Optimum Perveance Study for Neutral Beam Ion Source

T. S. Kim [*], S. H. Jeong, D. H. Chang, K. W. Lee, and S. R. In

Korea Atomic Energy Research Institute, Daejeon, Korea
[*]Corresponding author: tskim@kaeri.re.kr

1. Introduction

A new ion source has been designed, fabricated, assembled, and being tested on the test stand at KAERI (Korea Atomic Energy Research Institute) site [1]. The goal is to supply a neutral deuterium beam of 100 kV, 2 MW for heating KSTAR (Korea Superconducting Tokamak Advanced Research) plasmas during 2012 KSTAR campaign. The new ion source is expected to have higher optimum perveance than that of prototype ion source installed at KSTRA NBI system during 2011 campaign.

The ion source consists of a magnetic bucket plasma generator and a set of tetrode accelerator (extraction system) with circular copper apertures. In the extraction system, the Child-Langmuir law states that there is a simple relationship between the accelerating current and the acceleration voltage:

$$I = PV^{3/2}$$

The proportional constant, P, called perveance, this expression is dependent beam current and beam energy. For each accelerator system, there is a perveance which corresponds to the maximum transmission efficiency of the beam power. Minimizing divergence is important in maximizing transmission efficiency. The optimum perveance is defined where the beam divergence is at a minimum and it depends on only the accelerator geometry including the aperture size, the thicknesses of grids and grid gap spacing.

In this presentation, the numerical simulation and experimental results for the optimum perveance are described and discussed at several different conditions.

2. Basic Theory

For a single-stage extraction system as shown in figure 1, it is known that the optimum perveance decrease to a fraction of that given by the Child-Langmuir relation:

$$P_{opt} = 0.6P_0$$

Where $P_0 = 1.72\times10^{-7}(r_1^2/d_1^2)A/V^{3/2}$ is the perveance for the plane diode, r_1 is the radius of aperture in the first grid, and d_1 the first gap width [2]. For hydrogen or deuterium beam the ion species mix are taken into account by assuming that the beam is composed of three single beam currents referring to the tree species. The shape and the position of the ion emission surface (meniscus) are always automatically adjusting so that the ion flow is simultaneously emission-limited by the plasma ion current density and the space-charge limited by extraction voltage. Extracted ion current mainly depends on plasma density rather than extraction voltage. Considering effective mass, and effective gap distance, therefore, the aperture optimum perveance for a single-stage accelerator can be modified expressed experientially as [3]

$$P_{opt} = 3.26\times10^{-8}\cdot\frac{S}{(d1 + D1 + r2')\cdot(m_{eff})^{1/2}}$$

where S is the net extraction area, d1 the first gap distance, D1 the thickness of the first grid, r2' is the optimal value of r2 that is about 80 % of the geometrical radius, m_{eff} is the effective mass. It is more complicated for a two-stage extraction system and a numerical simulation codes are mainly used to design the accelerator.

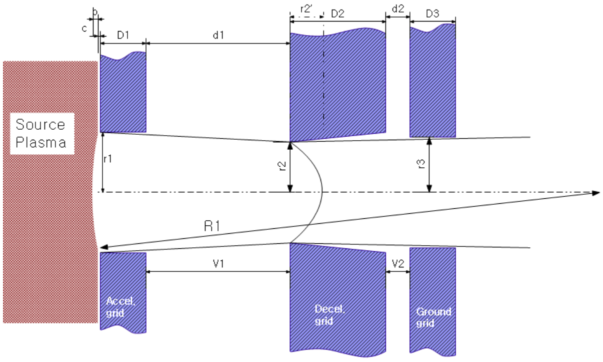

Fig. 1. Single-stage(three electrode) extraction system

3. Simulations and Experiments

The two-stage extraction accelerator has four electrodes: plasma (G1), gradient (G2), deceleration (G3), and ground (G4) grid. The first gap performs ion extraction and second gap performs ion acceleration. The optimum perveance of the accelerator can be determined by measuring beam divergence and beam transmission efficiency to the calorimeter. The divergence angle can be measured by viewing the light in the optical multi-channel analyzer (OMA, neutralizer-1) chamber in a direction transverse to the path of the beam [4]. The beam transmission efficiency to the calorimeter, which is at the 5.2 m from the exit of the ion source, can be calculated by water flow calorimetry (WFC).

