Simulation Study on Duoplasmatron With Optimization of Ion Beam Extraction System

Sae-Hoon Park and Yu-Seok Kim

***Abstract*— The ion beam extraction system for various ion sources must be designed and evaluated using optimized parameters such as the gap distance between electrodes, applied voltage, and beam properties, using several different programs. SIMION, a 3-D simulation program, can transport various particles at once, and it is useful for simulating beam trajectories from the ion source and the beam line. PBGUNS can be used to calculate the effect of the gap between the plasma electrode and the extraction electrode on the ion beam properties. We propose combining the SIMION and PBGUNS results to compensate for problems in the calculation for the plasma. The calculation result from PBGUNS is utilized to perform ion beam extraction, which is close to the plasma model in SIMION, which can be used to easily simulate beam trajectories and model electrodes. We proposed a simulation method using SIMION to develop a model using plasma information from the PBGUNS result.**

***Index Terms*— Duoplasmatron, ion source, PBGUNS, SIMION.**

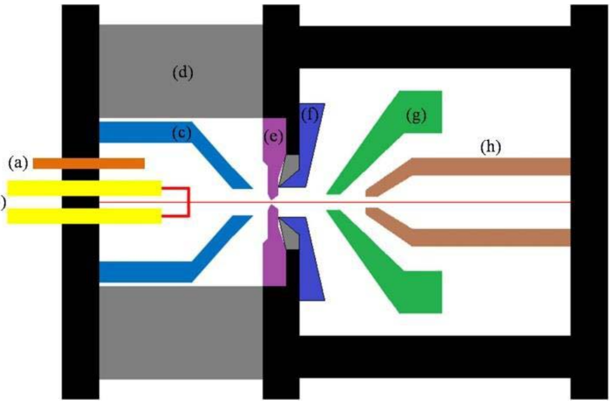

Fig. 1. Schematic of the simulated duoplasmatron ion source. (a) Gas inlet. (b) Filament. (c) Intermediate electrode. (d) Magnet. (e) Anode. (f) Expansion cup. (g) Extraction electrode. (h) Ground electrode.

I. INTRODUCTION

ION sources produce negatively or multiply charged ions, which are used in mass spectrometers, particle accelerators, and ion implanters [1]. The beam characteristics of an ion source determine the injection of ions into other parts of the accelerators and are selected to increase beam transmission and beam matching. Many ion sources are available with different discharge types, such as dc, arc, ac, radio-frequency driven, and laser-driven discharge [2].

The duoplasmatron is a gas ion source developed by von Ardenne. The device consists of two plasma regions: one between the cathode and the intermediate electrode, and the other between the intermediate electrode and the anode. The ion beam is extracted via the anode hole in the axial direction. An expansion cup at the extraction side of the anode reduces the ion beam density such that easier beam formation and transport are achieved [1], [3].

Ion beam extraction simulations can facilitate the design of an extraction system. In this paper, the simulation of duoplasmatron ion beam extraction is performed using two different types of simulators: Particle Beam GUN Simulations (PBGUNS) and SIMION. The purpose of the investigation is to evaluate the ion beam extraction system using the different characterizations from the two programs. PBGUNS is simulated on a rectangular array of squares using Poisson's equation in difference form at each point on the voltage arrays. SIMION solves for the potentials in the spaces between the electrodes, which are determined using the Laplace equation. In PBGUNS, current density from the cathode can be computed using Child's law (with Langmuir–Blodgett corrections for curved surfaces [4], [5]).

PBGUNS can simulate any type of 2-D, axially symmetric, relativistic, or nonrelativistic electron, ion, or beam. This simulator can automatically determine the plasma emission surface for positive or negative ion emissions. The program uses relaxation techniques to solve for the electric potentials on a large, rectangular array of squares, alternately computing potentials and trajectories [6]. SIMION is a simple 3-D electric field solver and particle tracer applied to the electrode structure. SIMION is used for the design and analysis of systems such as charged particle lenses, ion transport systems, mass spectrometers, detector optics, time-of-flight instruments, ion traps, and magnetic sectors [7].

