Evolution of Bootstrap-Sustained Discharge in JT-60U

Y. Takase[1)], S. Ide[2)], Y. Kamada[2)], H. Kubo[2)], O. Mitarai[3)], H. Nuga[1)], Y. Sakamoto[2)], T. Suzuki[2)], H. Takenaga[2)], and the JT-60 Team

[1)] University of Tokyo, Kashiwa, Chiba-ken, 277-8561 Japan
[2)] Japan Atomic Energy Agency, Naka, Ibaraki-ken, 311-0193 Japan
[3)] Kyushu Tokai University, Kumamoto, Kumamoto-ken, 862-8652 Japan

e-mail contact of main author: takase@k.u-tokyo.ac.jp

Abstract. A self-sustained state driven by the bootstrap current was achieved in JT-60U. Only perpendicular and counter tangential neutral beam injection were used so that the neutral beam driven current was negative. In the usual constant plasma current (I_p) feedback mode, a negative loop voltage and Ohmic heating (OH) coil recharging were observed. In the constant OH current mode, a negative loop voltage and a slow I_p ramp-up was observed. In the constant plasma surface flux feedback mode, a slow I_p ramp-up was observed with zero surface loop voltage. These results provide evidence of bootstrap overdrive. The dynamic response of a completely self-driven system with negligible external current drive was studied. At a toroidal field of 3.7 T, β collapses were often observed. The internal transport barrier (ITB) shrinks radially at such collapses, but then recovers partially. In a 4 T discharge in which β collapses were avoided, $I_p \geq 0.55$ MA was maintained for 2.5 s. The duration of such a self-sustained discharge without β collapses was limited by a slow degradation of ITB.

1. Introduction

In conventional tokamak operation, an OH center solenoid (CS) is used to start up and ramp up the plasma current (I_p) by induction. However, the presence of the CS prevents the realization of a compact, light-weight tokamak fusion reactor. Elimination of the CS has a large impact on the economic competitiveness of a tokamak fusion reactor, since a more compact, higher field design would become possible [1].. In addition, the external power required to drive the necessary I_p has a large impact on the recirculating power fraction, and therefore on the cost of electricity. A large improvement can be achieved by increasing the fraction of self-generated plasma current (*i.e.*, the bootstrap current fraction, $f_{BS} = I_{BS}/I_p$). The development of advanced tokamak scenarios aims at maximizing f_{BS}, without sacrificing high beta and high confinement. If it were possible to achieve $f_{BS} > 1$ (*i.e.*, bootstrap overdrive), this can be used for I_p ramp-up. In this case requirements for external current drive can be reduced substantially, and elimination of the current drive system may even be possible eventually.

In a previous experiment on JT-60U, a nearly CS-less operation leading to a high beta (β_N = 1.6, β_p = 3.6), high bootstrap fraction ($f_{BS} \geq 90\%$) plasma with high confinement (H_H = 1.6) was demonstrated [2]. However, because of the transient nature of this discharge, only a lower limit could be placed on f_{BS}. More recently, recharging of the OH transformer was observed [3], suggesting the possibility of bootstrap overdrive. Experiments were performed in order to demonstrate that I_p can be maintained entirely by self-driven current, and to study the dynamics of such a highly self-regulating system.

In this paper, three topics will be discussed: (1) response of a self-sustained discharge to perturbations such as a β collapse, (2) achievement of a nearly stationary discharge without β collapses, and (3) possible achievement of bootstrap overdrive. Experimental setup and control algorithms are described in Sec. 2. The dynamic response of bootstrap-sustained discharges to perturbations such as a β collapse are described in Sec. 3. Evidence for possible achievement of bootstrap overdrive is presented in Sec.4. Conclusions are given in Sec. 5.

2. Experimental setup and control algorithms

The poloidal field coil configuration of JT-60U is shown in Fig. 1, together with a typical equilibrium for bootstrap-sustained discharge. In the present experiment, an inward-shifted configuration was used. Locations of the flux loops and poloidal field pick-up coils are also shown. The loop voltage shown subsequently is measured by flux loop 8 located near the midplane on the inboard side.

