First Results from ICRF Heating Experiment in KSTAR

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Abstract. KSTAR is the Korean national superconducting tokamak aiming at high beta operation based on AT scenarios, and ICRF is one of the essential tools to achieve this goal. The Faraday shield and current straps have water-cooling channels built in for the eventual long pulse operation of KSTAR. Operation of the transmitter with an output power of 2 MW for 300s over the operation frequency range of 30-60 MHz, involves very severe conditions regarding stable operation of the system. After several failures of the amplifiers during the factory and site acceptance test, we eventually achieved a continuous output power of more than 1.9 MW for 300s over the whole operation frequency range. Commissioning of the ICRF system including the antenna was carried out along with the first plasma experiments of KSTAR in 2008 and about 150 kW ICRF power was successfully injected to the circular limited plasma with resonant double loop antenna, which may accumulate ITER-relevant operational experiences at the superconducting tokamak devices. In 2009 experimental campaigns, up to 300 kW has been successfully applied and about 50% increase of electron temperature was observed with RF power injection in the Fast Wave Electron Heating(FWEH) mode. According to the spectroscopic and residual gas analyses in 2009, H/D ratio and hydrogen retention in the wall was very high. Thus wall conditioning including high temperature baking on PFC was conducted for the efficient minority ion heating experiments planned for 2010. H minority heating in a diverted plasma configuration will soon be carried out in 2010, and the results will be presented in the conference.

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1. Introduction

KSTAR is the Korean national superconducting tokamak aiming at high beta operation based on AT scenarios, and ICRF is one of the essential tools to achieve this goal. The final ICRF power is scheduled to inject 6 MW to the plasma. The KSTAR site installation of the antenna, matching system and the transmitter was completed in 2007[1] and commissioning of the ICRF system was carried out along with the first plasma experiments of KSTAR in 2008. About 150 kW ICRF power was successfully injected to the circular limited plasma with resonant double loop antenna, which might accumulate ITER-relevant operational experiences at the superconducting tokamak devices.[2] In particular, the contribution by ICRF system to KSTAR's first successful discharge includes the vessel wall conditioning by ICRF discharge cleaning. In 2009 experimental campaigns, up to 300 kW has been successfully applied and about 50 % increase of electron temperature was observed with RF power injection in the Fast Wave Electron Heating(FWEH) mode. In this paper, the first ICRF experiments including commissioning ICRF system will be shown and results of the ICRF and ICWC experiments will be discussed.

2. ICRF system and commissioning

The ICRF antenna consisted of four current straps of which two straps were used for feeding 2 MW RF power in 2008 and 2009 campaign. Fig. 1 shows the schematic diagram of transmission line configuration and the antenna inside the vacuum chamber is shown in Fig 2(a) and (b). In 2008 and 2009 campaign, two straps-2 and -3 among four current straps were used. The Faraday shield and current straps have water-cooling channels built in for the eventual long pulse operation of KSTAR. They could operate for 300s with the duty cycle of 15 %. They are also protected at sides by two poloidal limiters covered with graphite tiles which intrude into the plasma past the shield by 10mm. The distance between the Faraday shield and poloidal limiter could be varied within 10 cm. Operation of the ICRF system with an output power of 2 MW for 300s over the operation frequency range of 30-60 MHz, involves very severe conditions regarding stable operation of the transmitter as well as the antenna and transmission line system. After several failures of the amplifiers during the factory and site acceptance test, we eventually achieved the continuous output power of more than 1.9 MW for 300s over the whole operating frequency range.[3] This was a very encouraging result for the development of the ICRF transmitter for ITER. The impedance matching between the resonant loop and the transmitter was done by two liquid stubs.

