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Empirical study of multidimensional Child-Langmuir law with plasma ion source extraction using round apertures

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Abstract. One dimensional Child-Langmuir (CL) law is commonly used in ion source physics to describe space charge limited ion extraction from the plasma. Recently 2D and 3D CL laws have been derived, but plasma ion extraction does not strictly meet the assumptions in these CL laws. Investigations on the applicability of the CL laws to ion source extraction were conducted using filament-driven ion source, measuring the beam currents as a function of extraction voltage. The experiments are complemented with simulations where IBSimu is used for studying the behaviour of plasma meniscus. Three different voltage regions were identified with low, moderate and high voltage. With moderate voltages the extracted beam current density shows signs of 3D CL law. The results indicate that for the total beam current CL laws are not valid but instead require collimation for the CL effects emerge.

1. Introduction

The classical Child-Langmuir (CL) law describes the maximum current density J for electron beam in a vacuum diode formed by inifinitely large planar anode and cathode with a given distance D and voltage difference V between them [1, 2]. The generalized 1D CL equation for the maximum current density is

$$J = \frac{4}{9}\epsilon_0\sqrt{\frac{2q}{m}}\frac{V^{3/2}}{D^2}, \tag{1}$$

where q and m are the charge and the mass of the particles and ϵ_0 is the vacuum permittivity. The physical interpretation of the CL law is that excessive space charge present in the diode gap forms a virtual cathode, which restricts the maximum current that can be extracted from the electrode. The 1D CL law assumes: (i) Indefinitely many particles to emit, (ii) particles do not have initial velocity, (iii) electrodes are infinite in the plane normal to the beam, and (iv) particle velocities are non-relativistic. The 1D CL law has recently been extented to 2D and 3D, i.e. the geometry of the emitter is taken into account [3, 4]. The 3D CL law is derived as an enhancement factor for the classical 1D case, i.e.

$$J_{3D} = J_{1D}(1 + F \times G), \tag{2}$$

where F is the mean-position factor (for non-relativistic beam $F = 1/4$) and G is the geometrical factor. For round emitter $G = \frac{D}{R}$, where R is the radius of the emitter. The 3D enhancement for the 1D CL equation is derived assuming that the particle flow is parallel and the emitter geometry is larger than the gap length, which is not always the case in plasma ion source extraction systems.

The classical 1D CL law is commonly used with plasma ion sources to describe the space charge limited ion emission at extraction voltages below the plasma density limited regime. However, ion source extraction is clearly not a 1D phenomena and even with the 3D expansion the dynamically changing plasma meniscus doesn't meet the criteria of fixed planar electrode in 3D CL law. Furthermore, the extracted ions do not have zero initial velocity as assumed in both 1D and 3D CL laws, but instead they are accelerated by the plasma sheath [5]. Here the meniscus is defined to be the equipotential surface where V is the plasma chamber voltage. The shape of the meniscus is determined by the extraction geometry, electric fields in the extraction region and plasma density and temperature. Nevertheless, it has been argued that the deviations from the assumptions can be considered small enough to apply the CL law for plasma extraction [6]. 3D CL effects on the beam current density extracted from a plasma ion source have been previously reported for a Penning type ion source with H^- beam [7].

In this study, the applicability of the 3D Child-Langmuir law to positive ion extraction is examined through experiments with different size round apertures, comparing the results to simulations. The beam currents were measured as a function of the extraction voltage in space charge and plasma limited regions.

2. Experimental setup and measurements

The experiments were carried out with a filament-driven DC-discharge multicusp ion source using argon plasma at the University of Jyväskylä Accelerator Laboratory [8]. Filament driven ion source was used as it produces highly repeateble and stable beams.

