Journal of the Korean Nuclear Society
Volume 35, Number 3, pp.226 ~ 233, June, 2003

Discharge Characteristics of a KSTAR NBI Ion Source

Doo-Hee Chang and Byung-Hoon Oh
Korea Atomic Energy Research Institute
150 Deokjin-dong, Yuseong-gu, Daejeon 305-353, Korea
doochang@kaeri.re.kr

(Received December 5, 2002)

Abstract

The discharge characteristics of a prototype ion source was investigated, which was developed and upgraded for the NBI (Neutral Beam Injection) heating system of KSTAR (Korea Superconducting Tokamak Advanced Research). The ion source was designed for the arc discharge of magnetic bucket chamber with multi-pole cusp fields. The ion source was discharged by the emission-limited mode with the control of filament heating voltage. The maximum ion density was 4 times larger than the previous discharge controlled by a space-charge-limited mode with fully heated filament. The plasma (ion) density and arc current were proportional to the filament voltage, but the discharge efficiency was inversely proportional to the operating pressure of hydrogen gas. The maximum ion density and arc current were obtained with constant arc voltage (80 ~ 100 V), as 8×10^{11} cm^{-3} and 1200 A, respectively. The estimated maximum beam current was about 35 A, extracted by the accelerating voltage of 80 kV.

Key Words : prototype ion source, KSTAR NBI, filament voltage, ion density, arc current, beam current, accelerating voltage

1. Introduction

The neutral beam injection (NBI) system is essential in the next step fusion research devices, such as ITER, for an auxiliary heating and current drive, because long pulse or continuous steady-state burning experiments are proposed and planed. At low temperatures, ohmic heating in all tokamak devices is quite powerful and, in large tokamaks, easily produces temperatures of a few keV. However, as the temperature increases, the collision frequency and the resistivity fall. Thus, at the required temperature for ignition the ohmic heating is much reduced, leading to the requirement for additional heating, such as NBI system. The NBI auxiliary heating system is also being developed and constructed for the KSTAR (Korea Superconducting Tokamak Advanced Research) tokamak [1]. The prototype long pulse ion source (LPIS) [2], which was developed originally by the Lawrence Berkeley National Laboratory (LBL) and used for the TFTR (Tokamak Fusion Test Reactor, USA) [3-5], has been designed and is constructed and upgraded for the KSTAR tokamak. The KSTAR NBI system has required the final beam power of 120 keV, 65 A with deuterium beam, in addition to the initial test beam of 90 keV, 45 A with hydrogen beam, for 300 s.

The second prototype LPIS for KSTAR NBI system, which was designed for 4 accelerating grid electrodes, was modified from the first prototype [2]. To increase the operational selectivities, extraction grids were changed from Molybdenum slits to copper circular apertures [6]. The beam extraction area of accelerating grids was also increased to compensate the transparency, from 12×43 to 13×45 cm^2. The modified prototype LPIS was designed basically for the arc plasma discharge in magnetic bucket chamber with multi-pole cusp fields. The discharge of bucket chamber was initiated with the help of primary electrons emitted from 32 tungsten filaments, arranged on the upper side of bucket. Discharge characteristics of the modified prototype ion source were investigated for the short pulse discharge of 200 ms.

Before the beam extraction experiment, the discharge characteristics of ion source should be defined. The maximum ion density, maximum arc power, and optimum operating pressure were observed for various discharge conditions in the hydrogen plasma. The optimum discharge efficiency was obtained for the ion source, and the suitable operating conditions of discharge plasmas were estimated for the experiment of beam extractions. To confirm the maximum ion density, the discharge efficiency of prototype ion source was obtained by the control of arc power and of operating gas pressure. The ion source was discharged by an emission-limited mode [3] with the control of filament heating voltage and temperature. It was found that the maximum ion density was significantly larger than the result obtained in the previous discharge with the first slit-type ion source. The previous discharge was controlled basically by a space charge limited mode with fully heated filaments [2]. The plasma (ion) density and arc current were proportional to the filament voltage. Otherwise, the discharge efficiency was inversely proportional to the operating pressure of hydrogen gas and was proportional to the arc voltage of primarily fast electron energy. The extractible maximum beam current from the prototype ion source was estimated, which can be extracted by using the accelerating beam voltage. There was a noticeable result that the filament heating voltage, which can be explained as ion density control from the stable discharge plasma, should be operated finely for the control of beam extraction with the accelerating voltage. Finally, before the experiment of beam extraction, the operating range of beam voltage and current was proposed for the prototype ion source.

