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Recent Progress Towards Steady State Tokamak Operation with Improved Confinement in JT-60U

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Abstract
In the JT-60U tokamak, optimization of high β_p mode and reversed shear mode plasmas are being done for establishment of scientific basis for steady state operation of tokamaks. In high β_p H-mode plasmas, $\beta_N = 2.9$ and $H_{89} = 2.2$–2.4 were sustained stationarily by using high triangularity configuration and pressure profile optimization. Steady state performance was limited by resistive low toroidal mode number instabilities. Stabilization of resistive modes by using a newly installed ECRF system was attempted and a decrease of mode amplitude was observed but complete stabilization could not be achieved. In reversed shear plasmas, high fusion performance with equivalent DT fusion power gain of 0.5 was sustained for 0.8 s or an energy confinement time. The duration was limited by disruptive beta collapse that was encountered when the minimum value of q became 2 even with moderate beta, $\beta_N \sim 1.2$. Stationary sustainment of ITB was demonstrated in a full CD reversed shear plasma with LHCD. The sustainment of reversed shear current profile by bootstrap current was demonstrated in an ELMy H-mode edge reversed shear plasma with a high triangularity in a high q regime. A confinement enhancement factor of 3.5 and β_N of 2 were sustained for 2.7 s with stationary current and pressure profiles. Ar puffing to H mode plasmas aiming at high confinement with high density and high radiation fraction was performed and $H_{89} \sim 1.4$ with radiation fraction of 80% was obtained at 70% of Greenwald density.

Keywords:
high β_p mode, reversed shear, internal transport barrier, tearing modes, ECCD, beta collapse, bootstrap current, radiative divertor, impurity injection.

1. Introduction
In the JT-60U tokamak, reactor-relevant plasma studies are conducted in support of ITER and steady-state tokamak operation. It is a prerequisite for the realization of steady-state tokamak reactors to sustain high energy confinement, high stability and a large bootstrap current fraction with full current drive and radiative divertor conditions. Higher beta and confinement are necessary in steady state tokamak reactors than in pulsed reactors because of high q operation and of the necessity for high bootstrap current. Hence experiments for the sustainment of high beta and high confinement are strongly related to the steady state operation of tokamaks.

In JT-60U, two approaches towards steady-state tokamak operation with large bootstrap fraction are being pursued. These are high β_p H-mode and reversed shear (RS) mode. In both modes, internal transport barriers, ITBs, are formed and improved confinement is obtained [1,2]. The high β_p mode has a monotonic q profile with weak shear and $q(0)>1$. In the RS mode

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plasmas, the minimum of q (q_{min}) exists and the ITBs are formed near the location of q_{min}. The density and temperature profiles in high β_p mode are usually peaked one or "parabolic type", while those in RS are often flat near the axis or "box-type" [3]. The confinement improvement is more enhanced in RS mode and the H factor larger than 3 is obtained even with an L-mode edge. This paper reports optimization of high β_p H-mode and RS mode plasmas for sustainment of high beta and high confinement as well as H-mode experiments as an example of high confinement and large radiation fraction.

The rest of the paper is organized as follows. In section 2, the sustainment of high β_p mode is presented. Section 3 treats sustainment of RS mode. Heat and particle control in the divertor is described in section 4. The summary is given in section 5.

2. Sustainment of High β_p H-mode

The stability of high β_p H-mode has been maximized by optimizing pressure profile and plasma shape. The major stabilities related to the beta limit in the high β_p H-mode are kink-ballooning mode in the core and the high-n ballooning mode at the edge; where n is the toroidal mode number. Too peaked profile results in beta collapse due to the kink-ballooning mode in low beta while the beta is limited by ELM (Edge Localized Mode) activities caused by high-n ballooning mode for too broad profile. The plasma shape or triangularity (δ) is related to the high-n ballooning mode. By increasing δ, the edge pressure gradient can be kept higher during ELMy H-mode [4]. In JT-60U, δ can be increased up to ~0.5 for ~1 MA discharges but the available δ decreases with the plasma current.

For sustainment of high beta in long pulse discharges, magnetic fluctuations appear and limit the beta. As a result, the beta and confinement in long pulse discharges are lower than those obtained transiently. In Fig. 1, the normalized beta, β_N and confinement enhancement factor over ITER89P L-mode scaling, H_{89} are plotted against edge safety factor, q_{95}. Sustainable β_N and H_{89} were about 60–70% of transient ones and $\beta_N <$ 2.7–2.9 and $H_{89} <$ 2.2–2.4 were obtained with high δ high β_p *H*-mode for a wide range of q_{95} (3.2–8).

