

Optimization of Poloidal Field Configuration for Electron Cyclotron Wave Assisted Low Voltage Ohmic Start-Up in TST-2

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We investigated electron cyclotron (EC) wave assisted low voltage Ohmic start-up in the conventional field null configuration (FNC) and the trapped-particle configuration (TPC) in the TST-2 spherical tokamak device. The upper pressure limit for successful burn-through increased when EC power was applied for both the FNC and TPC. On the other hand, at low prefill pressure, breakdown was delayed in the FNC start-up. The achievable plasma current also decreased especially at high EC power. By applying the TPC, fast breakdown was recovered even at high EC power. The plasma current ramp-up rate was also greater with TPC compared with FNC at the same loop voltage waveform. The lower prefill pressure limit for successful breakdown expanded in the TPC compared to that in the FNC. The higher vertical field decay index resulted in faster EC breakdown. The reduction of the upper pressure limit due to impurities was the same in the FNC and TPC indicating that the poloidal field configuration did not significantly affect the upper pressure limit for successful burn-through.

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1. Introduction

Aiming at steady-state tokamak operation, a superconducting central solenoid was adopted in recent fusion experimental devices. However, the challenge with the superconducting central solenoid is that the toroidal loop voltage is low (e.g., <0.5 V/m in JT-60SA [1] and ~ 0.3 V/m in ITER [2]). Electron cyclotron (EC) wave assistance has been shown to improve the reliability of the Ohmic plasma start-up substantially [3–6]. In these experiments, the field null configuration (FNC) which maximizes the connection length was used for breakdown. Fully non-inductive plasma start-up by EC wave using the trapped particle configuration (TPC) which is a vertical field configuration with positive decay index, has been studied on CDX-U [7–9], TST-2 [10, 11], LATE [12, 13] and QUEST [14, 15]. The TPC was first applied to Ohmic start-up with EC assist at the fundamental EC resonance in VEST [16]. The TPC start-up saved volt-second consumption and extended lower pressure limit compared with the FNC. The second harmonic EC-assisted Ohmic start-up with the TPC was also shown to have a wider pressure window for successful start-up on KSTAR [17].

In this paper, we have investigated the optimum poloidal field configuration for EC-assisted Ohmic startup in the TST-2 spherical tokamak. Especially, the impact of EC power and impurity on the FNC and TPC start-ups

were studied. This paper is organized as follows. The experimental setup is described in Sec. 2. Features of the conventional FNC start-up was investigated in Sec. 3. The EC power dependence of breakdown time for the FNC and pure toroidal field is investigated in Sec. 4. The optimum vertical field strength and decay index for the EC breakdown is investigated in Sec. 5. Finally, the comparison between start-up with the TPC and the FNC is shown in Sec. 6.

2. Experimental Set-Up

TST-2 is a spherical tokamak located at the University of Tokyo. Typical parameters of TST-2 are as follows: major radius $R_0 = 0.36$ m, minor radius $a = 0.23$ m, aspect ratio $A = R_0/a \geq 1.5$ and on axis toroidal magnetic field $B_{t0} < 0.3$ T [18]. The central solenoid is powered by discharges of two capacitor banks with double swing. EC wave was injected with X-mode polarization from the outboard side of the vacuum vessel at a frequency of 2.45 GHz and source power of 5 kW. The EC wave injection port is located at $(R$ [mm], Z [mm], Φ [rad]) = $(735, -250, 0)$. D_2 gas and N_2 gas were injected from $(R, Z, \Phi) = (725, 250, 5\pi/6)$ and $(270, -780, 7\pi/6)$, respectively.

