Formation of Spherical Tokamak Equilibria by ECH in the LATE Device

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Abstract. Main objective of the LATE (Low Aspect ratio Torus Experiment) device is to demonstrate formation of ST plasmas by electron cyclotron heating (ECH) alone without center solenoid. By injecting a 2.45 GHz microwave pulse up to 30 kW for 4 seconds, a plasma current of 1.2 kA is spontaneously initiated under a weak steady vertical field of $B_\mathrm{v} = 12$ Gauss, and then ramped up with slow ramp-up of B_v for the equilibrium of the plasma loop and finally reaches 6.3 kA at $B_\mathrm{v} = 70$ Gauss. This currents amount 10 percents of the coil currents of 60 kAT for the toroidal field. Magnetic measurements show that an ST equilibrium, having the last closed flux surface with an aspect ratio of $R_0/a \simeq 20.4\,\mathrm{cm}/14.5\,\mathrm{cm} \simeq 1.4$, an elongation of $\kappa = 1.5$ and $q_\mathrm{edge} = 37$, has been produced and maintained for 0.5 s at the final stage of discharge. The plasma center locates near the second harmonic EC resonance layer and the line averaged electron density significantly exceeds the plasma cutoff density, suggesting that the second harmonic EC heating by the mode-converted electron Bernstein waves (EBW) support the plasma. Spontaneous formation of ST equilibria under steady B_v fields, where plasma current increases rapidly in the time scale of a few milliseconds, is also effective and a plasma current of 6.8 kA is spontaneously generated and maintained at $B_\mathrm{v} = 85$ Gauss by a 5 GHz microwave pulse (130 kW, 60 ms).

1. Introduction

The spherical torus (ST) concept was proposed to be attractive [1] since it can realize high beta plasmas in a compact shape. For future ST fusion plants, however, removing the central Ohmic solenoid is considered to be a crucial step [2], since STs have only a limited space at the center column of the devices to ensure the virtue of low aspect ratio. It is therefore strongly desired to develop a non-inductive start-up scenario to initiate and ramp-up the plasma current to a level sufficient for the second heating and current drive by NBI to reach fusion burning. Electron cyclotron heating and current drive (ECH/ECCD) is potentially an attractive candidate for this purpose, since plasma initiation, and current start-up and ramp-up might be realized simultaneously. The requirement is only an injection of microwave power from a small launcher remote from the plasma without additional structures in the vicinity of the plasma, which allows a simplified, compact ST configuration. Although feasibility of this scheme is needed to be justified by large scale experiments in future, small scale experiments as presented here are desirable to establish physical and technical bases to encourage large scale experiments.

Main objective of the LATE (Low Aspect ratio Torus Experiment) device is to demonstrate formation of ST plasmas by electron cyclotron heating (ECH) alone without center solenoid. During two years after the previous Fusion Energy Conference where a preliminary result was reported [3], the operation conditions of LATE including discharge pulse length, microwave power and diagnostics, have been extended, increased and refined. It has been found that there are two kinds of discharge modes for formation of ST equilibria. The first one is slow formation of ST equilibria, where plasma current is ramped up in the time scale of a second with slow ramp-up of the external vertical magnetic field (B_v). The second one is the spontaneous formation of ST equilibria under steady B_v fields, where plasma current increases rapidly in the time scale of a few milliseconds.

2. Experimental Apparatus

LATE is a tiny device as shown in FIG. 1. The vacuum chamber is a stainless steel cylinder with an inner diameter of 1.0 m and a height of 1.0 m. The center stack is a stainless steel cylinder with an outer diameter of 11.4 cm, enclosing 60 turns of toroidal field coil. The return conductors are grouped into 6 limbs. This allows good accessibility to the vacuum chamber. There are four sets of poloidal field coils. The second set from the inboard side is for active control of vertical position of the plasma, and the rest three sets are for the external vertical fields and their currents are preprogrammed. There is no central solenoid for inductive current drive. Diagnostics are two channels of 70 GHz interferometer, a spectrometer, a video camera in visible range, single channel NaI scintillator for hard X-ray detection, Langmuir probes and four soft X-ray cameras. Magnetic data from thirteen flux loops are used for the analysis of the poloidal flux surfaces. Three 2.45 GHz magnetrons including two 5 kW CW magnetrons and one 20 kW 2 seconds magnetron, and a 5 GHz klystron (200 kW, 100 ms) are used for ECH. In all cases, microwaves are injected from radial ports, usually with the electric fields on the equatorial plane and with injection angles slightly deviate from the perpendicular direction to the toroidal field.