The magnetic fluctuations grow slowly (with ~100 ms growth time) and have m/n = 3/2, 2/1 and so on; here m is the poloidal mode number. The fluctuations observed in JT-60U high β_p H-mode plasmas have many features that are different from classical tearing modes and consistent with the neoclassical tearing modes (NTMs) [5]. First, they are observed even when classical tearing modes are stable or Δ' is negative. Second, there is a minimum value of β_N (β_N^{onset}) for appearance of fluctuations and β_N has to be reduced lower than β_N^{onset} to eliminate the existing fluctuations (hysteresis for beta). Furthermore, the island structure was observed in T_e profiles obtained using ECE radiometer with 2 cm spatial resolutions and the island width was consistent with the calculated one based on NTM [6]. Though we have many features consistent with NTM, we have not identified the cause of seed island that is necessary for appearance of NTM. We have no sawteeth in high β_p H-mode and fishbone instabilities are not observed either. The ELMs or error

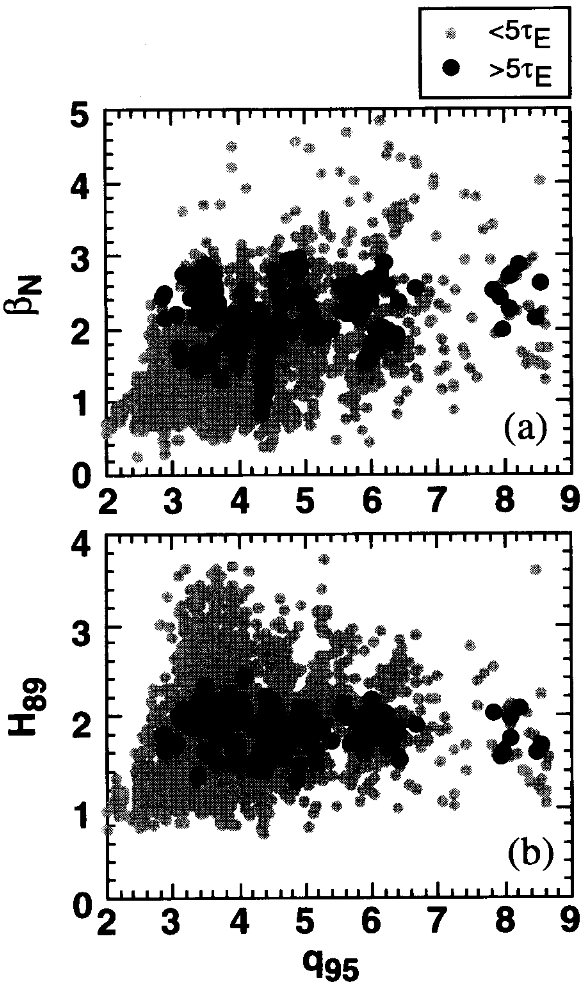

Fig. 1 (a) β_N and (b) H_{89} as a function of q_{95} in high β_p mode and high β_p H-mode plasmas. Gray circles denote the transient data whose duration was less than $5\tau_E$ while black circles denote the sustained data for longer than $5\tau_E$.

fields are candidates for the cause of seed islands.

In JT-60U experiments, β_N^{onset} increases with the density or electron collisionality. Hence higher density is favorable to obtain high beta in long pulse discharges. However, the confinement was degraded when the strong gas puff was applied to raise the density as shown in section 4. Thus we have an optimum density range to sustain high beta, which was about (3–3.5) × 10^{19} m^{-3} for 1.5 MA discharges with $\delta < 0.3$. At this density, β_N ~1.9, H_{89} ~2.2 and Q_{DT}^{eq} ~0.16 were sustained for 4.5 s [4].

The stabilization of NTM by ECCD was attempted using a newly installed EC system. The frequency is 110 GHz and the maximum injected power is 0.75 MW (1 MW at the gyrotron output). To date, the maximum pulse length was 2 s for 1 MW of gyrotron output and 5 s for 0.3 MW. The steerable mirror is installed at the injection port and the wave injection angle can be changed in the poloidal direction. In the resistive modes stabilization experiments, the wave injection angle was adjusted to the center of m/n = 3/2 islands which can be recognized by ECE measurements. It was observed that the amplitude of n = 2 magnetic fluctuation and that of electron temperature perturbation near the magnetic island decreased during the EC injection [6]. However, complete stabilization has not been attained. In this year, two more gyrotrons will be installed and clearer stabilization will be expected by injecting higher power.

