Commissioning Results of the KSTAR Neutral Beam System

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Abstract. The neutral beam injection (NBI) system is designed to provide the ion heating and current drive for the high performance operation and long pulse operation of the Korean Superconducting Tokamak Advanced Research (KSTAR). The KSTAR NBI consists of two beam lines. Each beam line contains three ion sources of which one ion source has been designed to deliver more than 2.5 MW of deuterium neutral beam power with maximum 120-keV beam energy. Consequently, the final goal of the KSTAR NBI system aims to inject more than 14 MW of deuterium beam power with the two beam lines. According to the planned NBI system, the first NBI system is to demonstrate the beam injection from one ion source into the KSTAR tokamak plasma in 2010 campaign including the system commissioning of each components and subsystems. In this paper, the construction and the commissioning of the first NBI system with one ion source is presented.

1. Introduction

One of the most important issues for the KSTAR tokamak [1] is a long pulse operation (300 s) to explore the physics of steady-state fusion plasma. To support the steady state operation of the KSTAR, a long pulse and high power neutral beam (NB) is positively necessary with the help of other RF heating systems. The 14-MW NB heating power in total is planned for the KSTAR physics operation requirement at 120-keV deuterium neutral (D0) beam.

Since 1995, the research and development work of the neutral beam injection (NBI) system for the Korea Superconducting Tokamak Advanced Research (KSTAR) has been performed by Korea Atomic Energy Research Institute (KAERI) using a test stand system. The test stand system was constructed mainly to ion sources, a power supply system and a beam line system that will be dedicated to the high performance and long pulse operation of the KSTAR. The bucket type positive ion source was developed KAERI from early stage of the KSTAR construction phase [2], and it has been demonstrated with 55 A of hydrogen ion beam at the energy of 100 keV with the pulse duration of 2 s. It was also achieved that the source could be operated with the extended pulse duration of 300 s for the lowered beam energy of 90 keV and 33 A of the beam current [3]. More recently, the plasma generator in the ion source was substantially replaced by a new plasma generator [4] to enhance the arc efficiency. The new plasma generator was developed by Japan Atomic Energy Agency (JAEA) in accordance to Korea-Japan fusion collaboration. The accelerator of the ion source was developed by KAERI [5]. After the successful achievement of the KSTAR first plasma in 2008, the detailed engineering design of the beam line and power supply system was also performed together with Korean companies from May, 2009. The design was based on the basic design and specifications accomplished by KAERI, and followed by the construction of the first NBI system, called as “NBI-1”, which had been started actually from September, 2009. This paper presents the overview of the KSTAR NBI-1 system and the results of the beam line commissioning and the first beam experimental results. Also, the future plan of the KSTAR NBI system commissioning is presented

2. Ion Source

The ion source consists of a large bucket as a plasma generator [4] and a tetrode accelerator system for the beam extraction. The bucket has a cross section of 25 × 59 cm^2 and 32 cm deep and is made of a “magnetic multipole bucket” anode. The anode chamber of the plasma generator is made of oxygen-free high conductivity (OFHC) copper. Azimuthal arrays in the beam direction of the Sm–Co permanent magnets spaced between cooling channels are lined up on the wall to create a cusp field around the inner wall of the chamber. Arrays of 12 thermionically emitting tungsten filaments (2.0 mm diameter) are used as a cathode. Each filament is mounted on a water-cooled filament feed-through, which is individually connected to each filament power supply. The accelerator grid modules are made of oxygen-free high conductivity (OFHC) copper with cooling channels through every row of the beam extraction holes. The aperture diameters of plasma grid (G1), gradient grid (G2), suppressor grid (G3), and exit grid (G4) are 7.6 mm, 7.2 mm, 6.8 mm, and 7.2 mm, respectively. The gap distances between G1 and G2 are 4 mm, 7 mm between G2 and G3, and 2.5 mm between G3 and G4, respectively. The number of holes of each grid is 568, and the transparency of the grid is 48% with a beam size of 11.5 × 45 cm^2. A schematic of the assembled ion source including four accelerating grid modules is shown in Fig. 1.

