Extraction and transport of ion beams from an ECR ion source

Saminathan, Suresh

Chapter 3

ELECTRON CYCLOTRON RESONANCE ION SOURCE

3.1 Introduction

Electron Cyclotron Resonance (ECR) Ion Sources are used to produce intense, high charge state ion beams of intermediate and heavy mass elements [1]. They are widely used to produce ion beams for accelerators, atomic physics research and industrial applications. In order to achieve ever higher intensities of ever higher charge states ion beams it is essential to obtain an in-depth understanding of not only the processes in the plasma of the ECR ion source but also of the beam formation, extraction and transport of the multiple-charge state and multi-component ion beams they produce.

In this chapter we discuss aspects of the physics and technology of ECR ion sources that are relevant for the work described in this thesis. First the historical development of ECR ion sources is briefly outlined in section 3.2. In order to understand the beam formation and extraction processes ECR ion source fundamentals are presented in section 3.3. Finally, a brief review of ECR ion source modeling including the Particle-In-Cell Monte-Carlo Collision (PIC-MCC) and KOBRA3-INP codes used in this study is given in section 3.4.

3.2 Brief history of the ECR ion source

The history of the ECR ion source starts in the late 1960s, when Electron Cyclotron Resonance Heating (ECRH) was developed as a technique to heat the plasma in magnetic confinement devices used in fusion research [1]. In 1969 it was proposed to produce high charge state ions in plasma devices using ECRH [40]. The first sources using ECRH to produce multiply charged ions were developed in 1972 in France by Geller et al. [41] and in Germany by Wiesemann et al. [42]. In 1974 Geller and his co-workers made a major step towards the ECR ion source by transforming a large mirror device (CIRCE) [43] into an ion source, SUPERMAFIOS [44]. SUPERMAFIOS was equipped with solenoids to generate an axial magnetic field and a hexapole magnet to produce a radial field. The superposition of the hexapole and solenoid fields produces a minimum-B magnetic field configuration that stabilizes the plasma against MHD instabilities [45]. It does this by creating closed ellipsoidal iso-B surfaces inside the plasma chamber with a magnetic field increasing in all directions from the center to the walls of the plasma chamber. At one of these surfaces the electron Larmor rotation is resonant with the injected microwaves and a very efficient heating of the plasma electrons is achieved. However, the electrical power consumption of this source was still very high $(3\ MW)$. The next step involved the development of lower power consumption sources by using high strength permanent magnets (NdFeB) for in particular the hexapole field. For example the MICROMAFIOS 10 GHz (1979) and CAPRICE 10 GHz (1983) ion sources with a power consumption of about 50 kW were realized by using solenoids for the axial field and NdFeB magnets, while the NEOMAFIOS 8 GHz source built in 1986 used NdFeB permanent magnets for both the axial and radial magnetic field.

An advanced ECR ion source (AECR) for the production of high charge state ions was built in 1990 by the LBNL ECR ion source group and upgraded (AECR-U) [46,47] in 1996. Slightly modified versions of this source are in operation at JYFL [48], KVI [49], Texas A&M University [50], NSCL [51], and ANL [52]. Meanwhile other laboratories around the world have also developed and successfully put ECR ion sources into operation (e.g. DECRIS in Dubna [53], ECR4 in GANIL [54], GTS in CEA/Grenoble [55], SERSE in Catania [56] and 18 GHz source at RIKEN [57], etc.). Nowadays ECR ion sources have matured to the level that they are commercially available.

As a result of three decades ECR ion source development a remarkable source performance has been obtained, e.g. the beam intensity of Ar^{8+} has increased from a few tens of μA to 2 mA [58]. This has mainly been achieved by using higher frequency microwave power and an accordingly increased magnetic field. In 1987 Geller and co-workers published semi-empirical scaling laws for optimizing ECR ion source design [59]. The most important scaling law is that the extracted beam intensity scales with the square of the microwave frequency. However, the use of normally conducting solenoids and permanent magnet multipoles limits to the frequency of the microwave power of about 18 GHz [60]. Advances in superconducting magnet technology have made it possible to use the ever higher frequency microwave sources developed for radar and satellite communication also in ECR ion sources. This has resulted in the emergence of the third generation ECR ion sources (e.g. VENUS, SECRAL, RIKEN-SC, SERSE, SUSI, etc.). A detailed account of the historical development of ECR ion sources can be found in references [1,61–63].

