NON-INDUCTIVE PLASMA START-UP USING ELECTRON BERNSTEIN WAVE MODE-CONVERTED FROM ELECTRON CYCLOTRON WAVE LAUNCHED FROM HIGH-FIELD SIDE ON SPHERICAL TOKAMAK, QUEST

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Non-inductive plasma current start-up is commonly recognized as a primary spherical tokamaks (STs) issue. In QUEST, plasma start-up with electron Bernstein wave (EBW) has been conducted, because EBW has the capability for effective plasma start-up due to its inherent immunity to plasma density limit. In addition, EBW has good heating/current drive (CD) efficiency even in low-temperature plasma. High field side (HFS) launch of the wave absorbed at the vicinity of the 1st electron cyclotron resonance (ECR) after mode conversion (MC) from electron cyclotron wave (ECW) could generate a closed flux surface (CFS) with a relatively high density of $(\omega_{pe}/\omega)^2 \sim 1$, here ω_{pe} and ω denote plasma frequency and injected ECW frequency, respectively. It found that EBWCD played an essential role in closed flux formation.

The QUEST spherical tokamak has performed plasma start-up experiments with EBWH/CD through a MC from an ECW propagating as X-mode (X-ECW) launched from HFS using a dedicated antenna for the experiment; because the HFS launched X-ECW is completely converted to EBW, unlike one launched from low field side (LFS). Two klystrons of 25 kW, 8.2GHz were used as the heating source. The antenna was installed on the HFS 17cm above the midplane. The ECW is expanded by approximately 60° in both the toroidal and poloidal directions, because the narrow space on the HFS limited the antenna size. Electron density, n_e and temperature, T_e profiles at the mid-plane were measured with Thomson scattering. The experimental results were superior in terms of higher I_P, n_e and good wave absorption compared to the LFS-launched case[1]. Assuming constancy of these parameters on the flux surface, calculations that could trace the ECW and EBW rays for the MC and subsequent EBW propagation and absorption is allowable. A typical situation in high and medium density cases is illustrated in Fig. 1. In the case of high density of $(\omega_{pe}/\omega)^2 \cong 2.0$, the ECW ray passes through an ECR without significant absorption, because the absorption of X-ECW is week in the case of $(\omega_{pe}/\omega)^2 > 1$[1]. However, the L-cutoff prevents X-ECW from propagating to the LFS and the ECW reflected back to the HFS in the case of high density, which was always observed at the beginning of the

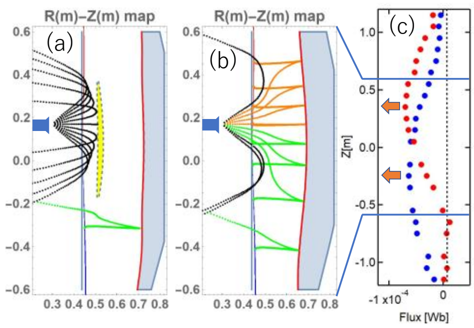

Fig. 1 (a) Typical conditions for EBW for the case of $(\omega_{pe}/\omega)^2 \cong 2.0$ B_T CCW for $N_\emptyset$=0.1 at the head of the antenna (see the blue mark) are illustrated on a R-Z map. Vertical blue and red lines denote 1st ECR and UHR. The yellow region indicates L-cutoff. Red and blue regions show EBW deposition regions to drive equilibrium I_P (red) and anti-equilibrium I_P (blue), here the direction is decided from top view. The black rays are ECW reflected by L-cutoff and a green ray indicates a reflected ECW at the center stack. The mode-converted EBW is absorbed at the vicinity of 1st ECR layer. (b) Typical conditions for $(\omega_{pe}/\omega)^2 \cong 1.8$. The orange and green rays show wave trajectory to drive equilibrium I_P and anti-equilibrium I_P, respectively. (c) I_P induced magnetic flux (red B_T CCW: blue B_T CW) on the center stack as a function of Z position. The left-directed arrow denotes equilibrium I_P direction.

discharges as described later. The ECW was likely to suffer from multiple reflections between the L-cutoff with the center stack. Then the ECW passes through accessible areas as shown in Fig. 1(a). The passing ECW gradually bends and eventually turns back at the vicinity of upper hybrid resonance (UHR). In the case of medium density (see Fig. 1(b)), most of rays can reach UHR. The group velocity of the wave slows down and the MC to EBW takes place. The HFS launched MC process is predictable, compared with the other MCs from ECW to EBW such as OXB and XB of LFS launch. This is why we decided to conduct experiments by installing a new dedicated antenna in the HFS on QUEST. The refractive index of the EBW at the vicinity of ECR is expressed as $N_{//} = N_{\emptyset}R + N_R B_R/B$, therefore EBWCD direction is almost determined by radial magnetic field, B_R, because the value of N_R significantly larger than the other values, where $N_{//}, N_{\emptyset}, N_R$ denotes the parallel, toroidal and radial refractive indexes. The driven current direction also depends on the TF direction, because TF direction almost decides the parallel direction. The feature was confirmed experimentally as shown in Fig.1(c). The EBW is completely absorbed in the theoretically predicted region. The current driven by EBW may be canceled out in total, but the anti-equilibrium I_P plays an essential role in forming CFS to make the current density focused.

