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ABSTRACT

A plasma sheath inside an ion source has a strong focusing effect on the formation of an ion beam from the plasma. Properties of the beam depend on the shape and location of the plasma sheath inside the source. The most accessible experimental data dependent on the plasma sheath are the beam phase space distribution. Variation of beam emittance is a reflection of the properties of the plasma sheath, with minimum emittance for the optimal shape of the plasma sheath. The location and shape of the plasma sheath are governed by complex physics and can be understood by simulations using plasma models in particle tracking codes like IBSimu. In the current study, a model of the D-Pace's TRIUMF licensed filament powered volume-cusp negative ion source is made using the IBSimu code. Beam emittance trends are compared between experiments and simulations.

INTRODUCTION

The electric field distribution in the vicinity of the ion source extraction is determined by the properties of the plasma, geometry of the electrodes around the plasma, and electric potential of the electrodes. Between the quasineutral plasma region and the extraction region, where mainly negative charges are present, a boundary layer known as the plasma sheath is formed. In this sheath, the separation of charges takes place due to the extraction field, and the beam is formed. The three dimensional shape of the sheath is determined by the interplay of the plasma charges, the charged particle beam formed, and the electric and magnetic fields in the extraction. The shape of the plasma sheath defines the extraction electric field shape locally and, therefore, affects its focusing properties in the region where the extracted beam still has a low velocity. Therefore, the sheath strongly affects the properties of the extracted beam.

The sheath can be modeled using approximate plasma models used in particle tracking codes, such as IBSimu,[1] which reproduce the plasma sheath by modeling both the extracted and nonextracted particle species. Qualitatively, the optical effect of the sheath is simple: with some operational parameters, the sheath possesses an optimal shape and location. By adjusting the plasma density, the shape of the sheath will become suboptimal. If the plasma density decreases, the plasma sheath will become concave, focusing the beam too much, and if the plasma density increases, the sheath becomes more convex, providing too little focusing to the extracted beam.

Emittance of a beam depends on the focusing at the plasma sheath. At the optimal shape of the sheath, the produced beam emittance has a minimum value. As the plasma sheath shape becomes suboptimal, beam emittance increases. Effects of beam focusing by magnetic and electric fields and the space charge forces are well-known and can be modeled accurately with existing tools. On the other hand, there is clearly a need for improvement of the plasma models used in these simulations. For example, significant deviations in the beam emittance behavior between IBSimu simulations and experiments have been observed.[2] One of the possible reasons

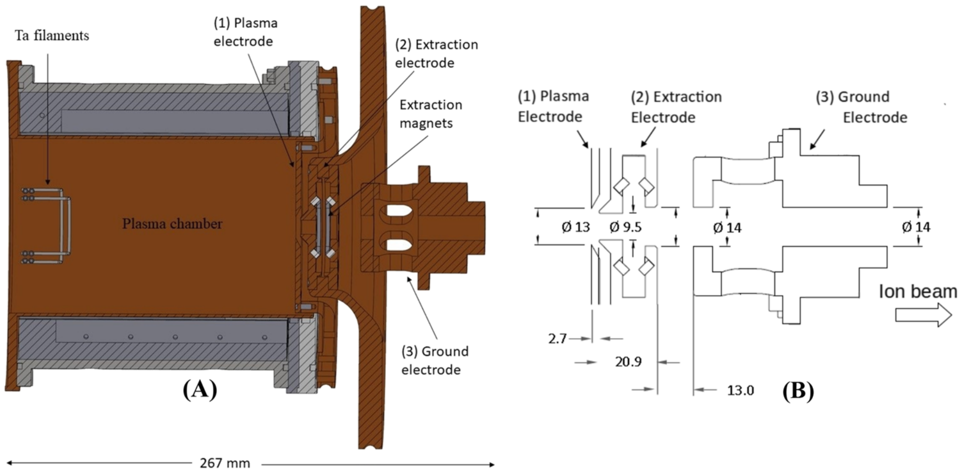

FIG. 1. (a) Section view of the ion source. (b) Schematic of the extraction system used. Dimensions are in millimeters.

for this is the underestimation of charge density near the plasma sheath in the simulations.

The current paper deals with the study of beam emittance of the ion beam extracted from the D-Pace's TRIUMF licensed filament powered negative ion source. Beam emittance values under different plasma conditions are determined experimentally and compared against results from IBSimu simulations.