For the RF interlock purpose, three independent methods were provided in KSTAR ICRF system.[4] 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 micro seconds. The second is an over voltage protection on the transmission line along resonant loops. The RF power is automatically recovered after 1 msec blank period activated by the first and second method. The third method was activated by central plasma control system (PCS). When the PCS detects a fault, it activates an interrupt signal to ICRF control system so that no RF power transfers to the tokamak. The three methods were operated successfully for the first and second campaign of the KSTAR ICRF experiments. The functions of the ICRF control and data acquisition system were realized by using independent digital signal processor (DSP) modules with customized peripheral boards. The number of DSP modules has increased year by year as the ICRF system has been expanded. Due to the distributed feature of the control system, increasing of control points does not disturb existing system. The DSPs are basically connected by the local TCP/IP network. Through this network, control and monitor signals which are not sensitive to the sampling time are transferred in a near real time. 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 an EPICS input/output controller (IOC). For a few fast communications, such as an internal interlock or trigger, an optical fiber was connected between the DSPs in the tokamak hall and transmitter room. The optical fiber connection is also used for the electrical ground isolation of diagnostic RF signals between the tokamak vessel and other systems.

3. Results and discussion

The first ICRF experiment was tried using the FWEH heating mode at 1.4 T of B_{TF} during 2008 campaign. The hydrogen gas was used. The toroidal magnetic field of KSTAR is fixed due to that 2^{nd} harmonic ECH assisted startup was tried in KSTAR and the available ohmic flux was very small at 2008. The ICRF frequency was set at 30.1MHz and two resonant loops were used. RF power up to 150 kW was delivered to the plasma. Three RF pulses with pulse length of 30 ms were injected and increase in the antenna loading resistance was observed during the RF pulse. The antenna loading resistance was about 1–3 ohms. The line intensity of C-III and bremsstrahlung (VB) was increased during the ICRF pulse, however no notable changes in the electron temperature and diamagnetic energy were observed during this pulse. The H_α was slightly increased during the RF pulse. In 2008 campaign, the available poloidal field swing was very limited so that the boundary of the circular plasma was very far from the outboard poloidal limiter. In order to increase the ICRF coupling, we intentionally moved the plasma column closer to the ICRF antenna, however, the heating effect was not clear and it was very difficult to distinguish the heating effect from the moving effect of the plasma.

Fig. 3 shows data from a typical ICRF shot in 2009 with a toroidal magnetic field of 2 T and the deuterium was used as the working gas. As ICRF frequency of the transmitter and the transmission line was set up as 45 MHz and it corresponded to FWEH mode at 2 T. Three ICRF pulses were injected to the circular limited plasma and up to 50% increase of electron temperature was observed, a significant improvement was done compared with 2008 experiments. This was believed to be due to the decreased distance between the plasma and the antenna as well as increased RF injection power. The distance from the limiter to the Faraday shield was decreased from 35 mm to 25 mm. The boundary of the circular plasma was limited by the outboard poloidal limiter. The plasma loading resistance increased as the injecting rf power ranging from 70 kW to 280 kW as shown in Fig. 4. If RF power is absorbed by only bulk plasma, the loading resistance does not depend on RF power because both the radiated power from antenna and absorbed power by the plasma are proportional to the square of antenna voltage. A sheath heating is another channel of RF power absorption at low RF power. In this case, the dissipated RF power mainly due to the ion acceleration in the rectified-sheath potential is proportional to the antenna voltage. Therefore, the loading resistance decreases as RF power increases.[5] If the local electron density around antenna is added due to the RF near field, fast wave propagation would be enhanced by modified fast wave cut-off layer. Therefore, monotonic increase of loading resistance with RF power may be conjectured as the enhancement of the fast wave propagation due to the additional ionization around antenna.

