3  Ion beam extraction from plasma

3.1  Introduction

Ion beam extraction system is one of the most important systems of the ion source. In order to extract ions from the plasma, and to accelerate and collimate them for subsequent focusing into the desired beam shape, an arrangement of carefully designed electrode must be used. This electrode system must create the proper configuration of electric fields at the surface of the ion source and along the acceleration path. The flexible fluid-like plasma surface where the ions are formed is called the plasma meniscus and the shape of the meniscus depends on the ion current density inside the plasma, applied extraction voltage, the current drawn from the plasma and the geometry of the electrodes. The design of the ion gun must take in to account the nature of this surface and must initiate the ion beam as free of aberration as possible, since subsequent correction of ion-optical defects, introduced in to the beam by the extractor is virtually impossible. Thus great care while design and fabrication of the extraction system is very vital.

The extraction system consists of two or more electrodes with single or multi apertures. The first electrode which is called as the plasma electrode, (PE) is mounted in such a way that it is directly in contact with plasma. Generally, high voltage power supply meant for extraction of the beam is connected to this electrode where the electrical polarity of the voltage should be that of the ion beam. The subsequent electrodes are assembled on to PE with a gap maintained by insulating spacers and the final electrode should be at ground so that extracted beam is at ground potential. The whole assembly has to be mounted by proper insulating holders which are properly designed to maintain concentricity and alignment of the extraction geometry with the focusing column. Figure 3-1 shows two of the various types of extraction geometry that are popularly used and the corresponding voltage levels. In the type shown in a) there are two
parallel plates with single apertures and the extraction voltage is applied between the two plates. In b) there are three electrodes with middle electrode biased to negative compared to both PE and the ground electrode. The purpose of the second electrode is to suppress the back flowing electrons into the ion source from the downstream region. This system is generally called as accel-decel system. For the work mentioned in this thesis, type a) is used.

![Figure 3-1 Extraction system scheme. a). Two electrode system. b). three electrode system](image)

3.2 Ion beam parameters

There are different measurable parameters that characterize the beam and the most important parameters that quantify the beam are listed below [38]

a) **Ion beam intensity**

Often mentioned as beam current, it is the number of charged particle crossing a particular plane of measurement per second. It is the most important parameter to characterize an ion source. Destructive and non destructive methods are available for measuring beam current. Faraday cup is the most simplest and popular one which is a destructive type.

b) **Emittance**

Emittance is a measurement of how large a beam is and how much it is diverging. It is measured in mm-mrad and is the product of position of the particle and divergence angle. Often emittance is normalized to beam energy because particles
when accelerated increase their longitudinal velocities without any change in the transverse velocity effectively reducing the divergence and hence after acceleration the emittance reduces although the emittance is invariant at different energies. In order to compare the emittance of ion sources at different energies, it is customary to normalize with product of $\beta \Upsilon$ or extraction potential.

c) **Brightness**

Brightness of an ion source is the measure of the ion current density produced in a given solid angle. Brightness and emittance are related to each other by

$$B_r = \frac{2I}{\pi^2 \varepsilon_x \varepsilon_y}$$  \hspace{1cm} (1)

Where $\varepsilon_x$ and $\varepsilon_y$ are normalized transverse emittances in x and y direction, respectively across the beam.

d) **Energy spread**

In a beam not all of the particles have the same energy. The energy distribution of the particles is a measure of the range of different particle velocities in the beam. It is effectively the longitudinal emittance of the beam measured in eV. The origin and size of the energy spread is different for different types of source. Energy spread is important because it will cause chromatic aberration blur and also may produce transverse emittance growth as the beam passes through magnets and accelerating gaps. The beam emittance can be transferred between longitudinal and vertical directions and vice versa.

e) **Mass or charge spectra**

By obtaining mass or charge spectra we can filter different charge states in the case of multiply ionized beam or impurities. Depending on the applications and the ion source, a mass analyser of the required resolution can be employed. In the case of FIB, this adds extra length, energy spread and aberrations to the ions. But it is very important to filter out the presence of higher charge states and same...
charge states of higher masses in the ion beam for getting a clear focus spot. Thus an offline experiment to optimize the ion source parameter for high charge state can be carried out.

A proper extraction system should satisfy the following conditions to fit well into a focused on beam system:

- It should produce a high current intensity ion beam. Thus loss of current in subsequent electrode has to be minimal. Central core of the ion beam should be selected by making use of fine aperture and hence the central core of the beam needs to have high brightness.

- It should generate stable ion beam within a small divergence. That is the emittance of the ion beam has to be small. This also imply that presence of degrading factors like magnetic field or transverse electric field in the extraction region have to be minimized wherever possible.

