Chapter 7

OPTIMIZATION OF THE KVI-AECR CHARGE STATE ANALYZER

7.1 Introduction

Measurements show that the low energy beam transport from the ECR ion source to the AGOR cyclotron suffers from significant beam losses, which limit the attainable intensities of the beam extracted from the cyclotron. The simulations described in chapter 5 and 6 show that the 110° analyzing magnet is not only one of the locations of beam losses but also causes a significant increase of the effective emittance due to its aberrations and the large beam dimensions. As the beam essentially fills the full aperture of the magnet the non-linear terms in the equation of motion caused by the higher-order field components have a strong influence on the beam properties [146]. Furthermore, the radius of curvature of the magnet is not very large compared to the beam dimensions, resulting in higher-order kinematics terms and a large contribution of the fringe field to the overall large action of the magnet on the beam [147].

In this chapter we present a study to improve the ion-optical properties of the analyzing magnet and to decrease the beam losses. We have found that this can be achieved by modifying the shape of the pole faces and increasing the magnet gap. First we describe in Sec. 7.2 a detailed study of the ion-optical aberrations of the analyzing magnet based on trajectory simulations and a second-order analysis of the beam transport through the analyzing magnet. Then in Sec. 7.3 a method is described to compensate the ion-optical aberrations of the analyzing magnet by adding hexapole components to its main dipole field. The chapter closes with a summary and outlook in Sec. 7.4.
7.2 Transport properties of the magnet

In order to understand the transport properties of the analyzing magnet (hereafter denoted as M110) a detailed 3D transport simulation has been performed with different starting conditions of the ion beam. In addition to this the second-order transfer coefficients of the magnet have been calculated from the location VT1 in front of the magnet to the location VT2 behind the magnet (see Fig. 4.6).

Fig. 7.1 shows the double focusing bending magnet used as a charged particle analyzer in the KVI-LEBT system. The magnet has a geometrical acceptance of 120 mm wide and 60 mm high, which is determined by the vacuum chamber. Its radius of curvature is 400 mm. The pole faces have a tilt angle of 37° to obtain simultaneous imaging in both transverse planes. The distance from the aperture of the plasma electrode to the effective field boundary (EFB) is 682 mm. The distance between the EFB and the image is 374 mm. This gives a first order magnification of 0.6.

An illustration of the complex non-linear behaviour of the particle trajectories is shown in Fig. 7.2. In the image plane of the analyzing magnet a 10 mm diameter diaphragm is used to select the charge state of interest. The trajectories of 24 keV He$^+$ ions passing through this diaphragm have been backtracked to the plasma electrode of the ECR ion source. The position of these particles are indicated in blue. The positions of the particles lost at the image plane have been indicated in red. Fig. 7.2 shows the positions of these two groups of particles at various locations in the first part of the LEBT system, i.e. behind the analyzing magnet at the location VT2 (a), behind the extraction
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**Figure 7.2:** Calculated spatial distributions for a fully space-charge compensated $\text{He}^+$ beam in the image plane of the analyzing magnet at the location VT2 (a) and behind the ground electrode at location VT1 (b) and at the aperture of the plasma electrode (c). The blue coloured particles are transported through the 10 mm collimator at the location VT2 while the red coloured particles are lost on the collimator.

The rotation of the beam caused by the magnetic fringe field is clearly visible in Fig. 7.2. Apart from the rotation the decreasing magnetic fringe field of the ECR source also has a strong influence on the beam focusing in the extraction system: without magnetic field a narrow waist would be present at the location of the puller electrode.

In order to separate the effects of the analyzing magnet from those of the properties of the beam extracted from the ECR ion source transport simulations have been performed with different initial conditions, assuming an initially rotationally symmetric uniform ion beam with an emittance of $60 \pi \text{mm mrad}$ at the location of VT1, i.e. the same emittance value as obtained in Sec. 5.3.1. The results of this simulation are shown in Fig. 7.3, which should be compared to the simulation with a realistic beam in Fig. 5.3.

