Development of a Completely CS-less Tokamak Operation in JT-60U

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Abstract. A completely CS-less I_p start-up to 100 kA was achieved by outer PF coils only. A field null is not necessary for I_p start-up, but the flux conversion efficiency is low in such a case. Optimization studies indicate that CS-less I_p start-up favors low neutral pressures, over 1 MW of EC power is needed in JT-60U for efficient utilization of flux swing, and the optimum location of the EC resonance is slightly to the high field side. I_p = 260 kA was maintained for 1 sec by NB only. The observed outward plasma shift indicates overdrive and I_p ramp-up should be possible, but the ramp-up efficiency is much lower than LHCD. Recharging of the CS was observed with only counter and perpendicular NB injection, indicating bootstrap overdrive. Based on these results, the following CS-less operation sequence seems promising: (1) formation of initial current (0.1 MA level) by outer PF coil swing and strong RF ionization (> 1 MW). (2) Subsequent ramp-up (to 0.5 MA level) by LHCD overdrive. (3) Further ramp-up (to > 1 MA) by NB heating (and/or self-heating by fusion) and B_v ramp-up. Bootstrap overdrive may contribute under certain conditions.

1. Introduction

In conventional tokamak operation, an Ohmic heating (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 center solenoid (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], but experimental demonstration of CS-less tokamak operation is required to justify such a design. 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

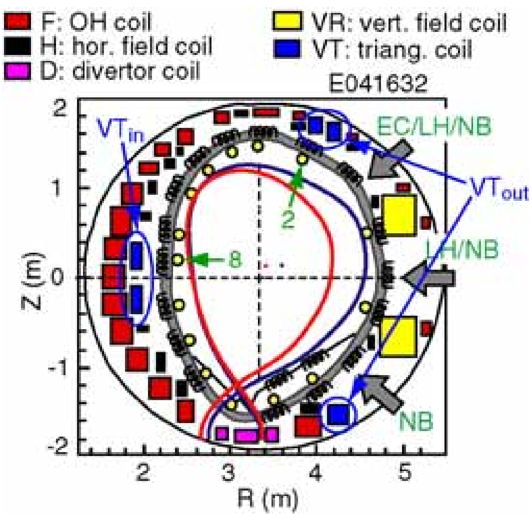

FIG. 1. JT-60U coil configuration and typical equilibria. The OH "center solenoid" (F coil) was not used in CS-less start-up experiments. The VT$_{in}$ coil was disconnected, and not used for completely CS-less start-up experiments.

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, and elimination of the current drive system may even be possible eventually.

In a previous experiment on JT-60U reported at the 2002 IAEA Conference, 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, this operation was not completely CS-free, since the triangularity control coil (VT coil) used for shaping had small but finite turns on the inboard side of the torus (labeled VT_{in} in Fig. 1), and contributed about 20% of the poloidal flux. In addition, because of the transient nature of this discharge, only a lower limit could be placed on f_{BS}.

In this paper, recent advances in the development of CS-less plasma current ramp-up scenarios and achievement of the bootstrap overdrive condition are reported. Conditions necessary for CS-less I_p start-up were investigated more systematically, and will be described in Sec. 2. Demonstration of a completely CS-less plasma current start-up to 100 kA will be discussed in Sec. 3. Evidence of achievement of the bootstrap-overdriven condition will be presented in Sec.4. Conclusions are given in Sec. 5.

