Noninductive Formation of Spherical Tokamak at 7 Times the Plasma Cutoff Density by Electron Bernstein Wave Heating and Current Drive on LATE


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Abstract. Noninductive formation of spherical tokamak by electron Bernstein (EB) waves at an extremely overdense regime has been explored in the Low Aspect ratio Torus Experiment device. The plasma current reaches ~10.5 kA and the electron density reaches 7 times the plasma cutoff density by injection of a 2.45 GHz microwave power of 58 kW. Such an increment of the density is found to be obtained when the ECR layer lies on the plasma core and the upper hybrid resonance layer lies to slightly higher field side of the 2nd ECR layer, where a good coupling to EB waves in their first propagation band may be realized. Thus an extremely overdense tokamak plasma has been for the first time produced and maintained solely by EB waves.

1. Introduction

Elimination of the centre solenoid (CS) from the tokamak fusion device is beneficial since the structure of the device will be significantly simplified and an economical fusion reactor with reduced size could be realized [1]. For spherical tokamak (ST) based devices such as CTF-ST and FNSF-ST [2, 3], removal of the CS is crucial because of the small tight space of the centre column to keep the aspect ratio sufficiently low. Without the CS, however, an alternative way of plasma initiation and current startup is required. Electron cyclotron heating (ECH) and current drive (ECCD) is an attractive candidate for noninductive startup since the microwaves for ECH/ECCD can be injected through a simple small launcher located sufficiently far from the plasma surface. Moreover, once the incident waves are mode-converted to electron Bernstein (EB) waves, EB waves can propagate into and cyclotron-heat the overdense core plasma. This is suitable particularly for ST plasmas since they are essentially overdense.

In the Low Aspect ratio Torus Experiment (LATE) device, startup and formation of ST plasmas by electron Bernstein (EB) waves has been explored. There are two advantages in using EB waves for formation of ST. One is based on the property that EB waves can have a high $N_e/N_i$ value more than 1 while electromagnetic waves cannot, which is favorable for current ramp-up. In the previous experiment, it was shown that EB waves can rapidly ramp up the plasma current as fast as ~260 kA/s, comparable to the lower hybrid ramp-up rate, where a current carrying electron tail is developed against the reverse voltage from self-induction by a forward driving force on the tail via cyclotron absorption of high $N_e/N_i$ EB waves [4, 5].
Another important aspect of EB waves is that there is no upper density limit for propagation and heating, which enables production and heating of plasmas at extremely overdense regime. In this paper, we report on an experiment of ST startup and formation by EB waves, in which the current reaches 10.5 kA and the density reaches more than 7 times the plasma cutoff density. EB waves heat efficiently bulk electrons as well as current carrying electrons to form an ST plasma at the density level well above the plasma cutoff density. Thus an extremely overdense tokamak plasma has been for the first time produced and maintained solely by EB waves.

2. Experimental Setup

The experiments are carried out in the LATE device [6]. The vacuum vessel is a cylinder with a centre post. There is no CS for the inductive current drive.

The microwaves at 2.45 GHz from four magnetrons consists of three 20 kW and one 5 kW are injected from low-field side mid-plane four launchers of open waveguide type with an oblique angle as shown Fig. 1. The transmission line on the port 10R has a polarizer to launch an incident wave with an arbitrary polarization in order to study the mode conversion physics to EB waves. The other three lines on the port 2R, 4R and 8R launch the linearly polarized waves with the electric field vector of waves on the mid-plane.

Main diagnostics are magnetic measurement with seventeen flux loops,
four chords 70 GHz microwave interferometers, Extreme ultraviolet (XUV) cameras with 20 vertical and 20 horizontal chords, a fast CCD camera for visible light plasma images and a spectrometer for visible light. An X-ray pulse height analysis (PHA) system with four Cd-Te detectors is also used to obtain photon energy spectra in energy range from 20 to 400 keV.

3. Experimental Results and Discussion

Figure 2 shows a typical discharge. When a microwave power of $P_{\text{inj}} = 10 \text{ kW}$ is injected under a weak vertical field of $B_v = 20 \text{ G}$, a plasma is initiated at the fundamental EC resonance layer. After a while, a plasma current is initiated and increases up to $\sim 2 \text{ kA}$, resulting in the formation of closed flux surfaces under the steady external field ($t \sim 0.04 \text{ s}$) [7]. Next, the plasma current ramps up with ramps of the microwave power and $B_v$, and finally reaches $I_p \sim 10.5 \text{ kA}$. The plasma is kept steady by $P_{\text{inj}} = 58 \text{ kW}$ under $B_v = 120 \text{ G}$ for 50 ms until the end of the microwave pulse. The forward X-ray measured along a tangential radius of $R_{\text{tan}} = 25 \text{ cm}$ develops both in energy range and photon counts as $I_p$ increases (Fig.2 (g)), indicating that the current is carried by an EB-wave driven fast electron tail as shown in the previous study [4, 5].

