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 injections 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 coil current mode, a negative loop voltage and a slow I_p ramp-up were observed. In the constant plasma surface flux feedback mode, a slow I_p ramp-up was observed with no inductive flux input. These results provide evidence of bootstrap overdrive. The dynamic response of a fully 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, $I_p \geq 0.5$ MA was maintained for over 2 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 central solenoid (CS) is used to start up and ramp up the plasma current (I_p) by induction. However, the presence of CS prevents 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.*, bootstrap current fraction, $f_{BS} = I_{BS}/I_p$). Hence, it is important to study the characteristics and controllability of plasmas with nearly 100% bootstrap current fraction. The development of advanced tokamak scenarios aims at maximizing f_{BS}, without sacrificing high β and high confinement. Furthermore, 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 the requirement for external current drive (CD) can be reduced substantially, and elimination of the CD system may even be possible eventually. This leads us to attempt experimental demonstration that bootstrap overdrive is indeed possible. These results have a fundamental impact on the design of low aspect ratio spherical tokamak (ST) reactors with no CS [2], and slim-CS tokamak reactors with only limited CS capability [3].

In a previous experiment on JT-60U, a nearly CS-less operation leading to a high β ($\beta_N = 1.6$, $\beta_p = 3.6$), high bootstrap fraction ($f_{BS} \geq 90\%$) plasma with high confinement ($H_H = 1.6$) was demonstrated [4]. 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 [5], 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. A more convincing demonstration of bootstrap overdrive was attempted using the newly implemented constant surface voltage feedback control to exclude the possibility of inductive CD.

In this paper, three topics will be discussed: (1) achievement of a fully bootstrap-driven discharge and a nearly stationary discharge which is nearly fully self-sustained, (2) response of a self-sustained discharge to perturbations such as a β collapse, and (3) achievement of bootstrap overdrive. Experimental setup and control algorithms are described in Sec. 2. Descriptions of a fully bootstrap-driven discharge and the dynamic response of self-sustained discharges to perturbations such as a β collapse are described in Sec. 3. Evidence 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 typical equilibrium flux surfaces of a bootstrap-driven discharge. Locations of the flux loops and poloidal field pick-up coils are also shown. The loop voltage shown in this paper is measured by flux loop 8 located near the midplane on the inboard side. Neutral beam (NB) trajectories projected on a poloidal cross section are also shown. The curved trajectories from the midplane indicate (co- or counter-) tangentially injected beams.

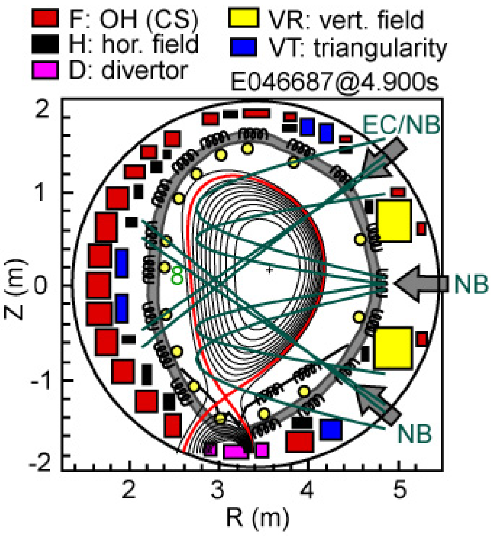

Fig. 1. JT-60U coil configuration and a typical equilibrium (E046687).

In the bootstrap-driven plasma experiments discussed in this paper, three different algorithms were used: (1) constant I_p control, (2) constant I_F (OH coil current, or CS current) control, and (3) constant surface flux control. The main vertical field coil (VR) was used for radial plasma position feedback control. The triangularity control coil (VT) was used either in the constant current mode to ensure no flux input from this coil, or the 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 control the locations of the X-point and divertor strike points. Co-tangential NBI was used during the start-up phase, but was 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.

