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# 3D SIMULATIONS OF THE CAPRICE ECRIS EXTRACTION SYSTEM

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*Abstract*

The simulation of the ion extraction from the Electron Cyclotron Resonance Ion Sources (ECRISs) is necessary for the optimization and development of the performance of ion sources. Due to the magnetic field configuration of the ECRISs the calculations need to be performed in 3D. For this reason simulations based on the C++ library "Ion Beam Simulator" (IBSimu) were developed. In this work, a physical model was implemented in IBSimu for performing detailed 3D simulations of ion extraction from a CAPRICE-type ECRIS. Simulations of multi-species Argon ion beam including Helium contribution as support gas extracted from CAPRICE are carried out. Simulation results are presented and compared to experimental findings, in particular for ion beam intensities and beam profiles measured with viewing screens.

## INTRODUCTION

Understanding and optimizing the performance of the ECR ion sources, particularly in terms of beam formation and transport, is crucial for their application in scientific research and industrial processes. In this work, a study of the CAPRICE ECRIS focusing on the comparison between experimental beam profile measurements and a novel three-dimensional simulation is presented. The use of a 3D simulation model provides a more comprehensive analysis of the ion source behavior compared to a two-dimensional approach and allows for a more accurate prediction of the ion extraction from an ECRIS source. The simulation results obtained using IBSimu [1], a versatile ion beam simulation tool, have been compared with experimental measurements. For the experiment, a viewing screen was employed to capture and analyze the beam profile, providing valuable data to benchmark the simulation.

## MATERIALS AND METHODS

### *Simulations*

For the simulations, the C++ library IBSimu was utilized. This software was designed for ion beam simulations calculating the ion trajectories. However, since the library was not originally intended for simulating ion beam extraction from deep within a plasma volume, several modifications were necessary to adapt the program for this purpose. Additionally, some fundamental assumptions regarding the ion extraction process had to be made. These assumptions align with the prevailing consensus in the field of ion sources, however, their applicability to this specific type of simulation requires further validation.

In the simulation, the ions are generated from a surface located at the center of the plasma chamber (see simulation results). This position was chosen based on the assumption that the plasma occupies the majority of the chamber and by results of previous simulations, which indicate that the ions for each ion beam extracted from an ECR ion source originate from various positions within the plasma volume [2]. By placing the ion origin at this location, the simulation aims to more accurately predict the real ion production and transport dynamics. Additionally, an initial plasma had to be defined to ensure accurate results for the simulation. For this simulation the plasma potential was set to 20 V and the plasma was positioned in the area inside the plasma chamber (from $x = 0$ m to $x = 0.17$ m). A 98% space charge compensation was also applied from $x = 0.204$ m to $x = 0.5$ m.

The simulations were conducted for various charge states of argon ($Ar^{3+}$ to $Ar^{10+}$) together with helium ($He^{+}$ and $He^{2+}$) and hydrogen ($H^{+}$) ions. The initial distribution of the different charge states and different ion species used in the simulation was based on a previously conducted experiment. The magnetic field parameters and electrode geometry (STL files) utilized in the simulation were based on the results of simulations previously performed [3]. The following Table 1 presents the parameters setting used for the simulation.

Table 1: Parameters Used in the Simulation

| Parameter | | Value | Unit |
|---|---|---|---|
| parallel ion temperature | $T_p$ | 0.1 | eV |
| transversal ion temperature | $T_t$ | 0.15 | eV |
| electron temperature | $T_e$ | 5 | eV |
| start energy of the ions | $E_i$ | 0.8 | eV |
| screening electrode voltage | | −2 | kV |
| plasma electrode voltage | | 15 | kV |
| number of ions | $N$ | 100000 | |
| plane of ion creation | | $x = 0.1$ | m |

The current density $j$ at the starting plane of the ions is not included as different values for this parameter were tested, and this parameter appears to have the biggest influence of the outcome of the simulations.

### *Experimental Setup*

The experimental setup employs a CAPRICE ECRIS (see Fig. 1), whose plasma chamber and ion extraction system are modeled in IBSmu by implementing its geometry, electric potential and internal magnetic field. This computer model is the base for all the simulations that will be presented in this proceeding.

