Status of LHFW research in KSTAR and Future Plan

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Abstract. The LHFW research has been conducted on KSTAR after successful feasibility study on VEST. With a newly developed SWA (Slotted Waveguide Antenna) of 2.45 GHz, for the first time LHFW experiment was carried out in the 2024 KSTAR campaign. The preliminary coupling experiment result shows that the LHFW (Lower Hybrid Fast Wave) can be coupled with short ROG (Radial Outer Gap) and high elongation (kappa) configuration in H-mode plasmas, which is in agreement with the coupling simulation characteristics of slow and fast wave with density. Unfortunately, the SWA was damaged by mis-alignment with poloidal limiter originated from chamber port length. A more thermal & sputtering resistant SWA is under development and it will be installed before the 2025 KSTAR campaign. If the LHFW coupling is confirmed on upcoming KSTAR campaign, higher power experiment will be pursued aiming for LHFW current drive.

1 Introduction

LHFW (Lower Hybrid Fast Wave) has been suggested as a promising current drive scheme for tokamak fusion reactor [1,2]. The feasibility study on VEST showed that current drive is possible confirming the elementary coupling and propagation characteristics of LHFW [3]. Recently, a LHFW research has been started on KSTAR to see whether the scheme is applicable to medium-size or reactor-relevant tokamaks. A suitable frequency for LHFW on KSTAR is 2.45 GHz so the relevant RF system including power, transmission line, vacuum window, antenna has been prepared and developed in aligned with the frequency [4]. In particular, a SWA (Slotted Wave-guide Antenna) was developed by using a rectangular waveguide in which corrugation walls are embedded to satisfy the parallel refractive index for the frequency [5,6]. After successful installation of the RF system, the first experiment was conducted in the 2024 KSTAR campaign. The current status and future plan are reported in the paper. The experimental setup is described including RF system schematic, antenna, and diagnostic in section 2. The experiment and analysis result are given with the diagnostic data and 1D full cold plasma wave coupling simulation result in section 3. Based on the analysis, operational scenarios are suggested for effective LHFW coupling and current drive experiment with a new antenna in the future. Finally, it is summarized in section 5.

2 Experimental Setup

2.1. RF System

A schematic of the RF system including microwave power, transmission waveguide, vacuum window, and the slotted waveguide antenna is shown in Figure 1.

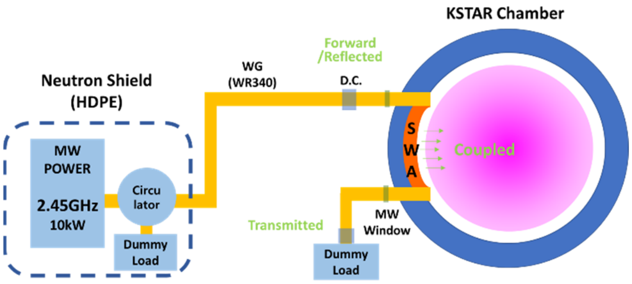

Fig. 1. Schematic of KSTAR LHFW RF System.

The RF power is a commercial solid-state of microwave power of 12 kW. It has a built-in circulator and a dummy load. The power is transmitted to the SWA through 5 m long rectangular waveguide and microwave window on P-port flange. The window is a pill-box type commercial RF feed-through made of alumina and copper with cooling channel. The KSTAR ports are as long as 2 meter due to superconducting magnet, so additional WR340 wave-guides are attached from the window to SWA. The installed the RF components from P-port flange to SWA are shown in Figure 2.

Fig. 2. RF components installed in KSTAR.

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2.2 Slotted Waveguide Antenna

The SWA is a slotted travelling wave type antenna using rectangular waveguides. The required parallel refractive index for LHFW coupling and propagation is determined by adjusting the height of the corrugation walls attached on the bottom of the waveguide inside. It ranges from 2.4 to 2.5 with frequency. The microwave fed at an input port is split into two rectangular waveguides and propagates along each waveguide. A part of the power is coupled to plasma through the horizontal slot on the top part of the wide side of the waveguide. The uncoupled microwave is combined at the end of the waveguides and finally goes to the output port. The dimension and the configuration are shown in the left part of Figure 3. The manufactured and installed SWA is shown in the right of the figure. More details can be found in the reference [5,6].

