Chapter 4

ECR ION SOURCE AND LOW ENERGY BEAM TRANSPORT

4.1 Introduction

This chapter presents a detailed description of the KVI-AECR ion source, low energy beam transport (LEBT) system and beam diagnostic devices. These are used in the simulations and measurements described in chapters 5–7. In this chapter the KVI-AECR ion source is described in Sec. 4.2, while the low energy beam transport (LEBT) system is described in Sec. 4.3. Section 4.4 gives a description of the various diagnostic devices used in this study.

4.2 KVI-AECR ion source

The ECR ion source of the AGOR facility at KVI is essentially a copy of the AECR ion sources installed in Berkeley (LBNL) [46], Jyväskylä (JYFL) [48] and Argonne (ANL) [52]. A schematic cross section of the KVI-AECR is shown in figure 4.1.

The ion source has an aluminum plasma chamber with inner diameter of 76.2 mm and a length of 320 mm. The plasma chamber holds the six NdFeB permanent magnet bars (see Fig. 4.2b) with lengths of 295 mm generating the hexapole field, which together with the axial mirror field produced by two solenoids generate the minimum-B configuration. The solenoids have an inner bore diameter of 208 mm. The magnetic field configuration is characterized by maximum values of 2.1 T and 1.1 T of the axial field at the injection and extraction planes, respectively, a minimum field of 0.36 T in the center of the plasma chamber and a maximum hexapole field at the radial wall of 0.9 T. The calculated magnetic field along the axis of the source is shown in Fig. 4.3. The field maxima are
shaped and enhanced by iron yokes around the coils and by iron plugs at the injection and extraction sides of the source. In order to optimize the intensity of the extracted ion beam the field maximum at the extraction side is lower than the field maximum at the injection side.

The plasma chamber is radially accessible through six slits located between the magnet bars of the hexapole magnet. These slits are used to improve the pumping of the plasma chamber by a 410 \( l/s \) turbo pump and also allow insertion of e.g. sputter probes and plasma diagnostics. Fig. 4.4 shows a photo of the injection plug with biased disk, RF wave guide, gas feed and an oven used for metal ion production.

The plasma is heated with 14.1 GHz microwaves generated by a 2 kW klystron amplifier. The microwave power is launched into the plasma chamber from the injection side via a rectangular waveguide connected off-axis to the plasma chamber. In addition to the main 14.1 GHz heating system, the source is also equipped with a 11–12.5 GHz,  

Figure 4.1: Advanced Electron Cyclotron Resonance Ion source (AECR) at KVI.
4.2 KVI-AECR ion source

Figure 4.2: Solenoids (a) and hexapole (b) used in the KVI-AECR ion source.

Figure 4.3: Calculated magnetic field along the axis of the KVI-AECR ion source (left scale) and calculated potential along the axis of the extraction system (right scale).

400 W Travelling Wave Tube Amplifier (TWTA), enabling two-frequency heating. The same wave guide is used for both RF power sources using a special coupler system. The plasma chamber is electrically isolated from ground and biased at the extraction voltage which can have a maximum value of 35 kV.
4.2.1 Extraction system

The ion beam is extracted from the KVI-AECR ion source with an accel-decel extraction system (Fig. 4.5) consisting of three electrodes, i.e. a plasma, puller and ground electrode. The plasma electrode has been designed according to the so-called Pierce geometry [92], with a cone half-angle of 67.5° with respect to the optical axis and is made of aluminum in order to enhance secondary electron emission from its wall. The puller and ground electrodes are made of stainless steel. The diameter of the plasma electrode aperture is 8 mm. The beam is extracted by a single puller system with an entrance aperture of 13 mm diameter and a length of 95 mm. A ground electrode is located behind the puller with an inner diameter of 53 mm and a length of 100 mm. The puller and ground electrodes have a fixed gap of 5 mm and are attached to a translation stage with a range of 20 mm. In this way the gap between the plasma and puller electrodes can be varied from 20 to 40 mm.

The plasma electrode is electrically connected to the plasma chamber and is therefore biased at the source potential ($V_{ext}$). The puller electrode has a negative potential ($V_{supp}$) of a few hundred volts. A typical potential distribution along the axis of the KVI-extraction system ($V_{ext} = 24.7$ kV, $V_{supp} = -300$ V) is shown in Fig. 4.3. The positive potential accelerates ions from the ECR ion source while the negative dip in the potential curve prevents the low-energy secondary electrons produced in the beam transport section downstream to be accelerated into the source thus enhancing the space-charge compensation of the extracted ion beam. The fringe field of the extraction solenoid extends up to the ground electrode as shown in Fig. 4.3.
The ion beam extracted from the KVI-AECR is transported to the AGOR cyclotron via the low energy beam transport (LEBT) system shown in Fig. 4.6. It consists of four bending magnets, one magnetic quadrupole triplet, fifteen electric quadrupoles (EQ), several electrostatic deflection plates and diagnostic elements. The properties of the four bending magnets installed in the LEBT system are listed in table 4.1. All electrostatic quadrupoles are identical and have a length of 120 mm and aperture of 70 mm. Electric quadrupoles are used instead of magnetic ones because the LEBT system was designed to be used for polarized proton and deuteron beams which suffer from depolarization when using magnetic quadrupoles [122, 123].