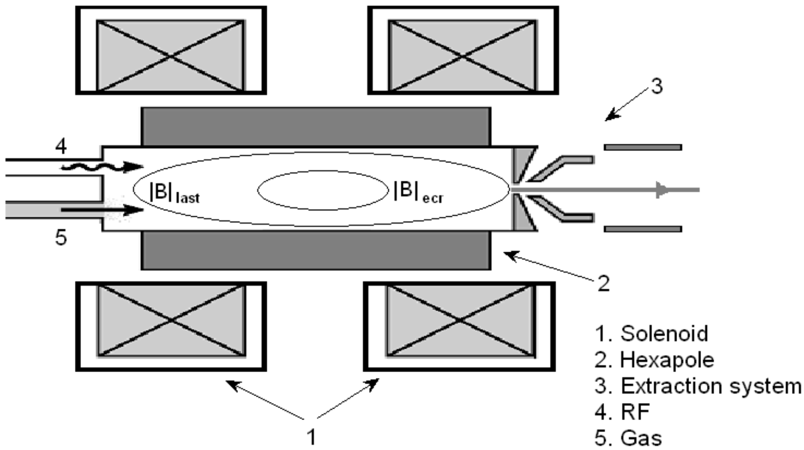


Figure 3.1: *Schematic view of an ECR Ion Source.*

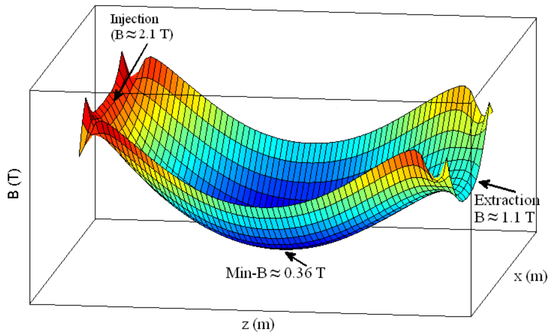
3.3 ECR ion source fundamentals

Figure. 3.1 shows a schematic drawing of an ECR ion source. Its main components are: *a)* Plasma chamber and vacuum system. *b)* Solenoid and hexapole magnets for axial and radial confinement of the plasma, respectively. *c)* Injection of neutral atoms or molecules (by oven, gas inlet, etc.) to be ionized. *d)* RF power input with appropriate frequency which is the source of energy for the electrons, so that high charge state ions can be created via successive ionization. *e)* Ion extraction system for the ion beam formation.

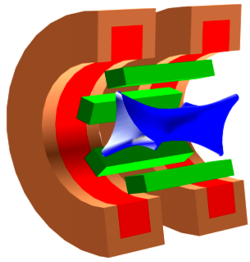
3.3.1 Magnetic confinement

The main draw back of a simple mirror structure (without hexapole) is that macroscopic plasma instabilities (e.g. MHD instabilities) are excited because the plasma pressure radially decreases with the magnetic field [1]. The plasma will therefore quickly escape in the radial direction from the trap. Therefore, in most ECR ion sources a multipole field, usually a hexapole, producing a radially increasing field is superimposed on to the mirror field to stabilize and thus better confine the plasma. This results in a so-called *minimum-B (min-B)* structure because the magnetic field strength has a minimum in the center of the structure and increases from there in all directions (Fig. 3.2a). Fig. 3.2b shows a 3D view of the resultant magnetic field of an ECR ion source. The $iso-|B|$ surfaces (magnetic isobars) in a min-B magnetic configuration are closed nested shells.

In a magnetic mirror charged particles that move exactly parallel to the magnetic field lines ($v_{\perp}=0$) have no magnetic moment and are immediately lost from the trap.



(a)



(b)

Figure 3.2: *Typical (Min-B) magnetic structure of a 14.1 GHz ECR ion source (a) and 3D view of ECR ion source magnetic field configuration (figure taken from Ref. [64]) (b).*

Particles that have no parallel velocity ($v_{\parallel} = 0$) are trapped forever. Whether or not a charged particle remains trapped depends on the ratio of the perpendicular and parallel velocity components, which defines the pitch angle α:

$$\tan(\alpha) = \frac{v_{\perp}}{v_{\parallel}} \tag{3.1}$$

When a particle moves in the direction of increasing magnetic field **B**, its perpendicular velocity increases because of the adiabatic invariance of the magnetic moment $\mu = \frac{mv_{\perp}^2}{2B}$ and consequently the parallel velocity has to decrease because of the conservation of total kinetic energy. Therefore, charged particles will bounce back and forth between the two high-field regions of the magnetic mirror, provided the perpendicular velocity component is large enough.

Since the magnetic moment (μ) of a particle is a conserved quantity, the pitch-angle at different axial positions z and z' only depends on the magnetic field:

$$\frac{\sin^2(\alpha)}{\sin^2(\alpha')} = \frac{B(z)}{B(z')} \tag{3.2}$$

The minimum pitch angle $\alpha_{\circ}$ at the midplane z = 0 (where the magnetic field has a minimum value B_{min}) for which a particle will be reflected at the position z = z' where the field has its maximum with value B_{max} is then

$$\alpha_{\circ} = \sin^{-1}\left(\sqrt{\frac{B_{min}}{B_{max}}}\right) = \sin^{-1}\left(\sqrt{\frac{1}{R_m}}\right) \tag{3.3}$$

with $R_m = B_{max}/B_{min}$ is the magnetic mirror ratio. The angle $\alpha_{\circ}$ defines the so-called *loss cone* [65, 66] in velocity space (Fig. 3.3). Particles inside the loss cone, i.e. $\alpha < \alpha_{\circ}$

