5 GHz Antenna for KSTAR LHCD System

#S. Park[1], H. Do[2], H. J. Kim[1], A. K. Aria[1], Y. S. Bae[1], H. L. Yang[1], M. Cho[2], Won Namkung[2], and H. Park[2]
[1] Tokamak Engineering Division, NFRI
Gwahangno 113, Yusung-gu, Daejeon 305-333, Korea, spark@nfri.re.kr
[2] Department of Physics, POSTECH
Hyoja-dong, Nam-gu, Pohang, Kyungbuk 790-784, Korea

Abstract

The Korea Superconducting Tokamak Advanced Research (KSTAR) is a fusion research facility aiming at the steady-state operation and advanced plasma experiment. To support these purposes, a high power lower hybrid current drive (LHCD) will be used to control the plasma current profile. This paper presents the KSTAR LHCD antenna system, which is a phased-array waveguide antenna launching waves to any direction by changing the phase difference between the grilled waveguides.

Keywords : KSTAR LHCD Antenna

1. Introduction

In order to investigate the steady-state operation and advanced plasma experiment for fusion plasma, the Korea Superconducting Tokamak Advanced Research (KSTAR) was designed and constructed [1]. To address these technical and scientific issues on KSTAR tokamak device, ancillary heating systems, which consist of neutral beam injection (NBI) and radiofrequency (RF) system, are proposed and used. The lower hybrids current drive (LHCD) system is one of the ancillary heating systems, and is mainly used for plasma current profile tailoring, which is occurred by the asymmetry in thermal velocity distribution based on Landau interaction between the wave and charged particle, rather than plasma heating [2]. In addition, the off-axis current driven by the LH wave can create broad or even hollow current profiles required in an “advanced tokamak” scenario for ITER by introducing a negative magnetic shear [3]. In KSTAR, 5-GHz LHCD system is designed to control the current profile and to support the long term plasma operation using off-axis non-inductive current drive [4]. The design and current status for the KSTAR LHCD system are presented in Section 2. The LHCD antenna for the LH wave injection into the fusion plasma is described in Section 3. Finally, the summary is in Section 4.

2. KSTAR LHCD system

The KSTAR steady-state LHCD system is designed to have a source power of 2 MW using four sets of klystrons. To supply the RF power for the LHCD system, the development of the klystron with the RF output power of 500 kW and with duration of 300 s at the frequency of 5 GHz, which is the same frequency as that intended for ITER, is the highest priority [5]. For the RF source of the KSTAR LHCD system, the prototype klystron was designed in consideration of the technical issues such as the output cavity and output window, and was developed by the Toshiba Electron Tubes and Devices (TETD) Company in Japan. The prototype klystron was tested at 460 kW for the pulse duration of 10 s and at 300 kW for 800 s at National Fusion Research Institute (NFRI) in Korea [6]. The RF power generated by the klystron is transmitted to the antenna in the propagation mode of TE_{10} through the transmission line which consists of the standard WR187 rectangular waveguide components. For the real time measurement of the RF output power radiated from the klystron, waveguide based bi-directional couplers are installed near the klystron and the input of the LHCD antenna. The output power is switched to either the plasma or the dummy load remotely by a high power waveguide switch. For the output power calibration of the klystron, the RF is switched

to the high power dummy load and the RF power is calculated by using the calorimetric methods based on the temperature variation between the coolant inlet and outlet. The transmitted RF power is divided evenly into 32 waveguide channels by the jungle-gym, which consists of waveguide components such as magic-tee, and then separated again into 4 rows by 4-way power splitter in the LHCD antenna. The RF power divided by the jungle-gym and 4-way splitter of the antenna is radiated into the plasma by the grill, which is the multi-waveguide launching structure and is composed of the array of properly phased rectangular waveguide, in the antenna.

For basic experimental study and operation experience of the LHCD system, an initial 5 GHz LHCD system (0.5 MW, 2 s) using the prototype klystron is under development. Figure 1 shows the block diagram of the KSTAR initial LHCD system.