ION SOURCE AND BEAM EMITTANCE

The schematic of the filament ion source used in the current study is presented in Fig. 1. H^- ions are generated inside the source mainly using volume production methods via dissociative electron attachment to vibrationally excited H_2 molecules.[3] Plasma is sustained inside the plasma chamber of the ion source via thermionic emission from electrically heated Ta filaments. The ion source uses three electrodes in the extraction system, consisting of the plasma electrode, the extraction electrode, and the ground electrode. The plasma electrode and the extraction electrode are biased positive with respect to the ion source for negative ion extraction. The coextracted electrons are dumped on the extraction electrode by the magnetic field created by the extraction magnets. The ion source is biased at a negative potential (−30 kV) with respect to the ground electrode by the bias power supply. The current measured on the bias power supply is an approximation of the total amount of charges reaching the ground region from the source. The ratio between the coextracted electron current and the bias power supply current is taken as the electron to ion ratio. More details about the ion source can be found in Ref. 4.

Beam emittance is measured at 368 mm downstream from the plasma electrode by using the D-Pace ES4 emittance scanner. This is an Allison-type[5] emittance scanner[6] which measures the beam intensity as a function of position (y) and angle (yp) simultaneously. An example of an emittance plot is shown in Fig. 2(a). Background noise in the emittance data is eliminated by discarding the intensity values below 4% of the maximum value. The variation in experimental beam emittance values for different amounts of H^- ions reaching the ground region (bias current) is shown in Figs. 3(a)–3(c), for 3 different extraction electrode voltages. The arc current determines the

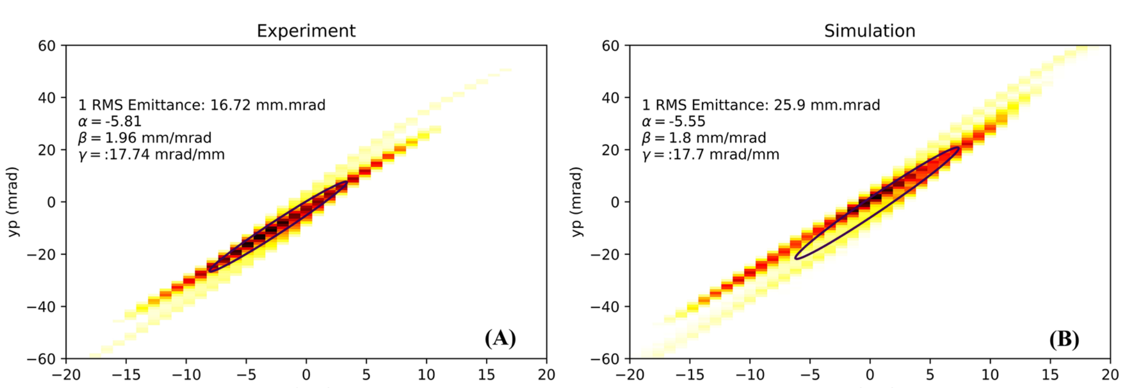

FIG. 2. Phase space plots for 17.2 mA H^- bias current at 3.5 kV extraction electrode voltage. (a) Experiment data. (b) Simulated using IBSimu.