We find that the values of the transported beam emittance in the horizontal ($x$-plane) and vertical ($y$-plane) planes differ only slightly for both cases. The beam emittance of the initially round beam at the location of VT2 is around $360 \pi \text{mm mrad}$ ($x$-plane) and $240 \pi \text{mm mrad}$ ($y$-plane). This is significantly larger than the design specification ($140 \pi \text{mm mrad}$) of the acceptance of the AGOR injection system [123]. Comparison of the two calculations shows that the observed beam losses and emittance growth (see Fig. 7.2) are essentially due to the transfer properties of the analyzing magnet. The calculated transmission through the diaphragm is 50% of the total transported beam. Fig. 7.4 shows various phase-space projection of the initially round beam. The colours indicate particles with various $x$-positions at the location of VT2. For this beam the phase-space distributions at the location of VT2 are distorted in a similar way as observed for a realistic beam in chapter 5 (see Figs. 7.4 and 5.7). This clearly indicates the dominant influence of the magnet properties on the ion beam transport.

The origins of the observed aberrations can be studied by calculating the higher-order transfer matrix of the M110 magnet. In order to correct the aberrations the relevant
nonlinear terms in the expansion of its transfer function have to be identified and subsequently reduced by optimization of the magnet geometry. For example, the second-order expansion for the coordinate \( x \) can be written as

\[
x_1 = (x|x)x_0 + (x|x')x_0' + (x|xx)x_0x_0' + (x|x'x')x_0'^2 + \]
\[
+ (x|yy)y_0^2 + (x|yy')y_0'y_0' + (x'|y'y')y_0'^2 + (x|\delta)\delta_0
\]
\[
+ (x|\delta\delta)\delta_0^2 + (x|x\delta)x_0\delta_0 + (x|x'\delta)x_0'^2\delta_0
\]

with similar expressions for the coordinates \( x' \), \( y \) and \( y' \) [148]. The second-order coefficients are a mix of both magnetic and kinematic effects. Both effects can be compensated by suitably modifying the pole faces of the magnet.

Tab. 7.1 shows the transfer map of the M110 magnet calculated with COSY INFIN-
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**Figure 7.4:** Calculated profiles behind the analyzing magnet (VT2) plotted as a function of $X$ with various colours. Spatial profile (a). Mixed phase-space $(Y \text{ vs } Xp)$ (b) and $(X \text{ vs } Yp)$ (c). Phase profile $(Xp \text{ vs } Yp)$ at the same location plotted as a function of $X$ (d).

ITY from the location VT1 to VT2. Fig. 7.5 shows the calculated phase-space distributions at the location of VT2 by applying the second-order coefficients (see Tab. 7.1) to the simulated phase-space distribution at the location VT1 (see Fig. 5.3). Comparison of Fig. 7.5 with Fig. 5.6, which gives the result of the full simulation, demonstrates the dominance of the second-order effects of the M110 magnet on the ion beam transport in comparison with the Fig. 5.6.

The parabolic shape of the image at location VT2 is mainly due to the interplay of $(y|yy)y_0^2$ and $(x|yy)y_0^2$. Particles with significant initial $y$ and $y'$ reach the image plane with significant $y$. This results in a crescent shape image in the $xy$-plane at the location of VT2 (see Figs. 7.2a, 7.3b and 7.5c). The $(x|x')x_0^2$ term causes the curved phase-space distribution in the $xx'$-plane. The bow-tie shape phase-space distribution in the $yy'$-plane (see Fig. 7.5c) is mainly due to the second-order terms in the $y$-column of Tab. 7.1. All these non-linear terms together cause a five-fold increase in the effective emittance of a
transported ion beam through the analyzing magnet. This leads to a decrease in the ion beam transport efficiency of the LEBT system downstream from the analyzing magnet.

### 7.3 Second-order correction

The analysis described in the previous section clearly shows the large effect of the analyzing magnet on the beam properties. We have therefore investigated the possibilities to improve the beam quality by correcting the aberrations of this magnet. The simulations show that the beam losses occurring on the pole face of the magnet can simply be prevented by increasing the magnet gap from 67 mm to 110 mm. Several methods for aberration correction have been reported in the literature [24, 147]. The most commonly used multipole correctors are magnetic hexapole and octupole fields. The action of magnetic multipole elements is most effective at positions where the particle beam is large, because these fields affect in particular particles that pass far from the optical axis. The second order aberrations of the analyzing magnet can be compensated by adding hexapole components to the dipole field of the analyzing magnet.