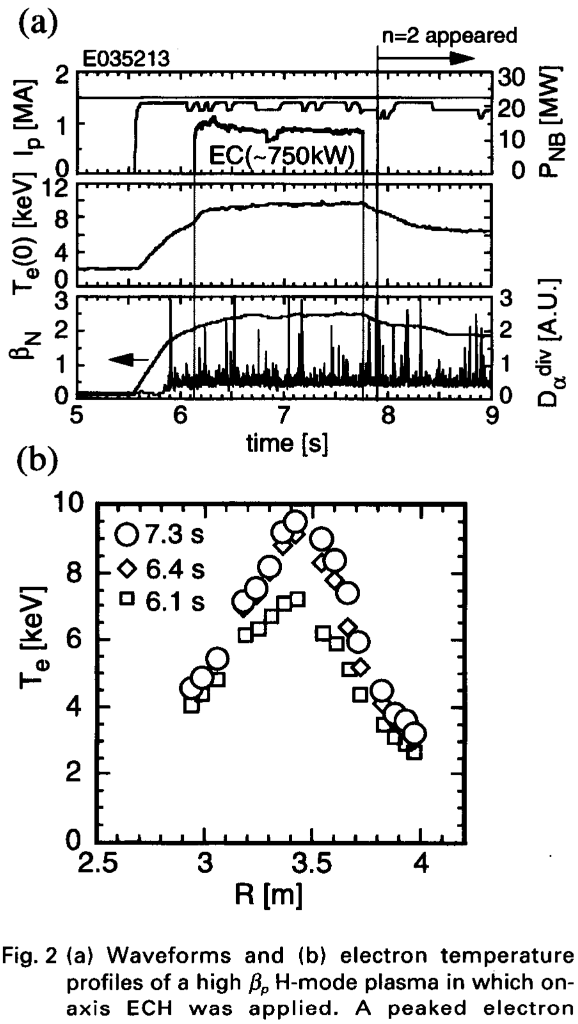

Fig. 2 (a) Waveforms and (b) electron temperature profiles of a high β_p H-mode plasma in which on-axis ECH was applied. A peaked electron temperature profile was formed by ECH; $n_e(0)$~4 × 10^{19} m^{-3} for t = 6.1–6.4 s. Modes with n = 2 appeared from t = 7.9 s and β_N was degraded.

Deposition of EC power on the axis of plasma was also attempted to increase $T_e(0)$ in high β_p plasmas. An example is shown in Fig. 2. The value of $T_e(0)$ was raised by ~1.5 keV and reached 9.5 keV at high density ($n_e(0)$~4 × 10^{19} m^{-3}) with the injection power of ~0.75 MW, which was less than 5% of NB power, and excellent heating performance was confirmed. High β_N of 2.4–2.5 was sustained for 1.4 s during ECH. These results are promising for the enhancement of current drive efficiency (η_{CD}) of NNB, the record of which is 1.3 × 10^{19} A/W/m^2 achieved in 1.5 MA high β_p H-mode with $T_e(0)$ ~8.6 keV [7] since η_{CD} increases with the electron temperature.

3. Sustainment of Reversed Shear

3.1 Sustainment of high fusion performance

In JT-60U RS plasmas, very high confinement (H_{89} >3) with an L-mode edge is obtained due to significantly reduced transport in the ITB layer that is located at a large radius. The equivalent fusion power gain, Q_{DT}^{eq} of 1.25 was achieved transiently at I_p = 2.6 MA and B_t = 4.4 T [9]. In these plasmas, the duration of high performance was limited by beta collapse that was encountered when q_{min} became 2. Efforts to sustain high fusion performance as long as possible were attempted. To extend the high performance period, one can either raise the performance as early as possible or delay/ suppress the beta collapse at q_{min} = 2.

