Extraction and transport of ion beams from an ECR ion source
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Chapter 6

EXTRACTION AND TRANSPORT OF A MULTIPLE CHARGE STATE NEON BEAM

6.1 Introduction

In the previous chapter we have described simulations and measurements on an essentially mono-component \( He^+ \) beam. The comparison of simulations and measurements for this beam showed the validity of our simulation approach. In this chapter we broaden our simulations to a multi-component neon beam.

In Sec. 6.2 the simulation of multiple charge state neon beam formation at the plasma electrode using the PIC-MCC code [33] is discussed. The simulation of the extraction of this beam including space-charge effects with the GPT code [37] is then described in Sec. 6.3. Finally, in Sec. 6.4 the transport of a \( Ne^{6+} \) beam up to the matching section of the AGOR injection system is studied using the GPT and COSY INFINITY [23] codes.

6.2 Beam formation of \( Ne^{q+} \)

Just as for the \( He^+ \) simulation discussed in chapter 5 we use the PIC-MCC code to determine the phase-space distribution of the \( Ne^{4+} \) ions at the aperture of the plasma electrode which is then used as input for the subsequent extraction and transport simulations. In order to simulate a realistic case that can be compared with experiments we have chosen the relevant parameters in the PIC-MCC code such that the ion source is optimized for \( Ne^{6+} \) production, i.e. an electron temperature of 1 \( keV \) and gas pressure
Figure 6.1: Calculated (red) and measured (green) charge state distributions of neon ions at the location of VT2. In the calculated charge state distribution the simulated beam loss from the plasma electrode to the location of VT2 is taken into account.

Figure 6.2: Calculated spatial distribution of Ne$^+$ ions at the aperture of the plasma (a) and effective beam radius ($2\sigma$) for each charge state of the neon ions at the aperture of the plasma electrode (b).

of $6.8 \times 10^{-7}$ mbar. With these parameters we obtain a charge state distribution at the plasma electrode. In order to compare this charge state distribution with a measured one at the location of VT2 behind the analyzing magnet we have calculated the charge state dependent loss factors for the transport from the plasma electrode to VT2, see Sec. 6.4. Calculated and measured charge state distributions at VT2 are shown in Fig. 6.1 as can be seen, the overall agreement is good. The calculated beam current through the aperture
of the plasma electrode is around 2.25 mA.

The spatial distribution of the neon ions integrated over all charge states at the aperture of the plasma electrode is shown in Fig. 6.2a. The triangular shape is caused by the magnetic field configuration of the ECR ion source. Looking into more detail shows that the spatial extent of the distribution depends on the charge state: for higher charge states the spatial distribution becomes progressively smaller. The $2\sigma$ radius of the ion distribution as a function of the charge state is shown in Fig. 6.2b. The PIC-MCC code also calculates the ion temperature as a function of the charge state. The mean ion temperature inside the plasma is 0.25 eV, but Ne$^{1+}$ ions have a temperature of only 0.15 eV, while the ion temperature slowly increases with increasing charge state. More details about the influences of the electron density, temperature, ion confinement time and gas pressure are discussed in Ref. [33].

### 6.3 Ion beam extraction

The simulations of the multiple charge state beam extraction discussed in this chapter have been performed with the GPT code [37] including space-charge effects. 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 Ne$q^+$ ions by calculating their trajectories from the plasma electrode to the first viewing target VT1 behind the ground electrode of the extraction system, see Fig. 4.6. In this simulation a planar sheath with a thickness of 15 Debye lengths ($\approx 1$ mm) is assumed between the plasma electrode and the ECR plasma [142] and the plasma potential is assumed to be 20 V [78]. The phase-space distributions of the Ne$q^+$ ions at the plasma-electrode aperture obtained in Sec. 6.2 provide the initial conditions for the trajectory calculations.
Figure 6.3: Calculated spatial distributions (left column) and horizontal emittance (right column) of 2.25 mA Ne$^{n+}$ beam ($V_{ext} = 24$ kV) 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.
First we study in subsection 6.3.1 the extraction of a fully-compensated $Ne^{q+}$ beam, i.e. the ions are assumed to move independently without interacting with each other. In subsection 6.3.2 we study beam extraction including space-charge forces for various degrees of compensation. In all cases the plasma electrode is biased at +24 kV and the puller electrode at −300 V.

