

CONFERENCE PRE-PRINT**DEVELOPMENT OF LOW INDUCTIVE ELECTRIC FIELD
PLASMA START-UP IN JT-60SA**

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Abstract

Plasma start-up experiments have been performed in JT-60SA under ITER-relevant low inductive electric field conditions. A systematic investigation was conducted to identify the key factors that determined the success or failure of start-up. Conventional ohmic field null configuration (FNC) start-ups were found to be strongly limited by high impurity content, while EC-assisted FNC was hindered by sensitivity to device model errors, which induced residual poloidal magnetic fields and outward plasma shifts, reducing the effectiveness of EC heating during burn-through. Spectroscopic diagnostics confirmed that there was no decisive difference in electron temperature or density between FNC and TPC during the breakdown phase, indicating that the essential distinction appeared in the burn-through phase. In contrast to FNC, the trapped particle configuration (TPC) applied a finite vertical magnetic field from the breakdown phase, enabling robust plasma position control and effective utilization of EC heating even under uncertainties in breakdown timing and device modeling. This robustness led to the achievement of the JT-60SA first plasma. Additional experiments demonstrated that TPC also enhanced EC-assisted breakdown, particularly in X2 mode, and allowed successful X2-only start-up. The lower power threshold for X2 start-up was identified to be approximately 0.7 MW, set by the requirement for impurity burn-through rather than breakdown itself. These results demonstrate that TPC enables reliable plasma start-up under ITER- and DEMO-relevant conditions through the combined effects of robust position control and efficient EC heating.

1. INTRODUCTION

Plasma start-up is the first and essential step in the operation of tokamak devices, establishing the conditions required for plasma current initiation and subsequent confinement. In conventional tokamaks, plasma start-up is achieved by applying a toroidal inductive electric field through the flux swing of the central solenoid (CS), combined with a field null configuration (FNC) that minimizes the poloidal magnetic field in the vacuum vessel to facilitate efficient electron acceleration along the toroidal direction. This configuration enables breakdown of prefilled neutral gas and burn-through of impurity radiation barriers.

In ITER and future DEMO-class reactors, however, the use of superconducting CS coils significantly limits the available flux swing, and thus the achievable toroidal electric field. The expected inductive electric field in ITER is approximately 0.3 V/m [1], which is substantially smaller than that of present-day large tokamaks. This raises concerns regarding the feasibility of reliable plasma start-up using conventional FNC methods. Demonstrations of plasma initiation under ITER-relevant low electric field conditions are therefore crucial for validating operational strategies in future devices.

JT-60SA is the world's largest superconducting tokamak, constructed under the Broader Approach collaboration between Japan and Europe. With a major radius of 2.9 m and advanced superconducting magnet systems, JT-60SA provides a unique platform to address ITER-relevant physics and operational issues. Importantly, during its first plasma operation campaign, the applied toroidal electric field was restricted to less than 0.15 V/m most of the time for safety reasons, providing an unprecedented opportunity to test start-up scenarios under even stricter conditions than ITER. In addition, the first plasmas were attempted without prior extensive wall conditioning, which meant that relatively high levels of impurity outgassing were present. These factors made JT-60SA an ideal environment to examine the robustness of plasma start-up methods for the first operations of forthcoming large superconducting devices.

The main objective of this study is to clarify the mechanisms that enabled successful plasma start-up in JT-60SA under such stringent low-field and impurity-rich conditions. Particular emphasis is placed on the comparison between the conventional FNC start-up scenario and the alternative trapped particle configuration (TPC) start-up scenario, in which finite vertical magnetic fields and electron cyclotron (EC) heating are utilized to enhance breakdown and burn-through through mirror confinement of perpendicularly accelerated electrons. Through this comparison, the effectiveness of TPC in providing robustness against residual magnetic field errors and impurity effects is evaluated, offering important implications for ITER and DEMO operation.

2. EXPERIMENTAL SETUP

JT-60SA is equipped with superconducting coil systems for the toroidal field (TF) coils, equilibrium field (EF) coils, and central solenoid (CS). The toroidal loop resistance of the vacuum vessel of JT-60SA ($16.5 \mu\Omega$) is significantly lower than that of JT-60U ($160 \mu\Omega$), requiring careful consideration of the effect of eddy current to optimize plasma start-up.

