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Formation and Sustainment of Low Aspect Ratio Torus Plasma by ECH in the LATE Device

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Abstract

A plasma current of $I_p \simeq 3$ kA is generated and maintained for 1 second by injecting a 2.45 GHz microwave power of 5 kW without Ohmic heating power. Magnetic measurements suggest that closed flux surfaces are formed. The electron density inferred from an interferometer is more than 1.0×10^{11} cm^{-3} which is beyond the plasma cut off density, suggesting that electron cyclotron heating by mode-converted electron Bernstein waves may be responsible for plasma heating and current drive. The plasma currents are observed to increase with the increase of RF power and equilibrium vertical field, and $I_p \simeq 5$ kA have been obtained by 2 GHz klystron power of 53 kW.

Keywords:

spherical tokamak, current drive, plasma production, electron cyclotron heating, electron Bernstein wave

1. Introduction

Since Peng and Strickler [1] introduced theoretical advantages of the spherical torus (ST) concept in 1986, there has been great interest in the ST. Their predictions have been experimentally verified on small ST's [2] and the next generation ST's recently began to operate [3,4].

Because of the narrow center column space in the ST devices, the inductive flux of ohmic coils is severely restricted. Non-inductive startup and current sustainment is therefore an important subject for ST. Heating and current drive schemes by means of such as the coaxial helicity injection [5] (CHI) and the electron cyclotron heating [6] (ECH) are now studied in several ST devices. As for ECH, using a microwave at the electron cyclotron frequency, plasma production, current start-up and sustainment may become possible. We cannot, however, take an advantage of the conventional ECH because ST plasmas are essentially overdense. The electron Bernstein (EB) wave heating is considered a possible way to the effective heating of these ST plasmas since EB waves can propagate and be absorbed via EC damping in such overdense plasmas.

The LATE (Low Aspect ratio Torus Experiment) device has been constructed to investigate the basic physical mechanism of plasma production, heating and current drive by the microwave power alone at electron cyclotron frequency in the low aspect ratio torus plasma. The main research objective of the LATE is to produce the ST configuration by ECH without Ohmic heating. In this paper, we report an start-up and sustainment of $I_P \sim$ 3 kA for 1 second by a 5 kW ECH power from a 2.45 GHz magnetron and some preliminary results of high power experiments with a 2 GHz - 350 kW - 0.1 s klystron.

2. Experimental Apparatus

The experiments are performed on the LATE device which is described in detail elsewhere [7]. Since our study is concentrated upon the non-inductive plasma

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production, the LATE has no ohmic solenoid. The stainless vacuum vessel is a 1-m-diameter and 1-m-height cylinder, which is evacuated with a turbo molecular pump to base pressures of $< 5 \times 10^{-5}$ Pa.

Both toroidal magnetic field coils and vertical magnetic field coils can be operated steady. A 11.4-cm-diameter center stack can flow 60 kAT which generates a fundamental ECH resonance layer (B = 875 G) for 2.45 GHz microwave at a radius of R = 13.7 cm. The vertical field coils consist of two sets of mirror-type coils.

The microwave power of ≤ 5 kW from a 2.45 GHz-CW magnetron is converted from a TE_{01} rectangular waveguide mode into a TE_{11} circular mode which is injected into the plasma through a circular quartz window. The power is launched from the outboard side on mid-plane at an oblique angle to the toroidal field. The injected wave is linearly polarized with the electric field parallel to the equatorial plane. It is expected in this setup that some portion of the wave is mode-converted into the EB wave via the so-called OXB process [8]. Another system for a 2 GHz - 350 kW - 0.1 s klystron has the same structure except for the size of a circular waveguide and a quartz window.

