Rapid Communications

Plasma Current Start-up, Ramp-up, and Achievement of Advanced Tokamak Plasmas without the Use of Ohmic Heating Solenoid in JT-60U

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Formation of a high performance plasma with $\beta_p = 3.6$, $\beta_N = 1.6$, $H_{H98y2} = 1.6$ without the use of the Ohmic heating solenoid was demonstrated for the first time. Plasma start-up and plasma current ramp-up were accomplished by vertical field and shaping coils, combined with heating and current drive by EC, LH and NBI. The q profile is deeply reversed with $q_{min} = 5.6$ at $r/a = 0.7$, and the bootstrap current fraction was at least 90%. This result opens up the possibility of eliminating the Ohmic heating solenoid, which has a great impact on improving tokamak and ST reactor designs.

Keywords: start-up, current ramp-up, current drive, bootstrap current, advanced tokamak

In conventional tokamak operation, Ohmic heating (OH) solenoid is used to ramp up the plasma current (I_p) inductively. If I_p ramp-up and sustainment could be accomplished without the use of the OH solenoid, substantial improvement can be achieved in the economic competitiveness of a fusion reactor by a more compact design with higher magnetic field [1,2]. In particular, elimination of the OH solenoid is a necessity for a low aspect ratio spherical tokamak (ST) reactor [3].

Plasma start-up and I_p ramp-up by electron cyclotron (EC) and lower hybrid (LH) waves and the vertical field (B_v) coil alone (RF tokamak) were first achieved on the WT-2 tokamak [4]. Several experiments have confirmed such a start-up scenario and its variations, and recently a quasi-steady-state plasma was maintained for 30 seconds on the TRIAM-1M tokamak [5]. However, these plasmas have low plasma current and low plasma density. It has been suggested that plasma heating and B_v ramp-up can provide efficient means of I_p ramp-up, especially in ST plasmas [6,7]. The first demonstration of plasma start-up, I_p ramp-up, and subsequent transition to a high-performance advanced tokamak plasma without the use of the OH solenoid is reported in this paper.

The experiment was carried out on the JT-60U tokamak. The poloidal field coil configuration is shown in Fig. 1, together with a large bore plasma (black) required during the LHCD (2 GHz) I_p ramp-up phase to maintain acceptable LH coupling, and an inward shifted small bore plasma (grey) used during the neutral beam (NB) heated high performance phase to reduce the

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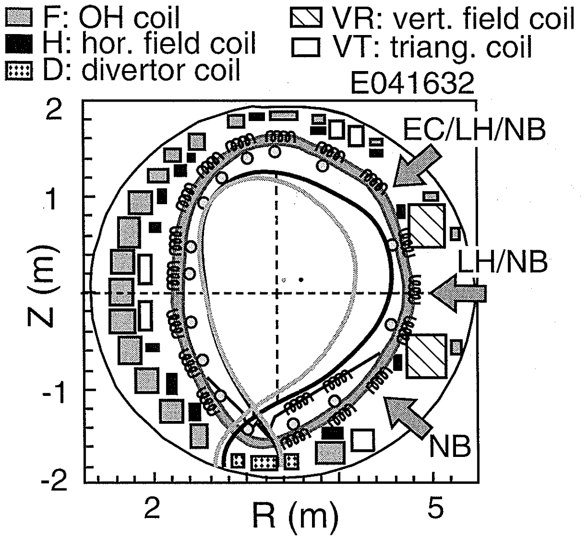

Fig. 1 JT-60U coil configuration and plasma equilibria for the LHCD phase (black) and the NB heating phase (grey). The OH coil (F coil) was not used in this experiment.

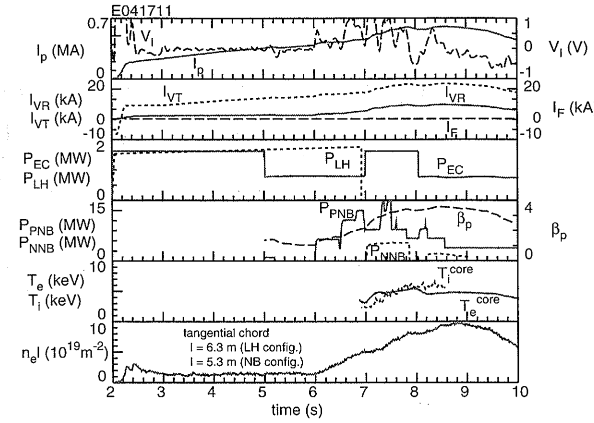

Fig. 2 High-performance plasma created without the use of the OH solenoid.

ripple loss and increase the density limit. In these experiments the current in the F-coil, which corresponds to the OH solenoid, was kept constant at zero (Fig. 2). The vertical field coil (VR) and the triangularity coil (VT) were used for I_p ramp-up, position control, and shaping control.

