Proceedings of the Korean Nuclear Spring Meeting
Gyeong ju, Korea, May 2003

Development of KSTAR Heating and Current Drive Systems for Long Pulse Operation

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Abstract

The heating and current drive systems are being developed to support long pulse, high β, advanced tokamak fusion physics experiments in the KSTAR tokamak. The heating and current drive systems consisting of neutral beam injection (NBI), ion cyclotron waves (ICRF), lower hybrid waves (LHCD) and electron cyclotron waves (ECH/ECCD) have been designed to operate for pulse lengths up to 300 sec and to provide a range of control functions including current drive and profile control. Development of key technologies for high power, long pulse operation has been on going. Substantial progress has been made on areas such as RF launchers, ion source, and high power supplies.

1. Introduction

The KSTAR tokamak (R_0 = 1.8 m, a = 0.5 m, κ = 2, δ = 0.8, B_T = 3.5 T, I_p = 2 MA, τ_{pulse} = 300 sec) [1] is under construction to perform advanced tokamak research in a high performance regime and to explore methods for achieving a steady-state operation for a tokamak fusion reactor. The baseline heating and current drive systems of KSTAR tokamak consist of neutral beam injection (NBI) and radio frequency (RF) systems: tangential NBI (beam energy < 120 keV, 8 MW), ion cyclotron waves (frequency range of 25-60 MHz, 6 MW), lower hybrid waves (frequency of 5.0 GHz, 1.5 MW), and electron cyclotron waves (frequency of 84 GHz, 0.5 MW). Depending on the operation scenarios, each system will be expanded to provide more power with a pulse length of 300 sec. The flexibility to provide a range of control functions including current drive and profile control derives from the use of multiple heating technologies.

The NBI system provides ion heating, current drive, core fueling, profile controls for pressure and current, and diagnostic requirements. All of the components such as ion source, beamline components, and power supplies have been developed to be able to operate for a pulse length of 300 sec. The ICRF system provides heating and on-axis/off-axis current drive for various operating scenarios over a range of magnetic fields with the frequency range of 25-60 MHz. High power density (~10 MW/m^2) launcher and the transmission components for transmitting MW level of RF power need to be developed for long pulse operation. The LHCD system will be used for a steady-state operation of the KSTAR and an off-axis current-profile control. In order to support flexible off-axis current-profile control, the capability to dynamically vary the wave number spectrum is provided with the array of phase shifters. The ECH system will be used for the initial plasma phase of the KSTAR tokamak to aid plasma breakdown, thereby lowering the loop voltage (and the integrated volt-sec) required to initiate plasma. The ECH system will be upgraded to the 1 MW electron cyclotron current drive (ECCD) system in the upgrade phase of the KSTAR tokamak for the study of MHD stability control and improved core transport.

Engineering design of each system has been completed and efforts have been focused on the development of key technologies for high power, long pulse operation. Fig.1 shows the layout of the planned KSTAR heating and current drive systems.

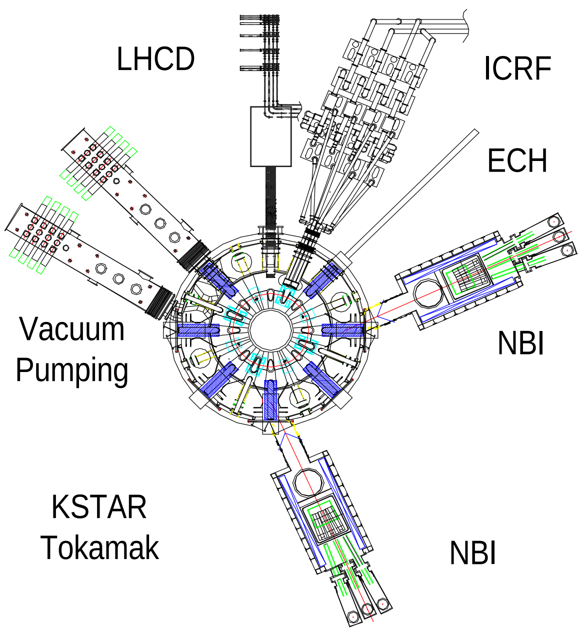

Fig. 1. Layout of the planned KSTAR heating and current drive systems.

2. Neutral Beam Injection System

The NBI system initially shall deliver 8 MW of neutral beam power to the plasma from one co-directed beam line, and shall be upgraded to provide 14 MW of neutral beam power with two co-directed beam lines. The system is arranged in a horizontal fan array and is aimed at a NBI duct of the tokamak with the beam tangency radius of 1.486 m. Whole components of the system which is shown in Fig. 2, are assembled in a 3 m (W) x 4 m (H) x 5 m (L) vacuum box and total length of the beam line from the source exit grid to the center of NBI duct is 10 m.