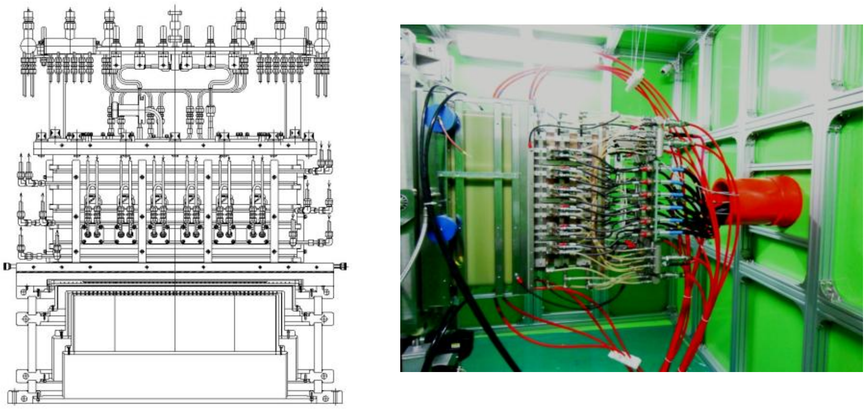

FIG. 1. The first ion source which is used for the KSTAR NBI-1 system.

3. Beam Line System

The beam line components accommodating one neutral beam from the first ion source are assembled into the main chamber with a volume of 45 m^3 (3 m x 5 m x 3 m). Figure 2 shows the NBI chamber and ion source with magnetic field shielding box made of 5-mm steel (SS400) with the size of width of 3500 mm, height of 2770 mm, and length of 3060 mm. The permalloy, a nickel-iron magnetic alloy, will be added inside the steel with an air gap to meet the allowed stray magnetic field of 0.5 G in the ion source region. The high voltage cables for the accelerating grid, gradient grid, and the cables for the filament and arc discharge are penetrating the shield box through the insulating cylinder made of fiber-reinforced plastic (FRP) with inner diameter of 220 mm, thickness of 20 mm, and length of 700 mm.

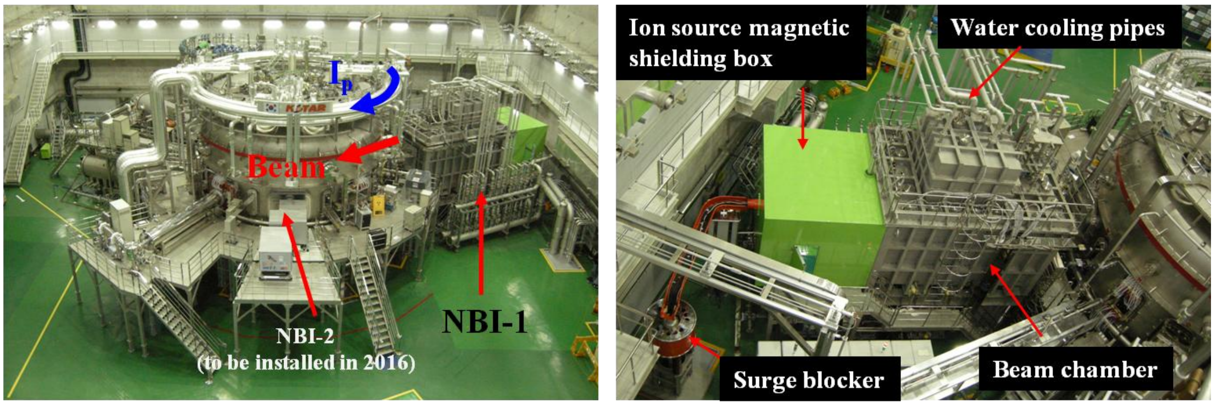

FIG. 2. The KSTAR NBI-1 system.