In order to separate the required charge state the extracted ion beam is transported through a double focusing 110° bending magnet (M110) [124]. The distance from the aperture of the plasma electrode to the effective field boundary (EFB) of this magnet is 682 mm. The distance between the image and the EFB is 374 mm. This gives a first order magnification of 0.6. In the KVI-LEBT system there is, in contrast to most other systems, no optical element between the ECR ion source and the analyzing magnet. In order to minimize beam losses and aberrations one or more optical elements (solenoid, einzel lens, quadrupole, etc.) are often used to match the emittance of the beam from the ion source to the acceptance of the analyzing magnet. In many laboratories a magnetic solenoid is used directly after the extraction system of the ECR ion source. In particular for high intensity beams containing many different charge states the charge state dependence of the focusing strength of the solenoid can be problematic as it may cause hollow beams due to space-charge effects [125]. An einzel lens (or other electrostatic systems) provides focussing that is independent of the charge state but hinders space-charge com-
pensation, which is most important in this region because of the high intensity of the beam before charge state selection.

The analyzed beam is then transported by a magnetic quadrupole triplet and an electrostatic quadrupole singlet (EQ1) to the 90° bending magnet (M90). The outer two quadrupoles in the quadrupole triplet are identical with a length of 110 mm and diameter of 50 mm. The length and diameter of the inner quadrupole are 180 mm and 50 mm respectively. After the M90 magnet the next three electrostatic quadrupoles (EQ2–EQ4) guide the beam to the M50 bending magnet. This magnet bends the beam over 50° after which the beam is transported by the next three electrostatic quadrupoles (EQ5–EQ7) to the M72 bending magnet. This magnet bends the beam over 72° to a 2.1 m long drift section after which the beam enters the matching section. After the matching section the beam is bent achromatically over 90° by an electrostatic deflector into the cyclotron injection line, which consists of three solenoids and an electrostatic inflector in the cyclotron center.

The five electrostatic quadrupoles in the matching section are used to match the beam emittance to the acceptance of the AGOR cyclotron. The three solenoids in the axial beamline provide the required orientation of the ion beam at the inflector entrance. Also the strongly increasing field along the cyclotron axis (stray field of the cyclotron) is an essential ingredient of the optics. The matching section and the solenoids are tuned to obtain maximum possible injection efficiency. The KVI-LEBT system also includes various electric/magnetic beam-steering elements to provide adjustments of both offset and tilt angle of the ion beam. More details can be found in Ref. [123].

Table 4.1: The properties of the bending magnets installed at the KVI-LEBT

<table>
<thead>
<tr>
<th></th>
<th>M110</th>
<th>M90</th>
<th>M50</th>
<th>M72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending radius (\rho_0) (mm)</td>
<td>400</td>
<td>240</td>
<td>290</td>
<td>240</td>
</tr>
<tr>
<td>Bending angle (\alpha) (degree)</td>
<td>110</td>
<td>90</td>
<td>50</td>
<td>72</td>
</tr>
<tr>
<td>Vertical gap (mm)</td>
<td>67</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Entrance pole face angle (\varepsilon_1) (degree)</td>
<td>37</td>
<td>0</td>
<td>15.63</td>
<td>30</td>
</tr>
<tr>
<td>Exit pole face angle (\varepsilon_2) (degree)</td>
<td>37</td>
<td>0</td>
<td>15.63</td>
<td>30</td>
</tr>
</tbody>
</table>
Figure 4.6: KVI-Low energy beam transport section.
4.4 Beam diagnostic tools

The efficiency of the ion beam transport through the LEBT system depends on many parameters. In order to measure these parameters and optimize the ion beam transport various beam diagnostic devices are installed in the KVI-LEBT system: Faraday cups, beam profile monitors and a pepper-pot emittance meter. We have also used these devices to benchmark our beam transport simulations. In this section the various beam diagnostic devices will be briefly discussed and their use explained.

4.4.1 Faraday cup

Beam current is an important optimization parameter for the ion source and beam transport system. Faraday cups (FCs) are the most commonly used devices for beam current measurements [126]. There are several FCs installed in the KVI-LEBT system, their locations are marked in Fig. 4.6. All FC’s are equipped with electron suppressor rings which are negatively biased to prevent electrons from escaping [127, 128].

4.4.2 Beam profile monitor

1D and/or 2D transverse intensity distributions are measured with harps (2 × 1D distribution) and viewing targets (2D distribution). A general review of these kind of beam diagnostics can be found in Ref. [129]. Here we briefly describe the wire harps and viewing targets installed in the KVI-LEBT system.