Prototypes of all of the beamline components for the NBI system have been fabricated to test 300 second capability, and with those components, the test stand has been set up in KAERI. Hypervapotron and swirl tube have been developed for the high-heat-flux components of 1 kW/cm^2 for up to 300 second pulse length. Hypervapotrons are used as a beam facing elements in the calorimeter and neutralizer, and swirl tubes are used in the ion dump. The test results with the compared experimental data between the two cooling elements will be used in determining the final one for the KSTAR NBI system.

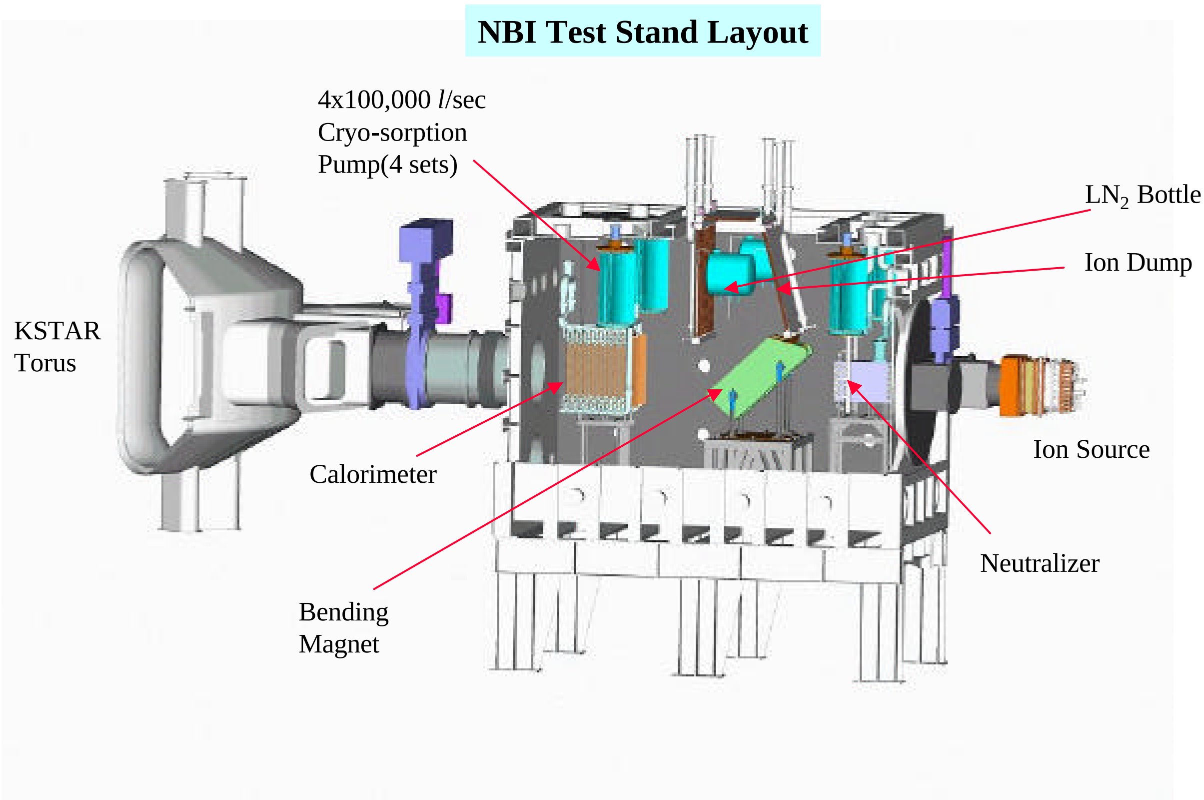

Fig. 2. NBI system and its components.

The prototype ion source has been fabricated with LPIS bucket source [2] modified from slit aperture grids to circular ones (Fig. 3). Uniform bucket plasma, the ion density of which is of the order of 10^{12} cm^{-3}, has been obtained [3] in an emission-limited mode, and beam extraction experiments are in progress. A neutralizer has been fabricated. The total length of gas filled neutralizing region is 2.4 m with the area of 14.7 x 46.2 cm^2. An OMA (Optical Multi-channel Analyzer) port for neutral beam diagnostics is aligned on the interface component with an angle of 60° to the beam axis.