2. Experimental Setup

The modified prototype ion source was designed basically for the arc plasma generator of bucket type with magnetic cusp fields and tungsten filaments. The shape of beam extraction grids is circular apertures, and the grid material is copper hole plates. Thus, the cooling line and supporting structure of 4 accelerating grid stages are modified for the proper assembly of circular aperture grids. The beam extraction area of accelerating grids is 13×45 cm^2 with the transparency of 0.36. A cusp anode discharge chamber and discharge electrodes are not changed from the first slit-type ion source [2]. The discharge experiment was carried out with the final assembly of 4 accelerating grid electrodes and without water cooling of 4 grid stages, because of the short pulse discharge for 200 ms.

The discharge power supplies (filament and arc

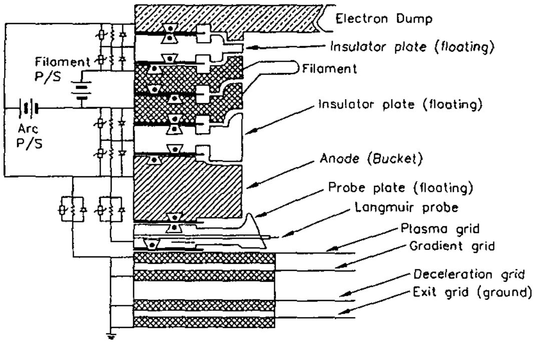

Fig. 1. Schematic Drawing of a Prototype Ion Source with the Power Connection

power supplies) were used the same as those used in the previous discharge experiment. The schematic drawing of prototype ion source for discharge experiment with the power connection is shown in Fig. 1. The maximum outputs of filament and arc power supplies were 15 V, 3200 A (DC/CW, 5500 A within 10 s) and 160 V, 1200 A (DC/CW), respectively. Filament and arc power supplies were isolated electrically to the ground potential through an isolation transformer. Eight un-cooled Langmuir probes (6 fixed probes and 2 movable probes) were installed on a probe plate, near the surface of plasma grid. The plasma (ion) density was measured by using one fixed probe (diameter of 1 mm and length of 3 mm, Molybdenum wire). Three types of passive devices (varistors, diodes, and resistors) were connected to the nearest electrode plates for the bloking of over-voltage, the fast dissipation of surface charge, and the slow absorption of surface charge, respectively. A probe plate was floated electrically to the ground potential, and the signal line from a Langmuir probe was connected directly to the input channel of isolation amplifier. To monitor the plasma density variation from the ion saturation current, the Langmuir probe were biased constantly with -50 V relative to the filament electrode during the discharge. A plasma grid under the probe plate was connected directly to the ground potential. The arc and filament power supplies were controlled remotely by a pre-programmed mode on the various operating conditions with optical transmission system of control signals. For the discharge operation of emission limited mode, filament and arc powers were controlled by constant voltage (CV) mode operation for about 15 s and 200 ms, respectively. The base pressure in the ion source was 4~8× 10^{-6} torr, and the hydrogen gas was injected, by using the pulsed puffing system, into two upper feeding lines on an electron dump through a storage reservoir (1ℓ, bottle type) and a mass flow controller (MFC). The storage bottle was connected near the electron dump for the stable gas injection, which restricted the initial gas starvation in the gas line during gas puffing pulse. The gas puffing system was also isolated electrically to the ground and was operated through an optical signal transmission system.

The ion source was cooled by a passive water-flowing system with constant input pressure of 4 atm and was pumped hydrogen gas by a turbo molecular pump (520ℓ/s) and a mechanical rotary pump (970ℓ/min). The ion saturation current from a Langmuir probe was transferred to the isolation amplifier through a typical electrostatic probe circuit, with a 50 Ω resistor. Output data from the discharge power supplies and a Langmuir probe were received and analyzed by a personal computer (PC) through the VXI (VMEbus eXtensions for Instrumentation) digitizers (maximum 20 MS/s).

