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Commissioning the ICRF System and an ICRF Assisted Discharge Cleaning at the KSTAR

Jong-Gu Kwak, Son Jong Wang , Young-Dug Bae, Chul Kyu Hwang, Sung Kyu Kim

Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong, Daejeon, Korea

KSTAR(Korean Superconducting Tokamak Advanced Research) is a national superconducting tokamak with the aim of high beta operation based on AT(Advanced Tokamak) scenarios, and ICRF(Ion Cyclotron Ranges of Frequency) heating is one of the essential tools to achieve this goal. The ICRF system also contributed to the first plasma experiments of KSTAR through discharge cleaning. The fabrication and HV(high voltage) test of the antenna and matching system were finished in 2006 and the installation of the antenna, matching system and the transmitter at the KSTAR site was completed in 2007. Antenna conditioning was carried out to improve the HV holding condition of the antenna installed on the KSTAR and to check on an EM(Electro-Magnetic) interference with other equipments such as the superconducting magnet monitoring system and other machine and/or plasma diagnostic systems. In this presentation, installation processes of the ICRF system (with an emphasis on the quality assurance procedures of KSTAR), as well as the results from the first RF discharge experiment for a discharge cleaning in and FWEH(Fast Wave Electron Heating) experiment for KSTAR 1st experimental campaign are outlined.

Keywords: KSTAR, ICRF, transmitter, antenna, cleaning

1. Introduction

KSTAR is a Korean national superconducting tokamak aiming at a high beta operation based on AT scenarios, and ICRF is one of the essential tools to achieve this goal.[1] The ICRF system also contributes to the first plasma experiments of KSTAR through discharge cleaning and assisting the discharge startup.

The fabrication and HV test of the antenna and matching system were finished in 2006 and final installation of the antenna, matching system and the transmitter at the KSTAR site was completed in 2007.[2][3] In this presentation, installation processes of the ICRF system including the transmitter (with an emphasis on the quality assurance procedures of KSTAR), as well as the results from the first RF discharge experiment for the discharge cleaning and ICRF experiments in KSTAR, are outlined.

2. Antenna and tuning system

The installed antenna consists of four straps, however, two straps are fed via RDL(Resonant Double Loop) and tuners for the KSTAR 1st experimental campaign. The Faraday shield profile of the installed antenna fits the magnetic surface of the separatrix in the standard diverted plasmas of the KSTAR as shown in Fig.1. The antenna is protected at its sides by two poloidal limiters covered with graphite tiles which intrude into the plasma past the shield by 5 cm. The RF output from the transmitter is fed into two tuners via one coaxial transmission line whose total length is about 80 m. The impedance matching is done by adjusting the two liquid stub-tuners whose matching conditions are checked with a network analyzer. Presently it is tuned at 30 MHz but it could be adjusted to other frequencies by changing the length of the U-link at the resonant loop and the tuning position of the tuners. The tuning position at the ICRF-DC(Discharge Cleaning) is the same as that for a vacuum antenna conditioning. This means that antenna loading resistance is very small at the ICRF-DC.

