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# KSTAR ICRF System for Long Pulse Operation

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## Abstract

The KSTAR (Korean Superconducting Tokamak Advanced Research) tokamak is being constructed to do steady state capable advanced tokamak fusion physics experiments. The ICRF system for the KSTAR tokamak has been designed to heat the plasma ions or to drive the currents required for long pulse operation. The system will deliver 6 MW (will be upgraded to 12 MW) of rf power to the plasma for 300 sec pulse length. Operational frequency range of 25–60 MHz has been selected and the phasing between current straps of the antenna will be adjustable during operation to control the current drive efficiency. The prototype antenna and key rf transmission line components such as vacuum feedthrough, liquid stub tuner and liquid phase shifter have been developed for long pulse, high power operation.

## Keywords:

ICRF, KSTAR tokamak, long pulse operation, heating and current drive

## 1. Introduction

One of the research objectives of KSTAR tokamak ($R_0 = 1.8$ m, $a = 0.5$ m, $\kappa = 2$, $\delta = 0.8$, $B_T = 3.5$ T, $I_p = 2$ MA, $\tau_{\text{pulse}} = 300$ sec) [1,2] is to perform advanced tokamak research in high performance regime and to explore methods for achieving a steady-state operation for a tokamak fusion reactor. Heating and current drive using fast wave in the ion cyclotron range of frequencies have been proposed as one of the main features for the advanced tokamak operation of KSTAR. The fast wave can be used to heat the plasma ions using a minority ion heating scheme, to drive the currents required for the steady-state operation and to modify the driven current density profile for better confinement.

The ICRF system will deliver 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 ICRF system is designed to meet the requirements that it operate at any frequency in the range of 25–60 MHz, the phasing between current straps of the antenna be adjustable quickly during operation, and it operate for long pulse length up to 300 sec. With the toroidal magnetic field, $B_T = 2.5$–$3.5$ T, rf transmitters must be operated over 25–60 MHz frequency range to cover the various heating and current drive scenarios [1]. The frequency range can be covered with two adjustable phase shifters in a resonant double loop. 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 [3].

For long pulse, high power operation, cooling is required in the antenna, transmission lines and transmitters to remove the dissipated rf power loss. Efforts have been made to develop key ICRF technologies for long pulse, high power operation of

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KSTAR ICRF system. A prototype ICRF antenna of 6 MW rf power and a vacuum feedthrough of 1 MW rf power have been developed. And tuning and matching components such as liquid stub [4] and liquid phase shifter are developed for reliable operation during high power transmission.

## 2. KSTAR ICRF System Design

The schematic of the KSTAR ICRF system is shown in Fig. 1: An antenna is mounted in the main horizontal rf port and composed of four current straps side by side. The phasing between current straps in the antenna will be adjustable quickly during operation to provide the capability of changing the current-drive efficiency. A resonant double loop consists of vacuum transmission line, a vacuum feedthrough and pressurized coaxial line with two adjustable phase shifters to cover any frequency in the 25–60 MHz frequency range. Three decouplers between the neighboring strap circuits are required to balance the power needed from each rf source. A matching system consists of a phase shifter and a stub tuner in each of the four lines driving the current strap resonant loops. 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 fast-wave current drive will be considered. Four rf sources cover the 25–60 MHz range and can deliver up to 2 MW into a matched load.

