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Present Status of the Multi-megawatt Long Pulse Ion Source Development

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Abstract

A multi-megawatt long pulse ion source has been developed for the neutral beam injection (NBI) system of the Korea Superconducting Tokamak Advanced Research (KSTAR). The beam extraction experiments of the ion source were carried out in the neutral beam test stand (NBTS). 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 120 kV/65 A deuterium beam and 300 s pulse length, and initial test beam of 90 kV/45 A with hydrogen. Arc discharges of the plasma generator have been controlled by the emission-limited mode, controlled by the applied heating voltage of cathode filaments. Stable and efficient arc plasmas with a maximum arc power of 100 kW have been produced by constant power mode operation of arc power supply. A maximum ion density of 8.3×10^{11} cm^{-3} was obtained by using electrostatic probes. An optimum arc efficiency of 0.46 A/kW was estimated. The decelerating voltage has been always applied prior to the accelerating voltage by the pre-programmable fast-switch control system. The time sequence of applied voltages is to suppress effectively the back-streaming electrons produced at the time of initial beam formation. A maximum beam power of 0.9 MW with hydrogen has been measured for a pulse duration of 0.8 s. Optimum beam perveance, deduced from the ratio of gradient grid current to total beam current, was 0.7 μperv. The experimental results of beam extraction at the accelerating voltage of ≤70 kV appear to be less than the expected ones.

1. Introduction

A neutral beam injection (NBI) system in the Korea Superconducting Tokamak Advanced Research (KSTAR) is being developed, constructed, and tested for an auxiliary plasma heating system [1]. A multi-megawatt long pulse ion source (LPIS) has been developed for the NBI system. The beam extraction experiments of the ion source were carried out in the neutral beam test stand (NBTS) of the KSTAR. The design requirements for the multi-megawatt LPIS in the NBI system were 120 kV/65 A deuterium ion beam and 300 seconds beam pulse length. Initial test ion beams of the ion source were 90 kV/45 A for 20 seconds with hydrogen. The beamline components have been developed for a neutral beam power of total 8 MW, injected finally to heat the core plasmas of the KSTAR, with three long pulse ion sources in a beamline. The multi-megawatt LPIS for the KSTAR neutral beam (NB) system, which has been designed for including a new set of tetrode accelerators, was modified from the previous prototype long pulse ion source [2]. Nevertheless, the plasma source was fabricated on the basis of same design concept. To increase the extractible beam quantity, the transparency of accelerator column was increased noticeably from 36 % with a diameter of 4.0 mm apertures to 49 % with 7.2 mm apertures.

Discharge characteristics of the long pulse ion source were investigated for a discharge duration of 5 s. The discharges of plasma generator were in advance characterized prior to the beam extractions. To realize the most efficient discharge conditions, the ion source had to be run on an emission-limited mode. In this mode, 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 multi-megawatt ion source have been tried for a short pulse length of 2 s. Due to the deficient reliability of accelerating high-voltage (HV) system to date, the beam extraction experiments have been limited at the accelerating voltage up to 70 kV (beam current of 12.5 A). The optimum beam perveance for the ion source has been investigated by observing the ratio of the gradient grid current to the total acceleration current, and the experimental perveance up to the accelerating of 70 kV was approximately 0.7 μperv. It was smaller than the design value of 1.6 μperv (hydrogen beam of 90 kV/45 A). Stable long pulse beams of 5~10 s have been tested at low accelerating voltage up to 23 kV (beam current of 4.4 A).

2. Experimental Setup

A. Arc Plasma Discharge

The multi-megawatt long pulse 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 32 cm depth. The discharge of plasma generator was initiated with the help of primary electrons emitted from the cathode consisted of 32 tungsten filaments, which has the wire diameter of 1 mm. Arc discharges of the plasma generator have been controlled by the emission-limited mode, controlled by the applied heating voltage of cathode filaments. Arc plasmas with a maximum arc power of 100 kW have been produced stably and efficiently by constant power (CP) mode operation of arc power supply under a given heating voltage of filament. The arc discharge of previous prototype ion source has been controlled by constant voltage (CV) mode operation [2].

