Extraction and transport of ion beams from an ECR ion source
Saminathan, Suresh

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2011

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Saminathan, S. (2011). Extraction and transport of ion beams from an ECR ion source University of Groningen: s.n.

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Chapter 8

EXTRACTION AND TRANSPORT AT THE GSI-EIS BEAMLINE

8.1 Introduction

In the framework of the KVI-GSI collaboration we have performed a simulation study of the extraction and transport of ion beams for the ion source test stand at GSI consisting of a CAPRICE ECR ion source [152] and the EIS beam analyzing system [153]. Section 8.2 briefly describes the CAPRICE ECR ion source and the EIS test bench at GSI. A simulation of He\(^+\) beams and measurements for this beam at location VT2 behind the beamline solenoid (see Fig. 8.1) is presented in Sec 8.3.

Furthermore, simulations have also been performed for Ar\(^{7+}\) beams with two different initial distributions, one calculated with the KOBRA3D-INP code [114] and the other one calculated with our PIC-MCC code [33]. The results are presented in Sec. 8.4. The simulations reported in this chapter assume fully space-charge compensated beams and concentrate on possible effective emittance growth due to ion-optical aberrations of the beamline elements.

8.2 CAPRICE and EIS test bench

The CAPRICE ECR ion source and the EIS test bench at GSI are schematically shown in Fig. 8.1. Three diagnostic chambers with viewing targets are installed at the EIS test bench, i.e. VT1 located directly behind the extraction system of the ion source, VT2 near
the location of the focal plane behind the beamline solenoid, while the third one, VT3, is located at the image plane of the analyzing system. A magnetic quadrupole has been installed in front of the dipole magnets to optimize the matching of the extracted ion beam to the acceptance of the analyzing system and at the same time improve its mass resolution. Emittance monitors can be installed at the locations of VT1 and VT3.

A schematic view of the CAPRICE ion source is shown in Fig. 8.2. The source has a relatively small plasma chamber with a length of 16 cm and a diameter of 6.6 cm. The axial mirror field is produced with two solenoids generating a magnetic field profile along the axis as shown in Fig. 8.3. The hexapole field is produced with a NdFeB permanent magnet in the Hallbach configuration [154]. The maximum field of this magnet at the plasma chamber wall is approximately 0.9 T. The electrons in the plasma of the CAPRICE source are resonantly heated with 14 GHz microwaves which are injected along the axis of the plasma chamber by a coaxial waveguide.

The ion beams are extracted from the ion source with an accel-decel extraction system (see Fig. 8.4). The extraction system consists of three electrodes: a plasma electrode with an aperture of 10 mm, a puller electrode with an aperture of 16 mm and a ground electrode with a maximum inner diameter of 40 mm. In all simulations we assumed that the plasma electrode is biased at +14.2 kV and the puller electrode at −1 kV.

A focusing solenoid is located behind the extraction system. The two dipole magnets of the analyzing system are equipped with shims and clamps to minimize aberrations. These could not be taken into account in our analysis because the drawings of these parts were not available.

8.3 Extraction and transport of \( \text{He}^+ \) beam

To simulate the extraction of the ion beam from the source and its subsequent transport through the low-energy beamline we used the General Particle Tracer (GPT) code [37]. For the quadrupole and dipole magnets the internal models of GPT were used. These models use realistic second-order fringe fields. More details of the GPT code are discussed in Sec. 2.4. Our previous calculations for the KVI-AECR ion source show that the fringe field of the hexapole magnet has a negligible effect on the trajectories of the extracted ions. Therefore, we did not include the fringe field of the hexapole magnet in the present beam extraction and transport simulations. We used the POISSON code [157] to calculate the solenoid magnetic field of the ion source, the electric fields in the extraction system and the magnetic field of the focussing solenoid, which all have axial symmetry.

In this section the results of a 14.2 keV mono-component \( \text{He}^+ \) beam is presented. For this beam a clean comparison with beam profile and emittance measurements is possible. The initial phase-space distribution of the \( \text{He}^+ \) ions in the plane of the plasma electrode aperture has been calculated with the PIC-MCC code. In this simulation a
8.3 Extraction and transport of $He^+$ beam

Figure 8.1: EIS test bench [155].

Figure 8.2: ECR ion source CAPRICE [156].
plasma sheath as described in chapter 5 was used. Furthermore, our previous simulation results presented in chapter 5 and chapter 6 show space-charge forces are negligible for the range of ion currents considered here. Therefore, we also assume that the beam is fully space-charge compensated, i.e. that the effective beam current is zero.

