WALL CONDITIONING PLASMA PRODUCTION USING FUNDAMENTAL AND SECOND HARMONIC ELECTRON CYCLOTRON WAVES IN JT-60SA

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The expansion of the electron cyclotron wall conditioning (ECWC) plasma produced at the fundamental resonance layer using the ordinary mode (O-mode) EC wave could be controlled by the poloidal magnetic configuration. The ECWC plasma at the second harmonic resonance layer, generated by the extraordinary mode (X-mode) EC wave, was produced locally and did not expand along the poloidal magnetic field line. The reconstruction of the ECWC plasma produced by the X-mode EC wave using Computer Aided Design (CAD) indicated that the plasma was mainly produced at the intersections of the injected and probably reflected EC rays with the second harmonic resonance layer.

Electron cyclotron wall conditioning is one of the candidates for inter-shot wall conditioning tools in superconducting devices. In JT-60SA and ITER, since the tokamak plasma is initiated from the inboard first wall as a limiter, fuel removal from the inboard first wall is necessary to start-up the tokamak plasma [1, 2]. To remove fuels from the inboard first wall efficiently, ECWC plasma needs to be expanded toward the inboard first wall because EC heated plasma is generated at a resonance layer due to a resonant process of EC absorption. In this study, plasma expansion using the different poloidal magnetic fields was investigated to discuss mechanisms of ECWC plasma production and expansion by the poloidal magnetic field [3].

We have conducted ECWC using helium working gas (He-ECWC) in JT-60SA with the experimental conditions summarized in Table 1 after hydrogen tokamak discharges. In one experimental sequence, one of two different EC waves (either 82 or 110 GHz) was selected, and three pulses of the EC wave were injected from a single upper oblique port in the direction normal to the toroidal field. The poloidal magnetic configuration was changed pulse by pulse as shown in Figs. 1 (a1) - (c1): the first 2 pulses were conducted with a Trapped Particle Configuration (TPC) at different *n*-indexes (curvatures) and the last one with a horizontal magnetic configuration. The produced plasma was monitored by a tangentially viewed visible camera. The hydrogen removal ratio against the residual molecules in the wall was evaluated using a quadrupole mass spectrometer.

As shown in Figs. 1 (a2) - (c2), the plasma produced at the fundamental resonance layer using the O-mode EC wave expanded along the poloidal magnetic field line. In the horizontal magnetic configuration, the plasma expanded in the entire torus volume. As shown in Figs. 1 (a3) and (b3), the plasma produced at the second harmonic resonance layer using the X-mode EC wave with the TPC did not expand along the poloidal magnetic field line. The plasma was produced locally around the center of the height direction and the lower position. As shown in Fig. 1 (c3), no clear plasma production was observed in the horizontal magnetic configuration.

As summarized in Table 2, the H_2 removal ratio by the O-mode EC wave depended on the poloidal magnetic configuration. The higher removal ratio of the TPC at $n = 0.7$ (1st pulse) compared to that at $n = 3$ (2nd pulse) could be due to its plasma interaction position being similar to that in the start-up phase of the tokamak plasma. The similar H_2 removal ratio observed in the horizontal magnetic configuration (3rd pulse) could be due to H_2 removal from the entire wall surface. No clear dependence on the poloidal magnetic configuration was observed for the X-mode. This should be due to the localized plasma production as shown in Figs. 1 (a3) and (b3).

Table 1 Experimental conditions of the He-ECWC.

	1st pulse	2nd pulse	3rd pulse
EC wave	(1) 82 GHz O-mode wave with an injection power of 0.8 MW (2) 110 GHz X-mode wave with an injection power of 0.5 MW		
B_T	1.79 T		
He gas pressure	(1) 1.1-1.7 mPa (2) 1.7-2.8 mPa		
Pulse width	0.3 sec (Duty cycle 1/100)		
Poloidal mag. conf.	TPC		Horizontal
	$n = 0.7$	$n = 3$	

To understand the mechanisms of plasma production by the X-mode EC wave, the position of the produced plasma is compared to that of the plasma reconstructed by CAD. As shown in Fig. 2, the radial and height positions of the plasma produced between the horizontal ports at P09 and P10 are consistent with those of the reconstructed plasma. The height position of the plasma produced at the lower part is inconsistent with the reconstructed plasma position. However, this plasma is expected to be produced by the reflected EC ray because a decrease in the toroidal field (or a shift of the resonance layer toward the inboard first wall) shifts the plasma in an upward direction. These results indicate that the X-mode EC wave produces the plasma locally at the intersections of the injected and probably reflected EC rays with the second harmonic resonance layer. This suggests a possibility that most of the injected EC power is absorbed by the injection and reflection passes. This local plasma production could hinder plasma expansion along the poloidal field line.