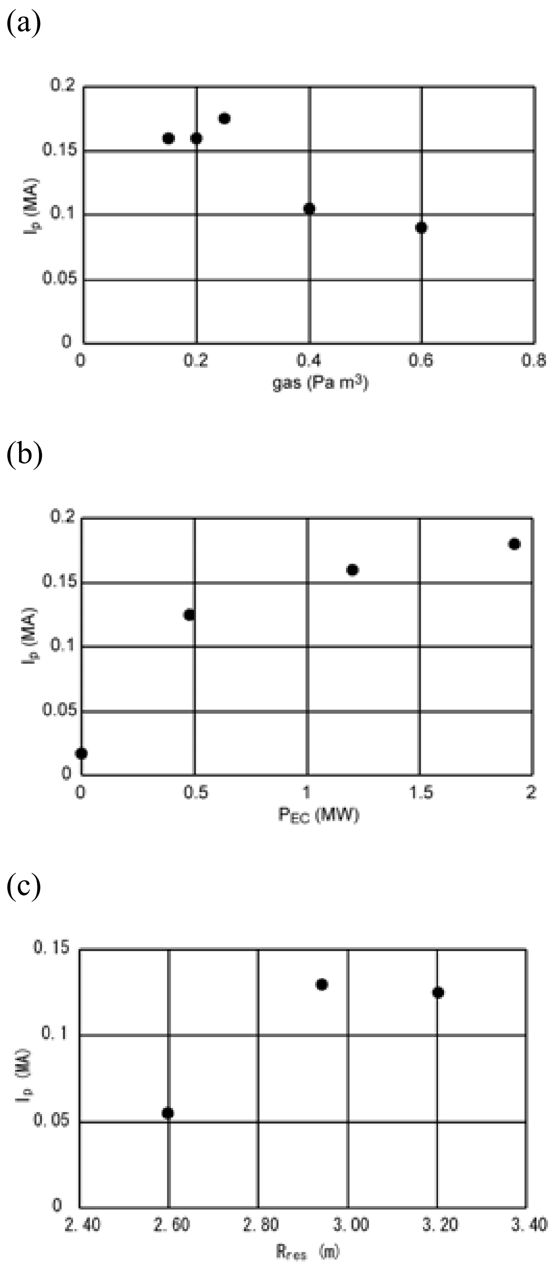

Fig. 2. (a) Dependence of I_p^{max} on prefill gas throughput. P_{EC} = 1.2 MW at B_t = 3.7 T. (b) Dependence of I_p^{max} on EC power P_{EC}. B_t = 3.7 T, gas throughput = 0.2 Pa m^3. (c) Dependence of I_p^{max} on the EC resonance position R_{res}. P_{EC} = 0.5-0.7 MW, gas throughput = 0.2 Pa m^3. Corresponding toroidal fields were 3.0, 3.4, and 3.7 T. The nominal center of the vacuum vessel is at R = 3.4 m whereas the inner wall is at R = 2.35 m.

2. Conditions for CS-less plasma current start-up

The poloidal field coil configuration of JT-60U is shown in Fig. 1, together with typical equilibria: a large bore lower hybrid current drive (LHCD) configuration (blue) and an inward-shifted neutral beam (NB) configuration (red). Locations of the flux loops and poloidal field pick-up coils are also shown. In the CS-less start-up experiments discussed in this section, the CS (F coil) current was kept constant at zero throughout the entire discharge. The main vertical field coil (VR) and the triangularity control coil

(VT) were used for I_p ramp-up, and for radial position and shaping control, while the horizontal field coil (H) was used for vertical position control. The divertor coil (D) was not used. Discharges discussed in this section used the VT_{in} coil, and therefore were not completely CS-free. Completely CS-less discharges are discussed in Sec. 3.

Controlled surveys were performed in order to determine the optimum condition for CS-less start-up. A typical plasma current waveform is shown in Fig. 3 (shot 42949). Plasma was initiated by preionization using the electron cyclotron (EC) wave at 110 GHz, and by ramping of the VT and VR coil currents from –7.5 kA to +6.8 kA and 0 to +1.1 kA, respectively (positive coil current is defined in the direction that produces vertical field B_v required for equilibrium). LH power was not used in this experiment. The plasma current ramps up to 0.18 MA and is held roughly constant for approximately 0.1 s.

The dependence of the maximum plasma current I_p^{max} on the total amount of neutral gas injected as prefill is shown in Fig. 2(a). It can be seen that CS-less I_p start-up favors lower neutral densities than normal start-up with the CS. As the gas throughput is increased, I_p^{max} decreases.

The dependence of I_p^{max} on the EC power P_{EC} is shown in Fig. 2(b). The achievable current does not increase linearly with the EC power (P_{EC}), but saturates for powers above about 1 MW. Above this power, I_p^{max} is determined by inductive flux input from coil ramps, not by P_{EC}. In JT-60U, 1 MW is sufficient to provide enough plasma source for I_p ramp-up. Although the achievable current decreases rapidly at lower powers, I_p start-up to 20 kA was achieved even with P_{EC} = 0.

The dependence of I_p^{max} on the EC resonance position is shown in Fig. 2(c). Although I_p^{max} is similar for the higher field cases (3.4 T and 3.7 T) the plasma cross section was largest at 3.4 T. I_p^{max} was substantially lower at B_t = 3.0 T, when the EC resonance was located at R = 2.6 m, close to the inner wall of the vacuum vessel which is located at R = 2.35 m.

3. Completely CS-less plasma current start-up

In order to demonstrate the feasibility of a completely CS-less plasma current start-up, the inner turns of the VT coil (VT_{in} in Fig. 1) were disconnected, and only the VT_{out} pair was used. Otherwise, the operational scenario was the same as that described in Sec. 2.

