Non-inductive Production of Extremely Overdense Spherical Tokamak Plasma by Electron Bernstein Wave Excited via O-X-B Method in LATE

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Abstract. Extremely overdense spherical tokamak (ST) plasmas are produced non-inductively with electron Bernstein waves (EBWs) mode-converted via O-X-B scheme. When the fundamental electron cyclotron resonance (ECR) layer is located at the plasma core and the 2nd harmonic ECR layer is near the outboard vessel wall and the upper hybrid resonance (UHR) layer is located between them, the line-averaged electron density increases and exceeds ~6 times the plasma cutoff density. When the 2nd harmonic ECR layer is located at the inboard side of the UHR layer, the density increases to not more than twice the cutoff density. These phenomena are observed at two different microwave frequencies by adjusting the position of the ECR layer nearly the same. These experimental results show that bulk electron heating with EBW excited in the 1st propagation band is effective while that with EBW in the 2nd propagation band is not because the 2nd harmonic ECR layer is difficult to be located in the core region due to low aspect ratio.

1. Introduction

Recently, the performances of spherical tokamaks (STs) have been investigated intensively in many experimental devices, and their fusion development path is presented in the review article [1]. Non-inductive startup and ramp-up is one of important issues in order to realize compact and low-cost ST devices in future. Many non-inductive start-up methods, such as coaxial helicity injection [2] and plasma merging [3], have been demonstrated successfully. Among them, electron cyclotron heating and current drive (ECH/ECCD) which uses microwaves at the electron cyclotron (EC) range of frequency has the benefit from the view point of reactor engineering because it needs only small launchers away from the plasma surface. Moreover, electron Bernstein waves (EBWs) are used for ECH/ECCD in the overdense plasma without density limit when the injected microwaves are mode-converted at the upper hybrid resonance (UHR) layer. They are advantageous to ST reactors which are operated in overdense state.

In the LATE device, non-inductive start-up by EBW has been investigated. The microwave at either 2.45 GHz or 5 GHz is injected in O-mode obliquely to the toroidal magnetic field from the outboard side on the mid-plane. The breakdown occurs at the electron cyclotron resonance (ECR) with a weak vertical field (Bv = 15 ~ 30 G), then, a toroidal pressure-driven current appears as an equilibrium current in the open magnetic configuration together with vertical charge-separation current [4]. As the electron temperature is increased by ECH and the toroidal pressure-driven current increases to cancel the applied external vertical field nearly, a cross-field-passing electrons (CFPEs) are generated and drive an additional toroidal current, resulting in formation of closed flux surfaces [5,6]. After the formation of closed flux surfaces, the plasma current is ramped up when the vertical field is increased, so that the toroidal equilibrium is maintained. The electron density exceeds the plasma cutoff density.

The injected O-mode wave is mode-converted at the plasma cutoff layer to the X-mode wave, which propagates to the UHR layer, and EBW is excited there. It propagates to the ECR layer, heats electrons and drives the plasma current. It is also shown that EBW can ramp-up the plasma current at the rate of ~260kA/sec as fast as lower hybrid waves [7]. Here, current-carrying high energy electrons are developed against the reverse electric field from self-induction by a forward driving force due to EC absorption of high N// EBWs. With 2.45 GHz microwave, a highly overdense plasma above the plasma cutoff density is produced when the fundamental ECR layer is located in the plasma core and the polarization of injected microwave is optimal for mode-conversion [8,9]. Recently, the power supply for the toroidal field coil has been reinforced and the position of the fundamental ECR layer for 5 GHz microwave can be located at the plasma core. In this paper, we report the results of EBW start-up experiment with 5 GHz microwave mainly.