Figure 3 shows the cross-sectional view of the KSTAR NBI-1 beam line system. There are one gate valve, two staged gas-cell neutralizer, and one bending magnet for the single-channel beam extraction from each ion source. The rectangular beam scraper after the bending magnet accommodates three beams. The movable calorimeter system has a v-shaped structure with an angle of 15 deg for the single-channel beam extraction. Each beam line component is designed to sustain with the condition of the heat load of about 20 MW/m^2 for the incident beam of 3 MW with the pulse duration of 300 s. To allow this continuous heat load, the first wall to the beam is fabricated with the hypervapotron structure to enhance the heat transfer from the beam to the water channel. The hypervapotron has many corrugations with the depth of 3 mm. The used material for the hypervapotron is a CuCrZr alloy because it has high mechanical strength and hardness at the high heat load condition. The hypervapotron structure is employed to the neutralizer walls, all the beam scrapers, the single-channel calorimeter, and beam duct scraper. Meanwhile, the three ion dump walls for the full, half, and the third energy component of the ion beam are array of many OFHC water tubes in which the 0.8-mm thick stainless steel swirl tape is inserted. The NBI-1 system is designed to use the individual bending magnet to deflect three ion beam channels after the neutralizers to the ion dump. The first bending magnet, which is installed on the centered beam channel, is fabricated to meet the requirement of the magnetic field integral of 65 kG·cm on the beam path for the deuterium beam energy of 120 keV.

The pumping system of the NBI-1 consists of roughing pumping system, three turbo-molecular pumps and one oil-free backing pump, and the cryo-sorption pumping system. On each wall side, the cryo-sorption pumping system consists of six nickel-coated aluminium thermal shield panels near the wall side, eight cryo-panels, and four chevron-typed carbon-coated baffles. The liquid nitrogen flows into the each chevrons of the baffle and the copper pipes riveted on the thermal shield each for the function of protecting cryo-panels from direct exposure to radiant heat and gases. The 20-K cryo-cooler cools the cryo-panel up to 20 K. The pumping speed of the total 16 cryo-pumps is estimated to be 1.2×10^6 liter/s at 20 K for deuterium gas. The assembly of the cryo-sorption pumping system is also shown in Fig. 3. The gases are fuelled to the ion source and the first stage of the neutralizer using each mass flow controller (MFC). The MFC controller is triggered to open the MFC valve with the set value of the flow rate. The vacuum pumping system is connected in parallel to purge the gas line from the deuterium gas tank to the pneumatic valve near the ion source and neutralizer. The ion source gas fuelling line and its instrumentation is put into the high voltage cabinet floated at the accelerating voltage.

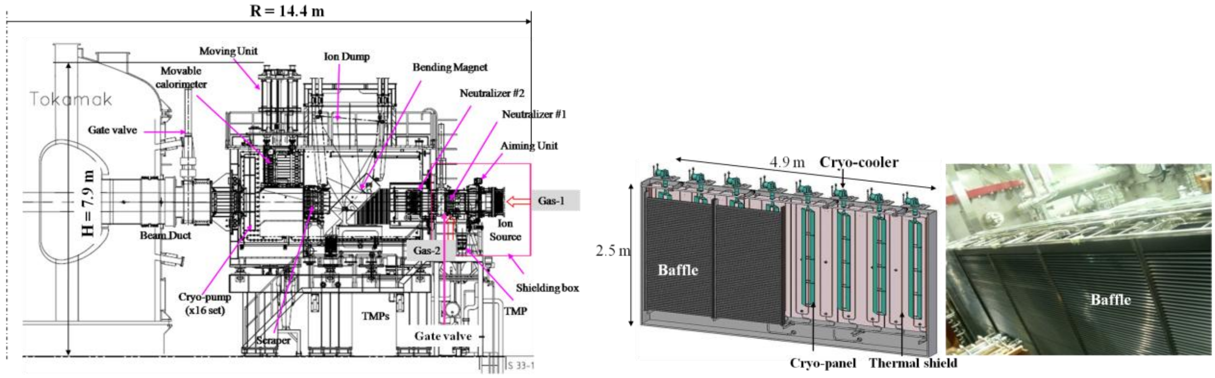

FIG. 3. (Left) The cross-sectional view of the KSTAR NBI-1 beam line. (Right) The cryo-sorption pumping system showing the 3D assembly view and the installation of baffle and thermal shield inside the opened chamber without cryo-panels and cryo-coolers.