The ICRF system also contributed to the first plasma experiments of KSTAR and the second campaign through discharge cleaning on the vessel. It has been well known that the wall condition is very important for obtaining the first plasma of the tokamak because it may affect the plasma initiation and current ramping processes through a radiative loss. But the traditionally used method, a glow discharge cleaning (GDC) cannot be used at the permanent toroidal magnetic field such as a superconducting machine and it is not favorable to turn off the permanent toroidal magnetic field during a daily tokamak shot, So the ICRF assisted discharge cleaning was one of the most promising candidates for a discharge cleaning of the inner wall between the KSTAR daily shots. KSTAR used ICRF antenna as the ICWC antenna and it was used as between shot ICWC. In 2008 campaign, ICWC was first tried and we got the decrease of plasma density as shot went for successive shots and it was believed that ICWC contributed to the first plasma generation of KSTAR.[2] In 2009, more systematic study was conducted to evaluate the effect of ICWC operation parameters on the impurity removal. The mixing ratio of H_2 to He was increased for the fixed duty ratio and the duty ratio of RF pulse was increased for fixed gas composition. The gas pressure was about $1x10^{-4}$ mbar. There were two groups in impurity molecules that showed the different characteristics with respect to the removal rate. The mass number of group-I were 26, 28, 40, 44 and group-II were 18, 20, and 32. While removal rates of group I impurities increased as H_2 flow rate and the duty ratio was increased, those of group II impurities decreased for the same variation. It was also observed that the partial pressures of group II impurities were suppressed during CW ICWC process but increased during post discharge as shown in Fig 5. Note that the A' is the post discharge region and two groups showed the different behaviours at A'. The reason was conjectured to be related with the dissociation energy of impurities. The group I has higher dissociation energy than group II except of CO_2 and C_2H_2. If the electron temperature of the plasma is higher than the dissociation energy of group II but less than that of group-I, most molecules of group-II are dissociated and reattach on the wall and we observe a little increase of partial pressure during RF power is on. As soon as RF power is off, dissociation rate of molecules rapidly decreases and then we might observe the increase of gas pressures of impurities(group-II) after the discharge. As the electron temperature could be controlled by RF power, it is planned that experiments will be conducted by the variation of electron temperature through controlling the injected RF power in 2010 campaign, and it is expected that some molecules of the group I will be member of group-II. Typical injected RF power was less than 30 kW during KSTAR ICWC experiments in 2008 and 2009.

H minority heating is the main ion heating scheme in KSTAR and the control of minority species such as hydrogen is very important step for the efficient ICRF heating. KSTAR in vessel components were covered by graphite tiles and graphite tiles could absorb a lot of the hydrogen and water molecules before installing inside chamber or it is exposed to air because of their high absorption characteristics. In addition, in-vessel components were not baked in 2008 and 2009 campaign. So it was necessary to check the hydrogen to deuterium ratio(H/D) for the next campaign. According to the spectroscopic and residual gas analyses, H/D ratio and hydrogen retention in the wall was very high in 2009 campaign. H/D ratio measured by the Ha emission did not decrease below 30 % over the whole campaign period. Note that H/D ratio was increased vey much just after the discharge cleaning with the hydrogen and the boronization were conducted.[6] The carborane gas was used during boronization in 2009. Thus the wall conditioning including high temperature baking on graphite tiles is necessary step for the efficient minority ion heating experiments planned for 2010. Baking on the in-vessel components were conducted in 2010 campaign over 250C over two days. H-minority heating in a diverted plasma configuration will be soon carried out in 2010, and the results will be presented in the conference.

For 2010 campaign, driven antenna straps were changed from innermost two straps to outermost two straps in order to decrease peak k_{par} from 16 m^{-1} to 6.5 m^{-1}. By reducing peak k_{par}, increasing of loading resistance and power coupling [7] would be expected for the enhanced KSTAR plasmas due to the better confinement and higher heating power. Also, wider separation of current straps reduced mutual couplings between straps which made balanced feeding to be difficult. The coupling between the farthest straps was ignorable compared the coupling of -22.6 dB between adjacent straps.

4. Summary

The KSTAR site installation of the ICRF antenna, matching system and the transmitter was completed in 2007 and commissioning of the ICRF system was carried out along with the first plasma experiments of KSTAR. About 150 kW ICRF power was successfully injected to the circular limited plasma with resonant double loop antenna in 2008. In particular, contributions by ICRF system to KSTAR's first successful discharge include wall conditioning by ICRF discharge cleaning. It was observed that there were two groups in the impurity molecules showing the different characteristics with respect to the removal rate. In 2009 experimental campaigns, up to 300 kW has been successfully applied and about 50 % increase of electron temperature was observed with RF power injection in the Fast Wave Electron Heating(FWEH) mode. For 2010 campaign, the driven antenna straps will be changed from innermost two straps to outermost two straps, increasing of loading resistance and power coupling would be expected for the enhanced KSTAR plasmas due to the better confinement and higher heating power.