FIG.3. Profiles of various quantities of the discharge in Fig. 2 (a)-(b) Current density and poloidal flux contours by magnetic analysis. Contours are equally spaced, (c) XUV chords, (d) X-ray and interferometer chords and the field line on LCFS, (e) XUV signal profiles.
Figure 3(a) and 3(b) show the evolution of the plasma current profile and poloidal flux contours estimated by the magnetic analysis using magnetic signals from seventeen flux loops [5]. Because of a high energy range of current carrying electrons around ~ 100 keV the current profile significantly shifts into the low field side beyond the last closed flux surfaces (LCFS).

The four chords measurement of line-integrated density in Figs. 2(c)-2(f) shows that the density reaches an extremely overdense regime in the final steady phase (t = 0.15 – 0.20 s). The horizontal chord line-integrated density (Fig. 2(c)) increases 2.5 times from t = 0.1 to 0.17 s, while its chord length inside LCFS does not change as shown in Figs. 3(a) and 3(b). The final line-averaged density reaches $n_e = 5.5 \times 10^{17} \text{ m}^{-3}$, that is more than 7 times the plasma cutoff density. The vertical chords line-integrated densities do not change during this interval, while their chord lengths inside LCFS shrink as shown in Figs. 3(a) and 3(b), also indicating that the density inside LCFS increases.

In this discharge, the upper hybrid resonance (UHR) layer is estimated to lie to slightly higher field side of the 2nd ECR layer as shown in Fig. 3(c). Then the incident electromagnetic waves are mode converted to EB waves at the UHR layer in their first propagation band (between the fundamental and the 2nd ECR layer), after which the EB waves propagate towards the fundamental ECR layer and may heat the bulk electrons as well as the fast electrons at the plasma core. XUV emission signals from the vertical chords crossing the ECR layer on midplane show a large increase towards the final steady phase as shown in Figs. 3(c) and 3(e), suggesting the heating just before the fundamental ECR layer. The increase is much larger than the increment in the vertical chords line-integrated densities (Figs. 2(d)-2(f)). This suggests that the electron temperature also increases towards the final stage at the plasma core. Figure 4 shows the time evolution of impurity line radiation spectra measured at a tangent radius of $R_{\text{tan}} = 18.1 – 26.5 \text{ cm}$. Impurity line radiations at higher excitation energies such as C V (304 eV) and O V (72 eV) appear after t = 0.12 s and strongly increase towards the final stage. This also suggests that the electron temperature increases towards the final phase.

On the other hand, if we set the ECR layer at a slightly higher field side, the electron density becomes much lower and the current also lower than the previous case mentioned above. Figure 5 compares discharges with $R_{\text{ECR}} = 21.3 \text{ cm}$ and $R_{\text{ECR}} = 18.5 \text{ cm}$ under the same conditions.
microwave power of 40 kW and $B_v = 105$ G. While the line-integrated density increases as the current ramps up to $I_p \sim 9.3$ kA when $R_{ECR} = 21.3$ cm (the same condition as the discharge in Fig. 2), the density does not increase and the current at the final stage becomes lower when $R_{ECR} = 18.5$ cm as shown in Fig. 5 (a)-(c). In this lower density case, the UHR layer is estimated to be just outside the 2nd ECR layer as shown in Fig. 5 (e). Therefore a large portion of the incident wave power may be mode-converted to EB waves and absorbed before the 2nd ECR layer. This may significantly reduce the power coupled to EB waves at the first propagation band, resulting in decreases in the density and the current at the plasma centre.

In the lower density case, the power deposition before the 2nd ECR layer may develop a group of energetic trapped electrons since the mirror ratio is

**FIG. 5.** Discharges with $R_{ECR}=21.3$ cm and $R_{ECR}=18.5$ cm: (a)-(c) Time traces, (d) current density and poloidal contours for $R_{ECR}=21.3$ cm, (e) for $R_{ECR}=18.5$ cm

**FIG. 6.** (a)-(b) Time evolution of hard X-ray spectra measured along vertical chords at $R=33$ cm and $R=40.5$ cm, (c)-(d) X-ray spectra at $t=0.1$ s ($R=40.5$ cm)
large in this region. Figures 6(a)-6(d) show time evolutions of hard X-ray spectra measured along the vertical chords at \( R = 33 \text{ cm} \) and \( 40.5 \text{ cm} \) outside LCFS. The X-ray develops both in energy range and photon counts much larger than the higher density case, suggesting that the energetic trapped electrons develop outside LCFS in the lower density case. Their toroidal precession generates a low toroidal current as appeared as a large expansion of the current profile from the LCFS as shown Fig. 5(c).

