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

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Abstract: The heating and current drive systems for the KSTAR tokamak are being developed to support long pulse, high β, advanced tokamak fusion physics experiments. 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 300 sec and to provide a range of control functions including current density and pressure profile control. Development of components including key technologies required for high power, long pulse operation has been on going. Substantial progress in the engineering area, has been made on RF antennas, ion source, and 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 on the 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). The flexibility to provide a range of control functions including current density and pressure profile control derives from the use of multiple heating technologies. Depending on the operation scenarios, each system will be expanded to provide more power with a pulse length of 300 sec.

The NBI system provides ion heating, current drive, core fueling, profile controls for pressure and current density, 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 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) antenna and the transmission components for transmitting MW level of RF power are under development for long pulse operation. The LHCD system will be used for a steady-state operation of the KSTAR tokamak and an off-axis current density profile control. In order to support flexible off-axis, current density 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 required for high power, long pulse operation.

2. Neutral Beam Injection System

The NBI system shall deliver 8 MW of neutral beam power to the plasma from one co-directed beam line with the beam energy of 120 keV. It will be in operation from the second experimental campaign of the KSTAR. [2] Whole components 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 the NBI duct is about 10 m. 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.

The prototype ion source of the KSTAR NBI system has been fabricated by modifying the LPIS bucket source [3] from slit aperture grids to circular ones (Fig. 1). The deuterium beam current at the maximum operating voltage (120 kV) is more than 65 A with an atomic ion (D^+) fraction of 80 % or more. Uniform bucket plasma with the ion density of the order 10^{12} cm^{-3}, has been obtained in an emission-limited mode, and beam extraction experiments are now in progress. Prototypes for all of the beamline components needed to transport the neutral beam from ion source to NBI port have been developed. They have to be actively cooled for 300 sec operation with the designed heat load of 1 kW/cm^2. As beam facing elements, hypervapotrons are used in the calorimeter and neutralizer, and swirl tubes are used in the ion dump (Fig. 2). The final beam-facing element will be determined by evaluating their cooling capability. Power supplies for the ion source have been developed. Arc and filament power supplies are controlled in a preprogrammed mode depending on operation conditions in order to make stable arc plasma during long pulse operation. The main specification of the acceleration power supply is a maximum current of 70 A and operational voltage of 30-120 kV with voltage and current ripples of 2 % peak-to-peak for 300 sec. The output voltage is controlled by a selection of the number of serially connected 9 transformer-rectifiers and 40 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.

A test stand of the KSTAR NBI system has been completed at Korea Atomic Energy Research Institute for the beam extraction experiments and for the test of the beam line components. Cryosorption pump with a pumping speed of 4.0 x 10^5 *l*/sec has been developed as a vacuum system in the test stand.

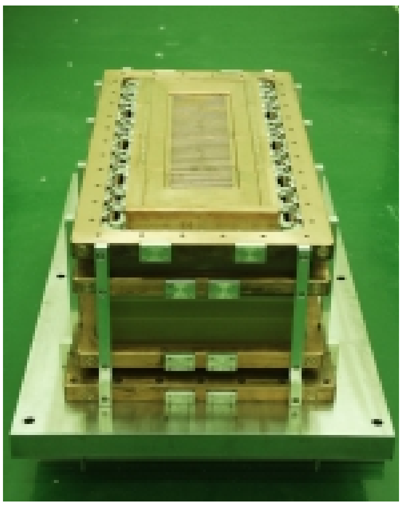

FIG. 1. Ion source grid

FIG. 2. Ion dump

3. ICRF System

The ICRF system will deliver 6 MW of RF power to the plasma using an antenna mounted in a mid-plane port. It will be in operation from the third experimental campaign of the KSTAR. KSTAR ICRF antenna are 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 without 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. High stand-off voltage and current without breakdown are required, and proper cooling methods to remove dissipated RF power loss need to be developed

A high power density (~ 10 MW/m^2) prototype ICRF antenna has been developed. 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. Without cooling, 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. 3 shows the fabricated antenna and Fig. 4 shows the time evolution of powers, the maximum voltage and test chamber pressure

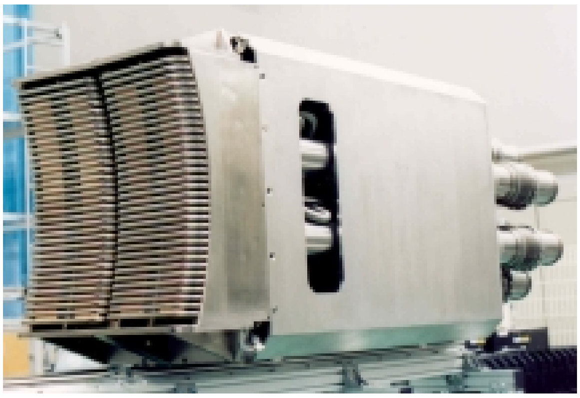

FIG. 3. Fabricated ICRF prototype antenna.

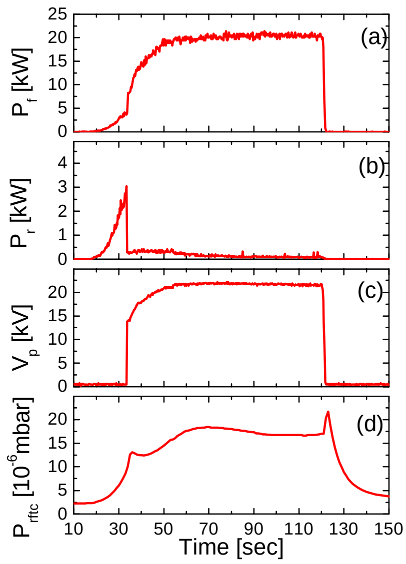

FIG. 4. Time evolution of (a) forward and (b) reflected powers, (c) the maximum voltage and (d) test chamber pressure.

