Start-up and Formation of ST Plasmas by ECH on the LATE Device

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Abstract. Experiments on start-up and formation of spherical tokamak (ST) plasmas by electron cyclotron heating (ECH) alone without ohmic heating (OH) have been performed in the LATE (Low Aspect ratio Torus Experiment) device. By injecting a 2 GHz/0.1 s microwave pulse at the power range of 20 - 50 kW and increasing the vertical field with time, the plasma current increases up to 5 kA. The magnetic measurements show that closed flux surfaces are formed and the outer most one has the aspect ratio $A \sim 1.4$ and the elongation $\kappa \sim 1.2$. The electron density is higher than the plasma cutoff density, suggesting that ECH by mode converted electron Bernstein waves (EBW) occurs.

1. Introduction

ST has good stability and confinement properties in high β plasmas as shown in recent experiments [1, 2] and a compact fusion reactor may be realized by ST. In order to produce the ST configuration, however, a large plasma current is needed, while there is a limited space around the center column for OH solenoids. Therefore, it is desirable to develop an effective current drive (CD) scenario to initiate, raise and sustain the plasma current by non-inductive methods. In these circumstances, start-up and formation by using ECH/ECCD is attractive [3], since plasma initiation, current start-up and sustainment can be realized simultaneously by using a microwave power at the electron cyclotron frequency. Once a target plasma with sufficiently high density and current for neutral beam injection (NBI) is produced by the ECH/ECCD method, fusion ignition may be achieved by subsequent NBI and then the plasma current self-sustained by the pressure driven current. Thus, central OH solenoid can be removed and a steady state ST fusion reactor with a simple structure may be realized. Main objective of the LATE device is to demonstrate start-up and formation of ST plasmas by ECH/ECCD alone without OH power. In this paper we report the results using a 2.0 GHz microwave power. We employ an oblique injection of microwaves to the toroidal field to ensure ECCD and also mode-conversion to EBWs to heat over-dense core plasmas [4].

2. Experimental Setup

Figure 1 shows the side view of the LATE device. The vacuum chamber is a stainless steel cylinder with an inner diameter of 100 cm and a height of 100 cm. The center stack is a stainless steel cylinder with an outer diameter of 11.4 cm with two rail Mo limiters attached outside and encloses 60 turns of toroidal field coil. There is no central solenoid for OH. The center stack can serve the constant toroidal coil current up to 180 kAT for 0.1 s. There are 3 sets of vertical field coils of which currents are controlled by preprogramming. The microwave power from a klystron (2 GHz, 350 kW, 0.1 s) is injected obliquely to the toroidal field from the outboard side with circular TE_{11} mode with E vector on the equatorial plane in order to excite EBWs via the O-X-B process [4] as shown in Figure 2. The plasma current is estimated from the 15 flux loop coils. The line-integrated electron density is measured by a 70 GHz microwave interferometer along a vertical chord at $R =$ 27 cm. The working gas is hydrogen.

3. Experimental Results

The time evolution of the typical discharge is shown in Figure 3. The toroidal coil current is $I_{\rm T}$ = 58.4 kAT with the ECR layer at R = 16.2 cm for 2.0 GHz. The initial plasma is produced by the fundamental EC resonance with a weak vertical field ($B_{\rm V} \sim$ 10 G at R $\sim$ 20 cm). By increasing both the injected microwave power $P_{\rm inj}$ and the vertical field $B_{\rm V}$ gradually from time $t = 0.05 - 0.077$ s, the flux loop signal Φ_5 (see Fig.1) increases slowly. This signal shows the net poloidal flux produced by the toroidal plasma current, after subtracting the flux produced by the vertical coil currents and eddy currents flowing in the vacuum chamber, therefore, is nearly proportional to the plasma current. The direction of the plasma current is opposite to that of the vertical coil currents. At this stage, the line-integrated electron density $N_{\rm e}L$ reaches $\sim 1 \times 10^{13}$ cm^{-2}. Then at t = 0.077 s, the density $N_{\rm e}L$ drops abruptly to 2.6 $\times 10^{12}$ cm^{-2} and the flux signal Φ_5 increases quickly. After t = 0.079 s, $P_{\rm inj}$ is set at constant value of 45 kW and the signal Φ_5 slowly increases as $B_{\rm V}$ is increased, while $N_{\rm e}L$ does not vary. After t = 0.12 s, $B_{\rm V}$ is kept constant and the signal Φ_5 becomes a constant value.

Careful adjustment of $B_{\rm v}$ ramp-up rate is needed to obtain stable current ramp-up discharges. As shown in Figs.3 (a) and (d), the flux loop signal increases roughly in proportion to $B_{\rm V}$ from t = 0.08 s to 0.12 s. Magnetic measurement shows that initial closed flux surface is formed at t = 0.08 s. Therefore, the current ramp-up and sustainment after t = 0.08 s is ascribed to ECH/ECCD inside the last flux surface, while the initial formation of closed magnetic surface may be ascribed to the current generation in the open vertical field with the appropriate mirror ratio as observed in CDX-U [5].