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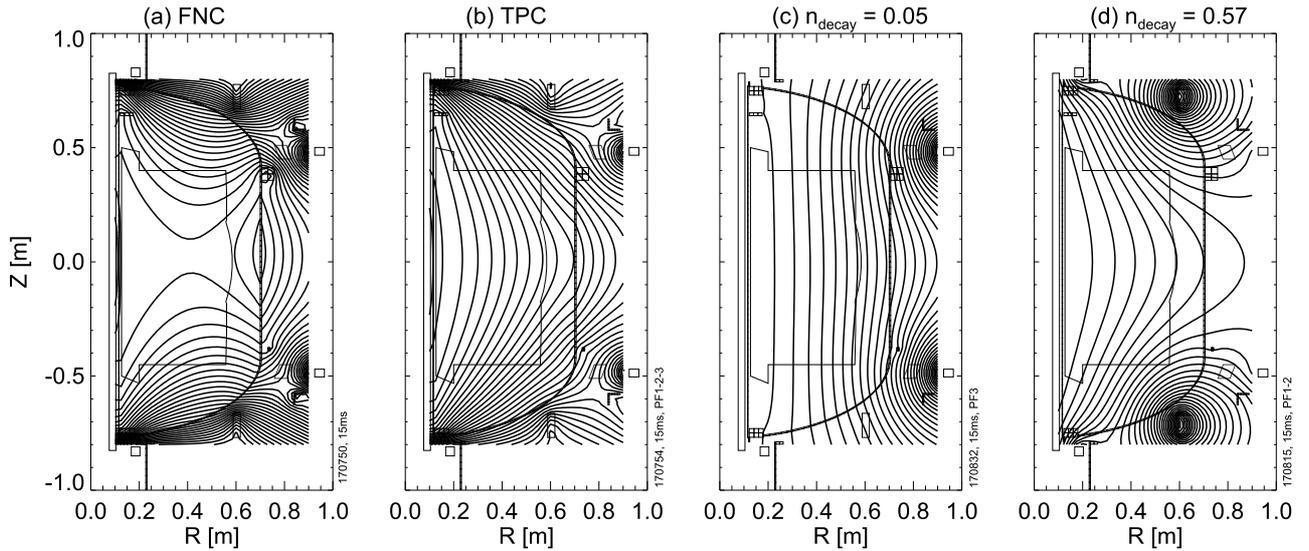


Fig. 1 Poloidal flux contours of (a) the FNC and (b) the TPC start-up just before the plasma current rise (15 ms). Poloidal flux contours of the vertical field configurations with (c) weak decay index ($n_{\text{decay}} = 0.05$) and (d) strong decay index ($n_{\text{decay}} = 0.57$).

3. Features of the Conventional FNC Start-Up

We investigated various parametric dependencies of FNC startup. The typical poloidal flux contours around the timing of breakdown is shown in Fig. 1 (a). Figure 2 (a) shows the parameter space for successful start-up when a short 0.8 kW EC pulse was applied only for pre-ionization. Here, breakdown was defined as a successful production of a plasma identified by a flash of light on the D_α radiation monitor (and the CCD camera). In a “successful” discharge, D_α radiation exhibited a peak at approximately 10 ms after the breakdown (radiation barrier) and decreased as the plasma current rose further (burn-through). A discharge with breakdown but without burn-through was termed “fizzle”. Practically, a discharge that had decreasing plasma current after the D_α radiation peak was classified as fizzle. The upper pressure limit was due to the failure of burn-through. The lower pressure limit was due to the failure of breakdown. The upper pressure limit decreased and lower pressure limit increased at lower loop voltage. At the lowest loop voltage, burn-through was possible only at 0.037 mTorr D_2 pressure.

Figure 2 (b) shows the parameter space for successful FNC start-up when the full 5.0 kW EC power was applied throughout the start-up to assist burn-through. The upper pressure limit increased especially at lower loop voltage where the EC heating power was comparable to the Ohmic heating power. At the same time, just above the lower pressure limit (black solid curve on the left side), excessive delay of breakdown was observed, which lead to failure of burn-through within the time window of start-up allowed by the TST-2 power supply. Although this region may not be entirely inaccessible with the adjustment of the vertical field waveform, it is practically unsuitable for operation

because the time to breakdown cannot be accurately predicted in such a boundary region and, pre-programming of vertical field waveform for proper plasma current ramp-up becomes difficult.

When 0.0078 mTorr N_2 gas was added at the prefill phase, the upper limit of D_2 prefill pressure decreased as expected from increased impurity radiation losses. With EC pre-ionization only, burn-through was no longer obtained at the lowest loop voltage. However, with full EC power, burn-through was obtained at the same loop voltage due to the increased upper pressure limit.

