1. Introduction

Fully non-inductive plasma start-up and current drive is a major issue for the spherical tokamak (ST) since the elimination of the central solenoid (CS) for inductive current drive is considered necessary for the ST-based fusion reactor. On the TST-2 spherical tokamak, non-inductive plasma current ($I_p$) ramp-up using the lower hybrid wave (LHW (200 MHz)) is being studied [1]. Two capacitively-coupled combline (CCC) antennas, located on the outboard side (outboard-launch) and on the top side (top-launch), are used to excite the LHW. Furthermore, bottom launch can be simulated using the top-launch antenna by reversing the direction of the toroidal magnetic field. Propagation and absorption of the LHW were investigated numerically for outboard-, top-, and simulated bottom-launch at low and high plasma currents. Results of the wave measurement revealed different propagation characteristics for different launching, which agree partially with the results of numerical calculation.

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2. Experimental Setup

Thirteen RFMPs were used in this experiment. Each RFMP consists of a single-turn coil formed by connecting the inner conductor to the outer conductor of a semi-rigid coaxial cable, metal enclosure for shielding, and a slit oriented in either toroidal or poloidal direction to select the RF magnetic field with particular polarization.

On the inboard side, eight RFMPs (10 mm × 15 mm rectangular loop) are arranged symmetrically about the mid-plane $z = 0$, as shown in Fig. 1. The ($R, z$) coordinates of RFMPs are $M_{\text{upper}}$: (+575, +100), $M_{\text{middle}}$: (+585, 0), $M_{\text{lower}}$: (+575, −100) on the outboard side, $M_{\text{in}}$: (+329, −450), $M_{\text{out}}$: (+535, −450) on the bottom side, and $A_{\text{pol}}$: (+113, +327), $B_{\text{pol}}$: (+113, +177), $C_{\text{pol}}$: (+113, +177), $D$: (+113, +27), $E_{\text{pol}}$: (+113, −27), $F_{\text{pol}}$: (+113, −177), $G_{\text{pol}}$: (+113, −177), $H_{\text{pol}}$: (+113, −327) on the inboard side. RFMPs on the outboard side and the bottom side consist of a single-turn coil wound around a teflon bobbin, and a metal enclosure with a slit in the poloidal direction. All RFMPs are located in the poloidal plane at a toroidal angle $\phi = −90^\circ$ measured from the center of the outboard-launch vessel and compared with predictions of numerical calculation. Experimental data were generally consistent with numerical calculation results of wave propagation and polarization.
The RF signals are measured by two oscilloscopes with bandwidths 500 MHz at 500 MSamples per second with 1 MWord memory (2 ms observation window) around $t = 60 \text{ ms}$ where $I_p$ reaches the maximum value. The signal intensity is evaluated by integrating the frequency spectrum from 199 MHz to 201 MHz. To measure the signals obtained by all thirteen RFMPs, four reproducible shots are required due to the limited number of the oscilloscope channels.

3. Wave Measurement Results

The time evolution of the typical non-inductive $I_p$ ramp-up discharge, comparing different cases of LHW launching, is shown in Fig. 3. In this series of experiment, low and high $I_p$ case was investigated for each launching condition, though the $I_p$ could not be controlled to be the same for each launching condition, with plasma currents of 5.5 kA to 11.7 kA for outboard launch (CW $B_t$), 6.3 kA to 19 kA for top launch (CW $B_t$), and 6.8 kA to 14 kA for simulated bottom launch (top launch with CCW $B_t$). The $H_{pol}$ RFMP was out of order for the top-launch experiment with CW $B_t$.

Figure 4 summarizes the RF signal intensities measured by the thirteen RFMPs. As shown on the right figure, the horizontal axis on the left figure is the distances from the midplane on the inboard side defined as the origin, measuring downward, then radially outward through RFMPs MP_in and MP_out, and finally vertically upward to the topmost RFMP on the outboard side (MP_upper). The vertical axis on the left figure is the measured RF signal intensity normalized by the injected LHW power. The normalized RF signal intensities are plotted for low $I_p$ and high $I_p$. The background noise level was measured in the absence of RF power injection. The signal level is at least two orders of magnitude greater than the noise level.