### 6.3.1 Extraction of a fully-compensated $Ne^{q+}$ beam

The ion trajectories have been calculated using the calculated 3D magnetic and electric fields of the ECR magnetic system and the extraction electrode system. From the trajectories the 4D phase-space distributions and various 2D projections at any location can be derived.

Fig. 6.3 (a) and (b) show the spatial profile and horizontal emittance of the multiple charge state neon beam at the location of viewing target VT1. The effective emittances of the beam in the horizontal and vertical planes are nearly identical. Values of the effective normalized horizontal emittance as a function of the charge state obtained from the simulation are given in Fig. 6.4. Comparison of the simulation results with those according to eq. (3.10) shows a clear discrepancy. According to Busch’s theorem the emittance of a beam formed in a magnetic field is proportional to the square of the initial radius (see Eq. 3.10). Fig. 6.2b shows that the effective radius of the spatial distribution...
Figure 6.5: Effective emittance of the neon beam for different degree of space-charge compensation for a total extracted of $2.25 \, \text{mA}$ direct after the extraction system (VT1).

Figure 6.6: Measured beam profiles of a $24 \, \text{kV}$ multiple charge state neon beam behind the ground electrode at location VT1.

of ions extracted from an ECR ion source depends on the charge state, with higher charge state ions concentrated more along the axis than lower charge state ions. Therefore, the effective extraction radius is smaller for highly charged ions. This reduces the dominance of the magnetic field emittance ($\propto r^2$) over the ion temperature emittance ($\propto r$) for highly charged ions. The simulated emittances agree reasonably well with measurements performed at other ECR ion sources, e.g., VENUS LEBT at LBNL [103, 145].
6.3 Ion beam extraction

Figure 6.7: Calculated spatial distribution for a 90 % space-charge compensated \( Ne^{q+} \) beam at location VT1. The various colour indicates the different charge state of the neon beam.

### 6.3.2 Extraction of a partly-compensated \( Ne^{q+} \) beam

For a fully space-charge compensated beam the nominal current is zero, while for a totally uncompensated beam the nominal current in the simulation would be 2.25 mA. This agrees very well with experimental values. The currents for the individual charge states correspond to their fraction in the beam according to the simulated charge state distribution in Fig. 6.1. The effects of space-charge on the extraction process have been calculated by increasing the nominal beam current in the simulation.

Fig. 6.3 also shows calculated 2D beam profiles and emittances at the location of the viewing target VT1 (behind the extraction system) for varying degrees of space-charge compensation. In this simulation we assume different levels of neutralization (100 %, 90 %, 80 % and 70 %), i.e. the simulation has been performed for beam currents of 0 % to 30 % of total beam current (2.25 mA). The sizes of the 2D beam profiles and consequently the emittances at the location of VT1 depend significantly on the degrees of space-charge compensation. Fig. 6.5 shows a strong increase of effective emittance with decreasing space-charge compensation. These simulations clearly show the importance of effective space-charge compensation in the extraction system.

As a first test of these simulations we have performed a beam profile measurement. The beam profile has been measured with a viewing screen behind the extraction system at position VT1. During the measurement the background pressure in the beamline was of the order of \( 10^{-7} \) mbar. Fig. 6.6 shows the measured spatial profile of the extracted neon beam. The total extracted current was restricted to 700 \( \mu A \) in order to prevent damage to the viewing target (sputtering and saturation of the light yield, etc.).

In addition to the emittance increase, effects of the ECR magnetic field on the spa-
tial distribution at the plasma electrode appear to be magnified due to the space-charge forces (see hot spots in Figs. 6.3 (c), (e), and (g)). During the beam extraction each ion acquires a kinetic-energy determined by the applied extraction potential and the charge state. The fringe field of the extraction solenoid causes a net beam rotation according to the Lorentz force as discussed in Sec. 3.3.4. In order to show the influence of the extraction solenoid of the ECR ion source on the extraction a multiple charge state neon beam the spatial profiles of the different charge states is shown in Fig. 6.7 for a 90% space-charge compensated beam. The figure shows a noticeable difference in rotation and size of the different charge state extracted from the ECR ion source.