4. EC Power Dependence of the FNC Start-Up

To further quantify the observed breakdown delay at high EC power and low pressure in the FNC, EC power scan was performed. The experiment was first conducted in a pure TF where there was no loop voltage and no vertical field. Figure 3 shows the EC power dependence of the time to breakdown from EC turn on. In the pure TF case (black circles), the time to breakdown increased as EC power increased. The breakdown time also became longer at lower D_2 prefill pressure. These results indicate that higher electron energy results in greater loss in the FNC.

To see whether the effect persists in the presence of loop voltage, similar power scan was performed with 0.7 V loop voltage. The waveforms of the CS and poloidal field coils were the same for all the discharges. The time to breakdown increased with EC power in this case as well, but breakdown was obtained at high EC power where no breakdown was possible in the pure TF. Figure 4 shows the time trace of the vertical field and the loop voltage. The vertical field was calculated based on the coil currents,

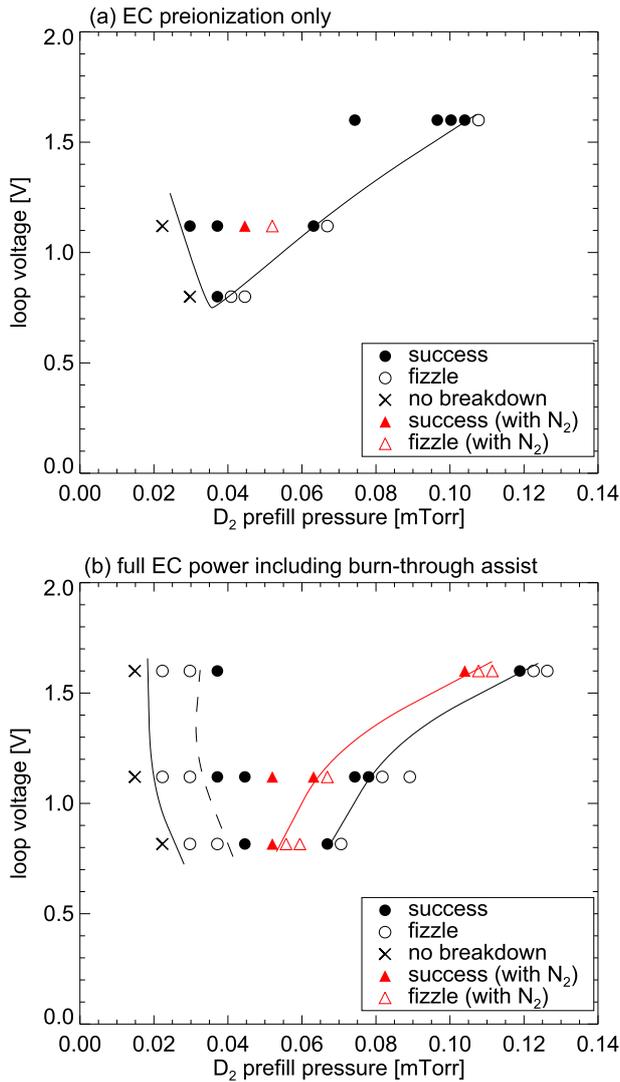


Fig. 2 Parameter space for successful FNC start-up versus the D_2 prefill pressure and the loop voltage without N_2 (black symbols) and with 0.0078 mTorr N_2 (red symbols). (a) EC power applied only for pre-ionization and (b) 5.0 kW EC power applied throughout the start-up to assist burn-through.

including the effect of the vacuum vessel eddy currents. The vertical field was calculated at the EC resonance radius (0.33 m) and at 0.10 m to the high- and low-field sides ($r/a \sim 0.4$), along the midplane (Fig. 4 (a)). Field null was formed for approximately 2 ms and the effect of vertical field became considerable afterwards. At 7 ms from EC turn on (Fig. 4, top axis), the strength of the vertical field was above 0.5 mT and the decay index was positive. Therefore, breakdown after 6 ms from EC turn on was probably due to the formation of the TPC.

These results show that the increase of EC power under the FNC makes the initiation of plasma more difficult. Such a concern can be mitigated by initiating the discharge in the TPC as shown in the following section.

