Progress in the Heating System Development Towards a Long Pulse Operation in KSTAR

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Abstract. The final efforts are being made at this moment to complete the assembly of the KSTAR tokamak until the end of 2007. After finishing it, a series of experiments to make the tokamak plasmas from the first plasma to the advanced plasma mainly including a long-pulse mode will be continued during 10 years. The ICRF and the NBI systems are expected to play important roles during the long pulse operation period, through selective heating of ions and electrons, controlling the pressure and current profiles, core fueling, and beam diagnostics for the KSTAR. In addition, the ICRF system contributes to the first plasma experiments through possible discharge cleaning and assisting the tokamak startup. In this paper, recent achievements in the development of the ICRF and the NBI heating systems are described with emphasis on the eventual long pulse operation as well as the first plasma experiments. The four-strap ICRF antenna, which should have the long pulse capabilities, has been successfully tested for up to 41 kV for a pulse length of 300 sec and for 46 kV for 20 sec in a the vacuum test chamber. A prototype KSTAR NBI system has been developed and being tested for the required long pulse operation (300 sec) at the designed beam power. At present, the system has successfully produced a 1 MW beam for 200 sec, and a 3.5 MW output beam for 4 sec.

1. Introduction

One of the important issues of the KSTAR tokamak is a long pulse operation up to 300 sec to explore the physics of steady state fusion plasma[1]. To support the long pulse operation, two neutral beam (NB) lines and an ICRF antenna will be installed on the KSATR tokamak and will provide selective plasma heating, current drive, core fueling, pressure profile control, and beam diagnostics. The deuterium beam power per beam line into the plasma is 8 MW with a particle energy of more than 100 keV, and ICRF power coupled to the plasma using 4 strap antenna is up to 6 MW. At this moment, assembly of the KSTAR tokamak is being done to complete the work until the end of 2007. After finishing it a series of experiments to make the first plasma and the main long-pulse plasma are planned during the machine operation period of more than 10 years [2]. The ICRF and the NBI systems have to play important roles to get the high-quality and long-pulse plasma. Also ICRF system is going to be used at the first plasma experiments for a discharge cleaning and an ICRF-assisted startup. In this paper, recent achievements in the development of ICRF and NBI heating systems are shown with an emphasis on the eventual long pulse operation as well as the first plasma experiments.

2. ICRF heating system

A four-strap ICRF antenna has been under development for high-power(6 MW) and long-pulse(300 sec) operations at KSTAR tokamak since 1996. An antenna was designed and fabricated in 2002 after successful, detailed tests of a proto-type antenna built in 1999[3]. The major modifications include: implementation of the water-cooling in antenna, water-sealing method, material of the Faraday shield, and the assembling procedure. For a 300-sec operation at a high power of 6 MW, the antenna has many cooling channels inside the current strap, Faraday shield, cavity wall, and vacuum transmission line (VTL) to remove the dissipated RF power and incoming plasma heat loads. The high power and long pulse capabilities of the antenna were experimentally estimated by performing two series of RF tests in 2004; with and without the water-cooling. Significant improvement in the antenna performance through active cooling was evident[4]. During the test campaign in 2005, we performed the RF tests with active cooling of the antenna and transmission line and the test results are shown in Fig.1. The standoff voltages of 41.3 kV for 300 sec and 46.0 kV for 20 sec, which exceed the design requirement of KSTAR ICRF system, are achieved. In addition, in order to estimate the performance of the antenna in a steady state operation, we extended the pulse length up 600 sec and 1000 sec, which are much longer than the design requirement of 300 sec. As a result we achieved a standoff voltage of 35.0 kV for 600 sec and 27.9kV for 100 sec without encountering any problems. Most of the cooling water connections on the antenna structure inside vacuum will be welded and present o-ring seals will be replaced with helicoflex sealings before installation on KSTAR vacuum chamber in 2007.

