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Beam Extractions of a Prototype Long Pulse Ion Source for the KSTAR NBI System

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Abstract

Preliminary beam extraction experiments of a prototype long pulse (300 s) ion source were carried out on the NBI Test Stand for the KSTAR. The prototype ion source consists of a magnet bucket plasma generator with multi-pole cusp fields, similar to the US LPIS, and a set of tetrode accelerator with circular apertures. Arc discharges of the plasma generator have been controlled precisely by both a space-charge-limited mode and an emission-limited mode. The emission-limited operation, well controlled by the applied heating voltage of cathode filaments, of plasma generator resulted in more efficient and stable discharges than the space-charge-limited mode. An optimum arc efficiency of 0.33 A/kW and maximum ion density of 8310^{11} cm^{-3} were obtained by using a Langmuir probe. Optimum beam perveance of the prototype ion source, which was deduced from the ratio of gradient grid current to the beam current, was 0.52. The preliminary beam extraction results obtained at ≤ 41 kV appear less than the expected.

1. Introduction

The neutral beam injection (NBI) heating system is being developed, constructed, and tested for the Korea Superconducting Tokamak Advanced Research (KSTAR) [1], at the Korea Atomic Energy Research Institute (KAERI). The KSTAR NBI ion source [2] is similar to the US Common Long Pulse Ion Source (CLPIS) [3] which had been developed originally in Lawrence Berkeley National Laboratory (LBNL) and has been used for the Tokamak Fusion Test Reactor (TFTR, USA) [4].

Because of the manufacturing difficulties and the high cost, it has been decided to duplicate the plasma generator portion used in the TFTR but re-design the accelerator column using circular apertures instead of slits in the US LPIS. It has been also decided that the fabrication and handling of molybdenum slit grids was very difficult processes in domestic industry. The prototype ion source has 568 apertures with a diameter of 7.2 mm and a transparency of 48.8%. The prototype source has an overall extraction area of 11.6345.4 cm^2, including the linear cooling channels along the shorter dimension on every rows.

The discharge of plasma generator was initiated with the help of primary electrons emitted from the cathode consisted of 32 tungsten filaments, arranged by parallel distribution on the upper side of generator. Discharge characteristics of the prototype ion source were investigated basically for the short pulse discharge of 500 ms, prior to the beam extraction experiments. For the most efficient discharge conditions, the prototype source has been run on an emission-limited mode, in which the arc discharge characteristics are controlled by the primary electron emission, that is the applied voltage to 32 filaments.

Preliminary beam extraction experiments of prototype ion source have been tried for short pulse length of 100 ms. Due to the poor voltage holding properties in the accelerator column, caused by arcing phenomena, during the beam extraction, the accelerating voltage has been limited up to 41 kV. The optimum beam perveance for the prototype source has been investigated by observing the ratio of gradient grid (the second accelerating electrode) current to the total beam current. The preliminary results obtained at ≤ 41 kV appear to be less than the required. A stable long pulse beam of 5 seconds has been extracted at a low accelerating voltage of 23 kV (beam current of 1.4 A).

2. Experimental Setup

Maximum output capabilities of discharge power supplies (filament and arc power supplies) were 15 V/3200 A and 160 V/1200 A, respectively. Filament and arc power supplies are isolated electrically from the ground potential through an high voltage isolation transformer, and located on an high voltage deck. The maximum output of accelerating power supply is 120 kV/70 A CW. The decelerating power supply can be operated up to 5 kV/ 25 A CW. A plasma grid (a first accelerating electrode) and a gradient grid (a second electrode) voltages are divided from the accelerating voltage by a resistor bank (total resistance of 25 kΩ). The typical ratio of the gradient grid voltage to the total accelerating voltage was 0.7.

