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Performance of 300 s-beam extraction in the KSTAR neutral beam injector

Doo-Hee Chang [a,*], Seung Ho Jeong [a], Tae-Seong Kim [a], Kwang Won Lee [a], Sang Ryul In [a], Young-Soon Bae [b], Jong-Su Kim [b], Hyun-Taek Park [b], Dong-Hyun Kim [b], Hyung-Lyeol Yang [b]

[a] Nuclear Fusion Engineering Technology Development Center, Korea Atomic Energy Research Institute (KAERI), Daejeon 305-353, Republic of Korea
[b] KSTAR Research Center, National Fusion Research Institute (NFRI), Daejeon 305-333, Republic of Korea

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ABSTRACT

The first neutral beam injector (NBI-1) has been developed for the Korea Superconducting Tokamak Advanced Research (KSTAR) tokamak. The first long pulse ion source (LPIS-1) has been installed in the NBI-1 for an auxiliary heating and current drive of KSTAR plasmas. The performance of 300 s ion beam extraction in the LPIS-1 was investigated on the KSTAR NBI-1 system, prior to the neutral beam injection for long pulse operation. The ion source consists of a magnetic bucket plasma generator with multi-pole cusp fields and a set of prototype tetrode accelerators with circular-type apertures. The inner volume of the plasma generator and accelerator column in the LPIS-1 is approximately 123 L. The nominal operation requirements for the ion source (IS) were a 100 kV/50 A deuterium beam and a 300 s pulse length. The extraction of ion beams was initiated by the formation of arc plasmas in the LPIS-1, called an arc-beam extraction method. A stable ion beam extraction of the LPIS-1 was achieved with 80 kV/27 A and a beam perveance of 1.19 microperv for a 300 s pulse length. Beam power deposition along the NBI-1 has been measured using water-flow calorimetry (WFC), and the sum of the deposited power on the ion source and beamline components was about 93% of the drained acceleration power ($V_{acc} \bullet I_{acc}$). The beam power deposition was compared to the calculated results of the beam transport with re-ionization (BTR) code.

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1. Introduction

A neutral beam injection (NBI) system is essential for next-generation fusion research devices, such as the International Thermonuclear Experimental Reactor (ITER), as an auxiliary heating and current drive because of the high performance required for long pulse or continuous steady-state burning-experiments [1,2]. The first NBI (NBI-1) system has been developed for the Korea Superconducting Tokamak Advanced Research (KSTAR) [3–5], as shown in Fig. 1. The first long pulse ion source (LPIS-1) was developed for the NBI-1 system, and the arc discharges of the ion source were characterized for the KSTAR NB injector [6]. The design requirements of the LPIS-1 for the KSTAR NBI-1 system were a 120 kV/65 A deuterium ion beam and a 300 s beam pulse length [7], and the nominal operation requirements for the ion source (IS) were a 100 kV/50 A deuterium beam and a 300 s pulse length. The beamline components of NBI-1 were developed initially for a total neutral beam power of 8 MW, originating from the deuterium ion beams and injected into the core plasmas of the KSTAR, with three LPISs in one beamline. The mission of the KSTAR NBI system aims at the injection of a deuterium beam power of more than 12 MW at a beam energy of 100 keV through two beam lines. According to the planned role of the NB injector, the NBI-1 system was operated for beam injection into the KSTAR tokamak plasma from the 2010 KSTAR campaign, including the system commissioning of each component and sub-system [8].

The first LPIS (LPIS-1) is composed of a plasma generator and a set of prototype tetrode accelerators. The plasma generator was developed by the Japan Atomic Energy Agency (JAEA) in Japan [9], and the prototype accelerator was developed by the Korea Atomic Energy Research Institute (KAERI) in Korea [10]. The LPIS-1 consists of a magnetic bucket plasma generator with multi-pole cusp fields, and a set of tetrode accelerators with copper circular apertures. The LPIS-1 has an overall beam extraction area of 11.5 × 45 cm^2 with linear water-cooling channels along the short dimension of every aperture array. The transparency of an accelerator column in the ion source is 48% with 568 apertures of 7.6 mm in diameter. The beamline components (BLCs) of the NBI-1 system include an optical multi-channel analyzer (OMA) duct (called a neutralizer-1, a front neutralizer), a neutralizer-2 (a second neutralizer), a bending

* Corresponding author. Tel.: +82 42 868 8673; fax: +82 42 864 1620.
E-mail address: doochang@kaeri.re.kr (D.-H. Chang).

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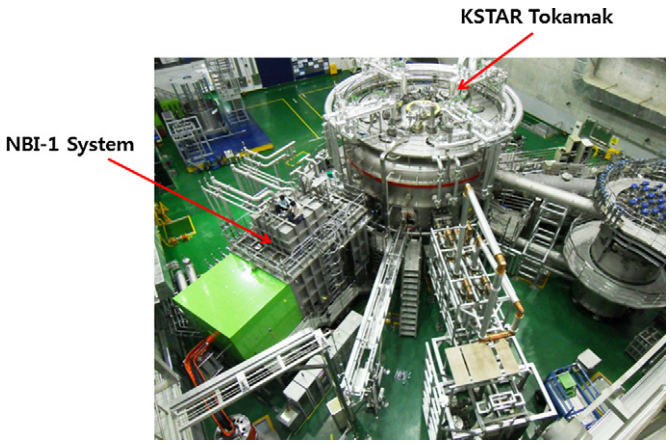

Fig. 1. NBI-1 system installed on the KSTAR tokamak.

magnet (BM), an ion dump (ID), a pre-calorimeter, a movable calorimeter, and a cryosorption pump system in a vacuum enclosure (a volume of $3 \times 3 \times 5$ m^3), as shown in Fig. 2. A beam duct was connected between the NB vacuum enclosure and the vacuum vessel of KSTAR. The BLCs of NBI-1 have been designed for the installation of three ion sources in one beamline. All data and parameters of the NB system were controlled by a control and data acquisition (CODAQ) system through an EPICS (Experimental Physics and Industrial Control System) based on an Ethernet interface.

