Development of Long Pulse Heating and Current Drive Systems for the KSTAR Tokamak

B.G. Hong 1), B.H. Oh 1), B.H. Choi 1), W. Namkung 2), Y.D. Bae 1), Y.S. Bae 2), M.H. Cho 2), Y.S. Cho 1), C.K. Hwang 1), S.R. In 1), S.H. Jeong 1), H.S. Kang 3), K.R. Kim 1), J.G. Kwak 1), K.W. Lee 1), S.J. Wang 4), J.S. Yoon 1)

1) Korea Atomic Energy Research Institute, Taejon, Korea
2) Pohang University of Science and Technology, Pohang, Korea
3) Pohang Accelerator Laboratory, Pohang, Korea
4) Soongsil University, Seoul, Korea

e-mail contact of main author: bghong@kaeri.re.kr

Abstract. The heating and current drive systems of the Korea Superconducting Tokamak Advanced Research (KSTAR) tokamak consist of neutral beam, ion cyclotron, lower hybrid and electron cyclotron system and are being developed to provide heating as well as current drive capability for long pulse length up to 300 sec. The systems also provide flexibility in the control of current density and pressure profiles for the study of advanced tokamak plasmas. The design has been completed and the long pulse relevant heating and current drive technologies are being developed.

1. Introduction

The heating and current drive systems based on multiple technology such as neutral beam injection (NBI), ion cyclotron range of frequencies (ICRF), lower hybrid current drive (LHCD), and electron cyclotron heating (ECH), will provide the heating and current drive capability as well as the profile control of current density and pressure to meet the mission and the research objectives of the KSTAR tokamak. [1] Fig.1 shows the layout of the planned KSTAR heating and current drive systems.

The KSTAR neutral beams are required not only to provide ion heating but also to provide current drive, current density and pressure profile control, and core fueling; to sustain plasma rotation; and to support diagnostics requirements. Requirements per an ion source are the maximum beam energy of 120 kV, the beam current of 65 A, and the beam pulse length of 300 sec. The KSTAR ICRF system provides heating for the plasmas, centrally peaked current drive, and off-axis current drive using mode conversion for various plasma operating scenarios over a range of the magnetic field. The ICRF system has been designed to operate at any frequency in the range of 25 – 60 MHz for long pulse length up to 300 sec. The lower hybrid system is required to investigate the physics issues related to the steady-state operation. It provides off-axis current profile control, efficient bulk current drive at low plasma temperatures, and electron heating. In order to support flexible off-axis current profile control, the capability to dynamically vary the wave number spectrum is provided. The ECH system will be used at the day one operation of the KSTAR tokamak to aid plasma breakdown, thereby lowering the loop voltage (and the integrated volt-sec) required to initiate plasma.

2. Neutral Beam Injection System

The NBI system initially shall delivers 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 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.

The prototype of KSTAR ion source was fabricated on the base of Long Pulse Ion Source (LPIS) bucket source [2] which has been developed by Lawrence Berkeley Laboratory for operation up to 30 sec. Modifications for 300 sec capability with appropriate tests are required for use in KSTAR tokamak. The required deuterium beam current per ion source at the maximum operating voltage is more than 65 A with an atomic ion (D^+) fraction of 80 % or more. Plasma parameters under various operation conditions, such as the filament current, the arc current, the pressure of the ion source, were measured by using Langmuir probes [3]. Beam line components including all hardware items needed to transport the neutral beam from ion source to NBI port, should be actively cooled for 300 sec operation. As an actively cooling device for the long pulse operation, hypervapotron elements were chosen due to their reliable performance and lower cooling water demands. Prototype hypervapotron has been developed.