Comparing the simulated beam profiles (see Fig. 6.3) with the measured beam profile at the location of VT1 (see Fig. 6.6) clearly favors the model with space-charge compensation higher than 90%. The size and shape of the simulated beam profile for the fully space-charge compensated beam (see Fig. 6.3a) is comparable with the measured beam profile.

6.4 Transport of Ne\(^{6+}\) beam

To study the properties of the LEBT system we have extended our simulations to a full beam transport through the entire LEBT system. However, because of the large amount of computational time we have only calculated the transport of the multiple charge state beam in 3D up to the location of VT3 behind the 90° bending magnet (see Fig. 4.6). For the transport up to the matching section of the LEBT system a beam envelope calculation with COSY INFINITY was performed.

The phase-space distribution of the fully space-charge compensated beam calculated at the location of VT1 (see Fig. 6.3a) is used as the starting condition for the transport simulation.

6.4.1 Full 3D simulation

The extracted multiple charge state ion beam (Ne\(^{q+}\)) from the ECR ion source is transported through the double-focusing analyzing magnet. The magnetic field strength of the analyzing magnet is tuned for transmission of Ne\(^{6+}\) ions. The transmitted Ne\(^{6+}\) ions are then further transported through the quadrupole triplet, electrostatic quadrupole and 90° bending magnet. From the calculated ion trajectories we then extract various two-dimensional (2D) cross sections of the four-dimensional (4D) transverse phase-space, e.g., 2D beam profiles and emittance plots, which will be compared with measurements. In Fig. 6.8 the calculated beam profile and emittances of the Ne\(^{6+}\) beam at the location of VT2 are displayed. The plot shows the distorted phase-space distributions of the Ne\(^{6+}\) beam. Similar experimental and simulation results have been reported in chapter 5 for the He\(^{+}\) beam. As discussed in chapter 5 the ion-optical aberrations and the large emittance...
6.4 Transport of $Ne^{6+}$ beam

Figure 6.8: Calculated spatial distributions for a fully space-charge compensated $Ne^{6+}$ beam in the image plane of the analyzing magnet at location VT2 (a). Calculated horizontal (b) and vertical (c) emittance plot of a fully compensated $Ne^{6+}$ beam at the same location VT2.

Figure 6.9: Calculated spatial profile (a) and phase profile $(X_p, Y_p)$ (b) behind the analyzing magnet at location VT2. Colours indicate the particle position in the horizontal direction $(x)$ at the location of VT2. Calculated radius $R_p$ as a function of $X$ in the image plane of the analyzing magnet at location VT2 (c).
Figure 6.10: Calculated spatial distributions for a fully space-charge compensated Ne\textsuperscript{6+} beam behind the 90° bending magnet at location VT3 (a). Calculated horizontal (b) and vertical (c) emittance plot of a fully compensated Ne\textsuperscript{6+} beam at the same location VT3.

of the ion beam extracted from the ECR ion source determine the efficiency of the beam transport. They lead to an increase of the effective emittance both in the horizontal and vertical planes. The calculated effective emittances of the transported beam in the horizontal and vertical plane are 345 \( \pi \) mm mrad and 240 \( \pi \) mm mrad, respectively, whereas the effective emittance at the location of VT1 is 66 \( \pi \) mm mrad. The beam loss during the transport from VT1 to VT2 according to the calculation is approximately 25 %.

Fig. 6.9b shows the phase-phase profile \((X_p, Y_p)\) at the location of VT2 behind the analyzing magnet. In the plot particles with a specific X-coordinate (see Fig. 6.9a) are indicated with different colours. The calculated angle \(R_p\) (see Eq. 5.1) at various \(x\) positions is shown in Fig. 6.9c. Fig. 6.9c clearly indicates that particles with larger transverse components are deflected more in the horizontal direction due to their smaller longitudinal momentum.