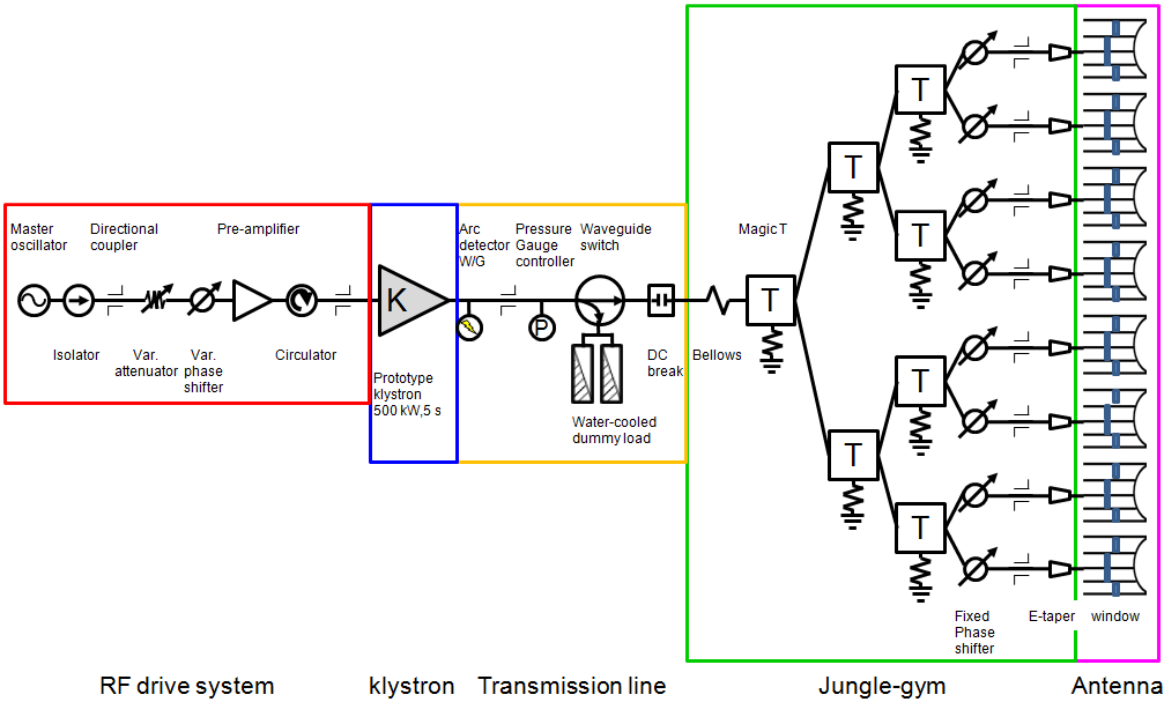

Figure 1: Block diagram of KSTAR initial LHCD system.

3. LHCD antenna

To inject the LH wave into the plasma, the multi-waveguide launching structure, so-called grill, is proposed and the grill, which is composed of 32 fully active waveguide columns by 4 rows, will be used in the KSTAR steady-state LHCD system. The number of waveguide channels in the grill is determined by the controllability of the power spectrum radiated from the antenna and the radiated power spectrum is controlled by the phase difference between adjacent waveguide columns in the antenna. The grill for the KSTAR LHCD antenna is designed to have the width of 5.5 mm, the height of 55 mm, and the gap of 1.5 mm between the waveguide columns and the waveguide size in the grill is chosen to have the power flux density below a weak breakdown condition and a higher $N_{\|}$ value of the fundamental peak than the accessible $N^{acc}_{\|}$ value given by the Golant condition [7].