A successful start-up to a level of 100 kA was achieved by induction from outboard coils only (VR and VT_{out}), with the assistance of EC preionization. Examples of such discharges (43665 and 43669) are shown in Fig. 3. For comparison, 42949 was obtained using VR, VT_{out} and VT_{in}, whereas 42959 used VR only. 41710 used LHCD in addition to EC to achieve further ramp-up of

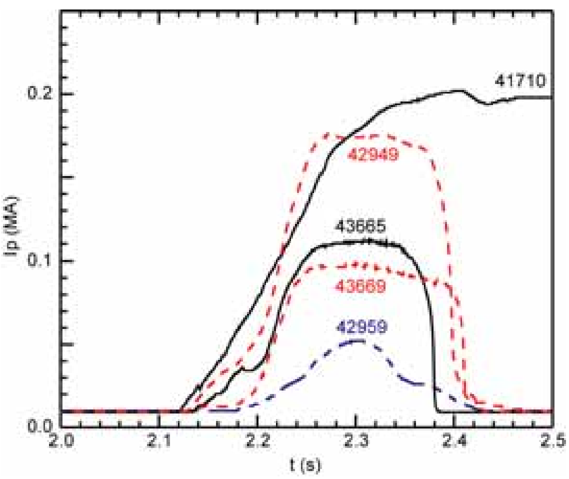

FIG. 3. Completely CS-free I_p start-up. 42959: VR only; 43665 and 43669: VR and VT_{out} only. In comparison, 42949 used VR, VT_{out} and VT_{in}. All discharges had EC preionization. 41710 used LHCD in addition for further I_p ramp-up. Clipping of I_p at 0.01 MA is artificial.

the plasma current. The total flux swing provided by the VR and VT coils (evaluated at a major radius of 3.4m) was 1.93 Wb for 41710 and 42949, 1.55 Wb for 42959, and 1.26 Wb for 43665 and 43669.

Plasma current start-up without a field null was clearly demonstrated, as shown in Fig. 4. This requires strong ionization. In JT-60U, 1 MW of EC power is sufficient. Initially, the vertical field is in the direction opposite to that required for equilibrium, $B_v = -0.08$ T. I_p starts ramping up immediately after VR and VT coils start ramping. However, the flux conversion efficiency is low for this case. A flux swing of 3.1 Wb produces only 85 kA, whereas normally 1.3 Wb is sufficient to make $I_p = 100$ kA.

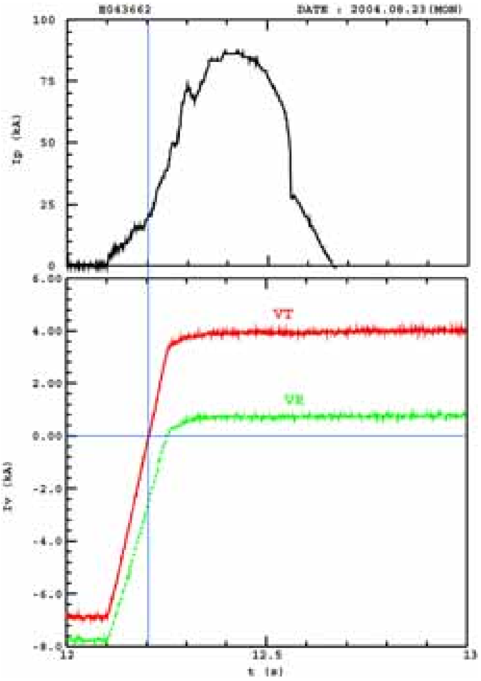

FIG. 4. Completely CS-free I_p start-up without a field null. I_p starts up while B_v is still in the opposite direction to that required for equilibrium.

4. Ramp-up by NB from low I_p

In the experiment reported in Ref. [2], LHCD was used to ramp up the plasma current from an initial level of 200 kA, and further ramp-up from 400 kA was accomplished by NB injection and B_v ramp-up. However, since it is desirable to reduce the number of heating / current drive systems in a reactor, an attempt was made to ramp up the plasma current from a low level of 200-300 kA by NB alone. Plasma was initiated using the CS and a diverted configuration was formed. The currents in the F coil (CS), VT coil and VR coil were all maintained at a constant level after 3.7 s, so there was no flux input from any of these coils. In the example shown in Fig. 5, the EC power was terminated at 5.1 s, and I_p was maintained at a constant level of 260 kA by NB power alone from 5.1 to 6.1 s. The NB injection power consisted of 3.8 MW of co tangential injection, 0.7 MW of counter tangential injection, 4.2 MW of perpendicular injection, and 2.9 MW of negative ion based co tangential injection. Because there was no position feedback, the plasma horizontal position (indicated by DR in Fig. 5) shifted outwards. This is an indication of overdrive, and I_p ramp-up is expected if the horizontal position is feedback controlled. The plasma is in ELMy H-mode with broad density and temperature profiles with $n_e(\rho=0.3) = 1.3\times10^{19}$ m^{-3}, $T_e(\rho=0.3) = 1.3$ keV and $T_i(\rho=0.3) = 1.3$ keV. In this example, the discharge collapsed at $\beta_N = 2$ ($\beta_p = 4$).