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 the inner conductor of the co-axial transmission line. The RF power test was successfully performed up to 43 kV (average) for 300 sec. A vacuum feedthrough for the transmission of 1 MW of RF power 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. The RF power test was performed up to a RF voltage of 32 kV (peak) for 300 sec without any problem. A phase shifter using liquid instead of gas for insulating dielectric medium was developed. We found that the liquid phase shifter can be used reliably since it has no sliding contact and can withstand the high RF voltage (> 50 kV).

4. Lower Hybrid System

The LHCD system will use four 500 kW (CW), 5.0 GHz klystrons and it will be in operation from the fourth experimental campaign of the KSTAR. 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 of RF 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 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 design of 3 dB power splitter, fixed-phase shifter, and taper section of the coupler has been optimized at 5.0 GHz using the High Frequency Structure Simulator (HFSS) program.

5. Electron Cyclotron Heating System

For the initial plasma phase, the ECH system will be used for pre-ionization using a single gyrotron whose RF frequency and RF power are 84 GHz and 500 kW with a 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 was delivered to Pohang University of Science and Technology, and a short pulse conditioning test with a pulse modulator operated at 20 μs with 60 Hz repetition rate has been successfully performed. The test results are shown in Fig. 5.

During the initial phase of the KSTAR tokamak operation, the toroidal magnetic field of 1.5 T is expected at the plasma center. Therefore, 84 GHz is the second harmonic resonant frequency of the ECH. Through the modification of the zero dimensional pre-ionization code developed earlier, we obtained the dependence of the electron temperature and plasma current build-up for different magnetic flux swing scenarios of the poloidal field coils. The dependence of the pre-ionization upon the plasma initial conditions is summarized in Table I. The RF power is transmitted to the KSTAR tokamak using standard oversized corrugated waveguide components with an inner diameter of 1.25 inches. An antenna capable of high power operation and having a two direction steerable mirror with fast actuation is under development for a number of important tasks such as plasma initiation, ECH-assist startup, detection of ECE signal. Turns are effected through the use of 90^o 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.

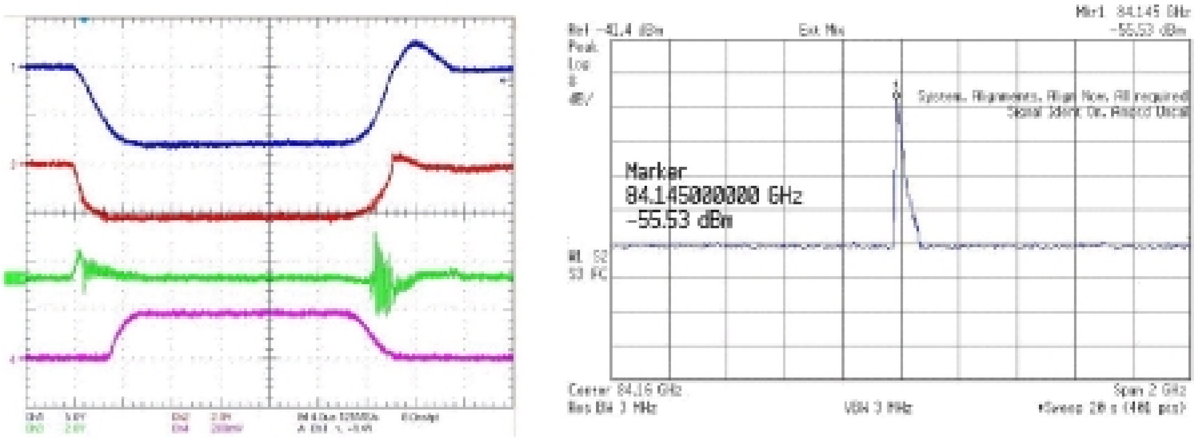

FIG. 5. The picked signals: (left) the beam voltage (ch1), the beam current (ch2), the body current (ch3), and the RF signal (ch4) from the miter bend, (right) the RF spectrum measured

TABLE I: SUMMARY OF THE PARAMETER DEPENDENCES OF THE PRE-IONIZATION.

	Fundamental harmonic	Second harmonic
RF power	≥ 10 kW	≥ 400 kW
Neutral density range for the plasma current start-up	≤ 2.0 x 10^{13}cm^{-3}	0.1 x 10^{13} ~ 0.5 x 10^{13}cm^{-3}
Error field (B_{err}) limit	≤ 13 mT	≤ 0.1 mT
Carbon impurity fraction	≤ 0.2 %	≤ 0.07 %
Oxygen impurity fraction	≤ 0.5 %	≤ 0.1 %
Iron impurity fraction	≤ 0.007 % for B_{err} = 5 mT (Sensitive)	≤ 0. 0003 % (Very sensitive)

6. Summary

The KSTAR heating and current drive systems are being developed to provide heating and current drive capability as well as current density and pressure profile control for a pulse length up to 300 sec. These systems will make the advanced tokamak operation of the KSTAR tokamak obtainable under long pulse operating conditions.

References

[1] G.S. Lee et al., "The KSTAR Project: Advanced Steady-State Superconducting Tokamak Experiment", Nucl. Fusion **40** (2000) 575.

[2] G.S. Lee et al., "Overview of the KSTAR Project" (Proc. 19th Int. Conf. Lyon, 2002), IAEA, Vienna (2002), http://www.iaea.org/worldatom/Meetings/2002/cn94auin.pdf.

[3] M.M. Menon, et al., Rev. Sci. Instrum. **56** (1985) 242

[4] C.K. Hwang, B.G. Hong, and D. Swain, "Fast sweep of current phases in ICH antenna straps", Fusion Engineering and Design **45** (1999) 127.