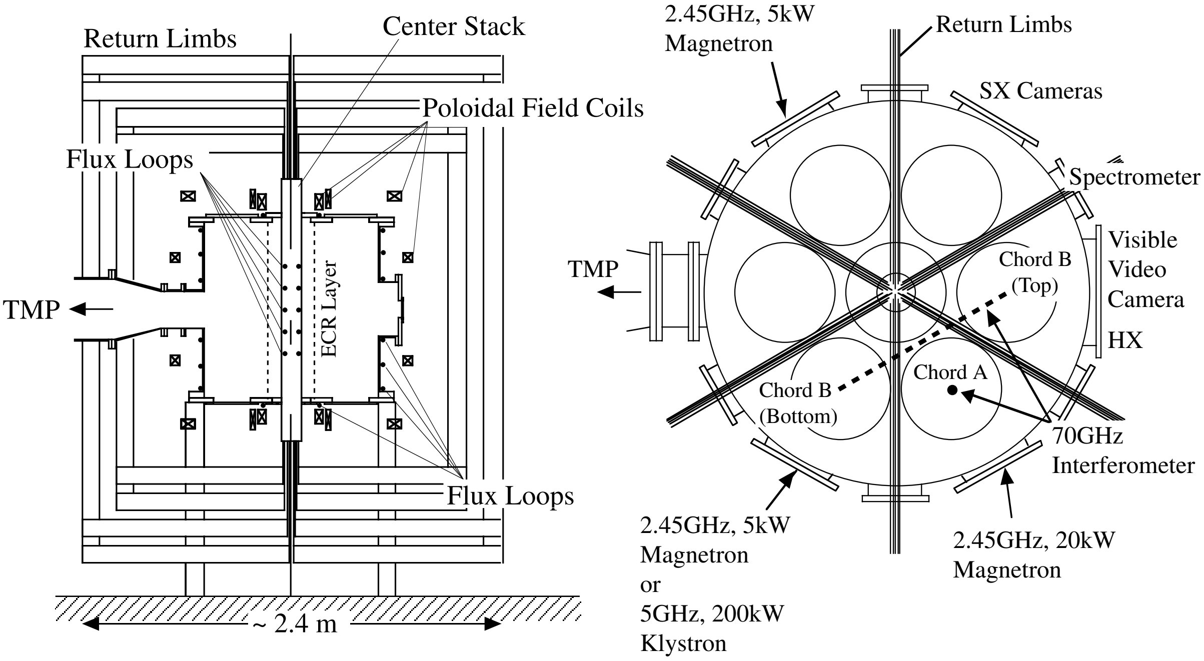

FIG. 1 The LATE (Low Aspect ratio Torus Experiment) Devise.

3. Experimental Results

3.1 Slow Formation of ST Equilibria

Figures 2 and 3 show a typical discharge by two 5 kW magnetrons (total 10 kW). First, a steady external vertical field ($B_{\rm v} = 12$ Gauss) is applied and hydrogen gas is introduced before microwave injection. The $B_{\rm v}$ decay index is set to be very low ($n = 0.07$ at $R = 27$ cm) and the field line is almost straight along the vertical direction as shown in FIG. 3 (f), which allows the production of an ST plasma with a large cross section in contrast to the previous case with $n = 0.46$ [3]. Second, microwaves generated by two magnetrons are injected from the outboard side through two radial ports at the mid plane at oblique angles with the linearly polarized electric field parallel to the equatorial plane. Then, an initial plasma is produced instantly at the fundamental EC resonance ($\omega = \Omega_{\rm ce}$) layer at $R = 13.7\,$cm as shown in FIG. 3 (a). The plasma quickly expands to the low field side (FIG. 3 (b)). The plasma current is generated and rapidly increases up to $1.2\,$kA ($t = 0.6\,$s), and an initial closed flux surface is produced as shown in FIGs. 3 (c) and (g). Third, the plasma current slowly ramps up by increasing the $B_{\rm v}$ field gradually in order to keep the higher current in equilibrium with increasing the 2nd magnetron power. The magnetic flux through the center stack at the midplane detected by the central flux loop ($\Phi_{\rm c}$) increases gradually in accordance with the increase of the plasma current during the ramp, indicating that a weak reverse voltage is applied on the plasma surface. The plasma current reaches $I_{\rm p} = 3.2\,$kA at $B_{\rm v} = 33\,$Gauss and is kept constant for 0.5 s until the microwave power is turned off. At this time the plasma density is four times as high as that at the initial stage and the visible light plasma image is relatively clear as shown in FIG. 3 (d), in coincidence with the virtual image of the separatrix (FIG. 3 (e)).