4. Power Supply System

The DC generation is based on the low voltage transformer with chopper stacks for the voltage control in unit of 600 volts and the high voltage (HV) transformer/rectifier systems for the dc generation of 20 kV, 30 kV and 50 kV. The DC output to 120 kV is obtained by the combination of the chopper array and HV transformer/rectifiers. The DC generator is fabricated to supply the maximum current of 70 A. The DC generator is located in the transformer yard and DC high voltage cable comes to the underground of the main experimental hall and is connected to high voltage deck that contains filament power supplies, arc power supply, and bias power supply for the surge blocker. The high voltage (HV) transmission line, which contains all of the HV-floated power cables to the ion source, passes through the surge blocker (or absorber) and is finally connected to the ion source. Figure 4 shows the single-line diagram of the power supply system and its installation at the yard and experimental hall of the KSTAR tokamak. The DC voltage is sensed at the DC sensing panel in which a high voltage probe is placed for the voltage control. The high voltage switching (HVS) system composed of MOSFET fast semiconductor switches pulses the DC to the high voltage deck for the accelerating grid (G1). The HVS output is also input to the voltage divider system which supplies the gradient voltage to G2 grid. The voltage divider system is made of the winding layers of 0.8-mm and 1.2-mm thick chromium-coated thin wires. The total resistance is 25.4 kΩ. There are 26 taps for the divided output voltage (G2 voltage) with a step of 2% of the input G1 voltage. Many turns of chromium-coated thin wires are inserted in the insulating oil tank which is capable of 120 kV and 5 A with a pulse duration of 300 s. For the JAEA ion source chamber (or plasma generator), twelve filament power supplies are installed inside the HV deck to heat each filament. Each filament power supply is capable of supply the maximum current of 200 A with 15 V. The positive output of the each filament power supply is common to the negative output of the arc power supply. The arc power supply provides the arc discharge inside the plasma generator with the current flow from the source chamber to 12 positive cables of the filament power supplies. The arc current through each positive cable returns to the negative output of the arc power supply. To interrupt the arc discharging for the fault condition of the arc current unbalance, DCCT current monitor is placed at the positive cable of the filament power supply at the HV deck.

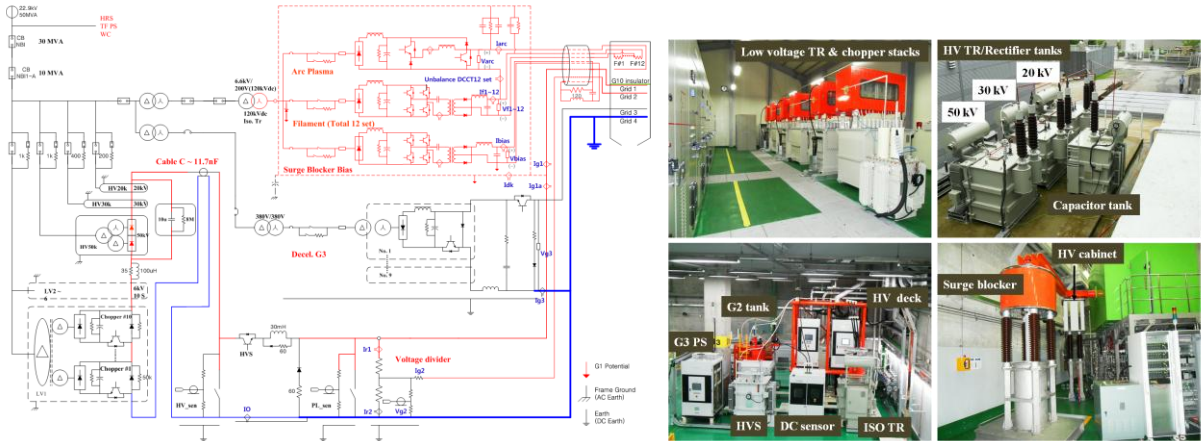

FIG. 4. (Left) Schematic of KSTAR NBI-1 power supply system, (right) the power supply installation.