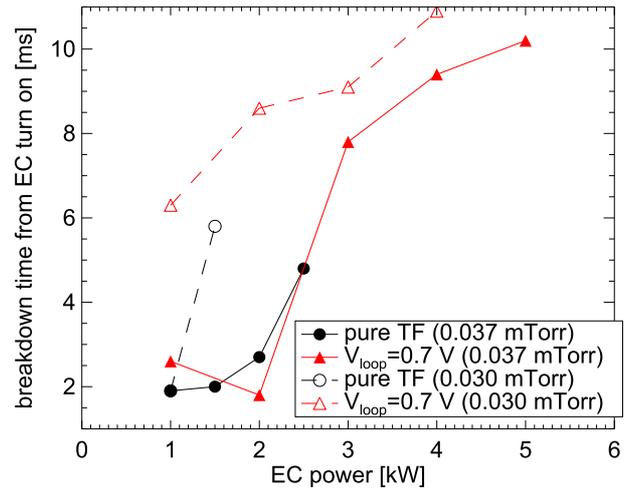


Fig. 3 EC power dependence of breakdown time from EC turn on. The start-up with pure TF (black circles) and the start-up with loop voltage (red triangles) in the FNC at 0.037 mTorr (filled symbols) and 0.030 mTorr (open symbols) D_2 prefill.

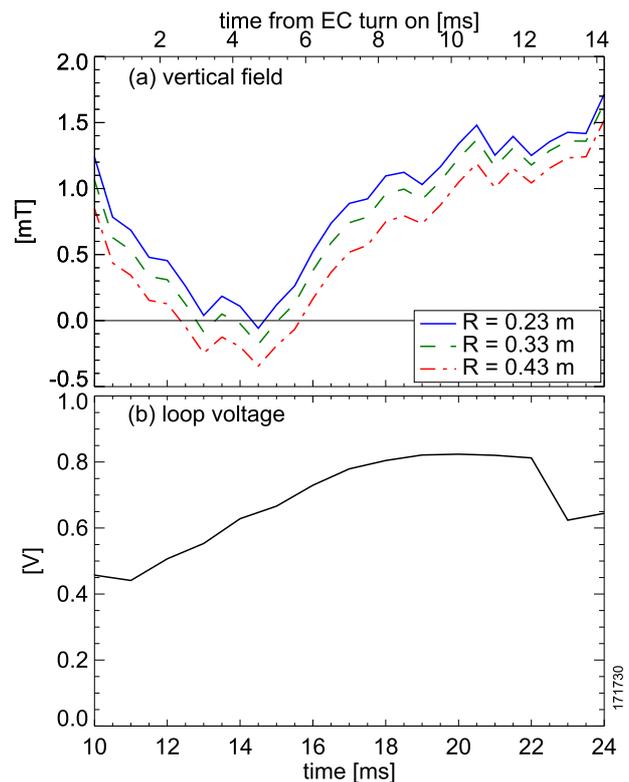


Fig. 4 The time trace of (a) the vertical field at $R = 0.23$ m (blue solid curve), 0.33 m (green dashed curve), 0.43 m (red dashed-dotted curve) and (b) loop voltage.

5. The Vertical Field Effect on Break-Down

We investigated the effect of vertical field strength and configurations for successful breakdown. It has been

known that higher decay index is better for EC start-up [11]. The vertical field decay index is defined as $n_{\text{decay}} = -(R/B_Z) \cdot (\partial B_Z / \partial R)$ and is a measure of the poloidal curvature of the field. Figures 1 (c) and (d) show the poloidal field configurations with weak decay index ($n_{\text{decay}} = 0.05$) and strong decay index ($n_{\text{decay}} = 0.57$). Figure 5 shows the dependence of breakdown time from EC turn on and maximum D_α emission on the vertical field for different vertical field strength with the two configurations. The experimental conditions were as follows: $B_{10} \sim 0.08$ T at 0.36 m, $R_{\text{ECR}} \sim 0.33$ m and 5.0 kW EC source power. Note that the pressure was higher for discharges with weak decay index since breakdown could not be obtained at any vertical field strength at the same pressure as the discharges with strong decay index. Nevertheless, D_α emission was greater for the discharges with strong decay index.