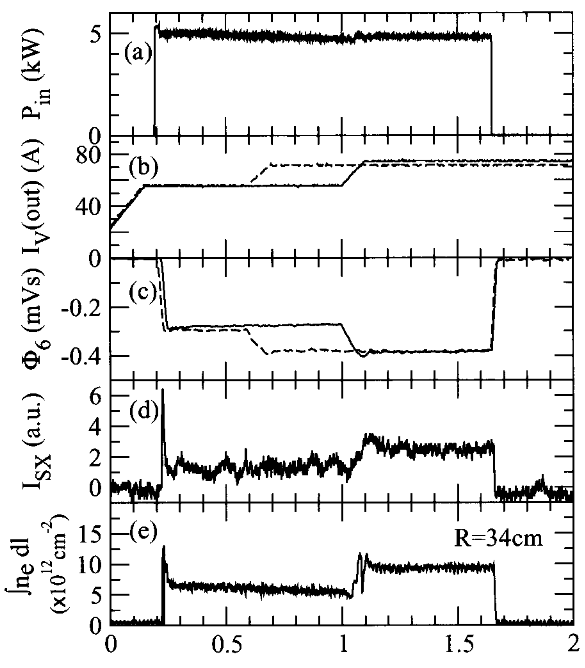

Fig. 1 Time traces of a discharge for I_T = 59.4 kAT, P_{RF} = 5 kW, and H_2 gas pressure $p_0 = 6 \times 10^{-3}$ Pa. (a) injected microwave power; (b) vertical coil current; (c) flux loop signal Φ_6; (d) soft X-ray emission signal from a SSB diode looking for the whole plasma; (e) line-integrated electron density along the vertical chord at R = 34 cm (see Fig. 2).

3. Experimental Results and Discussion

A. Experiments with a 2.45 GHz - 5 kW Magnetron

Experiments are performed in quasi steady-state. The microwave power is injected after both the toroidal and the vertical coil currents become steady, which have been ramped up to specified values in advance.

Figure 1 shows time histories of a discharge for the toroidal coil current of I_T = 59.4 kAT, the 2.45 GHz microwave power P_{RF} = 5 kW, and H_2 gas pressure $p_0 = 6 \times 10^{-3}$ Pa. When the microwave power is injected after the vertical coil current is raised up to a specified value, the flux loop signal Φ_6, wound around the vessel (see Fig. 2), falls in ~ 20 ms and then is kept constant. The negative variations of the flux signal correspond to the variations such that the applied vertical field is weakened, which means a net toroidal currents flow in the opposite direction of the vertical field coil currents. In this shot, the vertical field strength B_V is ramped up in the midst of the discharge. The flux loop signal Φ_6 is plotted with subtracting the contribution from this B_V

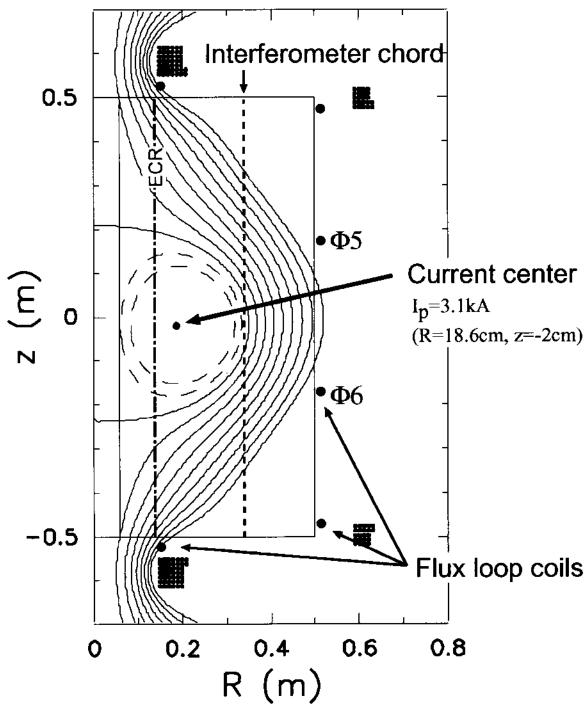

Fig. 2 A contour map of the poloidal flux with I_p = 3.1 kA for the discharge shown in Fig. 1 at t = 1.65 s.