In the higher density discharge, density gradient around the UHR layer increases towards the

**FIG. 6** (a)-(c) Polarizations of incident wave for (a) optimum mode conversion rate to EB waves, (b) no conversion to EB waves, (c) the system having no polarizer (port 2R, 4R and 8R). (d)-(j) waveforms comparing the two patterns of injection mode.
final stage. For the discharge shown in Figs. 2 and 3, the normalized density scale length is estimated to be as low as $L_n / \lambda_0 = n / (\lambda_0 \cdot dn/dx) \sim 0.1$ at the final stage, where $\lambda_0$ is the wavelength in free space. For this density gradient, the mode conversion rate from the incident wave to EB waves estimated by using a plasma slab model [8] becomes $\eta \sim 0.16$ for the present injection mode of the linearly polarized wave with the wave electric field on the midplane and $N_{\parallel} = 0.4$. Therefore a large portion of the incident wave may be multi-reflected between the outer vessel wall before being mode-converted to EB waves at the final extremely overdense phase. Following the method as described in Ref. [8], the polarization of the optimal injection mode (called g1 mode) for this density scale length is calculated to be the left-hand elliptically polarized one shown in Fig. 6(a). This injection mode have a conversion rate of $\eta \sim 0.83$. Since the density gradient is fairly steep at the final stage, this g1 mode approaches X-mode.

In order to study polarization effect to the mode conversion to EB waves at the final stage, we examine the two polarizations of incident wave, the g1 mode (Fig. 6(a)) and its orthogonal mode (g2 mode, shown Fig. 6(b)) having zero conversion rate, using a polarizer installed in the transmission line of the 20 kW injection system on the port 10R (see Fig. 1). Figure 6 shows the comparison of the two injection modes. In this experiment, only the polarization of 15 kW power injected from the port 10R is changed. The polarizations of the rest 28 kW power from the other three magnetrons on the port 2R, 4R and 8R remain unchanged with the linear polarization shown in Fig. 6(c). Firstly we search the minimum power to reach the final stage of $I_p = 9$ kA with the g1 mode injection, and then the polarization is changed to the g2 mode in the next shot. The results show that the plasma current and the density decrease just before the final steady phase and finally the discharge terminates with the g2 mode as shown in Figs. 6(f)-6(i). These can be attributed to the difference in the power coupled to EB waves between the two modes, being consistent with the linear theory.

Note that the mode-conversion rate of the rest 28 kW power becomes quite low at the final stage and a large portion of the power may be multi-reflected as mentioned above. In addition, the diameter of the launcher is almost the same as the free space wavelength and the waves spread from the launcher with a wide $N_{\parallel}$ spectrum. In spite of these limitations in the present experiment the difference between the two injection modes is observed reproducibly without exception. Thus we can expect a more efficient formation of ST plasma at an extremely overdense regime by a well-designed injection of incident waves including the polarization and the launcher geometry.

4. Summary

In the LATE device an extremely overdense tokamak plasma has been produced and maintained solely by EB waves when the UHR layer lies to slightly higher field side of the 2nd ECR layer. The current reaches $I_p = 10.5$ kA and the line-averaged density reaches more than 7 times the plasma cutoff density by a microwave power of $P_{\text{inj}} = 58$ kW. The time evolution of XUV emission signal profile shows a significant increase just before the ECR layer, indicating the heating of bulk electrons as well as a current carrying electron tail near the ECR layer at the plasma core. The increase is much larger than the increment in electron density, suggesting the electron temperature also increases at the plasma core.

When we set the ECR layer at a slightly higher field side so that the UHR layer becomes just lower field side of the 2nd ECR layer, the density becomes much lower and the current also
lower under the same injection power. The power deposition before the 2nd ECR layer may
develop a group of energetic trapped electrons outside LCFS and reduce the power coupled to
EB waves at the first propagation band, resulting in decreases in the density and the current at
the plasma centre.

Dependence of the injection polarization on the mode conversion rate from the incident wave
to EB waves is investigated at an extremely overdense regime and the results are consistent
with the linear theory. Based on these results, a more efficient formation of an extremely
overdense tokamak plasma is expected by a well-designed injection of incident waves
including the polarization and the launcher geometry.

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