With weak decay index (Fig. 1 (c)), the time to breakdown became longer at stronger vertical field. In this configuration, losses are expected to increase with the vertical field strength since the connection length becomes shorter, and the electrons are quickly lost along the field line. On the other hand, with strongly positive decay index (Fig. 1 (d)), the time to breakdown was earlier at stronger vertical field strength. This can be understood from the electron orbit analysis [19], which shows that the maximum perpendicular velocity of the confined electrons is proportional to the vertical field strength. On the other hand, D_α emission decreased above 1.5 mT. This can be at-

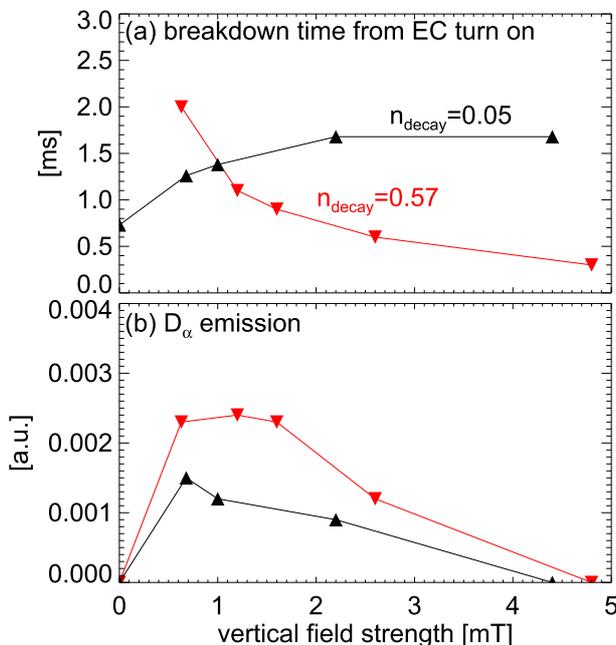


Fig. 5 The dependence on vertical field strength of (a) breakdown time from EC turn on and (b) maximum D_α emission. The vertical strength is calculated at $R = 0.33$ m. Black upward triangles: decay index = 0.05 and D_2 prefill pressure = 0.056 mTorr, red downward triangles: decay index = 0.57 and D_2 prefill pressure = 0.037 mTorr.

tributed to the current drive effect, which decreases at high poloidal field due to the reduced asymmetry of the trapped electron orbit [19]. In fact, closed flux surfaces spontaneously formed later in the discharge at 0.63 mT, which could have led to higher plasma density and temperature. These results show that there is a trade-off in the determination of the optimum vertical field strength; breakdown prefers higher field, but current drive and closed flux surface formation prefers lower field. To assist Ohmic start-up, we may use strong vertical field to help breakdown since the loop voltage can drive the plasma current efficiently.

6. Comparison of the TPC and FNC Start-Ups

In the typical FNC start-up in TST-2, field-null (< 0.5 mT) is maintained for about 3 ms after the TF ramp-up, and the vertical field is increased afterwards to balance the plasma current rise. The waveform for TPC start-up was created by applying a vertical field with positive decay index as a bias at the beginning of the discharge. Combined with the poloidal field generated by the central solenoid, this results in decreasing vertical field strength towards what was originally the timing of field null formation. This is ideal since the field is strong initially to allow for easy breakdown and decreases to facilitate closed flux surface formation.

The discharge waveform of the FNC and the TPC start-ups are shown in Fig. 6. The loop voltage was ap-