During the first plasma operation, the applied toroidal electric field was restricted to less than 0.15 V/m , significantly lower than the 0.3 V/m expected in ITER. Under these stringent conditions, electron cyclotron (EC) heating played a crucial role in plasma initiation. EC heating with frequencies of 82 GHz , 110 GHz and 138 GHz was available. Among them, 82 GHz and 110 GHz were used for breakdown assistance and subsequent burn-through. The resonance layers located at $R = 2.1 \text{ m}$ for 82 GHz fundamental resonance and at $R = 3.0 \text{ m}$ for 110 GHz second harmonic resonance when toroidal magnetic field B_T is 2.0 T .

To prepare start-up scenarios, the Tokamak Operation Scenario and Configuration Analysis (TOSCA) code [2] was employed. TOSCA calculates the time evolution of poloidal flux surfaces and simulates the free-boundary equilibrium, including the effects of eddy currents in passive conductors. The design of both FNC and TPC start-up scenarios was based on TOSCA simulations as shown in Fig. 1. However, during the first operation campaign, a discrepancy of $0.5\text{--}1 \text{ mT}$ was observed between predicted and measured poloidal magnetic fields. This discrepancy was thought to be caused by the error of the device model such as installation errors of CS/EF coils and magnetic sensors and limitations in passive structure modeling.

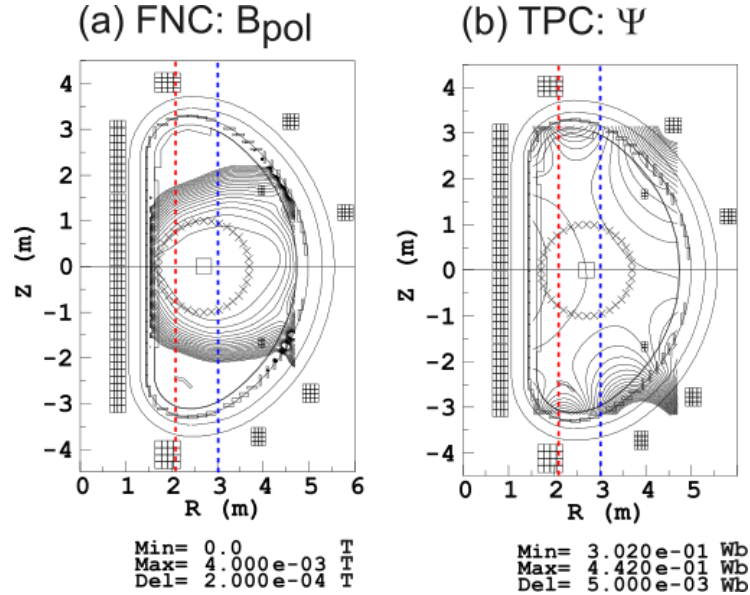


FIG. 1. Poloidal magnetic field distributions and poloidal flux (Ψ) surfaces at the breakdown timing ($t_{BD} = 0.1 \text{ s}$) calculated with the TOSCA code for the conventional field null configuration (FNC) and the trapped particle configuration (TPC). In FNC, the poloidal field is minimized over the vessel to facilitate breakdown, whereas in TPC a finite poloidal field is applied from the breakdown phase to provide the mirror confinement required for EC-heated electrons. The vertical red dashed line indicates the fundamental EC resonance layer at 82 GHz , and the blue dashed line indicates the second-harmonic EC resonance layer at 110 GHz .

Diagnostics employed to analyze plasma start-up included a residual gas analyzer (RGA) to monitor impurity outgassing, a CO_2 interferometer for line-averaged density, soft X-ray detectors with different filter thicknesses

for electron temperature estimation, and visible cameras to observe plasma formation and equilibrium evolution. In addition, visible spectroscopy of He I, H α , and C II emission lines was used to evaluate electron temperature and density during breakdown and to estimate impurity outgassing. These measurements were essential for distinguishing successful and unsuccessful start-up attempts and for validating simulation results.

3. RESULTS

3.1. Ohmic FNC start-up and impurity effects

To clarify the impact of impurities on plasma start-up, ohmic FNC experiments were conducted after the achievement of the first plasma. In these discharges, a higher electric field of $E_{\parallel} = 0.25$ V/m was applied exceptionally as shown in Fig. 2. Plasma breakdown was obtained with a prefill pressure more than 1 mPa; however, the discharge failed to achieve burn-through, and the plasma current did not sustain (Fig. 3a).