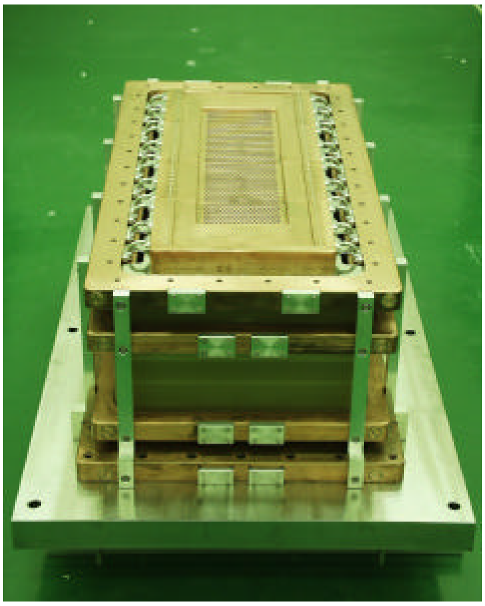

Fig. 3 Ion source

The bending magnet is designed to deflect the 120 keV deuterium beam 70° upward from the beam axis. Low carbon steel (S10C) is used for the pole and yoke, and stainless steel is used for the case of the epoxy-molded-coil. Actively cooled pole-protection-plates, an electron dump and pre-magnet scrapers are prepared for the long pulse operation. The ion dump, located above the bending magnet, consists of three sets of plates which are made by swirl tubes. OFC pipes (inner diameter : 16 mm, thickness : 2 mm) and swirl tape (thickness : 1 mm) are used in making the tube. The designed heat flux is 1 kW/cm^2. For the measurement of the ratio of the ion species, each plate has its own calorimetric system. The calorimeter made by Hypervapotron elements, is designed not only to measure the beam power but also to measure a beam profile. To limit the heat load less than 1 kW/cm^2 the target is designed as a vee shape, and the angle of which is 28°. Thermocouples are equipped on the Hypervapotrons to measure the temperature distribution. Cryosorption pump has been developed to cover the needed pumping speed of 4.0 x 10^5 *l*/sec in the test stand, where LHe is not available. The cooling method of shielding baffle is now being modified from LN_2 to electric cooler because of the operational inconvenience.

Fig. 4 shows the schematic circuit diagram of NBI power supplies. The arc & filament power supplies for each ion source are connected to their loads at the high voltage side with a power transmission line, which is terminated in an ion source housing filled with pressurized SF_6. The filament power supply converts 180 V ac three-phase power from Isolation Transformer to DC for heating the ion source filaments, which operates up to 15 V and 5500

A. The output is isolated from the ground and is referenced to the high voltage accelerator potential of 120 kV. To obtain a stable arc current, the output voltage of the filament power supply is altered through a control loop, whose reference is the actual arc current. When the accelerator system malfunctions, the arc current is suppressed by the action of the arc modulator across the output of the arc power supply. The supply can deliver up to 160 V, open circuit, to initiate discharge, and provides sufficient power to sustain the discharge with a current limit of 1200 A for safety. An acceleration power supply provides a maximum current of 70 A and operational voltage of 30 - 120 kV with voltage and current ripples of 2 % peak-to-peak during 320 seconds. The output voltage is controlled by a selection of the number of serially connected nine transformer-rectifiers and forty IGBT chopper modules. The control and monitoring system is developed in the environment of the Experimental Physics and Industrial Control System (EPICS) and VME bus system controlled by VX-works. An OMA system and an IR camera system have been prepared for the neutral beam diagnosics and the beam profile monitoring on the target.