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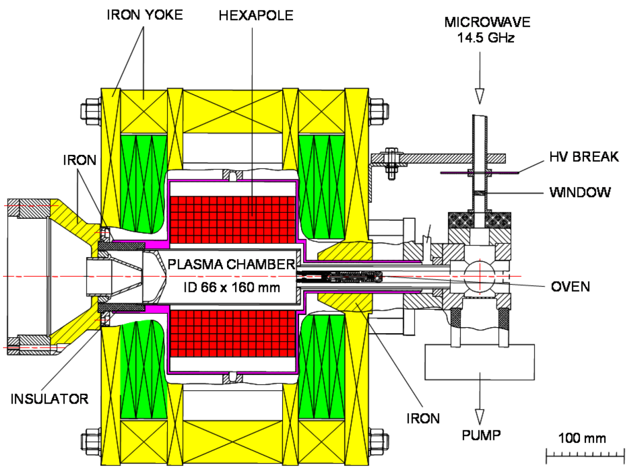


Figure 1: Schematic of the CAPRICE ECRIS.

The experimental data have been obtained from an ECR test stand. The ECR injector stand (EIS) includes an analysis system capable of measuring various parameters, including ion beam mass spectra and beam currents [4]. Figure 2 provides a schematic of the ECR test stand.

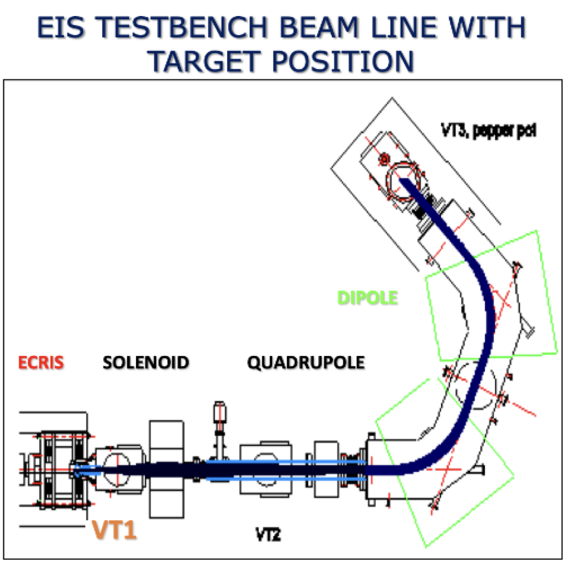


Figure 2: Layout of the EIS test bench.

During the measurement, the extraction parameters were set as in Table 2.

Table 2: Parameters during the Measurements

| Parameter | Value | Unit |
|---|---|---|
| extraction voltage | 15 | kV |
| screening electrode voltage | −2 | kV |
| total beam current | 1.63 | mA |
| gas pressure at source | $1.75 \times 10^{-6}$ | mbar |
| microwave power | 400 | W |

In order to have a better comparison with the simulations, it was decided to insert a viewing screen directly behind the ion extraction (VT1 in Fig. 2, approximately 32 cm behind the plasma electrode) to obtain clearer pictures of the ion beam profile. The viewing target, i.e. the viewing screen, mounted on a feed through is shown in Fig. 3.

To visualize the ion beam profile the viewing screen was coated with potassium bromide (KBr), as KBr glows upon ion impact. The side length of the used square shape viewing screen is 80 mm and it was introduced into the beam path at an angle of 45 degrees, see in Fig. 3. The working gas for the measurements was argon together with helium as auxiliary gas.