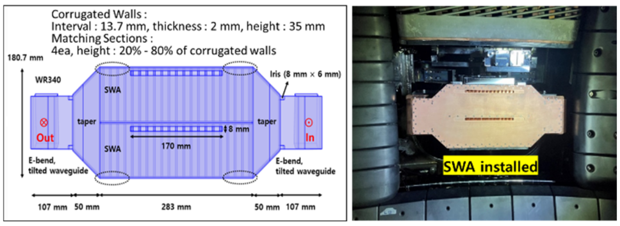

Fig. 3. Slotted Waveguide Antenna designed and installed.

2.3 Diagnostics

The most critical parameter for LHFW coupling is the density in front of the antenna. Three diagnostic data are monitored to figure out the density and coupling characteristics. The first is line averaged plasma density in SOL and Edge of TCI (Two Color Interferometer) channel 5 which has tangency radius of 2.16 m. The second and the third are ROG (Radial Outer Gap) and elongation(kappa), respectively, by PCS (Plasma Control System). Since the antenna is located below about 20 cm from the equatorial plane, the kappa should be considered to be another important parameter to know the density in front of antenna. The three parameters are illustrated in Figure 4.

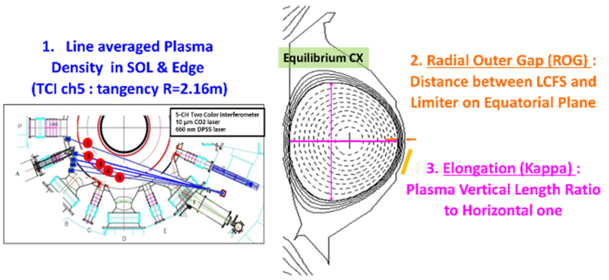

Fig. 4. Diagnostics for the density in front of antenna.

3 LHFW coupling experiment

3.1. Coupling characteristic simulation

The coupling characteristics of LHFW and LHSW are shown with regard to the plasma density in Figure 5. It is simulated with 1D full cold plasma wave code with WKB boundary conditions of two wave branches [7]. The LHSW coupling is high in low density range but it drops down if the density increases more. In contrast, the coupling of LHFW is consistently low if the plasma density is lower than the launching density that is about 8×10^{18} m^{-3} for $N_{\|}$ of 2.7 at B = 1.5 T. But it jumps up once the density exceeds the launching density. In summary, LHSW coupling decreases with increase of density while LHFW coupling increases with the density in front of antenna.

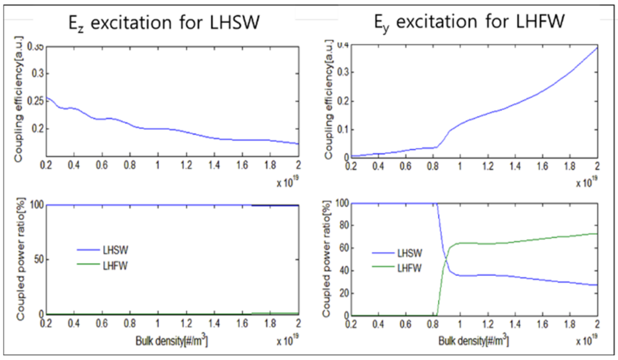

Fig. 5. Coupling characteristics of LHFW and LHSW.

3.2. Analysis of experimental results

Figure 6 shows the experimental data of shot number #36270 of 2024 KSTAR campaign. It includes plasma current, NB (Neutral Beam) power with D-alpha signal, three diagnostic data described in subsection 2.3, and the coupled power ratio for small power of 5 dBm. The plasma current ramps up during first 1 seconds in two steps and 500 kA sustains steadily for 1.5 seconds after that. Two NB power are injected up to 4.5 MW with step-wise wave form to form the plasma equilibrium appropriately.