EBW dispersion shows that EBW has resonances at the harmonics of EC frequency [10,11] and its propagation area in space is separated in a band structure by two adjacent harmonic ECRs when the magnetic field varies as in torus devices. In the ST plasmas, due to the low aspect ratio, multiple harmonic ECR layers exist in accordance with the strength of the magnetic field. Because EBW is excited at the UHR layer and can propagate only in the propagation band where the UHR layer is located, the wave power absorption is occurred at the lower harmonic ECR side, i.e., the high field side of the propagation band. For effective plasma heating, the wave power should be absorbed in the plasma core. Then, the positions of the harmonic ECR and the UHR layers are very important for effective EBW heating and current drive in ST. We consider a simple situation as follows: The position of the UHR layer on the midplane is usually located near the outboard wall almost independently on the magnetic field strength in overdense ST plasmas. When we want to locate a harmonic ECR layer in the plasma, the width of the propagation band, i.e., the distance between the harmonic ECR layers becomes narrow as the harmonic number increases. Therefore, when EBW is excited in the high harmonic propagation band, the wave power is expected to be absorbed in the plasma periphery. On the other hand, for the fundamental propagation band, the distance between the fundamental ECR layer and the 2nd ECR layer is wide enough to locate the fundamental ECR layer at the plasma core and the effective heating is expected. Above prediction is investigated in the LATE device by changing the magnetic field strength. The next section describe the experimental setup. The experimental results and discussions are presented in the third section. The summary is given in Section 4.

2. Experimental Setup

The LATE device has no center solenoid and the plasma is produced by microwave power only. The radius of center post is 0.057 m and the radius of the vacuum vessel is 0.5 m. The radial Mo limiter is set at R = 0.47 m. The maximum toroidal field Bt at R = 0.25 m is 1.63 kG. The toroidal coil current is supplied by a capacitor bank and regulated by transistor-stacks. Its flat-top duration is ~0.12 sec at Bt = 1.63 kG. The microwave power at 5 GHz is generated by a klystron in TE_{10} rectangular mode, transmitted to a transition and converted to TE_{11} circular mode, and then, converted to left-handed circular polarization by a polarizer. The microwave is injected through the ceramic window and into the vacuum vessel by a launcher at the radial port on the midplane which is an open circular waveguide type antenna with diameter of 0.117 m. The axis of the launcher is inclined at an angle of 15 degree to the toroidal direction at R = 0.5475 m. The microwave power at 2.45 GHz is generated by 4 magnetrons. The launching system is similar to that of 5 GHz microwave and the details are described in [9]. Three magnetrons are used in this experiment.

Four 70 GHz interferometers are equipped and by changing the probe beam paths with PIN diode switches, six line densities along the different paths are observed. Soft X-ray emission is detected by two sets of a 20 ch linear array of Si photodiodes installed as a pin hole camera, one at the top port, and the other at the radial port on the midplane to view the horizontal profile. Hard X-ray emission is detected by four CdTe detectors along both horizontal and vertical chords. The thermocouples are installed on the Mo plates which cover the bottom flange, the radial and top limiters to measure the heat flow. Plasma current and magnetic surface profiles are calculated from magnetic measurement with 17 flux loops.

3. Experimental Results and Discussions

Figure 1 (a) ~ (d) show the typical waveforms for non-inductive ST formation with 5GHz EBW in the 1st propagation band. The toroidal field Bt is 1.63 kG and the fundamental ECR layer is located at R = 0.228 m. The breakdown is initiated under the applied vertical field of 25 G and with 30 kW microwave power at an optimal neutral gas pressure of ~10^{-2} Pa. The 5 GHz microwave pulse width is 0.070 sec and the injected microwave power P_{inj} is increased up to 165 kW. The vertical field and the microwave power are increased almost linearly with time by pre-programmed waveforms. Then, the plasma current is ramped up to 9 kA and the line density at the tangency radius of R_T = 0.12 m increases and reaches 1.0 x 10^{18} m^{-2} at the end of the microwave pulse. Figure 1 (e) shows the plasma current and the magnetic surface profiles at time t = 0.070 sec. The last closed flux surface (LCFS) spreads to R = 0.29 m on the midplane. Assuming that the density is uniform within LCFS, the line-averaged density along RT = 0.12 m is 1.8 x 10^{18} m^{-3}. This value is 5.8 times the plasma cutoff density for 5 GHz (3.1 x 10^{17} m^{-3}). The line density along the vertical chord at R = 0.39 m is 7 x 10^{16} m^{-2} and the line-averaged density is estimated as 3 x 10^{17} m^{-3} by assuming that the plasma spreads uniformly along the chord within the plasma current profile. Then, the UHR layer may be located at R ~ 0.4 m and the 2nd ECR layer is ~0.05 m outboard side. These data show that EBW is excited in the 1st propagation band. The magnetic axis is located at R = 0.206 m and