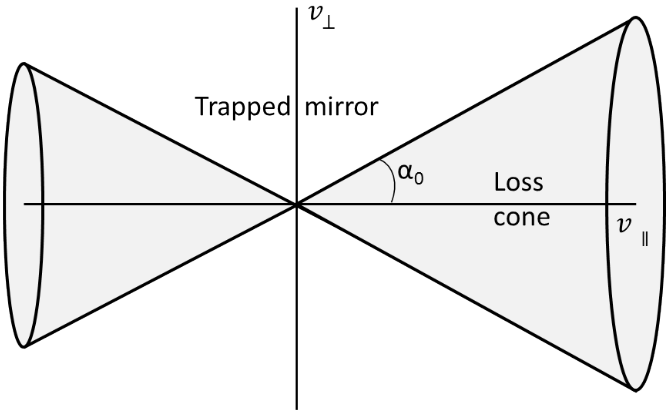


Figure 3.3: *Schematic view of the loss cone in the ECR ion source (Left cone: Injection side and Right cone: Extraction side).*

are not trapped and escape from the magnetic mirror system. Particles diffuse into the loss cone (and thus escape from the trap) through collisional scattering, microscopic instabilities, e.g. due to the interaction with the RF field, and non-adiabatic processes. Collisional scattering is often the dominant mechanism for diffusion into the loss cone. Collisional losses generally increase with plasma density and decrease with electron energy. A detailed analysis of the confinement of electrons and ions in an ECR ion source is complicated, since the magnetic confinement depends upon the ratio of the Larmor frequency and the collision frequency, which in turn depends on the energy and position of the particles. A global description of the dynamics of electrons and ions is given in the subsections 3.3.2 and 3.3.3.

For $R_m >> 1$ and assuming an isotropic velocity distribution the escape fraction ξ can be approximated as [1]

$$\xi \sim \frac{1}{2R_m} \tag{3.4}$$

For higher mirror ratios the confinement is better and consequently the production of high charge state ions is increased. On the other hand, the mirror ratio should not be too high since ions have to escape from the plasma trap in order to be extracted. Optimization of the mirror ratio is therefore one of the important elements in the design of ECR ion sources [56, 67–70]. For the KVI-AECR ion source, $R_m \sim 3.6$ and approximately 14 % of the particles escape immediately. The particle confinement time is determined by the probability to scatter into the loss cone.

3.3.2 ECR Heating

Plasma electrons trapped in the magnetic field of an ECR ion source follow helical paths along the field lines. The local frequency of the rotation around the magnetic field lines is the cyclotron frequency $\omega_{cyc} = eB/m$. By injecting microwave power with frequency ω_{RF} the electrons are accelerated or decelerated, depending on the phase of their gyration motion with respect to that of the local RF electric field, if the electron cyclotron resonance condition is fulfilled:

$$\omega_{RF} = \omega_{cyc} - k_{\|} v_{\|} \tag{3.5}$$

with ω_{RF} the wave frequency, $\omega_{cyc}(\overrightarrow{r})$ the cyclotron frequency of the particle at point r, $k_{\|}$ the RF wave vector and $v_{\|}$ the component of the electron velocity parallel to the magnetic field line. For $v_{\|} = 0$ equation 3.5 defines a surface in the min-B magnetic configuration of an ECR ion source, which is called the *resonance surface*.

The magnetic field at the resonance surface is given by $B \cong \frac{f_{RF}}{28}$, with B expressed in tesla and $f_{RF} = \omega_{RF}/2\pi$ the injected microwave frequency in gigahertz [1].

The study of electromagnetic wave propagation and ECR heating in a plasma is complicated due to collective phenomena. In a min-B configuration, electrons cross the resonance region many times and may, depending on the phases between their motion and the RF field, gain or loose energy. However, the energy gain of an electron at the accelerating phases is higher than the energy loss in the decelerating phases. Therefore, the electrons undergo a global heating called *stochastic ECR heating* [71] and rapidly reach keV energies, sufficient to ionize the atoms via successive single ionizations [1]. The typical range of the electron density of ECR plasmas is between 10^{11} and 10^{12} cm^{-3} depending on ion source parameters [72].

ECR plasmas are far from thermodynamical equilibrium and the electron energy distribution function (EEDF) is strongly non-Maxwellian [73]. Because of the confinement and the ionization, collision and diffusion processes the electron energy varies from several tens of eV to several hundreds of keV. Although there is a continuum of electron energies, the EEDF can conveniently be represented by three populations the energies of which are connected to the diffusion, ionization and confinement processes [74]: a cold one ($E_{kin} \sim 1$–100 eV), a warm one ($E_{kin} \sim 100$ eV–100 keV), responsible for the ionization processes [1] and a hot one (energy above 100 keV up to a few hundred keV).