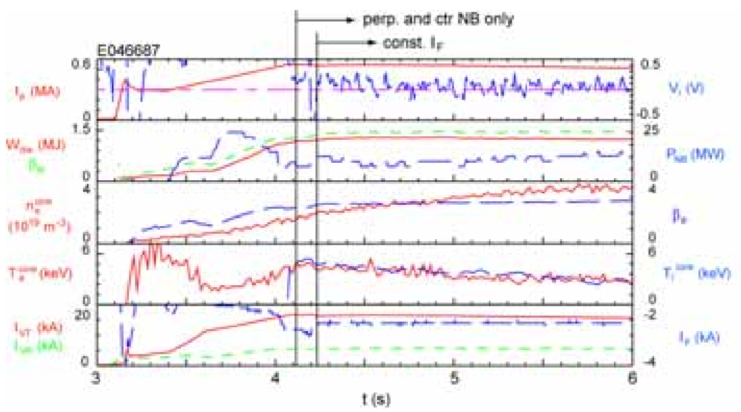

Fig. 2. A typical bootstrap-driven discharge (E046687). Only perpendicular and counter NBI are used after 4.1 s, and the CS current is kept constant after 4.2 s (constant I_F control). A fully bootstrap- sustained condition is realized around 4.6–4.7 s.

The objective of these experiments is to study the behavior of fully bootstrap-driven and overdriven discharges. Since it has already been confirmed by earlier experiments that the bootstrap-dominated plasma does not depend sensitively on the details of plasma start-up, 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 start-up using the CS, the CS current is kept constant after 4.2 s (constant I_F control). Co-tangential NBI was used during plasma start-up, but was turned off at 4.1 s. The stored energy is maintained at a level of 1.05 MJ by feedback control of the NBI power, which corresponds to β_N = 1.15 and β_p = 2.72. The constant W_p is maintained by a slowly increasing density and correspondingly decreasing electron and ion temperatures. Initially, I_p ramps up with the increase of the diamagnetic stored energy W_{dia} (subsequently referred to as the plasma stored energy W_p). During this time there is flux input from the increasing vertical field. It then reaches a steady level at 0.54 MA for a short time. In this discharge, no β collapse was observed, but the slow degradation of energy confinement after 5 s (indicated by the slowly increasing NBI power) lead to a slow decrease of W_p and I_p, as can be seen in the expanded view (Fig. 3). Once W_p starts decreasing, the vertical field ramps down, resulting in a slow decay of I_p over several seconds. In a discharge with lower plasma current (E046293), a constant I_p was maintained at 0.51 MA for 1.3 s mostly noninductively, but there was a small inductive contribution resulting from a slowly increasing W_p.

Profiles of the total current density (obtained by equilibrium reconstruction using MSE data), the inductively driven current density calculated from the loop voltage profile obtained from time evolution of equilibrium [6], and the calculated beam driven current density, are shown in Fig. 4 at a time when the loop voltage profile is nearly zero or slightly negative across the cross section. Such a period is maintained for 0.2 s. At 4.6 s, the calculated beam driven current is –35 kA (in the counter direction), and the inductive current is –5kA. The inferred bootstrap current of 583kA is slightly greater than the total current of 543kA. Although there

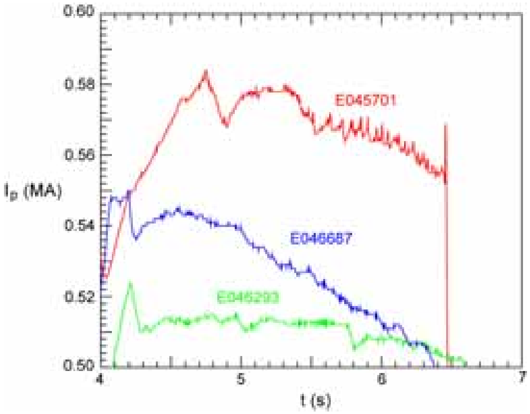

Fig. 3. Examples of bootstrap-driven discharge, all with constant I_p control. In E046687, 100% BS was achieved for 0.2 s at 0.54 MA, while in E046293 a nearly constant I_p was maintained at 0.51 MA for 1.3 s.