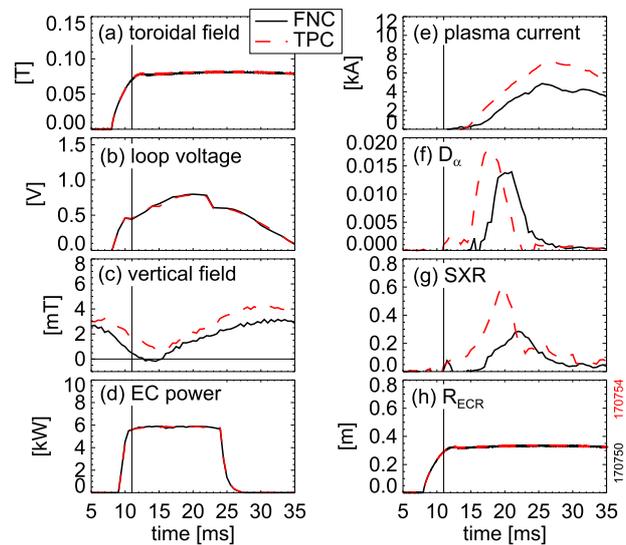


Fig. 6 The typical discharge waveform of EC-assisted low voltage Ohmic start-up with the FNC (black solid curve) and with the TPC (red dashed curve) at 0.045 mTorr D_2 prefill pressure. (a) toroidal field, (b) loop voltage, (c) vertical field, (d) EC power, (e) plasma current, (f) D_α radiation, (g) soft X-ray and (h) the EC resonance radius. The vertical line indicates the timing of breakdown.

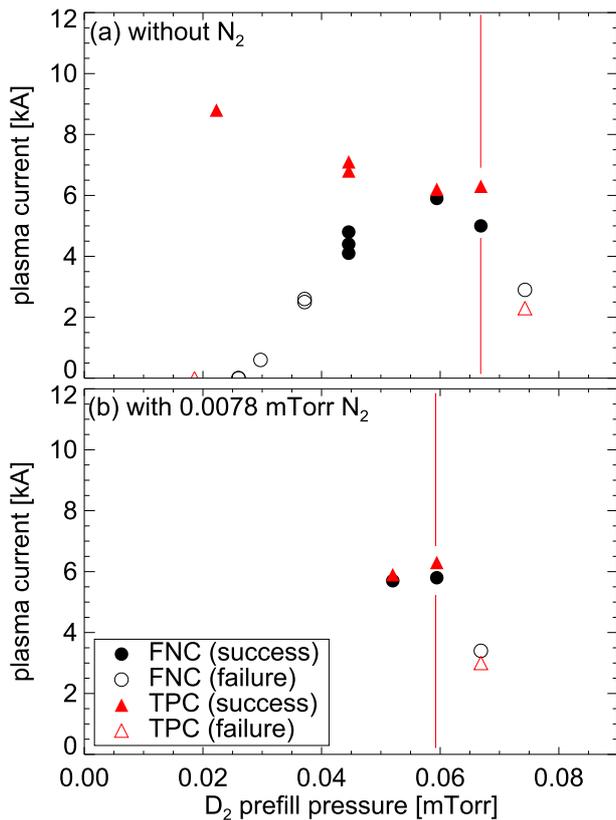


Fig. 7 The D₂ prefill pressure dependence of the start-up (a) without N₂ and (b) with 0.0078 mTorr N₂. Black circles and red triangles represent the FNC and the TPC start-ups, respectively. Filled symbols represent successful discharges and open symbols represent failed discharges (fizzle or no breakdown). The vertical red lines show the maximum pressure for successful start-up without and with impurities.

proximately 0.7 V (~ 0.3 V/m at the center of the vacuum vessel). The on-axis magnetic field of 0.08 T was applied, which corresponds to EC resonance layer located at 0.33 m. Figure 6(c) shows the vacuum vertical field waveform on-axis generated by the central solenoid and the poloidal field coils. Poloidal flux contours of the FNC and TPC at 15 ms are shown in Figs. 1 (a) and (b). The D₂ prefill pressure was 0.045 mTorr. At this pressure, prompt breakdown was obtained after applying EC power in the FNC and TPC (the vertical lines in Fig. 6). D _{α} and soft X-ray radiation was substantially enhanced in the TPC, which indicates production of denser and/or hotter initial plasma. This may be due to improved EC heating efficiency with the TPC that is designed to confine collisionless fast electrons effectively. At the same time, ramp up of plasma current in the TPC was faster than that in the FNC (Fig. 6(e)). Burn-through occurred 5 ms earlier in the TPC than in the FNC. Furthermore, higher plasma current was achieved with the TPC even though the loop voltage and the EC power were identical.

