (dashed line), H_{89}, deuterium recycling emission at the divertor, q_{min} and radius of q_{min} (ρ_{qmin}). In (b), from the top, electron density (n_e) profile, ion and electron temperature (T_i and T_e) profiles and q profile.

sustainment period, which was in contrast to that q_{min}>3 in the discharge described in the previous section. The discharge entered a higher confinement state at t ~7 s and H_{89} ~2.7 (HH_{98y2} ~1.5), β_N ~1.8 and W_{dia} ~ 3.9MJ were obtained. However, the confinement started to degrade at t =7.6 s. This type of confinement degradation was sometimes observed and may be related to the change radial electric field shear [13].

In Fig. 9, β_N and HH_{98y2} are plotted against q_{min}. In a lower q regime (q_{min}~2.5, q_{95}~5.5), β_N~2 was sustained for longer than $5\tau_E$ while high confinement (HH_{98y2}>~1.5) was sustained only within $2\tau_E$. Long sustainment of HH_{98y2}>~ 1.5 in a lower q regime will be pursued in future. Figure 10 shows sustained β_N, H_{89} and $\beta_N H_{89}$ in JT-60U RS plasmas. Before the last IAEA conference, sustained β_N and H_{89} for longer than 1.5 s were β_N ~1.5 and H_{89} ~1.7-2.2. In these two years, sustainment of β_N ~2 and H_{89} ~3 for a few seconds has become possible in high δ, high f_{BS} plasmas. Due to the improvement in stability and confinement, $\beta_N H_{89}$ has been enhanced remarkably as shown in Fig. 10 (c).

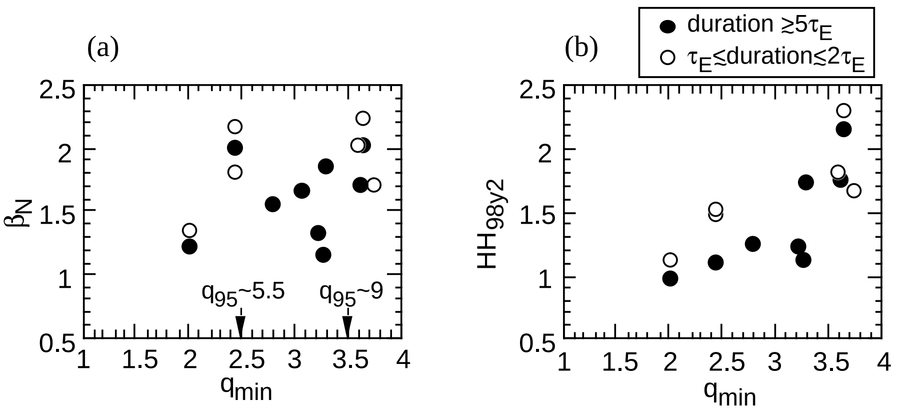


FIG. 9. (a) β_N and (b) HH factor (HH_{98y2}) as a function of q_{min}. Closed symbols denote values sustained for longer than ~$5\tau_E$, while open symbols denote values sustained for τ_E to $2\tau_E$.

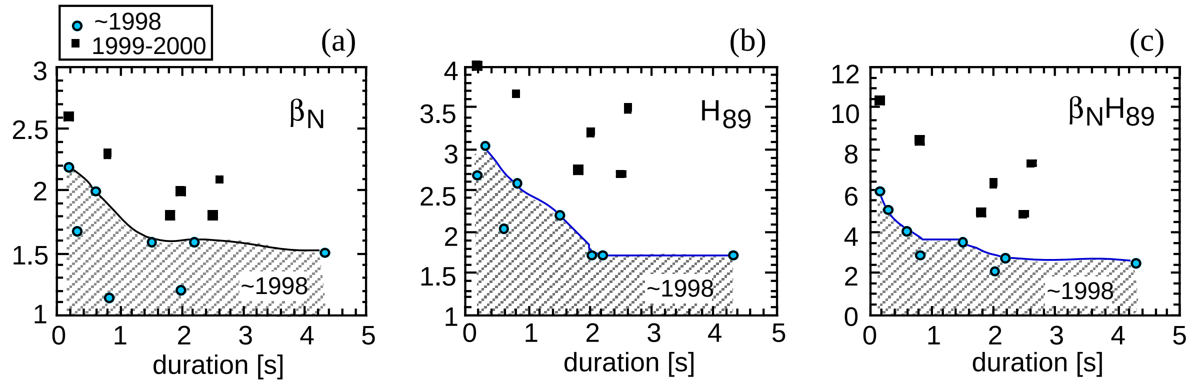


FIG.10. Sustained (a) β_N, (b) H_{89} and (c) $\beta_N H_{89}$ in RS plasmas. Circles denote the data before 1998 and rectangles denote the data during 1999-2000.

5. Conclusions

In a high current plasma with an L-mode edge, deuterium-tritium-equivalent fusion power gain, Q_{DT}^{eq} = 0.5 was sustained for 0.8 s (~ energy confinement time, τ_E) by adjusting plasma beta precisely using feedback control of stored energy. The duration was limited by a disruptive beta collapse at q_{min} ~2 as was the case in higher beta (Q_{DT}^{eq}) discharges.

In a high triangularity RS plasma with an ELMy H-mode edge, the shrinkage of radius of q_{min} was suppressed and high confinement was sustained by enhancing the bootstrap current peaked at the ITB layer. High poloidal beta (β_p ~2.7-3.2) and high bootstrap current fraction (~80%) were obtained in a high q regime (q_{95} ~9), which leaded to full non-inductive current drive condition and normalized beta (β_N) of ~2 and H-factor of H_{89}~3.5 (H_{98y2}~2.2) were sustained for 2.7 s (~ 6τ_E). Extension to a lower q regime is in progress.

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