During their oscillation in the magnetic mirror, the electrons and ions can be scattered into the loss cone. Thus the confinement time for electrons is related to the scattering rate for electron-electron and electron-ion collisions. Due to their low collision rates high energy electrons are well confined. On the other hand the cold electrons suffer more frequent scattering collisions and are not magnetically confined. However, they remain confined by the space-charge field of the plasma ions. The cross-sections for ionization exhibit broad maxima centered at $E_e \geqslant 3W_{ion}$ [75], with W_{ion} the binding energy of the electron to be removed, which lies in the range 5 eV to 1.5 keV. Consequently the cold electrons hardly contribute to the ionization process and only serve as a source to replenish the population of higher energy electrons. Also the high energy electrons ($E_e > 100\ keV$) do not significantly contribute to the ionization because of their low ionization cross-sections and low densities.

The production of multiply charged ions increases with microwave power up to a maximum after which it decreases because of RF induced plasma losses [76]. Stabilizing the plasma against RF induced instabilities is an important aspect of optimizing the source performance for the highest charge states. Injecting additional RF power at a lower frequency has been found to have such a stabilizing action: both the total RF power and the power at the upper frequency can be increased before instabilities occur resulting in a better performance of the source in terms of total intensity and charge state distribution.

3.3.3 Ion dynamics

The ECR plasma is a mixture of ions, electrons and neutrals that undergo collisions with each other. The charge-state distributions (CSD) of the beams extracted from an ECR ion source is strongly dependent on plasma parameters such as electron (n_e) and ion densities (n_q), temperatures, ion mass (m_i) and neutral density (n_0), etc. The steady-state rate equations for a specific species of multiply charged ion contain terms describing the ionization and loss processes. The loss processes include transport, radiative recombination and charge exchange. It has been shown that charge exchange and radiative recombination losses are relatively small compared to typical transport losses [77].

The colder electrons leave the ECR plasma faster than the ions due to their higher mobility. In order to maintain charge neutrality, the plasma therefore attains a positive potential with respect to the plasma chamber (the so-called *plasma potential*), which reduces the loss of low energy electrons by confining them electrostatically. The plasma potential in ECR ion sources has been extensively studied and reported in references [46, 76, 78]; depending on the conditions of operation of the source it lies in the range 10–50 V. In order to optimize the ECR ion source for multiply-charged ion production the ion temperature and the plasma potential should be as low as possible for better ion confinement [79].

Ions in the ECR plasma are confined by magnetic as well as electrostatic fields depending on the location of the ions and the plasma density. According to the model presented in Ref. [1, 80, 81] the ions in the core of the plasma ions are highly collisional and not confined by the magnetic mirror, but electrically confined by a negative potential dip created by the hot electrons. However, near the wall the ions are magnetically confined due to the low collisional rate caused by the reduced plasma density. The ions find their way to the ion extraction aperture, which is located on the axis of symmetry, through diffusion and scattering. The ions arriving at aperture in the plasma electrode are then accelerated by the applied extraction field, which is typically a few tens of *kV* potential difference with respect to ground.

We can summarize the general requirements for production of multiply charged ions in an ECR ion source as follows [1, 82]:

1. **Sufficient electron energy**: The electron energy should be high enough to produce the required charge state. This can be satisfied by ECR heating with sufficient microwave power.

2. **Long ion confinement**: The ions must be confined long enough in order to achieve the required charge state via successive single ionizations. This is achieved by the min-B configuration

3. **High plasma density**: In order to maximize the ion current it is important to produce a high density plasma. This can be realized by heating with high frequency RF power and correspondingly high magnetic fields.

4. **Low background pressure**: For high charge state ion production a low background pressure is important to minimize recombination and charge exchange processes. This sets constraints to the gas pressure.

In addition to the general scaling laws the performance of ECR ion sources has also been continuously improved experimentally by the introduction of new design concepts and techniques, such as biased disk [83], wall coating [67], gas mixing [84, 85], multiple frequency heating and tuning [86–89].

3.3.4 Extraction fundamentals

The performance of a source for highly charged ions is expressed in terms of beam brightness and charge state distribution. The plasma volume provides the ions, while the extraction system together with electric and/or magnetic fields of the source in the extraction region determine the properties of the ion beam extracted from the plasma volume. The particles passing through the extraction system acquire energy and a directed velocity in the electric and/or magnetic fields of the extraction system. Therefore, understanding the physics of an ion source extraction system is very important for the production of high intensity, high quality ion beams.