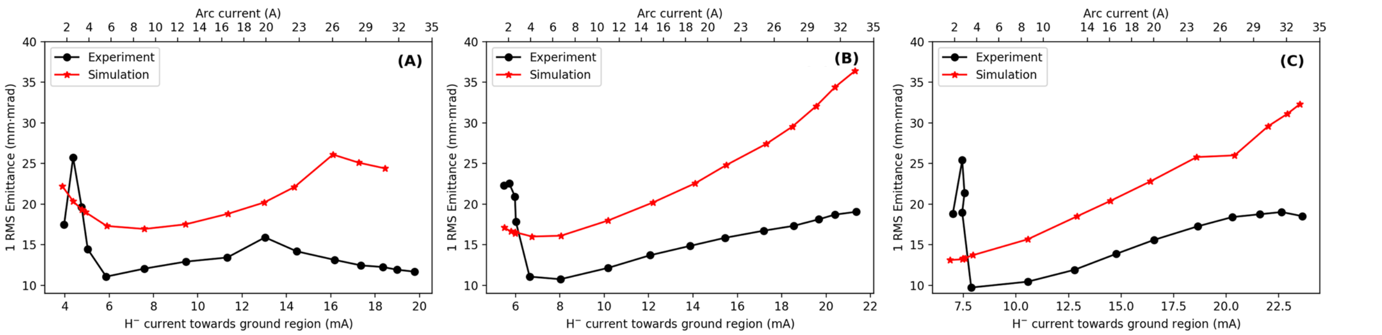

FIG. 3. Beam emittance comparison between experiment and simulation for 3 different extraction electrode voltages. (a) 3.0 kV, (b) 3.5 kV, and (c) 4.0 kV. Gas flow (15 SCCM), arc voltage (120 V), and plasma electrode voltage (5 V) are kept constant.

density of the plasma in the experiments. The experiment was performed by maintaining constant values of the gas flow (15 SCCM), arc voltage (120 V), and plasma electrode voltage (5 V). This ensures that the resulting changes in emittance values are only due to the variation in plasma densities for fixed electrode voltages. The graphs reveal an emittance minimum for all the experiments, which represents the optimal plasma sheath shape. A further increase in the arc current/plasma density leads to an increase in emittance. It can also be seen that the emittance minimum value decreases as extraction voltage increases. A decreasing trend for emittance values at higher arc currents can also be seen in the graphs, especially in Fig. 3(a) at arc currents higher than 20 A.

IBSimu SIMULATIONS

A model of the ion source plasma extraction was made using IBSimu. The simulation geometry started from inside the plasma ($z = -10$ mm) and extended until 368 mm from the plasma electrode in the direction of the beam. Beam emittance values in the simulation are measured at the end of this geometry, which represents the location of the emittance scanner in the experiments. The initial 60 mm length was simulated using a high resolution (0.4 mm) grid size (as in Fig. 4). The grid size cannot resolve the plasma sheath, but can still predict the plasma sheath shape as verified by higher resolution simulations. Grid sizes shorter than 0.4 mm provided the same phase space results. The remaining geometry (60–368 mm) used a lower resolution (0.8 mm) grid size (not shown).

The negative ion plasma extraction model in IBSimu[1] defines the equipotential surface between the bulk plasma and extraction, where the potential is the plasma electrode potential. The potential increases toward the bulk plasma due to the plasma potential and also toward extraction due to the positive extraction voltage. Extracted particle species from the plasma, negative ions, and electrons are defined in a plane inside the plasma at $z = -10$ mm. The negative ion current density (J_{H^-}) was chosen such that the simulation resulted in a negative ion current toward the ground electrode region that matched with the current recorded on the bias power supply during experiments. Electron current density (J_e) in the simulation was chosen to match with the electron to ion ratio observed in the experiments as the power supply current of the extraction electrode acting as the electron dump. Positive space charges are modeled by positive thermal ions and fast positive ions, defined by a trapped positive ion temperature and initial kinetic energy, respectively. Plasma parameters[1] (plasma potential = 5 V, ratio of fast compensating positive ions to negative charges = 0.2, initial drift energy of extracted particles = 5 eV, transverse negative ion temperature = 0.2 eV, and trapped positive ion temperature = 0.1 eV) for the simulations were chosen such that the emittance values matched as close as possible with the phase space distribution in experiments. The electrode voltages were the same as those in the