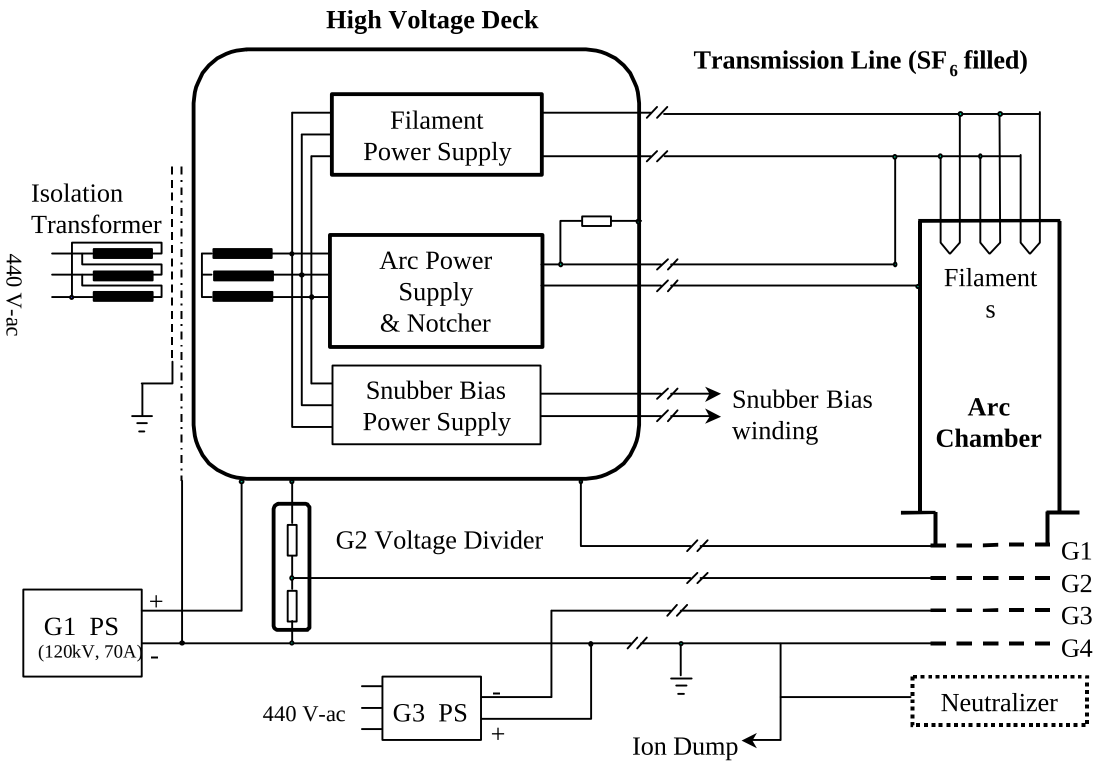

Fig. 4. Interconnection of NBI power supplies.

3. ICRF System

The ICRF system will deliver 6 MW of RF power to the plasma using a single four-strap antenna mounted in a mid-plane port. The system provides heating for the plasmas, centrally peaked current drive, and off-axis current drive using mode-conversion for various operating scenarios over the range of magnetic fields, B_T = 2.5 ~ 3.5 T. For B_T = 3.5 T, the frequency of ~ 50 MHz is good for H minority heating or second harmonic heating of D in D majority plasma. The frequency of ~38 MHz can be used as an on-axis fast wave current drive (FWCD) scheme for a steady-state operation of KSTAR. With a He^3 minority, operation between 30 MHz and 40 MHz may be possible for He^3 minority heating or off-axis current drive using mode-conversion.

As shown in Fig. 5, KSTAR ICRF antenna composed of four current straps side by side, each of which is grounded at the center and has a coaxial feed line connected to each end of the current strap. A resonant double loop consists of vacuum transmission line, vacuum feedthrough and pressurized coaxial line with two adjustable phase shifters. The feed line from 2 MW transmitter is connected to the tee. The capability of changing the current drive efficiency to control the current density profile is provided by changing the phasing between the antenna strap currents during operation. [4] The ICRF system should be able to deliver 6 MW of power to plasma withouting exceeding the 35 kV anywhere in the system. For high power, long pulse operation, relevant ICRF components have been developed in the area of the antenna, the vacuum feedthrough and the matching devices.

A high power density (~ 10 MW/m^2) prototype ICRF antenna has been developed. (Fig. 6) For 300 sec operation, the antenna has sophisticated cooling channels to remove the dissipated RF power loss and incoming plasma heat loads. Mechanical and high power RF tests were performed with the antenna installed in the RF test chamber. The peak voltages of 33.2 kVp for 60 sec and 25.2 kVp for 300 sec were found for 30 MHz, 30 kW of RF power. Fig. 6 Shows the fabricated antenna and Fig. 7 shows the time evolution of forward and reflected power.

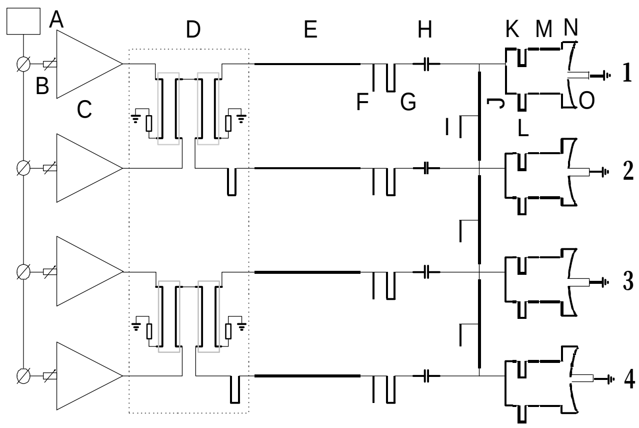

Fig. 5. Schematic of the KSTAR ICRF system.
A; Signal generator, B; Phase controller, C; 2 MW transmitter, D; ELM dump, E; Main transmission line, F; Stub, G; Phase shifter, H; DC break, I; Stub, J; Decoupler, K; Resonant loop, L; Phase shifter, M; Vacuum transmission line, N; Strap line, O; Current strap