Residual gas analysis revealed significant amounts of hydrogen ($\sim 3 \times 10^{-3}$ mPa), nitrogen ($\sim 4 \times 10^{-3}$ mPa), and water vapor ($\sim 3 \times 10^{-2}$ mPa). These measurements suggested that 6.2% of hydrogen atoms, 2.8% of nitrogen atoms, and 0.8% of oxygen atoms could have contaminated the plasma in E101002 in addition to 1 mPa of prefilled helium. DYON simulations [3] confirmed that burn-through could not be achieved with these amounts of impurity atoms, whereas successful start-up could be reproduced if the impurity fraction was reduced to 1% of H and 0.1% of O (Fig. 3b). These results indicate that the high impurity level during the first operation was a major obstacle to achieving burn-through under low $E_{\parallel}$ conditions.

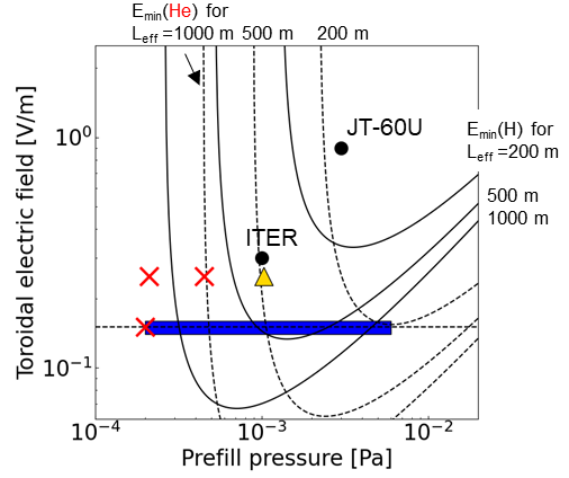


FIG. 2. Operational results of ohmic FNC start-up in JT-60SA. Red crosses indicate discharges where breakdown failed, and a yellow triangle denote a case where breakdown occurred but burn-through was not achieved. The blue shaded region represents the operational window where successful start-up was obtained using the TPC scenario. The background black solid and dashed lines show the predicted Townsend breakdown conditions for hydrogen and helium, respectively, with connection lengths of 200 m, 500 m, and 1000 m. For reference, typical operating points of JT-60U and ITER are also indicated by black dots.

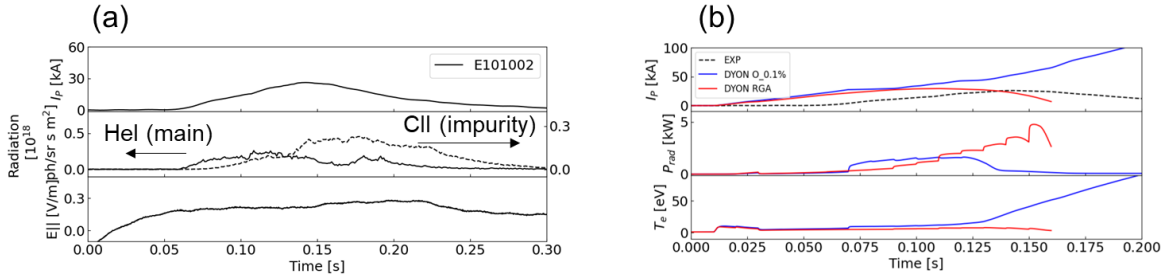


FIG. 3. (a) Time evolution of plasma current, He I and C II line emissions, and toroidal electric field ($E_{\parallel}$) in an ohmic FNC discharge (E101002) that failed to achieve burn-through. (b) Comparison of this discharge with DYON simulations. The red line corresponds to the case with 0.8% oxygen, 2.8% nitrogen and 6.2% hydrogen added to the prefilled helium gas, while the blue line corresponds to the case with 0.1% oxygen and 1% hydrogen. The experimental result is reproduced only when the higher impurity fraction is assumed, indicating that impurity content played a decisive role in the failure of ohmic FNC burn-through.