- Electrodes must be well aligned and should be easily mountable and the system should have high voltage withstanding capability

- All power supplies used in the extraction system and including the focusing lenses should have minimum ripple and high stability since they introduce energy spread in the beam which ultimately results in chromatic aberrations in the final focused spot.

- It should be as free of aberrations as possible.

3.3 Ion beam extraction from a plasma surface

The extraction of ions from plasma is governed by an equilibrium between the ambipolar flux of ions to the extraction aperture and the space charge effects in the extractor.
Ambipolar flux is given by equation (2) and is independent of extraction voltage. This is the maximum current that an ion source can produce.

\[ J_s = n_i q \frac{K T_e}{m} \]  \hspace{1cm} (2)

Where \( K T_e \) is the electron kinetic energy, \( n_i \) is the ion density in the plasma, \( m \) is the mass of the ion. The extraction potential, which tends to penetrate the plasma electrode aperture, is repelled by the plasma sheath potential; so an equipotential is formed which defines a curved boundary which is known as the plasma meniscus. The relative strength of the plasma and extraction potentials define the radius of curvature of the meniscus. Particles that cross the meniscus see the extraction field and are formed into a beam. The initial focusing of the beam depends on the curvature of the meniscus and hence on the current density within the plasma. The positive ion flow region downstream from the plasma meniscus is automatically adjusted to the state that the distance (gap) \( d \) between the meniscus and the extraction electrode are governed by Child-Langmuir equation (17)

\[ J_c = \frac{4 \varepsilon_0}{9} \sqrt{\frac{2 q \Phi^{3/2}}{m \omega^2}} \]  \hspace{1cm} (3)

Where \( \varepsilon_0 \) is the permittivity \( = 8.854 \times 10^{-12} \text{ (F/m)} \), \( q \) is the charge \( = \text{charge state} \times 1.602 \times 10^{-19} \text{ (C)} \), \( m \) is the mass number of ion \( \times 1.67 \times 10^{-27} \text{ (Kg)} \), \( \Phi \) is the potential drop across the gap \( d \). Thus, in a plasma source the shape and position of the ion emissive surface are always automatically adjusting so that the ion flow is simultaneously emission-limited by the plasma and the space-charge limited by the extraction voltage. Beam current density can be increased either by increasing the extraction voltage or by degreasing the gap between electrodes. The gap \( d \) (cm) is limited by the voltage breakdown limit given by \( V_b \)

\[ V_b \approx 6 \times 10^4 / d^{1/2} \]  \hspace{1cm} (4)

The emissive surface looks like rubber film on which pressures apply from either side. The plasma exerts pressure on the meniscus from inside and the electric field exerts counter pressure which depends on current density, extraction voltage, extraction geometry and shape and position of the meniscus. Since the plasma electrode determines the plasma potential and
produces a screening effect, only a slight electric field penetrates into the aperture. This screening effect is strongest at the electrode edge and hence the meniscus remains anchored to the electrode edge. A slight adjustment of the shape of the meniscus will cause a dramatic change in the extraction electric field near the meniscus. For all the ion beam applications, it is always best to have minimum divergence. In this case, the beam is initially convergent from concave meniscus in order to cancel the divergence caused by the space charge expansion and the extraction aperture lens effect leading to a parallel beam. This condition is called as optimum focusing or optimum matching. The optimum matching between current density and applied potential is obtained at a certain value of $I/V^{3/2}$ called as optimum perveance $P^*$ where all the extracted current pass through the extraction aperture (occur at optimum extraction voltage $V^*$).

In order to obtain the best extraction, the meniscus needs to be concave so that maximum current is extracted and all the ions pass through the extraction electrode. However, due to concave nature of the meniscus, ion beam is convergent with angle $\theta$. Since extraction system isolates zones of two different potentials, there is a lens effect as shown by Davisson and Calbick [40] causing divergence of the beam ($\psi$). Space charge effect also adds to the divergence of the beam. Convergence and divergence mechanism is shown in Figure 3-2. Ideal extraction system should have $\theta$ and $\psi$
in such a way that the net beam divergence remains zero. Under these conditions, the perveance of the
extraction system is optimum \( P^* \) \[41\].

\[
P^* = 0.47P_0
\]  \hspace{1cm} (5)

\[
P_0 \approx 1.71 \times 10^{-7} \frac{a^2}{d^2} \frac{q}{\sqrt{m}}
\]  \hspace{1cm} (6)

Where \( P_0 \) is the perveance of the planar extraction geometry and \( a \) is the aperture radius on
the plasma electrode.