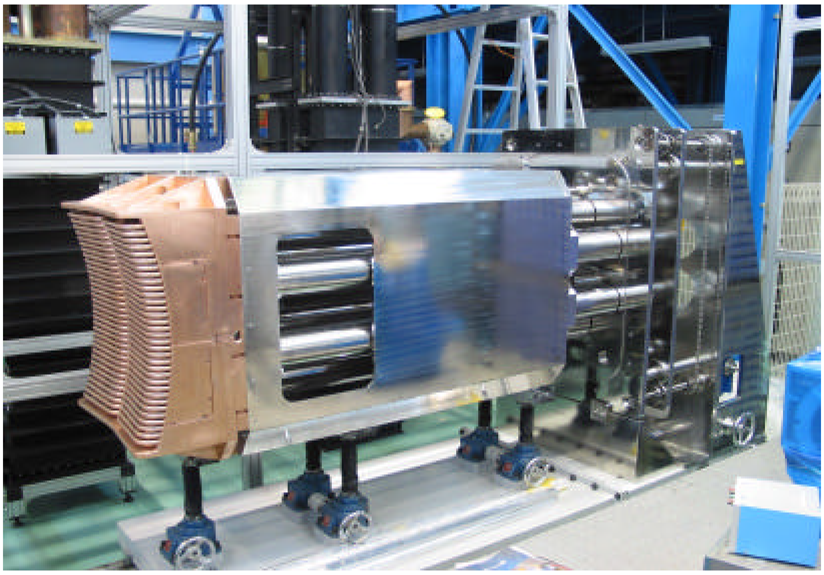

Fig. 6. Fabricated ICRF prototype antenna.

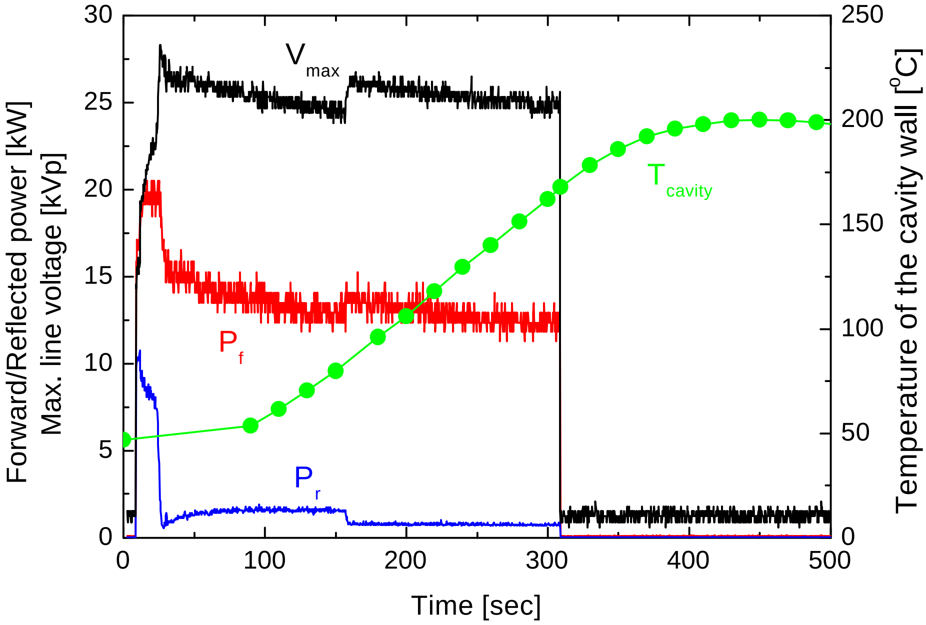

Fig. 7. Forward and reflected power, maximum line voltage vs. time.

The high power RF transmission components are developed for transmitting MW level of RF power continuously. High stand-off voltage and current without breakdown are required, and proper cooling methods to remove dissipated RF power loss need to be developed. To transmit the high RF power (MW level), co-axial transmission line must be cooled and must withstand the high RF voltage (> 30 kV) for a long time. A water-cooled co-axial transmission line was fabricated and tested for long pulse operation. The special connector for both water sealing and electrical contact was developed to provide the cooling water inside inner conductor of the co-axial transmission line. The RF power test for the water cooled co-axial transmission line with water cooling was performed up to 43 kV (average) at a pulse length of 300 second. A vacuum feedthrough is an important part of ICRF antenna. It transmit RF power while keeping the antenna in a high vacuum. Its performance is determined by the design of the insulating ceramic, inner and the outer conducters. A standoff voltage over 30 kV is required to transmit 1 MW of RF power. A feedthrough was developed, which has two alumina (Al_2O_3, 97%) ceramic cylinders and O-ring seal instead of a brazed seal for good mechanical and thermal strength. And the RF power test of the vacuum feedthrough was performed up to a RF voltage of 32 kV (peak) at a long pulse of 300 second at 30 MHz. Conventional phase shifter (trombone type) uses sliding contact and it often caused some problem due to local temperature increase and insulation breakdown for long pulse operation under high power. To solve such problems, the phase shifter using liquid instead of gas for insulating dielectric medium was developed. The liquid phase shifter can be used reliably in the high power continuous RF facilities since it has no sliding contact and can withstand the high RF voltage (> 40 kV). The RF power test for the liquid phase shifter showed RF voltage > 50 kV for 300 second. (Fig. 8)