For the transport of the beam from VT2 to VT3 the settings of the quadrupole triplet and electric quadrupole are taken from typical experimental settings for Ne\textsuperscript{6+} beam trans-
6.4 Transport of Ne\textsuperscript{6+} beam

Figure 6.11: Measured beam profiles of a 24 kV Ne\textsuperscript{6+} beam behind the 90° bending magnet at location VT3.

port. The matching is not perfect with the acceptance of the 90° bending magnet because of the large initial emittance from the ECR ion source and the distorted phase-space distribution after the analyzing magnet. Fig. 6.10 shows the simulated beam profile and emittances of a Ne\textsuperscript{6+} beam at the location of VT3 behind the 90° bending magnet. The calculated effective emittances of the transported beam in the horizontal and vertical planes are 265 $\pi\ mm\ mrad$ and 210 $\pi\ mm\ mrad$ respectively. During the beam transport the particles that are far from the beam axis are lost explaining the decrease in effective emittance between VT2 and VT3. The calculated beam loss during the transport from the location of VT2 to VT3 is around 20 %. A measured beam profile at the location VT3 is shown in Fig. 6.11. The size and shape of the simulated beam profile of the Ne\textsuperscript{6+} beam is similar to the measured one.

6.4.2 Beam envelope simulation

In addition to the 3D simulations we have also calculated the beam envelope using the code COSY INFINITY [23] up to third-order. The fringe fields of the optical elements are taken into account using built-in models [39]. In order to calculate the beam envelope through the LEBT system we defined an initial emittance of 65 $mm\ mrad$ for the Ne\textsuperscript{6+} beam at the location of the plasma electrode with an energy of 144 keV.

The calculated beam envelope plot for the Ne\textsuperscript{6+} beam is shown in Fig. 6.12. In order to estimate the increase in effective emittance through the LEBT system we have calculated the transfer map of the beamline from the location of VT2 to the location of
VT4 behind the M72 magnet (see Fig. 6.12) using the COSY INFINITY code. As discussed in the previous section the full 4D phase-space distribution of the Ne$^{6+}$ beam at the location of VT2 behind the analyzing magnet is known from the 3D simulations. By applying the transfer map calculated with COSY INFINITY to this phase-space distribution we can estimate the effective emittance at the location of VT4. Fig. 6.13 shows the effective emittance at the locations of VT1, VT2 and VT4 as a function of the fraction of the beam intensities included in the calculation. Comparison with the acceptance of the AGOR cyclotron, i.e. 140 $\pi$ mm mrad, shows that approximately 40 % of the extracted particles from the AECR ion source falls within this acceptance. Because the two transverse planes are decoupled the overall transmission into the cyclotron will then be in the range 15 — 20 %. Comparison of COSY INFINITY calculations up to second
6.5 Conclusions

We have simulated the extraction of a multiple charge state neon beam from the KVI-AECR ion source and its transport through the LEBT system using the GPT, LORENTZ3D and COSY INFINITY codes. The initial ion distribution was obtained with the PIC-MCC code. The properties of multiple charge state neon beam formation and extraction has been studied. The good agreement between simulations and measurements clearly indicates that our simulations reproduce the basic mechanisms of multiple charge state ion beam formation, extraction and transport. We find that the Ne\(^{6+}\) beam is fully space-charge compensated up to a beam current of at least 0.7 \textit{mA} and that the initial beam emittance is dominated by the conservation of canonical angular momentum. Our calculation show that the large beam losses observed can be explained by a combination of a large initial emittance of the beam and strong aberrations, particularly in the dipole magnets. There is no need to involve space-charge effects to explain the observed beam losses for the Ne\(^{6+}\) beam, which typically has an intensity of 350 \textmu A at the location

Figure 6.13: Calculated effective emittance in the horizontal plane (a) and in the vertical plane (b) of the Ne\(^{6+}\) beam at various locations of the LEBT system. Calculation at location VT1 and VT2 has been performed with GPT. Calculation at location VT4 has been performed with COSY INFINITY. In this plot losses along the beamline has been taken into account from VT1 to VT2 only. At location VT1 the emittance 140 \textit{pi mm mmrad} encloses nearly one 100 % of extracted particles from the source.

and third-orders shows little difference, which indicates the dominance of second-order effects as has also been deduced from the full 3D simulations.
VT2, despite the fact that electrostatic quadrupoles are used, which are expected to destroy space-charge compensation. The observed transmission of the $Ne^{6+}$ and similar beams from the ECR source to accelerated beam in the cyclotron, taking into account the cyclotron longitudinal acceptance and the beam losses in the analyzing magnet, is in good agreement with the prediction of the complete simulation.