The characteristics of long pulse beam extraction was investigated with a beam energy of 80 keV and a beam perveance of 1.19 microperv ($A \bullet V^{-3/2}$) for a 300 s pulse length prior to the beam extraction of 100 keV and 300 s pulse length. For this long pulse experiment, we may obtain the cooling capability of BLCs and LPIS-1 in the NBI-1 system. Beam power deposition along the NBI-1 system has been measured by using water-flow calorimetry (WFC), and the total extracted beam power ($V_{acc} \bullet I_{acc}$) was counted for the BLCs and LPIS-1 during the long pulse operation. Finally, the beam power deposition of long pulse beam extraction was compared to the calculated results of beam transmission using the beam transport with re-ionization (BTR) code.

2. Experimental setup

The LPIS-1 consists of a magnetic bucket plasma generator with multi-pole cusp fields and a set of prototype tetrode accelerators with circular copper apertures. A schematic drawing of the LPIS-1 for the discharge experiments and beam extractions is shown in Fig. 3. The plasma generator was developed by the Japan Atomic Energy Agency (JAEA), and the prototype accelerator was developed by the Korea Atomic Energy Research Institute (KAERI). The plasma generator has a cross section of 59×25 cm^2 and a depth of 32.5 cm, and the inner volume of the ion source, including the accelerator column with a cross section of 70.6×32 cm^2 and a depth of 33 cm, is approximately 123 L.

The arc discharge of the plasma generator was initiated with the help of the primary electrons emitted from the cathode consisting of 12 tungsten filaments, each of which has a wire diameter of 2 mm and a bent hairpin. The arc discharges of the LPIS-1 were controlled by using the space charge-limited mode, so the arc current does not depend upon the modest changes in the cathode temperature. In this mode, the arc discharge is controlled by an arc power or an arc voltage with sufficient primary electron emission. Arc plasmas up to an arc power of 70 kW were produced stably and efficiently at constant-power (CP, voltage of 57 V and current of 1044 A) operation of the arc power supply under a given heating voltage of the filament [6]. An arc power of 25 kW was applied to the plasma generator with a filament heating voltage of 11.9 V for the 300 s beam extraction. The accelerator grid modules were made of oxygen-free high-conductivity (OFHC) copper with cooling channels through every row of the beam extraction holes. The aperture diameters of the plasma grid (G1), gradient grid (G2), suppressor grid (G3), and exit grid (G4) were 7.6, 7.2, 6.8, and 7.2 mm, respectively. The gap distances were 4 mm between G1 and G2, 7 mm between G2 and G3, and 2.5 mm between G3 and G4. The number of holes of each grid was 568, and the transparency of the grid was approximately 48% with a beam size of 12×45 cm^2 [7]. Two separate cooling paths have been provided for each

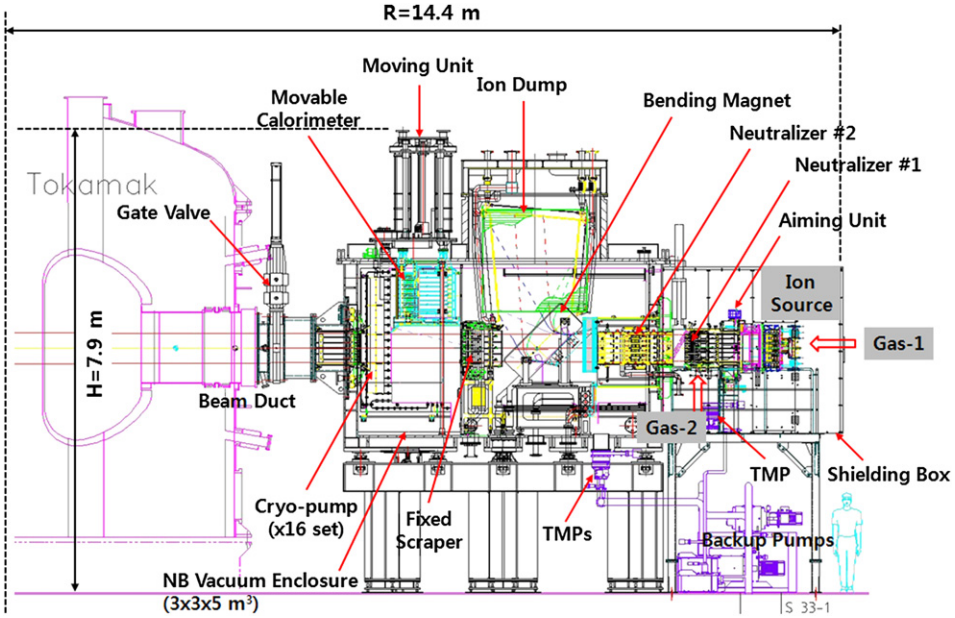

Fig. 2. Cross-sectional view of the NBI-1 system connected to the KSTAR torus.

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