Chapter 5

EXTRACTION AND TRANSPORT OF He⁺

5.1 Introduction

In order to achieve high quality beam transport from the ECR ion source into the cyclotron it is important to have detailed information on the initial phase-space distribution of the ion beam extracted from the source and to prevent growth of the effective emittance by space-charge forces and aberrations of the optical elements in the beamline. As a first step a detailed 3D simulation of the extraction and transport of an essentially mono-component Helium ion (He⁺) beam has been done and compared with measurements to assess its validity. The simulation consists of two parts. First an initial phase-space distribution is calculated at the plasma electrode aperture of the ECR ion source using our plasma simulation code (PIC-MCC) [33]. In the next step the He⁺ ions are tracked through the extraction system (an accel-decel lens), drift spaces and the 110° analyzing magnet (a double-focusing magnet). These elements form the first part of the beam transport system and are shown in Fig. 4.6. Both the space-charges of the ion beam and the magnetic fringe fields of the ECR ion source and analyzing magnet are fully taken into account. The effect of the space-charge forces is studied by varying the beam intensity in the simulations. Beam profiles and transverse emittances have been calculated and compared with measurements at various positions along the beamline.

This chapter is organized as follows: In Sec. 5.2 the He⁺ formation is described, while the simulation of ion extraction and transport is discussed in Sec 5.3 and Sec. 5.4, respectively. In Sec. 5.5 the results of the calculations are compared with measurements of the beam profiles and emittances at two different locations, i.e. directly after the extraction system and close to the imaging plane behind the analyzing magnet (Fig. 4.6).
5.2 Beam formation of He$^+$

The PIC-MCC Code simulates the ion dynamics in the ECR ion source plasma using the particle-in-cell method. The full 3D min-B magnetic field is used. Ionization, recombination and all other scattering processes are taken into account in the code. Here only a brief summary of this simulation is given, more details can be found in Ref. [33].

The simulation is started with an equal number of He atoms ($10^5$) and singly charged He$^+$ ions which are homogeneously distributed in the ECR ion source volume. The electron energy distribution is given by a single Maxwellian with the electron density determined by local charge neutrality. No electron dynamics is considered, the electron temperature is treated as a free parameter. The gas pressure in the chamber is defined by the particle statistical weight and by the total number of neutral particles in the chamber in the stationary situation. The electron temperature is tuned to fit the experimental charge state distribution (CSD) of the extracted He$^{q+}$ beam, and is around 250 eV.

The beam formation is determined by the ion motion in the plasma sheath that separates the plasma from the plasma electrode. Ions drifting towards the extraction hole are accelerated in the electric field of the plasma sheath to an energy equal to the plasma potential (typically a few tens of eV). The PIC-MCC code does not model the plasma sheath. In our extraction simulations using the GPT code a planar sheath with a thickness of 15 Debye lengths ($\approx 1$ mm) is assumed between the plasma electrode and the ECR plasma [142]. Based on measurements [78] we assume a potential difference of 20 V across the plasma sheath.

The calculated spatial distribution of the He$^+$ ions at the location of the plasma electrode is shown in Fig. 5.1a. A more detailed spatial distribution of the He$^+$ ions over the aperture in the plasma electrode is shown in Fig. 5.1b. It clearly exhibits the triangular symmetry of the min-B field configuration of the ECR ion source. The calculated dis-
5.3 Ion beam extraction ($He^+$)

We have already discussed in Sec. 2.3 that space-charge forces can have an important effect on the transport of a low-energy ion beam. However, the repulsive space-charge in a real ion beam is always to certain degree compensated by (secondary) electrons that are produced in collisions between beam ions and the residual background gas and/or by ion-wall interactions and are then trapped in the positive potential well of the beam. As discussed in Sec. 3.3.4 we will investigate the effect of space-charge compensation of the $He^+$ beam without explicitly taking into account the secondary electrons by calculating the ion trajectories for various beam intensities. We start by looking at a zero current beam, in which the particles move independently. This case corresponds to a complete space-charge compensation. We then look into a partly-compensated ion beam to study beam extraction including space-charge forces for various beam intensities, which implies that the space-charge compensation does not depend on the phase-space coordinates.

