DEVELOPMENT OF LOW INDUCTIVE ELECTRIC FIELD PLASMA START-UP IN JT-60SA

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The first plasma operation of JT-60SA was achieved at a low inductive electric field (0.15 V/m) with effective assistance from electron cyclotron (EC) heating as shown in Fig. 1. An operational scenario utilizing the mirror trap of EC-accelerated electrons proved instrumental for achieving plasma start-up prior to substantial discharge cleaning. This scenario demonstrated a higher tolerance to residual poloidal fields. Plasma start-up using second harmonic EC heating was also demonstrated at low inductive electric fields, and the required injection power was identified, providing valuable insights for plasma start-up scenarios in the initial operation of ITER.

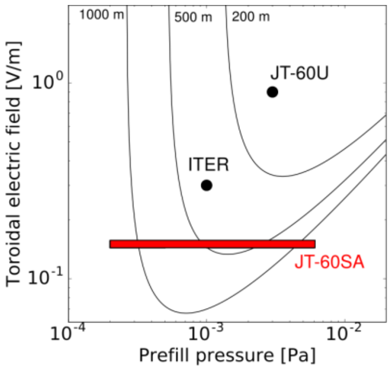

Fig. 1 Operational parameter ranges of JT-60SA regarding prefill pressure and toroidal electric field are depicted. Operational ranges were examined using He prefill gas. The minimum electric fields required for Townsend avalanche breakdown for H_2 with connection lengths of 200 m, 500 m and 1000 m, and the typical operational points for JT-60U and ITER, are shown for comparison.

Plasma start-up is the first critical challenge in the initial plasma operation of a new tokamak. Most tokamaks employ a field null configuration (FNC) start-up scenario, which creates a poloidal field null region during the breakdown phase to efficiently utilize the inductive electric field. However, in future large devices such as ITER and DEMO, which utilize superconducting central solenoids, the achievable inductive electric field is relatively low. For instance, the inductive electric field in ITER is expected to be 0.3 V/m [1], making plasma start-up with the FNC scenario challenging. In the first operation of JT-60SA, the inductive electric field was as low as 0.15 V/m. While plasma start-up at such low inductive fields has been demonstrated in several tokamaks, the development of low-electric-field start-up scenarios typically followed the substantial discharge cleaning using higher inductive fields, and no other large tokamak has initiated its operation under such constraints. This makes the first operation of JT-60SA a unique opportunity to validate the feasibility of plasma start-up in ITER.

The first tokamak plasma in JT-60SA was achieved using a scenario called trapped particle configuration (TPC) start-up as shown in Fig. 2. In this discharge, a clear formation of closed flux surface was observed at t=0.4 s. Application of EC heating is known to assist with neutral gas breakdown and the burn-through of radiation barriers of main and impurity species at low electric field levels. The TPC scenario utilizes a small poloidal field with a curved open poloidal flux contour for the mirror trap of EC-accelerated electrons. Note that the FNC start-up scenario, employing the same EC injection and prefill gas pressure, failed under similar conditions. Both fundamental resonance (82 GHz) and second harmonic resonance (110 GHz) heating were applied during these discharges at a toroidal magnetic field of 2.0 T. The burn-through of the main gas (He) was clearly observed in both cases, although substantial radiation from carbon, which was more than twice the level observed in the later phase of the experimental campaign, persisted. A notable difference between TPC and FNC start-up scenarios was observed in the soft X-ray signals and line integrated densities, indicating that plasma with higher density and temperature was achieved in the TPC start-up scenario. The initial magnetization current and voltage waveforms were optimized for both scenarios using the TOSCA code [2], which predicts the time evolution of the poloidal magnetic field, including the effects of eddy currents induced in passive conducting structures such as the vacuum vessel. However, a small discrepancy of approximately 1 mT was observed between the predicted and experimental poloidal magnetic fields, presumably due to modeling errors in the passive structures. In the FNC start-up scenario, this residual shifted the null region to the low-field side, hindering the formation of a stable initial tokamak equilibrium. Conversely, the TPC start-up