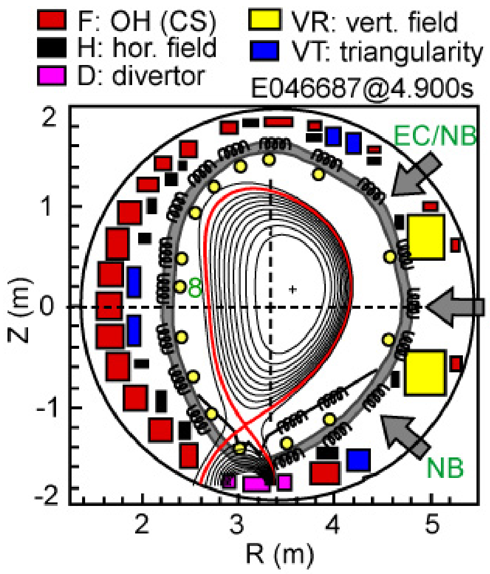

FIG. 1. JT-60U coil configuration and typical equilibria (E046687).

In the bootstrap-driven plasma experiments discussed in this paper, three different algorithms were used: (1) constant I_p control, (2) constant I_F (CS current) control, and (3) constant flux control. The main vertical field coil (VR) was used for radial plasma position feedback. The triangularity control coil (VT) was used either in the constant current mode to ensure no flux change contribution from this coil, or I_p proportional mode to maintain the same triangularity as I_p changes. The horizontal field coil (H) was used for vertical position feedback control, and the divertor coil (D) was used to maintain the X-point and divertor strike points. Co-tangential NBI was used during the start-up phase, but turned off during the sustainment/ramp-up phase. During this time, only perpendicular and counter-tangential NBI were used to ensure that there is no positive contribution of NB-driven current.

The objective of these experiments is to study the behavior of fully bootstrap-driven and bootstrap-overdriven discharges. Since it has already been confirmed by earlier experiments that the bootstrap-dominated plasma does not depend on the details of plasma startup, inductively formed reversed shear plasmas with I_p = 0.5–0.6 MA and B_t = 3.7–4.0 T were used. A typical bootstrap-driven discharge is shown in Fig. 2. After inductive startup using the CS, the CS current is kept

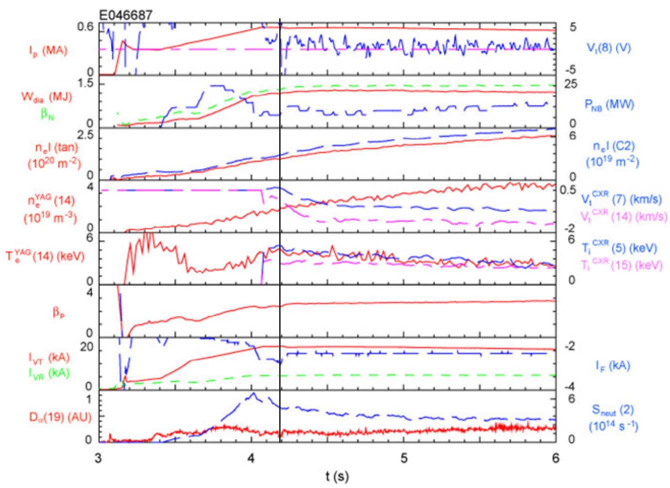

FIG. 2. A typical bootstrap-driven discharge (E046687). Only perpendicular and counter NBI are used after 4.1 s, and the CS current is kept constant after 4.2 s (constant I_F control). A fully bootstrap-sustained condition is realized up to 5.0 s.

at a constant current after 4.2 s (constant I_F control). Co-tangential NBI was used during plasma startup, but was turned off at 4.1 s. Thereafter, I_p ramps up slightly and reaches a steady level at 0.54 MA. The stored energy is maintained at a level of 1.05 MJ by feedback control of the NBI power, corresponding to β_N = 1.15 and β_p = 2.72. The constant stored energy is maintained by increasing density and correspondingly decreasing electron and ion temperatures. In this discharge, no β collapse was observed, but the slow degradation of the energy confinement after 5 s leads to a slow decrease of the stored energy and the plasma current. Both density and temperatures do not reach stationary states for another 1−2 s. This plasma has a large safety factor of q_{95} = 13, and q_{min} = 10 at ρ ≅ 0.8, as shown in Fig. 3. The region inside ρ ≅ 0.4 cannot be determined accurately, but the current density becomes very small and there is likely to be a current hole up to ρ ≅ 0.3. In this discharge the calculated NB driven current is approximately 50 kA in the counter direction.