For a given extraction geometry the divergence depends only the beam perveance. When
emissive and extracted current varies as \( \phi^{3/2} \), the optical performance of the extracted beam is
unchanged. Also the optimum perveance increases proportionally with the perveance of the
planar extraction geometry and hence as the square of the aspect ratio \( (P^* \propto (\frac{a}{d})^2) \). In the
work presented in this thesis, \( a = 0.5 \text{ mm} \) and \( d = 1 \text{ mm} \) giving rise the aspect ratio of 0.5.

Aperture radius of plasma electrode and the magnetic field at the extraction region
influence strongly on the emittance of the beam as given by \[42\]

\[
\varepsilon_{\text{radius}} = 0.016a \sqrt{\frac{KT_i}{M/q}}
\]  \hspace{1cm} (7)

\[
\varepsilon_{\text{mag}} = 0.032a^2B \sqrt{\frac{1}{M/q}}
\]  \hspace{1cm} (8)

Hence in the ion source developed in this thesis has no magnets of any kind and the radius of
plasma aperture is chosen as 0.5 mm. In some of the experiments the radius is chosen to be 1
mm with gap of 2 mm.

### 3.4 Simulation of ion beam extraction by IGUN

IGUN is used for the design and simulation of the extraction system \[43\]. IGUN is
specially designed ray tracing program for simulating the plasma region for the extraction of ion
beam and it also supports the simulation of focusing lenses. IGUN can handle 2D rectangular
and axi-symmetric problems with space charge considerations. IGUN has interactive (colored) graphics, e.g. equipotential lines and trajectories are seen on screen for each cycle of iteration, allowing the user to judge the convergence and saving time by breaking execution, if input parameters have been chosen wrong. Comprehensive plots of the results are available, e.g. a full emittance diagram, a diagram of fractional emittance against current, beam profiles in equidistant positions along the beam axis, and of surface fields along the problem boundary. A special feature of IGUN is the possible definition of curved dielectric boundaries within the frame of the input of boundary. The program is fully interactive and parameters, electrode geometry can be changed at any time interrupting the execution. Results are continuously displayed on the screen as program executes.

For the ion extraction from plasma surface in IGUN, the fall of potential to the wall of the discharge chamber (and through the hole of extraction) is simulated on the basis of the simplest one-dimensional sheath model, taking electrons with a Boltzmann energy distribution

\[ f(E) = \exp \left( -\frac{e(U_p - U)}{kT_e} \right) \]

And ions of constant directed velocity \( v_i \) corresponding to an energy

\[ eU_i = \frac{(M/2)v_i^2}{kT_i} \]

Although \( kT_e \) could differ from \( eU_i \), as long as one has no evidence to violate this, \( eU_i = kT_e \) equivalence can be used. In addition to \( eU_i \), which is a directed initial energy of the ions, you can simulate an ion temperature by specifying \( T_i \) and the number of split trajectories (NSPLIT) >1, to split up each ion trajectory in to NSPLIT rays with transverse energies, corresponding to an ion temperature of \( kT_i \). The most significant advantage of IGUN compared to other plasma extraction programs is the self determination of the ion extraction current during succeeding cycles, by matching the electric field gradient outside and inside of the plasma. By this, the Debye length and hence the emission current density of the plasma is determined in each cycle of iteration. Connected also with the use of the analytical potential function of the sheath is the numerical stability of this program: A Debye length of less than 1/10 of a mesh does not cause problems. Self adjusting does not work if the diameter of the bore in the extraction electrode is
not large as compared to its thickness. This becomes obvious if the convergence of extracted ion current and beam compression becomes poor.

Figure 3-3. Axis-symmetric simulation of Argon ion beam extraction from RF plasma. Equipotential contours and ion beam trajectories are plotted.

Three sets of electrodes having different aperture sizes were considered for the extraction geometry. The gap between the electrodes was selected in such a way that the aspect ratio maintained as 0.5. Figure 3-3 shows a IGUN model of the extraction system with 1 mm diameter together with optimised ion trajectories launched upstream of the plasma boundary and the equipotential lines. The plasma meniscus which is slightly concave shape is also shown in the figure. Due to its concave shape the trajectories are focused between the electrodes and with the diverging effect of lens action, the beam is made almost parallel. Electrodes are having aperture radius of 0.5 mm and are kept at 1.5 mm gap. The extraction aperture is kept very small In order to have small source size. To get a uniform curvature of field across the aperture, a conical edge is used and this improves the beam quality.

Figure 3-4 shows the variation of extracted current and RMS emittance as a function of extracted voltage for this geometry. Emittance has an optimum at 6 kV for this geometry, though current showed a tendency to increase with extraction voltage (Vext). Brightness at 6 keV was found to be around 12700 A/m²SreV.
Figure 3-4. Calculated emittance plot showing beam trajectories crossing the plane where the emittance is measured.