Two different extraction systems were built to study the 3D CL law effects on Ar^+ beam current density. Figure 1 **A** shows the first one, which is a grid based extraction consisting of the plasma electrode with a 3 mm diameter aperture, a fine mesh puller and a Faraday cup (FC) made of several concentric rings with 9 mm width and 1 mm spacing between them. The center of the cup is a round plate with 9 mm diameter. The gap length between the plasma electrode and the puller is 21 mm. This extraction system was designed to study the radial spread and distribution of the extracted beam, and to measure the total beam current, i.e. the sum of the currents of each ring. Figure 1 **B** represents the second system consisting of plasma and puller

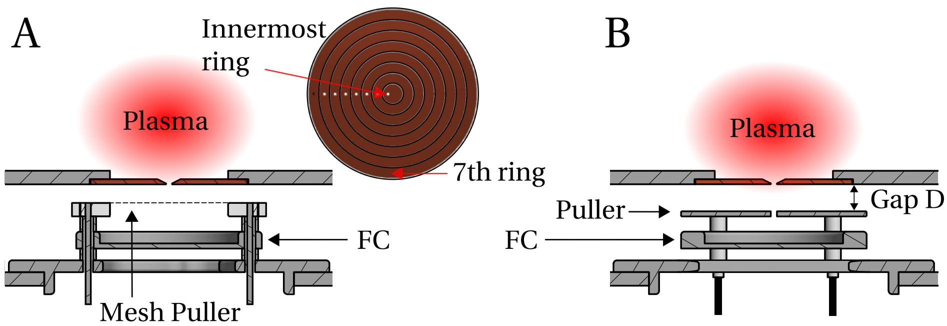

Figure 1: Extraction systems used in the study. **A** 1st extraction system with fine mesh puller and FC of concentric rings. **B** 2nd extraction system with equal diameter extraction and puller aperture.

electrodes with the same size round apertures ($R = 0.9, 1.8$ and 2.5 mm were used), and a FC measuring the beam current passing through the puller. The electrode apertures were chosen to be the same following the 3D CL theory which assumes that the emitter and collector have the same size and shape (beam has no transverse spread). The gap length was 16 mm which was chosen to achieve a flat plasma meniscus with reasonable extraction voltage (< 8 kV). This was inferred from extraction simulations. The beam current passing through the puller was measured as a function of the extraction gap voltage with several discharge currents. Discharge voltage was kept constant of 72 V, hence the plasma density was adjusted with discharge current.

The ion optical simulation code IBSimu [9] was used to study the behaviour of the extracted beam and the shape of the meniscus in simulations using the second extraction system geometry. The simulation parameters were chosen to match the known plasma parameters [10] and only the saturation current was matched to the measured value. After matching the saturation currents the extraction voltage was varied and the resulting current recorded. The voltage sweep was repeated with the same simulation parameters for all the different geometries (R of electrodes). The simulations provide insight especially to the changes in the meniscus geometry.

3. Results and discussion

Figure 2 **A** shows an example of the total beam current measurements with different discharge currents using the first extraction system (mesh puller) and ring FC. Higher extracted currents of Ar^+ were achieved with higher discharge current (plasma density). The beam current was always non-zero even without the extraction voltage, increasing rapidly when a low voltage was applied. After the initial jump the beam currents rise slowly, almost linearly, with the extraction voltage. It is clear that the measured total currents show no signs of the $V^{3/2}$ behaviour implied by the CL law in Eqs. 1 and 2. The beam currents recorded from different rings of the FC, shown in figure 2 **B** , reveal that with low extraction voltages the beam spreads in transverse direction. For example around 300 V the current from every ring is around 40 μA except for the innermost plate, which is about 20 μA. Increasing the extraction voltage focuses the beam and the currents near the center increase while the currents of the outermost rings decrease. With