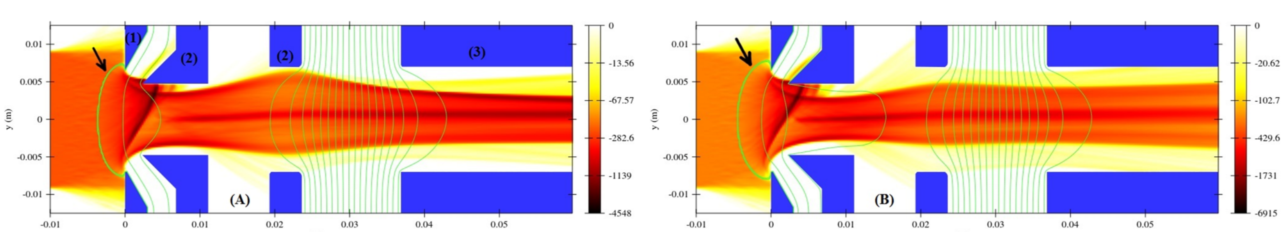

FIG. 4. IBSimu simulations showing the variation in the shape and location of the plasma sheath (indicated by the black arrow) for 2 different extraction electrode voltages (a) 3.0 kV and (b) 4.0 kV, using the same plasma current densities (55 A/m^2 negative ion density and 70 A/m^2 electron density). This results in beam emittance values of (a) 28.7 mm mrad and (b) 22.6 mm mrad. Electrodes [plasma (1), extraction (2), and ground (3)] are shown in blue color. Green lines represent equipotentials. The color bar represents the particle density.

experiment. Plasma electrode voltage was chosen to be 0 V in the simulations. The phase space data and emittance calculation were processed using the same code for both experiments and simulations (see Fig. 2).

RESULTS AND DISCUSSIONS

Experimental conditions were simulated using IBSimu and results are also shown in Fig. 3. Results indicate that IBSimu is capable of simulating the emittance trends in the negative ion source similar to the experiments. The emittance minimum also occurs in the simulations and is more evident for lower extraction voltages. This can be better seen in Fig. 5(a), where the beam emittance is represented as a function of total negative charge density in the simulations. The total negative charge density[2] inside the plasma can be represented as

$$\rho_{tot^-} = \rho_{\mathrm{H}^-} + \rho_e = J_{\mathrm{H}^-}/v_{\mathrm{H}^-} + J_e/v_e, \tag{1}$$

where J_{H^-} and J_e are the negative ion and electron current densities and v_{H^-} and v_e are the corresponding velocities. With the assumption that the extracted species uniformly fill the plasma electrode aperture, we can define an effective current from the above equation as

$$I_{\mathrm{eff}} = I_{\mathrm{H}^-}\left[1 + R_{ei}\sqrt{m_e/m_{\mathrm{H}}}\right], \tag{2}$$

where R_{ei} is the electron to ion ratio and m_e and m_{H} are the electron and the ion mass. I_{eff} is thus a representation of the total negative charge density in the simulated plasma. An increase of plasma density from the emittance minimum leads to higher emittance values in the simulations. This can be explained using the optical effect of the plasma sheath. The plasma sheath becomes less concave as plasma density increases, leading to a larger divergence and therefore an increase in emittance in the extraction. Figure 5(a) shows that emittance minimum values decrease for increasing extraction voltages as in the experiments. The plasma sheath is more concave when the extraction voltage is higher, for a fixed plasma density, leading to lower emittance. An increase in the extraction voltage causes a higher positive electric field near the plasma electrode pushing the positive ions toward the ion source. This causes the boundary of the quasineutral plasma to be shifted further toward the ion source. This is illustrated in Fig. 4. The decreasing trend of emittance at higher arc currents is also reproduced in the simulations in Fig. 3(a). Simulations reveal that there are many beams hitting the extraction electrodes at high arc currents and this beam collimation leads to a decrease in emittance values. The collimation occurs at a different current value in the simulations compared to experiments indicating a difference in the effect of the plasma sheath shape on beam divergence.

Even though the general trends in experimental beam emittance are reproduced in the simulations, the values of emittance in the simulations are different from those in experiments. At low currents, there is an abrupt increase in the emittance value from the emittance minimum. This is most likely due to some effect that cannot be modeled by IBSimu. At higher currents, the simulations produce too high emittance values compared to experiments. Considering this, it can be a possibility that the charge densities near the plasma sheath (negative ion densities and electron densities) are over estimated by the plasma model leading to a less concave plasma sheath. It is possible to add a density correction factor, R_{tc}, to modify the particle density near the plasma sheath. $R_{tc} = \rho_{tot^-}/\rho^*_{tot^-}$, where ρ_{tot^-} is the real particle density in the plasma and $\rho^*_{tot^-}$ is the apparent particle density for H^- ions and electrons. The effect of this factor on beam emittance in the simulations is shown in Fig. 5(b). As shown in the graph, the application of the correction factor moves the location of the emittance minima to higher currents, and this does not correspond to the experiment. It can be therefore concluded that plasma density estimation is not the reason for high emittance values in the simulations. It was also confirmed that a further reduction of transverse ion temperature does not have an effect on the emittance level. Therefore, there must be another reason for the higher emittance values in the simulations. It is quite probable that the deviation is a result of some effect near the plasma sheath that is not correctly modeled by IBSimu. Modeling should be very accurate in the extraction region as there are no compensating particles. A good candidate for the possible error is the planar definition of the beam flux at the simulation boundary in IBSimu. The assumption that the particles arrive at the plasma sheath as a planar flux causes an uneven distribution of particles at the sheath in the