Depending on the application the extraction system can take many different forms, consisting of as many as five electrodes and widely different geometries [90]. In the simplest case two separate electrodes are used (see Fig. 3.4a). In ECR ion sources usually a three-electrode extractor design is used, with an additional electrode (V_{supp}), which is biased to a relatively low negative voltage, inserted between the plasma (V_{ext}) and ground

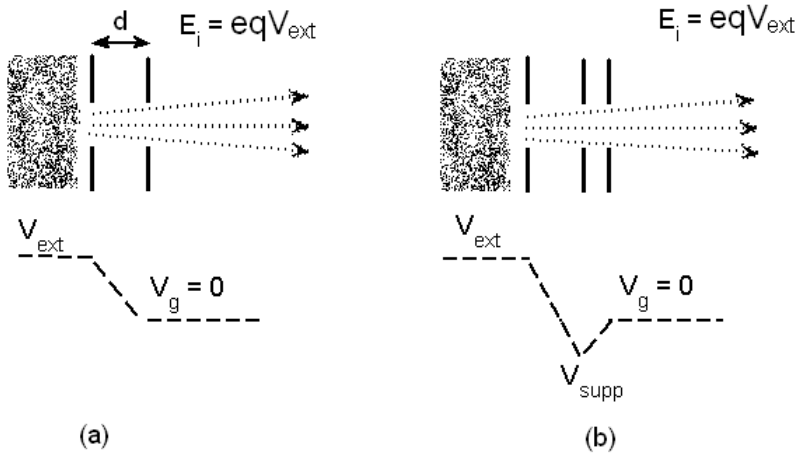


Figure 3.4: *Schematic view of two electrode extraction system (a) and three electrode extraction system (b). Figure adopted from Ref. [63].*

electrode (V_g) (Fig. 3.4b). This three electrode configuration is called an *accel-decel* extraction system, because ions are accelerated in the first gap and decelerated in the second gap. The middle electrode acts as a shielding electrode for the low energy electrons produced in the downstream region in order to improve the space-charge compensation for the extracted ion beam.

The ions available for beam formation at the plasma electrode have been transported from the inner region of the plasma by diffusion or plasma flow to the extraction region. When the plasma comes into contact with the plasma electrode a sheath with a thickness of the order of a Debye length (λ_D) is formed. The Debye length is given by

$$\lambda_D = \sqrt{\frac{\varepsilon_0 k T_e}{n_e e^2}} \tag{3.6}$$

where ε_0 is the permittivity of free space, k is the Boltzmann constant, e is the charge of the electron, T_e is the electron temperature and n_e is the electron density. In the ECR ion source the Debye length is typically a fraction of a millimeter. Ions in the plasma acquire a finite velocity directed towards the sheath boundary. Bohm showed that in order to satisfy the Poisson equation in the plasma sheath this velocity compound should exceed $\sqrt{kT_e/m_i}$ [91], with m_i the ion mass.

The quality of the extracted beam is determined by the trajectories of the ions in the extraction region. These are influenced by several factors, such as the applied electric field strength, the magnetic field in the beam formation region, the shape of the emitting plasma surface and the space-charge density in the resulting beam itself. The emitting 'surface' is the boundary between the plasma sheath and the ion beam, the so-called *plasma meniscus* [63]. Depending on the plasma density, extraction geometry and extraction voltage the plasma meniscus can vary between strongly convex and strongly concave. For a given geometry and voltage it will be convex at high plasma density, resulting in beam losses in the extraction system and concave at low density, leading to strong focussing and subsequent blow up due to space-charge forces if these are not properly compensated. Simulations indicate that the ideal shape of the plasma meniscus is a flat surface [63].

The current density of charged particles that can be extracted from the plasma by the electric field is limited by the plasma density and space-charge of the ion beam and can not exceed the Child-Langmuir law (assuming a planar plasma sheath and an ion beam without space-charge compensation [63, 66])

$$j_{sc} \simeq \frac{4}{9}\varepsilon_0\sqrt{2eq/m_i}\,\frac{V_{ext}^{3/2}}{d^2} \tag{3.7}$$

with ε_0 the vacuum permittivity, m_i is the ion mass, V_{ext} is the extraction voltage, and d is the length of the extraction gap (Fig. 3.4). This equation holds under space-charge limited conditions i.e. when the ion source is capable of producing more ions than can be removed at any time (space-charge limited mode) by the extraction system.

For positively charged ions with charge state q the energy E_i of the extracted ion beam is given by $E_i = eqV_{plasma}$, where $V_{plasma} = V_{ext} + V_p$. The plasma potential V_p is typically of order $10\ V$, and can usually be neglected ($V_p << V_{ext}$) in comparison with the extraction voltage of many kilo-volts.

In the above description it was assumed that there is no magnetic field in the beam formation region. In an ECR ion source, however, the ion beam formation and extraction is more complex due to the presence of a combination of electric and magnetic fields in the extraction region. This has a strong influence on the beam formation process.

(a) Position of the plasma electrode and ion confinement:

The position of the plasma electrode in an ECR ion source with respect to the magnetic configuration is an important parameter for the optimization of the production and extraction of the highly charged ion beam. In order to preserve the plasma confinement the extraction system should not influence the mirror reflection of the particles in the plasma. Therefore, it is generally located at the last closed $iso-|B|$ surface of the source (see Fig. 3.1). In this way only ions in the loss cone of the mirror are extracted.