The ion beam extraction and transport simulations discussed in this chapter have been performed with the GPT code [37], which allows for 3D particle tracking in arbitrary
electric and magnetic fields including space-charge effects. The space-charge models used in the GPT code have been shortly described in Sec. 2.4. The full 3D magnetic fields of the KVI-AECR ion source (solenoid and hexapole fields) and the electrostatic fields of the accel-decel extraction system have been calculated with the LORENTZ3D code [35] and imported in GPT. In this section we study the extraction of the $\text{He}^+$ ions by calculating their trajectories from plasma electrode to the first viewing target VT1 behind the ground electrode of the extraction system, see Fig. 4.6.

### 5.3.1 Extraction of a fully-compensated $\text{He}^+$ beam

Fig. 5.2 shows the $\text{He}^+$ ion trajectories through the accel-decel extraction system of the KVI-AECR ion source. The plasma electrode is always biased at $+24 \, \text{kV}$, the puller electrode at $-300 \, \text{V}$ and the ground electrode connected to ground potential. From the simulated ion trajectories we have calculated various two dimensional (2D) cross sections of the four-dimensional (4D) transverse phase-space, e.g. 2D beam profiles and
emittance plots, which can be compared to measurements. Fig. 5.3 shows the calculated 2D beam profile and emittances at the location of viewing target VT1 for a space-charge compensated beam. The phase-space distributions of the beam in the horizontal and vertical planes are nicely elliptical and nearly identical; the corresponding effective emittance $\varepsilon = 65 \pi \text{ mm mrad}$. During the ion beam extraction in the fringe field of the extraction solenoid, the ion beam triangle rotates due to the Lorentz force and simultaneously grows in size. The size is determined by the divergence of the extracted beam. To verify that the beam emittance is dominated by the fringe field of the extraction solenoid (see sec. 3.3.4) and hexapole we have performed a simulation of ion beam extraction without the magnetic field in the extraction region. In this case we find that the emittance of the extracted ion beam is negligible ($\approx 2 \pi \text{ mm mrad}$).

In order to study the effect of the hexapole fringe field on the ion beam extraction we have also performed a simulation with only the fringe field of the extraction solenoid, i.e. the fringe field of the hexapole is turned off. The result of this simulation are nearly identical to that of the full simulation. We therefore conclude that the fringe field of the hexapole is not important for the ion beam extraction from our source. In addition to the ECR magnetic field also the extraction potential influences the ion beam extraction, in particular the ion beam rotation and divergence. This has been tested in the simulations by changing the extraction potential and agrees with experimental observations.

### 5.3.2 Extraction of a partly-compensated $He^+$ beam

To study space-charge effects we have performed trajectory simulations including space-charge forces for different ion beam intensities of the $He^+$ beam. These simulations mimic beams with varying degrees of space-charge compensation.

Fig. 5.4 shows calculated 2D beam profiles and the horizontal emittances at the location of viewing target VT1 for an uncompensated beam with various beam currents. The PIC-MCC code predicts the total extractable $He^+$ current to be 450 $\mu$A, which is close to the measured beam current. The $He^{2+}$ contribution is around 10 % of the total beam current and has not been taken into account. In the simulations we have assumed various degree of space-charge compensation (95 %, 90 %, 80 %, 40 % and 0 %) by varying the beam current from 5 % to 100 % of the maximum value 450 $\mu$A. The 2D beam profiles of the space-charge compensated and uncompensated beams at the location of VT1 differ significantly (see Fig. 5.4). The uncompensated beam develops a hollow core and also the effect of the initial plasma distribution on the beam formation is amplified by the space-charge forces (see hot spots in Fig. 5.4). Figs. 5.4 (a) and (c) and 5.3 show a less pronounced change in the spatial profile between 90 % and 100 % space-charge compensation. Fig. 5.5 shows a nearly linear increase of effective emittance with decreasing space-charge compensation. These simulations clearly show the importance of effective space-charge compensation.
Figure 5.4: Calculated spatial distributions (left column) and horizontal emittance (right column) of 450 µA He\(^+\) beam with various degrees of space-charge compensation behind the ground electrode at location VT1. The percentage indicates the degree of space-charge compensation assumed in the calculation.
5.4 Ion beam transport ($\text{He}^+$)

At the beginning of the LEBT system a double-focusing dipole magnet analyses the extracted beam and selects the ions with the required charge-to-mass ratio. The selected component is then transported through a series of bending and focusing elements to the injection system of the AGOR cyclotron. The imperfections in the optical elements as well as the large emittance of the ion beam extracted from the ECR ion source provide a difficult challenge for the design of the LEBT system. In order to study the properties of the system we have simulated the ion beam transport through the LEBT system. In this section we study the beam transport up to the image plane of the analyzing magnet (at the location of VT2) both with and without space-charge compensation. The ion beam transport through the LEBT system up to the matching section is discussed in chapter 6.