One may divide the shot with two parts by the time zone around 1.2 seconds where the coupling ratio decreases abruptly and so can be called a transition. Since, as shown in the previous subsection 3.2, the decrease of coupling cannot be expected for LHFW with the decreasing ROG and increasing elongation that mean increase of the density in front of antenna, one can think the decrease of coupling stems from the suppression of LHSW coupling with increase of density. Before the transition, the average plasma density does not remain steadily above 6×10^{18} m^{-3}, LHFW launching density for $N_{\|}$=2.4, and the ROG is greater than or roughly equal to 0.06 m except for first 0.4 seconds. In addition, the kappa is lower than 1.5 considered to be a circular-like and almost circular in the first 0.4 seconds. After the transition, however, the plasma density increases gradually and peaks at around 2.2 seconds by H-mode transition accompanying large fluctuating D-alpha signal. And the ROG remains almost 0.06 m and drops around 2 seconds thanks to plasma expansion by H-mode development. The elongation is constantly maintained high at 1.7 and rises more by the H-mode transition.

Summarizing the plasma condition in view of LHWs, before transition the plasma density is too low for LHFW to couple due to long distance to bulk plasma by long ROG or low kappa as shown in the equilibrium at 0.8 seconds of Figure 6. In contrast, for LHSW it is suitable to couple efficiently and it is in good line with the coupling drop transition around 1.2 seconds discussed above. Meanwhile, after transition, the plasma condition becomes more favourable for LHFW to be coupled since the average plasma density increases gradually above LHFW launching density, remaining the ROG and kappa consistently at 0.06 m and 1.7, respectively. Finally, when the plasma density is significantly enhanced in front of the antenna around 2.0 seconds by H-mode transition, the LHFW coupling instantly becomes peak. The plasma configuration for the case is shown in the equilibrium at 2.12 seconds of the right part of Figure 5.

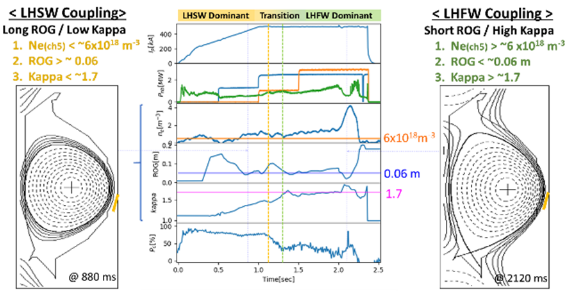

Fig. 6. LHWs coupling characteristics of #36270.

The three diagnostic values 6×10^{18} m^{-3} of average density, 0.06 m of ROG, and 1.7 of kappa for #36270 might be used as a guidance to figure out the coupling characteristic of other shots. Figure 7 shows the experimental data of shot number #36276. Applying the guide values to the diagnostic data, one can expect the LHFW coupling from the early part of the shot, about 0.4 seconds, because the ROG is much shorter as 0.02 m and the kappa is even higher as 1.9 in spite of marginal average plasma density. The coupling drops as ROG increases above 0.06 m at 1.8 seconds and it remains low until 4 seconds when the H-mode start to develop. As ROG drops and the density jumps by the H-mode transition after 4 seconds, the coupling ratio increases again. After that it shows fluctuating tendency with ROG and density variations in H-mode. Comparing with #36270 based on the guide diagnostic values, one can think LHFW coupling is dominant all the way for this shot.

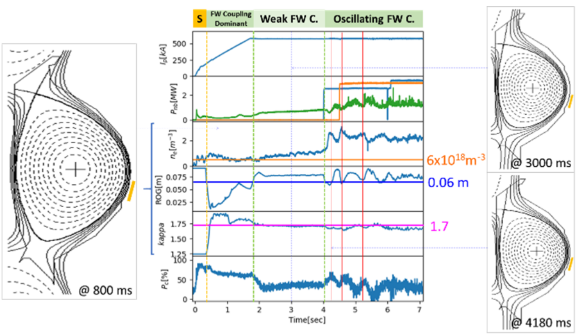

Fig. 7. LHWs coupling characteristics of #36276.

3.3. Damage of SWA

A microwave power injection of 10 kW was planned after the coupling experiment. However, the antenna was damaged unfortunately by heating as shown in the left part of Figure 8. And it is confirmed in the vacuum radiation increase by large opening as shown in the right part of the figure. It increases upto about 40 % before tokamak start at 0 seconds that is much higher compared to 10% before damage as shown in Figure 6 and 7. The cause of heating was due to 5 mm protrusion of the antenna from poloidal limiter surface. Precise measurement with 3D scanner revealed that the radial distance of the P-port flange from the tokamak center is about 13 mm shorter than original design.