In the case of outboard-launch, the poloidal magnetic field component is largest at MP_lower and MP_out. This result suggests that the LHW injected from outboard side propagates downward. It has been observed previously that the RF magnetic field has a poloidal polarization around these locations as expected from LHW launch [4]. After passing through outboard and bottom regions of the plasma, the wave reaching the inboard side has a strong toroidal...
polarization which now appears to correspond to the FW polarization. The poloidally polarized component (corresponding to the LHW polarization) measured at the upper inboard-side by $C_{\text{pol}}$ and $A_{\text{pol}}$ becomes weaker at higher $I_p$. This may indicate stronger damping of the LHW at higher $I_p$ predicted by the numerical analysis shown in the next section.

In the case of top launch, the RF power intensity measured by RFMPs in the upper half of the inboard side is over 100 times greater than in the case of outboard launch. The poloidal polarization is largest at $C_{\text{pol}}$. The RF power intensity is two orders of magnitude less at $B_0$, compared to $C_{\text{pol}}$ which is right next to $B_0$. In the lower inboard region, toroidal polarization becomes larger. The measured overall signal intensity becomes weaker as the distance from the top-launch antenna increases as expected naturally from the damping of LHW. The signal decreases at higher $I_p$ which is consistent with stronger absorption predicted theoretically. Significant differences could not be seen between outboard launch and top launch by RFMPs in the bottom and outboard regions.

Obvious differences can be seen for top launch when the direction of $B_t$ is reversed from CW to CCW (CCW $B_t$ corresponds to simulated bottom launch). For simulated bottom launch, the degree of polarization is weaker, and the RF signal intensity measured in the lower inboard region becomes larger than outboard launch and top launch. This indicates that the absorption is substantially weaker for CCW $B_t$ compared to CW $B_t$. The RF signal intensity decreases at lower half of the plasma by an order of magnitude at higher $I_p$, which suggests that stronger absorption is recovered at higher $I_p$.

### 4. Comparison with Numerical Calculation

Results of ray-tracing calculation using GENRAY are shown in Fig. 5. Each experimental sections performed in Sec. 3 were simulated. The ray trajectories are projected on a poloidal cross section, and the rays with 70% of the maximum power are shown. Figures 5 (a) and 5 (b) show the outboard launch case with CW $B_t$ with high $I_p$ and low $I_p$. The top launch case with CW $B_t$ with high $I_p$ and low $I_p$ and also CCW $B_t$ with high $I_p$ and low $I_p$ are shown in Figs. 5 (c-f). The color bar indicates the degree of polarization towards $B_t$ defined as

$$\theta_{\text{pol}} = \frac{180}{\pi} \tan^{-1} \left( \frac{|B_z|}{|B_0|} \right),$$

where $B_t$ and $B_0$ are calculated from the dispersion relation.

For outboard launch case, rays have $\theta_{\text{pol}} = 60^\circ$ polarization initially and propagate toward lower half of the plasma regardless of the $I_p$. This agrees with the experimental data shown in Sec. 3. However, the poloidal polarization becomes dominant close to the inboard side, whereas in the experiment, toroidal polarization is dominant. This suggests that mode conversion of LHW to FW is not accounted for properly in the numerical model. Further measurement and modeling are required to clarify this point.
Fig. 5 Results of ray-tracing calculation using GENRAY for (a) outboard launch with CW $B_t$ and high $I_p$, (b) with low $I_p$, (c) top launch with CW $B_t$ and high $I_p$, (d) CW $B_t$ and low $I_p$, (e) CCW $B_t$ and high $I_p$, and (f) CCW $B_t$ and low $I_p$. The color bar indicates the degree of polarization towards $B_z$ (Eq. (1)). For top launch with CW $B_t$, rays reach the upper inboard side around $z = +0.2$ m with dominantly poloidal RF magnetic field polarization. In the range between $z = +0.2$ m and $z = -0.2$ m polarization becomes dominantly toroidal in the core, the rays turn around radially, and polarization becomes more poloidal near the inboard wall. Toroidal, poloidal, and intermediate polarization exist in this region. This alternation of polarization direction can also be seen in Fig. 4 for the top (CW) case. At low $I_p$, up-shift of the parallel refractive index was weaker, resulting in weaker absorption. Therefore the RF signal intensity is expected to be larger than high $I_p$.