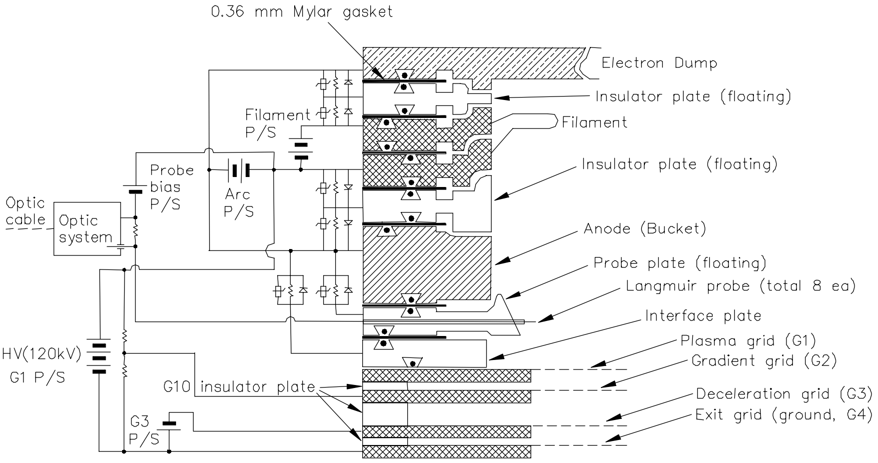

Fig. 1. Schematic drawing of power connections on the prototype LPIS for beam extractions

The schematic drawing of prototype ion source for discharge and beam extraction experiments is shown in Fig. 1 with the power line connections. Eight un-cooled and fixed Langmuir probes (molybdenum-wire tip, diameter of 1 mm, and length of 3 mm) were installed on a probe plate, near the plasma grid surface to determine the plasma (ion) density. Three types of passive protection devices (varistors, diodes, and resistors) were connected between all the adjacent electrodes. To monitor the plasma density fluctuations from the ion saturation current during a discharge, Langmuir probes were biased with a fixed –50 V relative to the filament cathode. Arc, filament, accelerating, and decelerating power supplies were controlled remotely with the self-protection functions for various operating conditions via optical transmission system of the control signals and monitoring outputs. To find the discharge characteristics by emission-limited mode, filament and arc powers were controlled by constant voltage (CV) mode operation for 15 s and 500 ms, respectively. But, in the beam extraction experiments, filament and arc powers were controlled by constant voltage (CV) mode and constant current (CC) mode operations for 8 s and 100 ms, respectively, because of the unstable outputs of arc power supply. The ion beams have been extracted from the start of arc plasma generation since the synchronous turn-on of accelerating and decelerating power supplies has been failed. The earlier turn-on of decelerating voltage than of accelerating voltage resulted in the open circuit of high-voltage fast switch, caused by the highest ramp-up of initial beam current, added by the back-stream electron current, in higher beam extraction voltage. For saving the filament lifetime, filament heating time for the beam extraction experiments was also reduced to half compared to the operations for finding the discharge characteristics. Before the beam extraction experiments, the facing surfaces of two or three adjacent grids have been conditioned and cleaned fully up to the holding voltage of 5 kV with plasma production by using the decelerating power supply (so called, Decel Cleaning Mode).

The NBI Test Stand [5] was pumped by using a system consisted of a TMP (pumping speed of 4200 ℓ/s) and a mechanical pump (pumping speed of 1500 ℓ/min). Hydrogen gas was injected by a pulsed puffing system, consisting of two feeding lines on the back plate (electron dump plate) of plasma generator through a storage reservoir (inner volume of 1 ℓ) and a mass flow controller. The base pressure and injected gas flow rate were $\sim 1.5310^{-6}$ torr and ~10 torr·ℓ/s, respectively. The prototype ion source was cooled by high-resistivity water at an input pressure of 5 atm. The output data obtained from the power supply, detecting device, and Langmuir probe were received by a personal computer (PC) through the VXI (VMEbus eXtensions for Instrumentation) digitizers (maximum sampling rate of 20 MS/s).

