DIPOLE MAGNET OPTIMIZATION FOR HIGH EFFICIENT LOW ENERGY BEAM TRANSPORT*

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Abstract

Losses in the low-energy beam transport line from the KVI-AECRIS to the AGOR cyclotron are estimated to be around 50 %. Numerical simulations of beam extraction and transport have been performed up to the image plane of the analyzing magnet. The simulations show overall good agreement with measurements of beam profiles and emittances. It was found that the beam losses are caused by a too small gap of the analyzing magnet. This magnet also suffers from large second-order aberrations causing a significant increase of the effective beam emittance in both horizontal and vertical directions. We show that by increasing the magnet gap and suitably modifying the pole surfaces the beam losses can be suppressed and the second-order aberrations significantly reduced. This results in a substantially lower effective emittance of the transported beam.

INTRODUCTION

The low-energy beam transport (LEBT) line connecting the electron cyclotron resonance ion source (ECRIS) with the AGOR cyclotron at KVI, Groningen suffers from undesired beam losses of up to 50%. A program has therefore been initiated to improve the transport efficiency of the beam line. We started with a detailed simulation of beam extraction from the ECRIS and transport of the beam through the 110° analyzing magnet. The simulations have been bench marked against measurements of the full 4D emittance of the beams in the image plane of the analyzing magnet with a pepperpot [4] emittance meter and measurements of beam profiles at the source exit. The simulations clearly show that the analyzing magnet is the cause of significant beam losses. In addition, aberrations caused by the magnet's fringe fields lead to a large increase of the effective beam emittance. The next step was to start an improvement program of the ion-optical properties of the analyzing magnet. By increasing the magnet gap and modifying the shape of the pole faces of the analyzing magnet its ion-optical properties can be greatly improved leading to an increase of the beam transport efficiency of the LEBT line.

The paper is organized as follows. First we will present a detailed discussion of the beam extraction and transport simulations and comparison with the emittance measurements. Then the first results of the work on the improvement of the analyzing magnet will be presented and discussed. The paper ends with a summary and outlook.

BEAM TRANSPORT

The ECRIS and the 110° analyzing magnet are shown in Fig. 1. The ECRIS is an ion source of the AECR type of LBNL, Berkeley with the Al plasma chamber built by the Jyväskylä group [1]. More details of our source are given in Refs. [2] and [3]. The analyzing magnet is an unclamped double focusing magnet with straight 37° tilted edges and a vertical gap of 67 mm. The dipole bends the beam over 110° with a bending radius of 400 mm. Two BaF_2 viewing targets have been installed, i.e. VT1 located directly behind the extraction system and VT2 located close to the image plane of the analyzing magnet. Later the viewing target VT2 has been replaced by a pepperpot emittance meter [4]. There are no optical elements between ECRIS and analyzing magnet.

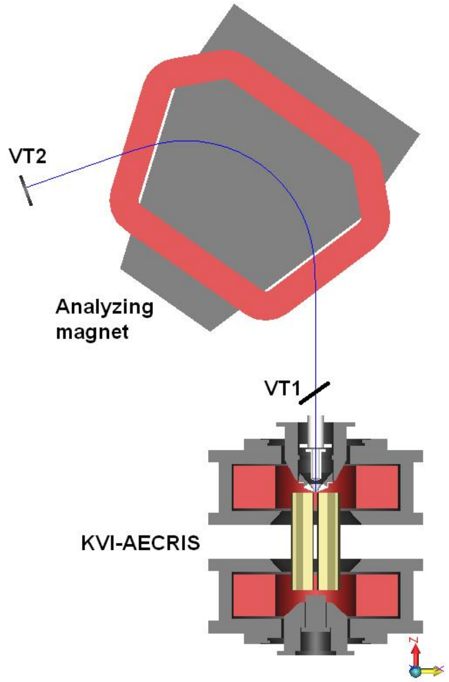

Figure 1: The KVI ECRIS and the 110° analyzing magnet.