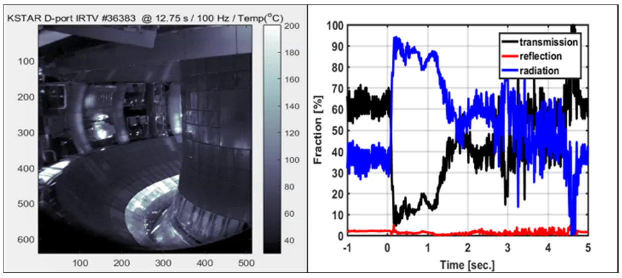

Fig. 8. Antenna damage picture and signal.

4 Discussion & Future Plan

4.1. Coupling & Scenarios

From the experiment analysis with diagnostic data and the coupling characteristic simulation in the previous section, we could suggest some guidance conditions for effective LHFW coupling and high power injection experiment on KSTAR in the future. The first is evidently that ROG should be kept less than at least 0.06 m. It is quite relevant to exponential decay length of the electric field in evanescent layer between antenna and plasma that is evaluated to be about 0.01 m. The second is that elongation should remain greater than 1.7. Circular plasma can give spacious rooms for LHSW to propagate easily in SOL region, so it should be avoided for more LHFW coupling than LHSW. The third is moderate control of H-mode. H-mode can provide obviously high density for effective LHFW propagation into central plasma. However, excessive density rather seems to hinder the coupling as shown peaky instantaneous coupling in Figure 6. Actually, too high pedestal top density can cause reflection by drastic change of refractive index of LHFW. In addition, in most cases it can accompany large periodic ELM crash that can give detrimental effect on antenna. A suitable H-mode control might be carried out through RMP (Resonant Magnetic Perturbation), because it can lower the pedestal top density and moreover suppress the detrimental periodic ELM density crash. Considering RMP is an important standard means for the stable H-mode, the operation scenario using RMP for LHFW is conforming to the main operational scenario of tokamaks.

4.2. New LHFW Antenna

Though the mislocation of the antenna to the limiter will be adjusted in the upcoming KSTAR campaigns, the unpredictable surge of plasma heat and particle can damage significantly the antenna surface and eventually stop the operation. In the context, a new antenna is under development using the narrow side of the rectangular waveguide and tungsten blocks for protection. If narrow side of the waveguide is used for radiation slot, each module of the antenna has less exposed area to plasma. And heat removal is facilitated by attaching thin cooling channel on the bottom of the wide side of the waveguide. Moreover, the tungsten block on the surface can protect the antenna copper body from the plasma sputtering. The configuration of the new antenna design is in Figure 9.

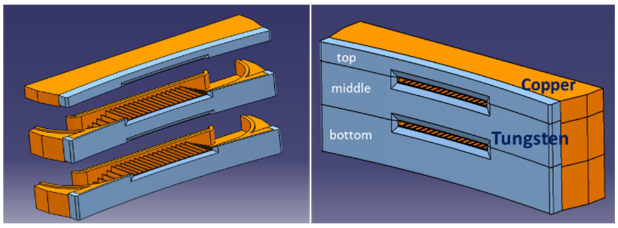

Fig. 9. New LHFW antenna design.

4.3. High Power Operation

The KSTAR LHFW antenna module has been developed to handle 100 kW power enabling extension to 1 MW in the future. So more than 100 kW is required for the full power test of current LHFW antenna module. Currently, only two solid-state microwave power of 12 kW have been prepared for short-term research. So much effort is required to secure the high power MW source through collaboration with fusion society in the near future.

5 Summary

For the first time LHWs coupling is observed with a traveling SWA in the experiment on KSTAR. LHFW coupling peaks at short ROG and high elongation in H-mode plasmas while LHSW coupling appears dominant at low density circular-like tokamak plasma with distant ROG. Based on the experimental coupling characteristics of LHWs, a scenario facilitating efficient LHFW coupling is suggested with short ROG, high kappa, and modest pedestal top density without ELM by RMP. A new antenna is under development to improve heat removal, sputtering damage, and compact-modular design for extension. It is planned to test the antenna on upcoming 2025 KSTAR campaign. If the coupling characteristic is confirmed again, high power injection experiment will be pursued aiming to LHFW current drive in the future.

Acknowledgement

The research is supported by the National R&D Program through National Research Foundations of Korea (NRF) funded by the Ministry of Science and ICT.
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