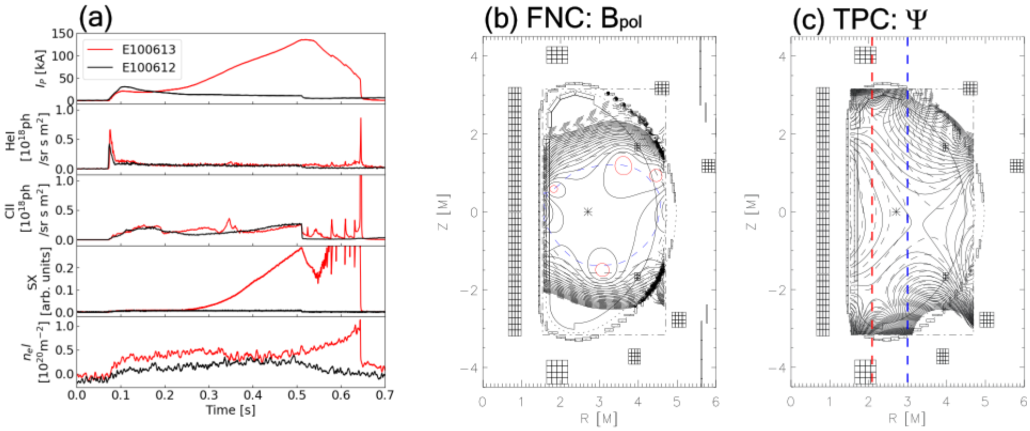

Fig. 2 (a) Comparison of discharge waveforms of initial trials of the FNC scenario (E100612) and the TPC scenario (E100613). (b) Comparison of poloidal magnetic field in the prediction (dashed) and the experiment (solid) in the FNC start-up scenario. The red solid contour and the blue dashed contour represent the region with the poloidal magnetic field less than 0.5 mT in the experiment and the prediction, respectively. (c) Comparison the poloidal magnetic flux in the prediction (dashed) and the experiment (solid) in the TPC start-up scenario with the location of the fundamental (82 GHz, red) and the second (110 GHz, blue) resocence layers.

scenario retained its curved field line structure, which remained suitable for confining EC-accelerated electrons despite the disturbances. Shot-by-shot compensation of the poloidal field residuals reduced them to less than 0.5 mT, eventually enabling a successful FNC start-up discharge.

Plasma start-up using only second harmonic EC heating (110 GHz) was also demonstrated at the low inductive electric field of 0.15 V/m. Pre-ionization by 110 GHz EC without a central solenoid flux swing was tested, revealing that breakdown could occur with poloidal fields similar to TPC start-up but not under complete null field conditions. As a result, only TPC-type start-up scenarios were tested with 110 GHz injection. Scans of prefill gas pressure, toroidal magnetic field, and EC power indicated that prefill gas pressures above 1 mPa and injection powers exceeding 0.6 MW were necessary for successful plasma start-up as shown in Fig. 3. Although the operational regime of the prefill gas pressure and the EC power for 110 GHz was narrower than for 82 GHz injection, successful plasma start-up was achieved using the TPC scenario.

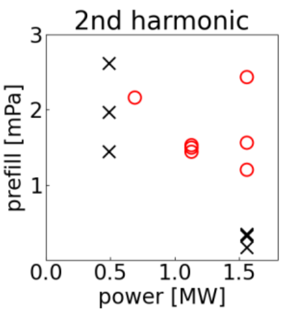

Fig. 3 Operational regime of the TPC start-up scenario using second harmonic EC heating (110 GHz). The toroidal field ranged from 1.7 to 2.0 T.

Attempts to achieve plasma start-up without EC heating were also conducted. In this case, the FNC scenario, relying solely on the inductive electric field, was used. At an inductive electric field of 0.15 V/m, plasma breakdown was not observed, even with a large field-null region where the poloidal field was less than 0.5 mT. Plasma breakdown was achieved by increasing the inductive electric field to approximately 0.3 V/m, but burn-through was unsuccessful, indicating that further wall conditioning is necessary for non-EC-assisted plasma start-up under ITER-like conditions.

Throughout the first operation of JT-60SA, the effective use of EC heating proved critical to plasma start-up at low inductive electric fields. While the EC-assisted FNC scenario demonstrated plasma start-up at inductive electric fields as low as half the value anticipated in ITER, the TPC scenario exhibited greater resilience to modeling errors in passive structures and an advantage in achieving plasma breakdown with second harmonic EC heating. These findings strongly encourage further investigation of the TPC start-up scenario for the first operation of ITER.

REFERENCES

[1] GRIBOV, Y., et. al., Progress in the ITER physics basis chapter 8: plasma operation and control, Nucl. Fusion **47** (2007) S385.

[2] SHINYA, K., Equilibrium analysis of tokamak plasma, J. Plasma Fusion Res. **76** (2000) 479-88.