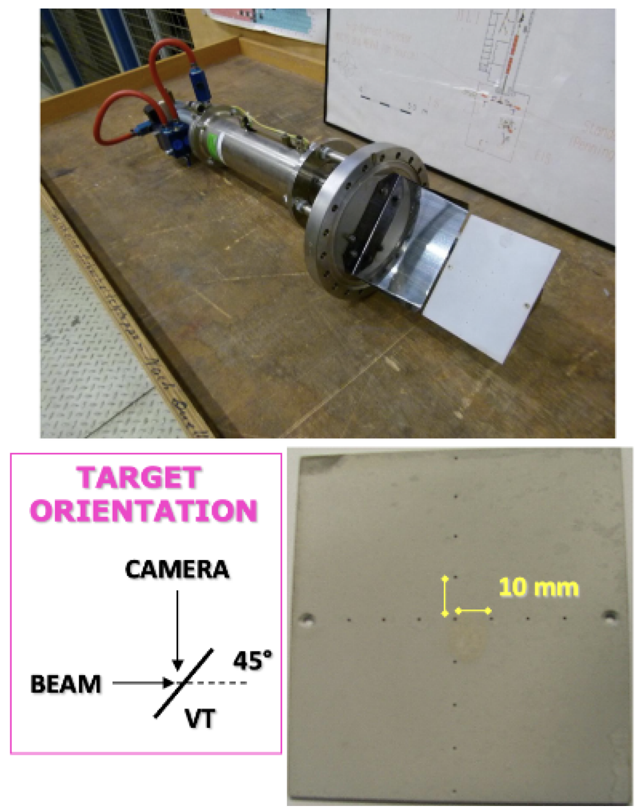


Figure 3: Top: Device for inserting the viewing screen. Bottom left: Alignment in beam path. Bottom right: Used screen with holes as distance markers.

## RESULTS

### *Simulation*

Figure 4 shows the results for the trajectories of the simulated ions for different current densities $j$ at the creation plane of the ions. The different colours represent the different ion species, the light green lines represent the electric potential lines, while the electrodes are depicted by the dark blue surfaces. It can be observed that as the initial current density decreases, the beam spreads more significantly indicating a considerable divergence and loss of beam intensity at lower current densities.

According to the simulation, the beam currents shown in Table 3 are obtained for the different current densities $j$ at the starting plane. Figures 5 to 7 show the beam profiles, at the end of the simulation box ($x = 0.5$ m), for the different

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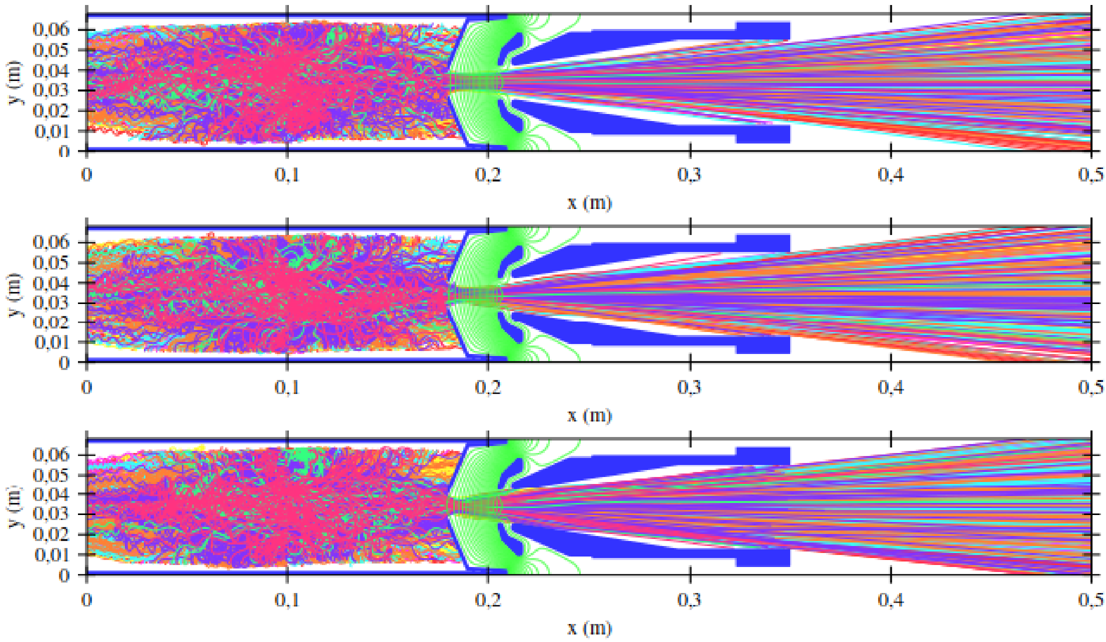


Figure 4: Ion trajectories for different current densities $j$ at the start plane $x = 0.1$ m. From Top to Bottom $j = 5, 3, 1$ A/m$^2$.

current densities $j$. As the current density increases, the expected triangular spiral geometry of the beam profile becomes progressively clearer. Upon closer examination, it can also be observed that ions are lost at the edges of all the beam profiles, a phenomenon that is particularly pronounced in the profile corresponding to the current density of 1 A/m$^2$. This phenomenon originates from the boundaries of the simulation which are exceeded at the edges of the beam profiles.