In the example shown in Fig. 2 ($B_T R$ = 13.45 Tm), a plasma with I_p = 0.2 MA was formed by a combination of EC (110 GHz) preionization and induction by VR and VT coils. The VR coil current was ramped from 0 to +1.1 kA (positive current is defined as the direction that produces B_v required for equilibrium) and the VT coil current was ramped from −7.5 kA to +6.8 kA from t = 2.1 to 2.25 s. Such an operation is necessary because if both coils were ramped from zero, the resultant B_v becomes too high to hold the plasma in equilibrium. These current ramps provided a loop voltage of 6 V. Plasma current started to ramp up at 2.12 s, while the total B_v was still negative. A transition to a diverted configuration is accomplished at 2.5 s, and further ramp-up to 0.4 MA was achieved by 6 s, by a combination of electron heating and current drive by EC and LH waves.

This current of 0.4 MA is high enough to confine the injected beam ions. Density was increased by gas puffing from 5.8 to 7 s to reduce the beam shine-through, and 85 kV NB injection was started from 6 s. The equilibrium was shifted from the LH configuration to the NB configuration from 6.5 to 7 s, and LH was turned off at 6.9 s. Tangential beams were injected first because of their smaller shine-through fraction. Perpendicular beams were injected under stored energy feedback, which resulted in the P_{PNB} waveform shown in Fig. 2. This was necessary to avoid the beta collapse caused by excessive heating. In addition to the noninductive current drive effect, I_p ramps up due to the flux provided by the current increase in VR and VT coils. Addition of the 376.5 kV negative ion based neutral beam (NNB) contributes to further ramp-up by current drive and β_p increase (NNB drop-outs were not intentional). In a similar discharge with higher NB power, a beta collapse terminated the plasma at I_p = 0.7 MA.

The plasma generated by this scenario had an internal transport barrier (ITB) and an edge transport barrier (H mode). The profiles of density and temperatures as well as the q profile at t = 8.5 s (minor radius is 0.915 m at this time) are shown in Figs. 3(a)-(d). The current density in the plasma core is nearly zero (current hole [8]), and the q profile is deeply reversed with q_{min} = 5.6 at r/a = 0.7 and q_{95} = 12.8. At 8.5 s, β_p = 3.6 ($\varepsilon\beta_p$ = 1.0), β_N = 1.6, and H_{H98y2} = 1.6 were achieved. Further optimization is still possible. These profiles and confinement improvement factor are typical of high-confinement reversed magnetic shear (RS) plasmas in JT-60U. A preliminary evaluation of the bootstrap current fraction yielded f_{BS} = 90% as a lower bound, assuming that there are no bootstrap currents inside the ITB. Such high bootstrap fraction and confinement improvement factor are favorable for realizing steady-state operation of a fusion reactor [9].

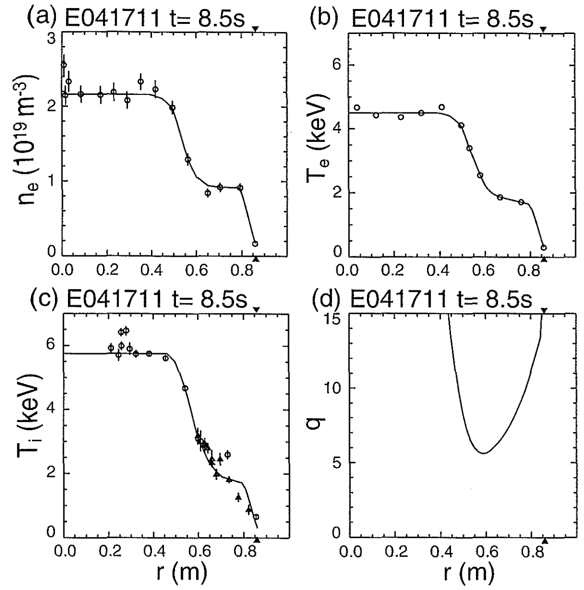

Fig. 3 Profiles of (a) electron density, (b) electron temperature, (c) ion temperature, and (d) safety factor for the discharge shown in Fig. 2 at t = 8.5 s.

In fact, it has already been demonstrated on JT-60U that a high-performance RS plasma with f_{BS} = 80% can be sustained by NBCD at I_p = 0.8 MA [10].

The results presented here give confidence in reducing, and eventually eliminating the Ohmic heating solenoid from a tokamak fusion reactor, which has a great impact on its economic competitiveness.

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