5. Control System

The NBI local instrumentation and control (I&C) system is a PLC-based system for the local input and output controller (IOC) for the beam line system and power supply system. The main control server is an EPICS-based controller. All the data from the instrumentation of the vacuum pumping system, thermocouples, gas fuelling the ion source and neutralizers, cryo-sorption pumping system, water cooling system, and CCD camera are transmitted to the PLC and EPICS server through TCP/IP Ethernet network. The NBI system is controlled and operated by a main EPICS server communicating with local PLC servers. The PLC of the power supply is used for the power supply control and the operation. All the operation parameter of the power supply is set by the PLC operator interface (OPI) which is just personal computer. The power supply PLC is communicated with a VME-based controller through RS232 communication interface. The VME-based controller is used for the DC voltage control and the pulsed output of all the power supplies by the duration set by the PLC. The on-timing of each power supply is determined by the trigger input coming from the local timing unit (LTU) trigger generator implemented in the main EPICS server. Another LTU for the timing of the gas fuelling to the ion source and the neutralizer is also implemented in the local EPICS server for the beam line system. The time-delayed two trigger signals from the LTU with respect to the power supply trigger signals are sent to the MFC controllers. A fast data acquisition (DAQ) called as D-TACQ is used for the data acquisition of all the power supply data. These data are stored in the local MDSPlus system.

6. Commissioning Results

6.1 Vacuum System Commissioning

The chamber is pumped out first by the roughing pumping (RP) system with the gate valve closed in the turbo-molecular pumping (TMP) system until the pressure reaches at 10^{-2} mbar. Then, TMP is operating with the gate valve closed in the roughing pumping system. In the first evacuation test of the beam chamber, it took so long time to reach the $1{\times}10^{-5}$ mbar. During the initial vacuum pumping test, the roughing pump was once contaminated due to large amount of water from the chamber. To remove the water inside the chamber, the chamber was baked out using eight halogen lamps placed on the top of the chamber at the position of the beam scraper. The cryo-sorption pumping system is commissioned flowing liquid nitrogen through the baffle and the thermal shield. Unfortunately, the cold leak of the liquid nitrogen channel was found in the right side of baffles and thermal shields. Therefore, the liquid nitrogen channel in the right side was closed, and the only left side of the baffles and the thermal shields are being used. With the use of only one side of the baffle and the thermal shield, the vacuum pressure reaches the minimum level of 1×10^{-6} mbar. The temperatures of the cryo-panel start to decrease while liquid nitrogen flows and decreases up to 225 K at the pressure level of 1×10^{-6} mbar. When eight cryo-coolers are run, the vacuum pressure of the chamber reaches at 3×10^{-7} mbar. Figure 5 shows the records of the vacuum pressure of the beam chamber during vacuum commissioning.

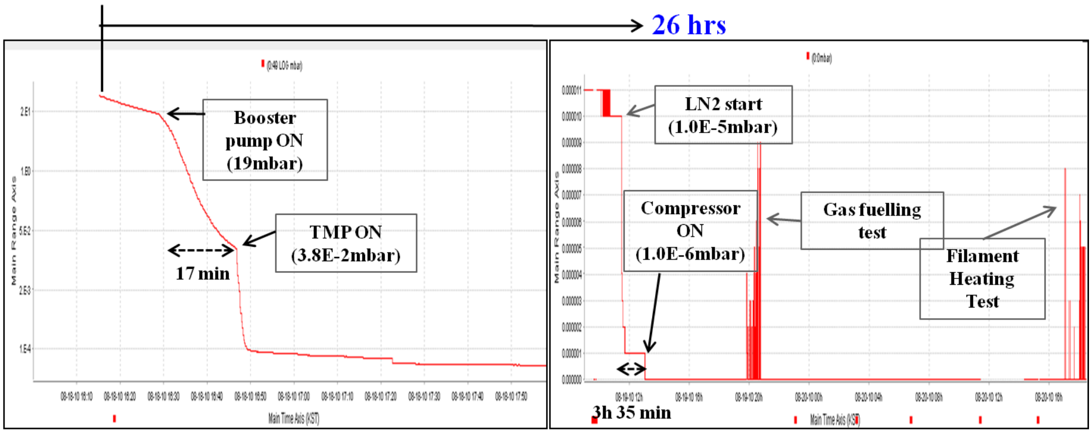

FIG. 5. The log of the vacuum pressure of the beam chamber in the vacuum commissioning.

The neutralizer cell is pumped by only one TMP. There is another big gate valve for the vacuum isolation of the ion source from the chamber. The TMP pumps down the ion source together and the pressure of 2×10^{-6} mbar is maintained. For the regeneration of the cryo-panels, the warm-up to the room temperature takes 24 hrs and the cool-down takes about 3.5 hrs. Therefore, the regeneration could be done in the weekend during the KSTAR campaign.