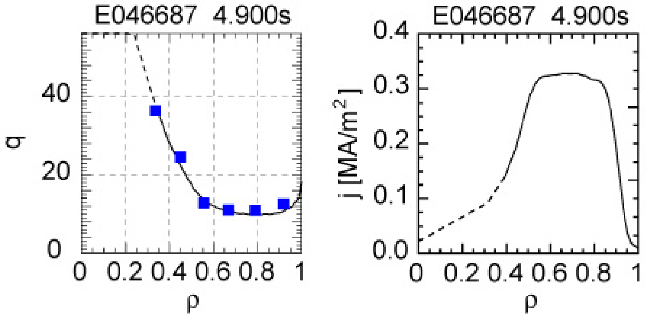

FIG. 3. Safety factor (q) and current density (j) profiles (E046687 at 4.9 s).

3. Dynamic response of bootstrap-sustained plasma

In earlier attempts at a toroidal field of 3.7 T, β collapses were often observed, as shown in Fig. 4. These β collapses are caused by an internal mode. In some cases, the discharge is terminated by a disruption due to the kink-ballooning mode, rather than going through repetitive β collapses. The condition for avoiding disruptive termination of discharge is not known at present. At β collapses, the ITB is eroded and the stored energy decreases. Radial profiles of the ion temperature at selected times in such a discharge are shown in Fig. 5. In this example, at a small β collapse at 5.7 s, the ITB is eroded and the temperature gradient becomes flat in the region 0.6 < r_o < 0.8 m, where r_o is the volume averaged minor radius. At a larger β collapse at 6.6 s, the ITB radius shrinks further to r_o ~ 0.5 m, then recovers partially. By 8.1 s the ITB radius has recovered slightly. Such cycles consisting of a β collapse and partial recovery are repeated at intervals of about 1 s. Since the recovery after a β collapse is not perfect, both the stored energy and I_p decrease gradually as a result of ITB radius shrinkage. In this discharge, I_p decreases from its maximum value of 0.64 MA at 5.7 s to 0.53 MA at t = 9.0 s.

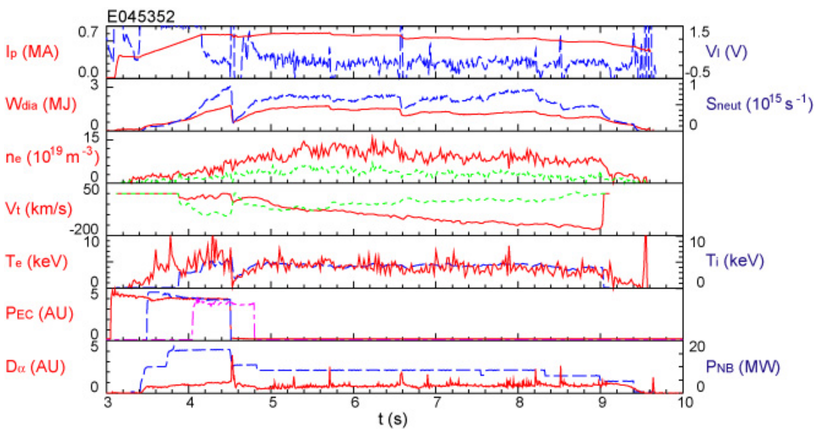

Fig. 4. A discharge with repetitive β collapses and subsequent recovery (E045352). Constant I_F control was used after 4.7 s.