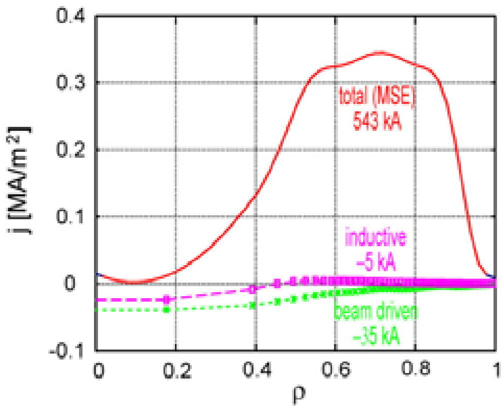

Fig. 4. Profiles of the total current density (measured by MSE), calculated inductively driven current density, and calculated beam driven current density (E046687 at 4.6 s).

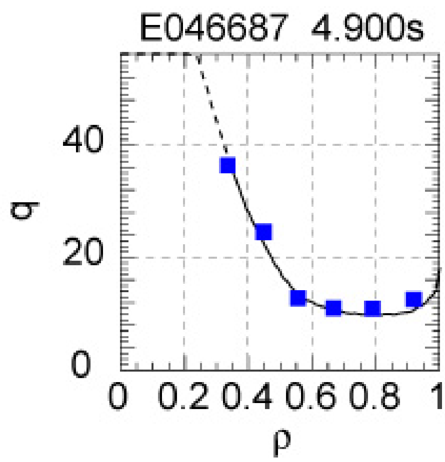

Fig 5. Safety factor (q) profile (E046687 at 4.9 s)

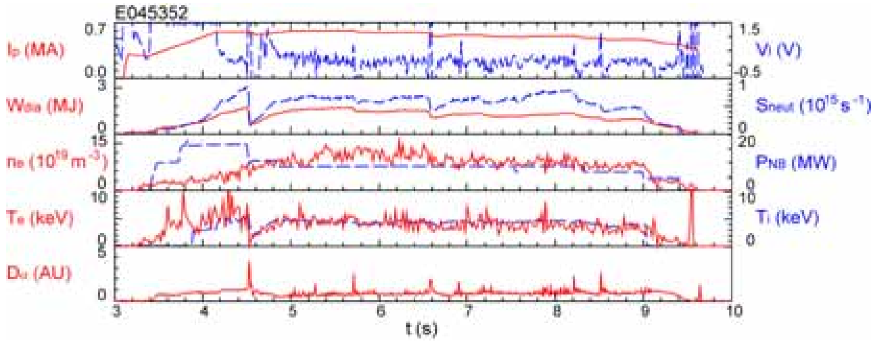

Fig. 6. A discharge with repetitive β collapses and subsequent recovery (E045352). Constant I_F control was used after 4.7 s.

is a rather large uncertainty of nearly 50kA in the determination of the bootstrap current, it is clear that the bootstrap current fraction of approximately 100% (possibly exceeding 100%) was achieved. This plasma has a large safety factor of $q_{95} = 13$, and $q_{min} \cong 10$ at $\rho \cong 0.8$ (Fig. 5). The region inside $\rho \cong 0.4$ cannot be determined accurately, but the current density becomes very small and a current hole is likely to be formed up to $\rho \cong 0.2$–0.3. In this discharge, the region of steep gradient in the ion temperature (T_i) profile extends over a wide range from $\rho \cong 0.6$ to near the plasma boundary, where ρ is the normalized volume averaged minor radius. The shape of the T_i profile does not change greatly during the slowly decaying phase of W_p and I_p, in contrast to the case with repetitive β collapses discussed in the next section. During the current decay phase, the bootstrap current is no longer sufficient to maintain a constant I_p. Both density and temperatures do not reach stationary states for another 1−2 s.

3. Dynamic response of self-sustained plasma

In the examples described in the previous section, a slow degradation of confinement resulted in a reduction of I_p that could be self-sustained. When β is higher, β collapses can occur. In earlier attempts at a toroidal field of 3.7 T, β collapses were often observed, as in the example shown in Fig. 6. These β collapses are believed to be caused by the kink-ballooning mode [7]. In some cases, discharge is terminated in a disruption rather than going through repetitive β collapses. At β collapses, ITB is eroded and W_p decreases. Evolutions of the T_i and q profiles in such a discharge are shown in Fig. 7. In this example, at a small β collapse at 5.7 s which occurred at W_p = 1.3 MJ, ITB is eroded and the temperature gradient becomes flatter in the region $0.6 < \rho < 0.9$. At a larger β collapse at 6.6 s, the ITB radius shrinks farther, then makes a spontaneous recovery. By 8.1 s the ITB radius has recovered slightly, but not to the original radius. Such cycles consisting of β collapse and partial recovery are repeated at intervals of about 1 s. Since the recovery after a β collapse is not perfect, both W_p and I_p decrease gradually as a result of ITB radius shrinkage. The radius of q_{min} also shrinks as ITB shrinks. In this discharge, I_p decreases from its maximum value of 0.61 MA at 5.7 s to 0.50 MA at t = 9.0 s. In this kind of discharge, the plasma current is determined by the bootstrap current, not by external sources such as NBCD or induction by the OH coil.