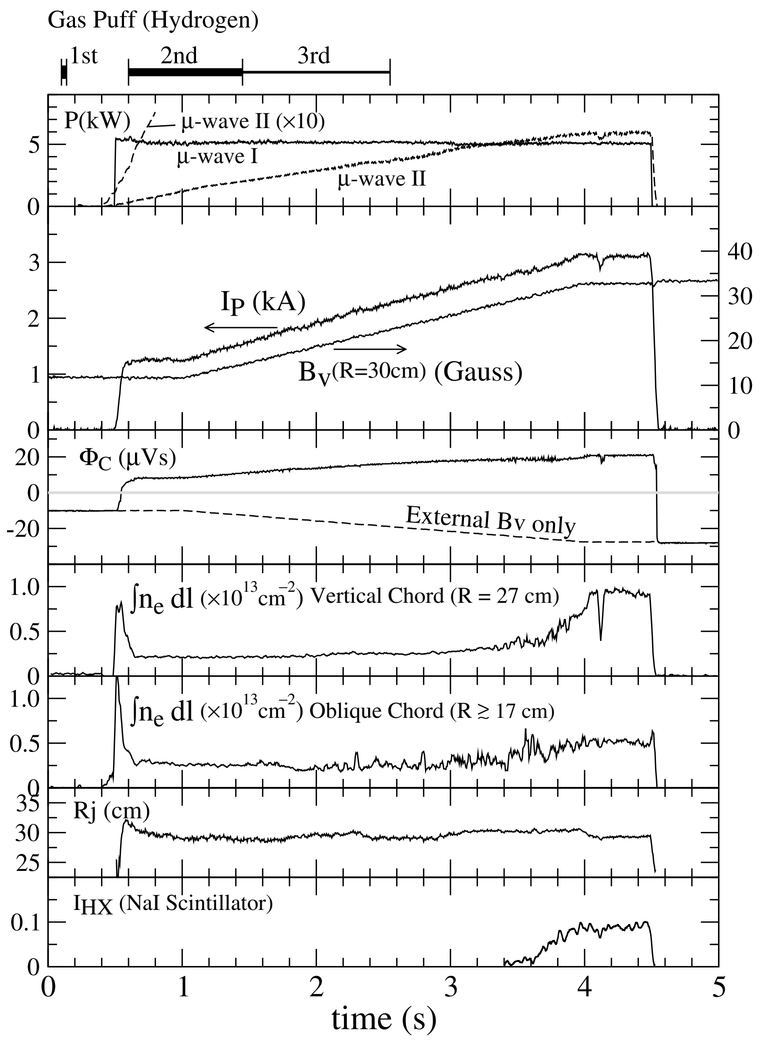

FIG. 2 Time traces of 2.45 GHz 10 kW discharge.