II. SIMULATION METHOD

A schematic of the simulated duoplasmatron ion source is shown in Fig. 1. The ion is axially extracted from the plasma of the low-pressure arc between cathode and anode. To obtain an enhanced plasma density and a high ionization degree in front of the anode aperture, the discharge is concentrated by the

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TABLE I

DIMENSIONS OF DUOPLASMATRON ION SOURCE USED IN SIMULATION GEOMETRY

Anode aperture diameter	1 mm
Expansion cup aperture diameter	6 mm
Extraction electrode aperture diameter	8 mm
Extractor-expansion cup gap	8 mm to 12 mm
Extraction voltage	20 kV to 50 kV
Bias voltage	−5 kV

intermediate electrode and the effect of a strong axial magnetic field [8]. The plasma is concentrated by the double layer to be able to pass the intermediate electrode channel and reach the anode. The ion density in front of the anode is increased, and thus, the extracted ion current is increased. The maximum potential occurs between the intermediate electrode and the anode, thus accelerating ions toward the anode [1].

The simulation model has three electrodes: the plasma electrode, bias electrode, and ground electrode. The dimensions of the duoplasmatron ion source and the electrode voltages are shown in Table I.

Ion trajectories from the plasma surface were simulated at different extraction voltages and Bohm current densities for the duoplasmatron ion source structure; its plasma meniscus is used as SIMION input data. The influence of the extraction gap on the beam emittance and trajectories was investigated. The variable parameters in the simulation were the extraction voltage, extraction gap, and current density.

III. PBGUNS SIMULATION

PBGUNS is an interactive computer program used for Poisson simulation of most types of axially symmetric and 2-D electron, ion beam extraction, and transport systems [9].

The simulation process was carried out to determine the current density and evaluate the proton's energy and space-charge effect. The influence of the distance between the plasma electrode and the extraction electrode on the beam emittance was simulated for a concave plasma meniscus. The voltage of the plasma electrode was 20 to 50 kV and that applied to the extraction electrode was fixed at −5 kV for various initial current densities. We estimated the current density using both Child's law and the Bohm current density for the formation of the plasma meniscus, for which plasma meniscus data was extracted and applied as SIMION input data. The Child–Langmuir law is applicable in the space-charge-dominated region [10], [11]

$$j_c = \frac{4\varepsilon_0}{9}\sqrt{\frac{2Z_i e}{m_i}}\frac{V_0^{3/2}}{d^2} \qquad (1)$$

where Z_i is the charge state, m_i is the mass (kg) in a gap of width d(mm), and V_0 is the applied voltage (V). If the vacuum current limit exceeds the plasma source ($j_p < j_c$), the surface recedes to the left. The available ion current density is given by the Bohm expression [12]

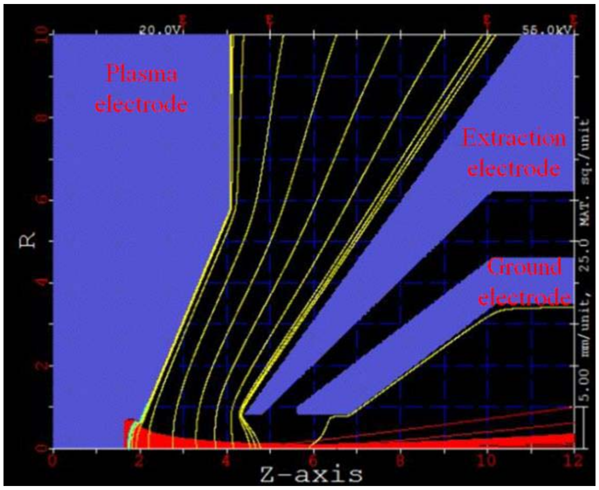

Fig. 2. Geometry of duoplasmatron ion source used in the PBGUNS simulator including the plasma, extraction, and ground electrodes; ion trajectories; and equipotential lines. This figure was created using PBGUNS with an applied voltage of 50 kV and a gap distance of 12 mm.