A conceptual drawing of the multi-megawatt ion source for discharge and beam extraction experiments with the power supply connections is shown in Fig. 1. The maximum outputs of 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 are located on the high voltage deck. To monitor the plasma ion 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 on the fixed positions around a probe plate (Fig. 1). They were biased negatively 40~50 V relative to the cathode. To obtain stably the arc power of ≤100 kW, the filament voltage of 6.2~7.5 V has been applied typically. The ion density non-uniformity of 10 % in the plasma generator has been found from the ion saturation current of electrostatic probes.

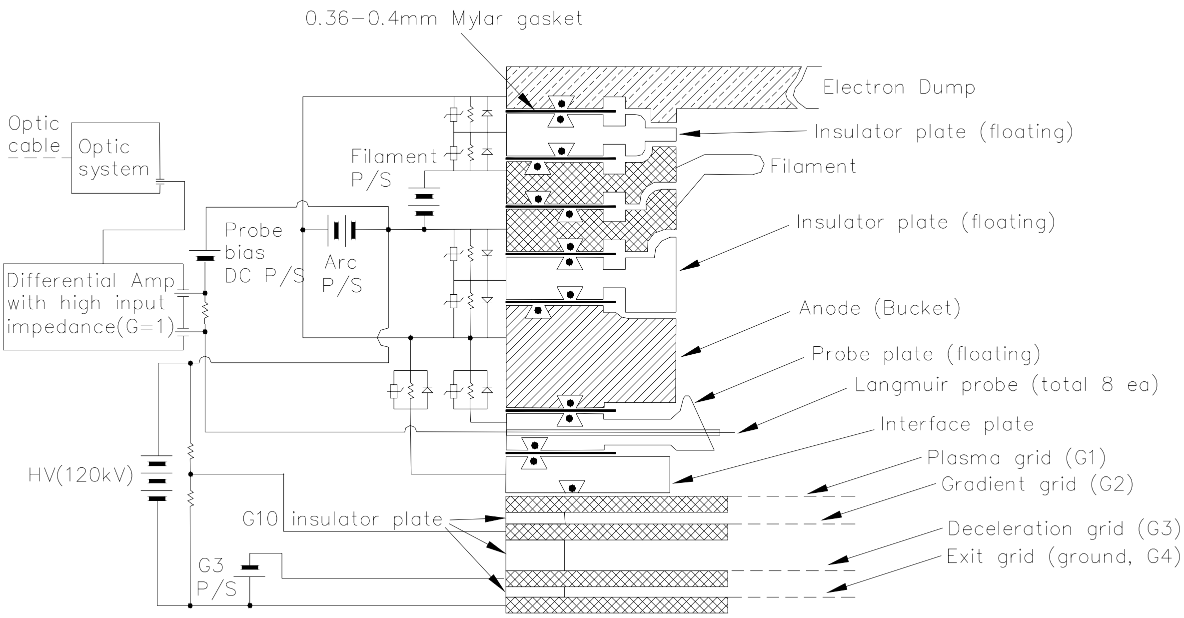

Fig. 1. Conceptual Drawing of a Multi-megawatt Long Pulse Ion Source with the Power Supply Connections

The operating pressure for the discharge and beam extraction of ion source was ~8×10^{-3} mbar, and the base pressure in the NBTS was ~3×10^{-7} mbar. The NBTS has been pumped by using a cryo-pumping system of 80,000 ℓ/s, including a refrigerator connected to a liquid-nitrogen (LN_2) container. The pumping system has been installed on the downstream side of neutralizer duct. The multi-megawatt ion source and the beamline components in the NBTS have been cooled actively by the high-resistivity water (~1.2 ㏁•cm) with a maximum input pressure of 5 atm.