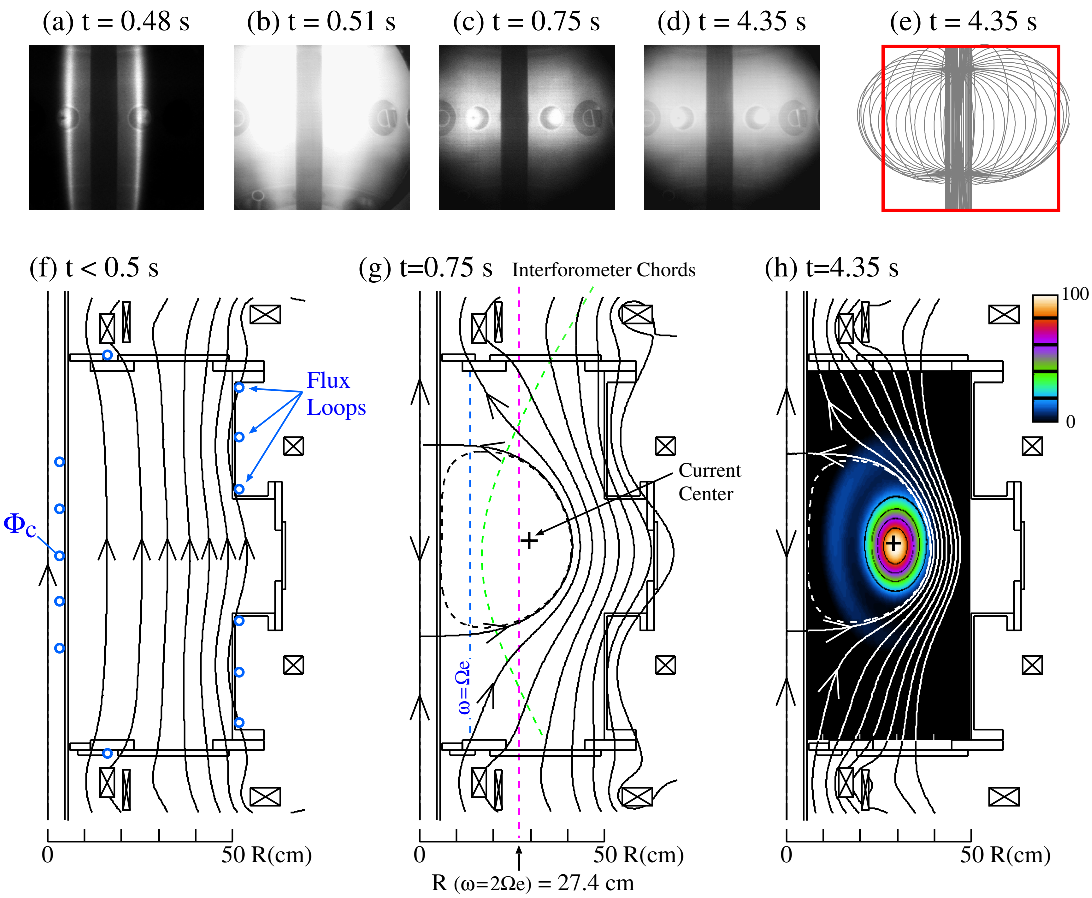

FIG. 3 (a-d) Visible light plasma images and (f-h) poloidal flux contours at various times in Fig.1. In addition, (e) virtual image of separatrix and (h) SXCT image at the last stage of the discharge. Images in (a) and (c) are intensified by 4 and 2 times, respectively, compared with the others.

Although the shape of the last closed flux surface as well as the radial location of plasma current center (R_{j} in FIG. 2) essentially does not change from the initial stage to the final stage as shown in FIGs. 3 (g) and (h), the electron density increases rapidly towards the final stage of the discharge without gas puffing at this time, where hard X ray signal in the photon energy range of $h\nu \sim 20\,\mathrm{keV}$ is also detected. Furthermore, impurity line radiations at relatively high excitation energies (O V (72 eV) and C V (304 eV)) are observed to appear in accordance with the increases of the density in the final stage of discharge. These behaviors suggest that the confinement improves at the final stage of the discharge. Although precise electron temperature can not be measured at the moment, the final plasma has relatively high electron density and temperature and emits radiations in the vacuum ultra violet range with signal intensities strong enough for soft X-ray computer tomography (SXCT) imaging of the plasma cross section as shown in FIG. 3 (h). The image also elongates vertically in accordance with the elongated flux surface and the image center coincides with the plasma current center estimated from the magnetic analysis. This center is located near the second harmonic EC resonance layer at $R = 27\,\mathrm{cm}$. The line averaged electron density estimated from the vertical chord interferometer at $R = 27\,\mathrm{cm}$ is three times as high as the plasma cutoff density for 2.45 GHz microwave at the final stage. These results suggest that the second harmonic ECH by the mode-converted electron

Bernstein waves (EBW) could be responsible for heating and current drive in the present plasma.

