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# Commissioning of the first KSTAR neutral beam injection system and beam experiments

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## HIGHLIGHTS

- The first neutral beam injection (NBI) system equipped with one ion source was developed and successfully commissioned in KSTAR.
- A MW-deuterium neutral beam was successfully injected to the KSTAR plasma with maximum beam energy of 95 keV.
- L-H transition was observed with neutral beam heating.
- The 300-s long pulse beam extraction was achieved for 1 MW neutral beam.

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## ABSTRACT

The neutral beam injection (NBI) system was designed to provide plasma heating and current drive for high performance and long pulse operation of the Korean Superconducting Tokamak Advanced Research (KSTAR) device using two co-current beam injection systems. Each neutral beam injection system was designed to inject three beams using three ion sources and each ion source has been designed to deliver more than 2.0 MW of deuterium neutral beam power for the 100-keV beam energy. Consequently, the final goal of the KSTAR NBI system aims to inject more than 12 MW of deuterium beam power with the two NBI for the long pulse operation of the KSTAR. As an initial step toward the long pulse (~300 s) KSTAR NBI system development, the first neutral beam injection system equipped with one ion source was constructed for the KSTAR 2010 campaign and successfully commissioned. During the KSTAR 2010 campaign, a MW-deuterium neutral beam was successfully injected to the KSTAR plasma with maximum beam energy of 90 keV and the L-H transition was observed with neutral beam heating. In recent 2011 campaign, the beam power of 1.5 MW is injected with the beam energy of 95 keV. With the beam injection, the ion and electron temperatures increased significantly, and increase of the toroidal rotation speed of the plasma was observed as well. This paper describes the design, construction, commissioning results of the first NBI system leading the successful heating experiments carried in the KSTAR 2010 and 2011 campaign and the trial of 300-s long pulse beam extraction.

## 1. Introduction

One of the most important issues for the KSTAR tokamak [1] is long pulse operation (300 s) to explore the physics of steady-state fusion plasmas. To achieve the steady state operation of KSTAR in the future, a long pulse (300 s) and high power neutral beam

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(NB) is mandatory as well as other wave heating systems. In the original plan, a total of 14-MW (8 MW for first NBI and 6 MW for second NBI) of NB heating power was planned for the KSTAR physics operation requirement at 120-keV deuterium neutral ($D^0$) beam energy. But, the plan for the total beam power and maximum beam energy has been changed for the first beam injection system due to the technical difficulty in accelerator development and limited space needed for the high voltage insulation. The target operating beam energy and current will be 100 keV and 50 A for deuterium beams, respectively. Considering 50% neutralization efficiency and 80% transmission efficiency of each beam line, the neutral beam power supplied by each ion source will be 2 MW. Therefore, the total six ion sources will supply deuterium neutral beam power of 12 MW to KSTAR.

Since 1995, the research and development work of the neutral beam injection (NBI) system for the Korea Superconducting Tokamak Advanced Research (KSTAR) device has been performed by the Korea Atomic Energy Research Institute (KAERI) using a test stand system. The test stand system consisted of ion source, a power supply system, and a beam line system that was dedicated to the high performance and long pulse operation of KSTAR. A bucket type positive ion source was developed by KAERI from an early stage of the KSTAR construction phase [2], and a hydrogen ion beam has been demonstrated with a current of 55 A at an energy of 100 keV and a pulse duration of 2 s. An extended pulse duration of 300 s was also achieved for the lowered beam energy of 90 keV and 33 A of beam current [3]. More recently, the ion source bucket chamber was substantially replaced by a new one [4,5] to enhance the arc efficiency. The new ion source bucket chamber was developed by Japan Atomic Energy Agency (JAEA) in accordance with Korea–Japan fusion collaboration. The accelerator of the ion source was developed by KAERI [6]. 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 designs and specifications accomplished by KAERI, and followed by the construction of the first NBI system, called “NBI-1”, started from September 2009. This paper presents the overview of the KSTAR NBI-1 system, the results of the beam line commissioning, and the first beam experimental results. Also, the future plan is shortly presented.