3.2. Comparison of FNC and TPC during the breakdown phase

In the very first start-up attempts of JT-60SA, EC-assisted FNC scenarios were tested. Breakdown was achieved with 82 GHz fundamental heating and with combined 82 GHz fundamental plus 110 GHz second harmonic heating. However, despite obtaining breakdown, the plasma failed to reach burn-through as shown in Fig. 4a. On the other hand, the first plasma of JT-60SA was achieved with TPC (E100613) just after the unsuccessful attempt using FNC (E100612), and the plasma current increased to ~ 130 kA.

Visible spectroscopy of He I lines was used to estimate electron temperature and density during the early breakdown phase ($t < 0.15$ s). According to collisional–radiative (CR) model calculations, the intensity ratio of the 728.1 nm to 706.5 nm He I lines can be treated as a function of electron temperature, while the ratio of the 667.8 nm to 728.1 nm lines is sensitive to electron density with only weak sensitivity to temperature [4].

Using these diagnostics, no decisive difference in electron temperature or density was found between a failed FNC discharge (E100612) and a successful TPC discharge (E100613) during the breakdown phase (Fig. 4a). Additionally, it was found that electron temperature higher than E100613 could be observed in the other failed FNC discharge with lower prefill pressure (Fig. 4b). This indicates that the different outcomes—failure in FNC and success in TPC—were not due to the quality of the breakdown itself, but rather to differences in the burn-through phase, where plasma position control determined the effectiveness of EC heating.

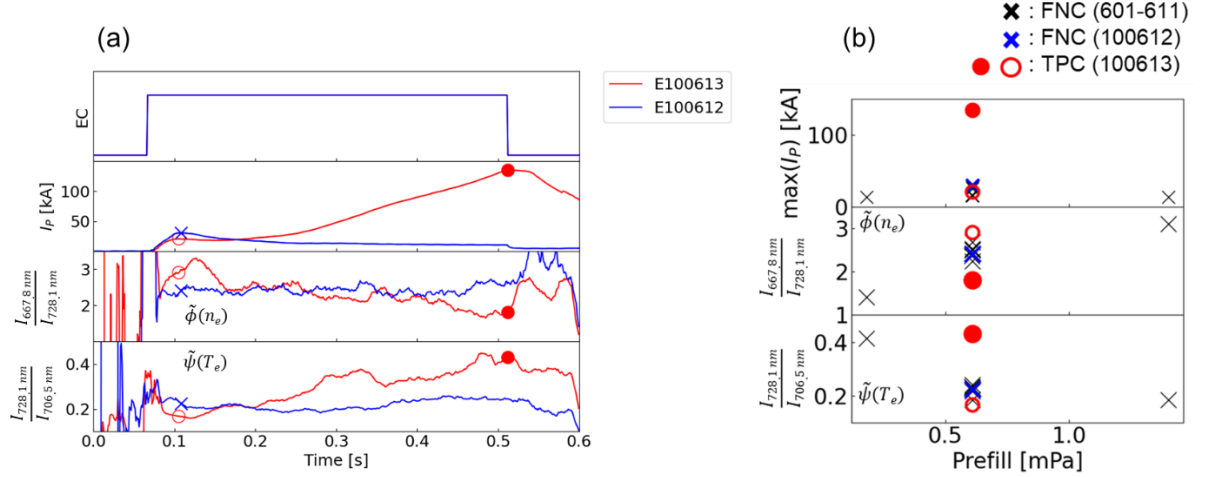


FIG. 4. (a) Comparison between a TPC discharge that achieved the first plasma (E100613) and an FNC discharge just prior to it that failed to achieve burn-through (E100612). Shown are the EC injection timing, plasma current, the He I 667.8 nm / 728.1 nm line intensity ratio (reflecting electron density), and the He I 728.1 nm / 706.5 nm ratio (reflecting electron temperature). (b) Prefill gas pressure dependence of plasma current and He I line ratios (667.8nm/728.1nm, 728.1nm/706.5nm) for EC-assisted FNC discharges conducted before the first plasma. These results show that comparable electron density and temperature to those obtained in the successful TPC discharge were achieved, confirming that the decisive difference between FNC and TPC lay not in the breakdown phase but in the burn-through phase.