3. Analyses

The extracted ions should be on the magnetic field-free condition at a plasma grid stage. But, in real experimental situation the magnetic field

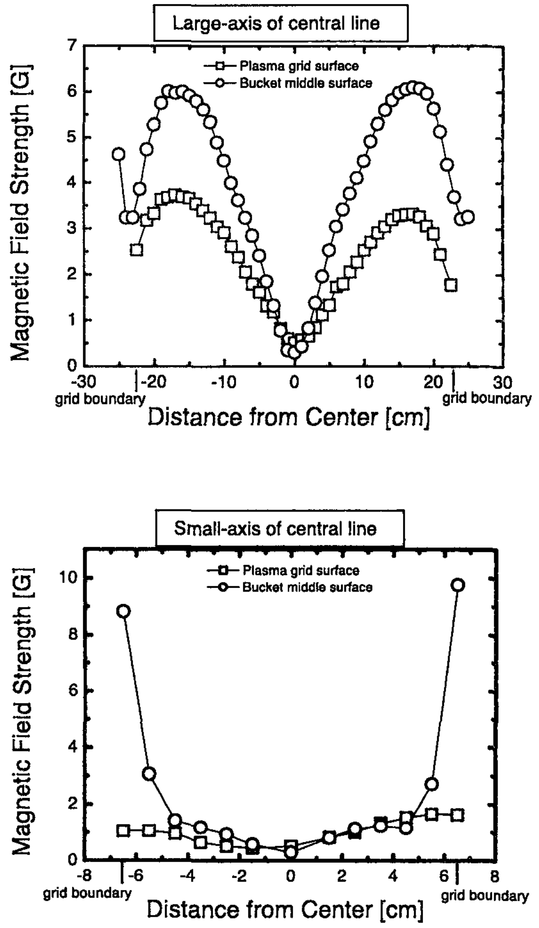

Fig. 2. Distribution of Magnetic Field Strength on the Large Axis (a) and Small axis (b) Positions of Central Line at the Middle of Inner Bucket and at the Surface of Plasma Grid

strength can be non-zero by the mis-alignment of permanent magnets outside the chamber bucket. The measured magnetic field is shown in Fig. 2, at the position of two central axes in the middle of inner bucket and in the surface of plasma grid. In these measurements, the background field was about 0.4 gauss in the laboratory. The magnetic field effects should be considered for the Langmuir probe analysis. The gyro-radius of ion (ρ_i) and electron (ρ_e) in hydrogen plasma with the field of 5 gauss were about 45 cm and 1 cm, respectively. So, 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 unmagnetized plasma [7]. The plasma density (n_p) can be obtained from the ion saturation current (I_{is}) by using the following equation for an unmagnetized plasma.

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

where, A_s is the probe surface area including sheath thickness, m_i is the ion mass, and the electron temperature (T_e) was estimated as 5 eV for this calculation.

In general theory of ion beam extraction, the perveance, $\sqrt{P=I/V^{3/2}}$, as an ion beam parameter, was originally used as a measurement of electrode capability and was a function of the electrode geometry [8]. I is the extractible/extracted beam current, and V is the accelerating voltage. Perveance of the prototype ion source was estimated as 9.5 μ perv, with an accelerating voltage of 36 kV, deduced for the deuterium beam extraction of 120 kV and 65 A. We assumed that almost all ions in the transient region, originated from the theory of plasma-sheath transient [9], flowed into the accelerating high voltage region in which there was the extracted ion beam flow. The ions in the transient region have passed the meniscus with the initial movement of ion sound velocity, $c_s = T_e / m_i$, where $Te = 5eV$. The meniscus was the boundary on that the accelerating electric field was zero between the transient region and the accelerating region. Thus, we estimated that the ion saturation current from a Langmuir probe was the same as the extractible