The neutral beam power supplies convert the primary power from the MFG to controlled DC power as required to the ion sources and associated auxiliaries. Each ion source has an independent power supply system capable of operation alone or as a group by local control system or remotely by the central instrument and control system. In order to make stable arc plasma during long time, arc and filament power supplies are controlled in a preprogrammed mode which can be changed depending on operation conditions. The acceleration power supply has the feature of step modulation, which consists of an inverter voltage controlled module of up to 30 kV and 5 modules of fixed voltage of 20 kV. All the modules with IGBT output switch are connected in series and make it possible to control the output voltage continuously from 0 to 120 kV. The control system requires approximately 5,000 signal points for the power supplies, 2,000 for diagnostics, and 1,500 for beamline controls and services. The system software shall be composed in the Experimental Physics and Industrial Control System (EPICS) environment, and VME bus controlled by VX-works be used as a standard in measurement and control.

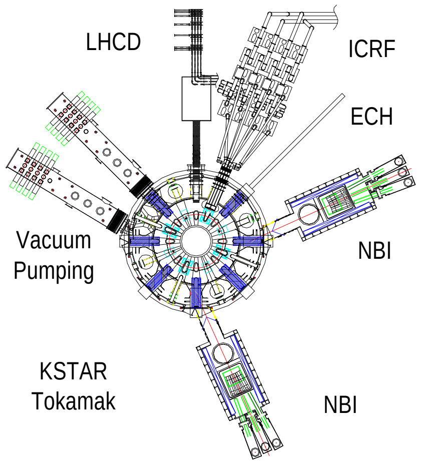


FIG. 1. Layout of the planned KSTAR heating and current drive systems.

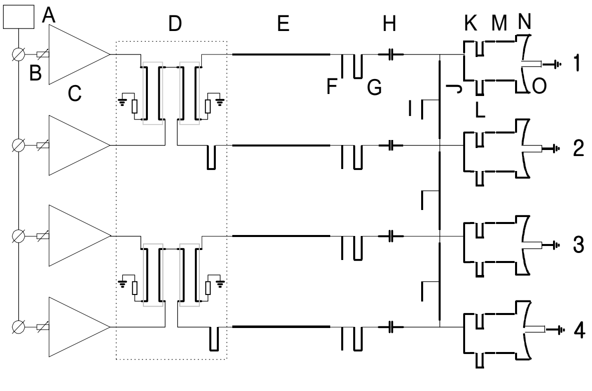


FIG. 2. Schematic of the KSTAR ICRF system. A; Signal generator, B; Phase controller, C; 2 MW transmitter, D; ELM dump, E; Main transmission line, F; Stub, G; Phase shifter, H; DC break, I; Stub, J; Decoupler, K; Resonant loop, L; Phase shifter, M; Vacuum transmission line, N; Strap line, O; Current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

A test stand of the KSTAR NBI system is in preparation at Korea Atomic Energy Research Institute for the beam extraction experiments of the developed prototype ion source, and for the measurement of the heat removal capability of the beam line components. Most of the components developed for the NBI system could be used and tested in the test stand. A calorimeter was developed to handle 3 MW of beam power during 20 sec for the test stand and a cryosorption pumping system is in development for the use in the test stand. The desired minimum pumping performance of the needed cryosorption pump is 2 × 250000 *l*/s. Also 2 MW (CW) cooling water system is in preparation. The designed water flow rate is 100 *l*/sec in the pressure of 5 kgf/cm^2. The characteristic resistance of the cooling water will be controlled at the value higher than 1 MΩ•cm.

3. ICRF System

The ICRF system initially delivers 6 MW of rf power to the plasma using a single four-strap antenna mounted in a midplane port and will be capable of 300 sec operation with 12 MW of rf power to the plasma through two antennas located in adjacent ports. The schematic of the KSTAR ICRF system is shown in Fig. 2. An antenna is mounted in the main horizontal rf port, each of which is grounded at the center and has a coaxial feed line connected to each end of the current strap. The phasing between current straps in the antenna will be adjustable quickly during operation to provide the capability of changing the current drive efficiency. [4] By adjusting two phase shifters in a resonant double loop, any frequency in the range of 25 – 60 MHz can be covered. Three decouplers between the neighboring strap circuits are required to balance the power needed from each rf source. Each decoupler consists of a length of transmission line between the loops with an adjustable stub at the midpoint. As an optional upgrade, a combiner/splitter circuit that acts as an "ELM dump" circuit when the current straps are driven with $\pi/2$ inter-strap phasing for FWCD will be considered. The performance analysis indicate that the ICRF system should be able to deliver 6 MW of power to plasma without exceeding the 35 kV anywhere in the system.

