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《Technical Note》

Development and Testing of a Prototype Long Pulse Ion Source for the KSTAR Neutral Beam System

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Abstract

A prototype long pulse ion source was developed, and the beam extraction experiments of the ion source were carried out at the Neutral Beam Test Stand (NBTS) of the Korea Superconducting Tokamak Advanced Research (KSTAR). The ion source consists of a magnetic bucket plasma generator, with multi-pole cusp fields, and a set of tetrode accelerators with circular apertures. Design requirements for the ion source were a 120 kV/65 A deuterium beam and a 300 s pulse length. Arc discharges of the plasma generator were controlled by using the emission-limited mode, in turn controlled by the applied heating voltage of the cathode filaments. Stable and efficient arc plasmas with a maximum arc power of 100 kW were produced using the constant power mode operation of an arc power supply. A maximum ion density of 8.3×10^{11} cm^{-3} was obtained by using electrostatic probes, and an optimum arc efficiency of 0.46 A/kW was estimated. The accelerating and decelerating voltages were applied repeatedly, using the re-triggering mode operation of the high voltage switches during a beam pulse, when beam disruptions occurred. The decelerating voltage was always applied prior to the accelerating voltage, to suppress effectively the back-streaming electrons produced at the time of an initial beam formation, by the pre-programmed fast-switch control system. A maximum beam power of 0.9 MW (i.e. 70 kV × 12.5 A) with hydrogen was measured for a pulse duration of 0.8 s. Optimum beam perveance, deduced from the ratio of the gradient grid current to the total beam current, was 0.7 μperv. Stable beams for a long pulse duration of 5~10 s were tested at low accelerating voltages.

Key Words : long pulse ion source, KSTAR neutral beam system, emission-limited mode, ion density, optimum arc efficiency, optimum beam perveance

1. Introduction

A neutral beam injection (NBI) system, to be used as an auxiliary plasma heating system for the Korea Superconducting Tokamak Advanced Research (KSTAR), is being developed, constructed, and tested at the Korea Atomic Energy Research Institute (KAERI) [1]. A prototype long pulse ion source (LPIS) has been developed for the NBI system [2], and the beam extraction experiments of the ion source were carried out at the Neutral Beam Test Stand (NBTS) of KSTAR. The design requirements for a prototype LPIS for the NBI system were a 120 kV/65 A deuterium ion beam and a 300 seconds beam pulse length, as well as an initial test ion beam of 90 kV/45 A for 20 seconds with hydrogen. The prototype beamline components have been developed for a neutral beam power of a total 8 MW, ultimately injected to heat the core plasmas of KSTAR, with three long pulse ion sources in a beamline.

The prototype LPIS for the KSTAR neutral beam (NB) system, which has been designed to include a new set of tetrode accelerators, was modified from the previous prototype ion source [2]. Plasma source was fabricated on the basis of the same design concept. To increase the extractible beam quantity, the transparency of the accelerator column was significantly increased, from 36 % with a diameter of 4.0 mm apertures to 48.8 % with 7.2 mm apertures.

Discharge characteristics of the prototype ion source were investigated for a discharge duration of 5 s. The discharges of the plasma generator were characterized prior to the beam extractions. To achieve the most efficient discharge conditions, the ion source had to be run at an emission-limited mode, during which the arc characteristics were controlled by the primary electron emission, that is basically the applied voltage to the cathode filaments.

Beam extraction experiments with the prototype ion source have been tried for a short pulse length of 2 s. Current unreliability of the accelerating high-voltage (HV) system has limited the accelerating voltage of these beam extraction experiments to 70 kV (beam current of 12.5 A). The optimum beam perveance for the prototype ion source has been investigated by observing the ratio of the gradient grid current to the total acceleration current, and the experimental perveance for up to 70 kV was ~0.7 μperv. This was smaller than the design value of 1.6 μperv. Stable long pulse beams of 5~10 s have been tested at low accelerating voltages of up to 23 kV (beam current of 4.4 A).

In this paper, we describe the prototype ion source, the discharge operation mode, and the beam extraction, using a modified accelerator for the ion source.