It was observed that q_{min} = 2 could be passed through in ELMy H mode edge RS plasmas at 1.5 MA and 3.5 T [9]. Hence we tried to make an H-mode edge in high current (>2 MA) high field (4.3 T) RS plasmas using a similar technique used to obtain H-mode at medium current plasmas or changing NB toroidal momentum input from balanced one to co-directional dominant one. Although we certainly obtained H-mode transition, collapses were encountered during current ramp when we continued the co-directional NB injection. These collapses are supposed to be related to locked modes since the toroidal rotation at the plasma edge became nearly zero for co-directional injection case (the edge rotates in the counter direction for balanced injection case in JT-60U, which is mainly due to formation of negative radial electric field through ripple loss of beam ions). When we returned to balanced injection after the H-mode transition, the edge pedestal continued to weaken and the edge returned to L-mode ultimately. It is not yet possible to sustain the H-mode edge in high current, high field RS plasmas in JT-60U.

It was also attempted to reduce the beta or to change the toroidal rotation just before $q_{\rm min}$ became 2. For the balanced NB injection case, collapses were observed even with low β_N of 0.8~1. When the counter injection was employed with same β_N, plasma survived even though a mini collapse occurred at q_{min} = 2. This may suggest that q_{min} = 2 collapses can be suppressed by the toroidal rotation shear, but the optimization of this technique has not been investigated.

To raise the performance as early as possible, we employed the stored energy feedback control technique that has been developed [8] and is shown in Fig. 3. In this discharge, the stored energy (W_{dia}) feedback control

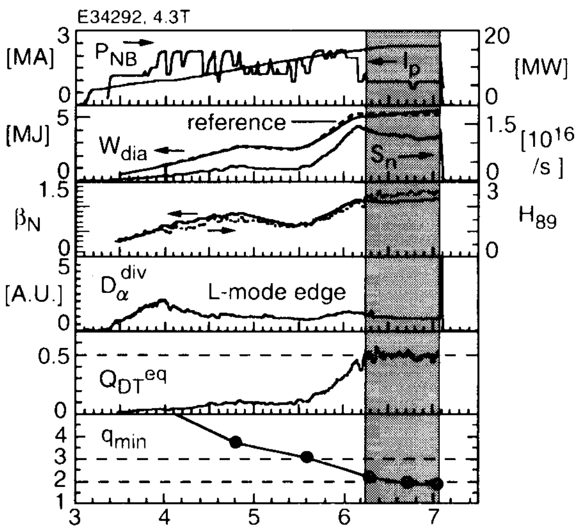

Fig. 3 Waveforms of a RS plasma in which Q_{DT}^{eq} = 0.5 was sustained for 0.8 s. From the top, plasma current (I_p) and NBI power (P_{NB}), reference value (dotted line) and experimental value (solid line) of stored energy (W_{dia}) and neutron emission rate (S_n), β_N and H_{89}, deuterium recycling emission at the divertor, Q_{DT}^{eq} and q_{min}.

started at t = 4.0 s and continued to the end of discharge. In the second box of Fig. 3, the reference value of W_{dia} by a dotted line and the measured value of W_{dia} by a solid line are shown. 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 and was kept constant to suppress collapses at q_{min}~3. After t = 5.6 s, W_{dia} started to increase and reached 5.3 MJ at 6.2 s and was kept constant after that. As the W_{dia} increased, H_{89} also increased and Q_{DT}^{eq} = 0.5 was reached. The timing of ramp up of W_{dia} (from 2.7 MJ to 5.3 MJ) was adjusted to reach high performance (5.3 MJ) state as early as possible without suffering collapses. As a result, Q_{DT}^{eq} = 0.5 was reached at 6.25 s and was sustained until 7.05 s or the beta collapse at $q_{\rm min}$~2. The duration was 0.8 s or equal to the energy confinement time. During the same period, β_N = 1.1–1.2, H_{89} = 2.5–2.7, $T_i(0)$ = 12–14 keV were sustained.

3.2 High confinement high bootstrap reversed shear

For long sustainment of RS plasmas, the necessity of current profile control to suppress the change of q profile or decrease of q_{min} is highlighted in the fact that the passing q_{min} = 2 was difficult as shown in the above section. Also current profile control is necessary to sustain the location of ITB; in the ELMy H-mode RS, q_{min} = 2 could be passed but the location of ITB moved inward according to the inward movement of location of q_{min} which was caused by ohmic current penetration into the core [9]. In JT-60U, application of LHCD for sustainment of reversed shear configuration has been intensively performed. First, sustainment of q profile with low beta (without ITB) was demonstrated [10] and sustainment of higher beta plasma with ITB was achieved later [11]. In the later case, β_N~0.9, β_p~0.7 were sustained with full noninductive CD conditions including bootstrap current (I_{BS}/I_p~0.23) at 0.85 MA and 2 T.