There is a loss cone at both ends of the source, which are in general not identical in size because of the different magnetic field maxima at either end (see Fig. 3.2a). By using a larger axial magnetic field at the so-called injection side of the source (see Fig. 3.3) the loss cone at this side is smaller, resulting in a higher output of ions on the extraction side. The extracted ion current I_q of charge state q is approximately half the ion loss rate [1]

$$I_q \approx \frac{1}{2}\frac{n_q eqVol}{\tau_q} \tag{3.8}$$

where n_q is the density of the ions of charge state q, τ_q the ion confinement time; Vol is the part of the plasma volume that maps along the magnetic field lines into the extraction area, i.e. the plasma volume may not be the same for different ion species.

(b) Extraction geometry, potential, current and plasma meniscus:

The accel-decel system used in ECR ion sources generally has a Pierce-type plasma electrode (first electrode) and various shapes for the puller electrode (second electrode), while the grounded electrode (third electrode) is in most cases a simple cylindrical pipe. The Pierce theory was originally developed for electron guns assuming zero magnetic field, zero thermal energy and electrons uniformly emitted from a planar cathode. The Pierce theory is also applicable to positive ion beams by reversing the electric field direction and changing the charge to mass ratio of the electron to that of the ion. According to the Pierce theory, the plasma electrode should make an angle of 67.5° with respect to the optical axis to produce a transverse electrostatic field that exactly balances the space-charge field of the electron beam [92], assuming space-charge limited extraction conditions.

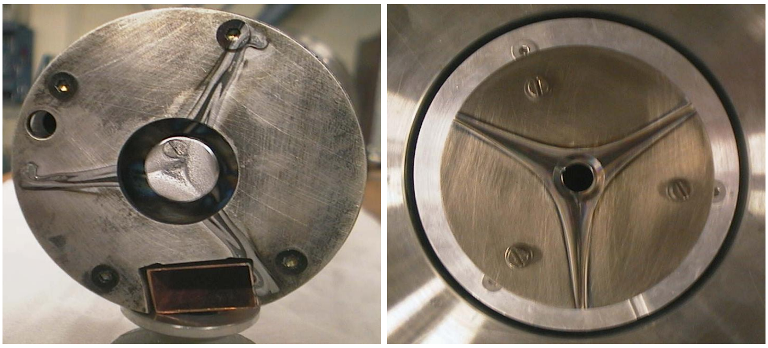
The plasma provides an ion current to the extraction aperture given by Eq. 3.8. Dividing this by the area of the extraction aperture gives the extracted current density j_{sc}, which should be equal to the space-charge limited current density, Eq. 3.7. This equality defines the shape of plasma meniscus and thereby the effective distance (d) in Eq. 3.7.

In an ECR ion source the shape of plasma meniscus is difficult to predict. It depends upon the plasma parameters, the shape of the plasma electrode, the extraction potential and the local magnetic field. The inhomogeneity in the plasma density across the extraction aperture leads to further complications of the plasma sheath model (see Eq. 3.6). A fully three-dimensional plasma sheath model for the ion extraction from an ECR ion source has not yet been developed.

(c) Magnetic field and ion temperature:

The loss of axial symmetry of the simple mirror field by the addition of the radial multipole field to create a min-B configuration has important consequences for the electron and ion trajectories in the trap. It causes according to calculations [93, 94] a triangular pattern in the plasma distribution at the injection and extraction sides, which is indeed observed in practice [95] (Fig. 3.5b and 3.5a). Fig. 3.5 shows the plasma sputter marks on the injection and extraction sides of the KVI-AECR ion source due to the ECR ion source magnetic field configuration (see Fig. 3.2b). The plasma density drops axially and radially outside the resonance zone [96, 97]. Therefore, the ion motion outside the resonance zone is dominated by the magnetic field rather than by collisions resulting in the triangular beam pattern.

Furthermore, Fig. 3.5b shows that the shape of the plasma facing side of the plasma



(a) (b)

Figure 3.5: *Injection plug with biased disk (a) and Plasma electrode (b).*

electrode is not very important in ECR ion sources, because the ions that are extracted have diffused from the plasma core that is concentrated around the plasma chamber axis [1]. The properties of the extracted beam are mainly determined by the local electric and magnetic fields between the plasma and puller electrodes [98, 99].

During the ion beam extraction from the ECR ion source the triangular beam pattern rotates due to the magnetic field in the extraction region. The angle of rotation is in first-order given by the following formula for magnetic lenses [100]:

$$\Theta = \sqrt{\frac{Q}{8m_i V_{ext}}} \int B_z dz \tag{3.9}$$

with Q the charge of the extracted ion, V_{ext} the extraction voltage, m_i the mass of the extracted ion and B_z the axial magnetic field strength. This is illustrated in Fig. 3.6, where the angle of rotation as a function of the mass number to charge state ratio (m/q) for an extraction potential $V_{ext} = 24\ kV$ and $\int B_z dz \approx 0.077\ Tm$ has been plotted. The calculation has been done for the KVI-AECR ion source.