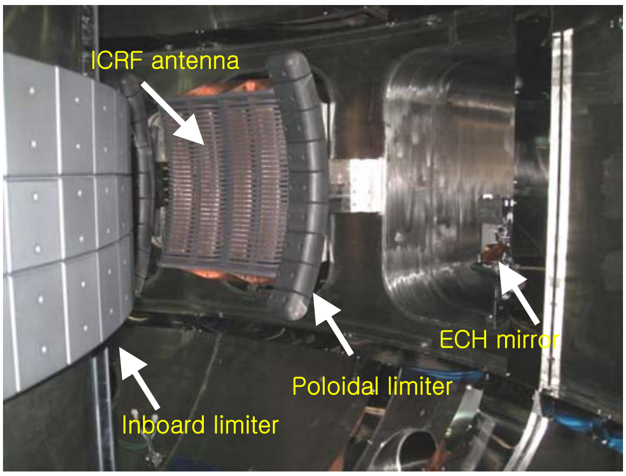


Fig.1. Invessel components and ICRF antenna

author's e-mail: jgkwak@kaeri.re.kr

Unexpected voltage rise is the most harmful or probable event for the ICRF system. The RF voltage exceeding a certain limit (~35 kV for 9-3/16" transmission line) may destroy the RF components. High VSWR, which can be expressed by maximum and minimum RF voltages, also degrades the performance of a transmitter. This event can be caused by a variation of the loading resistance due to the edge plasma fluctuation including an abrupt plasma termination or arcing in the transmission line. To protect the system, three independent methods are provided. The first is a self protection of the transmitter. High VSWR detected at the output of the transmitter cuts the RF input of the transmitter within tens of μs. The input is recovered delayed by several ms automatically. The second is an over voltage protection. If one of the four voltages measured at the resonant loops exceeds a preset value, the input of the transmitter is disconnected within μs. The disconnection will not be automatically recovered and recorded as ICRF fault. The third method is activated by central PCS. When the PCS detects a fault in which the PCS gives up control of the plasma discharge, it activates a no-go signal of the ICRF. The three methods were operated successfully for the first campaign of the KSTAR ICRF.

The functions of the ICRF control and data acquisition system are realized by using six independent digital signal processor (DSP) modules with customized peripheral boards. The number of channels(ADC-18, DAC-4, DIN-16, DOUT-8) for the board is thought to be enough for a specific function. The C codes written in each DSP do not exceed several hundred lines so that their maintenance is relatively simplified. The DSPs are basically connected by local a TCP/IP network which is disconnected to the outer world. Through this network, control and monitor signals which are not sensitive to the sampling time are transferred in a near realtime. At the end of a tokamak shot, the sampled arrays are collected through the same network. The governing controller of this network is made of a single PC with a Linux operating system equipped with a EPICS input/output controller (IOC). Because the most time-demanding functions are reserved to the DSPs, the CPU usage of the PC was less than 10 %.

For a few fast communications, such as an internal interlock or trigger, a optical fiber was connected between the DIN/DOUT of DSPs. The governing PC only knows the post-event for the monitoring purpose.

2. Commissioning the 2 MW transmitter

The ICRF heating and current drive scenario for the KSTAR eventually requires 4 units of 2 MW transmitters with a frequency range from 25 to 60 MHz for achieving final goal. The first KSTAR transmitter is a modified FMIT(Fusion Material Irradiation Test) transmitter consisting of four amplifier stages. Its frequency range is from 30 to 60 MHz and it is planned that a frequency band below 30 MHz is covered by modifying an existing cavity or manufacturing a new cavity. An amplitude-modulated 1mW frequency source drives a 500 watt solid state wideband amplifier, which in turn drives three tuned triode/tetrode amplifier stages. The tube employed in the final power amplifier is a 4CM2500KG tetrode fabricated by CPI(Communications & Power Industries). The anode power supply is a simple rectifier with an ignitron crowbar . After a fabrication of the cavity and power supply was completed in 2004, several failures of the tube during a factory and a site acceptance test occurred before eventually achieving 1.9 MW for 300 s at 33 MHz in 2007. Finally, we also succeeded in achieving 1.9 MW at 45 MHz and 1.8 MW at 60 MHz which is an upper frequency band of the transmitter. The electrical efficiency of the FPA(Final Power Amplifier) is about 70 %. It is well known that the rf power of the tetrode is decreased as the frequency is increased and a stable power generation at high frequency is one of the critical issues for the ITER ICRF system. So this is a very encouraging result for the development of an ICRF transmitter for the ITER. Fig.2 shows the achieved rf power vs. the frequency.

3. ICRF-DC and ICRF experiments

The vessel consists of SUS316 and inboard is partly covered by three rows Graphite tiles. The poloidal limiter is installed at the antenna side to protect the ICRF antenna module and to limit the outer plasma boundary. The material of the poloidal limiter is Graphite. The notable point is that the front surface of the ICRF antenna is coated by B4C. The coating thickness is about 100 um. ECH mirror and some diagnostic windows are located very far from the poloidal limiter and they are also protected by a shutter for a non-used period.

The vacuum vessel mainly comprises of a main vessel, a pumping duct, a long viewport duct, which has 100 m^2 of a total surface area without a port and 100 m^3 of an inner volume including a port. The main pumping unit is composed of eight turbo molecular pumps (TMP) and two cryo-pump systems. Pumping capacities of each TMP and the cryo-pumps are 2,800 liter/s and 10,000 liter/s, respectively. A differential pumped RGA is installed at the end of the pumping duct for measurements of the partial pressures and the RGA partial pressure is calibrated by a comparison with the pressure gauge. The diagnostics for a discharge cleaning is a differential pumped RGA attached to a pumping duct and a cold cathode and a hot cathode gauge attached to the vessel and the pumping duct respectively. To analyze the discharge characteristics, a microwave interferometer, Bremsstahlung, H-alphas and a TV camera were used.