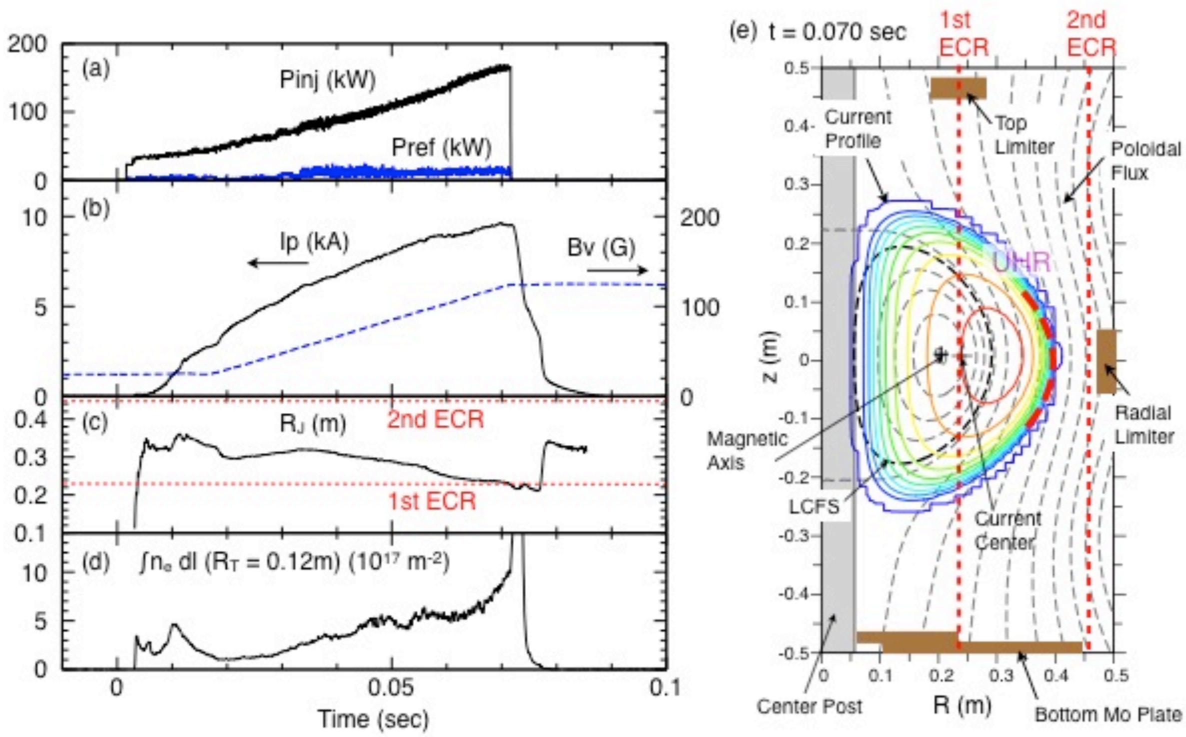

Fig. 1: Discharge waveforms at Bt = 1.63 kG, R_{ECR} = 0.228 m. (a) injected and reflected microwave power, (b) plasma current (solid) and vertical field (broken), (c) position of current center, (d) line density at the tangency radius of 0.12 m. (e) Plasma current profile and magnetic surfaces at t = 0.070 sec.

the distance between the magnetic axis and the 1st ECR layer is 0.022 m. The heating position is near the plasma core and EBW may heat the plasma efficiently.