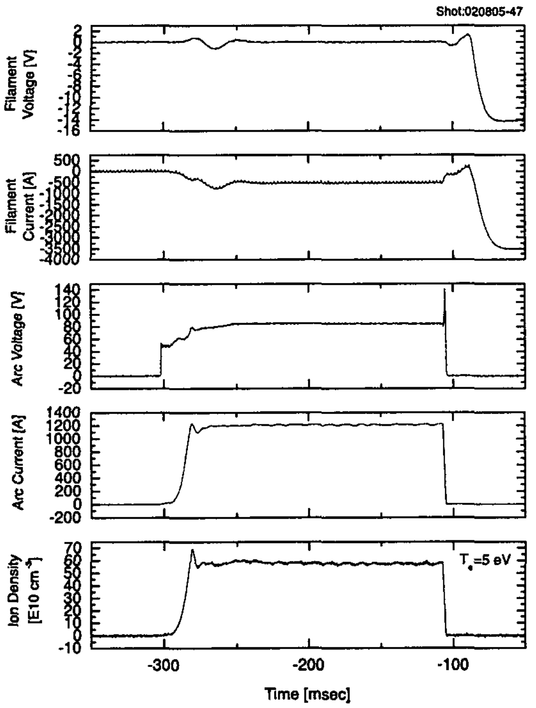

Fig. 3. An Example of Time Evolution for the Result of Discharge Experiment

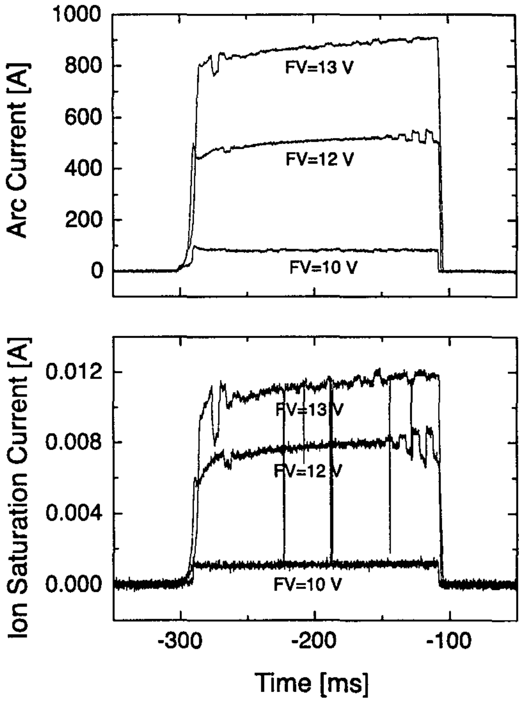

Fig. 4. Typical Discharge Characteristics of Emission Limited Mode

ion current. Therefore, the perveance matched beam current can be deduced with an estimated perveance value, for the extraction voltage.

4. Results and Discussion

An example of time evolution for the result of discharge experiment is shown in Fig. 3. For this discharge result, the filament power supply was operated by the constant voltage (CV) mode to maintain the stable filament heating temperature during the discharge period. The filament current was decreased during the discharge because of the increase of filament resistance and the power loading to filaments from the plasma. The arc power supply was operated by constant voltage (CV) mode, but its result was likely to be as the constant current mode since the arc current was initially over the maximum output current of power supply, 1200 A. Thus, the output of arc voltage was also less than initially setting value of 100 V. Figure 4 shows a typical discharge characteristic of emission limited mode. The arc current and ion saturation current were increased as the increase of filament heating temperature (filament voltage, FV). This result shows that the arc discharge can be controlled easily by the emission limited mode with filament heating temperature. The arc current (I_{arc}) and plasma (ion) density (n_p) are shown in Fig. 5, as a function of the filament heating voltage. The arc voltage and ion density were dramatically increased by the slight increase of filament voltage. The maximum ion density, 8×10^{11} cm^{-3}, with optimum arc

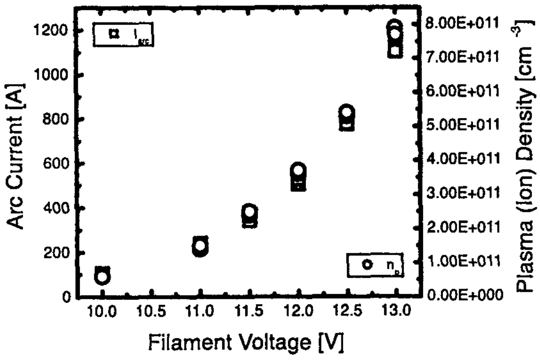

Fig. 5. Arc Current (I_{arc}) and Ion Density (n_p) as Filament Heating Voltage (FV)