The results of the development will be applicable for the long pulse, high power operation of ICRF system. The test results show that they are reliable RF components for long pulse up to 300 seconds and high power (MW level) transmission.

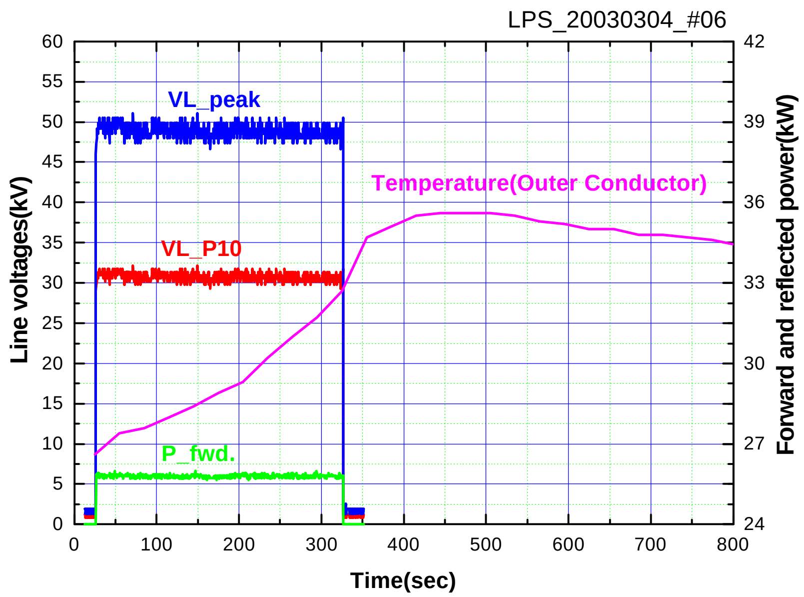

Fig. 8. RF power test result of the liquid phase

4. Lower Hybrid System

The LHCD system will use four 500 kW (CW), 5.0 GHz klystrons. The RF power will be delivered through approximately 40 m long parallel transmission lines composed of waveguide components, such as DC breaks, 3 dB dividers, E-bends, H-bends, oversized straight pieces, phase shifters, and etc. from 4 klystron tubes to the coupler. Approximately 20 % of the insertion loss is expected, and we plan to deliver at least more than 1.5 MW microwave power. The coupler is being designed in collaboration with the Princeton Plasma Physics Laboratory. It will be composed of two modules that are assembled at upper and lower positions. Each module has a waveguide antenna of 2 rows of 32 guidelets near the plasma. Therefore, the KSTAR front coupler is composed of 4 rows of 32 guidelets, and each klystron feeds 8 columns of guidelets of the waveguide antenna. The short dimension of the standard WR187 waveguide is reduced to 0.55 cm (E-plane taper) before the inputs of upper and lower modules. Each input with the same phase is again divided vertically into two branches using a 3 dB power splitter. The two vertical outputs will be in the same phase via a fixed-phase shifter. Water loads in the matching waveguide of the splitter serve dual functions; dummy load and the heat removal of the reflected power. The longer dimension of waveguide, 4.75 cm in each module is tapered up to a larger width 5.5 cm, in order to reduce the RF power flux density down to 3.87 kW/cm^2 at the guidelets maintaining the shorter dimension of 0.55 cm. The coupler shall be fabricated by stacking 32 metal plates with the waveguide patterns milled on. The layout of the transmission line and the cross sectional schematic of the coupler metal plate are seen in Fig. 9. The design of 3-dB power splitter, fixed-phase shifter, and taper section of the coupler has been optimized for 5.0 GHz using the High Frequency Structure Simulator (HFSS) program. Fig. 10 shows the design results; the power of the incident wave is split in half and each splited wave–fronts arrives at the end simultaneously.