B. Ion Beam Extraction

The beam extraction experiments have been carried out for the accelerating voltage up to 70 kV because of the deficient reliability of accelerating HV power supply system to date. Arc plasmas have been supplied at the arc power of 50 kW (filament voltage of ≤7.2 V), and decelerating voltages ranged from -1.0 to -1.5 kV. The accelerator column of the multi-megawatt ion source employs 586 circular apertures with a diameter of 7.2 mm and a transparency of 49 %. It has an overall beam extraction area of 11.6×45.4 cm^2 with the linear water-cooling channels along the short dimension of every aperture arrays. In the previous prototype ion source [2], the accelerator column had 1552 apertures over the area of 13×45 cm^2 with a diameter of 4.2 mm, a transparency of 36 %. Three types of the grid gap in an accelerator column, between the plasma grid (the first grid) and the gradient grid (the second grid), between the gradient grid and the suppressor grid (the third grid), and between the suppressor grid and the exit grid (the forth grid), were 4.5 mm, 11 mm, and 2.5 mm, respectively.

The maximum output of 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 accelerating power supply are controlled by the series regulation of power semiconductor devices. The plasma grid and the gradient grid voltages were divided from the accelerating voltage by a resistor bank of total 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 have been applied repeatedly during a beam pulse by re-triggering mode operation (up to 100-repetitions) of HV switches, when the beam disruptions have been occurred. The rising time of accelerating voltage was typically ≤25 μs. For stable beam extractions, the decelerating voltage has been 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 initial beam formation, by the pre-programmed fast-switch control system. For the extractions of beam for 2 s, typically the filaments have been heated for ≤19 s, the arc discharges continued for ≤6 s, and the gas introduced for ≤11 s. The beam has been extracted in the latter half of an operating time sequence, because in general the arc discharge plasma has been more quiescent and stable in the latter half of a discharge duration. Stably long pulse beams for 5~10 s have been tested up to the low accelerating voltage of 23 kV. Before the beam extraction experiments, the facing surface of two or three adjacent grids has been conditioned and cleaned fully with the plasma production by using the decelerating voltage with the current of 10 A (so called as the Decel Cleaning Mode). In this cleaning mode, there were two different connections of decelerating power supply. A negative 1.0 kV of the decelerating voltage was connected to the gradient grid or to the suppressor grid and other three grids connected to ground potential, even though the accelerating voltage wires have been detached from the ion source and the HV deck. The driving of high current in the decelerating power supply can cause the damage on the grid surfaces.

3. Analyses

A practical method of testing the optimum beam perveance is to measure the beam power (with calorimetry) delivered to the beam target normalized to the accelerating power (I_{acc}•V_{acc}), where the V_{acc} is the accelerating voltage, and I_{acc} is the beam current. Another direct way of this kind of investigation is to find the ratio of the gradient grid current (I_{grad}) to the total beam current (I_{acc}) against the perveance (1 μperv≡10^{-6} ampere•$volt^{-3/2}$). Since the inverse of the ratio represents the quality of the beam, this way of investigation can lead to the knowledge about an optimum perveance of the accelerator.

Even though the perfect beam focusing is considered for the case of any no loss of beam particles during the beam extraction processes, it can be assumed that the extraction current density is the same one as the ion saturation current density of the electrostatic probe. Thus, the extractible ion beam current can be predicted, easily and directly, by the measurement of ion saturation currents using the electrostatic probe without actual extraction of ion beam particles.

4. Results and Discussion

The discharge characteristics of the plasma generator have been studied without extracting beams. In Fig. 2, both the arc power (P_{arc}) and the plasma ion density (n_p) are plotted against the filament heating voltages. This is the typical control of emission-limited mode discharge.