When we increase the ramp-up rate of the $B_{\rm v}$ field, the ramp-up rate of the plasma current also increases. The plasma current up to 4.15 kA has been so far achieved at $B_{\rm v} = 46$ Gauss by two 5 kW magnetrons. It is also noted that the currents increases with the increase of vertical elongation of the plasma cross section by decreasing the decay index of $B_{\rm v}$ field. However, there appears an unstable vertical displacement of the plasma column when the decay index decreases below $n = -B_{\rm v}/(dB_{\rm v}/dR) = 0.05$ at $R = 27$ cm and we need active control of the vertical position. With the active control at the decay index of $n = 0.02$ and the addition of the third magnetron power (20 kW), the plasma current so far reaches 6.3 kA at $B_{\rm v} = 70$ Gauss as shown in FIG. 4 (a). This currents amount 10 percents of the toroidal coil currents (60 kAT). Magnetic measurements show that an ST equilibrium, having the last closed flux surface with an aspect ratio of $R_0/a \simeq 20.4\,{\rm cm}/14.5\,{\rm cm} \simeq 1.4$, an elongation of $\kappa = 1.5$ and $q_{\rm edge} = 37$, has been produced and maintained for 0.5 s at the final stage of discharge. The magnetic field line on the last closed flux surface already reveals the characteristics of ST equilibria at $q_{\rm edge} = 37$ as shown in FIG. 4 (b).

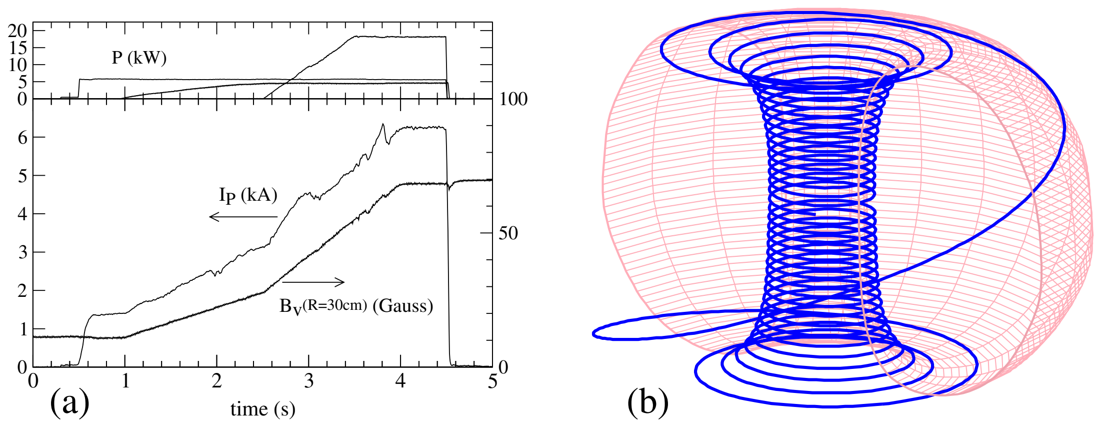

FIG. 4 (a) Time traces of the 6.3 kA discharge and (b) Field line on the last closed flux surface.

3.2 Spontaneous Formation of ST Equilibria

It is interesting that a closed flux surface can be spontaneously produced by ECH under a steady $B_{\rm v}$ field as observed in FIG. 2 ($t \sim 0.6$ s). This had been already reported to be possible both in the experiments in CDX-U and DIII-D at a large decay index of $B_{\rm v}$ [4], and it was shown that various pressure driven currents were spontaneously generated in the ECR plasma under a steady $B_{\rm v}$ field. A character in the present LATE case is the appearance of a clear current jump, where plasma current increases rapidly in the time scale of a few milliseconds, even at a low decay index of $n < 0.1$ and after the jump a closed flux surface is formed and maintained.

Figure 5 shows a case for injection of a 5 GHz microwave pulse of 130 kW under $B_{\rm v} = 85$ Gauss. The toroidal coil current is 90 kAT and the fundamental ECR layer is located at $R = 10$ cm. Time evolution of the plasma images on the video camera shows that the break-down takes place at the ECR layer and the plasma expands quickly to the lower field side. In accordance with the plasma expansion a plasma current starts to flow and increases slowly up to 2 kA, and then, suddenly it rises quickly in the time scale of a few milliseconds and reaches 6.8 kA, and after that the current is maintained to the end of the microwave pulse.