$$N_{\|} = \frac{\Delta\phi}{kp} + n\frac{2\pi}{kp} \tag{1}$$

$$N_{\|}^{acc} = \frac{\omega_{pe}}{\omega_{ce}} + \sqrt{1 + \left(\frac{\omega_{pe}}{\omega_{ce}}\right)^2 - \left(\frac{\omega_{pi}}{\omega}\right)^2} \tag{2}$$

where k, ΔΦ, p, and n are the vacuum wavenumber, the phase shift between adjacent waveguides, the geometric periodicity of the waveguide, and a integer mode number, respectively. And ω, ω_{pe}, ω_{pi}, and ω_{ce} are the wave frequency, the local electron plasma frequency, the local ion plasma frequency, and the local electron cyclotron frequency, respectively. The KSTAR steady-state LHCD antenna is designed to change the $N_{||}$ value of the fundamental peak from 1.43 to 3.58 by varying the phase difference and the power directivity is calculated at 95 % for ΔΦ = 60° and 60% for ΔΦ = 150° by the coupling code calculation [8]. In addition, RF-driven current and current drive efficiency by using LH wave has been studied with Brambillar code and Lower hybrid Simulation Code (LSC). The RF-driven current and the current drive efficiency are significantly affected by the electron density and temperature profile. By the 5 GHz, 2 MW LH wave, the driven current of ~ 400 kA and the current drive efficiency of ~15 % are calculated with the B_T = 3 T, I_p = 2 MA, T_e = 5 keV, $n_{peak\_e} = 0.5 \times 10^{20}$ m^{-3} in KSTAR [9]. To control the radiated power spectrum of the LH wave during the KSTAR plasma pulse in real time, the real time feedback system for phase difference between adjacent waveguide columns in the antenna will be used. In addition, the real time feed system used to minimize the difference of the output power and phase between the klystrons is planned to use.

The initial design of the antenna for the KSTAR LHCD system has been developed based on the TPX LHCD system in collaboration with PPPL and is composed of the rear waveguide channel having the 3-dB splitter, the front waveguide channel containing a fixed phase shifter for compensation of the phase difference due to the splitter, and the grill [4]. To feed the RF power into the antenna, the RF power generated by the each klystron is divided into 8 upper and lower waveguide channels by the jungle-gym. However, recently, the LHCD antenna design is changed to have 4-way splitter instead of the upper and lower waveguide channels based on 3-dB power splitter and this antenna design is applied to the initial LHCD system. Figure 2 shows the KSTAR initial LHCD antenna system. By the change of the LHCD antenna design, it is expected to reduce the size of the jungle-gym and the purchasing cost for high power RF components.

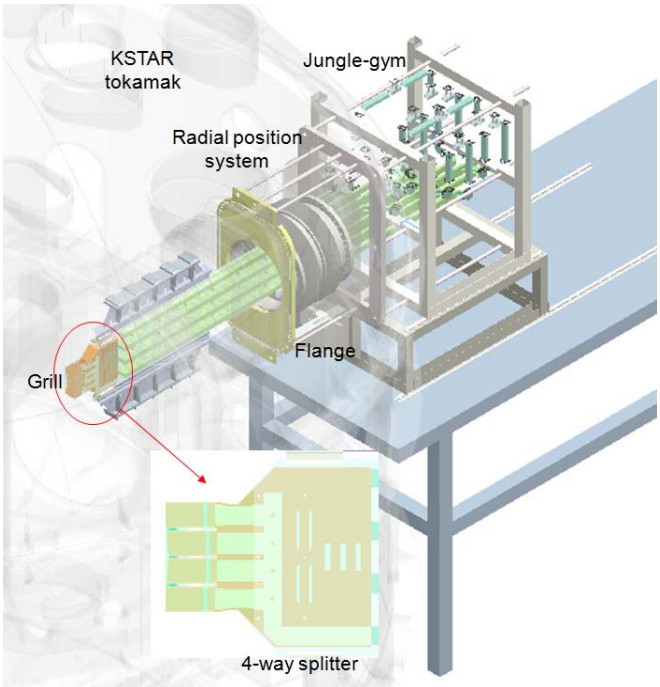

Figure 2: KSTAR initial LHCD antenna system

For the long pulse operation of 300 s, the heat removal from the grill mouth is the critical issue. However, the current LHCD antenna has been designed without consideration of the cooling. In order to achieve the steady-state operation, new design features of the antenna is required to remove the heat from the waveguide channel and grill. For the cooling of the antenna, two solutions are suggested to overcome this issue. One is to use the fully active multi-junction (FAM) gill with active water cooling in the stacked metal