3. Analyses

The plasma ions should be on the magnetic field-free condition at a surface of plasma grid. But, in real experimental situations the magnetic field strength for the multi-pole cusp fields can be non-zero by the mis-alignment of permanent magnet outside the bucket chamber. The measured magnetic field on the surface of plasma grid was 1.0~3.5 gauss, with the background field of 0.4 gauss near the NBI Test Stand. The effect of magnetic field should be also considered for the analysis of Langmuir probe data. The gyro-radius of ion (ρ_i) and electron (ρ_e) in hydrogen plasmas with the magnetic field of ~5 gauss were about 45 cm and 1 cm, respectively. Thus, the probe can be considered as the case of weakly magnetized plasma ($\rho_i > \rho_e > r_p$), where r_p is the probe radius. In weakly magnetized plasma, the probe analysis is the same as the case of un-magnetized plasma [6].

The plasma (ion) density (n_p) can be obtained from the ion saturation current (I_{is}) by using the following equation for an un-magnetized plasma. A_s is the probe surface area including sheath thickness,

$$I_{is}=\exp(-1/2)n_p e\, A_s(T_e/m_i)^{1/2},$$

m_i is the ion mass, and the electron temperature (T_e) has been assumed as 5 eV for the calculations.

In general theory of ion beam extraction, the perveance, $P=I/V^{3/2}$, where I is the extracted ion current in ampere and V is the accelerating voltage in volt, controls the ion beam optics. Given the design parameter of 120 kV/ 65 A (for D^+ beams) of the US LPIS and the compensation for the transparency of total beam area difference between US LPIS (transparency of 0.6) and the prototype ion source and for the isotope mass in the beam current density by space-charge effect, the expected perveance of the prototype ion source for ordinary hydrogen beam would have been 1.83 μperv (1 μperv≡10^{-6} $A\cdot V^{-3/2}$). It can be assumed that the extraction current density would be the same as the ion saturation current density of Langmuir probes, supported by the theory of plasma-sheath for the plasma-beam transition regime [7]. Then, we can predict, easily and directly, the extractible ion beam current by measurement of ion saturation current using Langmuir probe without actual extraction of the ion beam particles.

4. Experimental Results

The discharge characteristics of prototype ion source have been investigated, in advance, without any beam extractions from the plasma generator. It has been found that the discharge

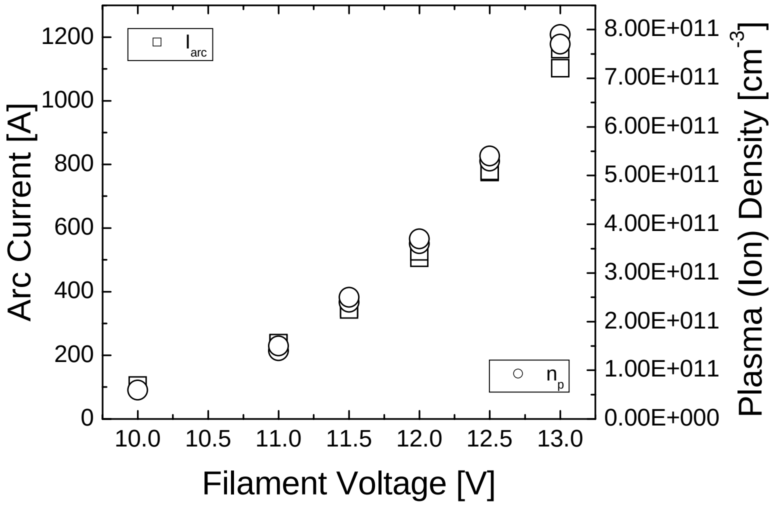

Fig.2. Arc current (I_{arc}) and plasma (ion) density (n_p) as an applied filament heating voltage