Long pulse relevant ICRF heating technologies have been developed. For 300 sec operation, the antenna has many cooling channels inside the current strap, Faraday shield, cavity wall and vacuum transmission line to remove the dissipated rf loss power and incoming plasma heat loads. A prototype ICRF antenna was fabricated and tested. The mechanical test results satisfy the requirements of the KSTAR antenna. The vacuum feedthrough for 1 MW rf power transmission is designed to have two alumina (Al_2O_3, 99.7 %) ceramic cylinders and O-ring seal instead of a brazed seal for good mechanical and thermal strength. For long pulse operation, water cooling channels for the inner conductor and a gas (N_2) for the ceramics are provided. Matching devices, liquid stub tuner and liquid phase shifter, have been developed, which use the difference between rf wavelength in liquid and in gas due to the different relative dielectric constant. Rf test (50 kW, 30 MHz) shows that they have a high stand-off voltage (> 40 kV) and they are reliable for the long pulse, high power transmission.

4. Lower Hybrid System

The system initially provides 1.5 MW LH RF power to the KSTAR plasma at a frequency between 5.0 GHz and 5.7 GHz through a horizontal port and the LH RF power shall be upgraded to 3.0 MW. On the optimum LH frequency for the KSTAR tokamak, we consider followings; we first consider the density limit above which wave damping is mostly in ions, reducing therefore drastically the current-drive efficiency. For the higher LH-wave frequency, the density limit is given higher value [5]. Therefore, a higher LH frequency greater than 5.0

GHz is preferred. Next, we consider the available high power CW klystrons for higher frequencies. But, there are no high power CW klystrons available for frequencies between 5.0 GHz and 5.7 GHz. Therefore, we are going to develop a suitable one from the state of art for high power CW klystrons [6]. Finally, we consider the optimum $N_{||}$ values and weak conditioning operation in the waveguide antenna. The $N_{||}$ values and the power flux densities in the waveguide antenna are investigated with the practical manufacturing and cooling of waveguide antenna. From these considerations, the LH frequency will be selected as a frequency between 5.0 GHz and 5.7 GHz.

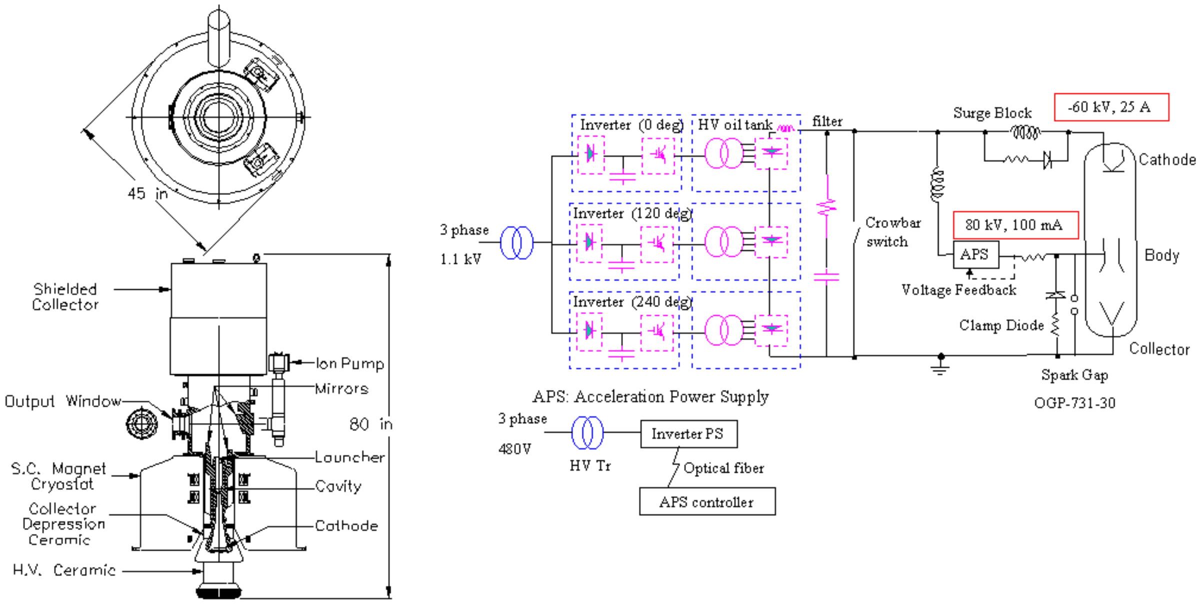
In order to support flexible off-axis current-profile control, the capability to dynamically vary the wave number spectrum is provided with the array of phase shifters. The LH launcher and transmission system shall be designed for a steady-state operation. The RF powers will be transmitted from 4 klystrons to a launcher through the waveguide networks. The launcher shall be designed in collaboration with the Princeton Plasma Physics Laboratory in the near future.