A high bootstrap current fraction (70–80%) is required for steady state operation. So sustainment of RS with higher bootstrap current fraction is important and is directly related to steady state tokamak operation. We can expect a hollow current profile is naturally formed and sustained under high bootstrap current fraction. However, it is not known whether the pressure and current profile are sustained stationarily under high bootstrap fraction because the current profile is strongly affected by the pressure profile through bootstrap current while the pressure profile may be changed by the current profile through the effect of magnetic shear on the transport. Hence experiments to demonstrate high bootstrap RS and to study the evolution of pressure and current profiles are planned. Since high β_p is required to achieve high bootstrap current fraction, an ELMy H-mode RS with high δ configuration and high q_{95} was selected; higher stability (β_N) is expected in the high δ configuration as shown in the high β_p H-mode experiments while higher β_p with same β_N is obtained for higher q_{95}.

Figure 4 shows a typical discharge in which sustainment of RS with high bootstrap current fraction was demonstrated. The initial current ramp up to 1 MA was employed to establish a strong ITB with moderate beta (β_N <1.5) without suffering collapses. The plasma current was ramped down during t = 6 to 6.8 s and β_p was increased from 2.0 to 2.6. During t = 7.3 to 10 s, β_N ~2.0 (W_{dia} ~ 2.4 MJ), β_p ~2.6–3 were sustained (B_t = 3.4 T, I_p = 0.8 MA, q_{95} ~9, δ ~0.4). The profiles of temperature, density and q are shown in Fig. 4 (b). The density and q profiles are shown for 3 timings (t = 7.5, 8.5, 9.5 s). From this figure, it is found that density and q profiles were sustained almost stationarily. The location of q_{min} was ~65% of plasma minor radius and the value of q_{min} was ~3.5. Using these profiles, the bootstrap current fraction was estimated to be ~80% while the NBCD current was estimated to be 200 kA or 25% of plasma current. Hence full noninducitve CD is supposed to be maintained during t = 7.3 to 10 s. This can be confirmed from the fact that loop voltage was nearly zero as shown in Fig. 4 (a). A distinctive feature of this discharge is that very high confinement or H_{89} ~3.5 (τ_E ~0.4–0.5 s) was sustained. This is attributed to the large ITB radius as shown in Fig. 4 (b) and high edge stability due to high δ. Although H_{89}>3 was