Several computer codes have been used in the simulation process including an ECRIS simulation code PIC-MCC [5], and the particle tracking codes LORENTZ-3D [6] and

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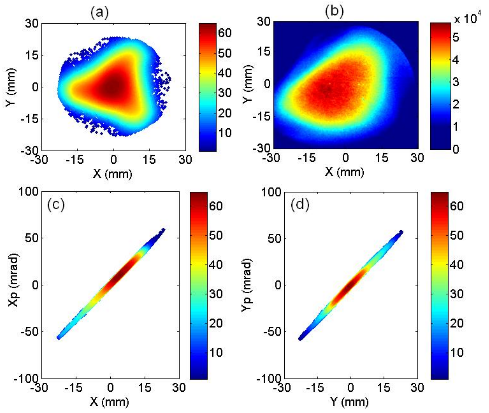

Figure 2: Calculated spatial distribution of a fully space-charge compensated He$^+$ beam behind the ground electrode at the location of VT1 (a). Measured He$^+$ beam profile at the same location (b). Calculated horizontal (c) and vertical (d) emittance plot at the same location.

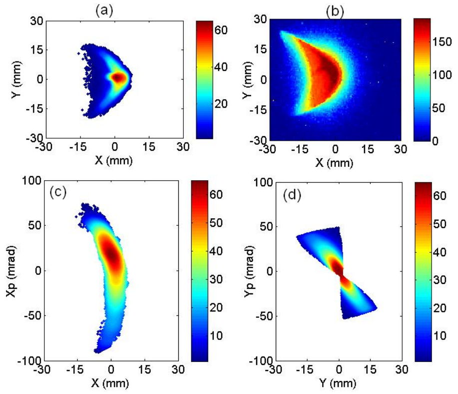

Figure 3: Calculated spatial distributions of a fully space-charge compensated He$^+$ beam in the image plane of the analyzing magnet at the location of VT2 (a). Measured He$^+$ beam profile at the same location (b). Calculated horizontal (c) and vertical (d) emittance plot at the same location.

COSY INFINITY [7]. We used LORENTZ-3D also to calculate the electric field in the accel-decel extraction system and the magnetic fields of the ECRIS and the analyzing magnet. All simulations and measurements have been done for a 24 keV He$^+$ beam. First the initial 5D phase-space distribution of the He$^+$ ions at the ECRIS extraction aperture is calculated with our PIC-MCC code. This distribution yields the start values of the spatial and angular coordinates of the ions for the subsequent calculation of the ion trajectories through the extraction system and analyzing magnet using the LORENTZ-3D code. Previous work has shown that space-charge forces are not important, so these have not been taken into account in the present simulations [8]. Finally, from the calculated ion trajectories various 2D cross sections of the 4D transverse phase space are extracted, e.g. 2D beam profiles and emittance plots, which can then be compared with measurements. Emittance values are always given as effective RMS emittances incorporating 95% of the beam.

The calculated and measured beam profiles and the calculated horizontal and vertical emittances of the extracted He$^+$ beam at the location of VT1 directly behind the extraction system and at the location of VT2 close to the image plane of the analyzing magnet are shown in Fig. 2 and 3, respectively. More details about the simulation can be found in Ref. [8]. As can be seen, the calculated and measured beam profiles at both locations compare favorably. The simulations indicate that $\approx 30\%$ of the beam is lost during the transport through the analyzing magnet, mostly because of its too small gap. Furthermore, the parabolic envelope of the beam profile behind the analyzing magnet indicates a large second order image aberration caused by the analyzing magnet. This also leads to a significant increase of the effective beam emittances. The calculated horizontal and vertical emittance at the location of VT1 is 65 π mm mrad, which is increased by as much as five times in the horizontal plane and four times in the vertical plane at the location of VT2 behind the analyzing magnet.

A more stringent test of the beam transport simulations is comparing the calculated emittances with measured ones. We have therefore measured the 4D phase-space distributions with a pepperpot emittance meter installed at the location of VT2 behind the analyzing magnet. Measured horizontal and vertical emittance plots are shown in Fig. 4. The measured value of the horizontal emittance is 390 π mm mrad and of the vertical emittance 320 π mm mrad. Since the agreement between measurements and simulations is satisfactory we conclude that the most important factors determining beam extraction and transport are well understood.