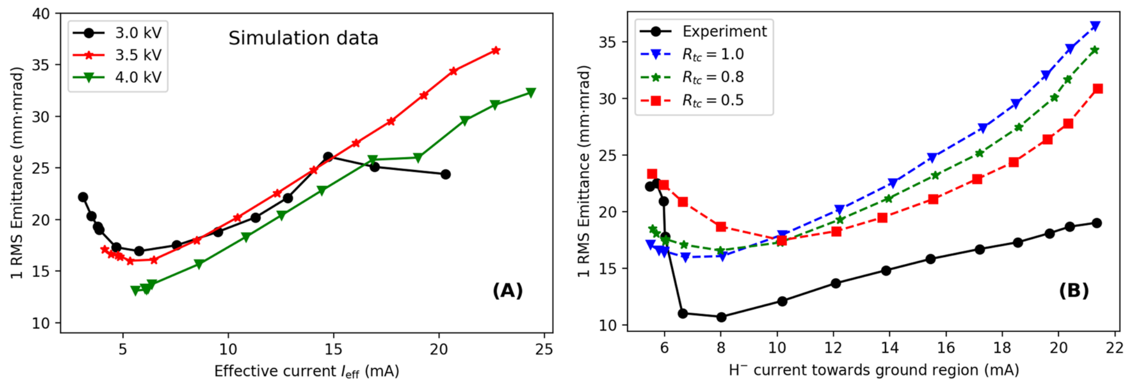

FIG. 5. (a) Variation in beam emittance for different simulated plasma densities. (b) Effect of the correction factor R_{tc} on beam emittance. The R_{tc} = 1.0 curve is the same as that in Fig. 3(b).

case of the highly curved sheath, and this can lead to an incorrect prediction of sheath shape. Such an effect would also explain the deviation in the current level where collimation happens in the case presented in Fig. 3(a).

CONCLUSIONS

The shape and location of the plasma sheath inside the ion source, which forms the boundary between the quasineutral plasma and the beam, influence the emittance of the ion beam. A plasma model of the ion source made using IBSimu could reproduce the observed emittance trends of the ion source and focusing action of the plasma sheath. But a mismatch in emittance values between experiments and simulations is also seen, which can be attributed to limitations in the plasma model in IBSimu. Future works aim at studying the factors causing these differences. More experiments need to be conducted to study the effect of the electrode to ion ratio on the emittance at different gas flows. An attempt in refining the effect of particle densities on the plasma sheath properties will also be considered.

REFERENCES

[1] T. Kalvas, O. Tarvainen, H. Clark, J. Brinkley, and J. Ärje, "Application of 3D code IBSimu for designing an H^-/D^- extraction system for the Texas A&M facility upgrade," AIP Conf. Proc. **1390**, 439–448 (2011).

[2] T. Kalvas and J. Lettry, "Deviation of H^- beam extraction simulation model," AIP Conf. Proc. **2052**, 050007 (2018).

[3] K. Jayamanna, F. Ames, I. Bylinskii, M. Lovera, and B. Minato, "A 60 mA DC H^- multi cusp ion source developed at TRIUMF," Nucl. Instrum. Methods Phys. Res., Sect. A **895**, 150–157 (2018).

[4] A. George, S. Melanson, D. Potkins, M. Dehnel, H. McDonald, C. Philpott, and N. G. Broderick, "Effect of magnetic filter in a volume production multicusp ion source," AIP Conf. Proc. **2052**, 050015 (2018).

[5] P. W. Allison, J. D. Sherman, and D. B. Holtkamp, "An emittance scanner for intense low-energy ion beams," IEEE Trans. Nucl. Sci. **30**(4), 2204–2206 (1983).

[6] P. Strehl, *Beam Instrumentation and Diagnostics* (Springer, 2006), Vol. 120.