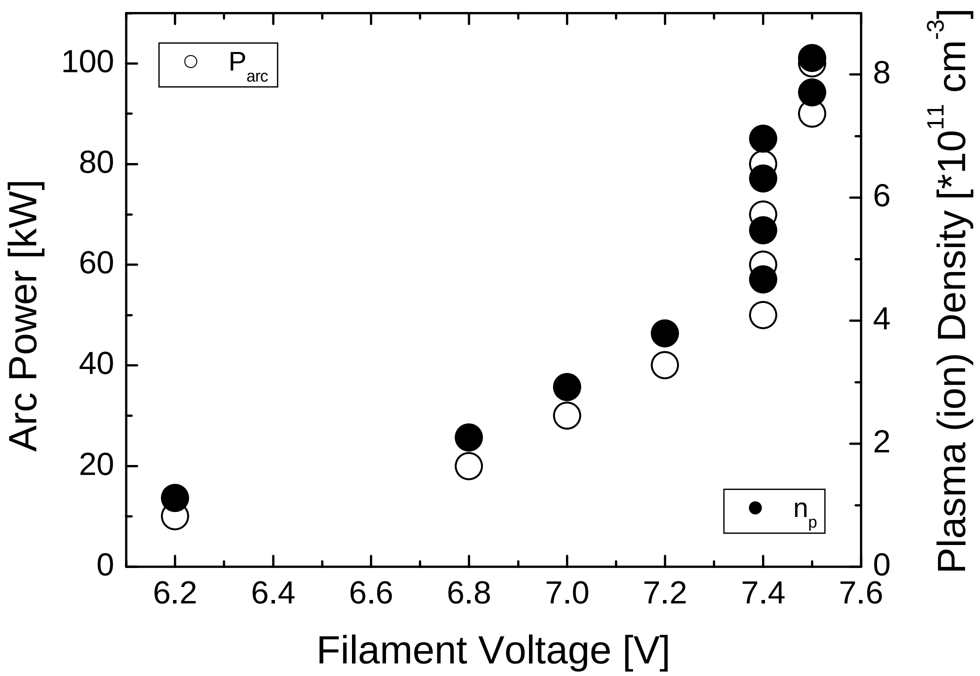

Fig. 2. Arc Power (P_{arc}) and Plasma Ion Density (n_p) against the Applied Filament Heating Voltages for the Emission-Limited Mode Operation of Arc Discharges

The filament heating temperature, represented by the filament voltage, alone controls the level of arc powers and ion densities. The filament voltage of 7.5 V leads to the arc power of 100 kW (with the arc current of 1200 A which was a limit of the output current) and a maximum ion density of 8.3×10^{11} cm^{-3}. In general, the ion density of plasma generator linearly increases with the increase of discharge arc power. These behaviors are similar to those of the US CLPIS [4]. The maximum ion density obtained by the CP mode operation of arc power in the LPIS was similar to the CV mode operation in the previous prototype ion source, but the arc power needed to reach the maximum ion density in the CP mode operation was less by approximately 10 % than the CV mode operation.

Figure 3 shows the deduced beam current from the ion saturation current of electrostatic single probes for the CP mode operation of arc power, as a function of the discharge arc power for the beam extraction area (49 % of 11.6×45.4 cm^2). The arc efficiency, defined as the extractible ion current per kW of arc power, is obtained from the slope of the linear fit of data points. The optimum arc efficiency of 0.46 A/kW was estimated for the CP mode operation of arc discharge, and this was more effective than the CV mode operation of previous prototype ion source (0.4 A/kW). Thus, it can be concluded from the facts described above that the CP mode operation of arc discharges was more effective than 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 actually extracted beam currents are ultimately governed by the beam perveance range for the tetrode accelerator column.