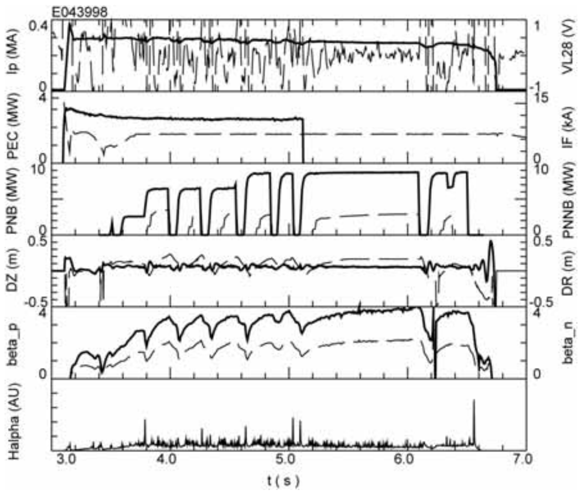

Fig. 5. Plasma current sustainment by NB only. The currents in the F coil (CS), VT coil and VR coil are all constant after 3.7 s. EC power is switched off at 5.1 s. I_p is sustained at a constant level of 260 kA for 1 s by NB only. Left y-axis for solid traces.

5. Bootstrap overdrive

In the experiment reported in Ref. [2] only a lower limit of $f_{BS} \geq 90\%$ could be placed on the bootstrap current fraction, because of the transient nature of the discharge. Discharges with slower time evolutions and less neutral beam driven current were produced in order to evaluate the bootstrap current fraction more accurately. An example is shown in Fig. 6. Plasma was initiated at t = 3.1 s and the plasma current was ramped up to 600 kA by induction using the CS. ECH power (P_{EC} = 0.7 MW, perpendicular injection) was applied from t = 3.25 s to the end of the discharge. Neutral beam heating (balanced tangential injection and perpendicular injection) was applied from t = 3.4 s. In several shots $\beta_p \cong 4$ was achieved, and in discharges with B_T = 3.7 T $\beta_N \cong 2.5$ was obtained. These values are substantially higher than discharges reported in Ref. [2]. The negative loop voltage and the positive slope of the F coil (OH coil, see Fig. 1) current during the later part of the discharge indicate clearly that this plasma is overdriven non-inductively. A preliminary analysis indicates that the bootstrap fraction of greater than 100% was realized. Even when the contribution of the beam pressure is neglected, the calculated bootstrap fraction was 105%, consistent with the experimentally observed negative loop voltage and CS recharging. However, the current density profile has not reached a steady state yet, and there is a positive inductively driven current near the center of the plasma.

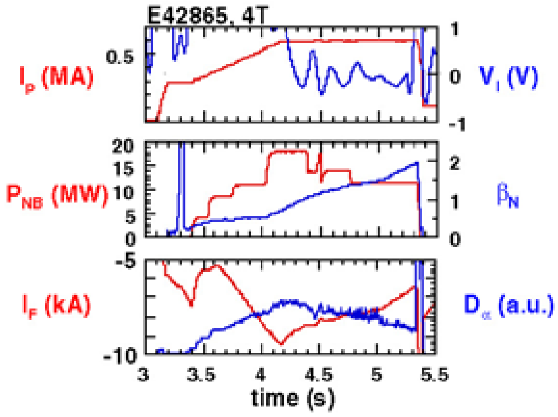

Fig. 6. Non-inductively overdriven discharge. The CS current is being recharged and the loop voltage is negative. The stored energy keeps increasing despite the reduced NB power.

