TRANSVERSE PHASE-SPACE DISTRIBUTIONS OF LOW ENERGY ION BEAMS EXTRACTED FROM AN ECR ION SOURCE*

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Abstract

Transverse phase-space distributions of low-energy ion beams extracted from ECR ion sources often show higher-order effects caused by ion-optical aberrations. Understanding these effects is mandatory to keep emittance growth and the resulting beam losses in low-energy beam transport lines under control. We present results of an experimental and theoretical study of beam extraction and transport in the AGOR injection line at KVI. Particle tracking simulations have been performed of a multi-component neon ion beam extracted from an ECR ion source to calculate 4D phase-space distributions at various positions along the beam line. The simulations compare well with beam profile and emittance measurements.

INTRODUCTION

Ion beams extracted from Electron Cyclotron Resonance (ECR) ion sources have relatively large and correlated transverse emittances compared to other types of ion sources. This, together with the high currents (up to tens of mA's) and low energies (up to tens of keV/amu) of the extracted multiply-charged ion beams often leads to significant losses during the subsequent beam transport. This is even a greater problem in the new generation of fully superconducting ECR ion sources because of their larger magnetic fields and extracted ion currents. Much work is being done by various groups to better understand and minimize these beam losses using beam diagnostic and/or simulation tools. However, there are often significant discrepancies between quantitative simulations and measurements, see e.g. [1]. Reasons for these disagreements could be a poor knowledge of the initial phase-space distributions of the extracted ion beams and/or poor handling of higher-order beam effects.

At the AGOR cyclotron facility of the Kernfysisch Versneller Instituut (KVI), University of Groningen, we have performed a study of the formation and extraction of helium and neon ion beams from the KVI ECR ion source and the subsequent transport through the low-energy beam line [2]. The study consists of detailed simulations of beam transport and measurements of beam profiles and transverse emittance distributions at various locations along the beam line. To check the validity of this approach we have first applied it to an essentially mono-component He^{+} beam [3]. The simulation results compare very well, both qualitatively and quantitatively, with measurements. Here we present the results of simulations and beam profile measurements of a multi-component neon beam. First we briefly describe the experimental setup and simulation tools, then the results are presented and discussed and we finish with conclusions and outlook. In both simulations and measurements described below the parameters have been chosen such as to optimize the production and transport of a Ne^{6+} ion beam with a kinetic energy of 144 keV.

EXPERIMENTAL SETUP AND SIMULATION TOOLS

The KVI-AECR (Advanced Electron Cyclotron Resonance) ion source and first section of the low-energy beam transport line including the 110° analyzing and 90° bending magnets, a magnetic quadrupole triplet and electrostatic quadrupole singlet and three BaF_2 viewing targets VT1-3 are schematically shown in Fig. 1. The ion source is a 14 GHz AECR ion source with an electrostatic accel-decel extraction system and is described in detail in Ref. [4]. The analyzing magnet is a double-focusing one with a geometrical acceptance of 120 mm in the horizon-

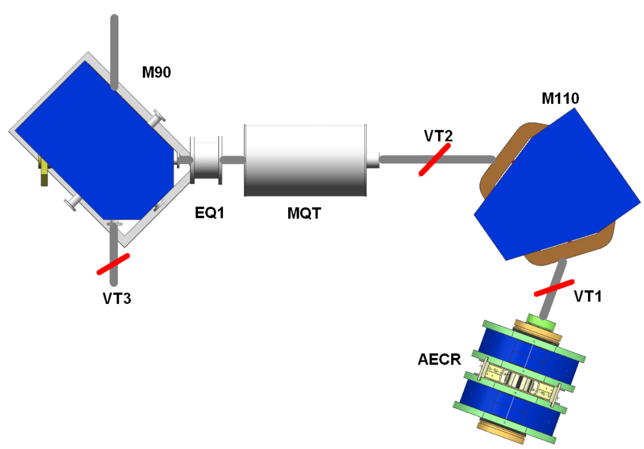

Figure 1: AECR ion source and first section of the low energy beam transport line. The locations of the three viewing screens are indicated as VT1, VT2 and VT3.

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tal and 60 mm in the vertical direction. Viewing targets VT1 and VT2 can be inserted into the beam line before and behind the analyzing magnet, respectively, to measure the spatial distribution of the ion beams. VT1 is positioned at a distance of 334 mm in front of the effective field boundary of the analyzing magnet, while VT2 is located close to the image plane of this magnet. Instead of VT2 we can also insert a pepper-pot emittance meter to measure transverse phase-space distributions [5], but this has not been used in the present work. Leaving the analyzing magnet the ions are guided to a 90° bending magnet by two focusing elements, i.e. a magnetic quadrupole triplet and an electrostatic quadrupole singlet. The 90° magnet has a cylindrically-shaped magnet yoke and bends the ions either clockwise towards the cyclotron or anti-clockwise towards viewing target VT3.