It is also possible to minimize a large second-order aberration by keeping the beam inside the magnetic field narrow, i.e. using an extra focusing element [149, 150]. However, this requires additional optical elements between the extraction system and the analyzing magnet.

#### Table 7.1: The different columns correspond to the final coordinates \(x; x'; y; y'\) and the last column is used for the coordinate identification. The rows contain the various expansion coefficients, which are identified by the exponents of the initial condition. For example, the sixth entry in the first column is the expansion coefficient \((x|x')x_0x'_0\) [39]. These coefficients have been calculated with COSY INFINITY [23] using a built-in fringe field model. Dimensions are in \(m\) and \(rad\).
7.3 Second-order correction

Figure 7.5: Spatial distributions for a fully space-charge compensated $\text{He}^+$ 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 $\text{He}^+$ beam at the same location VT2. The calculations were made with COSY INFINITY.

magnet, which in our case is difficult because of lack of space. Therefore, we have chosen to further investigate the option of superimposing multipole fields on the dipole field of the analyzing magnet as previously developed by Leitner, et al. [151].

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 hexapole component, while the central part of the pole face shape is modified to obtain a quadratically decreasing magnetic field to correct the horizontal hexapole component. The modified pole face shape of the analyzing magnet is shown in Fig. 7.6. We used COSY INFINITY to quickly estimate the required hexapole strengths and then the LORENTZ3D code for the fine tuning of the pole face shape and for trajectory calculations.

The phase-space distribution calculated at the location of VT1 (see Fig. 5.3) is used as the initial condition for the transport simulations. The space-charge force is not taken into account, i.e. a fully-compensated $\text{He}^+$ beam is assumed.
The calculated beam profile and emittance plots at the location of VT2 for the optimized pole shape are shown in Fig. 7.8. It should be pointed out that the location of VT2 is slightly displaced with respect to the image plane of the analyzing magnet. Shifting VT2 to the image plane would still improve the beamspot. Comparison of Fig. 7.9 with Fig. 5.7 shows that the correlation between the transverse angle \( R_p = \sqrt{X_p^2 + Y_p^2} \) and \( X \) has been almost completely removed by the optimization of the magnet. As can be seen in Fig. 7.8(a) and (b) a small (\( \approx 10\% \)) fraction of the beam particles is deflected too much. The simulation shows that these particles are 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. According to the simulations the full beam is transported to the location of VT2 and the horizontal and vertical effective emittances are decreased with a factor of two compared to the uncorrected values.
Figure 7.8: Calculated spatial distribution for a fully space-charge compensated $\text{He}^+$ beam at the location of VT2 behind the modified analyzing magnet (a). Calculated horizontal (b) and vertical (c) emittance plots at the same location.

Figure 7.9: Calculated profiles for the analyzing magnet with the modified pole face at location (VT2) plotted as a function of $X$ with various colours. Spatial profile (a). Mixed phase-space ($Y$ vs $X_p$) (b) and ($X$ vs $Y_p$) (c). Phase profile ($X_p$ vs $Y_p$) at the same location plotted as a function of $X$ with same colours (d).
7.4 Conclusions

The simulations described in this chapter demonstrate that the $110^\circ$ analyzing magnet is the main cause of beam losses and emittance growth of the transported beam. The beam losses can simply be prevented by increasing the pole gap of the magnet from 67 mm to 110 mm. Insight into the aberration coefficients of the magnet has been obtained by expanding its transfer map up to second-order. Using this transfer map together with detailed 3D magnetic field and ion trajectory calculations we propose to modifying the pole faces of the analyzing magnet by adding hexapole terms to the main dipole field. This will result in a significant reduction of the beam losses and effective emittance growth due to the analyzing magnet. We estimate that such a modification will increase the effective transport efficiency to the AGOR cyclotron as calculated in Sec. 6.4.2 from 16 % to 45 %.