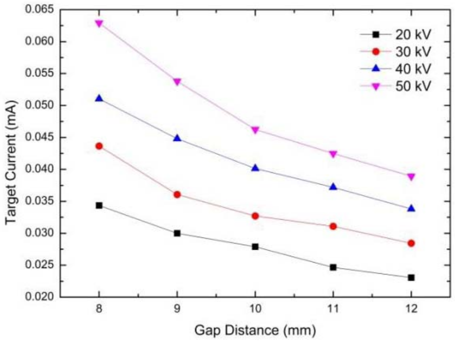

Fig. 3. Influence of the applied voltage on the target current for different gap distances.

$$j_p \cong 0.6eZ_i n_i\sqrt{kT_e}/m_i \qquad (2)$$

We estimated the Bohm current density in A/m^2 using (2) at a 10-eV electron temperature; this parameter was used to normalize the emission current densities based on the injected current density for a given particle density. The maximum current j_c which can be extracted from the source is provided theoretically by the Child–Langmuir equation. Having an ion beam extraction that is nearly parallel to the optical axis is a necessary condition for optimal transport [13]. The simulation result for ion source extraction is shown in Fig. 2. All simulations were conducted with the maximum beam current; the optimization of the mesh size was performed based on a smooth meniscus [14].

The influence of the target current on the applied voltage and gap distance is shown in Fig. 3. The target current decreases as the gap distance increases. The target current increases as the applied voltage increases. For all of the examined gap distances, beam spreading was observed at the exit plane, which means that the exit plane current density had a Gaussian distribution at low applied voltages.

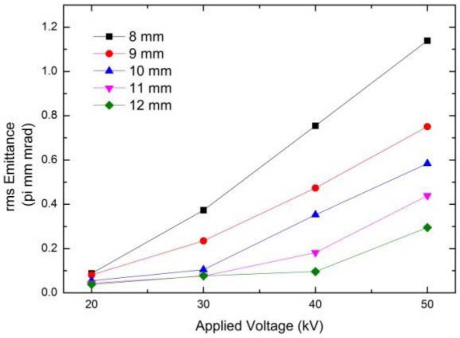

Fig. 4. Influence of the rms emittance for different gap distances and applied voltages.

In the case of the 8- and 9-mm gap distances, optimal transport was achieved when the ions exited the source in parallel trajectories at 20-kV applied voltage. For the 10- to 12-mm gap distances, optimal transport was observed when the ions departed from the source in parallel trajectories at applied voltages of 20 and 30 kV. The maximum value of the exit plane current density was high at 40 and 50 kV.

The influence of the beam current on the beam emittance was simulated for different gap distances, as shown in Fig. 4. The ion trajectories were fully transported into the extraction region without any beam loss for all cases, except that of the 8-mm gap and the 50-kV applied voltage. In all cases, the beam diverges at the end of the simulation with a negative α Twiss parameter.

The beam emittance and beamwidth were observed to decrease with increasing gap distance, as shown in Fig. 4. The ion trajectories determine the focal point, which advances to the plasma meniscus when the applied voltage increases. This phenomenon means that the beam emittance increases as a consequence of the increased beam divergence due to the ion trajectories. The target beam current and emittance in the 8-mm case are higher than in the other cases. This indicates that the ion density in the 8-mm case is also higher. For the same electrode structure, the optimum current density, which is calculated from the ion density using the Bohm expression, has an influence on the beam quality. As shown in Fig. 4, the beam quality can be improved when the initial current density is decreased, despite the decrease of the target current.

Each gap distance and applied voltage has an optimal beam extraction condition. Using this condition, the low beam current is able to compensate for the low beam divergence and beam emittance.

IV. SIMION Simulation

SIMION uses the potential array approach to estimate electrostatic fields created by user-defined electrode geometries [15]. SIMION version 8.1 was used to simulate the same geometry as that examined with PBGUNS simulator as shown in Fig. 5. We have simulated singly charged ion trajectories from a plasma meniscus with different gap distances and different applied voltages at the plasma electrode, for which plasma information (shape, position, and curvature) is obtained by PBGUNS results. With SIMION, the influence of the applied voltage on the beam emittance was investigated.