2. Arc Discharges in the Plasma Generator

The prototype ion source consists of a magnetic bucket plasma generator with multi-pole cusp fields, based on the US Common Long Pulse Ion Source (CLPIS) [3], and a set of tetrode accelerators with circular apertures. Dimension of the plasma generator is a cross section of 64×26 cm^2 and a 32 cm depth. The discharge of the plasma generator was initiated with primary electrons emitted from the cathode, consisting of 32 tungsten filaments, each of which has a wire diameter of 1 mm. Arc discharges of the plasma generator were controlled by using the emission-limited mode, controlled by the applied heating voltage of the cathode filaments. Arc plasmas with a maximum arc power of 100 kW were produced stably and efficiently by using a constant power (CP) mode operation of the arc power supply, under a given heating voltage of the filament, even

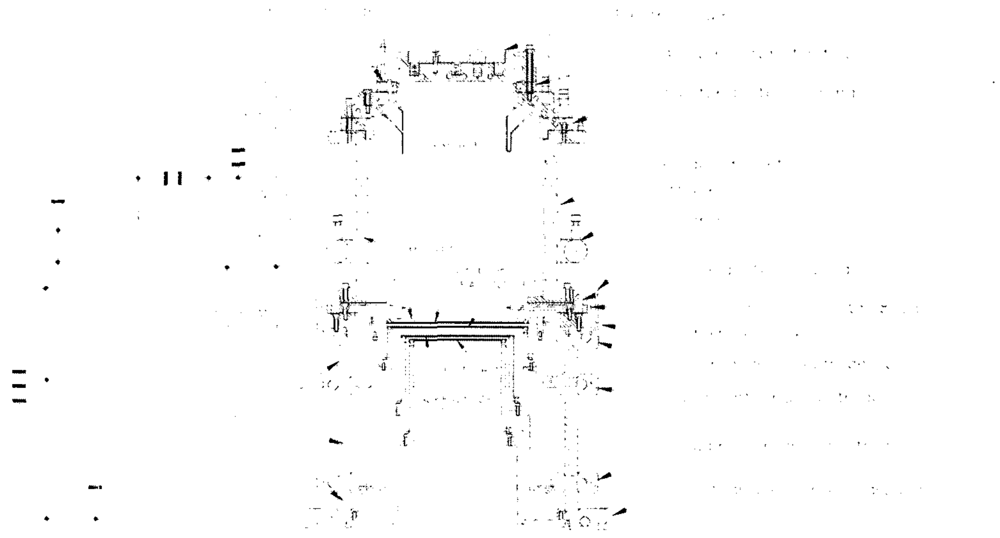

Fig. 1. Schematic Drawing of a Prototype Ion Source with the Power Supply Connections

though the discharge of the previous prototype ion source was controlled by using a constant voltage (CV) mode operation. A schematic drawing of the prototype ion source for the discharge and beam extraction experiments with the power connections is shown in Fig. 1. The maximum outputs of the discharge power supplies (filament and arc power supplies) were 15 V (dc), 3200 A CW and 160 V, 1200 A CW, respectively. Filament and arc power supplies are isolated electrically from the ground potential through an HV isolation transformer and located on the high voltage deck. To monitor the plasma density from the ion saturation currents via 8 resistors of 400 Ω, 8 electrostatic single probes (molybdenum-wire tip, with a diameter of 1 mm and a length of 3 mm) of an un-cooled type were installed at fixed positions around the probe plate (Fig. 1). These electrostatic single probes were biased to negative 40~50 V, relative to the cathode. To obtain a stable arc power of ≤100 kW, a filament voltage of 6.2~7.5 V was applied. An ion density non-uniformity of ≤10 % in the plasma generator was found by measurement of the ion saturation current.

The operating pressure for the discharge and beam extraction of the ion source was $\sim 8 \times 10^{-3}$ mbar, and the base pressure in the NBTS was $\sim 3 \times 10^{-7}$ mbar. The NBTS was pumped by using a cryo-pumping system of 80,000 *l*/s, which included a refrigerator connected to a liquid-nitrogen (LN_2) container. The pumping system was installed on the downstream side of the neutralizer duct. The prototype ion source and the beamline components in the NBTS were cooled actively with high-resistivity water (~1.2 MΩ · cm), with a maximum input pressure of 5 atm.