6.2 Ion Source Conditioning

The initial operation of the ion source was started from the filament heating. Each filament is heated from the 2 volts to 12 volts looking over the vacuum pressure change. The vacuum pressure increased due to outgas from the chamber wall during the filament heating. The filament voltage and current measured at the ion source were almost the same at all 12 filaments. The filament current is about 140 amps for the 12 volts. Next, the arc discharge in the source chamber was done after the filament conditioning. The characteristics of the arc discharge are investigated scanning the vacuum pressure at the source chamber by changing the gas flow rate from 70 sccm (standard cubic centimetres per minute) to 400

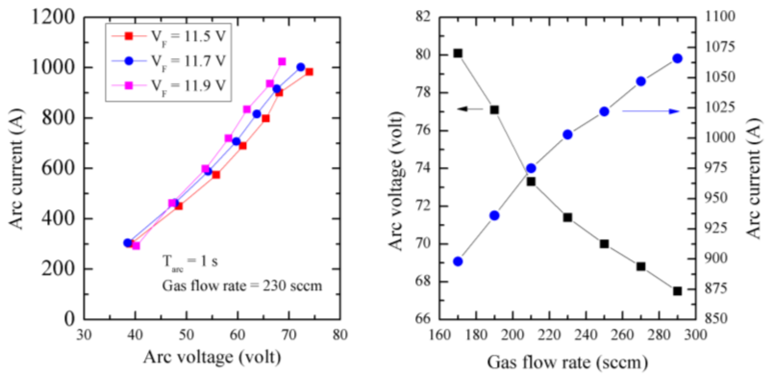

FIG. 6. The arc current as a function of the arc current with the gas flow rate of 230 sccm (3×10^{-3} mbar at the ion source) for different filament voltages and (right) the arc voltage and the arc current as a function of the gas flow rate with the constant arc power of 70 kW.

sccm and the filament voltage for the given arc power. The arc power is also scanned from 4 kW to 70 kW. The optimum gas flow rate is found out with 230 sccm at the source chamber which corresponds to vacuum pressure of about 3×10^{-3} mbar (8×10^{-4} mbar at the neutralizer chamber). Figure 6 shows the arc voltage and the arc current in the arcing discharge with the constant arc power mode. The arc current increases with the gas pressure at the ion source and the filament voltage.

Next procedure of the ion source conditioning was the high voltage insulation test at the grid. The high voltage is applied to the accelerating grid up to 82 kV and the decelerating grid up to -3 kV with the maximum pulse duration of 30 s. The 80 kV is the target beam voltage in this 2010 KSTAR campaign. The surface cleaning of grids with an arc discharge as the final procedure of the ion source conditioning is done by using the operation of decel-cleaning modes. There are two kinds of decel-cleaning modes; single-gap cleaning mode and dual-gap cleaning mode. For the dual-gap cleaning mode, the accelerating grid (G1) and the gradient grid (G2) are connected electrically to the ground grid (G4). In this case, only the decelerating grid (G3) is tied to the decelerating (negative) voltage. The beams are extracted by the decelerating grid voltage under the limit of the 10 A as the arc power being increased. These beam extractions are done more than total 300~500 s until no arcs occur inside the adjacent grids. For another dual gap cleaning mode, the accelerating grid (G1) and the decelerating grid (G3) are connected to the ground grid (G4). In this case, the gradient grid (G2) is tied to the decelerating voltage. For the single-gap cleaning mode, the accelerating grid and the gradient grid are tied to the decelerating grid. The single-gap cleaning mode is done for the cleaning between each adjacent grid separately. The operation of single-gap cleaning mode can be used when this dual-gap cleaning turned out not enough to clean the grid surfaces. Both cleaning modes are attempted in the grid cleaning. Many arcs occurred in the initial grid cleaning pulses. After many pulses, the arcs are disappeared. During the grid cleaning, the retriggering mode is used limiting maximum three arcs during the pulse. The retriggering interval time was 50 ms.