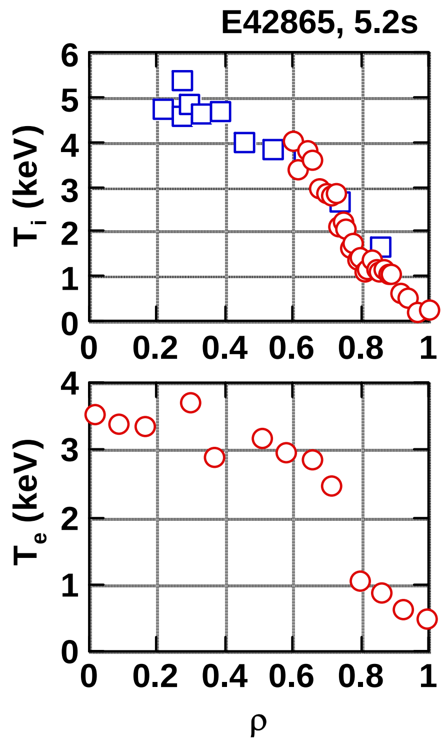

Fig. 7. Ion and electron temperature profiles during bootstrap overdrive. Formation of an internal transport barrier with a large radius (ρ = 0.8) is visible on temperature profiles.

After reaching a flat-top current level of 600 kA, the stored energy keeps increasing in spite of the fact that the neutral beam power is decreasing progressively. The time derivative of the stored energy increases around t = 5 s, when ELM activity ceases. The ion and electron temperature profiles measured at t = 5.2 s indicate that a very wide ITB with a normalized foot radius of ρ_{foot} = 0.8 is formed, as shown in Fig. 7. This ITB radius is larger than that reported in Ref. [2] which had the ITB foot at ρ_{foot} = 0.7. Such a large ITB radius may be contributing to maximizing I_{BS}. The broader pressure profile may also be responsible for the higher β_N obtained in these discharges.

A clearer indication of bootstrap overdrive can be seen in the discharge shown in Fig. 8. Co-tangential neutral beam injection was terminated at t = 4.5 s, leaving only perpendicular and counter tangential beams thereafter. The beam-driven current should be in the counter direction (opposite to I_p). Even during this time, plasma is being overdriven as indicated by the constant I_p and the positive time derivative of the F coil current. It is expected that the plasma current would ramp up if the F coil current were kept constant.

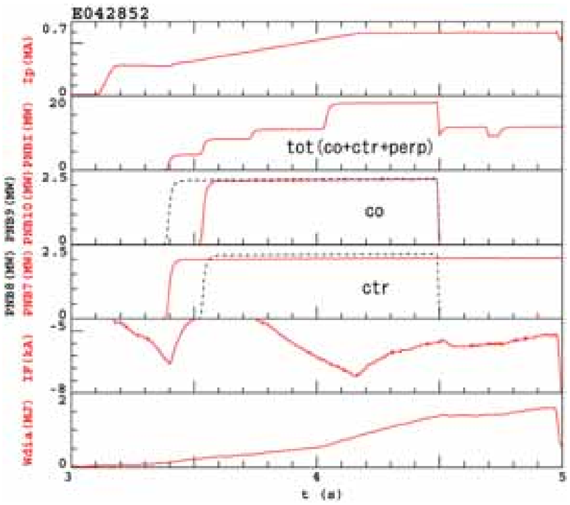

Fig. 8. Bootstrap overdriven discharge. Constant I_p is maintained while F coil is being recharged with only perpendicular and counter tangential beam injection after t = 4.5 s.

5. Conclusions

Controlled surveys indicate that CS-less start-up favors lower neutral densities than normal start-up with the CS, and the EC fundamental resonance to be placed on the high-field side of the plasma center, but not too close to the inner wall. The EC power necessary for full utilization of inductive flux is about 1 MW in JT-60U.

A completely CS-less start-up to a plasma current of 100 kA was achieved with the outboard coils only (VR and VT_{out} coils) alone. It was demonstrated that I_p start-up without a field null is possible if there is a strong source of ionization (1 MW of EC power in JT-60U).

An indication of bootstrap overdrive was obtained by predominantly perpendicular neutral beam (NB) heating. The negative loop voltage and the positive slope of the F coil current during the later part of the discharge indicate clearly that the plasma is overdriven non-inductively. β_p of up to 4 and β_N of up to 2.5 have been achieved in such plasmas, with a very large normalized ITB radius of ρ_{foot} = 0.8. A more convincing evidence of bootstrap overdrive was observed when only counter-tangential and perpendicular beams were injected, in which case the beam driven current should be in the counter direction.

These results offer encouragement to CS-less operation of a tokamak fusion reactor, which has a large impact on the economic competitiveness of a reactor. A large reduction in the recirculating power could be realized by utilizing high-bootstrap operation and bootstrap overdrive.

Acknowledgments

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