ramp, and thus shows the net variation of poloidal flux produced by the plasma current. When the vertical field coil current is ramped up at a rate of 160 A/s from t = 1.0 s to 1,1 s, the plasma current is increased. The current is sustained and monotonically increased until the microwave power is turned off. In the case that the B_V is ramped earlier in a discharge, a plasma current is maintained for 1 second after the B_V ramp (dotted line). The soft X-ray emission signal and the line-integrated electron density are also increased with the B_V ramp, indicating that the plasma parameters are improved. The line-averaged electron density at the end of the discharge is $\bar{n}_e \simeq 1.0 \times 10^{11}$ cm^{-3} even if the plasma is filled uniformly in the entire vessel, and is beyond the plasma cut off density (7×10^{10} cm^{-3}).

The magnitude of the plasma current is calculated from the measured flux variation in six loop coils (see Fig. 2). Assuming that the plasma current is a toroidal filament current, its magnitude and position is determined by using the least square method such that the measured flux data is fitted the most. In the discharge shown in Fig. 1, a toroidal current of I_P = 2.6 kA flows at (R, Z) = (18.1 cm, –1.5 cm) just before the B_V ramp (t = 1.0 s), and I_P = 3.1 kA at (R, Z) = (18.1 cm, –2.0 cm) at the end of the microwave pulse (t = 1.65 s). In this discharge, the current position is hardly changed during the B_V ramp. The loop voltage produced by the B_V ramp is about 3 mV and the resulting Ohmic heating is negligible. These results suggest that the increase of the plasma current and the improvement of plasma parameters are not attributed directly to the B_V ramp but to some change in the coupling between current-carrying electrons and the microwave. Further experiments are left for the study on this mechanism.

Figure 2 illustrates the contour map of the poloidal flux inferred from the fit for I_P = 3.1 kA. This indicates that the closed flux surfaces are created. The outermost surface is limited on the casing of the center stack, and has an aspect ratio of $A \sim 1.4$. The current center is slightly outside the ECR layer. The microwave interferometer chord is shown in Fig. 2, and the line-averaged density exceeds the plasma cut off density as mentioned above. These results suggest that electron cyclotron heating by mode-converted electron Bernstein wave may be responsible for plasma heating and current drive. The injected waves may be mode-converted to the EB waves via the OXB process, or possibly XB process with multiple wall reflections. For the density profile roughly inferred from Langmuir probes and the microwave interferometer, both the processes can be taken place. The process of the mode conversion is not clarified.

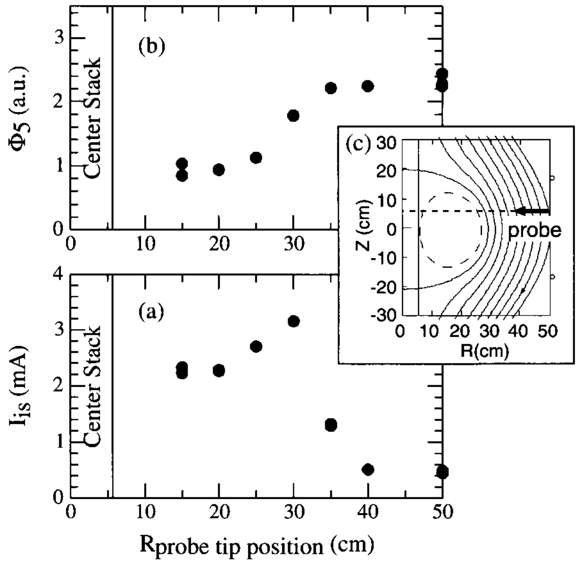

Fig. 3 (a): Radial profile of the ion saturation current at z = +6.8 cm; (b): Flux variation in the No. 5 flux loop coil as a function of the location of the probe tip; (c): Flux contour inferred from the magnetic measurement.

