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Formation of ECH Spherical Tokamak on LATE

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Abstract

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. 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.

I. Introduction

It is expected that ST has good stability and confinement properties in high β plasmas and the compact fusion reactors may be realized by ST. Experiments in the middle-size ST's such as NSTX and MAST are being performed eagerly and promising results have been obtained [1, 2]. To produce the ST configuration, a large plasma current comparable to the toroidal field coil current should be driven, while there is a limited space around the center column for central solenoid coils for OH. Therefore, it is necessary to develop a effective current drive (CD) scenario to initiate, raise and sustain the plasma current by non-inductive methods.

One of the candidates is the ECH/ECCD method. Using a microwave in the electron cyclotron range of frequency, plasma production, plasma current start-up and sustainment can be realized simultaneously. When it is shown that the ECH/ECCD method is effective to produce sufficiently high plasma current and density, fusion ignition may be obtained by applying neutral beam injection (NBI) to this target plasma and the plasma current may be self-sustained by pressure driven current. Thus, central solenoid coils for OH can be removed and the steady state ST fusion reactor with a simple structure will be realized. It should be emphasized that the ECH/ECCD method needs no structures in close proximity to the plasma, which is quite advantageous for the reactor design. Main objectives of the LATE device are to realize start-up and formation of ST plasmas by ECH/ECCD alone without OH power (ECH Spherical Tokamak) and also to demonstrate EBW heating and current drive in over dense plasmas.

The scenario of such ECH Spherical Tokamak formation is as follows: First, the breakdown and production of a initial plasma is easily obtained near the EC resonance layer. Next, applying a weak vertical field superimposed to a toroidal field, the field lines connect the top and the bottom of the plasma and the toroidal current flows to short the charge separation caused by the grad B drifts in the vertical direction. The external field with a proper mirror ratio improves the particle confinement and the toroidal current increases further, resulting in the formation of closed flux surfaces. Once the closed flux surfaces are formed, particle confinement is further improved and the density may easily exceeds the cutoff density. Then the injected microwaves are reflected back and do not penetrate into the core plasma. But, linear theory predicts that the adequate choice of the injection angle and the polarization of microwaves admits the effective mode conversion to EBW at the upper hybrid resonance layer [3, 4]. EBW propagates into the core plasma without density limit and heats electrons efficiently even in low temperature plasmas. The resultant high electron temperature by ECH and the upshift of the refractive index parallel to the magnetic field lead to efficient ECCD, and the large plasma currents will flow (including the bootstrap currents). In this way, ST plasma will be produced by the microwave power only.

II. Experimental Setup

Figure 1 shows the side view of the LATE device. There are no central solenoid coils for OH [5]. The vacuum chamber of LATE is a stainless steel cylinder with an inner diameter of 100 cm and a height of 100 cm. There are Mo limiters to bound the plasma. The center stack can serve the constant toroidal coil current up to 180 kAT for 0.2 s or 60 kAT in steady state. There are 3 sets of vertical field coils whose currents are controlled by preprogramming. The microwave power from a klystron (2 GHz, $\leq$ 350 kW, $\leq$ 0.1 s) is injected obliquely to the toroidal field from the outboard side in circular TE_{11} mode with E vector parallel to the toroidal field (O-mode). 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.

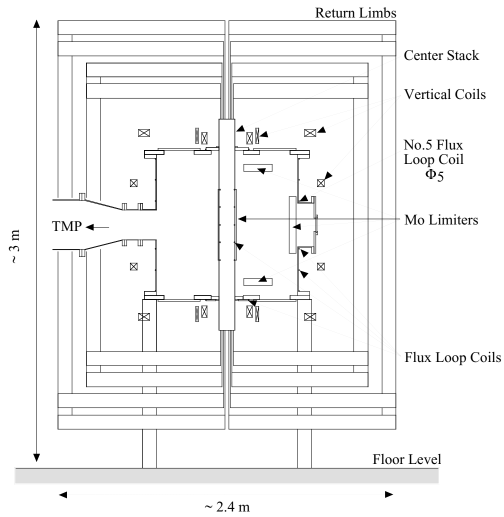

Fig.1 The LATE device

III. Experimental Results

The time evolution of the discharge is shown in Fig.2. The toroidal coil current $I_{\rm T} =$ 58.4 kAT. 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). As 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, subtracting the flux produced by the vertical coil currents and eddy currents flowing in the vacuum chamber. The direction of the plasma current is opposite to that of the vertical coil currents. At this stage, the line-integrated electron density $N_{\rm e}L$ becomes $\sim 1 \times 10^{13}$ cm^{-2}. Then at $t = 0.077$ s, the density $N_{\rm e}L$ decreases abruptly to 2.6 $\times 10^{12}$ cm^{-2} and the flux signal Φ_5 increases rapidly. After $t = 0.079$ s, $P_{\rm inj}$ is set at constant value of 45 kW and the signal Φ_5 still 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.

Figure 3 shows the contour map of the poloidal flux at $t = 0.14$ in Fig. 2, 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 and closed flux surfaces are formed. The outer most flux surface bounded by the 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 length 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 exceeds the cutoff density for 2 GHz microwave (5 $\times 10^{10}$ cm^{-3}). This fact suggests that the electron Bernstein waves may be mode converted by the O-X-B scheme, heat the plasma and drive the plasma current.