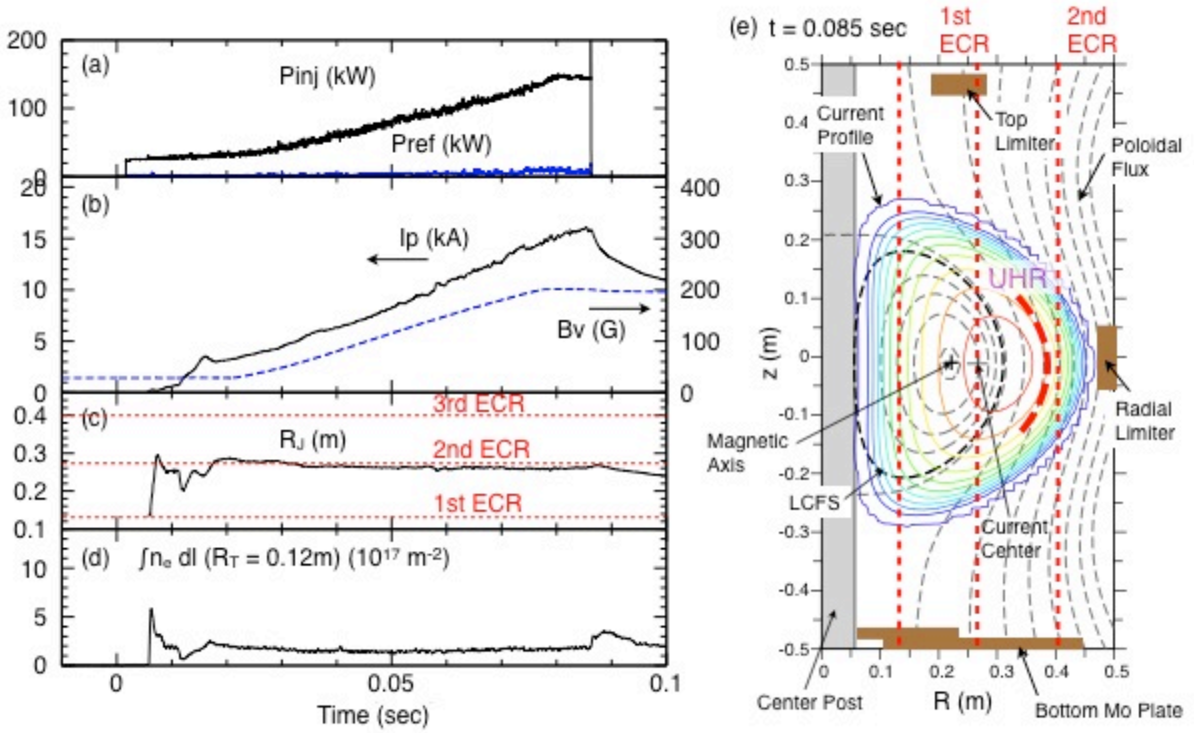

Fig. 2: Discharge waveforms at Bt = 0.96 kG, R_{ECR} = 0.134 m. (a) injected and reflected microwave power, (b) plasma current (solid) and vertical field (broken), (c) position of current center, (d) line density at the tangency radius of 0.12 m. (e) Plasma current profile and magnetic surfaces at t = 0.085 sec.

Figure 2 (a) ~ (d) show the typical waveforms for ST formation by 5 GHz EBW in the 2nd propagation band. The toroidal field Bt at R = 0.25 m is 0.96 kG and the fundamental ECR layer is located at R = 0.134 m. The 5 GHz microwave pulse width is 0.085 sec and the injected microwave power P_{inj} is increased up to 150 kW. The vertical field is increased almost linearly up to 205 G by pre-programmed waveforms. Then, the plasma current is ramped up to 16 kA, while the line density at RT = 0.12 m is nearly constant at ~2 x 10^{17} m^{-2}. Figure 2 (e) shows the plasma current and magnetic surface profiles at t = 0.085 sec. The last closed flux surface (LCFS) spreads to R = 0.31 m on the midplane. The line-averaged density is 3.6 x 10^{17} m^{-3} and ~1.2 times the plasma cutoff density. The line density along the vertical chord at R = 0.39 m is nearly zero. The UHR layer is estimated to be located around 0.35 m and EBW is excited in the 2nd propagation band. In this case, the magnetic axis is located at R = 0.221 m and the distance between the magnetic axis and the 2nd ECR layer is 0.047 m. The heating position is rather outside of the plasma core and EBW may not heat the plasma efficiently.