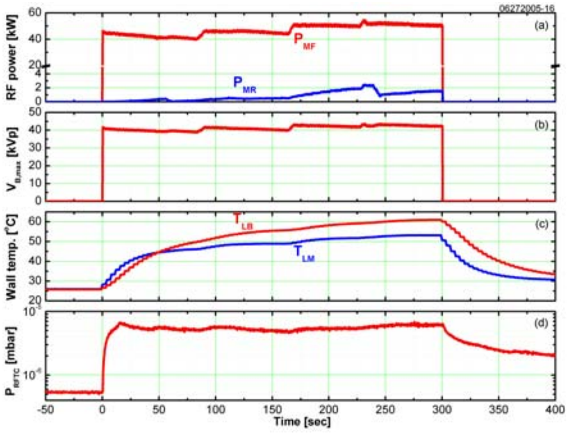

Fig.1. Time evolutions of rf power(a), maximum line voltage(b), temperature of antenna cavity wall(c) and pressure at the vacuum chamber(d) measured during 300-sec long-pulse test.

For stable rf power feeding to the antenna, a three wavelengths-long resonant loop configuration was designed and constructed for fixed-frequency operation at f=30 MHz. The rf current amplitude/phase should be the same/opposite for the upper and lower parts of the each antenna strap. The feeding point of the resonant loop is located near the maximum impedance position where the electrical length difference between the upper and lower parts of the loop is equal to the half wavelength. The high impedance of the feeding point is reduced by a quarter-wavelength transmission line transformer. The DC breaker will be used to disconnect the low frequency current loop which may be caused by stray magnetic flux. A feasibility study for the resonant loop design indicated load-resilient operation capabilities of the KSTAR antenna, which is essential for ELMy plasma conditions. The cold rf test and high voltage breakdown test of the resonant loop will be completed by October, 2006.

The factory acceptance test of the 2 MW rf source, whose frequency range is from 30 to 60 MHz, was completed in a pulse operation mode. Its cavity is the modified version of FMIT(Fusion Material Irradiation Test) transmitter and the vacuum tube for final amplifier stage is CPI’s 4CM2500KG. The full power operation lasting up to 300 sec is planned in November 2006 and then the transmitter will be transported to the KSTAR site where final commissioning test will be done. Fig. 2 shows the 3-D view of ICRF system including antenna, resonant loop, and their supporting structure.

The operation of ICRF system is controlled in real-time through an EPICS-based system in conjunction with the central control system for the KSTAR tokamak. There are four or more sub-unit control systems based on DSP(Digital Signal Process) controller. The functions of these units include detection and positioning of the arc, real-time calculation of antenna impedance, and feedback control of rf power during the operation in addition to the routine data acquisition and control. Phase and amplitude of rf signal for the diagnostics of the system are measured using DSP unit based on the down converted 20 kHz IF systems providing wide dynamic range and uniform rf frequency response. Because the device drivers can be shared between among every subsystem of the central control system, the control software system development process has been significantly reduced. In addition, a preliminary experimental study on

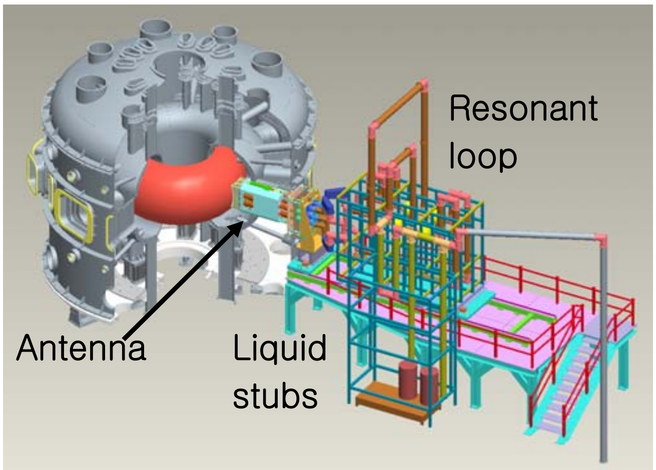

Fig.2. 3-D view of ICRF system

ICRF-assisted discharge cleaning and tokamak startup will be carried out during 2006-2007 on ASDEX-U which is similar in torus dimension to KSTAR. The results from these experiments will be incorporated in the final ICRF-assisted discharge cleaning and the startup plan for KSTAR.