3.3. Position control in the burn-through phase and its susceptibility to device model errors

In the FNC scenario, the poloidal magnetic field, which consists of the radial and vertical components, is designed to be zero at the breakdown timing ($t_{BD} = 0.1$ s in JT-60SA) as shown in Fig. 5. Therefore, the vertical magnetic field must be ramped up in synchrony with the plasma current growth after t_{BD} in order to maintain a stable equilibrium. This requirement makes FNC particularly sensitive to the actual timing of breakdown. For example, in discharge E100612, breakdown occurred earlier than the design value, and the plasma current ramped up more rapidly than expected. As a result, the available vertical field was insufficient, and the plasma moved outward.

As shown in Sec. 3.2, in the first operation phase of JT-60SA, the high impurity level combined with the very low toroidal electric field made it difficult to achieve burn-through by ohmic heating alone. Thus, effective use of EC heating was essential not only for the breakdown but also for the burn-through phase. However, once the plasma shifted outward, it moved away from the EC resonance layers, and the EC heating became ineffective.

In addition, differences between the device model used for scenario optimization with the TOSCA code and the actual machine behavior were observed in the first operation phase. When the device model was updated by adjusting the CS/EF coil positions to improve consistency with magnetic measurements, it was found that the zero crossing of the vertical field was delayed by approximately 30–40 ms (Fig. 5). Using this corrected model, equilibrium calculations with TOSCA for discharge E100612 revealed that the plasma remained in an outer-

limiter configuration until ~ 160 ms after breakdown at 70 ms. This result indicates that EC heating could not be effectively absorbed during the crucial burn-through phase (Fig. 6a). Hence, FNC was shown to be highly sensitive to both the timing of breakdown and the uncertainties in the device model, which explains why the first plasma could not be achieved with this configuration.

In contrast, in TPC a finite vertical magnetic field is applied from the breakdown phase. This field not only ensures mirror confinement of EC-heated electrons but also stabilizes the plasma in an inner-limiter configuration from the very beginning. In the first plasma discharge E100613, the vertical field during the breakdown phase was approximately 2 mT, and the required ramp-up of the vertical field during the burn-through phase was only about one-third of that in FNC (Fig. 5).

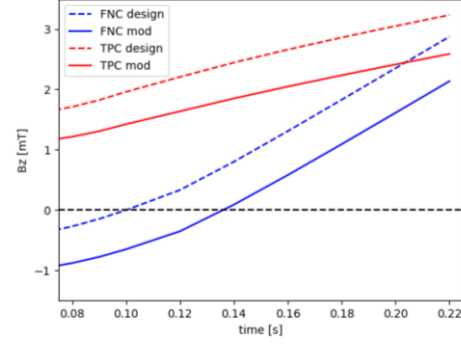


FIG. 5. Vertical magnetic field at $R = 2.7$ m during the breakdown phase calculated with the TOSCA code. Blue curves correspond to the FNC scenario and red curves to the TPC scenario. Dashed lines represent results obtained with the initial device model used for the design of the start-up scenario prior to the experiment, while solid lines represent recalculations with the updated device model adjusted to match magnetic measurements. The updated model reveals a delay of 30–40 ms in the vertical field rise compared with the design model, which contributed to the reduced position control capability in FNC.