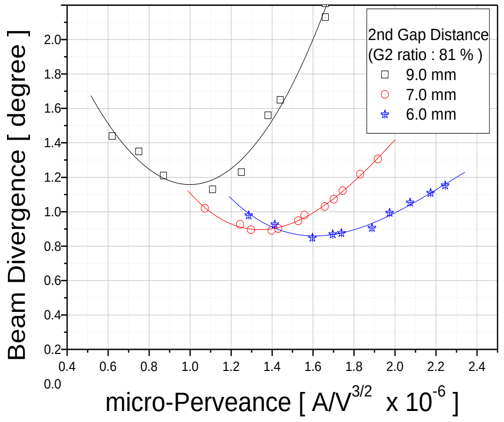

fig. 2. Hydrogen perveance scan of prototype ion source at 60 kV

The beam optics was varied from below optimum perveance(~0.6 uP) to an above optimum perveance (~3.0 uP). Beam pulses were fired into the calorimeter at each perveance setting. Each beam pulse was of ~3 s duration. The beam pulses were spaced at about 3 min intervals to allow the calorimeter cooling circuit to remove the energy deposited by the previous pulse. During the pulse, the Hα (for Hydrogen) light in the OMA chamber was recorded for beam species and vertical beam divergence characterization. Fig. 2 shows variation results of the beam divergence angle according to the beam perveance for three different gap distances of the prototype ion source [5]. Assuming single-stage accelerator for simplifying calculations, the equation introduced in previous section indicates that the optimum perveance are 1.12 up, 1.38 up, and 1.61 up for second gap width of 9.0 mm, 7.0 mm, and 6.0 mm, respectively. As effective gap distance decreases, the optimum perveance increase.

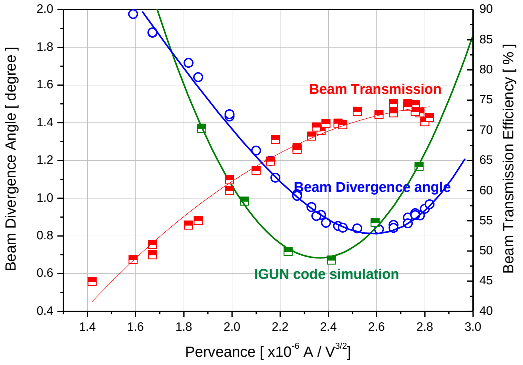

Fig. 3. Hydrogen beam transmission efficiency and divergence angle according to the beam perveance at 50 kV. Green line is numerical simulation results using IGUN code for a new ion source.

For an effective mass, base on the Child-Langmuir law scaling it would be expected that the difference in optimum perveance between helium and hydrogen would be between a factor of 2 ($\sqrt{4/1}$) and 1.15 ($\sqrt{4/3}$). From the experimental results as shown in Fig. 3 and fig. 4, the effective mass is about 1.7, in agreement with a weighting based on the measured ion fractions (55 % H^+, 15 % H_2^+, 30 % H_3^+) for a new ion source.

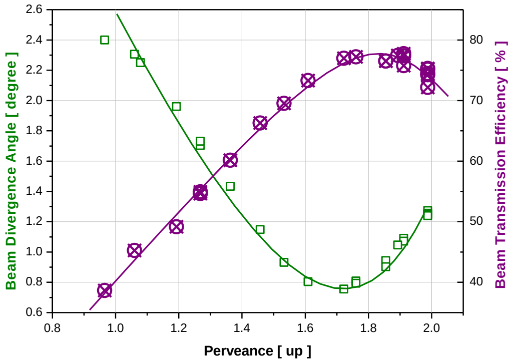

Fig. 4. Helium beam perveace scan at 50 kV for a new ion source

3. Conclusions

The optimum perveance for a effective mass and the effective gap distances are investigated and studied experimentally. The optimum perveance decreased by a factor of $(d_{eff})^2 = (d1 + D2 + r2')^2$ and $\sqrt{m_{eff}}$. Measured optimum perveances are good agreement with the simulation and analytical value. The experimental optimum perveance values of two-stage extraction accelerator can be also approximated by the optimum perveance equation for single-stage extraction system. The optimum perveance is influenced by the effective mass and measuring the accurate ion beam species fraction is also important.

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