In discharge E045701, similar to E046687 shown in Fig. 2, I_p > 0.55 MA was maintained for 2.5 s. The β collapse was avoided by raising the toroidal field to 4.0 T. A reversed shear plasma with I_p = 0.55 MA was formed inductively. After t = 4.0 s, the neutral beam injection power was reduced to 7 MW, and only perpendicular and counter tangential NBI were used to prevent current drive. The OH coil current was kept constant after t = 4.0 s to prevent generation of inductively driven current (constant I_F control). Since the plasma radial position was feedback controlled by the VR coil (main vertical field coil), plasma heating will result in flux change, and therefore can drive I_p inductively. The VT coil (triangularity control coil) was feedback controlled to vary proportional to I_p to maintain the plasma shape. Under this control algorithm, both VR and VT coils work to amplify the change of I_p. Thus, if I_p decreases, the vertical field is reduced, which contributes to further I_p ramp-down. I_p increased from 0.55 MA at 4.0 s to 0.58 MA at 4.7 s due to build up of plasma stored energy. During this time the loop voltage (measured on the inboard wall near the midplane) is positive. The loop voltage becomes zero at 5.1 s and I_p is maintained at a nearly constant level for 1.3 s. However, because the stored energy is not completely constant, and there is a small variation in I_p. This plasma has β_N = 1.2, β_p = 3.0, a large ITB radius, and a current density profile peaked near the edge with an extremely low internal inductance of l_i=0.34. The neutral beam driven current is calculated to be approximately −50 kA and the inductively driven current is calculated to be nearly zero (±50 kA). The calculated bootstrap current exceeds the total plasma current, but excluding the bootstrap current in the central region, where current hole is believed to be formed, brings it down to the level approximately equal to the total plasma current.

It is possible to maintain a bootstrap-driven discharge by avoiding

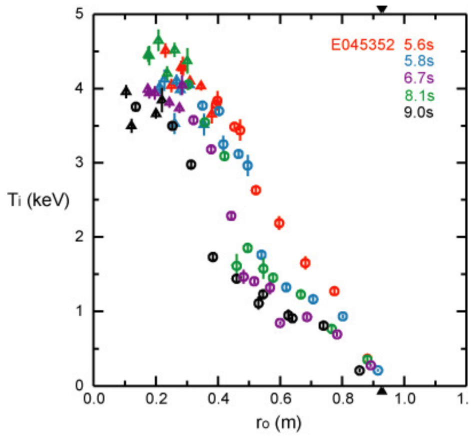

Fig. 5. Evolution of the ion temperature profile in a discharge sustained by self-driven current (E045352). At each beta collapse, the ITB radius shrinks, but then recovers partially.

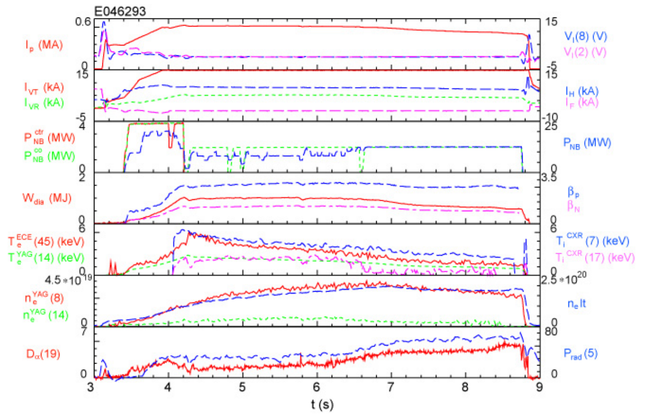

Fig. 6. Bootstrap-driven discharge (E046293). A nearly constant I_p is maintained at 0.52 MA for about 1.5 s. Constant I_F control after 4.0 s.