5. Acknowledgements

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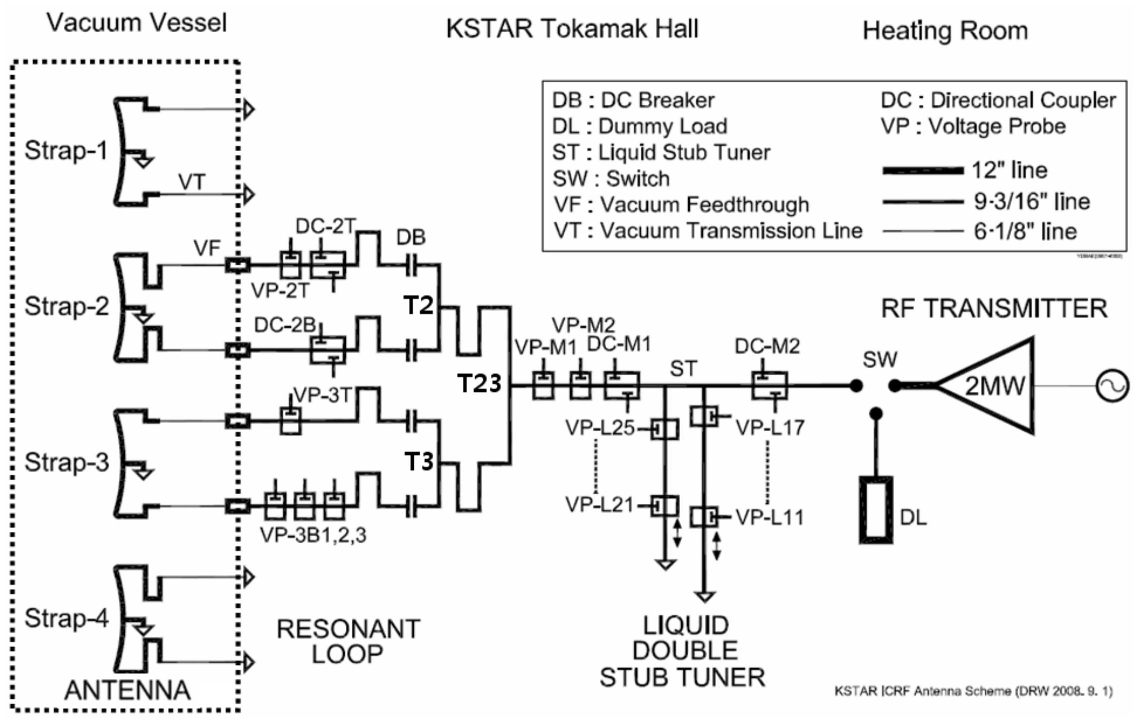


FIG. 1 The RF circuit of the ICRF system in 2008 and 2009 campaign. An RF power is supplied to the two inner current straps(#2 and #3) through a double liquid stub tuner and the resonant loops. The positions of voltage probes(VP) and directional couplers(DC) are indicated. In 2010 campaign, straps(#1 and #4) will be used.