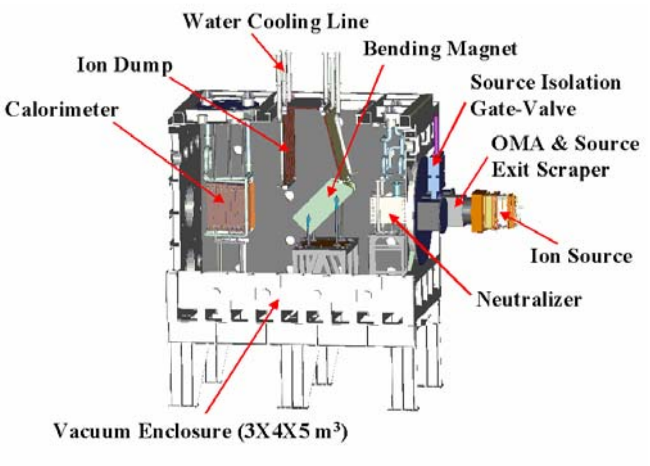

Fig.3. Inner structure of the prototype KSTAR NB system.

3. NBI heating system

All of the NB components, such as an ion source, beam line components, and relatedpower supplies, should be developed to cover a distinctive KSTAR parameter of 300-sec long pulse on the bases of the proven technologies. A prototype KSTAR neutral beam system, whose main objective is to test the developed ion source [5] and beam-line components, such as the calorimeter, neutralizer, bending magnet, ion dumps, and cryo-sorption pump, has been constructed as in Fig. 3, and now the prototype system is in normal operation to execute the following missions;

(1) Test the developed ion source which is designed to make a deuterium beam of 120 keV energy during 300 sec. And establish the necessary upgrade points for the final version.

(2) Test the developed NB power supplies with the beam loads, and optimize the system for the long pulse scenario.

(3) Test the developed beam line components with high power beam and high gas loads. Critical points for the long pulse operation should be studied.

(4) Develop the best NB operation scenario to create a high quality neutral beam.

An experimental set up for a beam extraction of the ion source is shown in Fig. 4. Power supplies, passive snubbers to protect the ion source, Langmuir probes, filaments, electrodes for a plasma discharge, and beam extraction grids constitute an ion source circuit for a plasma generation and beam extraction. The hydrogen gas is injected into the ion source by two gas feed lines at the top of the ion source, and the pressure of the ion source is measured at the OMA chamber. The normal base pressure is 2.5×10^{-5} mbar, and the operation pressure during an arc discharge of the ion source is from 6.0×10^{-3} to 9.0×10^{-3} mbar. The beam extraction experiments are concentrated to create a high energy, high current, and long beam during a test. The critical component to determine the experimental condition is the ion source. Fig. 5 shows the longest beam results which had been made by

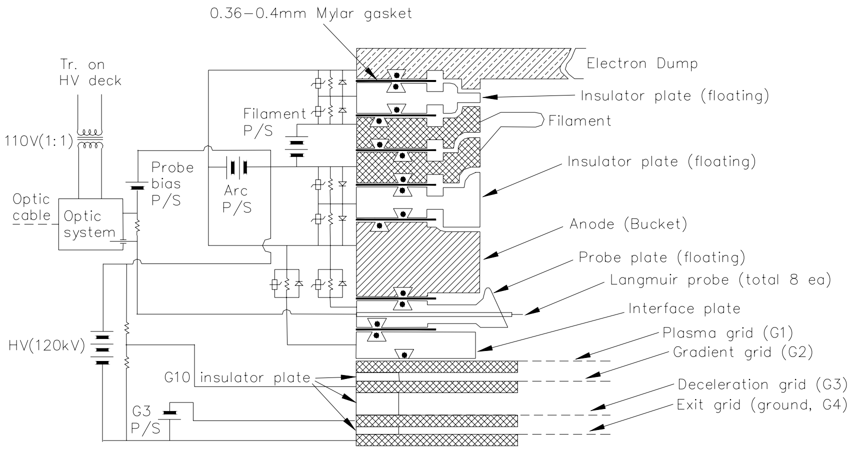

Fig. 4. Schematic circuit diagram for a beam extraction.

a JT-60 ion source. 1 MW hydrogen beam was created during 200 sec with 7 short stops. The pressure was controlled constantly by 2 sets of cryo-sorption pumps. The increase of the water temperature was saturated at 14° C after 6 seconds of the beam start with the target temperature of 175° C during the operation. Fig. 6 shows the beam extraction results of the highest current with the present KSTAR prototype ion source. Hydrogen beam of 36 A with an energy of 95 keV was created and loaded onto the system during 4 seconds. The