GDC was performed over-night after a daily tokamak shot and early morning before a tokamak shot. Pure hydrogen discharge was used for the initial 1 hour followed by a He discharge for removing the hydrogen attached to the vessel during the H discharge. The partial pressures of the hydrogen, water, nitrogen and carbon compounds were increased during the He-GDC as shown in Fig.3. ICRF assisted DC was used between the tokamak shots and it lasted for around 10 min. The injected RF power was limited to 30 kW by the high voltage on the transmission line and the antenna from a low antenna loading resistance and the pulse duration was restricted by no water cooling to the antenna straps and the Faraday shield. The operational pressure region was from 10-3 to 10-4 mbar for the He and H discharges. The B_{TF} was varied from 0.5 to 1.4 T. The antenna loading resistance was slightly increased and the plasma density was decreased as the B_{TF} was increased. Depending on the B_{TF} and RF frequency, a selective heating between an ion and an electron could be implemented. Whereas the plasma density was decreased at the flap top region for a successive shot when we applied the ICRF-DC at around shot #900, there is no change in the plasma density regardless of the ICRF-DC. Only the H_2 partial pressure was changed for the ICRF-DC and the calculated H_2 removal rate was about 3.6 Pa-m^3/h. This is less effective than the other machine results. More systematic study on a discharge cleaning with a more refined RGA system is necessary for the next campaign.

The first ICRF experiment was tried using the FWEH heating mode at 1.5 T of B_{TF} . The frequency is 30 MHz and two resonant loops are used. RF power up to 150 kW is delivered to the plasma as shown in Fig 4. The line intensity of C-III and VB is increased during the ICRF pulse, however no changes in Te and Wdia are observed during this pulse. In order to increase the ICRF coupling, we intentionally moved the plasma column closer to the antenna, however, the heating effect is not clear. The front antenna surface is a D-shape however, the first KSTAR plasma is a circular shape and the distance between the antenna and limiter is a little bit longer(5 cm) so that the RF coupling is very low. We expect the heating effect to be clear for the next campaign by upgrade the following things such as using a minority heating mode, shortening the distance between the antenna and the poloidal limiter.

4. Inspection on the antenna after the campaign

After the experimental campaign, the internal structure of the vacuum vessel including the ICRF antenna was inspected for a post-mortem analysis and it was found that some parts of the antenna structure including the poloidal limiter are covered by an unknown material. The non transparent area of the current strap behind the faraday shield is also coated by unknown material as shown in Fig 5(a) and poloidal limiter adjacent to the ICRF antenna is also covered as shown in Fig 5(b). Only the front surface was coated by B_4C and the deposited area is easily removed by sand paper and revealed cooper color. Deposited area of the side surface of the poloidal limiter has a configuration of the antenna shape.

5. Summary

Since 1996, the KSTAR ICRF system has been designed and fabricated and it was finally installed at the KSTAR site in 2007. Finally it contributed to a successful first plasma generation in 2008 via the ICRF-DC. In addition, up to a 150 kW rf power was coupled to the 1st plasma with the FWEH mode. Based on the first experimental campaign, we expect the ion heating to be better for the next campaign by shortening the antenna plasma distance and a using minority heating mode.

References

[1] Lee G.S., et al., Nuclear Fusion 40 (2000) 575.
[2] Bae, Y.D., et al., Nuclear Fusion 43 (2003) 805.
[3] Kwak, J.G., et al., Nuclear Fusion 47 (2007) 463.