5.4.1 Transport of a fully-compensated $\text{He}^+$ beam

In this simulation the full 3D magnetic field of the analyzing magnet calculated with LORENTZ3D is taken into account. The phase-space distribution at the location of VT1 (see Fig. 5.3) is used as the input for the transport simulation.

We have calculated the ion beam trajectories through the analyzing magnet up to the image plane (VT2). From the ion trajectories we extract various two dimensional (2D) cross sections of the four-dimensional (4D) transverse phase-space, i.e. 2D beam profiles and emittance plots, which are compared with measurements. Fig. 5.6 shows the beam profile and emittance at the location of VT2. The triangular spatial distribution

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**Figure 5.5:** Effective emittance of the $\text{He}^+$ beam for different degree of space-charge compensation for a total extracted of $450 \mu\text{A}$ directly after the extraction system (VT1).
of the extracted beam at the location of VT1 (see Fig. 5.3) is distorted into a crescent-shaped distribution (see Fig. 5.6a). This is an indication of strong aberrations, in particular second-order, in the analyzing magnet. Because of this the horizontal and vertical emittances are also distorted. Quantitative details are discussed in chapter 7.

The calculated effective emittances of the transported beam in the horizontal and vertical plane are $360 \pi \ mm\ mrad$ and $240 \pi \ mm\ mrad$ respectively. The beam loss during the transport from the location of VT1 to VT2 is around 25 %. It is mainly due to the rather small vertical aperture of the magnet, which explains the smaller effective emittance in the vertical plane.

In order to visualize the correlations at the location of VT2 the phase-space distributions for various combinations of coordinates have been plotted in Fig. 5.7. These distributions clearly show a correlation between the horizontal and vertical phase-space coordinates. The colours indicate particle positions in the horizontal ($x$) direction at the
location of VT2 as shown in Fig. 5.7a. Comparison of the effective emittances before and after the analyzing magnet clearly shows the deleterious effects of the aberrations of the magnet.

The angle $R_p$ is calculated as,

$$R_p(x) = \frac{1}{N} \sum_{Y=1}^{N} \sqrt{X_p^2 + Y_p^2}$$

Figs. 5.7 (a) and (d) indicate that a correlation exist between the x-coordinate in the focal plane of the analyzing magnet and the transverse angle $R_p$, which is proportional to the transverse momentum of the particles. In Fig. 5.8 the average value of the angle $R_p$ is plotted as a function of the x-coordinate of the particles. Since the measured phase-space coordinates are relative values they have been shifted by the right amount to overlap with the simulated points. Both simulated and measured values (with the pepperpot emittance meter) are shown and agree well clearly exhibiting an almost linear correlation.

The simulation results show that the aberrations of the analyzing magnet and the large beam emittance cause a five-fold increase in the effective emittance. Therefore it
is very important to take into account higher-order effects in the design of ion optical systems of large emittance beams. A detailed study of a possible correction scheme for the second-order terms is discussed in chapter 7.

5.4.2 Transport of a partly-compensated $\text{He}^+$ beam

In analogy with the extraction simulation we have also performed a transport simulation of the ion beam from the location of VT1 to VT2 taking into account space-charge forces. We have used the calculated phase-space distribution at the location of VT1 shown in Fig. 5.4 (i) and (j), i.e. the totally uncompensated beam as initial conditions. Fig. 5.9 shows the calculated spatial and phase-space distributions at the location of VT2. The effective emittance of the transported beam increases significantly due to the space-charge force and aberrations of the analyzing magnet. In this simulation the calculated beam loss, mainly due to the small vertical aperture of the magnet, during the transport from the location of VT1 to VT2 amounts to about 60%. The horizontal and vertical emittances of the transported beam are $1300 \pi \text{ mm mrad}$ and $550 \pi \text{ mm mrad}$, respectively. Such a large increase in emittance is easy to measure, so that comparison with emittance measurements will show us how effective space-charge compensation really is.

5.5 Measurements

To validate the simulations discussed in the previous sections we have performed beam profile and emittance measurements. The beam profiles have been measured with viewing screens behind the extraction system at position VT1 and close to the image plane of
the analyzing magnet at position VT2. Furthermore the full 4D emittance has been measured with a pepper-pot emittance meter at location VT2 behind the analyzing magnet. The ECR ion source was tuned in such a way that the extracted ion beam was mainly $He^+$ ($\approx 500 \, \mu A$) with a minor $He^{2+}$ component ($\approx 65 \, \mu A$). The beam profile measurement system and the pepperpot emittance meter have been discussed in Sec. 4.4.