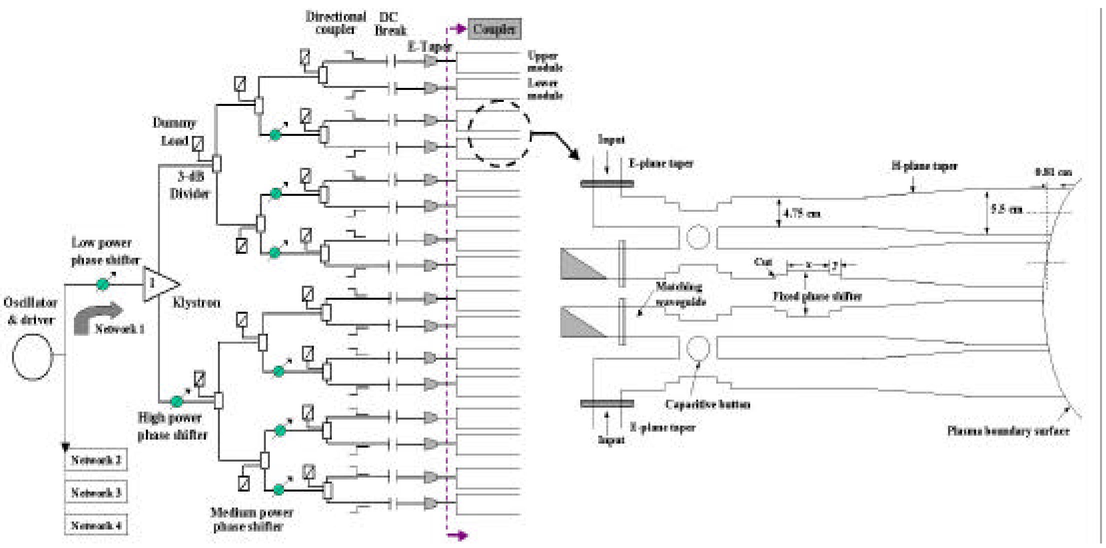

Fig. 9. The layout of the 5.0 GHz LHCD system.

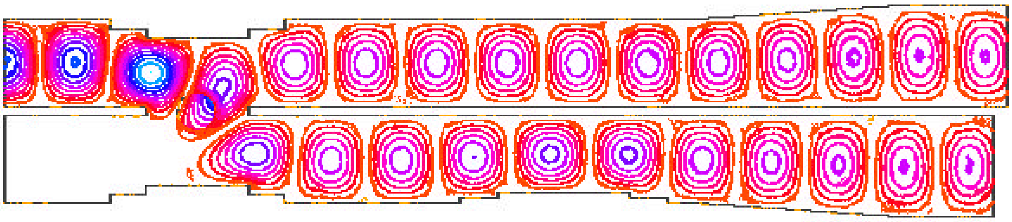

Fig. 10. The design result of a 3-dB power splitter, a fixed phase shifter, and a taper section

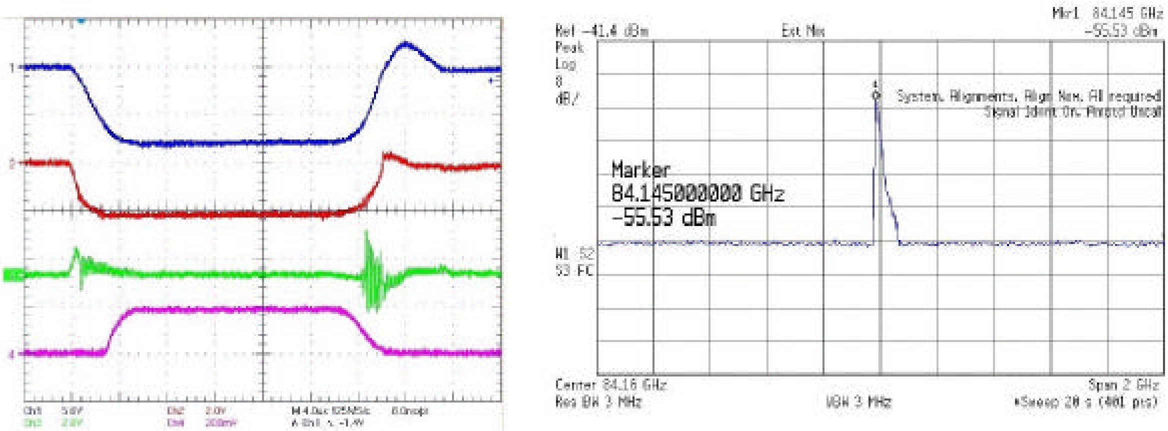

Fig. 11. The picked signals: (left) the beam voltage (ch1), the beam current (ch2), the body current (ch3), and the RF signal (ch4) from the miter bend, (right) the RF spectrum measured by the spectrum analyzer. The beam voltage and the beam current are 80 kV and 26 A.