The D₂ prefill pressure window for successful start-up

was investigated. Figure 7 shows the D₂ prefill pressure dependence of the maximum plasma current in the discharge started with the TPC and FNC. Between the two configurations, no significant difference was observed on the upper prefill pressure limit. This is expected since the upper pressure limit is likely to be determined by the power balance between the EC and Ohmic heating and the radiation and ionization losses.

With decreasing prefill pressure, the maximum plasma current increased more or less monotonically in the TPC, whereas it decreased with a peak around 0.06 mTorr in the FNC. The start-up with FNC failed below 0.04 mTorr due to a large delay in the breakdown. Therefore, TPC had an advantage not only in terms of the extension of the lower pressure limit for successful start-up, but also of faster plasma current ramp-up at low pressure.

The effect of impurity on the TPC start-up was investigated to see if there is any difference with the FNC start-up. The result is shown in Fig. 7(b). With N₂, the upper pressure limit decreased in both configurations. No clear difference of impurities on the upper pressure limit was observed between the TPC start-up and the FNC start-up.

7. Discussion

The TPC start-up performed significantly better than the FNC start-up at low pressure. On the other hand, no large difference was observed between the two configurations at high pressure, including the cases where substantial impurities were introduced. These results show that the poloidal field optimization only affects the initial phase of the plasma start-up, that is, breakdown and closed flux surface formation, and does not strongly affect burn-through. The insensitivity of burn-through to the field configuration can be understood if this process is governed by the power balance of Ohmic and EC heating and the ionization and radiation losses. Only the total volume of the plasma and the vessel matters, and the detail of the geometry does not come into play.

On the other hand, the loss mechanism around breakdown is likely to be completely different for the TPC and FNC. Since electron confinement is provided basically by collisions in the FNC, increased electron energy at high EC power leads to longer mean free path and increased losses. In contrast, collisionless energetic electrons are confined well in the TPC. Although these electrons can still be lost by diffusion of the confined orbits driven by EC heating and inductive electric field, we have shown experimentally that breakdown is much less sensitive to EC power in the TPC compared with the FNC. The breakdown results in the FNC and TPC are summarized in Table 1. Note that burn-through is easiest at the lower left corner (low pressure and high EC power), but breakdown becomes difficult in this parameter regime in the FNC.

In ITER, the plasma volume is much smaller than the vessel volume [20] and the neutral pressure that is

Table 1 Comparison of time to breakdown between FNC and TPC in terms of prefill pressure and EC power. Circles: fast breakdown, triangles: slow breakdown, crosses: very slow breakdown.

	FNC		TPC	
	low pressure	high pressure	low pressure	high pressure
low EC power	Δ	\circ	\circ	\circ
high EC power	\times	\circ	\circ	\circ

high enough for pure Ohmic breakdown may result in plasma density that is too high for successful burn-through. EC assistance will help burn-through especially on post-disruption discharges with high impurity radiation. However, application of high EC power may result in excessive delay of early plasma formation in the conventional FNC. Delicate EC power modulation such as starting at sufficiently low EC power for breakdown and increasing the power as the burn-through phase is approached, is possible. The recently studied TPC offers an alternative and likely a much simpler, and hence, reliable solution; that is, to apply a high enough EC power for burn-through from the outset with the TPC to assure successful early plasma formation.

8. Conclusions and Future Work

Optimization of the poloidal field configuration for EC-assisted low voltage Ohmic start-up was performed in TST-2. Application of EC power throughout the burn-through phase increased the upper prefill pressure limit regardless of the poloidal field configuration. However, in the conventional field null configuration (FNC), large delay of breakdown at low pressure made start-up more difficult. The breakdown delay increased with EC power. This was mitigated by applying trapped particle configuration (TPC) that is a vertical field configuration with strong positive decay index. With the optimized vertical field structure, breakdown time was observed to decrease with stronger vertical field. As a result, lower pressure limit decreased, and faster plasma current ramp up was achieved in the TPC start-up compared with the FNC start-up under the same loop voltage and EC power waveforms. In both poloidal field configurations, the upper pressure limit decreased by the same fraction when N_2 gas was added.

All experiments presented here were performed with the fundamental EC resonance heating. For future work, Ohmic start-up assist at the second harmonic EC resonance

is necessary. This will benefit large tokamak devices that mostly use second harmonic EC heating.

Acknowledgments

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