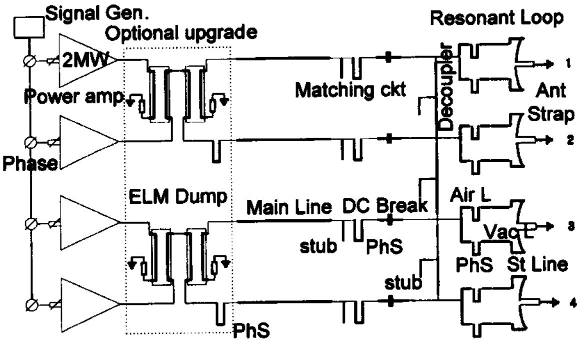

Fig. 1 Schematic of the KSTAR ICRF system

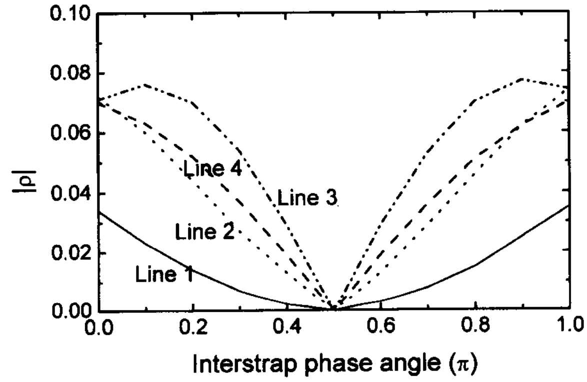

Fig. 2 Absolute value of the reflection coefficient vs. interstrap phase angle at 38 MHz.

Fig. 2 shows the absolute value of the reflection coefficient ($\rho$) after the decouplers as the phase interval of the voltages at the tee varies from 0 to $\pi$. Curves are drawn for each four straps. As the phase angle deviates from $\pi/2$, $\rho$ departs from zero on all the lines, but in the worst case, $\rho$ is less than 0.08 corresponding to less than 1% reflected power toward the transmitters. The analysis shows that for the plasma loading change of 4–8 $\Omega$ with tuners set to 6 $\Omega$, the VSWR (Voltage Standing Wave Ratio) can be kept within 1.5.

## 3. Antenna Development

The antenna is mainly composed of center-grounded 4 current straps, singe-layer Faraday shield and 4-section cavity, forming a plug-in type. Inside the vacuum vessel, the front surface of the Faraday shield is located at +2 cm outside flux surface of the reference equilibrium. The antenna is constrained to be 830 mm high and 730 mm wide in order to fit through the port. The antenna structure is radially movable up to 10 cm under vacuum (but not during a shot) so that the antenna position relative to the plasma can be adjusted to optimize the power transferred to the plasma. Wall mounted poloidal limiters made of CFC tiles are located on both sides of the antenna to protect the antenna. 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 load. The Faraday shield is made of Cu plated and $B_4C$ coated Inconel 625 tube. The thermal and stress analysis during normal operation show that the maximum stress are 160 MPa in the Faraday shield tube and 53 MPa in the current strap, which are below allowable stress (3Sm) of 756 MPa for the Inconel 625 (Faraday shield tube) and 414 MPa for SUS304 (current strap). The disruption induced stress on the Faraday shield tube is found to be 40 MPa and this is also well below allowables. Fig. 3 shows an detailed drawing the ICRF antenna.

We fabricated the prototype ICRF antenna (Fig. 4). The Faraday shield is made of Cu plated SUS316L tube.

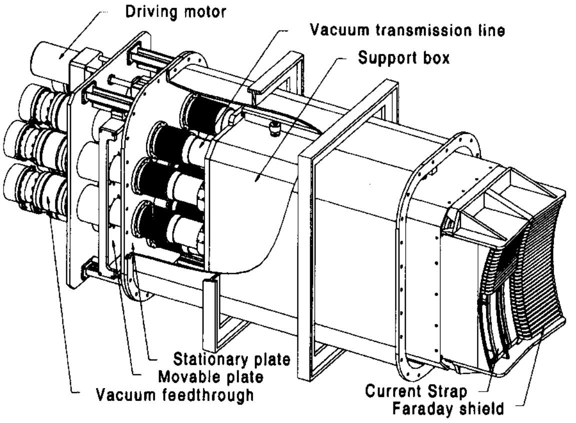

Fig. 3 Detailed drawing of the antenna.