Figure 3 shows the Bt dependence when P_{inj}, Bv and gas puffing are set at the same conditions. The horizontal axis is the radial position of the fundamental ECR layer R_{ECR} and is equivalent to the half radius of the 2nd harmonic ECR layer. The plasma current does not depend on the position of the ECR layer, which means that production and acceleration of current-carrying high energy electrons are not affected by the position of the ECR layer. The line density increases when $R_{ECR} > 0.19$ m and significantly when $R_{ECR} > 0.22$ m. Experiment for $R_{ECR} > 0.23$ m is not able to be done because of the limitation of the toroidal field coil power supply. The soft X-ray emission detected through Al 50 nm film along the same tangency radius ($R_T = 0.12$ m) as that of the line density increases more rapidly than the line density, suggesting bulk electron heating. On the other hand, the hard X-ray emission along the vertical chord at R = 0.33 m decreases while the line densities along the vertical chords at R = 0.31 m and 0.39 m increase. This emission comes from the high energy trapped electrons moving in the low field side of LCFS. Then it shows that the high energy trapped electrons decrease. The heat flow to the bottom Mo outer plate decreases in accordance with the decrease of the hard X-ray emission. These dependencies suggest that when the position of the 2nd harmonic ECR layer is shifted to outboard side and exceeds R > 0.38 m, absorption by the high energy electrons at the 2nd harmonic ECR layer is avoided and EBW is mode-converted at the UHR layer at R ~ 0.4 m, excited in the 1st propagation band and heats the bulk electrons at the fundamental ECR layer effectively.

Similar experiment is carried out with 2.45 GHz microwave. As the microwave frequency is nearly a half, the strength of the magnetic field is also reduced to half and the same position of ECR is examined. Figure 4 shows the Bt dependence in the case of 2.45 GHz start-up. The line density increases significantly when 0.19 m < R_{ECR} < 0.24 m and becomes maximum at R_{ECR} ~ 0.21 m. The plasma current increases ~15 % in the same condition. Dependencies of the soft X-ray emission and the hard X-ray emission are similar to the case of 5 GHz start-up. Then, the significant increase of density is confirmed with two different microwave frequencies in the same radial position of the ECR layer. In the case of 2.45 GHz start-up, there appears an optimal position for increasing the density. This is explained that

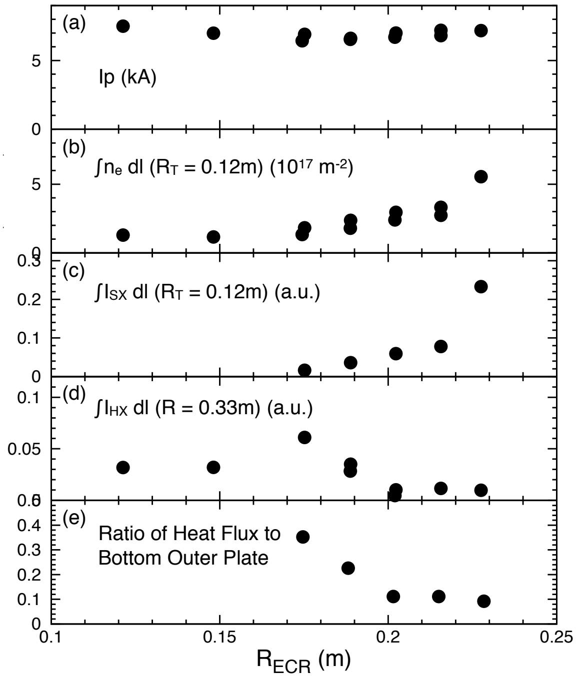

Fig. 3: Dependence on the position of the fundamental ECR layer in discharges with 5 GHz microwave : (a) plasma current, (b) line density, (c) soft X-ray emission through Al 50 nm film, (d) hard X-ray emission, (e) ratio of heat flow to the bottom outer plate to injected microwave power. $P_{inj} = 90$ *kW,* $B_v = 78$ *G.*

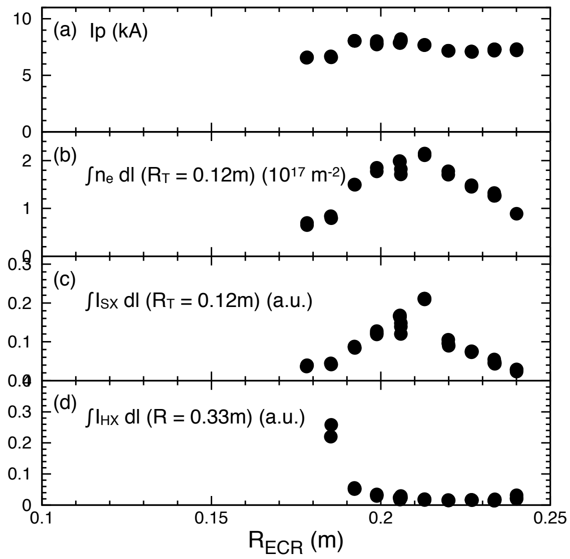

Fig. 4: Dependence on the position of the fundamental ECR layer in discharges with 2.45 GHz microwave : (a) plasma current, (b) line density, (c) soft X-ray emission, (d) hard X-ray emission. $P_{ini} = 32$ *kW,* $B_v = 90$ *G.*