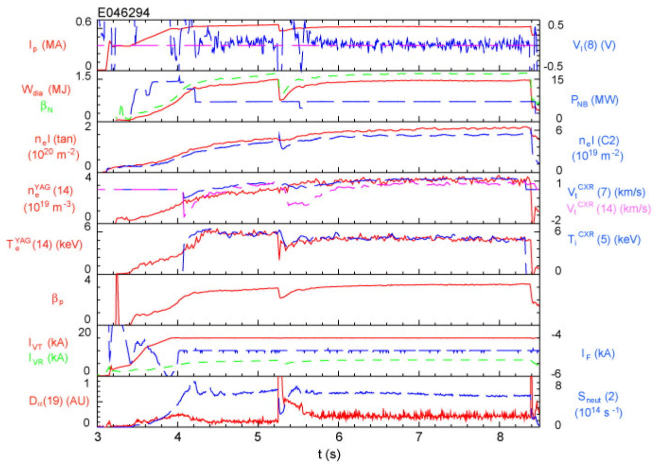

Fig. 7. "Mostly" bootstrap-driven discharge. After a β collapse at 5.2 s, a nearly constant I_p is maintained at 0.52 MA for about 2 s. Constant I_F control after 4.0 s.

β collapses. This can be accomplished by reducing the stored energy and/or raising B_t to prevent reaching the β limit. In the discharge shown in Fig. 6, the CS current was kept constant after 4.0 s, and only perpendicular and counter NBI are used after 4.2 s. A nearly constant I_p is maintained at 0.52 MA for about 2 s.

In order to compare a “completely” bootstrap-driven discharge and a “mostly” bootstrap-driven discharge, a perpendicular NBI was replaced by a co-tangential NBI in a discharge otherwise identical to that shown in Fig. 6. In the “mostly” bootstrap-driven discharge shown in Fig. 7, energy confinement was better and the plasma current was maintained stably for a longer time. The net NB-driven current in the “mostly” bootstrap-driven discharge is calculated to be about 20% of the total current, so the bootstrap fraction was about 80%.

4. Bootstrap overdrive

The discharge shown in Fig. 6 was repeated with constant flux control. The plasma surface flux is determined by real time reconstruction using the Cauchy condition surface (CCS) method [4]. The CS current is adjusted to maintain the plasma surface flux constant. The loop voltage on the plasma surface is given by

$$V_\mathrm{l} = -\, M_{\mathrm{l,CS}}\, \mathrm{d}I_{\mathrm{CS}}/\mathrm{d}t - M_{\mathrm{l,PF}}\, \mathrm{d}I_{\mathrm{PF}}/\mathrm{d}t - M_{\mathrm{l,pl}}\, \mathrm{d}I_\mathrm{p}/\mathrm{d}t = V_\mathrm{l}^{\mathrm{ext}} - L_{\mathrm{ext}}\, \mathrm{d}I_\mathrm{p}/\mathrm{d}t\,, \qquad (1)$$

where $M_{\mathrm{l,CS}}$, $M_{\mathrm{l,PF}}$, and $M_{\mathrm{l,pl}}$ are the mutual inductances between a virtual voltage loop on the plasma surface and the CS, PF coils (mainly VR and VT coils in case of JT-60U), and the plasma, $V_\mathrm{l}^{\mathrm{ext}}$ is the surface loop voltage due to external circuits, and the external inductance L_{ext} is the same as $M_{\mathrm{l,pl}}$. Multiplying this equation by I_p yields the energy balance equation [5]

$$V_\mathrm{l} I_\mathrm{p} = P_{\mathrm{ext}} - \mathrm{d}W_{\mathrm{ext}}/\mathrm{d}t = \mathrm{d}W_{\mathrm{int}}/\mathrm{d}t - \underline{P_{\mathrm{el}} + V^2/R_{\mathrm{Sp}}}\,, \qquad (2)$$

where $V_\mathrm{l} I_\mathrm{p}$ is the Poynting flux across the plasma surface, $P_{\mathrm{ext}} = V_\mathrm{l}^{\mathrm{ext}} I_\mathrm{p}$ is the inductive power input from external circuits, $W_{\mathrm{ext}} = L_{\mathrm{ext}} I_\mathrm{p}^2/2$, $W_{\mathrm{int}} = L_{\mathrm{int}} I_\mathrm{p}^2/2$, and $W = W_{\mathrm{ext}} + W_{\mathrm{int}}$ are external, internal, and total poloidal field energies, P_{el} is the power converted to electromagnetic energy (ramp-up power) and V^2/R_{Sp} is the resistive power dissipation. The last two terms on the right