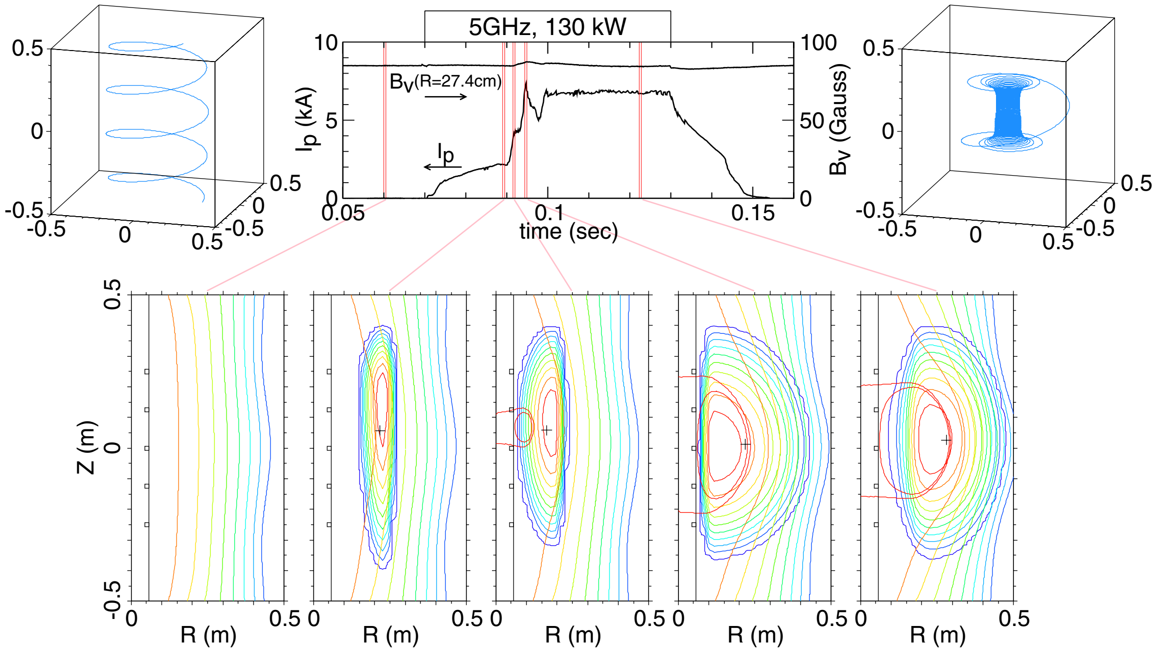

FIG. 5 Time traces for spontaneous formation of ST equilibrium and evolutions of the current distributions and the poloidal flux surfaces. In the cubicles at left and right sides are shown the field lines before microwave injection and at the final steady stage of discharge at $I_\mathrm{p} = 6.8$ kA, respectively.

Time evolutions of the poloidal flux contour and the current distribution are analyzed by using a model current profile and displayed in FIG.5. The current profile just before the current jump ($t = 0.089$ s) is stretched vertically near the second harmonic EC resonance layer ($R = 20$ cm). After the first jump, it expands to the strong field side and a small closed flux surface touched to the center stack appears, and after the second jump the current profile as well as the closed flux surface expands to the weak field side. At the final steady stage the current distribution is detached from the surface of the center stack and a broad current profile expanded to the outboard wall of the vessel is formed. Here the plus notation (+) denotes the location of the current center in the approximation of the single current loop for the dipole moment of the current distribution. Its location in the final steady stage is between the second and third harmonic EC resonance layer. The line averaged electron density in the final steady stage exceeds the plasma cutoff density. These results suggest that EBW supports the plasma also in this case. It is remarkable that the open field configuration before the microwave injection spontaneously changes into a closed field configuration by ECH as shown in FIG. 5.

The minimum microwave power for the spontaneous formation of closed flux surfaces is nearly proportional to the applied B_v field strength. In the case of the 2.45 GHz experiments, we have a closed flux surface with $I_\mathrm{p} = 3.2$ kA at $B_\mathrm{v} = 32$ Gauss by a 20 kW pulse and the plasma is similar to those formed by the slow formation, although the required microwave power is larger in the spontaneous case.