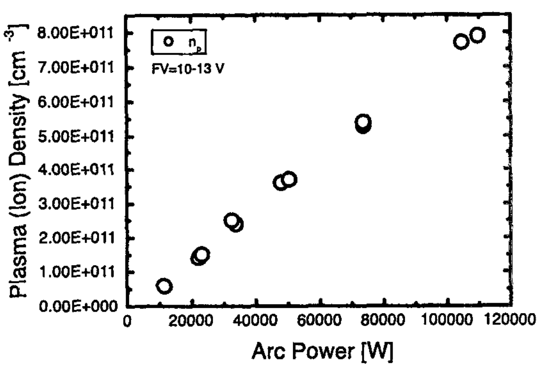

Fig. 6. Variation of Ion Density for the Discharge Arc Power

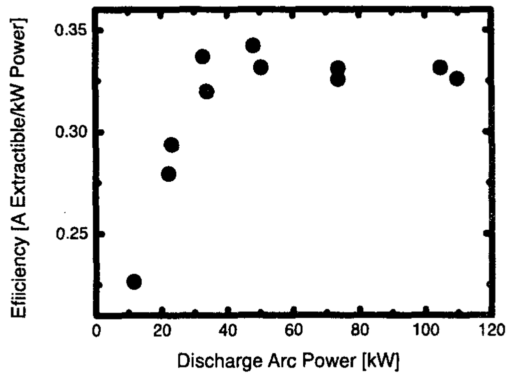

Fig. 7. Efficiency of Plasma Generator for the Beam Extraction as the Arc Power

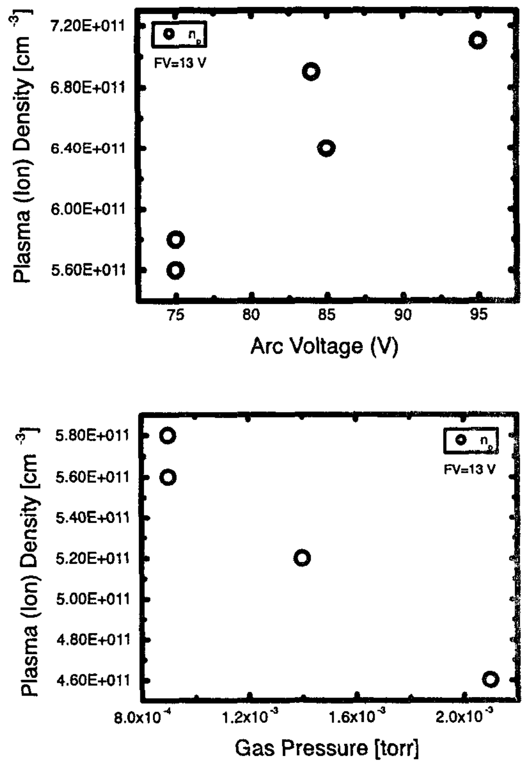

Fig. 8. Ion Density as the Discharge Arc Power and the Operating Gas Pressure

current, 1200A, was 4 times larger than that obtained in the previous discharge with the first prototype ion source. The previous discharge was controlled basically by a space charge limited mode with fully heated filament current. Figure 6 shows the variation of ion density for the discharge arc power, and the ion density was increased linearly as the increase of arc power. The discharge efficiency, estimated with the ratio of extractible beam current to arc power, is shown in Fig. 7. Optimum arc efficiency, 0.34 A/kW, of plasma generator for the beam extraction was obtained initially at 40~50 kW of discharge arc power. Figure 8 shows the ion density for the discharge arc voltage and the operating gas pressure, with filament voltage of 13 V. The plasma (ion) density, which can also be considered

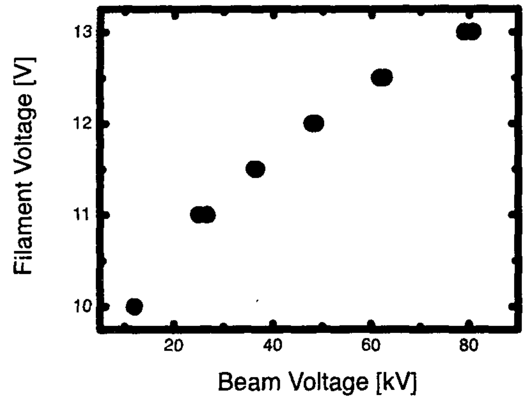

Fig. 9. Filament Voltage as the Accelerating Beam Voltage

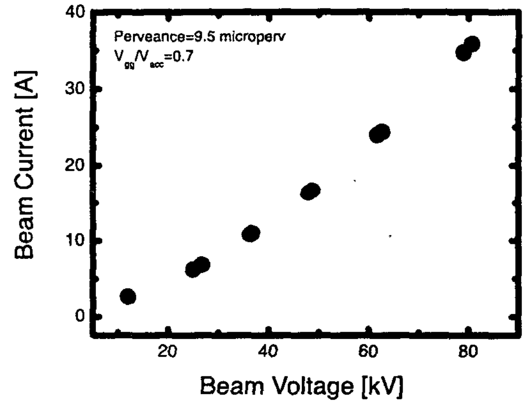

Fig. 10. Perveance Matched Extractible Beam Current for the Accelerating Beam Voltage

as the discharge efficiency, was inversely proportional to the operating pressure of hydrogen gas but proportional to the arc voltage of primarily fast electron energy. In the beam extraction experiment, the range of filament voltage (10~13 V) to control the discharge by emission limited mode was very small for obtaining the range of accelerating beam voltage, 10~80 kV, as shown in Fig. 9. This result shows that the fine control of filament heating voltage is indispensible for the experiment of beam extraction, as the increase of the beam voltage. Finally, the perveance matched extractible beam current, estimated with the ion saturation current and with deduced perveance, 9.5μ perv, is shown in Fig. 10, as a function of the accelerating voltage. The ratio of gradient grid voltage to the total beam voltage (V_{gg} / V_{acc}) was 0.7, where V_{gg} was the gradient grid voltage and V_{acc} was the total accelerating voltage. The maximum extractible beam current was about 35 A for the ion beam extraction from hydrogen plasmas with the beam voltage of 80 kV.