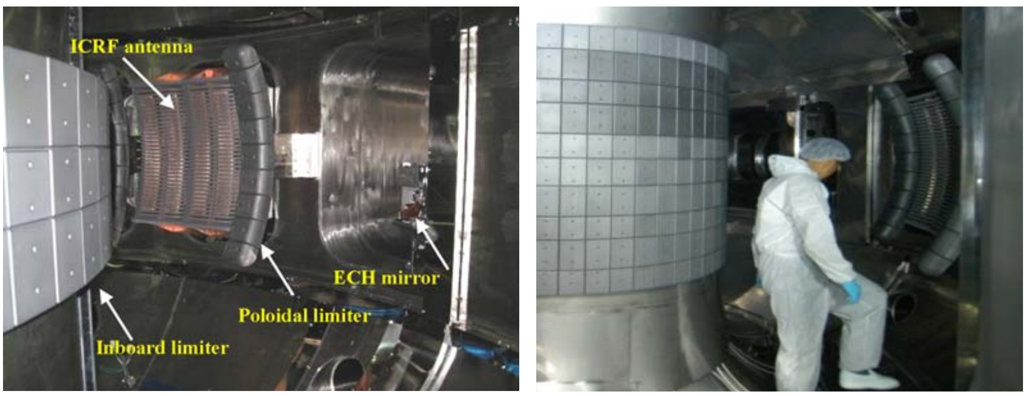
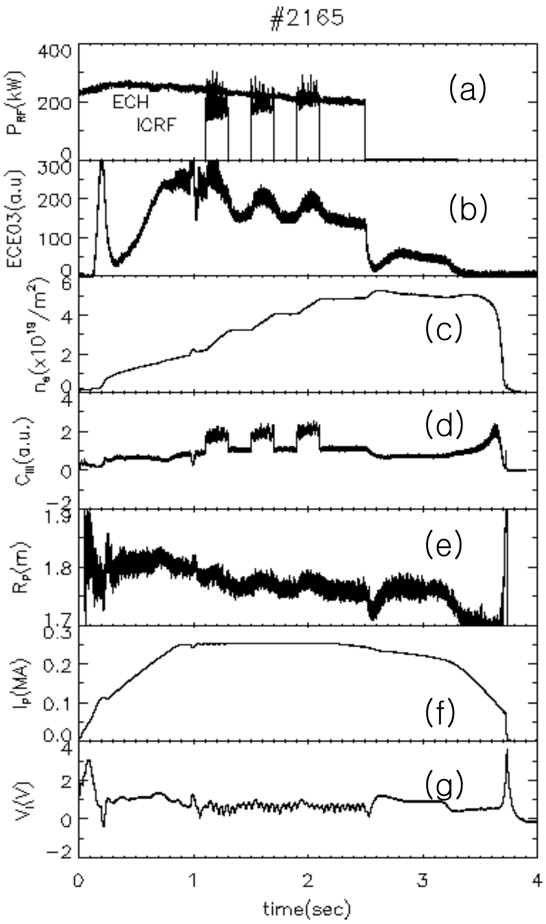


FIG. 2 In-vessel components and ICRF antenna in 2008 (a) and 2009 campaign(b). Additional inboard tiles were attached in 2009 campaign.



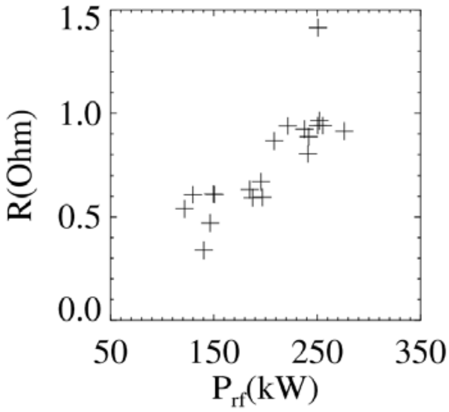
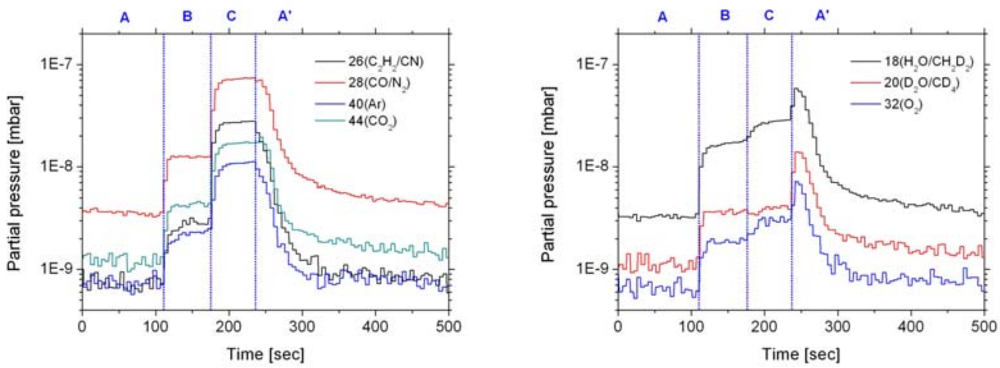


FIG. 4. Plasma loading resistance vs. rf power.

FIG.3. Typical ICRF shot data(#2165) in 2009 campaign (a) ICRF/ECH power, (b)ECE signal,(c) line integrated density, (d) carbon-III line intensity,(e) plasma position, (f) plasma current,(g) loop voltage



(a) (b)

FIG 5. The partial gas pressures during CW discharge for group-I(a) and group-II(b). The gas was injected from region B and ICWC was conducted during C. Note that the A' region is the post-discharge and two groups showed the different behaviours.