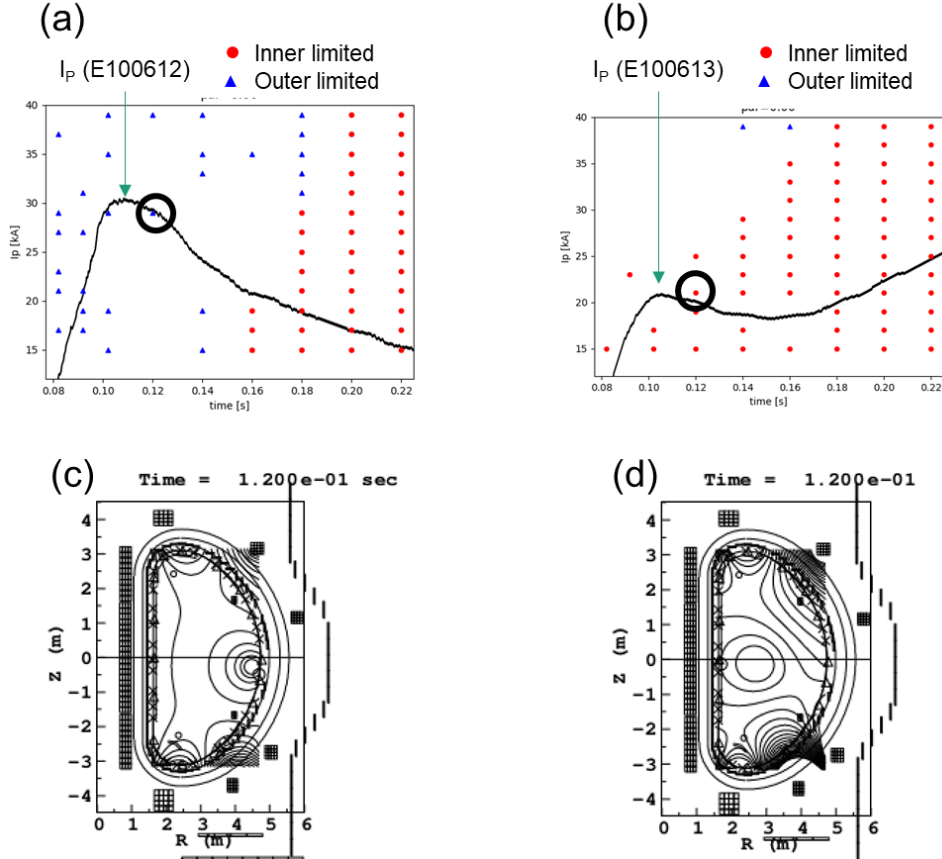


FIG. 6. (a, b) Plasma current evolution during the burn-through phase of an unsuccessful FNC discharge (E100612) and a successful TPC discharge (E100613), together with equilibrium calculations performed with the TOSCA code for assumed plasma currents of 15–39 kA. Red circles denote equilibria where the plasma remained inner-limiter limited, while blue triangles denote outer-limiter configurations. (c, d) Equilibrium results at $t = 0.12$ s (indicated by the black circle in panels (a) and (b)), showing that in E100612 (FNC) the plasma shifted to the outer limiter, whereas in E100613 (TPC) the plasma maintained an inner-limiter configuration, allowing effective EC heating during burn-through.

As a result, even if breakdown occurred earlier than the design t_{BD} , the plasma could remain inner-wall limited and continue to absorb EC power effectively in TPC. Furthermore, TOSCA calculations showed that even in the presence of device model errors, the plasma could maintain the inner-limiter configuration as long as the plasma current remained below ~ 25 kA just after breakdown (Fig. 6b).

These results demonstrate that, compared with FNC, the TPC scenario provides more reliable plasma position control during the burn-through phase, even under the uncertainties intrinsic to the initial operation of a new device, such as variations in breakdown timing and imperfections in the device model. This robustness enabled effective utilization of EC heating and led to the achievement of the first plasma in JT-60SA.

3.4. Effect of TPC configuration on EC-assisted breakdown

As discussed in Sec. 3.2, no decisive difference in electron temperature or density was observed between successful and unsuccessful start-up discharges during the early breakdown phase, in the EC-assisted start-ups with combined 82 GHz and 110 GHz injection that led to the first plasma. This indicates that the presence or absence of plasma initiation was not determined solely by the quality of the breakdown phase.

To further investigate the influence of the magnetic configuration on EC-assisted breakdown, experiments were carried out in which steady currents were applied to the CS and EF coils to form the TPC poloidal field structure while suppressing the inductive electric field ($E_{||} \approx 0$). These discharges were compared with FNC conditions in which the CS and EF coil currents were set to zero, producing a null magnetic field in the vacuum vessel. EC waves were then injected in both cases to examine the plasma formation process.