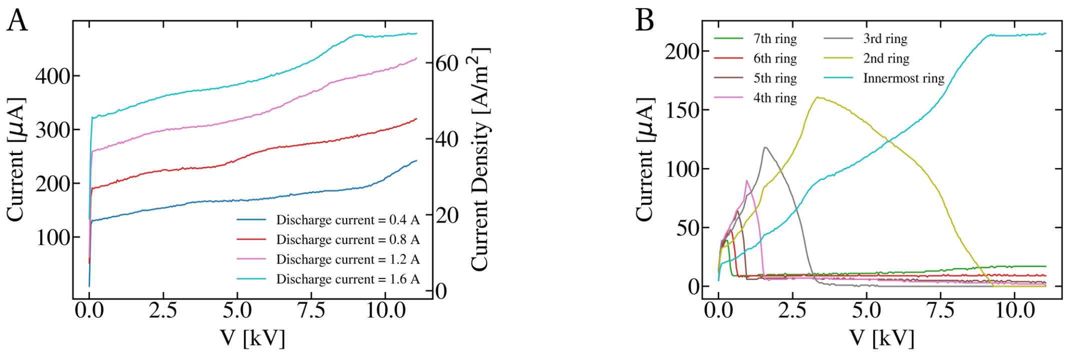

Figure 2: Measurements with first extraction system. Gap length is 21 mm and plasma aperture diameter 3 mm. **A** Total Ar^+ currents measured by the ring FC as a function of extraction voltage with different discharge currents. **B** Currents measured by the different ring sections of the Faraday cup as a function of the extraction voltage.

zero extraction voltage only a very small number of ions are autoextracted to the FC by the positive plasma potential. When the extraction voltage is applied a plasma sheath is formed in the proximity of the plasma electrode, which explains the abrupt increase of the beam current. Increasing the voltage further only moderately increases the total beam current due to the sheath accelerating more particles towards the plasma aperture. On the whole this experiment shows that CL law doesn't hold for the total current extracted from plasma ion source.

Figure 3 **A** shows the measured current densities with the second extraction system where the electrodes aperture sizes are matched and plasma densities are equal. All the current densities are calculated as the measured beam current divided by the extraction aperture area. These data reveal three extraction voltage regions: The emission (or plasma density) limited saturation currents are reached with high extraction voltage, the beam is space charge limited at moderate voltages and the current densities are almost equal at low extraction voltage. The main results are: (1) in space charge limited region bigger R leads to lower current density, (2) bigger R leads to higher saturation current density, not only current and (3) with bigger R the emission limited region is reached with higher voltage.

The first observation follows directly from the 3D CL law as for bigger R the geometrical factor G is smaller. Intuitively, in the space charge limited region, if the transverse charge distribution of the beam is constant, then bigger R means more charge and stronger space charge forces which leads to smaller beam current density.

The second result is explained by the behaviour of plasma meniscus: The location and, therefore, the area of the meniscus is more sensitive to voltage with larger aperture size (this point is elaborated on when discussing the simulations). So when comparing different extraction aperatures for example with high voltages the area of the concave meniscus has increased more with bigger R than with smaller R. This bigger meniscus harvests more ions from a larger effective area and explains the second result.

The third result follows from the previous two: with smaller R the beam current density is higher in the space charge limited region but lower in the emission limited region, so saturation current densities must be reached wih lower voltages (when compared to bigger R). After the saturation current densities are reached, increasing the extraction voltage results in larger area of the meniscus harvesting more ions from the plasma. At the same time the beam is overfocused and collimated, which reduces the measured current densities at high gap voltages, as seen in the measurement (see fig. 3 with $R = 0.9$ mm).

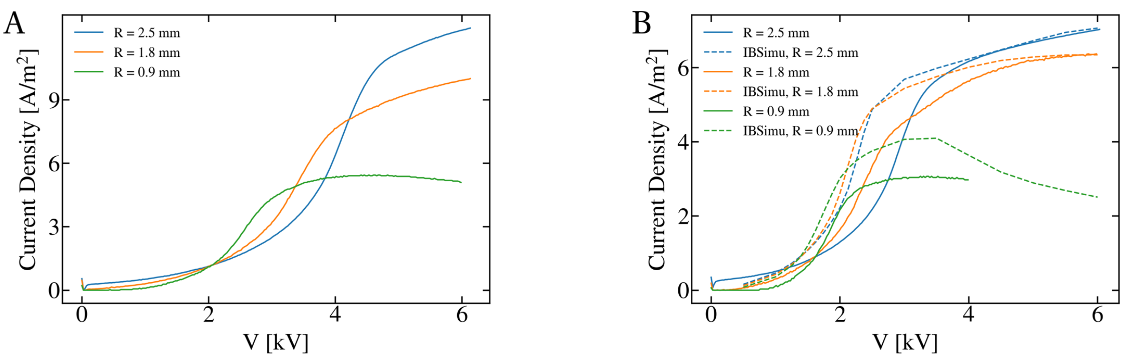

Figure 3: Measurements using second extraction system with gap length of 16 mm. **A** Measured currents densities as a function of extraction voltage. **B** Current densities compared with IBSimu simulations. Note that **A** and **B** have different discharge currents and plasma densities.