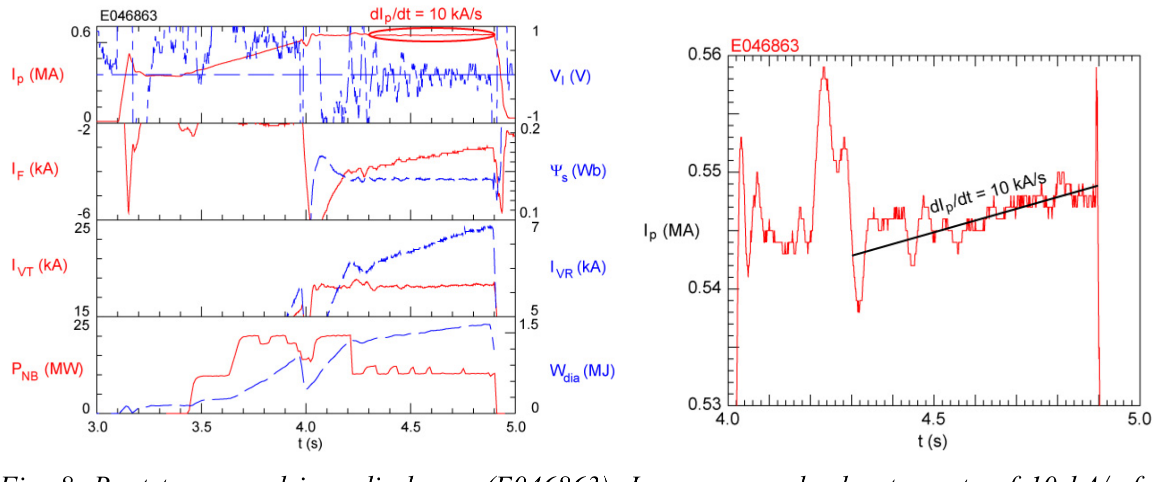

Fig. 8. Bootstrap overdriven discharge (E046863). I_p ramps up slowly at a rate of 10 kA/s for about half a second with constant surface flux (zero surface loop voltage). The frame on the right is a greatly expanded view of the plasma current. Constant flux control after 4.2 s.

hand side of Eq. (2) are, more precisely, $\int \boldsymbol{E}\cdot\boldsymbol{j}\, \mathrm{d}V = VI_{\mathrm{p}} = VI_{\mathrm{NI}} + V^2/R_{\mathrm{Sp}}$, where the noninductive current $I_{\mathrm{NI}} = I_{\mathrm{CD}} + I_{\mathrm{BS}}$ is further divided into the driven current (NB driven current in this case) and the bootstrap current, and V/R_{Sp} is the inductively driven current (R_{Sp} is the "Spitzer" resistivity, corrected for neoclassical effects). The voltage V is effectively the average loop voltage over the plasma cross section.

In the constant flux feedback operation, $V_{\mathrm{l}}I_{\mathrm{p}}$ is kept at zero. When the plasma current ramps up, $P_{\mathrm{ext}} = \mathrm{d}W_{\mathrm{ext}}/\mathrm{d}t > 0$ is supplied by external circuits. Equation (2) can be rewritten to give

$$P_{\mathrm{el}} = \mathrm{d}W/\mathrm{d}t - P_{\mathrm{ext}} + V^2/R_{\mathrm{Sp}} = -\, VI_{\mathrm{NI}}\ . \tag{3}$$

When this quantity is positive, plasma current ramp-up is achieved. In this case the work that noninductive current does against the negative electric field is positive. An example is shown in Fig. 8. The main vertical field coil (VR coil) current increases to hold the plasma radial position constant in response to the slowly increasing stored energy. This normally results in a positive loop voltage, but the CS (F coil) current is recharged to keep the surface flux constant, and zero loop voltage is realized. Therefore, there is no flux input into the plasma from the external circuits. In spite of this fact, I_{p} ramps up slowly at a nearly constant rate of 10 kA/s for about half a second. Since the NB driven current is in the negative direction, this is a strong indication that the plasma is overdriven by the bootstrap current. The increasing I_{p} contributes a negative loop voltage, but this is cancelled by the external circuits to keep zero loop voltage. The ramp-up rate is definitely positive, but is very small because I_{p} is only weakly overdriven.