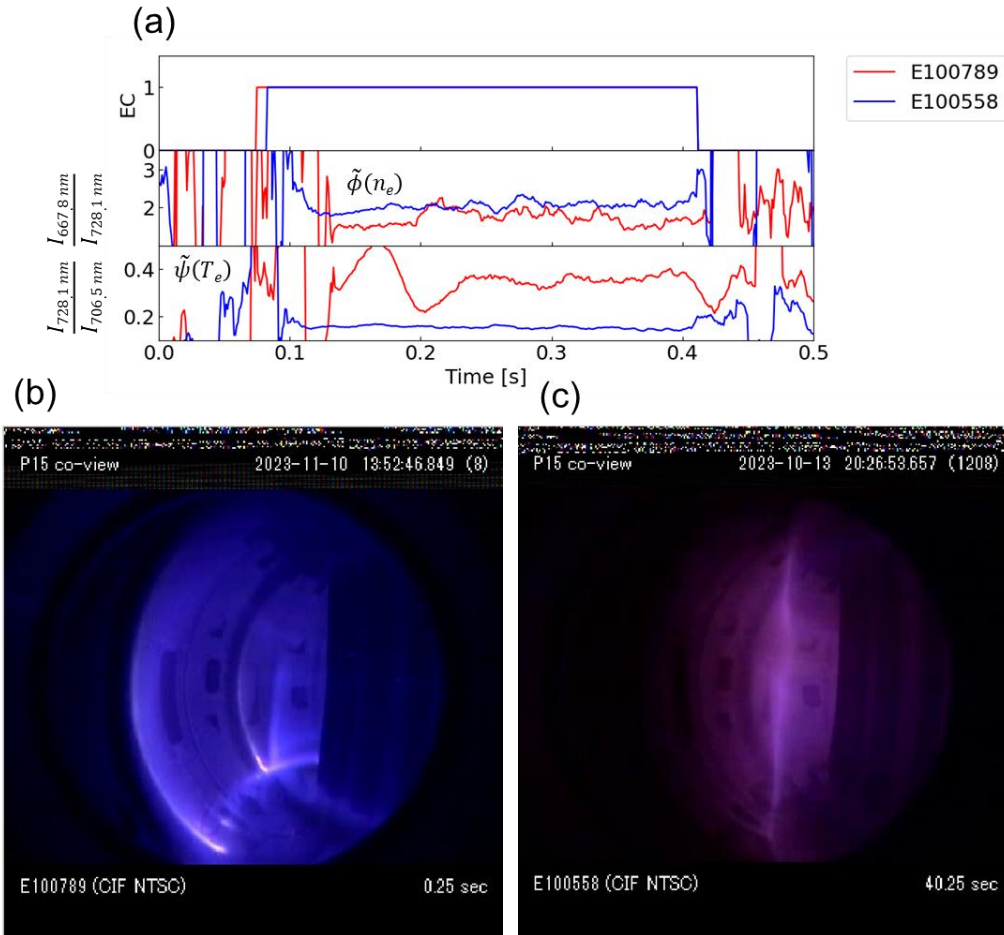


FIG. 7. Comparison of EC-assisted breakdown at nearly zero inductive field ($E_{||} \approx 0$) between TPC and FNC configurations. (a) Time evolution of EC injection, the He I 667.8 nm / 728.1 nm intensity ratio (sensitive to electron density), and the He I 728.1 nm / 706.5 nm ratio (sensitive to electron temperature). (b) Visible camera image for TPC at 0.25 s. (c) Visible camera image for FNC at 0.25 s. The timestamp of 40.25 s shown in the FNC image corresponds to 0.25 s after the sequence start at 40 s, the same timing as in (a).

When the 82 GHz O1 mode was applied, plasma emission filling the vacuum vessel was observed with both FNC and TPC, indicating that fundamental EC heating was able to generate extended plasma regardless of the configuration. In contrast, when the 110 GHz X2 mode was injected, a clear difference emerged. In TPC (e.g. discharge E100789), visible camera images showed plasma extending throughout the vacuum vessel, similar to the O1 case as shown in Fig. 7b. In FNC (e.g. discharge E100558), however, the plasma remained localized near the resonance layer and did not expand broadly (Fig. 7c).

Analysis of He I line ratios, as described in Sec. 3.2, was applied again for these discharges, and revealed that the electron temperature in the plasma generated with TPC was higher than that in FNC under X2 heating (Fig. 7a). This indicates that the finite vertical field in the TPC configuration improved electron confinement and heating efficiency even during the breakdown phase.

These results demonstrate that the TPC configuration is effective not only in the burn-through phase, but also in enhancing EC-assisted breakdown, particularly for X2 mode heating. This additional robustness of TPC further explains why it enabled successful plasma start-up in JT-60SA under ITER-relevant low $E_{||}$ conditions.