4. Discussions and Future Prospects

4.1 Current-Drive Mechanism

The first candidate of the current drive in the present experiments is ECCD, that is, direct results of wave induced deformation in the electron velocity space. If we take a most simple model of the Fisch-Boozer mechanism ignoring the toroidal effects and the spatial loss of current carrying electrons, the present power level of 10-100 kW is sufficient to maintain the current of several k Amps even if the bulk electron temperature is several tens of eV, since the major radius is small and the density ($\sim 10^{11}\,\mathrm{cm}^{-3}$) is quite low. However, the presence of fast electrons in a few tens of keV range suggests that such a simple model is not the case. More important is the presence of strong mirror or neoclassical effects in the low aspect ratio field configuration. This may strongly change the ECCD mechanism.

Another candidate is the current generation due to the pressure gradient. Although the various mechanisms of pressure driven currents under open field configurations were invoked and discussed [4], the case in the current jump where the configuration quickly changes from the pure open configuration to partially closed one is a newly found result and has not been addressed theoretically. Even in the case at the steady stage after the current jump and in the case of the slow formation of ST equilibria, the fraction of the toroidal currents outside the closed flux surface, i.e., in the open field region is still significant (typically 30-50 percents of the total currents) in the present level of 6 kA. This is also a new regime for investigation of the current generation and the plasma equilibria. It is also noted that trajectories of passing fast electrons in a few tens of keV range deviate significantly to the weak field side from the closed flux surface since the present current level is much lower than the Alfven critical current of 17 kA. Therefore, it is quite important and interesting to investigate in future how the current distribution evolves as the current ramps up over 17 kA, where the current fraction in the open field region may become negligible and the bootstrap current dominates in the various types of pressure driven currents in a full low aspect ratio configuration.

4.2 Electron Bernstein Wave Heating

The experimental results that the density significantly exceeds the plasma cutoff density and the plasma center locates near the second or third harmonic EC resonance layer suggest strongly that the mode converted EBWs are responsible for heating of plasma by the harmonic EC resonance absorption of EBWs, since EBWs can be strongly absorbed even in the low temperature plasmas. In the 2.45 GHz experiments at the levels of 5-10 kW and the current of 3 kA, there has been found no strong dependence of the polarizations of wave fields and the injection angles of injected microwaves on the performance of discharges. These results suggest that the injected waves are mode-converted into EBWs via multi reflections between the vessel wall and the plasma layer at the upper hybrid resonance. The simple model estimation on mode conversion [5] shows roughly ~ 50 percents efficiency of mode conversion rates, since the wave length in free space is nearly the same order of the plasma radius. On the contrary, the estimation shows a good efficiency (~ 90 percents) for the case of 5 GHz cases if the density gradient at the outer boundary is appropriate. Thus we can expect a more efficient formation of ST equilibria by a well-designed injection of 5 GHz microwaves both in the polarization and the injection angle.

5. Summary

By injecting a 2.45 GHz microwave pulse up to 30 kW for 4 seconds, a plasma current of 1.2 kA is spontaneously initiated under a weak steady vertical field of $B_\mathrm{v} = 12$ Gauss, and then ramped up with slow ramp-up of B_v for the equilibrium of the plasma loop and finally reaches 6.3 kA at $B_\mathrm{v} = 70$ Gauss. This currents amount 10 percents of the coil currents of 60 kAT for the toroidal field. Magnetic measurements show that an ST equilibrium, having the last closed flux surface with an aspect ratio of $R_0/a \simeq 20.4\,\mathrm{cm}/14.5\,\mathrm{cm} \simeq 1.4$, an elongation of $\kappa = 1.5$ and $q_\mathrm{edge} = 37$, has been produced and maintained for 0.5 s at the final stage of discharge. The plasma center locates near the second harmonic EC resonance layer and the line averaged electron density significantly exceeds the plasma cutoff density, suggesting that the second harmonic EC heating by the mode-converted electron Bernstein waves (EBW) supports the plasma. Spontaneous formation of ST equilibria under steady B_v fields, where plasma current increases rapidly in the time scale of a few milliseconds, is also effective and a plasma current of 6.8 kA is spontaneously generated and maintained at $B_\mathrm{v} = 85$ Gauss by a 5 GHz microwave pulse (130 kW, 60 ms).

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