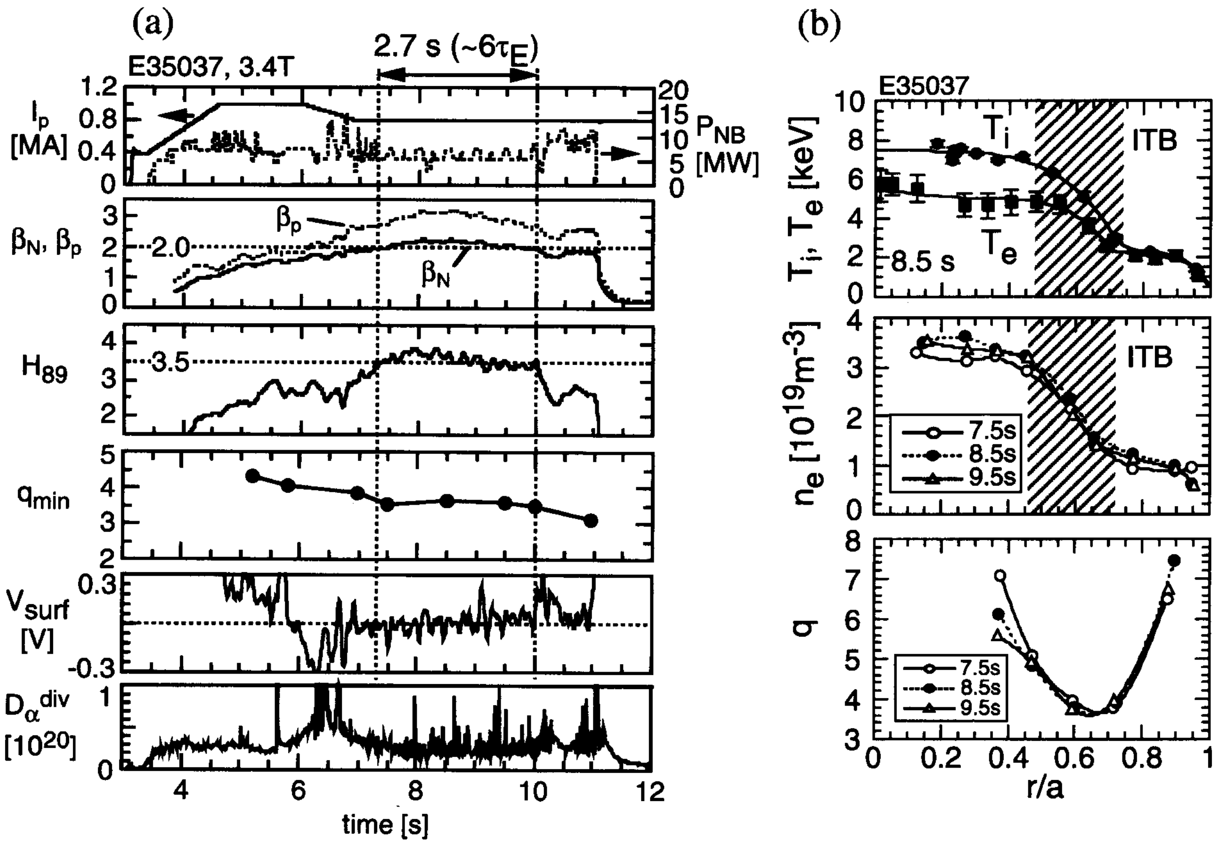

Fig. 4 (a) Waveforms and (b) profiles of a RS plasma in which high confinement and high bootstrap current fraction were sustained for 2.7 s. In (a) from the top, plasma current (I_p) and NBI power (P_{NBI}), β_p (dotted line) and β_N (solid line), H_{89}, q_{min}, surface loop voltage V_{surf}, deuterium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

obtained in JT-60U RS transiently, the confinement in long pulse ($>5\tau_E$) was restricted to $H_{89}<1.7$ in the previous ELMy H-mode RS with lower β_p (<1.3) [9]. In addition to the increase of triangularity, the outward displacement of ITB location caused this improvement of confinement. Smaller ITB radius ($r/a < 0.4$–0.5) was obtained in the long-pulse lower β_p plasmas due to the current penetration. Hence these results indicate that high confinement can be sustained in ELMy H RS if the appropriate current profile is sustained stationarily. Since the confinement of long pulse high β_p H-mode is $H_{89} < 2.4$ (including high q_{95} regime) as shown in Fig. 1 (b), the confinement of the discharge shown in Fig. 4 is the highest one sustained in JT-60U plasmas.

4. Heat and Particle Control in the W-shaped Divertor

A large radiation fraction is required for long pulse operation, especially in the next step device, to reduce the heat load to the divertor plates and to suppress the damage to the divertor materials. One of the major issues is to integration of high confinement in the core and the large radiation fraction in the edge, SOL or divertor plasmas. To enhance the radiation power in the divertor plasmas, high density, low temperature and high impurity content are favorable. To keep high confinement and high fuel purity in the core plasma, we have to suppress backflow of neutrals and impurities from the divertor to the core. To achieve these objectives, W-shaped divertor with pump was employed in JT-60U in 1997 [12]. In 1997–1998, the pumping slot was located at the inner (high field side) divertor while both inner and outer sides are pumped in 1999.

In the W-shaped divertor, the capability of heat handling was improved and sustainment of ELMy H-mode with heating power of ~20 MW for 9 s was demonstrated; the total heating energy reached 200 MJ [7]. This is a significant improvement from the open divertor, in which a carbon burst happened and degraded the confinement in several seconds. As for the particle handling, efficient helium exhaust was demonstrated in ELMy H-mode plasmas [13].