5. Electron Cyclotron Heating System

For the initial plasma phase, the ECH system will be used for only pre-ionization using a single gyrotron whose RF frequency and RF power are 84 GHz and 500 kW with the pulse length up to 2.0 sec. The nominal operational voltage and current of the gyrotron are 80 kV and 25 A, respectively. The gyrotron has been fabricated and successfully tested at CPI. It is delivered to POSTECH, and under short pulse conditioning test with a pulse modulator operated at 20 μs with 60 Hz repetition rate. The test results are shown in Fig. 11. The frequency of the RF signal (84 GHz) is detected by a spectrum analyzer connected to the pickup-horn antenna attached to the miter bend. During the initial-phase KSTAR operation, the toroidal magnetic field of 1.5 T is expected at the plasma center. Therefore, 84 GHz gyrotron frequency is the second harmonic resonant frequency of the ECH. The power is transmitted to the KSTAR tokamak using standard oversized corrugated waveguide components with an inner diameter of 1.25 inches and a two-mirror antenna. Turns are effected through the use of 90° miter bends. The ECH system is designed to have vacuum capability evacuated to a pressure of ≈ 1 x 10^{-5} torr by two turbo-molecular pumps at the mirror optical unit (L-box) and at the position before the antenna. The vacuum state of ECH system is maintained with a CVD diamond window. The RF gate valve is used for the isolation of the ECH system during the maintenance and repair of the ECH system or KSTAR tokamak. The overall system layout is shown in Fig. 12. The ECH system will be upgraded to the 1 MW system for the Electron Cyclotron Current Drive (ECCD) in the upgrade phase of the KSTAR tokamak.

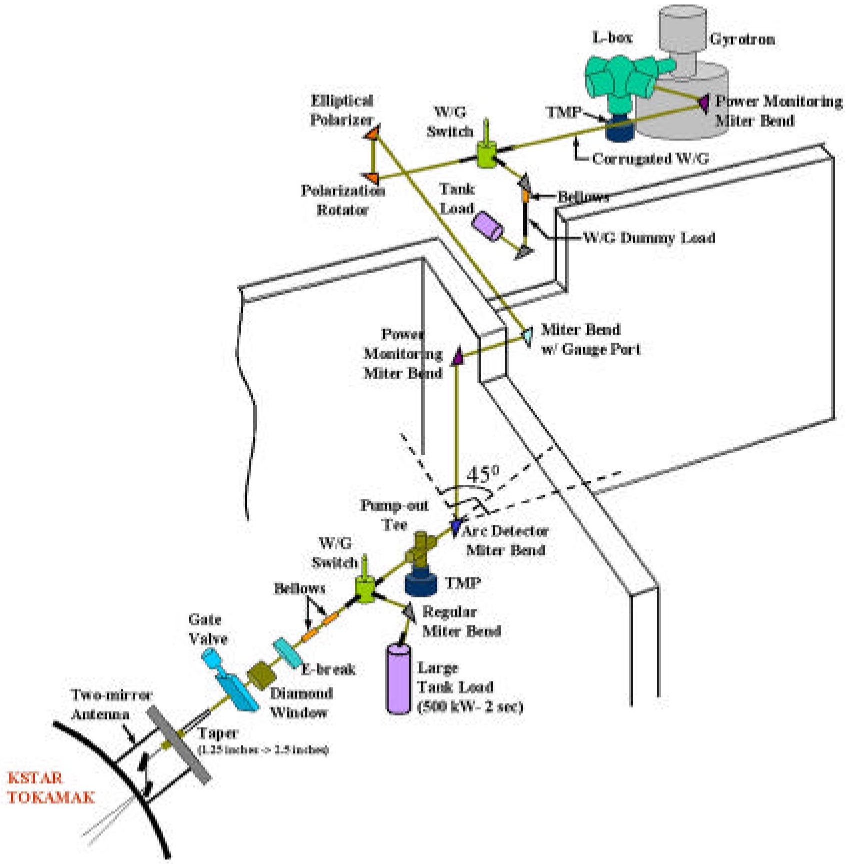

Fig. 12. The layout of the KSTAR 84 GHz ECH system.

6. Summary

The KSTAR heating and current drive systems are being developed to provide the heating and current drive capability as well as the current density and pressure profile control for pulse length up to 300 sec. These systems will make the advanced tokamak operation of the KSTAR tokamak be obtainable and maintained for long pulse operating condition. The results of the technology development will make the heating and current drive systems key components for the advanced tokamak operation of the KSTAR tokamak.

Acknowledgement

This work was supported by the Korean Ministry of Science and Technology under KSTAR Project Contract.

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