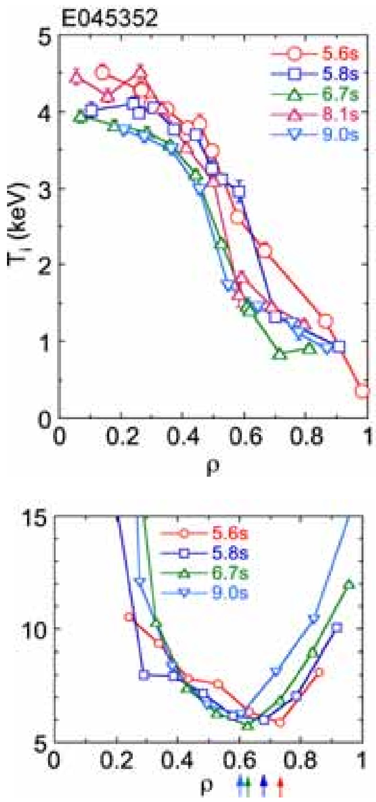

Fig. 7. Evolutions of the T_i profile and the q profile in a discharge sustained by self-driven current (E045352). At each β collapse, ITB radius shrinks, then recovers partially.

In discharge E045701, I_p > 0.55 MA was maintained for over 2 s (Fig. 3). The β collapse was avoided by reducing W_p to 1.2 MJ and raising the toroidal field to 4.0 T to avoid reaching the β limit. After forming a reversed shear plasma with I_p = 0.55 MA inductively, NBI power was reduced to 7 MW at t = 4.0 s, and only perpendicular and counter-tangential NBI were used to prevent positive contribution from NBCD. The OH coil current was kept constant after t = 4.0 s (constant I_F control). The plasma radial position was feedback controlled by the VR coil, and the VT coil was varied proportional to I_p to maintain the same plasma shape. Under this control algorithm, both VR and VT coils work to amplify the change in I_p. Thus, if I_p decreased, the vertical field is reduced, which contributes to further ramp-down of I_p. After 4.0 s, I_p increased and reached 0.58 MA at 4.7 s due to build up of W_p. During this time the loop voltage is positive. At 4.7 s NBI power is reduced to prevent W_p from exceeding the target value of 1.2 MJ. The loop voltage becomes nearly zero at 5.1 s (but still slightly positive because of the slowly increasing W_p) and I_p is maintained at a constant level for 0.3 s. NBI power drops again at 5.4 s, and after that W_p is not able to recover completely, and results in a slowly decreasing I_p. Similarly to E045352, this plasma has β_N = 1.2, β_p = 3.0, a large ITB radius, and a current density profile peaked near the edge. 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.

In order to lengthen the duration of the stationary sustained state, two units of perpendicular NBI were replaced by one unit of co-tangential NBI (Fig. 8). The robustness of steady sustainment was improved greatly by the addition of only a small fraction of co-NBCD. The net NB-driven current is calculated to be +40kA. Since the inductively driven current is nearly zero at t = 7 s, the bootstrap current must be carrying the remaining 480 kA (f_{BS} ~ 0.9). In contrast to the slowly degrading energy confinement observed in the fully BS-driven discharge, energy confinement was maintained at a high level (1.2 MJ was maintained with 5.9 MW, instead of 1.0 MJ with 8.1 MW for E046293), and a nearly constant plasma current of 517−520kA was sustained for over 2s.