5.5.1 Beam profile

The measured beam profiles at viewing targets VT1 and VT2 are shown in Fig. 5.10 (a) and (b), respectively. During the measurement the background pressure in the beam-line was in the order of $10^{-7} \, mbar$. It should be noted that the beam profile measurement
Figure 5.11: Calculated spatial distributions at the location of MCP in the pepperpot emittance meter behind the analyzing magnet at location VT2 (a). Beam profiles of a 24 kV He\(^{+}\) beam measured by MCP through pepperpot at the location of \(x = 0\) m in the image plane of the analyzing magnet at VT2 (b).

using a \(\text{BaF}_3\) viewing target only gives qualitative information about the beam intensity of the incident beam because of saturation of the light yield with increasing current density.

A specific feature of the pattern shown in Fig. 5.1 is that the ion flux into the extraction aperture has a pronounced triangular symmetry. This results in a triangular shape of the extracted ion beams, which is confirmed in Fig. 5.10a. The same beam shape is also measured at other ECR ion sources, e.g., VENUS LEBT at LBNL [143]. Comparing the simulated beam profiles (see Figs. 5.3 and 5.4) with the measured beam profile at the location of VT1 (see Fig. 5.10a) favors the simulation of ion beam extraction with a degree of space-charge compensation \(\geq 95\%\) (see Figs. 5.3a and 5.4a). The size and shape of the simulated beam profile for the fully space-charge compensated beam is comparable with the measured beam profile at the location of VT1. However, there is a slight difference in the amount of beam rotation between the simulated and measured beams. This may be due to a slight difference between the actual and calculated fringe fields and/or the degree of space-charge compensation.

Similarly, the calculated beam profile at the location of VT2 (see Fig. 5.6a) is compa-
rable with the measured beam profile at the same location (see Fig. 5.10b). The calculated crescent-shaped beam profile also appears in the measurement at the location of VT2.

5.5.2 Emittance

A much more stringent test of the simulations is obtained by comparing them with measurements of the 4D transverse phase-space distribution of the beam. In order to do so we have replaced viewing target VT2 with a pepper-pot emittance meter [139, 144].

![Figure 5.12: Measured beam emittance of a 24 kV He$^+$ beam in the image plane of the analyzing magnet at location VT2, horizontal emittance (a) and vertical emittance (b).](image)

The measurement with the emittance meter was simulated with the calculated phase-space distributions of the transported ion beam at the location of the emittance meter, as displayed in Fig. 5.6. The calculated spatial distribution at the location of the MCP is shown in Fig. 5.11 (a). Fig. 5.11 (b) shows the measured spatial profile for He$^+$ ions using the pepperpot device with the holes in the pepperpot mask positioned at $x = 0$. The good agreement between the measurements and simulations demonstrates the validity of our full 3D simulations.

Fig. 5.12(a) and (b) show the horizontal and vertical 2D phase-space profiles extracted from the measured 4D phase-space data of the transported ion beam. The measured effective beam emittance in the horizontal plane is $390 \pi \text{ mm mrad}$ and in the vertical plane $320 \pi \text{ mm mrad}$. Comparison of the plots in Figs. 5.6 and 5.12, shows similar aberrations in both simulation and experiment. The size and shape of the simulated phase-space distributions are similar to those found experimentally. The good
agreement between simulation (see Fig. 5.6) and measurement clearly indicates that our simulations reproduce the basic mechanisms of beam formation, extraction and transport. Also the fringe fields and aberrations of the analyzing magnet seen to be well represented in the simulations.

5.6 Conclusions

We have simulated the extraction of a He\(^+\) beam from the KVI-AECR ion source and its transport through the analyzing magnet using the GPT and LORENTZ3D codes. The initial ion distribution was obtained using the PIC-MCC code. The good agreement between calculated beam profiles and emittance plots and measured ones shows that all relevant processes are properly incorporated in the simulations. It implies that this type of detailed simulations are a valuable tool to design optimized beam transport systems for large emittance low energy ion beams. We find that the He\(^+\) beam is essentially fully space-charge compensated up to a beam current of at least 0.5 mA and that the initial beam emittance is dominated by the conservation of canonical angular momentum.