Figure 4 shows the contour map of the poloidal flux at t = 0.14 s in Fig. 3, reconstructed from the magnetic measurements. In this analysis, the plasma current is replaced by 3 filament currents and the values and positions are calculated with the least-squares fitting method. The result shows that the total plasma current $I_{\rm p}$ = 5 kA flows. The outer most flux surface bounded by the inboard Mo limiters has the aspect ratio $A \sim$ 1.4 and the elongation $\kappa \sim$ 1.2 ($R \sim$ 18 cm, $a \sim$ 13 cm, $b \sim$ 16 cm). Assuming that the plasma diameter along the interferometer chord is 40 cm, the line-averaged electron density at R = 27 cm is 6.5 $\times 10^{10}$ cm^{-3}, which slightly exceeds the cutoff density for 2 GHz microwave (5 $\times 10^{10}$ cm^{-3}). When the initial hydrogen filling pressure is slightly increased, a discharge with four times higher electron density is obtained. In this discharge, however, the final driven current is 1 kA and the plasma center estimated from the magnetic measurements is relatively outwards (R = 28 cm). These results suggest that the mode-converted EBWs via the O-X-B scheme heat the plasma and drive the current.

Figure 5 shows theoretically estimated mode-conversion rate to EBWs from electromagnetic waves obliquely injected at the optimal angle with different polarizations versus the scale length of electron density gradient at the upper hybrid resonance layer. Although good conversion rate is expected for both elliptically polarized Quasi-O mode and left-handed circularly polarized mode, the rate for the present linear polarized mode is poor. We are now going to modify the ECH system in order to inject the microwaves in the circular or QO modes.

4. Summary

The plasma current can be started-up and increases up to 5 kA by injecting a 2 GHz microwaves with 20 - 50 kW. The magnetic measurements show that closed flux surfaces are formed with the aspect ratio $A \sim$ 1.4 and the elongation $\kappa \sim$ 1.2. The electron density is higher than the plasma cutoff density, suggesting that ECH/ECCD by mode-converted EBWs occurs.

References

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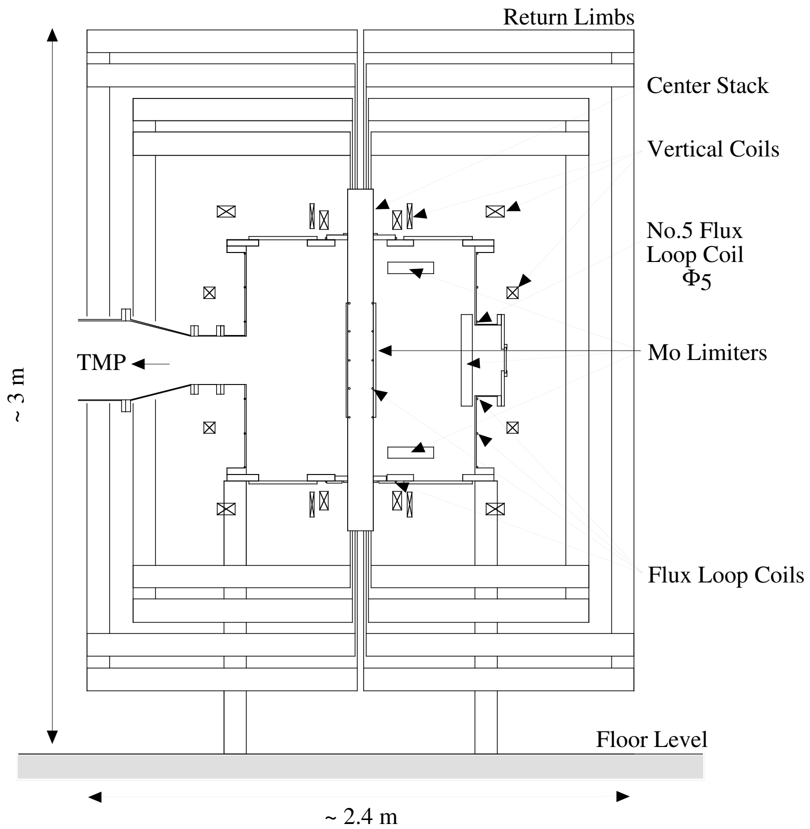