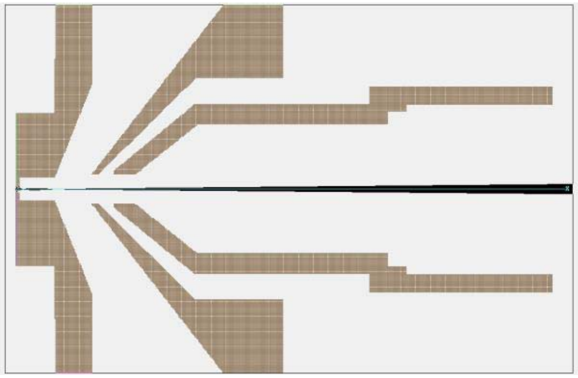

Fig. 5. Results of the SIMION simulation of the duoplasmatron extraction system for concave plasma meniscus shapes. See Fig. 1 for details of the electrode structure.

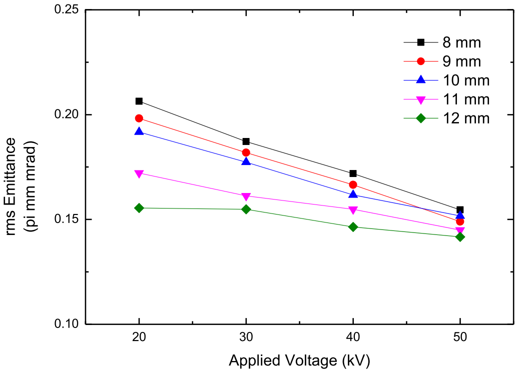

Fig. 6. Influence of the applied voltage on the rms emittance at different gap distances.

Simulation of the singly charged ion trajectories for concave plasma meniscus shapes from the PBGUNS data was studied while including the space charge effect. The plasma meniscus data was obtained from the shape, size, and position of PBGUNS fine matrix data and output data. SIMION supports charge repulsion when this condition is applied, which accounts for Coulomb's-law-like particle interaction to realistically simulate repulsion between all beam particles or beam lines. The plasma meniscus shape was determined from the PBGUNS results, which are different for all cases. The ions will be simulated with the space charge effect; the number of ions considered was 500.

The influence of the beam current on the beam emittance was simulated for different gap distances in PBGUNS; the distance between the plasma electrode and the extraction electrode was the same in SIMION. The geometry consisted of an anode, an expansion cup, an extraction electrode, and a ground electrode. The voltage applied to the plasma electrode varied from 20 to 50 kV and the extraction electrode voltage was fixed at −5 kV. The influence of the applied voltage on beam emittance and ion trajectories of the duoplasmatron ion source was studied. The ion beam trajectories were simulated with a concave plasma meniscus using PBGUNS at different voltages and gap distances. If the space charge effect is significantly increased, the values of each condition tend to be similar to each other. The emittance increases as the gap distance decreases and applied voltage decreases. The beam emittance was observed to decrease with increasing applied voltage [16], as shown in Fig. 6. This phenomenon can be explained using the equation in [17]. The ion beam trajectories passed through the electrode structure with no collisions.

V. CONCLUSION

The duoplasmatron ion source is made up of a cathode, an intermediate electrode, an anode, and an extraction electrode. The source consists of two plasma regions, namely, between the cathode and the intermediate electrode (with lower density plasma) and between the intermediate electrode and the extraction electrode (with higher density plasma). The system can extract positive, negative, or multiply charged ions based on adjustment of the magnetic field and intermediate electrode geometry. The examined parameters, i.e., the applied voltage, current density, and gap distance, were varied to study their effect on the ion source structure. The beam emittance was observed to decrease with increasing gap distance in the maximum beam current condition. Each gap distance and applied voltage has an optimal beam extraction condition. The ion trajectories exhibited a stable beam distribution and improved beam quality. SIMION and PBGUNS can both easily calculate the ion beam trajectories (for various trajectories) and evaluate the space charge effect. Unlike PBGUNS, SIMION cannot calculate the plasma condition. We expect that results from the SIMION with PBGUNS simulations compensate for problems in the calculation of the plasma state. The calculation result from PBGUNS is utilized to perform ion beam extraction, which is close to the plasma model of SIMION, which easily simulates beam trajectories and model electrodes. We have proposed a simulation method using SIMION to design the model based on the plasma information from the PBGUNS result. The calculation results without plasma information were unavailable, unlike the PBGUNS results.

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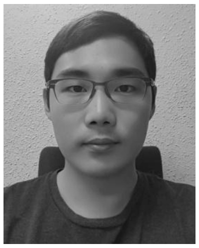

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