The wire harp consists of a set of 24 tungsten wires with a diameter of 20 μm fixed on an insulating ceramic frame in two planes (horizontal (x) and vertical (y)) [128]. The harps are equipped with an electron suppressor ring to minimize the effects of secondary electrons. The current on the individual wires is digitally averaged over 400 ms and used to reconstruct the beam profile. The locations of the harps are marked in figure 4.6.

A viewing target is a simple method to determine the full 2D beam profile. We have used a BaF₃ coated metal disk as a viewing target. The metal disk is a 4 mm thick aluminum plate with a diameter of 70 mm. Three viewing targets have been used to measure the beam profiles, one (VT1) is located behind the extraction system, the second one (VT2) close to the image plane of the analyzing magnet and the third one (VT3) behind the M90 bending magnet (see Fig. 4.6).

The scintillator light from the screen is observed with a monochrome CCD camera. The recorded images are then analyzed off-line using image processing tools. The advantage of a viewing target is that it gives immediate qualitative information about the intensity, size and shape of the incident beam (see Figs. 5.10). The main disadvantage of this method is that it is very difficult to correlate the recorded images to the beam intensity because of the rapid deterioration of the scintillating material by low energy heavy ion beams [14]. Therefore, it is very important to minimize the exposure time and to
replace the viewing target frequently. Furthermore, due to the fabrication technique the surface of the viewing target is not perfectly homogeneous, possibly leading to variations in light yield over the surface. Because of these issues we have used the viewing screens only for qualitative measurements.

### 4.4.3 Pepperpot Emittance meter

The concept of beam emittance has been discussed in sections 2.2.2 and 3.3.4. Measurement of the transverse emittance is important for the evaluation of the performance of the ion source and associated beam transport system. Here we describe an instrument [130] that has been developed at KVI to measure the full four-dimensional (4D) transverse phase-space density distribution.

In order to measure the emittance we have to determine the trajectories of the beam particles. Several methods of measuring the transverse emittance such as the Allison scanner, slit scanner, quadrupole method and pepper-pot method, etc. have been described in the literature [131–138]. The widely used Allison type emittance scanner measures the 2D phase-space distribution in either the horizontal or vertical plane. This device is thus not able to measure correlations between the transverse emittance planes, i.e. it measures a 2D projection of the full 4D phase-space distribution. It is therefore not suitable to measure the emittance of beams from ECR sources, which exhibit correlations between the two transverse emittance planes. A good understanding of the beam prop-
properties requires the measurement of the full 4D phase-space distribution. The pepperpot technique that we have adopted does measure the full 4D phase-space distribution and thereby allows a complete analysis of the properties and transport of the beam.

The operation of a pepperpot emittance meter is schematically indicated in Fig. 4.7, which also shows the main components. A 3D view of the KVI device is displayed in Fig. 4.8

The pepperpot plate is a 25 $\mu m$ tantalum foil with a vertical row of 20 holes with a diameter of 20 $\mu m$ and a pitch of 2 mm. This pepperpot plate is mounted on a water-cooled copper block that can absorb 150 W of beam power. The assembly can be moved through the beam by a stepper motor driven translation mechanism with a positioning accuracy better than 10 $\mu m$. The instrument can be easily adapted to a different phase-space distribution by replacing the pepper plate with one having a suitable hole pattern.

The ions that are transmitted through the holes in the pepperpot plate are detected with a position-sensitive detector positioned 51.3 mm downstream of the pepperpot plate. The detector consists of two micro-channel plates in chevron configuration and a phosphor screen, both with an effective diameter of 41.5 mm. The light emitted by the phosphor screen is imaged by a mirror and a lens system onto a CCD camera mounted outside the vacuum. The MCP, phosphor screen and mirror assembly are mounted on a carriage which can be moved in and out of the beam pneumatically. The measurement is performed by scanning a 1D vertical row of holes in the horizontal direction. This method
was chosen because the large horizontal divergence of the beam at the measurement location would compromise the resolution in the $x$-direction if a 2D array would have been used. The full four-dimensional phase-space distribution $\rho(x, x', y, y')$ of the ion beam can be reconstructed by stepping the pepper plate through the beam in the $x$-direction and taking a CCD image at each step. An entire series of these images measured with the pepperpot emittance meter at the image plane of the analyzing magnet in the KVI-LEBT is shown in Fig. 4.9. More detailed information about the KVI-4D pepper-pot emittance meter is presented in Ref. [130, 139].

Two dimensional projections can be constructed from the measured full 4D phase-space density distribution $\rho(x, x', y, y')$ by integrating over the other two variables, e.g. the standard $(x, x')$ distribution is calculated as

$$\rho(x,x') = \int_y \int_{y'} \rho(x,x',y,y') dy dy'$$  \hspace{1cm} (4.1)

Once the second-order moments are calculated from the 2D phase-space distributions as defined in equation 4.1 the effective emittance can be calculated using equation 2.10:

$$\varepsilon_{xx} = 4\sqrt{x^2 \cdot x'^2 - xx'^2}$$  \hspace{1cm} (4.2)

More detailed information about the pepper pot emittance meter data analysis is presented in Ref. [133, 136–138, 140, 141].