3. Beam Extractions from the Prototype LPIS

To date, the beam extraction experiments have been carried out using an accelerating voltage limited to 70 kV because of the unreliability of the accelerating HV power supply system. Arc plasmas have been supplied at an arc power of 50 kW (filament voltage of ≤7.2 V), and the decelerating voltages have ranged from -1.0 to -1.5 kV. The accelerator column of the prototype ion source employs 568 circular apertures; it has a diameter of 7.2 mm and a transparency of 48.8 %. It has an overall beam extraction area of 11.6×45.4 cm^2 with linear water-cooling channels along the short dimension of each aperture array. In the previous prototype ion source, the accelerator column had 1552 apertures over an area of 13×45 cm^2 [2]; it had a diameter of 4.2 mm and a transparency of 36 %. There are three grid gaps in the accelerator column: the gap between the plasma grid (the first grid) and the gradient grid (the second grid) was 4.5 mm; the gap between the gradient grid and the suppressor grid (the third grid) was 11 mm; and the gap between the suppressor grid and the exit grid (the forth grid) was 2.5 mm. The maximum output of the accelerating power supply was 120 kV, 70 A CW, and the decelerating power supply was rated for -5 kV, 25 A CW. The switching elements of the accelerating power supply were controlled by the series regulation of the power semiconductor devices. The plasma grid and the gradient grid voltage were divided from the accelerating voltage by using a resistor bank of 25 kΩ. A typical ratio of the gradient grid voltage to the total was 0.76 after optimally adjusting the ion optics. The accelerating and decelerating voltages were applied repeatedly during each beam pulse by using a re-triggering mode operation (up to 100-repetitions) of the HV switches, when beam disruptions occurred. The rising time of the accelerating voltage was typically ≤ 25 μs. For stable beam extractions, the decelerating voltage was always applied prior to the accelerating voltage (delay time ≤ 2 ms), in order to suppress effectively the back-streaming electrons produced at the time of an initial beam formation, by the pre-programmed fast-switch control system. For extractions of the beam for 2 s, the filaments were typically heated for ≤ 19 s, the arc discharges continued for ≤ 6 s, and the gas was introduced for ≤ 11 s. The beam was extracted in the latter half of the operating time sequence, because in general the arc discharge plasma has been more quiescent and stable in the latter half of the discharge duration. Stable long pulse beams for 5~10 s were tested at a low accelerating voltage of 23 kV. Before the beam extraction experiments, the facing surfaces of two or three adjacent grids were conditioned and fully cleaned with the plasma production by using the decelerating voltage with a current of 10 A (so called as the Decel Cleaning Mode). In this cleaning mode, there were two different connections for the decelerating power supply. A negative 1.0 kV of decelerating voltage was connected to the gradient grid or to the suppressor grid and the other three grids were connected to the ground potential, even though the accelerating voltage wires were detached from the ion source and the HV deck. It should be noted that the driving of a high current in the decelerating power supply could cause damage to the grid surfaces.

4. Results and Discussion

Discharge characteristics of the plasma source were studied without extracting the beams. In Fig. 2, both the arc power and the plasma ion density are plotted against the filament heating voltages. This is a typical control of the emission-limited mode discharge. The filament heating temperature alone, represented by the filament voltage, controls the level of the arc powers and ion densities. A filament voltage of 7.5 V leads to an arc power of 100 kW (with the arc current of 1200 A, which was the limit of the output current) and a maximum ion density of 8.3×10^{11} cm^{-3}. In general, the ion density of the plasma generator increases linearly with an increase of the discharge arc power. These effects are similar to those of

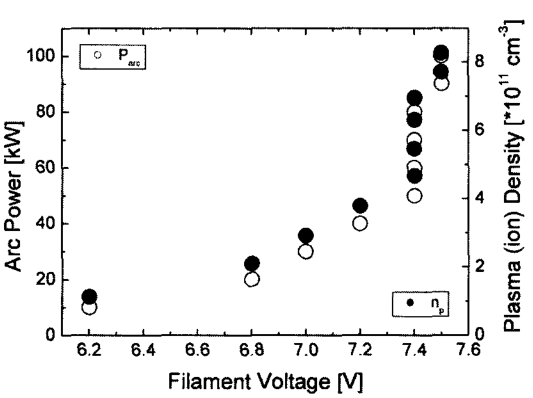

Fig. 2. Arc Power (P_{arc}) and Plasma Ion Density (n_p) Against the Applied Filament Heating Voltage for the Emission-Limited Mode Operation of the Arc Discharges

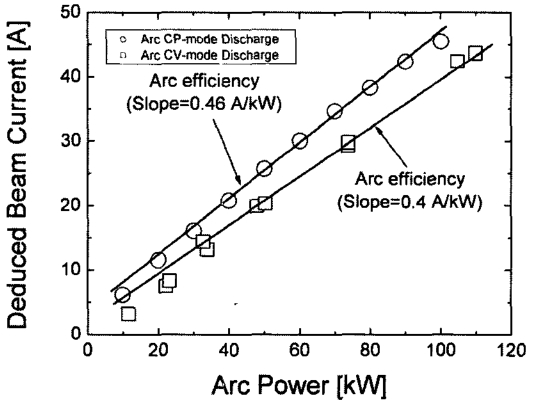

Fig. 3. Deduced Beam Current of the Ion Saturation Current, as a Function of the Discharge Arc Power, and Arc Efficiency for both the CP and the CV Mode Operations of the Arc Power