The effective emittance value of the extracted beam at the location of VT1 directly behind the extraction system is 140 \( \pi \ mm \ mrad \) in both planes. The method for calculating the effective emittance is discussed in Sec. 2.2.2. The spatial profile and transverse phase-space distribution in the horizontal plane at the location of VT2 behind the solenoid are shown in Fig. 8.5 for a few different settings of the solenoid current. For the horizontal and vertical effective emittances of the \( He^+ \) beam at this location we find values of approximately 160 \( \pi \ mm \ mrad \) in both planes.
8.3 Extraction and transport of \(He^+\) beam

Figure 8.5: Top row: Calculated spatial distribution of a 14.2 keV \(He^+\) beam at the location of VT2 behind the beamline solenoid with increasing focusing strength of the beamline solenoid (from figure left side to right). Bottom row: Calculated phase-space distribution in the horizontal plane of the same beam.

Figure 8.6: Calculated spatial distribution of the \(He^+\) beam at the location of VT3 behind the analyzing system (a). Horizontal (b) and vertical (c) phase-space distributions at the location of VT3.

The magnetic quadrupole in front of the analyzing magnets has been optimized to match the acceptance of the analyzing magnets. We then transported the beam through the analyzing magnets and calculated both the spatial and transverse phase-space distributions in the center of diagnostics box VT3 behind the analyzing system. These are shown in Fig. 8.6. Calculated horizontal and vertical effective emittances of the \(He^+\) beam in the image plane of the analyzing magnet are 340 \(\pi \text{ mm mrad}\) and 200 \(\pi \text{ mm mrad}\), respectively. This is significantly larger than the effective emittances calculated in front of the analyzing system and caused by non-paraxial effects and ion-optical aberrations. However, the real emittances might be slightly smaller than the calculated ones, because we did not take into account the real fringe fields of the analyzing system. The calculated transmission for the \(He^+\) beam from the ground electrode to the image plane of the
Figure 8.7: Measured beam profiles of a He$^+$ beam at the location of VT2 behind the beamline solenoid with increasing focusing strength from figure (a) to (c). Measured beam profiles of a He$^+$ beam at the location of VT3 behind the analyzing (d) [158].

Comparison of the calculated beam profiles in Fig. 8.5 with the measured beam profiles (see Fig. 8.7) at the location of VT2 behind the beamline solenoid shows that the shape of the simulated beam profiles are similar to those found experimentally. The transport simulations through the solenoid show that the beam has a hollow core and large aberrations in the focal plane of the solenoid for both sets. The large initial emittance of the beam extracted from the ECR ion source causes it to fill the aperture of the solenoid to a very large extent and therefore the spherical aberrations of the solenoid [18] strongly influence the image quality. Charged particles far from the optical axis experience a stronger force and will cross the axis before those particles that are more close to the axis. This leads to the hollow beam profile at the location of VT2 (see Figs. 8.10 and 8.11). It has been reported that the use of a solenoid in LEBT systems can lead to significant beam degradation and hollow beams [125, 149, 150, 159–162], in particular...
8.4 Extraction and transport of \( \text{Ar}^{7+} \) beam

For intense multiple-charge state beams. The proposed explanation is that this is caused by a strong focusing of particles with a higher charge-to-mass ratio compared to particles with a smaller charge-to-mass ratio. The space charge forces then push the particles with a smaller charge-to-mass ratio radially outward. Our simulations show, however, that even without space-charge effects a solenoid can produce a hollow beam profile because of image aberrations. Also the calculated beam profile at the location of VT3 behind the analyzing magnet (see Fig. 8.6a) exhibits similar features as the measured beam profile at the same location (see Fig. 8.7d). The qualitative agreement between simulation and measurement clearly indicates that our simulations reproduce the basic mechanisms of beam formation, extraction and transport.

For the simulation of an \( \text{Ar}^{7+} \) beam we have used two sets of initial condition in order to assess their influence. Set A has been calculated with the KVI PIC-MCC code. In this calculation the geometry and magnetic field configuration of the GSI CAPRICE ECR ion source have been used. The initial conditions of set A are given at the plasma electrode of the source.

Set B has been calculated with the KOBRA3-INP code also using the geometry and magnetic field configuration of the same source. In this set the initial conditions are defined at the location of viewing target VT1, at the exit of the extraction system. The data were provided by Mr. P. Spädtke, GSI. Both sets contain around 64000 particles. For a direct comparison of both sets the particles of set A were tracked through the extraction system and the fringe field of the ion source to the location at which B has been specified.

The spatial distribution and emittances for both sets at the location VT1 are displayed in Figs. 8.8 and 8.9. The effective emittance of set A amounts to 120 \( \pi \text{ mm mrad} \), while for set B it is 510 \( \pi \text{ mm mrad} \). We attribute the large difference between these two values to the different radial dependence of the ion density distribution across the plasma electrode aperture for sets A and B. Only emittance measurements directly after the extraction system will resolve this issue.