when R_{ECR} > 0.22 m, the distance between the magnetic axis and the fundamental ECR layer becomes large and the core heating may come to be difficult. In the case of 5 GHz start-up, the density may decrease if the toroidal field were more stronger than 1.63 kG.

In Figure 5, in order to compare the two discharges, one with EBW excited in the 1st propagation band (Fig.1, R_{ECR} = 0.228 m, red lines) and the other with EBW excited in the 2nd propagation band (Fig. 2, R_{ECR} = 0.134 m, blue lines), the time traces of plasma parameters are plotted on the plane with axis of combination of plasma current Ip, net-injected microwave power P_{net} and line density. The plasma current is large and increased linearly in accordance with P_{net} for EBW in the 2nd propagation band while the plasma current become saturated for EBW in the 1st propagation band (Fig. 5 (a)). This is due to the large increase of density for EBW in the 1st propagation band (Fig. 5 (b)). In this experiment, the start-up duration is short and the steady state is not achieved. It is difficult to say the "start-up efficiency" but the product of plasma current and line density divided by the net-

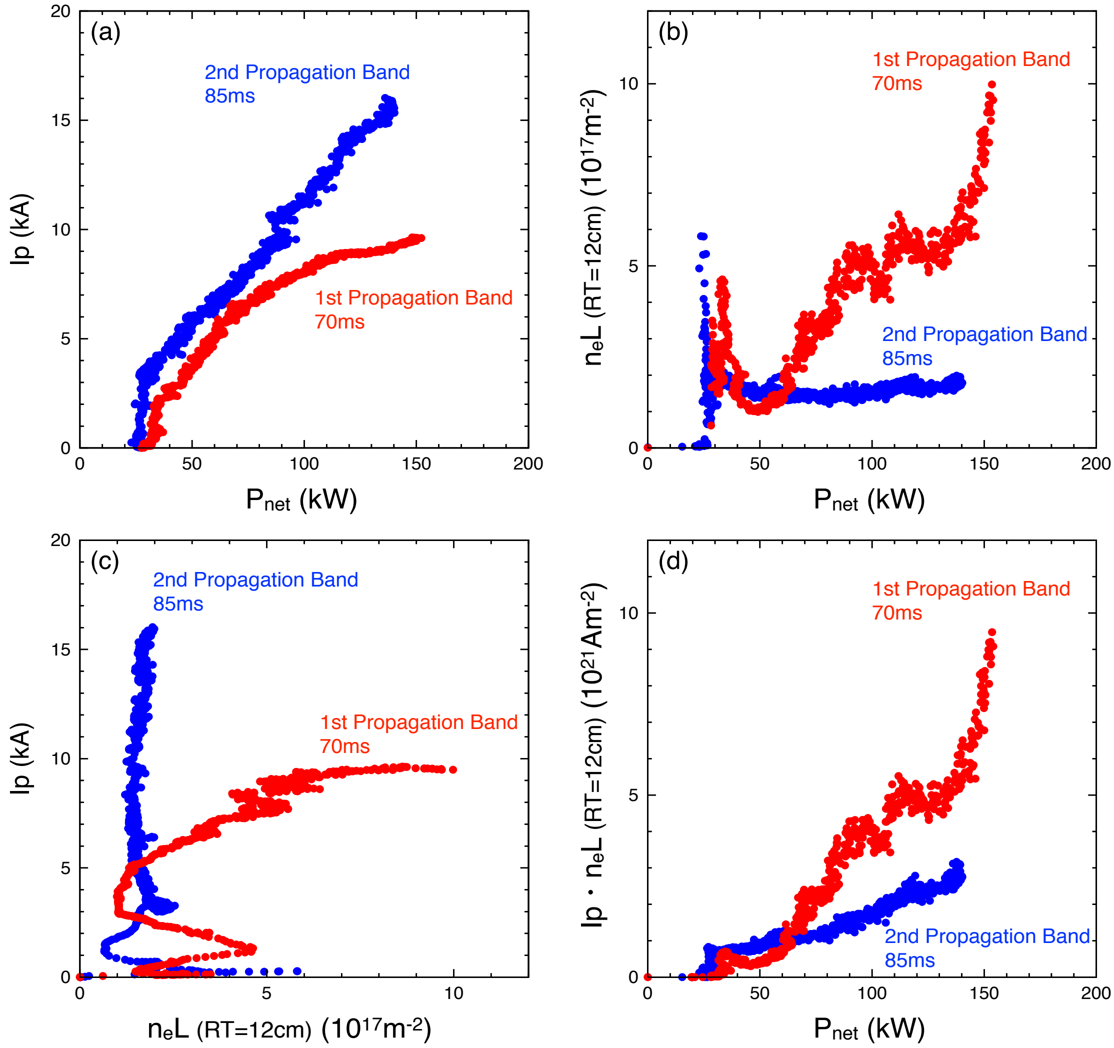

Fig. 5: Time traces on (a) plasma current vs. net-injected microwave power plane, (b) line density vs. net-injected microwave power plane, (c) plasma current vs. line density plane, and (d) product of plasma current and line density vs. net-injected microwave power plane. Red lines show the discharge with EBW excited in the 1st propagation band and blue ones show that with EBW excited in the 2nd propagation band.

injected microwave power may be a figure of merit for start-up. Figure 5 (d) shows the time trace of the product of plasma current and line density against the net-injected microwave power. The slope of the trace is a kind of figure merit for start-up and it shows that start-up with EBW in the 1st propagation band is better.