efficiency in terms of plasma density per arc power was more reliable for the emission-limited mode than the space-charge-limited mode. This operating mode was already reported and recommended by previous developers of the US LPIS [4]. Both the arc current (I_{arc}) and the plasma (ion) density (n_p) were plotted in Fig. 2 as a function of the filament heating voltage while the arc power was fully applied with the arc voltage kept constant at around 100 volts. This result is essential and typical for the emission-limited mode discharge property, namely, the filament temperature (emission rate of primary electrons represented by the filament supply voltage) controls efficiently the level of arc power and ion density in the discharges. A maximum ion density of 8310^{11} cm^{-3} was obtained with an arc current of 1200 A in the prototype ion source. It has been found that the arc efficiency was increased with the arc voltage, because the arc voltage represents the primary electron energy, and was decrease as the filling gas increases. Figure 3 shows the deduced beam current from the ion saturation current of a Langmuir probe, as a function of discharge arc power, estimated with total extraction area (48.8% of 11.6345.4 cm^2) of the prototype source. Optimum arc efficiency, defined as the extractible ion beam current per kW of arc power, was obtained from the slope of linear fit of the data points. The optimum value is about 0.33 A/kW, as shown in Fig. 3. This optimum value implies that an arc power of 136 kW is supplied to support the extraction of 45 A beam with hydrogen ions from the prototype ion source, even though the actual beam current extracted is ultimately governed by the beam perveance range for the tetrode accelerator column.

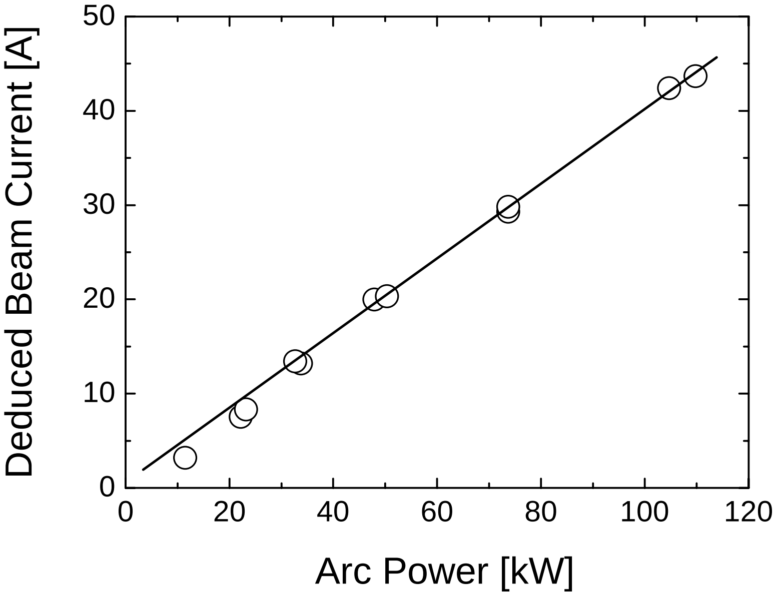

Fig. 3. Deduced beam current from the ion saturation current of a Langmuir probe, as a function of discharge arc powers

The preliminary beam extraction experiments have been carried out for a short pulse length of 100 ms and for the limited voltage of ≤ 41 kV, with the starting of beam extraction from the time of plasma generation (so called, Arc Beam Extraction Method). Although the “dry” voltage holding capability of accelerator column has been tested up to 60 kV, the column suffers from the voltage breakdowns in the presence of beam or from the opening of high-voltage fast switch, caused by the highest ramp-up of initial beam current, added by the back-stream electron current. In Fig. 4, a typical time evolution of the beam extraction results at an applied accelerating voltage of 41 kV and a ratio of 0.7 for the accelerating voltage to the gradient. During the beam extraction experiments, arc plasma was produced by the CC mode operation of arc power supply. The expected beam current with the perveance of 1.83 μperv and the experimental beam current are shown in Fig. 5, for the accelerating voltage. It has been assumed that the low beam current for the experiments to the expected was caused mainly by the mis-alignment of accelerating column and by the un-wanted beam species with higher particle mass, such as a water (H_2O^+), from the impurity plasma production induced by the wall-recycling processes of bucket generator wall. Figure 6 shows the perveance scan