Table 3: Simulated Total Beam Current at $x = 0.5$ m Dependent on the Current Density $j$ at the Starting Plane

| **Current density $j$** | **Beam current at x =0.5 m** |
|---|---|
| 5 A/m$^2$ | 3.2 mA |
| 3 A/m$^2$ | 2.1 mA |
| 1 A/m$^2$ | 0.9 mA |

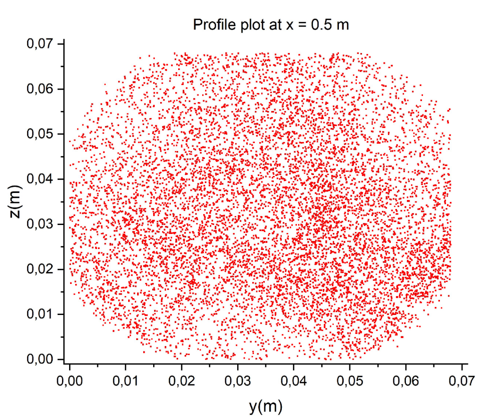


Figure 5: Beam profile for a current density $j$ of 1 A/m$^2$.

The simulations also provided the emittance of the beam at the position $x = 0.5$ m. Since it was not possible to measure the emittance during the measurements, the emittances

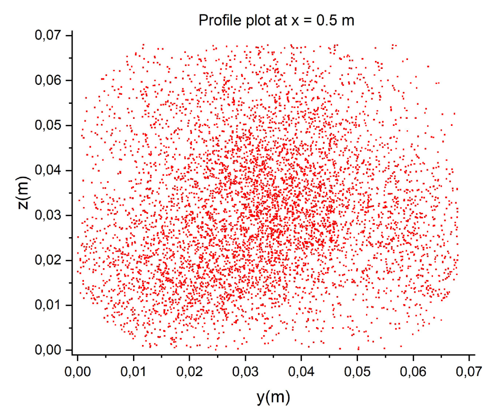


Figure 6: Beam profile for a current density $j$ of 3 A/m$^2$.

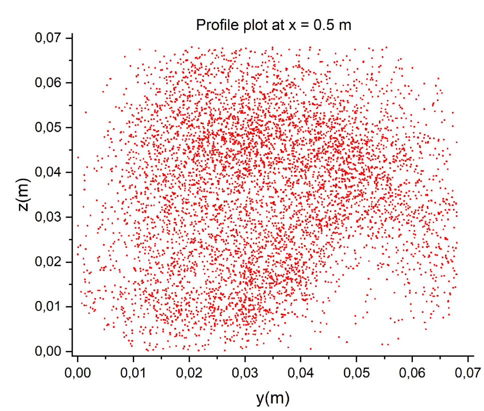


Figure 7: Beam profile for a current density $j$ of 5 A/m$^2$.

were not used for the benchmarking. For the sake of completeness the simulated emittances in the $(y, y')$ phase space are shown in Fig. 8 where also the Twiss parameters are reported. The figure shows clearly that the emittance $\epsilon$ is bigger for lower current densities, which indicate that the

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beam is not optimized at lower current densities. However, it should be noted that the emittances considered here are only suitable for phenomenological assessments, as the beams are cut off at the simulation boundaries.