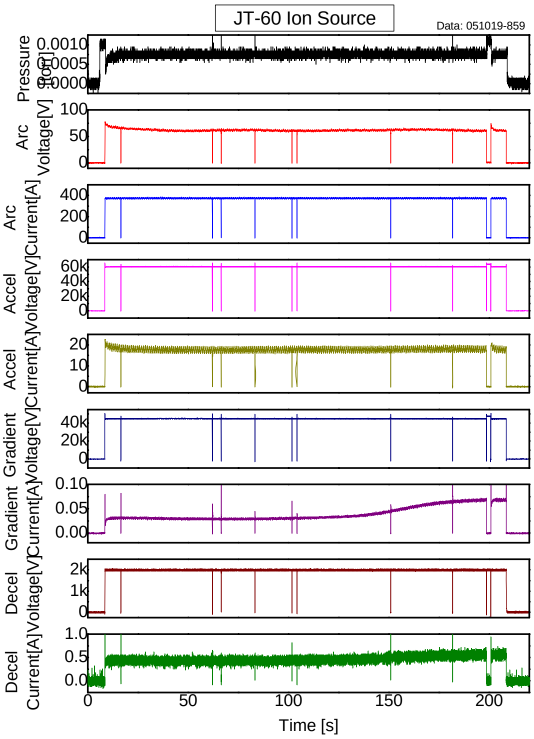

Fig. 5. Long-pulse beam extraction results (60 keV, 18 A, 200 sec beam).

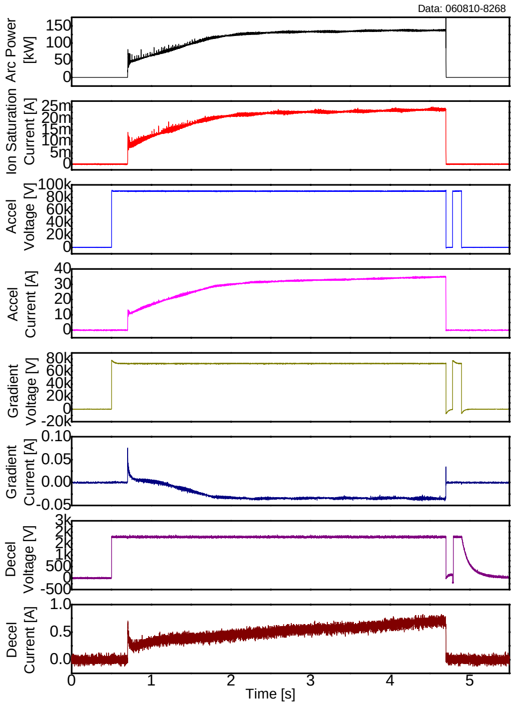

Fig. 6. High-current beam extraction results (95 keV, 36 A, 4 sec beam).

maximum energy which has been tested in the system is 100 keV at 24 A of a beam current during 3 sec. The time and current limits with the prototype ion source at presents were from the ion source and power supply system. Higher current and longer beam experiments are being prepared by upgrading the ion source and acceleration power supply. An OMA system was used for estimating the quality of the extracted beams by the values of ion ratio and beam divergence, and the results were checked by water calorimetric system. The measured ion ratios were 70 %, 8 % and 22 % for the beams of H^+ , H_2^+ and H_3^+ respectively, and the beam divergence was less than 1°.

Beam power deposition in the prototype system along the beam lines has been measured by a water calorimetric system, which is composed of flow meters, thermocouples, and a noise-filtered DAS system. To measure the deposition, a 7-sec hydrogen beam of 80 keV and 23 A was used. An arc discharge of 75 kW supported the beam plasma. The power transmission rates of an accelerator and the beam line components are summarized in Table I. 95.5 % of the total beam power was measured by the water calorimetric system. The 4.5 % power loss in the measurement is expected to be

Table I. Beam Power Deposition on Beam line and Ion Source components.