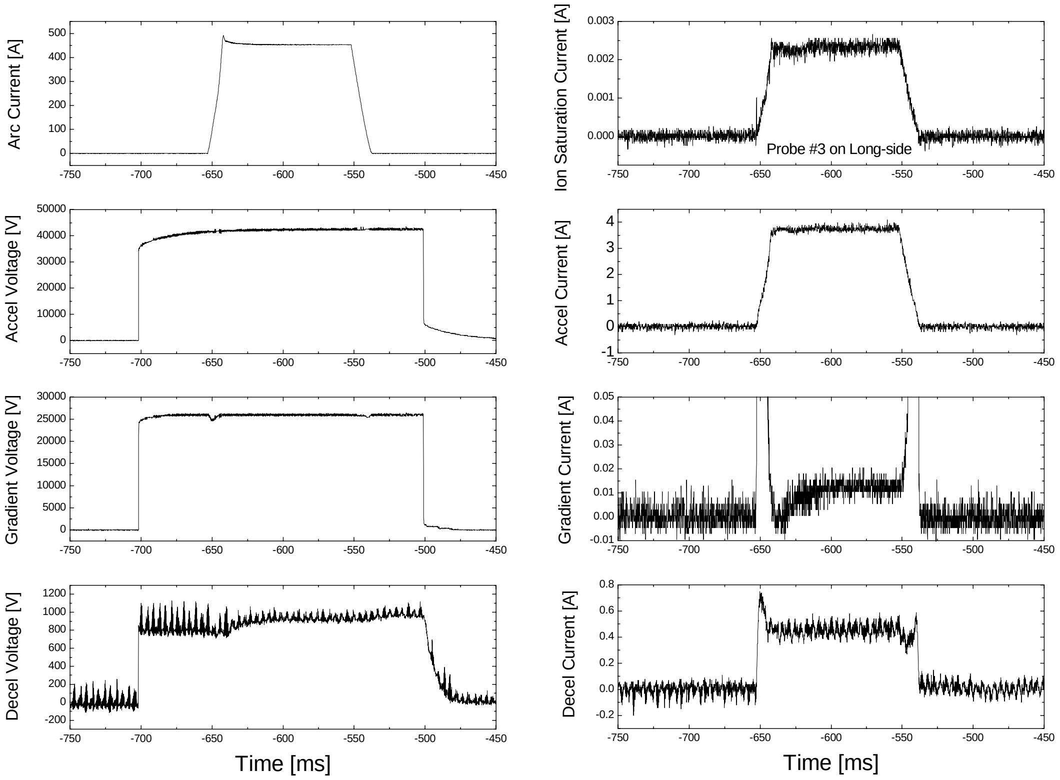

Fig. 4. Typical time evolution of the beam extraction results at an applied accelerating voltage of 41 kV and a ratio of 0.7 for the accelerating voltage to the gradient.

at ≤ 41 kV, where the ratio of gradient grid current (I_{grad}) to total beam current (I_{acc}) is plotted against the perveances. Since the inverse of the ratio represents the quality of beams, this way of investigation can lead to the information about an optimum perveance of the accelerator.

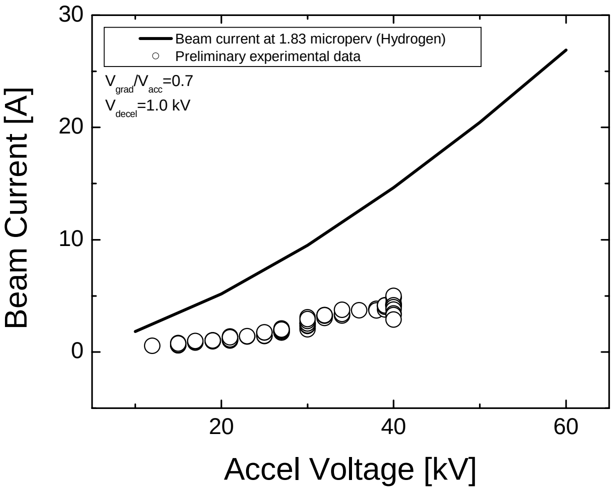

Fig. 5. Comparison of expected and extracted beam currents for the accelerating voltage