For the subsequent beam transport simulations the current through the solenoid and the setting of the quadrupole have been optimized to obtain a minimum beam spot size in the focal plane of the solenoid and a maximum transmission through the analyzing system. The same settings have been used for both sets. We assumed full space-charge compensation in the simulations. The spatial profile, horizontal and vertical phase-space distributions of the \( \text{Ar}^{7+} \) beam in set A at the location of VT2 are shown in Fig. 8.10. Fig. 8.11 shows the profiles of the ion beam for set B at the same location. The beam was then tracked through the analyzing magnets and the spatial and transverse phase-space distributions of the \( \text{Ar}^{7+} \) beam in the center of the diagnostics box (at the location VT3)
behind the analyzing system were calculated for both sets of initial conditions. These distributions are shown in Fig. 8.12 for the beam in set A and in Fig. 8.13 for the beam of set B. Because of its large emittance 40 % of the beam is lost during the transport for set B, while for set A the transmission is 100 %. For the Ar$_7^+$ beam we observe a hollow core in the focal plane of the solenoid with both datasets (see Figs. 8.10 and 8.11), similar to what was found for the He$_3^+$ beam.

In the previous chapter it has been shown that it is very important to reduce the filling of the analyzing magnet, in particular in the vertical direction that usually has the smallest gap, in order to minimize beam losses and aberrations. In the GSI low energy beamline this reduction of the vertical beamsize in the analyzing magnets is done with the solenoid and a subsequent vertically focusing quadrupole. However, the simulation results show that the solenoid produces large aberrations with a hollow beam profile. As a result the effective emittance after the beam transport through the analyzing magnet is significantly
Figure 8.10: Calculated spatial distribution of the $Ar^{7+}$ beam with initial set A at the location of VT2 behind the beamline solenoid. Horizontal (b) and vertical (c) phase-space distributions at the location of VT2.

Figure 8.11: Calculated spatial distribution of the $Ar^{7+}$ beam with initial set B at the location of VT2 behind the beamline solenoid. Horizontal (b) and vertical (c) phase-space distributions at the location of VT2.

increased. The phase-space distributions of the $Ar^{7+}$ beam at the location of VT3 behind the analyzing magnets are rather similar for both initial distributions, although the spatial distribution of set B shows some hot spots that are absent in the simulation for set A. The ion beam transported through the solenoid and the analyzing magnet has a large effective emittance because of the aberrations of the solenoid and the dipole magnets and the large initial emittance, in particular for the set B. The horizontal and vertical effective emittances for the set A beam in the image plane of the analyzing magnet are $220 \, \pi \, mm \, mrad$ and $205 \, \pi \, mm \, mrad$, respectively. The effective emittance values for the set B beam at this location are $300 \, \pi \, mm \, mrad$ and $450 \, \pi \, mm \, mrad$, respectively.

8.5 Conclusions

We have performed simulations of extraction and transport of $He^+$ and $Ar^{7+}$ beams for the CAPRICE ECR ion source and EIS test bench at GSI, Darmstadt. The results of $He^+$ beam have been compared with measurements at the location of VT2 behind the beamline solenoid. The qualitative agreement between calculated beam profiles and measured ones
Figure 8.12: Calculated spatial distribution of the $\text{Ar}^{7+}$ beam with initial set A at the location of diagnostics box VT3 behind the analyzing system. Horizontal (b) and vertical (c) phase-space distributions at the location of VT3.

Figure 8.13: Calculated spatial distribution of the $\text{Ar}^{7+}$ beam with initial set B at the location of diagnostics box VT3 behind the analyzing system. Horizontal (b) and vertical (c) phase-space distributions at the location of VT3.

shows that the basic physics is well reproduced in the simulations.

The spherical aberration of the solenoid in combination with the large beam size results in a hollow beam profile in its focal plane. Previously this phenomenon has been solely attributed to space-charge effects; our simulation shows that there is no need to invoke space-charge effects to produce this phenomenon.

From a comparison of the simulations for the test bench at GSI and the setup of the AECR ion source at KVI we draw the following conclusions:

- The insertion of a solenoid between the ion source and the analyzing magnet leads to a significant increase of the effective emittance already before the analyzing magnet and thereby amplifies the effect of the aberrations of the analyzing magnet itself and increases the beam losses in the system.

- The use of a vertically focussing quadrupole in front of the analyzing magnet reduces the beamsize in the fringe fields at the entrance and exit of the magnet and thereby reduces the effect of the aberrations on the effective emittance of the charge state analyzed beam. It is preferable to use a magnetic lens for two reasons: the space-charge compensation in this high intensity region is not adversely affected...
and the different charge states will be vertically focussed at different locations along the beam axis, thus reducing space-charge effects.