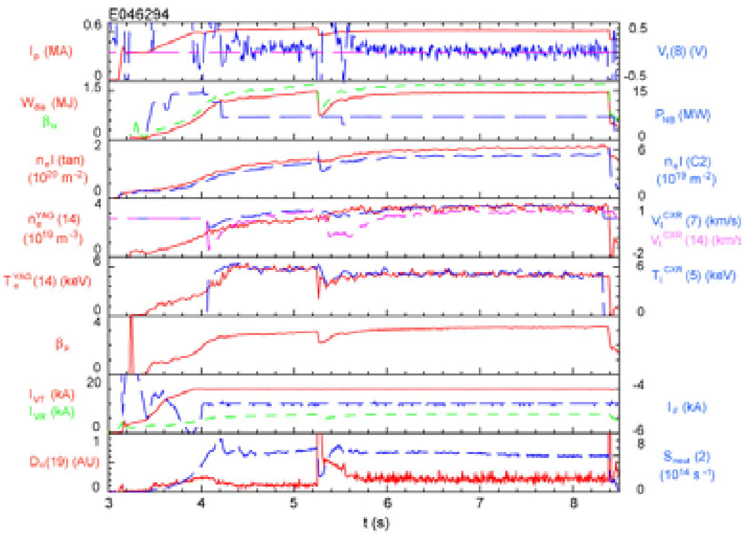

Fig. 8. Mostly bootstrap-driven discharge with co-NBI. After a β collapse at 5.2 s, a nearly constant I_p is maintained at 0.52 MA for about 2 s. Constant I_F control after 4.0 s.

4. Bootstrap overdrive

In order to evaluate I_p ramp-up or CS recharging by bootstrap overdrive, energy balance for the poloidal manetic field energy is considred. The loop voltage induced on a virtual flux loop located on the plasma surface is given by

$$V_l = -\, M_{l,OH}\, dI_{OH}/dt - \sum M_{l,PF}\, dI_{PF}/dt - M_{l,pl}\, dI_p/dt = V_l^{ext} - L_{ext}\, dI_p/dt\,, \qquad (1)$$

where $M_{l,OH}$, $M_{l,PF}$, and $M_{l,pl}$ are the mutual inductances between the virtual flux loop and the OH coil, the PF coils (mainly VR and VT coils in case of JT-60U), and the plasma, V_l^{ext} is the surface loop voltage due to external circuits, and the external inductance L_{ext} is the same as $M_{l,pl}$. It is assumed here that the effect of time variation of L_{ext} can be ignored. In the usual constant I_p mode, the dI_p/dt term is zero. In the constant OH coil current mode, the dI_{OH}/dt term is zero. In both cases, noninductive overdrive produces a negative surface voltage. In the constant I_p mode OH coil recharging should be observed, whereas in the constant OH coil current mode, I_p ramp-up should be observed. In the constant surface flux mode, V_l is zero, ensuring that no net flux crosses the plasma surface. In this case, I_p rampup becomes a direct indication of noninductive overdrive. Multiplying the expression for V_l by I_p yields the energy balance equation [8, 9]

$$V_l I_p = P_{ext} - dW_{ext}/dt = dW_{int}/dt - P_{el} + V^2/R_{Sp} \, , \tag{2}$$

where $V_l I_p$ is the Poynting flux across the plasma surface, $P_{ext} = V_l^{ext} I_p$ is the inductive power input from external circuits, $W_{ext} = L_{ext} I_p^2/2$, $W_{int} = L_{int} I_p^2/2$, and $W = W_{ext} + W_{int}$ are the 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 hand side of Eq. (2) are, more precisely, $\int \boldsymbol{E} \cdot \boldsymbol{j} \, dV = VI_p = VI_{NI} + V^2/R_{Sp}$, where the noninductive current $I_{NI} = I_{CD} + I_{BS}$ 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 surface flux feedback operation, $V_l I_p$ is kept at zero. When I_p ramps up, $P_{ext} = dW_{ext}/dt > 0$ is supplied by external circuits. Equation (2) can be rewritten to give

$$P_{el} = dW/dt - P_{ext} + V^2/R_{Sp} = - VI_{NI} \, . \tag{3}$$

Noninductive overdrive means that the noninductive current exceeds the total I_p. In this case a reverse electric field is generated inside the plasma. The work that the noninductive current does against the reverse electric field, P_{el}, becomes a source of poloidal field energy, and I_p ramp-up is achieved.