For a fixed value of $P_{\rm inj}$, the flux signal Φ_5 which is roughly proportional to the plasma current increases with time as the externally applied vertical field $B_{\rm V}$ is increased with time. But when $B_{\rm V}$ becomes too large, Φ_5 decreases suddenly and becomes nearly zero during the discharge. Then, if $P_{\rm inj}$ is more increased, Φ_5 does not decrease and continue to increase at larger $B_{\rm V}$. In Fig. 4, the maximum flux change in Φ_5 is plotted as a function of $B_{\rm V}$ at $R = 20$ cm for various $P_{\rm inj}$. Results with low injected microwave power at 2.45 GHz are also plotted. The obtained maximum value of Φ_5 is nearly proportional to $B_{\rm V}$ and increases with $P_{\rm inj}$. Calculating $I_{\rm p}$ as obtaining Fig.3, it is confirmed that $I_{\rm p}$ is proportional linearly to $B_{\rm V}$ and the relation is roughly consistent with a simple ST equilibrium model [6] .

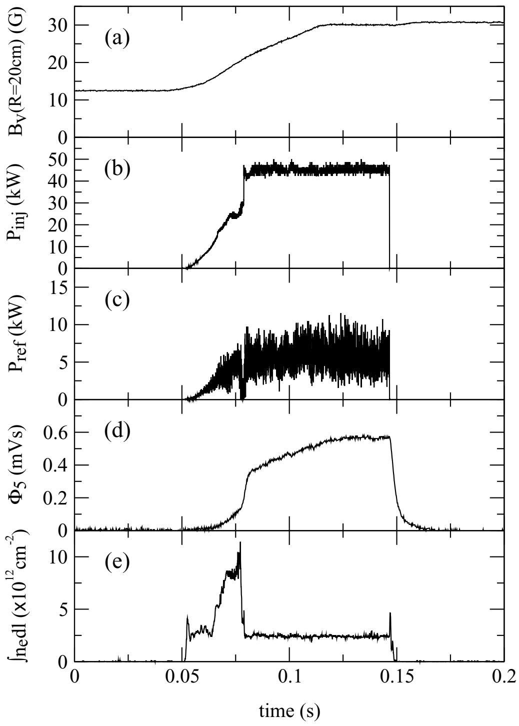

Fig.2 Waveforms of discharge : (a) external vertical field at $R = 20$ cm, (b) Injected microwave power, (c) Reflected microwave power, (d) No.5 flux loop coil signal and (e) line-integrated electron density measured along vertical chord at $R = 27$ cm

IV. Summary

Start-up and formation of ST plasmas by ECH alone have been carried out on LATE. By injecting the microwave power (45 kW, 0.1 s) and increasing the vertical field during the discharge, plasma current is produced and ramped up to 5 kA. From the magnetic measurement, it is shown that closed flux surfaces are formed. The outer most flux surface has the aspect ratio $A \sim 1.4$ and the elongation $\kappa \sim 1.2$. The line-averaged electron density is 6.5×10^{10} cm^{-3}, which is higher than the plasma cutoff density. This fact suggests that the injected microwave is mode converted and EBW heating is occurred. The maximum plasma current increases with the injected microwave power, and is proportional to the applied vertical field strength and the relation is roughly consistent with the ST equilibrium model.

Acknowledgements

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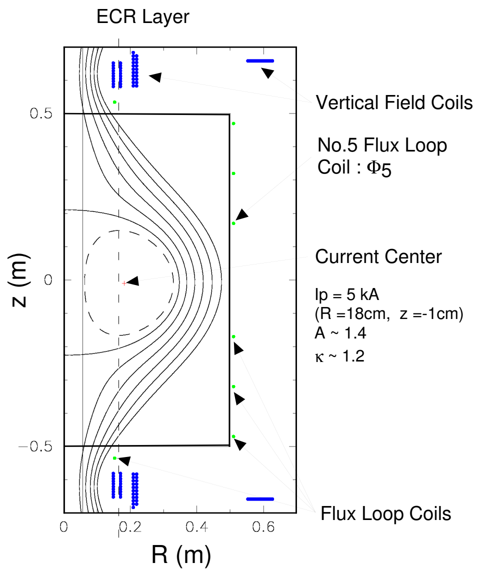

Fig.3 Contour map of the poloidal flux at t = 0.14 s

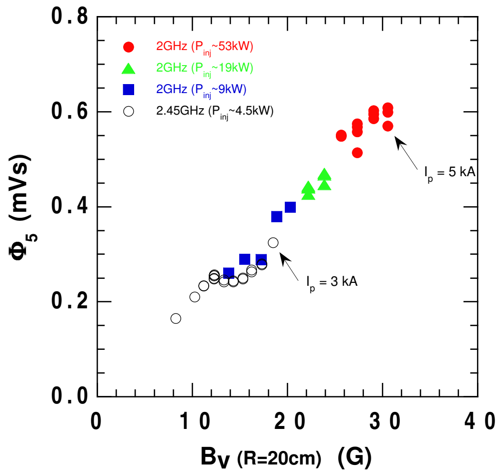

Fig.4 Dependence of the maximum flux change in the No.5 loop coil Φ_5 on B_v for P_{inj} = 9, 19 and 53 kW. The results with 2.45 GHz/4.5 kW microwave are also plotted.