Figure 3 **B** compares IBSimu simulations to the measurements. Here the simulated beam current density was matched with measured emission limited current with 2.5 mm radius. For the $R = 1.8$ mm case the simulated saturation beam current densities are in good agreement with the measured ones. In the $R = 0.9$ mm case IBSimu overestimates the saturation currents slightly. This happens because the beam current density was matched with larger radius hence the effective areas of the menisci are not equal. In the space charge limited region the simulated current densities follow the CL law similar to the experiment, i.e. bigger R leads to slightly smaller current density. However, the space charge limited current densities are overestimated for all the radii. Regardless, these comparisons show that, overall, IBSimu reproduces qualitatively the trends observed in the experiment.

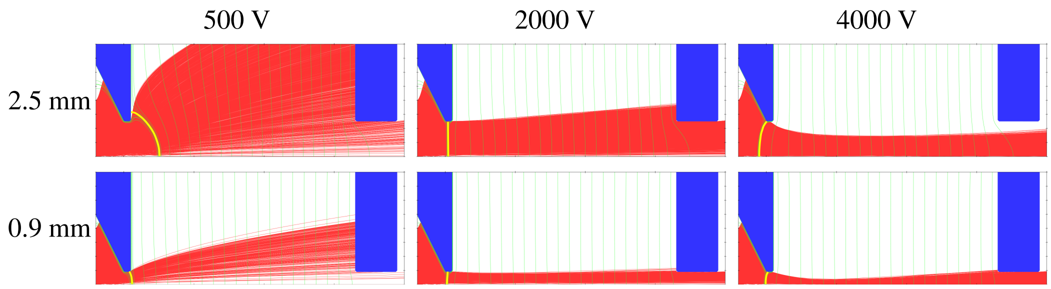

Figure 4: Simulation results, where the upper row is with $R = 2.5$ mm and the lower one with $R = 0.9$ mm and the gap length was 16 mm. Meniscus is highlighted with yellow arc.

Figure 4 shows examples of the simulations with the extraction voltages of 500, 2000 and 4000 V. With 500 V the beam is dispersing heavily with both apertures, though the meniscus is more convex with the $R = 2.5$ mm case than with $R = 0.9$ mm. At 2000 V almost all of the beam goes through the puller aperture in the $R = 0.9$ case while with larger radius the beam is collimated substantially. With 4000 V the beam is collimated only in the $R = 0.9$ mm aperture case. The aforementioned observation that with bigger R the meniscus is more sensitive to extraction voltages is clearly visible in the simulations. Furthermore, the area of the meniscus can be calculated with spherical surface approximation and then compared to the extraction aperture area. For example in the 4 kV case the area of the meniscus is only 4% bigger with $R = 0.9$ mm but 21% bigger with $R = 2.5$ mm i.e. the effective area of the meniscus changes more with bigger R.

4. Conclusions

The measurements in this paper show that the CL law is not applicable to the total beam current extracted from plasma ion sources, which is mainly due to the role of the plasma meniscus. Instead, a puller electrode with a beam limiting aperture is required for the CL law to emerge. In that case three voltage regions are found, the beam current being space charge limited only in the intermediate region.

The dependence of the beam current density on the aperture radius R in the space charge limited region is predicted by the 3D CL law, where bigger R leads to smaller current density. Direct comparison between theory and measurements are not done here, as the deviation of the plasma extraction from the CL law assumptions (meniscus vs. planar electrode) makes the comparison inaccurate.

Similar experiments are planned with rectangular apertures investigating the 3D CL effect on plasma ion sources even further. The experiments will be complemented by particle-in-cell simulations to study the plasma meniscus behaviour in the three voltage regimes identified here.

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