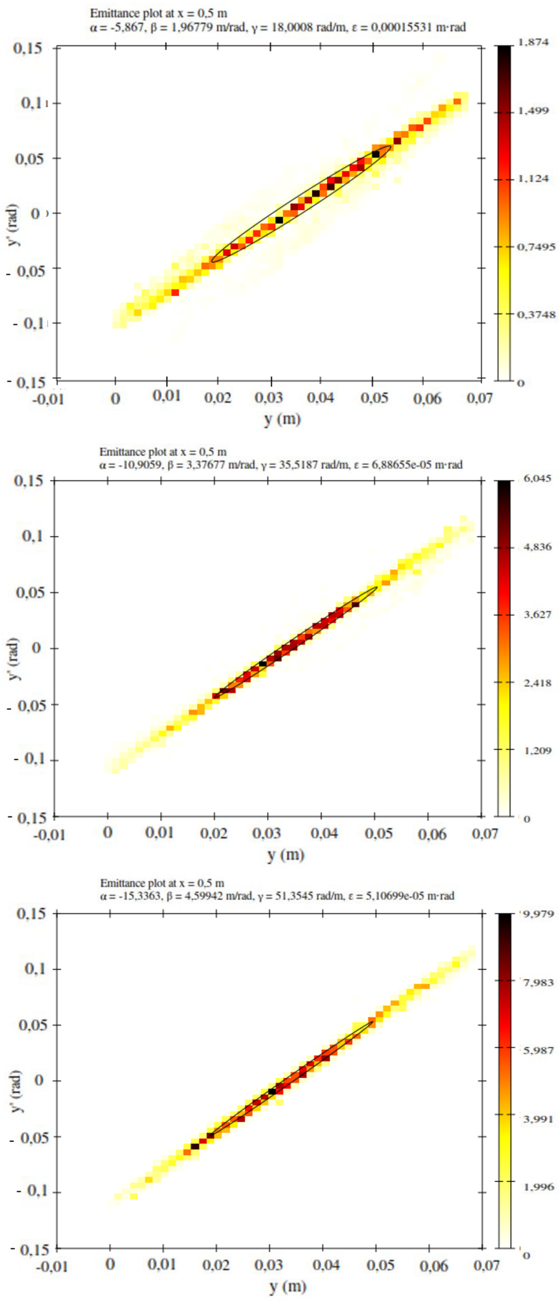


Figure 8: Beam emittances at the position $x = 0.5$ m for the different current densities $j$ at the start plane. From top to bottom $j = 1, 3, 5\ \mathrm{A/m^2}$.

### *Experimental Results*

Figure 9 shows a beam profile taken during the measurements. The brighter areas in the picture indicate regions where a higher concentration of ion impacts on the screen. The characteristic triangular spiral structure of the beam, originating from the hexapole used in the setup, is clearly visible. The image shown was not corrected from the distortion caused by the angle in which the screen was put into the beam. The diameter of the measured beam profile is just under 7 cm, closely matching the simulated beam diameter (of approximately 7 cm). This image was used as a reference for comparison with the simulation results to verify the accuracy and progress of this work.

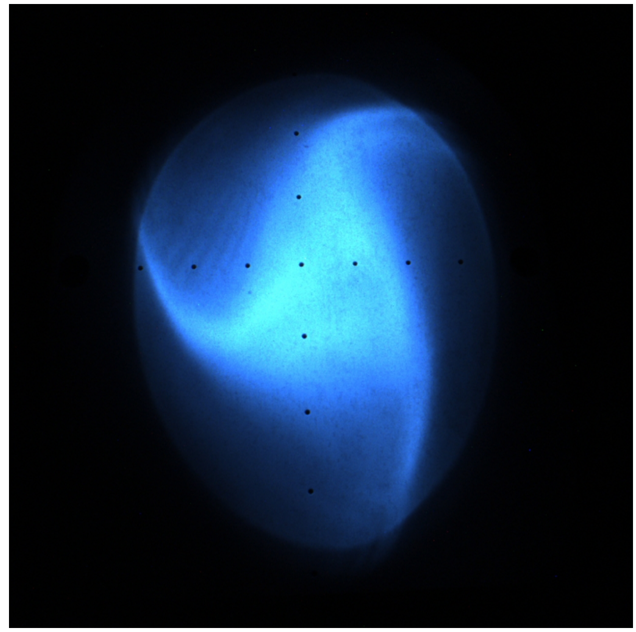

Figure 9: Picture of a beam profile.

## CONCLUSION AND OUTLOOK

We find that the simulations provide a reasonable prediction of the beam profile for the CAPRICE-ECRIS, with the results already closely matching the experimental measurements. The primary difference between the simulation and the experimental measurements lies in the beam profile itself: in the experimental data, the profile appears significantly sharper and rotated by 45 degrees counterclockwise compared to the simulation. The beam current, however, shows only slight discrepancies between the two, where the simulation with the starting current density $j = 3\ \mathrm{A/m^2}$ is closest to the measurements.

Future work will focus on testing various parameter configurations until the optimal setup is found that best replicates real-world conditions, especially the beam profile. Once the correct configuration will be identified, the simulation framework will be extended to explore different plasma electrode geometries. These new simulations will also be validated against experimental measurements to ensure accuracy and consistency with observed results.

## ACKNOWLEDGEMENTS

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