A clearer indication of bootstrap overdrive can be seen in the discharge with constant I_{p} control, shown in Fig. 9. Co-tangential neutral beam injection was terminated at t = 4.5 s, leaving only perpendicular and counter tangential beams thereafter. Even during this time, the plasma is being overdriven as indicated by the constant I_{p}, negative V_{l}, and the positive time derivative of the CS current I_{F} (CS recharging). The Poynting flux, given by $V_{\mathrm{s}}I_{\mathrm{p}}$, where V_{s} is the plasma surface loop voltage, is clearly negative, indicating that the flow of poloidal field energy is outward across the plasma surface. This indicates that the poloidal flux (and the poloidal field energy) is being generated in the plasma by noninductive current overdrive. As in other cases, the beam-driven current is calculated to be about 50 kA, opposite to I_{p}. Therefore, overdrive must be from the bootstrap current. The total plasma current is kept constant by sucking the generated poloidal field flux into external circuits (mainly the CS). The plasma current would ramp up slowly if the CS current were kept constant. The dashed line for W_{dia} after the β collapse at 5.0 s indicates that it is not calculated correctly during this time because

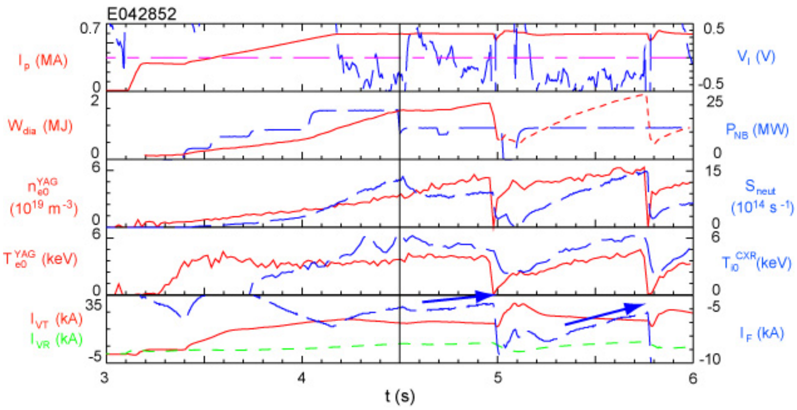

Fig. 9. Bootstrap overdriven discharge (E042852). Constant I_p is maintained while CS is being recharged. A negative loop voltage indicates expulsion of poloidal flux from the plasma. The dashed line for the diamagnetic stored energy W_{dia} after the β collapse at 5.0 s indicates that it is not calculated correctly during this time.

of saturation of integrated magnetic signals. Nevertheless, it is clear that a strong increase of the stored energy occurs during this period as evidenced by rapidly increasing density, temperatures, and neutron rate, which results in a much stronger recharging of the CS compared to the period just before 5.0 s.

5. Conclusions

In this work, sustainment of a nearly constant I_p by self-driven current, without any external co-current drive, was demonstrated. The response of such self-sustained plasmas to perturbations such as a β collapse was studied. A self-recovery of the ITB and I_p was observed after a β collapse. However the recovery is not complete, and both the W_p and I_p degrade slowly. A self-sustained plasma without β collapses was also realized, but a slow degradation of ITB resulted in a slow decline of W_p and I_p. A more sophisticated control of the pressure profile and/or current profile may be necessary to maintain the self-sustained state in steady state.

Indications of bootstrap overdrive were observed as recharging of the CS current in both the constant I_p mode and the constant flux mode. In the constant I_p mode, the surface loop voltage was clearly negative, indicating noninductive creation of poloidal flux inside the plasma and expulsion to the outside. Since only counter-tangential and perpendicular NBI were used, the flux must be created by the increase of bootstrap current driven by the increasing pressure.

In conclusion, good progress was made in realizing and understanding bootstrap-dominated discharges. Extension of these results to higher I_p (lower q), and a more complete characterization of the controllability of such plasmas, including approach to a steady state, remain topics of further research.

Acknowledgments

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