For the integration of high core confinement and large radiation fraction, argon (Ar) injection into ELMy H-mode plasmas was performed. The results are shown in Fig. 5 in comparison with deuterium gas puff (without impurity seeding) plasmas. The typical conditions are $I_p = 1.2$ MA, $B_t = 2.5$ T, δ ~0.35 and P_{NB} ~20 MW. To enhance the radiation fraction, higher (edge) density is favorable as shown in Fig. 5 (b). However, the core confinement tends to degrade as the density increases as shown in Fig. 5 (a). This is supposed to be caused by shrinkage of the edge pedestal width at the high density with strong gas puffing. In deuterium puffing cases, H_{89} quickly decreased with the density and became ~1–1.1 at the density of 70% of Greenwald density (n^{GW}). On the other hand, when Ar was puffed, the degradation of confinement with the density was reduced significantly and the confinement at the high density regime was improved. One of the causes of this improvement of confinement is supposed to be a reduction of deuterium gas puff in the Ar injection cases. The radiation fraction was also increased by ~10–20% in the Ar injection cases. As a result, H_{89} ~1.4 with radiation fraction of ~80% was obtained at $n_e/n^{GW} = 0.7$ or until the detachment occurred.

When the radiation fraction increased too high, the core plasma temperature decreased, Ar penetrated into the core, and the confinement was lost. To sustain the

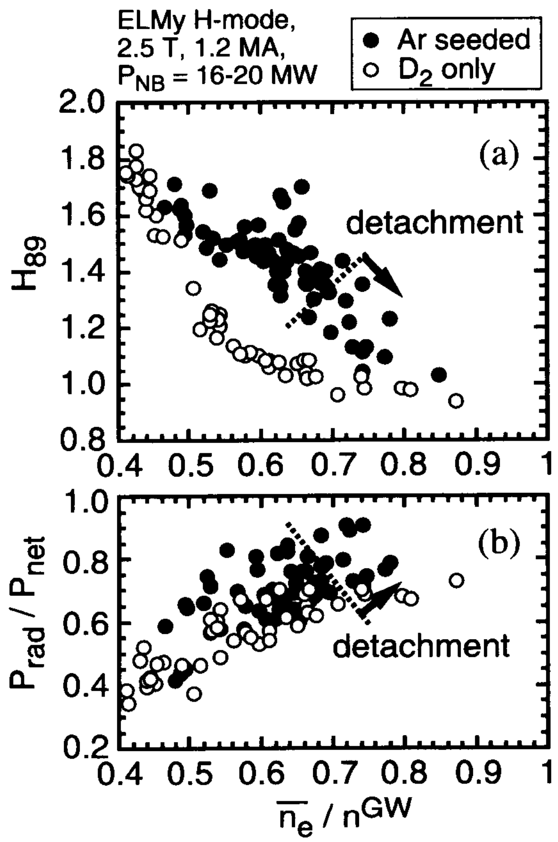

Fig. 5 (a) H_{89} and (b) radiation fraction versus the density normalized to the Greenwald density. Open symbols denote deuterium gas puff cases while closed symbols denote Ar injection cases.

radiation fraction in a suitable range, feedback control of radiation from the edge plasma adjusting the Ar puffing rate was employed in this series of experiments. Typically, radiation fraction of ~65% and H_{89} ~1.4 was sustained for 2.6 s at n_e/n^{GW} ~0.65.

5. Summary

In JT-60U, experiments towards steady state tokamak operation are being executed mainly in high β_p mode and RS mode plasmas. In high β_p H-mode plasmas, $\beta_N < 2.7$–2.9 and $H_{89} < 2.2$–2.4 were sustained in high δ (<0.5) configurations. The steady-state performance was limited by low *n* resistive modes. A newly installed EC system was employed to deposit EC power at the islands and a slight decrease of mode amplitude was observed but complete stabilization is not yet obtained. In a RS mode plasma with an L-mode edge, $Q_{DT}{}^{eq}$ = 0.5 was sustained for 0.8 s, which was equal to the energy confinement time, at 2.4 MA and 4.4 T. The stored energy feedback control was useful to extend the high performance period but the duration was limited by beta collapses which occurred when q_{min} became 2. Sustainment of *q* profile and ITB structures was successfully done both by LHCD and by bootstrap current. By LHCD, β_N ~0.9 was sustained at 0.85 MA, 2 T. In the bootstrap current scenario, β_N ~2, β_p ~2.6–3, bootstrap current fraction ~80% and H_{89} ~3.5 were sustained in an ELMy H-mode RS with 0.8 MA, 3.4 T, q_{95} ~9 and δ ~0.4. Argon injection into ELMy H-mode plasmas improved the confinement at the high density and H_{89} ~1.4 with radiation fraction of ~80% was obtained at 70% of Greenwald density.

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