An indication of bootstrap overdrive can be seen in the discharge with constant I_p control, shown in Fig. 9. Co-tangential NBI 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

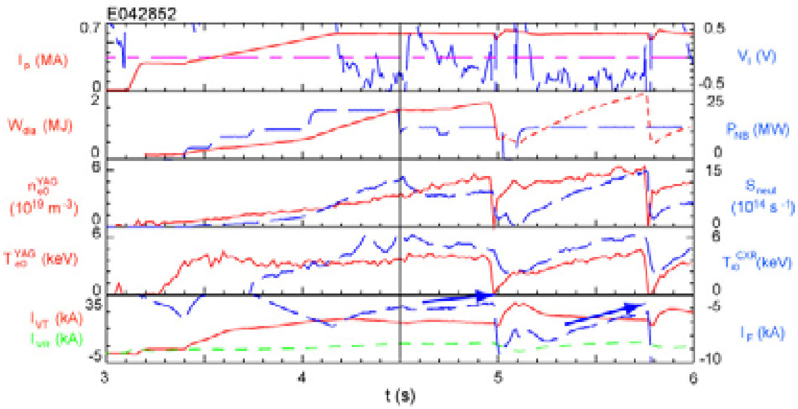

Fig. 9. Bootstrap overdriven discharge (E042852). Constant I_p is maintained while CS is being recharged. A negative loop voltage indicates expulsion of poloidal flux from the plasma. The dashed line for the diamagnetic stored energy W_{dia} after the β collapse at 5.0 s indicates that it is not calculated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

recharging). The Poynting flux, given by $V_s I_p$, 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 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 of saturation of integrated magnetic signals. Nevertheless, it is clear that a strong increase of W_p occurs during this period as evidenced by the rapidly increasing density, temperatures, and neutron rate, resulting in a much stronger recharging of the CS compared to the period just before 5.0 s.

In order to demonstrate bootstrap overdrive more clearly, the constant surface flux control was implemented to rule out the possibility of inductive CD. In this mode, the poloidal flux at the plasma surface is determined by real time equilibrium reconstruction using the Cauchy condition surface (CCS) method [10]. The plasma surface flux is kept at a constant level by feedback control using the OH coil. This method ensures that there is no net flux crossing the plasma boundary, and I_p ramp-up becomes a direct indication of noninductive overdrive. An example is shown in Fig. 10. The main vertical field coil (VR coil) current increases to hold the plasma radial position constant in response to the slowly increasing W_p. This normally results in a positive loop voltage, but the CS (F coil) current is recharged to keep the surface flux constant, and zero surface loop voltage is maintained. Therefore, there is no flux input to the plasma from 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 also cancelled by the external circuits to keep the surface loop voltage at zero.

The ramp-up rate is definitely positive, but is very small because I_p is only weakly overdriven. For comparison, in the LHCD rampup discharge reported in the 2002 IAEA Fusion Energy Conference [4], which was substantially overdriven, the ramp-up rate was about 40kA/s. Considering that the present discharge is only slightly overdriven, the ramp-up rate of 10kA/s is not an unreasonably small value.