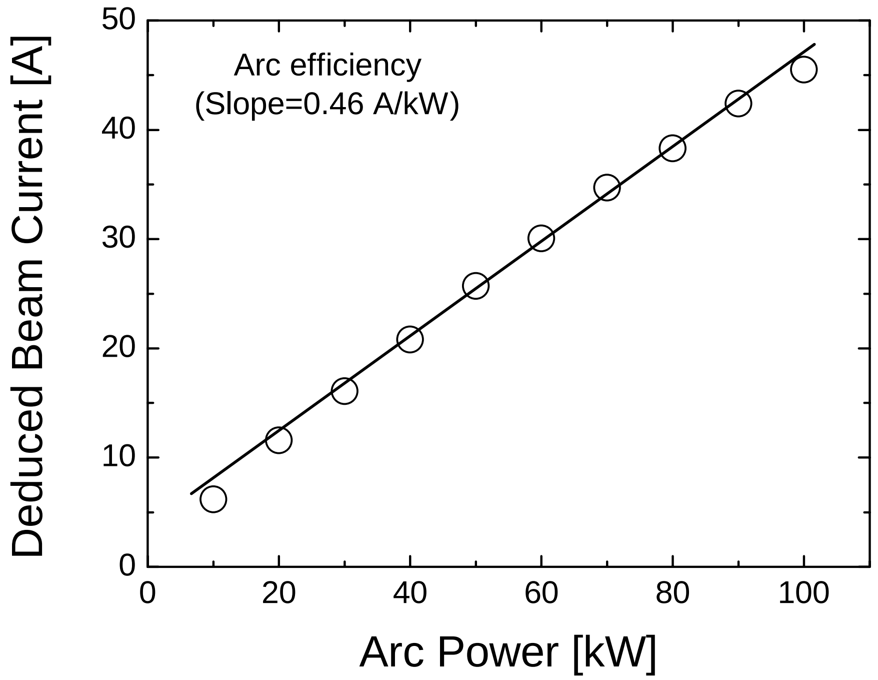

Fig. 3. Deduced Beam Current of the Ion Saturation Current, as a Function of the Discharge Arc Power, and Arc Efficiency for the CP Mode Operation of Arc Power

The relationship between the extracted beam currents and ion saturation currents (I_{is}) from the electrostatic probe has been defined for the LPIS by using a typical linear curve fitting methods, as shown in Fig. 4. Using this linear equation, the extractible beam currents can be predicted for the higher accelerating voltages prior to the actual beam extractions. The experimental equation was I_{acc} [A]=1.7 I_{is} [mA]21.2. This linear equation implies that the beam current of 29 A can be extracted from the maximum ion saturation current of 17.7 mA in the LPIS. The expected relationship between the beam current and the ion saturation current was I_{acc} [A]=2.58 I_{is} [mA] with the total beam area and the transparency, considering the probe surface area.

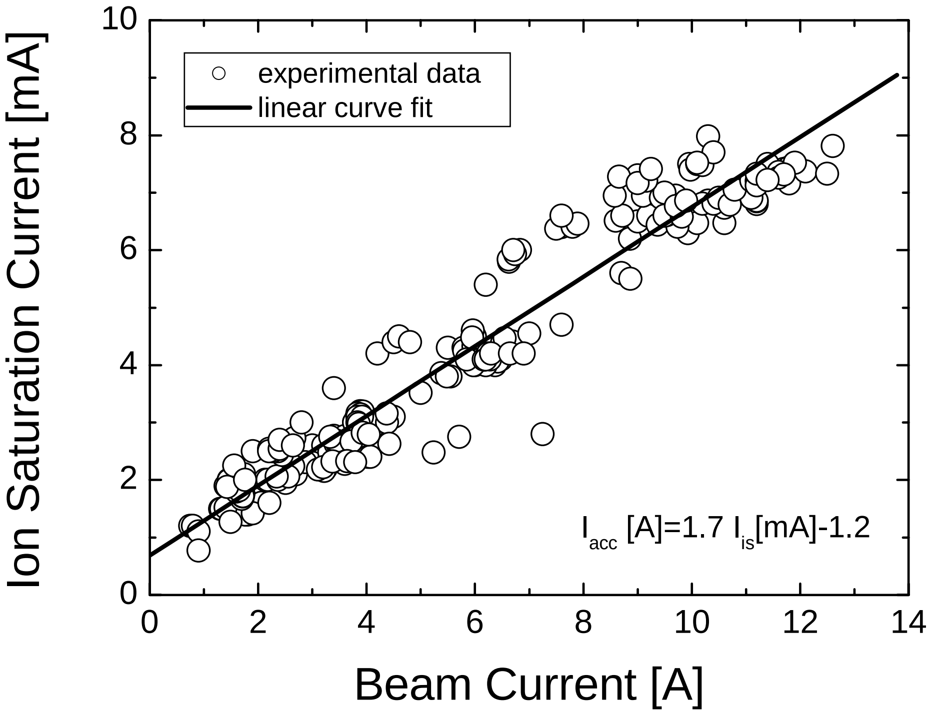

Fig. 4. A Fitted Curve of Ion Saturation Currents against the Extracted Beam Currents for the LPIS

Figure 5 shows a perveance scan at the accelerating voltage of 35~60 kV (beam current of 5.5 A~10.4 A) and the arc power of 22~37 kW, where the ratio of the gradient grid current (I_{grad}) to the total beam current (I_{acc}) is plotted against the perveance. An 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 the 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. A maximum beam power of 0.9 MW (70 kV/ 12.5 A/0.7 μperv) has been measured for beam duration of 0.8 s. Stable long pulse beams of 5~10 s have been tested up to a low accelerating voltage of 23 kV (beam current of 4.4 A/1.26 μperv).