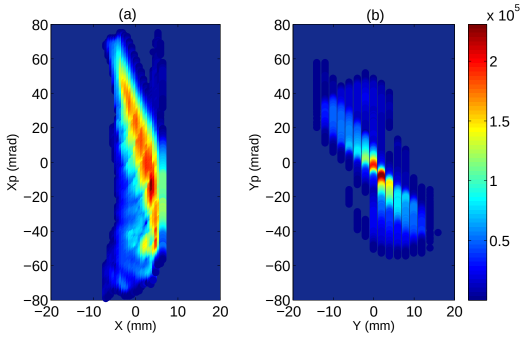

Figure 4: Measured horizontal (a) and vertical (b) beam emittances at the location of VT2 behind the analyzing magnet.

MAGNET OPTIMIZATION

As a next step we used our simulation tools to investigate ways to improve the transport and imaging properties of the analyzing magnet. To decrease the beam losses the pole gap is increased from 67 to 110 mm. The second order aberrations of the analyzing magnet can be compensated by adding sextupole components to the dipole field of the analyzing magnet. We started with a similar pole face shape as used in the design of the VENUS analyzing magnet of LBNL [9]. The pole faces at the entrance and exit sections are shaped in such a way that a quadratically increasing field is obtained to correct the vertical sextupole component, while the central pole face shape is modified to obtain a quadratically decreasing magnetic field to correct the horizontal sextupole component. The modified pole face shape of the analyzing magnet is shown in Fig. 5. First we used COSY INFINITY to quickly estimate the required sextupole strengths and then the LORENTZ-3D code for the fine tuning.

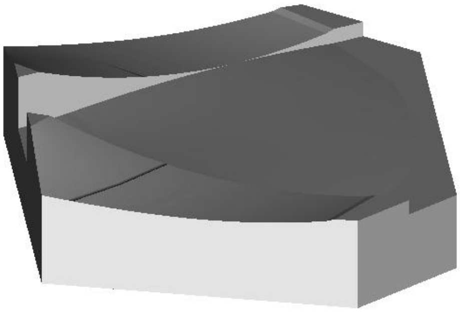

Figure 5: Pole face of the analyzing magnet including the sextupole correction.

The calculated beam profile and emittance plots for the optimized pole shape are shown in Fig. 6. As can be seen in Fig. 6a and 6b a small ($\approx 12\%$) fraction of the beam particles is deflected too much. The simulation shows that these particles are also on the left side of the beam before entering the analyzing magnet. By carefully decreasing the field integral on the inner side of the magnet we might remove this tail without affecting the vertical focusing too much. This is currently being investigated. According to the simulations the full beam is transported to the location of VT2 and the horizontal and vertical emittances are decreased with a factor of two compared to the uncorrected values.

SUMMARY AND OUTLOOK

We have simulated the extraction and transport of a He$^+$ beam from the KVI ECRIS to the image plane of the analyzing magnet. The good agreement between calculated and measured beam profiles and emittance plots shows that the basic physics is well reproduced in the simulations. We have shown that the analyzing magnet causes beam losses and suffers from large second-order aberrations yielding a four-fold increase in the effective beam emittance. Finally we have shown that the beam losses can be prevented by increasing the magnet gap and that the second-order aberrations can be significantly reduced by modifying the shape of the magnet poles.

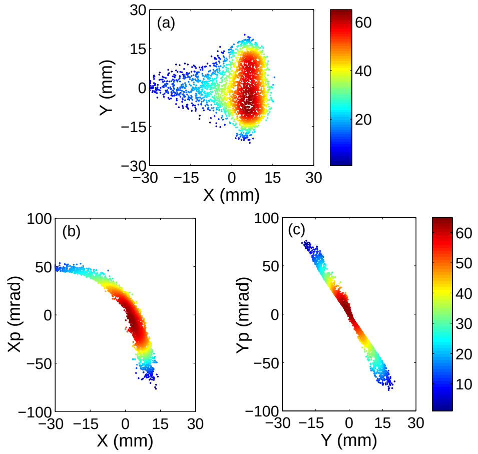

Figure 6: Calculated spatial distribution for a fully space-charge compensated He$^+$ beam at the location of VT2 behind the modified analyzing magnet (a). Calculated horizontal (b) and vertical (c) emittance plots at the same location.

Based on our simulations we will modify the pole face of the existing analyzing magnet to include the second order correction optics and extend the simulations to the entire low-energy beam line.

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