To check this flux surface closure, radial profiles of the ion saturation current are taken with floating double probes scanning shot by shot. In Fig. 3, the radial profile at z = +6.8 cm is shown together with the magnitudes of Φ_5 and poloidal flux contours for which measurements are performed. The abscissae in the Fig. 3 (a) and (b) represent the location of the probe tip. The ion saturation current increases abruptly near the outermost magnetic surface which is inferred from the magnetic measurement, and, in accordance with it, Φ_5 decreases due to disturbing the flow of the plasma current. These results show consistency with the magnetic measurement. The corresponding measurement in the vertical direction at R = 24.5 cm is also performed, confirming the consistency with the magnetic measurement.

The magnitudes of the flux variation in experiments with 3–5 kW microwave power and the various vertical field strengths, are summarized in Fig. 4. Since the locations of the current center are almost the same through these experiment, Φ_6 indicates a quantity proportional to the plasma current. The flux variation of Φ_6 increases almost linearly with B_V under a fixed microwave power, but become saturated and decreased when B_V is too strong (crossed symbols: P_{RF} = 3 kW).

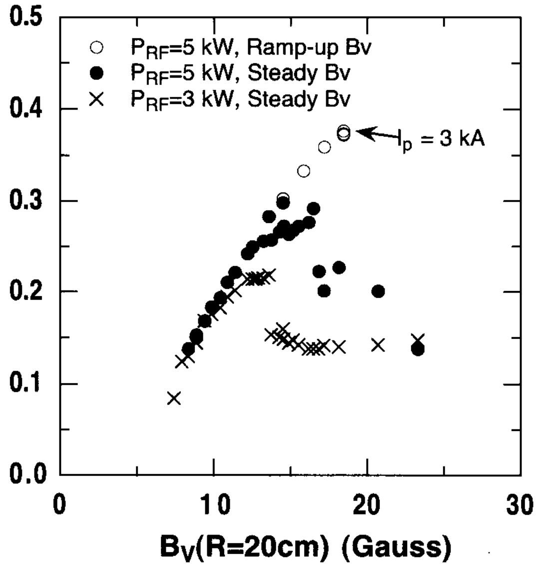

Fig. 4 The flux variation in the No. 6 loop coil versus the vertical field strength.

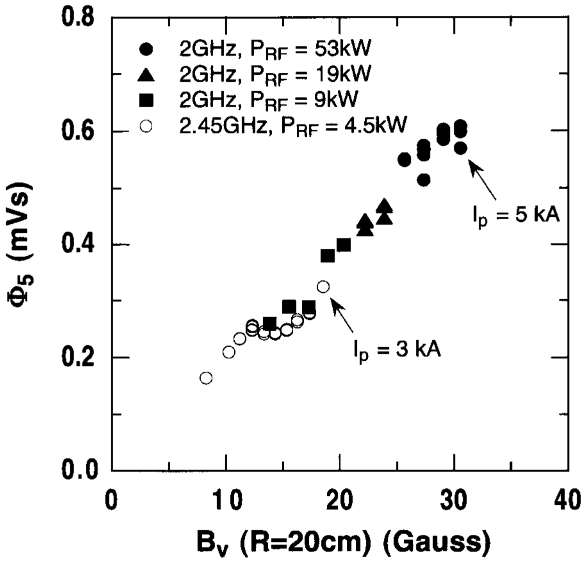

Fig. 5 The flux variation in the No. 5 loop coil versus the vertical field strength for P_{RF} = 9, 19, 53 kW at 2 GHz. Results with 2.45 GHz microwave (P_{RF} = 4.5 kW) are also shown.

With higher microwave power (filled circles: P_{RF} = 5 kW), this saturation is shifted to the stronger B_V regime and accordingly reached a larger Φ_6. In addition, when B_V is ramped up as shown in Fig. 2 (open circles: P_{RF} = 5 kW), Φ_6 increases without saturation.