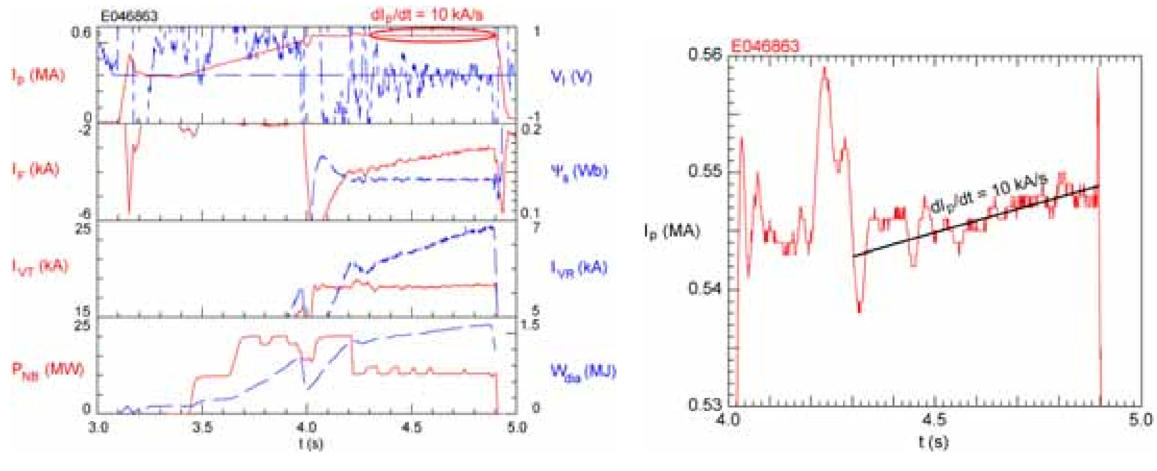

Fig. 10. Bootstrap overdriven discharge (E046863). I_p ramps up slowly at a rate of 10 kA/s for about half a second with constant surface flux (zero surface loop voltage). The frame on the right is a greatly expanded view of the plasma current. Constant surface flux control is used after 4.2 s.

5. Conclusions

A fully bootstrap-driven discharge with a bootstrap fraction of 100% was realized. A loop voltage profile of nearly zero or slightly negative across the cross section was maintained for 0.2 s. In this discharge, of the total current of 543 kA, the calculated beam driven current was −35 kA and the inductive current was −5kA. A slow degradation of energy confinement resulted in a slow decline of W_p and I_p. In other discharges at higher β, repetitive cycles of β collapse and spontaneous self-recovery were observed. Shrinkage of the ITB radius and abrupt decreases of W_p and I_p were observed at each β collapse. Since the recovery is not perfect, both W_p and I_p decreased slowly on average. A more sophisticated control of the pressure profile and/or current profile [11, 12] would be necessary to maintain the self-sustained state in steady state. The addition of a co-NBCD (< 10% of the total I_p) helps steady sustainment of I_p greatly. Indications of bootstrap overdrive were observed as OH transformer recharging in the constant I_p mode, in which 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 have been created by the increase of bootstrap current driven by the increasing pressure. Further evidence of bootstrap overdrive was observed using the newly implemented constant surface flux feedback control, which ensures no net flux input to the plasma. A steady I_p rampup at a rate of 10kA/s was achieved for 0.5s.

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. Since ST reactors can operate at high q of around 10, bootstrap-dominated operation assisted by a small amount of external current drive may be utilized by developing appropriate control methods.

Acknowledgments

This work was carried out as a joint work under the Facility Utilization Program of JAEA, and was partially supported by Japan Society for the Promotion of Science under Grant-in-Aid for Scientific Research No. 16106013.

References

[1] NISHIO, S., *et al.*, in Fusion Energy 2002 (Proc. 19th Int. Conf., Lyon, France, 2002) (Vienna: IAEA) CD-ROM file FT/P1-21 and http://www.iaea.org/programmes/ripc/physics/fec2002/html/fec2002.htm.
[2] STAMBAUGH, R.D., *et al.*, Fusion Technology **33** (1998) 1.
[3] TOBITA, K., *et al.*, this conference FT/P5-22.
[4] SHIRAIWA, S., *et al.*, Phys. Rev. Lett. **92** (2004) 035001.
[5] USHIGOME, M., *et al.*, Nucl. Fusion **46** (2006) 207.
[6] FOREST, C.B., *et al.*, Phys. Rev. Lett. **73** (1994) 2444.
[7] TAKEI, N., *et al.*, "Intermittent beta collapse after NBCD turn-off in JT-60U fully non-inductive reversed shear discharges," submitted to Plasma Phys. Control. Fusion (2006).
[8] FISCH, N.J., KARNEY, C.F.F., Phys. Rev. Lett. **54** (1985) 897.
[9] TAKASE, Y., KNOWLTON, S., PORKOLAB, M., Phys. Fluids **30** (1987) 1169.
[10] KURIHARA, K., *et al.*, Fusion Eng. Des. **51-52** (2000) 1049.
[11] SAKAMOTO, Y., *et al.*, this conference EX/P1-10.
[12] SUZUKI, T., *et al.*, this conference EX/6-4.