The emittance of the ion beam extracted from an ECR ion source is determined by two factors: (1) the ion temperature [12] and (2) the magnetic field in the extraction region of the ECR ion source [12, 13] (see Fig. 4.2b). To estimate both contributions to the emittance it is assumed that the electric field has no azimuthal variation, that the plasma density distribution is uniform across the aperture of the plasma electrode and that the ion temperature is given by a Maxwellian temperature distribution inside the plasma. The emittance of the ion beam extracted from the ECR ion source under these assumptions is given by [12]:

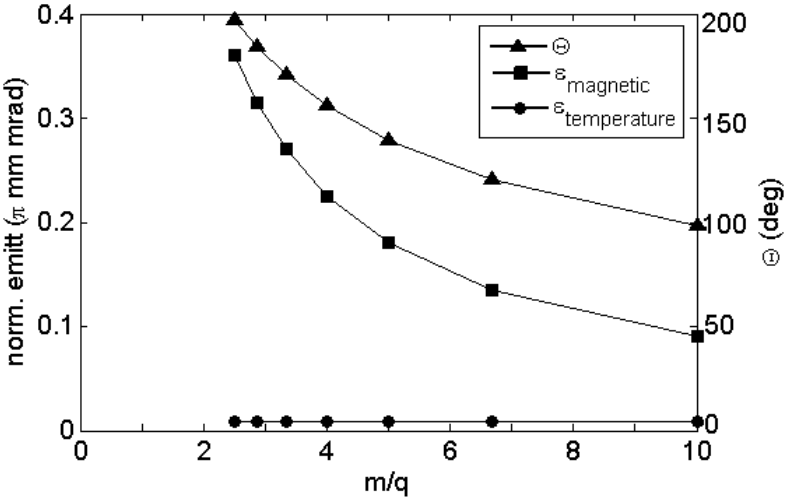


Figure 3.6: *Calculated normalized emittance values (left scale) and angle of rotation (right scale) for KVI-AECR ion source extraction conditions.*

$$\varepsilon = r_0\sqrt{\frac{kT_i}{2QV_{ext}}} + r_0^2 B_0\sqrt{\frac{Q}{8m_iV_{ext}}} \tag{3.10}$$

where r_0 is the aperture of the plasma electrode, k the Boltzmann constant, T_i the ion temperature, m_i the ion mass, Q the charge of the ion, V_{ext} extraction potential and B_0 the magnetic field at the aperture of the plasma electrode.

Fig. 3.6 shows the two contributions to the emittance as a function of m/q for the KVI-AECR ion source with typical extraction parameters ($r_0 = 4\,mm$, $B_0 = 1.1\,T$, $V_{ext} = 24\,kV$ and $kT_i = 1\,eV$ Ref. [101]). Eq. (3.10) shows that for a given atomic mass the emittance of the extracted ion beam is expected to be larger for higher-charge state ions. However, this is in contradiction with the general observation that higher charge state beams have a smaller emittance, as quantified by e.g. measurements of the emittance after the analyzing magnet of the AECR-U at LBNL [102]. Possible explanations based on plasma physics and ion production processes, such as a dependence of the radial transport on the charge-to-mass ratio of the particles, are proposed in Ref. [103]. Since highly charged ions appear to be concentrated more on the axis of the ECR ion source as compared to low charge state ions [93], the effective extraction radius is smaller for highly charged ions and thus their emittance as well.

3.4 ECR ion source modeling

The large increase in ECR ion source performance in the last two decades has been realized on the basis of more or less empirically established macroscopic design rules. Further improvements will depend more and more on a better understanding of the underlying plasma physics and ion extraction in ECR ion sources. However, this is a very complicated and challenging problem because of the collective character of plasma behavior and the huge ranges in time and length scales involved.

To illustrate the complexity of ECR ion source behavior we show in Fig. 3.7 measured beam profiles behind the extraction system for two different operating conditions of the ECR ion source differing only in gas pressure and extraction solenoid current. The operating conditions corresponding to Fig. 3.7a are the standard conditions giving a high beam current, good stability and optimum beam transport efficiency. The operating condition for the hollow beam profile (see Fig. 3.7b) results in significantly reduced performance in terms of intensity, stability and transport efficiency.

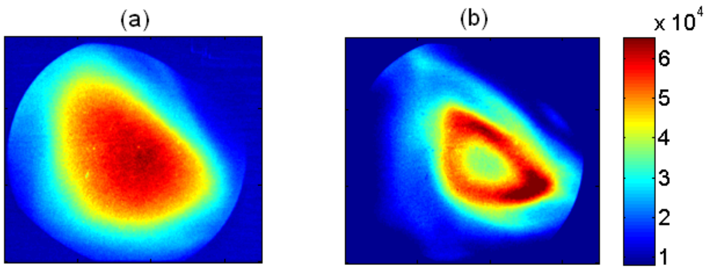


Figure 3.7: *Measured He^+ beam profile behind the extraction system for stable operation (a) and an unstable operation (b) in the KVI-AECR ion source.*

Many groups have developed numerical modeling and simulation tools for ECR ion sources, but detailed three-dimensional, self-consistent simulation codes treating both the electron and ion dynamics in ECR plasmas are still lacking. Also at KVI an ECR ion source simulation code has been developed which has been used in this thesis to determine the phase-space distributions of ions in the plane of the plasma electrode. These distributions are used as initial conditions for ion extraction and transport calculations described in chapters five, six and eight. Before describing the KVI plasma simulation code a brief overview will be given of the simulation efforts done by other groups.