Another practical method to investigate the optimum perveance is to actually measure the beam power delivered to the target normalized to the accelerating power ($I_{acc} \cdot V_{acc}$). Optimum

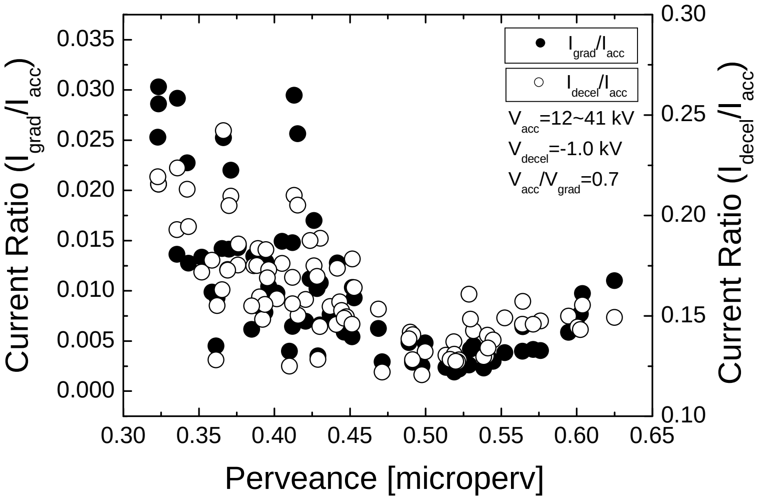

Fig. 6. A result of perveance scan for the prototype ion source

beam perveance of the prototype ion source, which was deduced from the ratio of gradient grid current to the beam current, was 0.52. This implies that the beam current 7.6 A can be extracted for the accelerating voltage of 60 kV (even though, 26.9 A with 1.83 μperv), using the present prototype ion source. The plotting of output results from the ratio of decelerating suppressor current (I_{decel}), measured by the negative voltage supply, to prevent the flow of back-stream electrons, to beam current were also similar to the deduced perveance curve in the figure. For this less perveance obtained than the expected, the beam current has been very low compared to the applied accelerating voltages, as shown in Fig. 5. To overcome this low perveance value, more careful designs, fabrications, installations, conditionings, and experiments of the prototype long pulse ion source should be needed, afterwards.

5. Discussion and Conclusions

Preliminary positive ion beam extraction of a prototype long pulse ion source (300 s) has been carried out on the Test Stand for the NBI heating system of KSTAR tokamak, at the KAERI. The effective discharges of plasma generator with multi-pole cusp magnetic bucket have been achieved by the emission-limited mode operation with the control of filament heating voltage. With the investigation for various discharge characteristics, the maximum ion density of 8310^{11} cm^{-3} was obtained, and optimum arc efficiency of 0.33 A/kW was deduced from the ion saturation current of a Langmuir probe. The beam extractions were limited to 41 kV of an accelerating voltage. It would be estimated that at this range of beam extraction the discharge arc power of 30~40 kW was sufficient. It was decided that the fine control of applied filament voltage was indispensable for the effective beam extraction experiments along the variation of accelerating beam voltages. The preliminary investigating result of optimum beam perveance of 0.52 μperv for the prototype LPIS seems to be less than the expected of 1.83 μperv. To overcome this low optimum beam perveance, more careful designs, fabrications, installations, conditionings, and experiments of the prototype long pulse ion source should be needed. In next step, It can be expected that the upgraded re-alignment of accelerating column and the careful conditioning of plasma generator would increase noticeably the optimum beam perveance and would improve the properties of extracted beams.

Acknowledgements

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