## 2. Ion source

The ion source consists of a large bucket as a plasma generator [5] and a tetrode accelerator system for the beam extraction. All the elements that constitute the ion source are designed to cope with 300 s beam extraction, essentially steady-state operation. The bucket has a cross section of 0.25 m × 0.59 m, a depth of 0.32 m, and has a “magnetic multipole bucket” anode. The bucket chamber is made of oxygen-free high conductivity (OFHC) copper. Azimuthal arrays of Sm–Co permanent magnets spaced between cooling channels are lined up on the wall in the beam direction to create a cusp field around the inner wall of the chamber. Arrays of 12 thermionically emitting tungsten filaments (0.002 m diameter) are used as a cathode. Each filament is mounted on a water-cooled feed-through and these are individually connected to each filament power supply. To enhance the beam extraction efficiency, defined as the ratio of ion beam extraction current to the consumption of the arc discharge power by $I_b/P_{\rm arc} = I_b/(I_{\rm arc} \times V_{\rm arc})$, the JAEA bucket chamber was designed to produce the high arc discharge efficiency by the effect of electron confinement with good arrangement of the permanent magnets and filament cathode with their configuration. Where, $I_b$ is the beam extracted current, $I_{\rm arc}$ the arc discharge current, and $V_{\rm arc}$ is the arc discharge voltage in the ion source bucket chamber. Also, the ion source bucket chamber was electrically insulated from the plasma grid by 0.0036-m thick insulating material of the epoxy impregnated laminate called as G10.

The accelerator grid modules are flat plate made of OFHC copper with cooling channels between every row of the beam extraction holes. Each grid has total 568 straight cylindrical holes, the transparency of the grid array is 48% for a beam size of 0.115 m wide and 0.45 m high. There is no beam focusing function in the present grid structure. 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 are 4 mm between G1 and G2, 7 mm between G2 and G3, and 2.5 mm between G3 and G4, respectively. As mentioned in introduction, the accelerator grid modules are prototype developed by KAERI. Its beam optics was designed to have a beam perveance by maximum $K = 1.3$ micro-perveance for deuterium beam, where $K$ is defined as $I_b/V_{\rm acc}^{3/2}$ [μ-P] with beam acceleration voltage $V_{\rm acc}$. A schematic of the assembled ion source including four accelerating grids is shown in Fig. 1. The ion source bucket chamber was made and provided by JAEA in the framework of the KO–JA fusion collaboration. The bucket chamber was combined with KAERI accelerator, and was tested at the NBI test stand at KAERI for a long pulse plasma generation up to 200 s but with hydrogen beams.

## 3. Beam line system

The beam box (chamber) of the KSTAR NBI-1 system was designed with a very compact volume of 45 $m^3$ (3 m × 5 m × 3 m) to accommodate a total of three ion sources each with independent neutralizer cells and gas feeding. The beam line components accommodating one neutral beam from the first ion source were designed with original specifications of more than 2 MW neutral beam power for the KSTAR 2010 campaign. Fig. 2 shows the installation of the first neutral beam injection system (NBI-1) at the KSTAR tokamak. The magnetic field shielding room surrounding ion source is made of 0.005 m thick SS400 steel with a width of 3.5 m, height of 2.77 m, and length of 3.06 m. Permalloy, a nickel–iron magnetic alloy, will be added inside the steel with an air gap to meet the allowed future stray magnetic field limit less than 1 G. The limitation requirement of stray magnetic field was originated from TPX design which was referenced for the magnetic field shielding design for the KSTAR NBI system [7] in the ion source region. The above stray magnetic field limit will be assessed on the beam deflection by beam simulation code in future. The high voltage cables for the accelerating grid, gradient grid, and the cables for the filament and arc discharge penetrate the shield box through an insulating cylinder made of fiber-reinforced plastic (FRP) with the inner diameter of 0.22 m, the thickness of 0.02 m, and the length of 0.7 m.

Fig. 3 shows a horizontal cross section view of three tangential neutral beam lines of NBI-1 system from each ion source. The beam tangency radii are 1.48 m and 1.73 m for the first neutral beam (centered) and the second neutral beam (in outboard direction), respectively. The third beam line will be in the inboard direction with the beam tangency radius less than 1.3 m. The second and third beams will be spaced at a 4° angle from the first beam center line so as to have the crossing point of three neutral beams in horizontal plane at 10.2 m from the last exit grid.

Fig. 4 shows a vertical cross-sectional view showing the components of each beam line and cryo-pumping system. From the beam port entrance, the beam line components are a big gate valve with inner diameter of 1 m in the duct line between the chamber and the port entrance, a big circular formed bellows with inner diameter of 1.003 m, an electrical DC break with stand-off voltage of 5 kV, a movable calorimeter for the neutral beam dump, a large rectangular beam scraper, a bending magnet, ion dumps for