An initial effort of ECR ion source plasma simulation was done by the Grenoble group [104–107]. They have developed a zero-dimensional code that simulates the electron and ion dynamics in a self-consistent manner by solving the Fokker-Planck equation in velocity space. With this code they could qualitatively reproduce several phenomena observed in real ECR ion sources, including the biased-disk, gas mixing and afterglow effects. A detailed quantitative description is of course not possible because no spatial degrees of freedom have been taken into account.

The GEM2D code (General ECR ion source Model) [108–110] under development at FARTECH, Inc, aims at predicting the steady state ECR ion source plasma self-consistently. The advantage of the code is that the electron density, temperature and ion density in the ECR ion source and the CSD of the ion beam extracted from the ECR ion source are calculated by using operational parameters, such as RF power, RF frequency, gas pressure and device configurations as input. However, the code assumes rotational symmetry so that the real 3D magnetic geometry is not taken into account.

The ECR ion source group at LNS, Catania is working on the development of a numerical code to model the electron and ion dynamics in an ECR ion ion source using a Monte Carlo approach [75, 111, 112]. The objective of the simulation is to understand the effect of frequency tuning and two frequency heating on ion dynamics, beam formation and beam brightness, etc. However, the code is not yet predicting the electron/ion dynamics in the ECR source in a self-consistent way [113].

The KOBRA3D-INP [114] code has been developed at INP, Germany by P. Spädtke to model ion sources and space-charge effects during beam extraction and transport. In this code collisions are neglected so that the production and diffusion of multiply charged ions are not calculated. The main assumption is that the ions are magnetized in the whole plasma chamber and that the motion of the charged particles is determined by the magnetic field only [115–117]. The code does not calculate the charge state distribution of the extracted ions, instead the experimentally observed distribution has to be used as input to the code. The code calculates the spatial distribution of the extracted ions by tracing them from their starting positions at the plasma chamber wall along the magnetic field lines that pass through the extraction aperture. The simulation of ion beam extraction from the ECR ion source can be performed with the same code by using the calculated 3D spatial distribution. The major limitation of the code is that it does not simulate the production of multiply charged ions in the ECR ion source, because collisions and diffusion are not taken into account.

Mironov et al. have written a code based on the Particle-In-Cell Monte-Carlo Collision (PIC-MCC) method to model the ion dynamics in an ECR ion source plasma [33, 118]. This code simulates the full 3D ion dynamics in an ECR ion source and has been used to study charge state distributions, ion confinement times, ion temperatures, gas mixing effect and the isotope anomaly, as well as the wall coating effect. The main approximation made in the code is that the electron energy distribution is given by a single Maxwellian with the electron density determined by local charge neutrality and the electron temperature (T_e) is used as a fitting parameter. This implies that the simulations assume a steady-state plasma with a single isotropic electron momentum distribution throughout the plasma and without any internal electric fields. Both ion-ion and electron-ion collisions are taken into account, i.e. electron-ion heating, ion-ion temperature equilibration, ion diffusion and the ionization dynamics are all included in the plasma model. Charge-exchange and recombination processes are neglected because of their low probability in the simulated plasma conditions.

The movement of ions with different masses and charge states is tracked in the three-dimensional min-B field magnetic trap of the ECR ion source using a leapfrog particle mover [119]. The motion of neutral particles is modeled by taking into account scattering and energy losses when they hit the chamber walls. Collisions between charged particles are computed using the model of Nanbu [120]. The collision partners are chosen randomly inside a computational cell using the method of Takizuka-Abe [121].

Simulations are started with equal numbers of neutrals and singly-charged particles uniformly distributed over the source volume. This ensemble of particles is then allowed to evolve until a stationary condition is reached. The total number of particles in the simulation is kept constant by injecting a neutral particle (with room temperature energy distribution) into the plasma chamber for each heavy particle lost through the extraction aperture. Approximately 50 % of the heavy particles remain neutral in the stationary state and the local plasma density is determined dynamically by the balance between the ionization rate and the in-and out-flow of the ions in each mesh cell. In the stationary state, the extracted ion currents can be calculated from the flux of ions through the extraction aperture. More details are given in Ref. [33]. Results of simulated charge state and phase-space distributions are reported in chapter 5 and 6.

Despite the fact that the electron dynamics is not taken into account and that the electron distribution is a simple Maxwellian, it has been demonstrated that this code yields very relevant results for the ion dynamics and the production of highly-charged ions [33]. We have used the code to calculate the charge state distributions and 6D phase-space distributions to perform the three-dimensional simulations of multiply charged ion beam extraction and transport to the injection system of the AGOR cyclotron installed at KVI.