plates. Although it gives the good power spectrum, there is not enough space to install the coolant channel due to the stainless steel septa of 1.5 mm. The other is to use the passive-active multi-junction (PAM) grill. Though the number of waveguide columns in the antenna is reduced by a half, it is effective for antenna cooling. For the development of the steady-state LHCD antenna, the antenna design is planned to conduct through the collaboration with CEA in France.

4. Summary

For fusion research, the KSTAR tokamak was designed and constructed in Korea. The KSTAR steady-state LHCD system is designed to control the current profile for the long pulse operation and advanced tokamak experiments. The RF power of 2 MW generated from four klystron with the output power of 500 kW for 300 s at 5 GHz is divided into 32 waveguide columns by the jungle-gym and radiated into the plasma through the grill (32 × 4) after power splitting it the LHCD antenna. For basic experimental study and operation experience of the LHCD system, the KSTAR initial LHCD system (0.5 MW, 2 s) is under development. To inject the LH wave into the plasma, the LHCD antenna is designed based on the 4-way splitter and the fully active waveguide grill without active cooling. For the steady-state LHCD system, the PAM type antenna will be designed in collaboration with CEA in France.

References

[1] G. S. Lee, M. Kwon, C. J. Doh, B. G. Hong, et al., “Design and construction of the KSTAR tokamak”, Nucl. Fusion, vol. 41, pp. 1515-1523, 2001.

[2] X. Litaudon, R. Arslanbekov, G. T. Hoang, E.Joffrin, et al., “Stationary magnetic shear reversal experiments in Tore Supra”, Plasma Phys. Control. Fusion vol. 38, pp. 1603-1626, 1996.

[3] J. Mailloux, B. Alper, Y. Baranov, A. Becoulet, et al., “Progress in internal transport barrier plasma with lower hybrid current drive and heating in JECT (Joint European Torus)”, Phys. Plasma vol. 9, pp. 2156-2164, 2002.

[4] S. Park, H. Do, J. H. Jeong, W. Namkung, et al., “Development status of KSTAR 5 GHz LHCD system”, Fusion Eng. Des. vol. 85, pp. 197-204, 2010.

[5] ITER DDD of “Lower Hybrid Heating and Current Drive System”, G 54 DDD 2 01-07-19W 0.2.

[6] H. DO, S. Park, J. H. Jeong, Y. S. Bae, et al., “Test results of 5 GHz, 500 kW CW prototype klystron for KSTAR LHCD system”, Article in press (2011).

[7] Young S. Bae, Moo H. Cho, Won Namkung, S. Bernabei, et al., “Launcher Study for KSTAR 5 GHz LHCD system”, J. Korean Phys. Soc. vol. 49, pp. S314-S319, 2006.

[8] J. Stevens. M. Ono, R. Horton, J. R. Wilson, “Edge density profile effects for lower hybrid waveguide coupling”, Nucl. Fusion, vol. 21, pp. 1259-1264, 1981.

[9] A. K. Aria, Y. S. Bae, H. L. Yang, M. Kwon, et al., “Simulation Study of Current Drive Efficiency for KSTAR 5 GHz LHCD”, 19th Topical Conference on Radio Frequency Power in Plasma, Newport, USA , 2011.

Acknowledgments

This research work is partly supported by R&D Program through the National Fusion Research Institute of Korea (NFRI) funded by the Government funds and MEST, Korea via Fusion Research Grand of NRF.