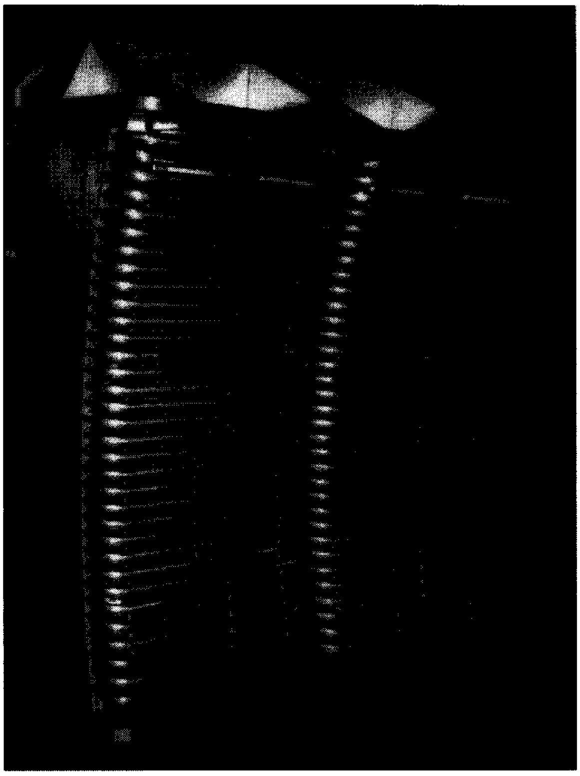

Fig. 4 Fabricated antenna picture

The prototype antenna will be tested in a rf test stand which consists of a 100 kW transmitter, transmission line, tuning and matching components, a vacuum feedthrough and a test chamber.

## 4. Vacuum Feedthrough Development

We developed prototype 6″ vacuum feedthrough for 1 MW rf power transmission. The vacuum feedthrough 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 which is important in long pulse operation. Fig. 5 shows the detailed design of the vacuum feedthrough. Calculations of the electric field and resulting rf dissipation power density show that with 30 kV imposed between inner and outer conductors, ~ 1 kW power for conductor and ~ 150 W power for ceramic need to be cooled. Independent inlet and outlet water cooling channels are installed to cool the inner conductor. For cooling of the ceramics, a gas ($N_2$) is circulated in space between the two cylinders and the outer conductor. Other part of the pressurized section of the transmission line is filled with 3 atm $N_2$ gas.

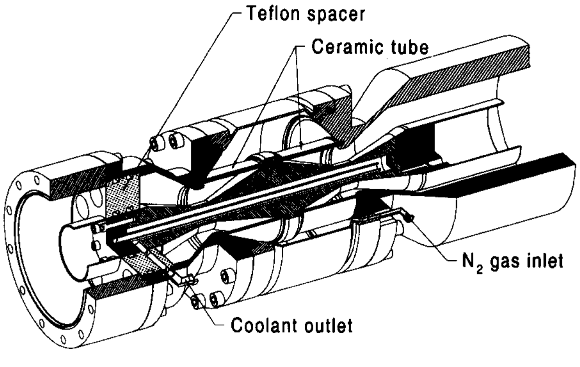

Fig. 5 Detailed drawing of the vacuum feedthrough.

Electrical performance will be tested to investigate the effects of heating on the conductors and the insulators.

## 5. Tuning and Matching Components Development

The liquid stub tuner and phase shifter use the difference between rf wavelength in liquid and in gas due to the different relative dielectric constant. They have no sliding contact and can withstand high rf voltage and liquid surface can be shifted during high rf voltage without rf breakdown. We developed a 4 m long, 6″ stub tuner and an U-shaped, 9″ phase shifter with 130° phase variation at 30MHz. Silicon oil was used as a liquid (dielectric constant, $\varepsilon_L = 2.72$). Initial rf test (50 kW, 30 MHz) shows that they have a high stand-off voltage (>40 kV) and they are reliable rf components for the long pulse, high power transmission.

## 6. Summary

Design of the ICRF system for long pulse operation

(300 sec pulse length) of the KSTAR tokamak has been completed. To support the design, efforts have been made to develop the steady state ICRF heating technologies. Antenna, vacuum feedthrough, and key tuning and matching components for long pulse, high power transmission have been developed.

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