Test-Stand Component	**Power Loading (%)**	**BTR-code rate (%)**
plasma Grid (Up, Down)	0.4, 0.35	
Gradient Grid (Up, Down)	0.2, 0.18	
Suppressor Grid (Up, Down)	0.01, 0.01	
Exit Grid (Up, Down)	0.09, 0.11	
OMA Duct 1(R-D), 2(L-U)	3.01, 3.18	7.4
Neutralizer	7.66	4.1
BM Scraper & wall	1.81	0.58
Ion Dump (full-energy)	40.28	50.5
Ion Dump (half-energy)	2.67	1.6
Ion Dump (third-energy)	5.25	2.4
Calorimeter	30.29	30.8
TOTAL	95.5	97.4

by the heat loss in the beam line components and measurement errors. The water temperatures were saturated within 6 sec for the beam line components, but they are not saturated for the grids of the ion source even after 20 sec. The simulation results of a beam power transmission by a Beam Transmission with a Re-ionization (BTR) code are also included in the table. One degree divergence was assumed in the BTR calculation. The compared results with the measured and BTR results show that the beam divergence of the ion source is near 1°. The calorimetric data of the 3 ion dumps also provided beam species data of the ion source.

The cryo-sorption pump [6] has to have a large pumping speed to pump out a considerable amount of gas loads from the ion source and a neutralizer for a long pulse operation. The pumping speed of a panel has been measured with panel temperatures as shown in Fig. 7. It shows that a hydrogen pumping is effective when the temperature decreases to less than 20 K. A pumping speed of 1.0 x 10^5 l/sec per a panel has been earned after a cooling time of 7 hours. Neutral efficiency was measured with the gas flow rate into the neutralizer. Neutralizer gas was injected at the middle of the neutralizer independently from the ion source system. More than 800 sccm is necessary to create an effective neutral beam in the prototype system. The experiments show that the neutralization efficiency of the hydrogen beam is 46 % at 70 keV, and 46 % at 80 keV. They agree well with the theoretical results.

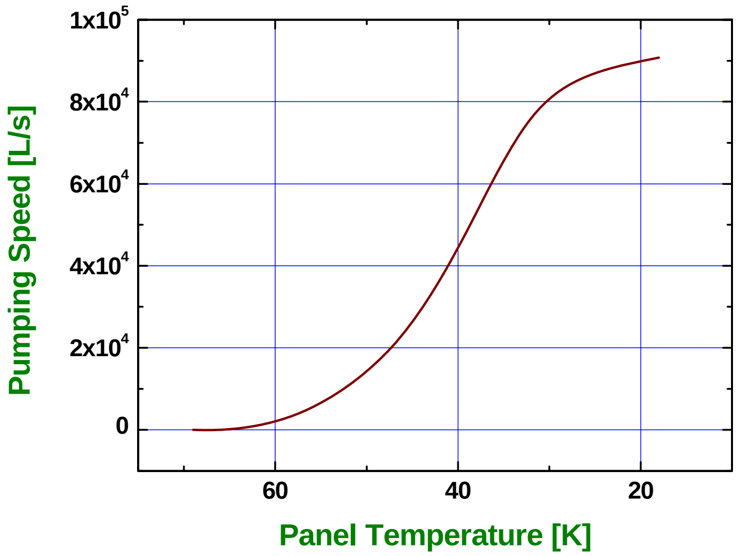

Fig. 7. Pumping speed with the cryo-sorption panel temperature.

4. Summary

One of the important missions for the KSTAR tokamak is to accomplish the advanced tokamak operation mode in a long-pulse. To support the final goal, the ICRF and the NBI system have been developed, and will be installed in a proper time schedule at the KSTAR tokamak. During the test campaign in 2005 the stand-off RF tests with active cooling of the antenna and the transmission line were performed, and the parameters of stand-off voltages of 41.3 kV for 300 sec and 46.0 kV for 20 sec have been achieved. A prototype KSTAR Neutral Beam system has been developed and tested successfully for its long pulse operability for 300 sec at the designed beam power. Presently, the system has produced a 100 keV/24A beam for 3 sec, 95 keV/36A beam for 4 sec, and a 60 keV/18A beam for 200 sec. The test and upgrade with the developed prototype system will be continued until next year, and on the bases of the final results, the first beam line will be installed in KSTAR to supply the beam power into the plasma from 2010.

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