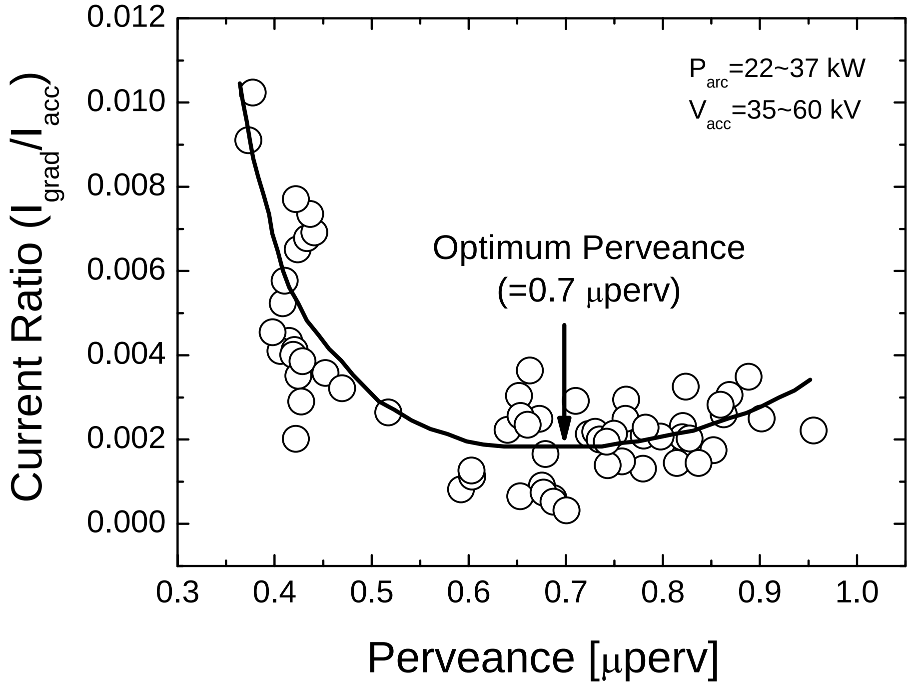

Fig. 5. Current Ratio of the Gradient Grid Current (I_{grad}) to the Total Beam (I_{acc}) for the Beam Perveance Scan (P_{arc} is the Arc Power, and V_{acc} is the Accelerating Voltage)

5. Conclusions

Beam extraction experiments of a multi-megawatt LPIS have been carried out for the NB system of the KSTAR. The magnetic bucket plasma generator fabricated domestically performed very well in an emission-limited mode discharge with the control of filament heating voltage. Stable and efficient arc plasmas with a maximum arc power of 100 kW have been produced by a CP mode operation of 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 ion saturation current by using electrostatic single probes. The relationship between the extracted beam currents and ion saturation currents from the electrostatic probe was I_{acc} [A]=1.7 I_{is} [mA]21.2 for the LPIS by using a typical linear curve fitting methods. Using this linear equation, the extractible beam currents can be predicted for the higher accelerating voltages prior to the actual beam extractions. The beam extraction experiments were limited to the accelerating voltage of ≤70 kV, and at these levels the discharge arc power of ≤50 kW (filament voltage of ≤7.2 V) was sufficient. It has been found that fine control of filament heating voltage was indispensable for the beam extraction experiment along with the varying beam voltage. A maximum beam power of 0.9 MW with calorimetry for beam duration of 0.8 s has been successfully tested at the accelerating voltage of 70 kV. Optimum beam perveance of 0.7 μperv has been deduced from the ratio of gradient grid current to total beam current. The experimental results of beam extraction in the prototype LPIS obtained at the accelerating voltage of ≤70 kV appear less than the expected ones. As a next step of R&D, the output range of accelerating power supply will be tested up to 90 kV, and the accelerator will be reassembled for more precise structure, which will provide better voltage holding properties and higher beam perveance (higher beam current), to reach the scheduled hydrogen beam of 90 kV/45 A/1.67 μperv.

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