The simulations consist of two parts. We first use a Particle-In-Cell Monte-Carlo Collision (PIC-MCC) code to simulate the ion dynamics in the ion source plasma and to calculate the phase-space distribution of Ne^{q+} ions at the 8 mm diameter aperture of the plasma electrode. The code uses a realistic 3D representation of the min-B magnetic field geometry of the ion source. The electron dynamics is not calculated. Instead, it is assumed that the electron distribution is given by a single Maxwellian with the electron density determined by the requirement of charge neutrality and the electron temperature taken as a free parameter. A more detailed description of the PIC-MCC code can be found in Ref. [6].

The phase-space distribution of the ions at the plasma electrode is then used to extract initial conditions for the subsequent trajectory simulation of the extraction and transport of the ion beam. The 3D trajectory calculations have been done with the GPT code which takes space-charge forces into account [7]. Beam extraction is determined by the ion motion in the plasma sheath that separates the plasma from the plasma electrode. Ions starting in the plasma electrode aperture are accelerated in the electric field of the plasma sheath to an energy equal to the plasma potential (assumed to be 20 V). The 3D electric and magnetic fields in the extraction region (including the solenoid and hexapole fields of the ion source) and the magnetic field of the analyzing magnet have been calculated with the Lorentz3D code [8]. Internal models of the GPT code have been used to calculate the fields of the electric and magnetic quadrupoles and 90° bending magnet in the beam line section behind the analyzing magnet. In this way the 4D transverse phase-space distributions of the ion beam at the positions of VT1-3 have been calculated from which spatial beam profiles and transverse beam emittances can be extracted and compared with measurements.

RESULTS

First we have calculated the extraction and transport of a multi-component Ne^{q+} beam up to the position of VT2 taking space-charge forces into account. As already mentioned, the simulations have been performed for the case where the ion source is optimized for Ne^{6+} production. For this we had to set the electron temperature in the PIC-MCC code to a value of 1 keV. The total extracted neon current (integrated over all charge states) was calculated to be 2.25 mA and is in good agreement with experimental values.

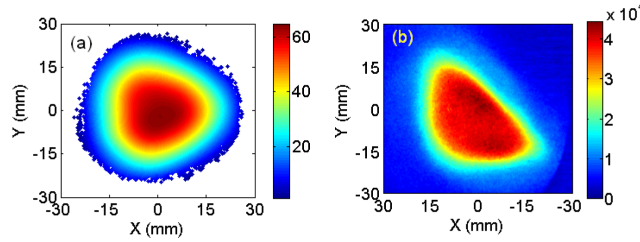

Figure 2: Calculated (a) and measured (b) profiles of a multi-component neon beam behind the extraction system at the location of VT1. The extraction voltage is 24 kV.

In practice ion beams are always space-charge neutralized to a certain degree by (secondary) electrons that are produced in collisions between beam ions and the residual background gas and/or by ion-wall interactions. We have tried to determine the degree of space-charge compensation without taking the electrons explicitly into account by performing simulations with varying effective beam current. The degree of space-charge compensation has been varied between 100% and 70%, with 100% compensation corresponding to zero effective beam current and 70% to 0.675 mA effective current. The simulations show a strong effect of the degree of space-charge compensation on both the spatial and emittance distributions of the beam at the location of VT1. As can be expected, the beam sizes and emittances increase significantly with decreasing degree of space-charge compensation. Moreover, the calculated beam profiles show clear structures with hot spots and hollow cores when the beam is not fully space-charge compensated [2]. However, the measured beam profile at VT1 (Fig. 2) is very smooth and does not show any structures. From this we conclude that the neon beam is fully space-charge compensated. In all following simulations we have therefore assumed a fully space-charge compensated beam.

The phase-space distribution calculated at the location of VT1 has been used as initial distribution for the subsequent beam transport line. We have calculated the ion beam trajectories through the analyzing magnet, quadrupole focusing elements and 90° bending magnet up to the VT3 and extracted from these beam loss factors, beam profiles and transverse beam emittances. Using the beam loss factors we have calculated the charge-state distribution of the neon beam at the location of VT2 behind the analyzing magnet. This is shown in Fig. 3 together with a measured charge-state distribution. Calculated and measured charge-state distributions agree very well.