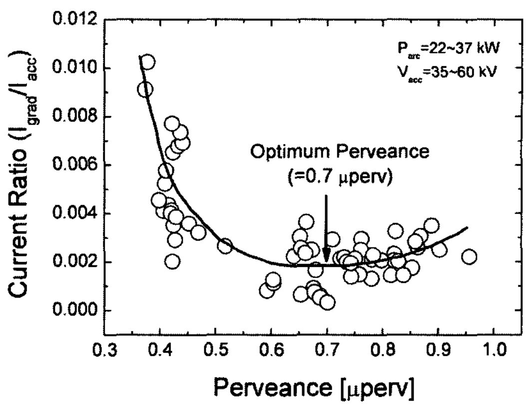

Fig. 4. Current Ratio of the Gradient Grid Current (I_{grad}) to the Total Beam (I_{acc}) for the Beam Perveance Scan (P_{arc} is the Arc Power, and V_{acc} is the Accelerating Voltage)

the CLPIS [4]. The maximum ion density obtained using the CP mode operation of the arc power with the prototype LPIS was similar to the CV mode operation of the previous prototype source; however, the arc power needed to reach the maximum ion density in the CP mode operation was approximately 10 % lower than that needed using the CV mode operation. Figure 3 shows the deduced beam current from the ion saturation current of the electrostatic single probes for both the CV and the CP mode operations of the arc power, as a function of the discharge arc power for the beam extraction area (48.8 % of 11.6× 45.4 cm^2). The arc efficiency, defined as the extractible ion current per kW of the arc power, is obtained from the slope of the linear fit of the data points. An optimum arc efficiency of 0.46 A/kW was estimated for the CP mode operation of the arc discharge, and this was more effective than the CV mode operation of the previous prototype source (0.4 A/kW). Thus, it can be concluded from the facts described above that the CP mode operation of the arc discharges was more effective than that of the CV mode operation. This arc efficiency implies that an arc power of 100 kW is sufficient to support the extraction of 45 A of hydrogen ions. Of course, the actual extraction current is ultimately governed by the beam perveance range for the tetrode accelerator column.

Figure 4 shows a perveance scan at 35~60 kV (beam current of 5.5 A~10.4 A), where the ratio of the gradient grid current (I_{grad}) to the total beam current (I_{acc}) is plotted against the perveance

(1 μperv≡10^{-6} ampere·volt$^{-3/2}$). Since the inverse of the ratio represents the quality of the beam, this method of investigation can lead to knowledge about the optimum perveance of the accelerator. Optimum beam perveance was 0.7 μperv accepted at the lowest point in the figure. A beam current of 20 A can be effectively extracted at an accelerating voltage of 90 kV, implying that this experimental result is less than half of the expected beam power of 90 kV/45 A hydrogen. Another practical method of testing this kind of investigation is to measure the beam power (with calorimetry) delivered to the beam target normalized to the accelerating power ($I_{acc} \cdot V_{acc}$), where V_{acc} is the accelerating voltage. A maximum beam power of 0.9 MW (70 kV/12.5 A/0.7 μperv) was measured for the beam duration of 0.8 s. Stable long pulse beams of 5~10 s were tested at a low accelerating voltage of 23 kV (beam current of 4.4 A/1.26 μperv).

5. Conclusions

Beam extraction experiments of a prototype LPIS were carried out for the NB system of the KSTAR tokamak. The magnetic bucket plasma generator, which was fabricated domestically, performed very well at an emission-limited mode discharge by using the control of the filament heating voltage. Stable and efficient arc plasmas with a maximum arc power of 100 kW were produced by using the CP mode operation of an arc power supply. An ion density as high as 8.3×10^{11} cm^{-3} was obtained, and an optimum arc efficiency of 0.46 A/kW was deduced from the measurement of the ion saturation current by using electrostatic single probes. The beam extraction experiments were limited to the accelerating voltage of ≤70 kV, and at these levels a discharge arc power of ≤50 kW (filament voltage of ≤7.2 V) was sufficient. It was found that fine control of the filament heating voltage, along with varying of the beam voltage, was indispensable for the beam extraction experiment. A maximum beam power of 0.9 MW, with calorimetry for a beam duration of 0.8 s, was successfully tested at the accelerating voltage of 70 kV. An optimum beam perveance of 0.7 μperv was deduced from the ratio of the gradient grid current to the total beam current. The experimental results of the beam extraction for the prototype LPIS obtained at an accelerating voltage of ≤70 kV did not meet our expectations. The next step of our research will involve testing the output range of the accelerating power supply up to 90 kV; the accelerator will be reassembled for a more precise structure, which will provide better voltage holding properties and a higher beam perveance (higher beam current), to reach the scheduled beam of 90 kV/45 A/1.67 μperv.

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