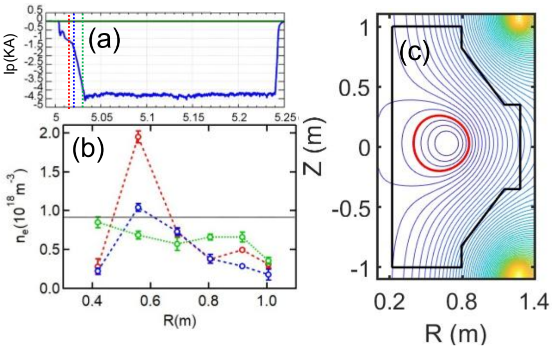

Fig. 2 The time evolution of I_P in the case that the equilibrium I_P region located in the bottom area (B_T CW), is plotted in the diagram (a). Three lines denote the timing of n_e measurement with Thomson scattering. The measured n_e profiles are plotted in the diagram (b). The line color corresponds to the time indicated in the diagram (a). A horizontal line represents $(\omega_{pe}/\omega)^2 = 1$. Magnetic flux surface reconstructed by an equilibrium code at 5.05s is shown in the diagram (c). The red circle shows the LCFS. An antenna cover was positioned at R=0.4m.

The most apparent feature in HFS launched experiments was the formation of a CFS, although CFS was never seen in the case of the LFS launch in the same magnetic configuration. The typical waveform of I_P in the case of B_T CW (The equilibrium I_P would be driven in the bottom side.) is shown in Fig. 2(a). Smooth I_P ramp-up and high density could be obtained. Actually, at the time of 5.05s, the CFS had been formed and $(\omega_{pe}/\omega)^2 \cong 1$ was achieved as shown in Fig 2(b) and (c). Before the CFS formation, the value of n_e was satisfied with $(\omega_{pe}/\omega)^2 \cong 2.0$. This means an L-cutoff appeared in front of the antenna, therefore equilibrium I_P is effectively driven in the bottom side. While, abrupt I_P ramp-up and significant density reduction down to 1/3 were observed in the case of B_T CCW. The lower density caused shifting UHR closer to the antenna and the equilibrium I_P was focused in front of the antenna. Once a small CFS had been formed, both magnetic configuration and n_e profile had changed, and then conventional EBWCD in the CFS dominantly worked. It should be noted that the final CFS had the same parameters such as I_P and n_e in both B_T directions.

We would like to confirm the EBWCD efficiency, η_{CD} in open flux surface (OFS) and CFS configurations. In the case of OFS, the estimation is a little complicated, because equilibrium and anti-equilibrium $I_P s$ are canceled out in total. The substantial EBWCD efficiency should be estimated by adding both $I_P s$. A TF inversion experiment has been conducted to obtain the sum of both $I_P s$. Under the assumption of the same pressure driven current in both cases, the sum of both $I_P s$ is determined to be 0.6 kA by a current reconstruction technique[2] in the case of $P_{RF} = 40kW$. The value of η_{CD} is $0.015\,A/W$, which is comparable to that in X-ECW at 1st ECR expected in future fusion pilot plant, STAR at low density and temperature region[3]. The value of η_{CD} in the case of CFS was $0.1\,A/W(4kA/40kW)$ even in the low T_e region less than 100 eV. It should be noted that the anti-equilibrium I_p may be driven by EBWCD even in the CFS, and a part of equilibrium I_p may be canceled out. The value of η_{CD} $(0.1\,A/W)$ in the CFS is higher than that in STEP $(0.03\ A/W\ at\ 98GHz, T_e = 4keV)$ calculated with fully relativistic EBW simulation[4]. This observation in QUEST provides a bright outlook for the plasma current start-up in future ST-based fusion reactors, if we can solve the problem of having to install an antenna in the narrow HFS area. Focusing the wave is also important to minimize the anti-equilibrium I_p.

In conclusion, EBWCD played an essential role in plasma start-up in the HFS launch of X-ECW. The most apparent feature in HFS launch, was a formation of CFS, nevertheless CFS has never provided in the case of the LFS launch in the same magnetic configuration. The observed current drive efficiency in the CFS condition is higher than that expected in future fusion pilot plants.

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