6.3 Beam Extraction

Figure 7 shows the beam extraction results. The optimum arc power is investigated to get the beam perveance close to the designed value of 1.2 μ-perv as the accelerating beam voltage increases. The waveforms of voltage and current at the filament and arc power supplies, the accelerating power supply, and the decelerating power supply are also shown in Fig. 7. An ion beam energy of 6.5 MJ is extracted in the accelerator column with 80 kV and 27 A. As shown in Fig. 7, the beam is initiated by the arc discharge. The beam current rises very slowly to the flat level with a slope of about 58 A/s at the initial current ramping region. But, it takes about 1 s for the current reaches to the flat level. The pre-arc discharge without the acceleration voltage (no beam extraction) is attempted for the prompt current rise. Figure 8 shows the typical shot of the beam extraction using the pre-arc discharge. The beam current rises very fast within 50 ms. The method would be useful for the beam injection with a short pulse duration into the torus avoiding the slow beam current rise. Figure 9 shows the beam divergence of extracted deuterium beam at the accelerating voltage of 60 kV and at the deceleration voltage of -3 kV varying the arc power from 10 kW to 24 kW. The ion source has a wide operation range within the beam divergence of 1 deg which is the KSTAR requirement for the deuterium neutral beam injection. The minimum divergence is obtained at the 16 kW arc power with the beam perveance of 1.16 μ-perv.

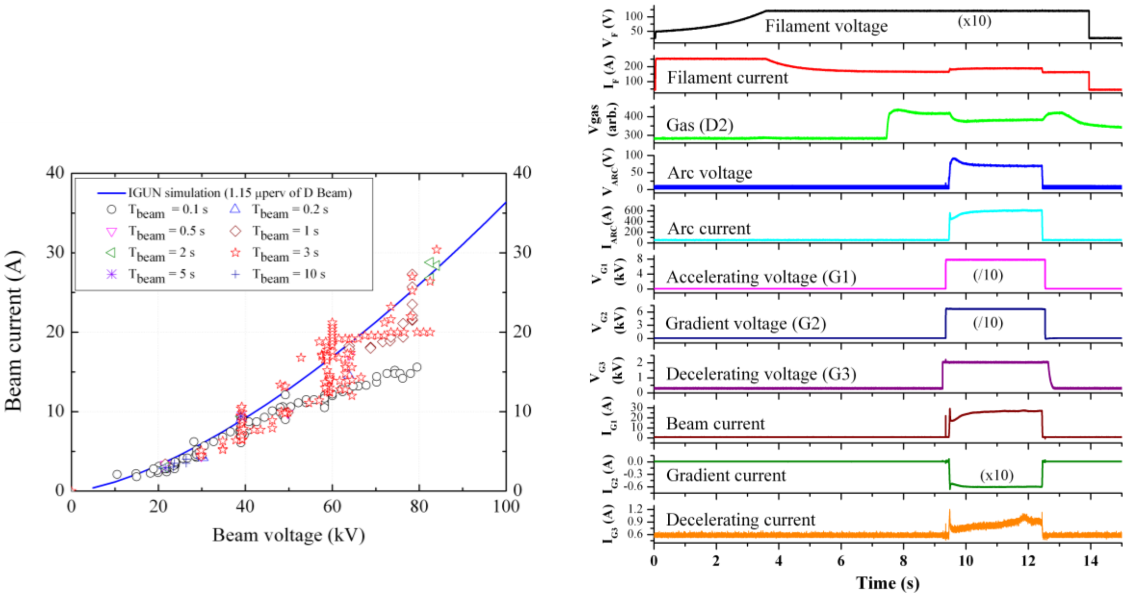

FIG. 7. (Left) The achieved beam data and (right) the waveforms of the 3-s beam extraction with the beam energy of 80 keV and the beam current of 27 A. The filament voltage and current are those of the filament no. 3.

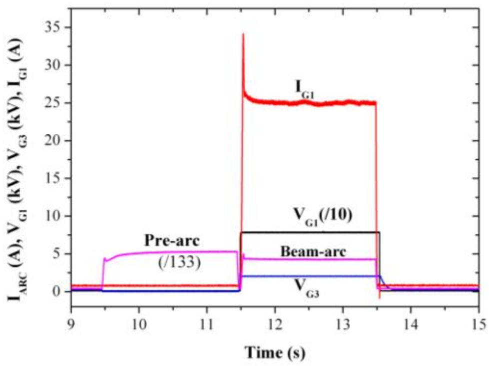

FIG. 8. The beam extraction with pre-arc discharge in the source chamber in advance of the onset of the accelerating voltage and the main beam arc.