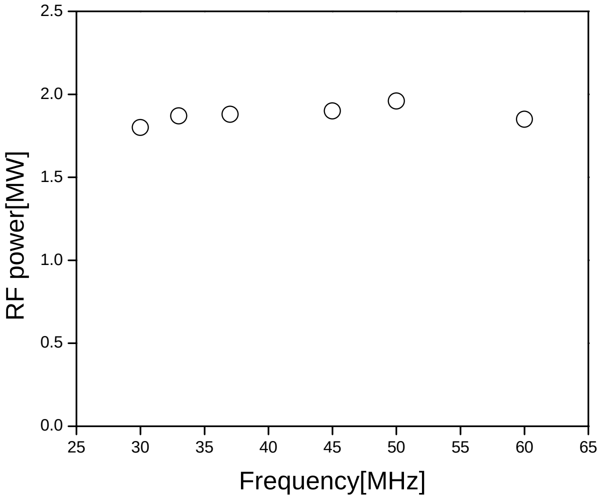


Fig.2. RF power vs. frequency

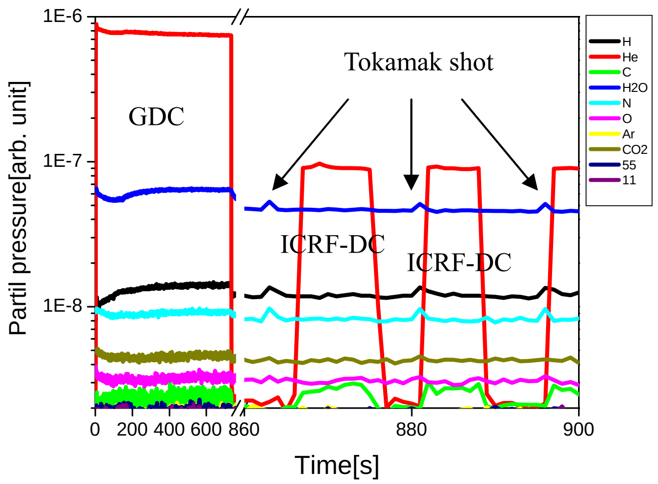


Fig.3. Time evolution of GDC and ICRF-DC

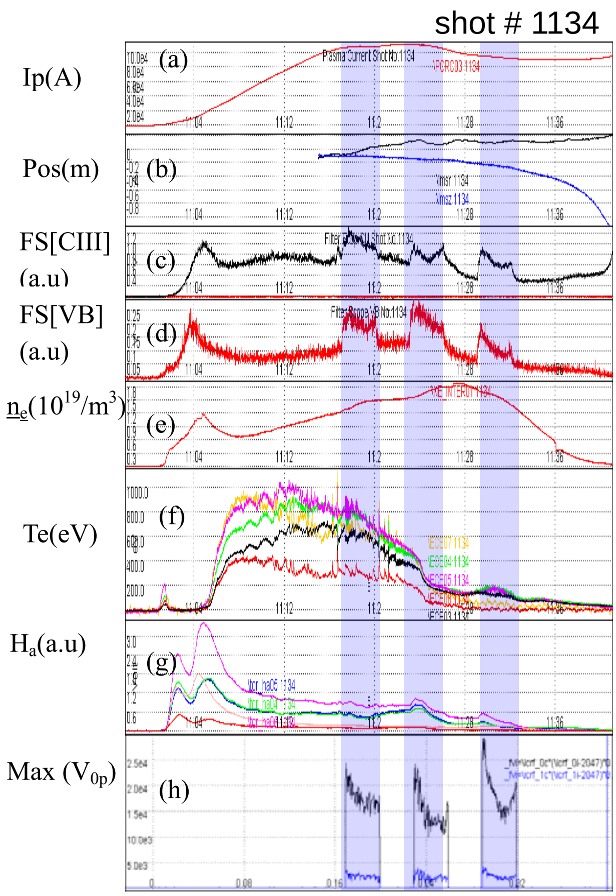
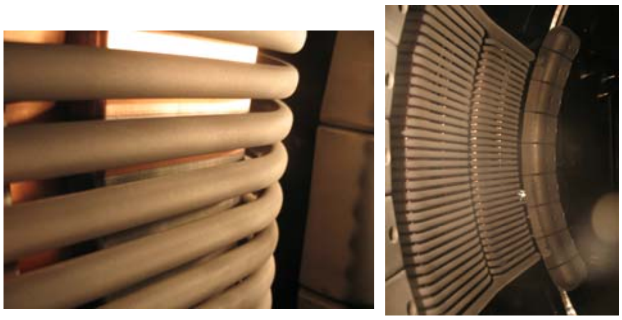


Fig.4. Time evolution of plasma current(a), plasma position(b), impurity(C-III)(c), Bremsstahlung (d), plasma density(e), Te by ECE(f), H-α(g) and Max. voltage on the antenna(h).



(a) (b)

Fig 5. Deposited area of antenna and poloidal limiter