In the case of the start-up with EBW in the 2nd propagation band, the 2nd ECR layer is inevitably located at off-axis and core plasma heating is not expected. Then, the bulk electron density is limited to a low value (less than twice the cutoff density). EBW power is mainly absorbed in the low field (outboard) side of LCFS due to Doppler effect by tail electrons which become trapped and lost directly to the wall. Non-inductive ST start-up with EBW excited in the 1st propagation band is more effective from the view point of both plasma current and density rise.

4. Summary

Dependence of non-inductive start-up of ST with EBW excited via O-X-B scheme on the position of the ECR layer is investigated in detail. When the fundamental ECR layer is located at the plasma core and the 2nd harmonic ECR layer is near the outboard vessel wall and the UHR layer is located between them, the line-averaged electron density increases significantly and exceeds ~6 times the plasma cutoff density. When the 2nd harmonic ECR layer is located at the inboard side of the UHR layer, the density increases to not more than twice the cutoff density. This may be attributed to the fact that in ST plasma due to low aspect ratio, the 2nd harmonic ECR layer is difficult to be located in the core region and efficient heating is not expected. These phenomena are observed at two different microwave frequencies by adjusting the position of the ECR layer nearly the same. Non-inductive ST start-up with EBW excited in the 1st propagation band is more effective from the view point of both plasma current and density rise.

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References

[1] ONO, M. and KAITA, R., Phys. Plasmas 22 (2015) 040501.

[2] RAMAN, R. et al., Phys. Rev. Lett. 97 (2006) 175002.

[3] SYKES, A. et al., Nucl. Fusion 41 (2001) 1423.

[4] KURODA, K., et al., Plasma Phys. Control. Fusion 58 (2016) 025013.

[5] MAEKAWA, T., et al., Nucl. Fusion 52 (2012) 083008.

[6] YOSHINAGA, T., et al., Phys. Rev. Lett., 96 (2006) 125005.

[7] UCHIDA, M., et al., Phys. Rev. Lett., 104 (2010) 065001.

[8] UCHIDA, M., et al., Fusion Energy 2012 (Proc. 24th Int. Conf., San Diego, USA, 2012), IAEA-CN-197/EX/P6-18.

[9] TANAKA, H., et al., Fusion Energy 2014 (Proc. 25th Int. Conf., St. Petersburg, Russian Federation, 2014), IAEA-CN-221/EX/P7-41.

[10] BERNSTEIN, I. B., Phys. Rev. 109 (1958) 10.
[11] CRAWFORD, F. W., J. Appl. Phys. 36 (1965) 2930.