Figure 9 also shows the Doppler shifted spectrums of full energy (E), half energy (E/2), the third energy (E/3), and tenth components (E/10) originated from D^+ ions, D_2^+ ions, D_3^+ ions, and D_2O^+ respectively. The H_α and D_α line from the background plasma is also shown in the spectrum. After the analysis of the atomic beam species ratio, the optimum operation condition will be found out by the Doppler shifted spectrum measurement to meet the KSTAR requirement of 80% deuterium atomic ion (D^+) fraction.

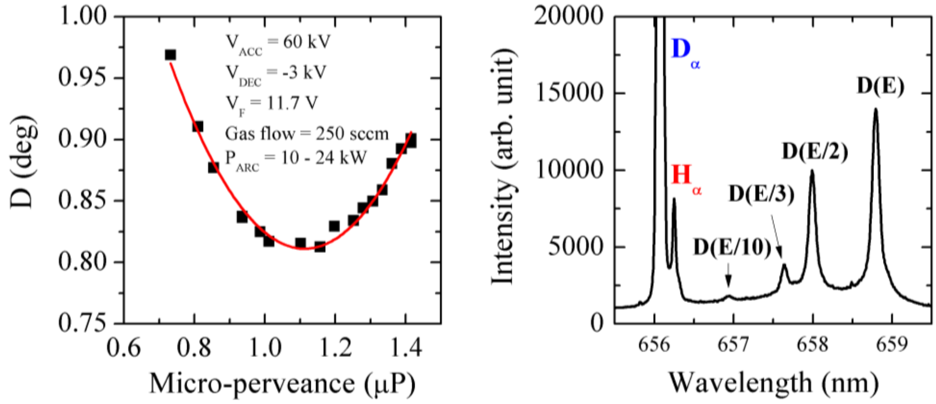

FIG. 9. (Left) The divergence and the perveance of extracted beam varying the arc power, (right) and the Doppler shifted spectrum for the acceleration voltage of 63 kV, the beam current of 18.7 A, the gas flow rate of 250 sccm, and the arc power of 24 kW.

7. Summary

The construction and the commissioning of the KSTAR first neutral beam system is completed for the operation in 2010 campaign. The beam chamber is constructed to accommodate three beam channels from three ion sources. All the beam line components are designed for 2.7 MW deuterium neutral beam injection at 120-keV beam energy with the pulse duration of 300 s. In this construction phase, the beam line components are installed only for one-beam channel associated with one ion source. The first ion source is composed of the plasma source chamber developed by JAEA and the accelerator system developed by KAERI. The vacuum commissioning of the chamber and the ion source is successfully completed. The ultimate vacuum pressure of 3×10^{-7} mbar is achieved using the half of the cryo-pumping system due to the cold leak of the liquid nitrogen channel in the other half of the cryo-pumping system. A deuterium-ion beam energy of 6.5 MJ is successfully extracted in the accelerator column with 80 kV and 27 A. The optimum operation regime was also investigated to achieve the target perveance of 1.2 μ-perv and the beam divergence less than 1 deg. To provide the estimation of the NB power at the front of the beam duct, neutral beam power measurement using the calorimeter will be carried out before the first beam injection to the KSTAR during the 2010 campaign. Also, the gas puffing conditions will be optimized for the good neutralization efficiency as well.

Acknowledgement

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References

[1] Lee, G.S., et al., “The KSTAR project: An advanced steady-state superconducting tokamak experiment,” Nucl. Fusion **40** (2000) 575.

[2] Jeong, S.H., et al., “Study on an azimuthal line cusp ion source for the KSTAR neutral beam injector,” Rev. Sci. Instrum. **79** (2008) 02B310.

[3] Oh, B.H., et al., “Long pulse beam extraction with a prototype ion source for the KSTAR neutral beam system,” Rev. Sci. Instrum. **79** (2008) 02C101.

[4] Dairaku, M., et al., “Development of a plasma generator for a high power NBI ion source,” JAEA Technology 2008-091 (2008) (in Japanese).

[5] Kim, T.S., Jeong, S.H., and In, S.R., “Numerical Simulation for the accelerator of the KSTAR neutral beam,” Rev. Sci. Instrum. **81** (2010) 02B106.