3.5. Plasma start-up with X2 mode using TPC

Based on the results in Sec. 3.4, which demonstrated the beneficial effect of the TPC configuration for X2-mode EC-assisted breakdown, plasma start-up using only the 110 GHz X2 mode was attempted in TPC scenarios.

In these experiments, the prefill gas pressure was scanned between 0.2 and 2.6 mPa, while the injected EC power was varied between 0.5 and 1.5 MW. It was found that at prefill pressures below 0.4 mPa, breakdown failed even with 1.5 MW of injected power as shown in Fig. 8. In contrast, at prefill pressures above 1 mPa, breakdown was achieved with as little as 0.5 MW of injected power. The lower power limit required for breakdown could not be determined within the present parameter range.

The toroidal magnetic field was scanned from 1.7 to 2.0 T, and no significant dependence of the breakdown condition on the toroidal field strength was observed. When the subsequent burn-through phase was examined, it was found that a discharge at 1.7 T with 0.5 MW injection failed to achieve burn-through, while at 1.8 T with 0.7 MW injection burn-through was obtained. These results suggest that the effective lower limit of the injected EC power required for successful X2-mode start-up in JT-60SA is about 0.7 MW, determined by the power needed to sustain burn-through rather than by the breakdown condition itself.

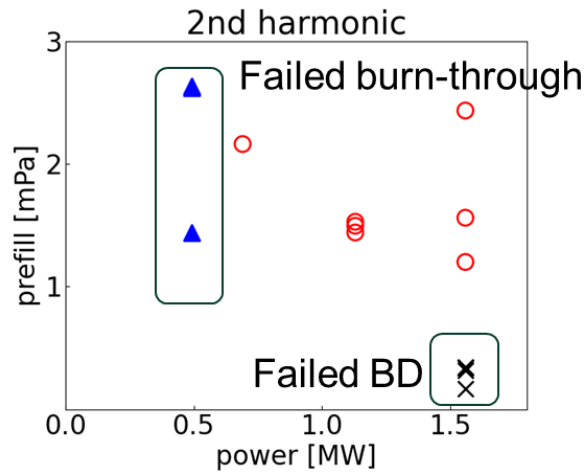


FIG.8. Results of TPC start-up experiments using only the 110 GHz X2 mode. Red circles indicate successful plasma start-up, black crosses represent discharges where breakdown failed, and blue triangles denote cases where breakdown occurred but burn-through was not achieved. These results show that the effective lower power threshold for X2-mode start-up in JT-60SA is determined by the power required for burn-through rather than for breakdown.

4. CONCLUSION

Plasma start-up experiments in JT-60SA have been conducted under ITER-relevant low inductive electric field conditions. A series of investigations clarified the key factors that determined the success or failure of start-up and demonstrated the critical role of the trapped particle configuration (TPC).

First, ohmic FNC start-up attempts were strongly limited by impurity content, as supported by DYON simulations. EC-assisted FNC experiments revealed that the configuration was also highly sensitive to device model errors, which caused residual poloidal fields and outward plasma displacement, thereby reducing the effectiveness of EC heating during the burn-through phase.

In contrast, the TPC scenario enabled robust plasma position control owing to the finite vertical magnetic field applied from the breakdown phase. This robustness allowed effective EC heating both during breakdown and burn-through, mitigating the sensitivity to impurity content, device model uncertainties, and fluctuations in breakdown timing. As a result, TPC led to the achievement of the JT-60SA first plasma.

Furthermore, spectroscopic analysis showed that the difference between FNC and TPC did not originate from the breakdown phase itself but from the subsequent burn-through phase, where plasma position control determined whether EC heating could be fully utilized. Additional experiments confirmed that TPC also improved the efficiency of EC-assisted breakdown, particularly in the X2 mode, leading to successful start-up with X2-only heating. The lower power threshold for X2 start-up was identified to be approximately 0.7 MW, set by the requirement to achieve burn-through rather than by the breakdown condition.

In summary, these results demonstrate that TPC provides a reliable and ITER-relevant approach to plasma start-up under low $E_{||}$ conditions, ensuring effective utilization of EC heating. The successful demonstration in JT-60SA highlights the importance of robust position control utilizing TPC for achieving impurity burn-through and provides essential guidance for the development of start-up scenarios in ITER and DEMO.

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