5. Electron Cyclotron Heating System

The ECH system will be operated at 84 GHz which is corresponding to resonant magnetic field of 3 T. Nominal operations at the full field (3.5 T) will make the electron cyclotron resonance to be approximately at $r/a = 0.6$. A 0.5 MW, 84 GHz gyrotron is the microwave source for KSTAR ECH system. The pulse length and the output mode are 2.0 sec and HE_{11} mode, respectively. Standard corrugated waveguide components will be used in the transmission system for lower power loss. Turns are effected through the use of 90^o miter bends. The diameter of corrugated waveguides is 1.25″. The ECH system is designed to have vacuum capability evacuated to a pressure of $\approx 1 \times 10^{-5}$ torr by a turbomolecular pump at the mirror optical unit (L-box) and a similar pump on a special section of waveguide. The L-box has a role of focusing the microwave from the gyrotron into the 1.25″ corrugated waveguide with a matching aluminum mirror. The waveguide lines incorporate forward and reverse power flow monitoring in a miter bend. Before the microwave is launched into plasma, it passes a waveguide window, two waveguide bellows, a DC break, a gate valve, and a tapered section from 1.25″ to 2.5″. A tapered section is selected for good directivity of radiation. The vacuum state of ECH system is maintained with a waveguide vacuum window. The window shall be CVD window. The microwave is launched by a launcher system that is composed of a fixed mirror for focusing and a movable mirror for adjusting the direction of incidence. The transmission line is designed so that there are 5 segments. Before ECH launcher, the transmission line is designated to ETL1 and ETL5 corresponds to the line just after gyrotron.

Gyrotron System

The gyrotron system is composed of a gyrotron, a superconducting system, and the power supply system for operating the gyrotron tube. A gyrotron and superconducting system are now being fabricated by CPI for the microwave source of KSTAR ECH system. The power supply is being constructed by POSCON. The gyrotron will employ an internal converter, a diode gun, and a sweeping depressed collector. HE_{11} mode is generated through an internal mode converter inside the gyrotron. Power modulation will be possible over the range of 100 kW to 500 kW by modulation of beam voltage. The superconducting magnet for the 84 GHz gyrotron will employ a vacuum insulated liquid helium chamber to maintain the cryogenic environment required for operation of the coils, and a cryocooler to extend the liquid helium hold time. The power supply for the gyrotron includes a main power supply and an acceleration power supply (APS). The main power supply employs a 1 kHz inverter power supply. It will be able to provide the maximum high voltage of -80 kV and 25 A with a pulse duration of 2 sec. The acceleration power supply is designed for the beam acceleration and the beam voltage modulation in range of ±10 kV with the frequency of 1 kHz. Fig. 3 shows the schematic drawing of the gyrotron tube and its power supply.



(a) (b)

FIG. 3. (a) Schematic layout drawing of 84 GHz, 500 kW gyrotron system and (b) its power supply.

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.

Acknowledgement

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