Fig.1 The LATE device

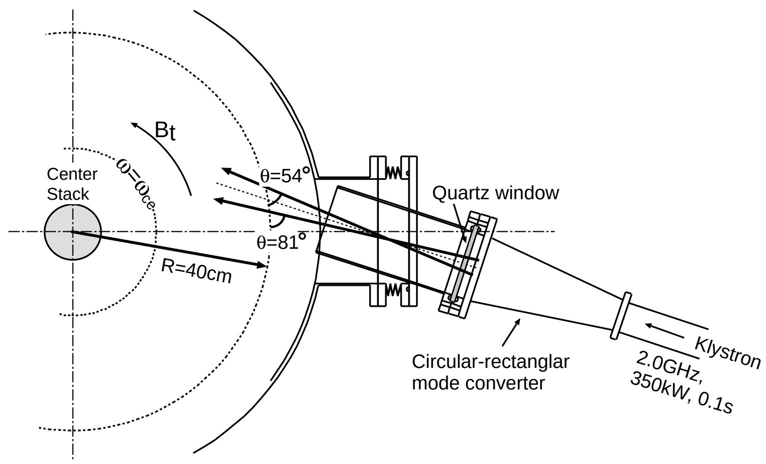

Fig.2 The 2 GHz launcher

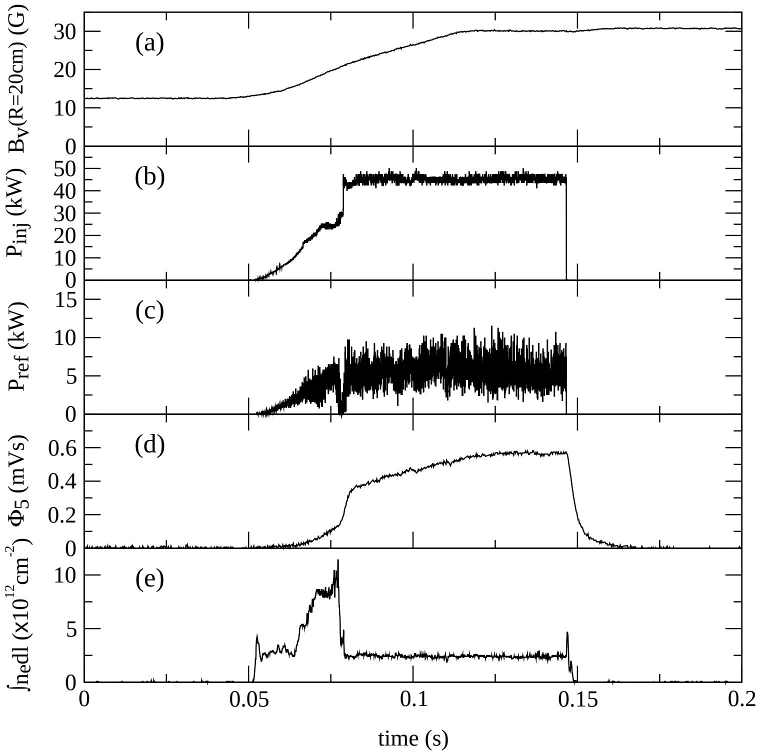

Fig.3 Waveforms of discharge : (a) external vertical field at $R = 20$ cm, (b) Injected microwave power, (c) Reflected microwave power, (d) No.5 flux loop coil signal and (e) line-integrated electron density measured along vertical chord at $R = 27$ cm

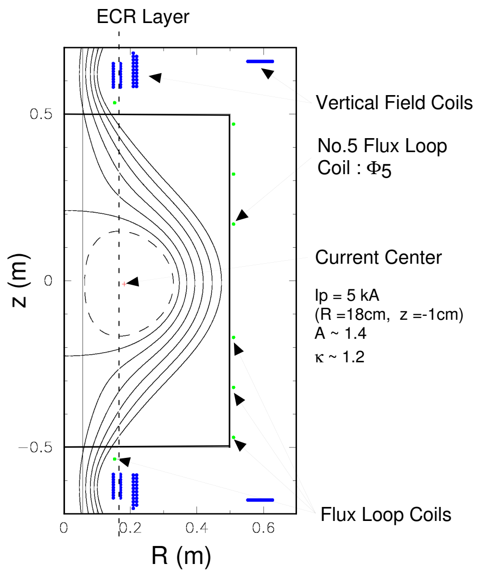

Fig.4 Contour map of the poloidal flux at $t = 0.14$ s

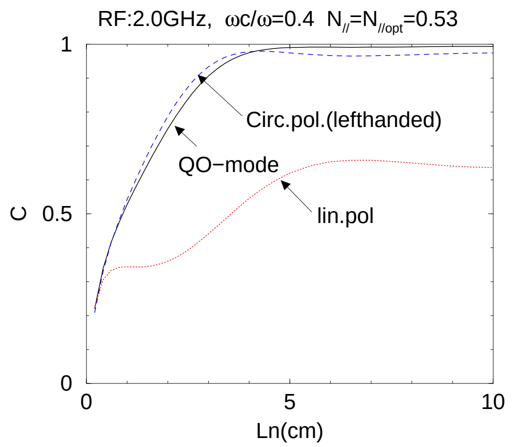

Fig.5 Mode-conversion rate to EBWs from electromagnetic waves with various polarizations.