5. Conclusions

The discharge characteristics of a prototype ion source was investigated for the NBI heating system of KSTAR (Korea Superconducting Tokamak Advanced Research) tokamak. The prototype ion source was designed for the arc discharge of magnetic bucket chamber with multi-pole cusp fields. The ion source was discharged by the emission-limited mode with the control of filament heating voltage. It was found that the arc discharge was controlled easily by the emission limited mode with filament heating temperature. The maximum ion density of 8×10^{11} cm^{-3} with optimum arc current and constant arc voltage was 4 times larger than that obtained in the previous discharge with the first prototype ion source. The previous discharge was controlled basically by a space charge limited mode with fully heated filament current. The optimum arc efficiency, 0.34 A/kW, of plasma generator was obtained initially for the beam extraction of discharge arc power, 40~50 kW. The plasma (ion) density and arc current were proportional to the filament voltage, but the discharge efficiency was inversely proportional to the operating pressure of hydrogen gas. It was found that the range of filament voltage to control the discharge by emission limited mode was very small for the range of accelerating beam voltage, 10~80 kV. The fine control of filament heating voltage is indispensible for the experiment of beam extraction as the beam voltage changes. The perveance matched extractible beam current was estimated with the ion saturation current and deduced perveance, 9.5μ perv. The maximum beam current of 35 A, extracted from the beam voltage of 80 kV, was estimated for the hydrogen ion beam.

Acknowledgements

This work has been supported by the Project of KSTAR NBI System. The authors thank the staffs of Nuclear Fusion Research Laboratory in the Korea Atomic Energy Research Institute (KAERI), especially to Dr. Jin-Choon Kim for his co-experiment and discussion and to Mr. Chang-Seok Seo for his construction and assembly of ion source, for their comments and technical supports.

References

1. G. S. Lee and M. Kwon, "Status of the KSTAR Project and Fusion Research in Korea", 12th Int. Toki Conf. on Plasma Phys. and Controlled Nucl. Fusion, Dec. 11-14, Toki, Japan (2001).
2. B. H. Oh, K. R. Kim, and B. H. Choi, "Discharge characteristics of a long pulse ion source for the Korea Superconducting Tokamak Advanced Research neutral beam system", *Rev. Sci. Instrum.*, 71 (2), 1 (2000).
3. P. A. Pincosy, K. W. Ehlers, A. F. Lietzke, H. M. Owren, J. A. Paterson, R. V. Pyle, and M. C. Vella, "Developement of the plasma generator for a long pulse 10×40 neutral beam", *Rev. Sci. Instrum.*, 57 (11), 2705 (1986).
4. P. D. Weber, H. M. Owren, J. A. Paterson, P. A. Pincosy, R. V. Pyle, R. P. Wells, and M. C. Vella, "120-kV testing of a 10×40-cm prototype of the U.S. common long pulse neutral beam source", *Rev. Sci. Instrum.*, 57 (11), 2714 (1986).
5. M. C. Vella, W. S. Cooper, P. A. Pincosy, R. V. Pyle, P. D. Weber, and R. P. Wells, "Development testing of the U.S. common long pulse source at 120 kV" , *Rev. Sci. Instrum.*, 59 (11), 2357 (1988).
6. B. H. Oh and B. J. Yoon, "Design of an Asscelerator with Circular Aperture Grids for the KSTAR High-current Ion Source", *Sae Mulli (The Korean Physical Society)*, 42 (5), 237 (2001).
7. I. H. Hutchinson, Principles of Plasma Diagnostics, p. 50, Cambridge University Press, Reprinted in the USA (1990).
8. A. T. Forrester, Large Ion Beams, p. 99, John Willy & Sons Inc. Printed in the USA (1988).
9. I. G. Brown, The Physics and Technology of Ion Sources, p. 23, John Willy & Sons Inc. Printed in the USA (1989).