B. High Power Experiments with a 2 GHz - 350 kW Klystron

A new antenna for 2 GHz - 350 kW klystron has been installed to investigate higher microwave power regime, and some preliminary results are obtained. During the microwave pulse of 100 ms, the vertical field is ramped up in first 80 ms and steady in the rest 20 ms.

The plasma currents are observed to increase with an increase of the microwave power and the equilibrium vertical field. In Fig. 5, the magnitudes of the flux variation of Φ_5 at the end of microwave pulse are plotted as a function of B_V. The plasma currents up to 5 kA have been so far obtained with 53 kW microwave power. It is noted that the current does not increase linearly with the microwave power. In the high power regime, it is found that there is an overdense region outside the magnetic surface, thus this may prevent the microwave power from being absorbed in the core plasma. The control of density profiles is needed for higher power experiments.

In Fig. 6, the obtained plasma current is compared with an equilibrium model developed by Ludwig and Andrade [9] for low aspect ratio tokamak plasma. The

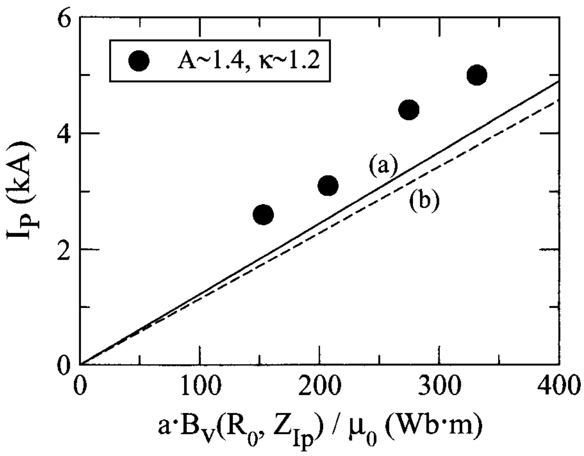

Fig. 6 Observed plasma currents are plotted as a function of the vertical field at the current center. Solid line (a) shows a possible equilibrium vertical field for A = 1.4, κ = 1.74, δ = 0.411, and R_0' (a) = −0.678 in ref. [7]. Dashed line (b) shows the vertical field which satisfy the force balance with a given toroidal plasma with A = 1.4 and κ = 1.2, using a plasma self-inductance and a mutual inductance in ref. [8].

results of both the 2.45 GHz RF and the 2 GHz RF experiments are plotted. The solid line (a) represents a possible equilibrium solution that is calculated for a given aspect ratio of A = 1.4 with some constraints on the geometric parameters describing the plasma cross section. This solution has an elongation $\kappa = 1.74$ and a triangularity $\delta = 0.411$. Another comparison is made with the vertical field which satisfy the force balance with a given toroidal plasma with no internal pressure, using a self-inductance and mutual inductance developed for an arbitrary aspect ratio by Hirshman and Neilson [10]. The dashed line (b) shows the equilibrium vertical field calculated for $A = 1.4$ and $\kappa = 1.2$. The magnitudes of the observed current are roughly consistent with the equilibrium vertical fields in both the models. This suggests that the low aspect tokamak configuration is formed by ECH power alone.

4. Summary

A plasma current of 3 kA is produced and maintained for 1 second by 5 kW ECH power at 2.45 GHz without Ohmic heating. The magnetic measurements indicate that the closed flux surfaces are formed and the outermost surface has an aspect ratio of $A \sim 1.4$. The plasma current is decreased when the probe is inserted inside the closed flux surface, confirming the consistency with the magnetic measurement. The central density exceeds the plasma cut off density, suggesting the heating by the electron Bernstein wave.

The new antenna for a 2 GHz - 350 kW microwave has been installed and preliminary results are obtained. The plasma current is observed to increase with the microwave power and the equilibrium vertical field, and the plasma current up to 5 kA has been obtained with 53 kW ECH power. The magnitudes of the obtained plasma current are roughly consistent with the theoretical equilibrium vertical field for the low aspect ratio tokamak plasma.

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