The reason why the plasma produced by the O-mode EC wave expands along the poloidal field line may be the lower absorption rate of the O-mode EC wave compared to that of the X-mode EC wave. The lower absorption rate enables the EC ray to pass through the resonance layer multiple times by multiple reflection at the wall, generating plasma along the fundamental harmonic resonance layer. The plasma at the resonance layer expands along the poloidal field line. The reduction in the absorption rate of the X-mode EC wave may also lead to plasma production along the second harmonic resonance layer and expansion along the poloidal field line.

Throughout the study, it is found that the X-mode EC wave produces plasma locally at the intersections of the injected and reflected EC rays with the second harmonic resonance layer. This could be because most of the EC power is absorbed at the layer by the injection and reflection passes. The local plasma production could hinder the plasma expansion along the poloidal magnetic field line. The expansion of the plasma produced by the O-mode EC wave at the fundamental resonance layer can be controlled by the poloidal magnetic configuration. This could be because the plasma is produced along the resonance layer by multiple reflection at the wall due to the lower absorption rate of the O-mode EC wave compared to that of the X-mode EC wave.

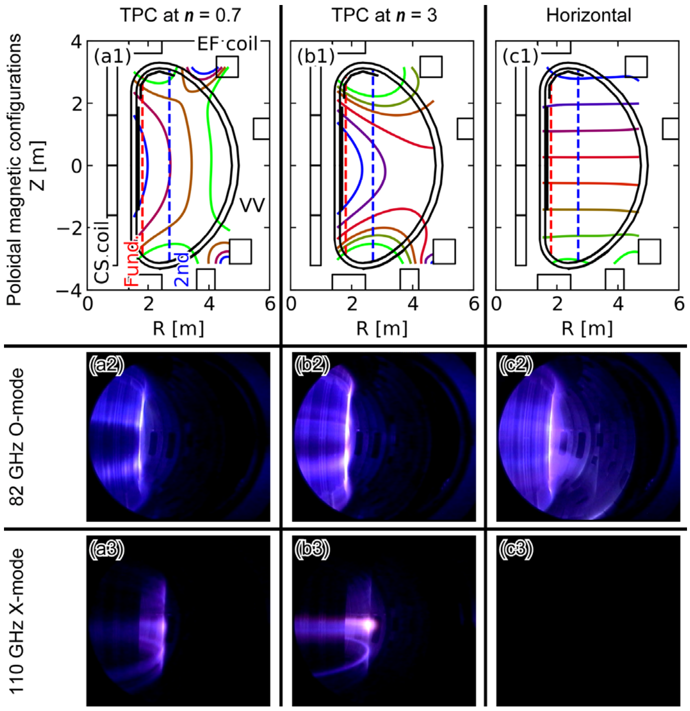

Figure 1. Helium ECWC plasma produced by different poloidal magnetic configurations and EC waves. (a1) - (c1) Poloidal magnetic configurations for O and X-mode ECWC: (a1) TPC at n = 0.7, (b1) TPC at n = 3, and (c1) horizontal magnetic configuration. (a2) - (c2) Plasma produced by 82 GHz O-mode EC wave and (a3) - (c3) 110 GHz X-mode EC wave. A fundamental and second harmonic resonance layers are located at R = 1.81 m and 2.70 m, respectively, for the EC wave with frequencies of 82 GHz and 110 GHz.

Table 2 H_2 removal ratio for the different pulses.

	1st pulse	2nd pulse	3rd pulse
O-mode	0.9%	0.6%	0.9%
X-mode	0.4%	0.5%	---

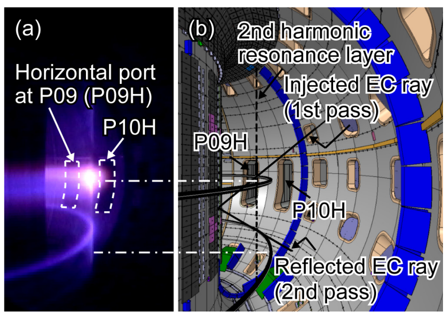

Figure 2. Comparison of (a) He-ECWC plasma produced by 110 GHz X-mode EC wave with (b) plasma reconstructed by CAD. The plasma is reconstructed based on the assumption that the plasma is produced at the intersections of the injected and reflected EC rays with the second harmonic resonance layer.

[1] T. Wakatsuki et al 2024 Nucl. Fusion **64** 1040035.
[2] M. Kocan et al 2015 Nucl. Fusion **55** 033019
[3] M. Fukumoto et al 2025 Nucl. Mater. Energy **42** 101816.