The simulations show that during the transport of the Ne^{6+} beam from VT1 to VT2 the beam emittances increase with a factor between 4 and 5, i.e. from a value of

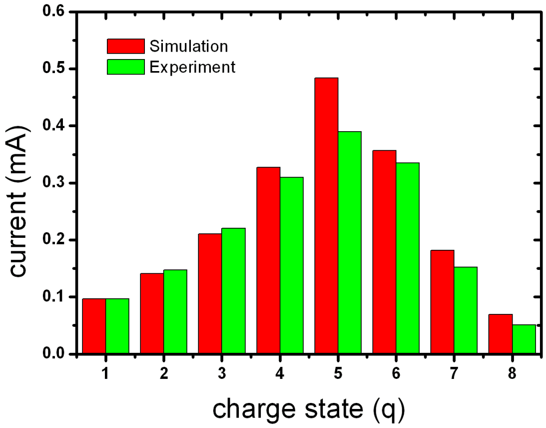

Figure 3: Calculated and measured charge-state distributions of neon ions at the location of VT2.

66 π mm-mrad at VT1 to 345 π mm-mrad for the horizontal and 240 π mm-mrad for the vertical emittance at VT2 [2]. These values refer to the 4-rms emittance [9]. The emittance blow-up is caused by strong second-order aberrations of the analyzing magnet. The beam loss during transport of the beam through the analyzing magnet is calculated to be approximately 25 % and is mainly caused by the rather small vertical aperture of the magnet, which also explains the smaller vertical emittance. The same effects also occur in the He^+ simulations and can be ameliorated to a large extent by adding suitable hexapole components to the dipole field of the analyzing magnet to correct its second-order aberrations. We estimate that this would increase the overall beam transmission from 16% to 45% [2].

Finally, Fig. 4 shows a calculated beam profile and transverse beam emittances of a 24 kV Ne^{6+} beam at the location of VT3 behind the 90° bending magnet. A measured beam profile at this location is shown in Fig. 5 and, as can be seen, the agreement is reasonably good.

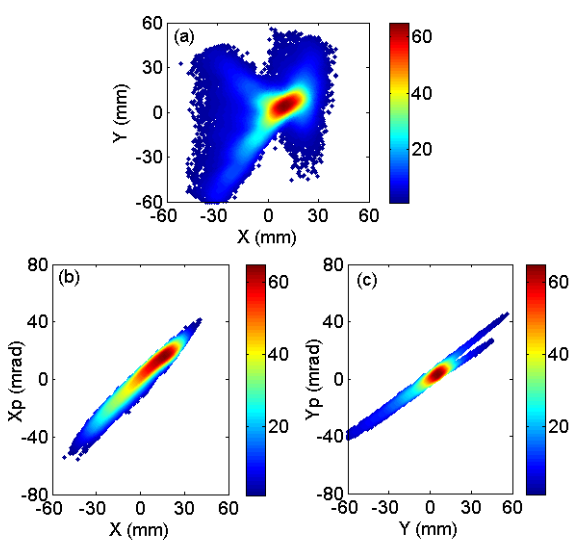

Figure 4: Calculated beam profile (a), horizontal (b) and vertical (c) beam emittances of Ne^{6+} beam behind the 90° bending magnet at the location of VT3.

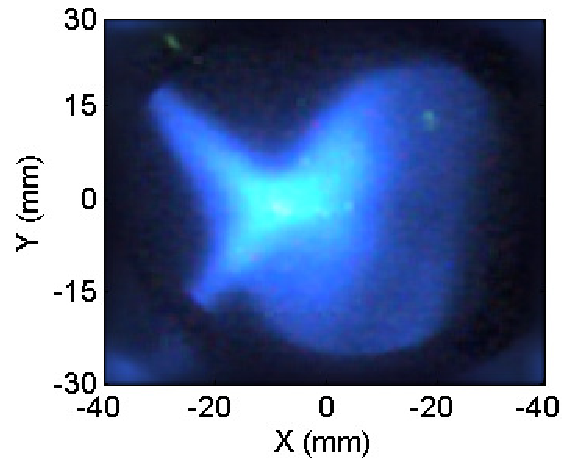

Figure 5: Measured beam profile of a 24 kV Ne^{6+} beam behind the 90° bending magnet at the location of VT3.

CONCLUSIONS AND OUTLOOK

We have shown that by carefully modelling the ion dynamics in ECR ion sources and the electric and magnetic fields of ion optical elements the transport of multicomponent ion beams in low-energy beam transport lines can be faithfully simulated using particle tracking methods. Independent-particle tracking can be used since the ion beams are fully space-charge neutralized, at least for beam currents up to a few mA. However, emittance blow-up caused by non-paraxial beams and ion-optical aberrations in beam-line elements can lead to significant beam losses. They can be prevented to a large extent by minimizing the cross-sections of the beam and by suitable compensation of the aberrations.

These ion-optical design aspects become even more important for the next generation of superconducting ECR ion sources, since these sources have much stronger magnetic fields and thus also larger beam emittances than in our case. In addition, because of the much larger beam currents space-charge compensation should be given adequate attention.

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