For top launch with CCW $B_t$, at high $I_p$, the RF magnetic field polarization is dominantly poloidal in the upper inboard region. The wave power decreases as the rays move downward. A comparison between the calculated ray powers and the measured RF powers are shown in Fig. 6 for top (CW) and top (CCW) cases. In this figure, the RF power is plotted in linear scale and the ray power is normalized by the initial power. Reflected around $z = +0.2$ m propagate towards the plasma center and to the outboard region, and are reflected at the outboard edge again. At low $I_p$, rays which are reflected around $z = +0.2$ m propagate downward and fill the inboard bottom region more density compared to the high $I_p$ case as shown in Figs. 5(e) and (f). These results agree with the experimental observation that the RF signal intensity in the lower inboard region is an order of magnitude higher at low $I_p$ than at high $I_p$.

5. Summary

Wave measurements were performed on TST-2 using RFMPs for three different modes of LHW excitation, outboard launch, top launch, and simulated bottom launch (top launch with reversed $B_t$). In particular, RFMPs on the inboard side could measure wave polarization. Experimentally, different characteristics were observed depending on LHW excitation mode and $I_p$. Measured powers on the outboard RFMPs and bottom RFMPs did not vary significantly among different LHW excitation modes. In contrast, RF power distribution measured by inboard RFMPs changed drastically for different excitation modes. RF signal intensities detected by inboard RFMPs were much stronger for top launch compared to outboard launch. RF signal intensity and polarization were compared with results of numerical calculation.

For outboard launch with CW $B_t$ and high $I_p$, results of ray-tracing calculation are partially consistent to experimental results that wave propagate in the lower plasma region. On the other hand, the polarization of RF magnetic field on the inboard side did not agree with the ray-tracing calculation. Possibility of mode conversion to FW needs to be investigated further. For top launch with CW $B_t$ and high $I_p$, results of ray-tracing calculation are consistent with experimental observation. RF magnetic field polarization on the inboard side is dominantly poloidal in the upper region, becomes more toroidal in the middle.
region near the midplane, and dominantly poloidal again in the lower region. For top launch with CCW $B_t$, results of ray-tracing were again consistent with experimental data. The wave power is strong in the upper inboard region. The comparison of ray powers shown in Fig. 6 implies that ramp up to higher current may be achieved for the top (CCW) case than either the outboard case and the top (CW) case since ray power damping is stronger. Rays with down-shifted parallel wavenumber fill a broad range of edge plasma on the inboard side at low $I_p$, and the RF signal intensity decreased as $I_p$ increased. RF signal intensities detected by outboard and bottom RFMPs were similar for both top (CW) and top (CCW) cases.

In conclusion, spatial distributions of wave power, phase, frequency spectrum, and wave polarization were measured by thirteen RFMPs surrounding the plasma cross section. In particular, wave propagation changed drastically depending on $I_p$ except for the outboard launch case, but experimentally, the dependency of RF power distribution on $I_p$ could not be seen apart from reduction in amplitude. In order to resolve this discrepancy and to make a more quantitative comparison, expansion of the RFMP system for higher spatial and polarization coverage is necessary. This will contribute to identify optimum $I_p$ ramp-up scenario.

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