The simulation shows that at about 350 µA of Ar current on the target at 5 kV, the solution converges and gives the best emittance. Experimentally also it is verified that about 250 – 350µA of Ar ion beam is achieved with least divergence. The simulations are very close to the experimental results.

### 3.5 Experimental results

Ion beam extraction is carried out using two electrode single aperture extraction system as mentioned above. The aspect ratio of the gap between the electrode to aperture is kept as 0.5. E. R. Harrison [44] and Coupland et. al [41] have demonstrated and described that with the simple two electrode-single aperture extraction system having an aspect ratio of 0.5, it is possible to obtain ion beam with low divergence and good perveance. Plasma electrode (PE) is kept very thin (0.5 mm) to enable high current extraction. PE has a protrusion at the periphery so that when mounted on the system, it gets proper contact with the flange which carries ion source and where the high voltage power supply is connected. Ceramic balls are used for maintaining the gap between both the electrodes. The electrodes and the spacers are assembled in perfectly machined slot in the stainless steel flange carrying the ion source. All the grooves are so machined that the optical column fits exactly concentrically to these electrodes. The alignment of extraction electrodes is a critical task in producing high quality beam. A
faraday cup made of steel with secondary electron suppression is used for measuring the current in all the different experiments.

3.5.1. Enhancement of extracted current by modification in plasma chamber

The electron density and positive ion densities are functions of power deposited in the plasma. Thus increasing the RF power is an obvious solution for increasing the extracted current. Also increase in the power density keeping the same power by changing the source volume is an alternative to this. Figure 3-5 shows the extracted current Vs Vext for two different plasma chamber volumes. One with 50 cm$^3$ volume will be referred as large plasma volume (LPV) and one with 25 cm$^3$ will be known as small plasma volume (SPV). This experiment is done with extraction electrodes with 3 mm aperture dia, RF power of 100w and chamber pressure of 0.01 mbar. Up to $V_{\text{ext}} = 1.4$ kV, both curves are just the same but above 1.4 kV the increase of current in the case of SPV is greater than that of LPV.

![Figure 3-5 Current extracted from argon plasma for two different plasma chamber volumes](image)

At 6 kV extraction voltage, current extracted from a SPV was 340 µA greater than that extracted from LPV. There is no sign of saturation of extracted current as seen in the figure. It seems, the extracted ion current may increase with constant slope with higher power and
higher extraction voltages. However, for the production of focused ion beams, currents extracted with larger potentials where the Child-Langmuir law does not hold, are not suitable as there exists a strong crossover within the extraction system contributing to large aberrations and divergence. As shown in Figure 3-6 there is a higher variation of extracted current with RF power in the case of SPV and the current yield is 8 µA/W where as in the case LPV, the yield is only 5 µA/W.

Although ion source shows the capability of producing still higher currents, we have limited the operation at about 160 W, since at higher powers ion energy spread increases above 5 eV and also ion source may require water cooling.

![Figure 3-6 Variation of extracted current with RF power for two different plasma chamber volume](image)

**3.5.2. Extraction features for different parameters**

Figure 3-7 Extracted current from argon plasma for 2 different extraction diameters shows the V-I characteristics obtained from Argon beam extracted by two different extraction apertures each having a diameter of 1 mm and 2 mm. The source parameters are kept similar for both the experiment and the current is recorded with variation in the extraction voltage. It was seen that the shape and nature of the V-I curve is very much dependent on the
electrode geometry, and pressure. Under most of the experimental conditions it was seen that the V-I curve follows $V^{3/2}$ law as suggested by Child-Langmuir (C-L) law up to a certain voltage. It is observed that there is a deviation from Child-Langmuir law after certain extraction voltage forming a ‘knee’ in the curve. At higher extraction potential, the force on the plasma meniscus by the extraction potential exceeds the force by the sheath potential in the plasma and hence the meniscus takes a shape with smaller radius. This causes crossover to move upstream and form within the extraction region. Some portion of the current gets obstructed by the second electrode of the extraction system. So the significant part of the extracted current from the plasma is intercepted by the ground electrode and rest is read by the Faraday cup and V-I curve no more follows the Child-Langmuir formula. From the knee point onwards, current linearly vary as voltage increases.

![Figure 3-7 Extracted current from argon plasma for 2 different extraction diameter](image)

On both the curve shown in Figure 3-7 Extracted current from argon plasma for 2 different extraction diameter, a prominent knee showing the variation from C-L law is seen. Where 2 mm extraction aperture found to extract more current as expected, the slope after knee point in this case is also steeper. For 2 mm extraction aperture, each 11 V change in $V_{ext}$ raised the extracted current by 1 µA, whereas 1 mm aperture extraction system required 45 V for each
µA. 3 mm extraction aperture does not show a knee point in the curve as seen in Figure 3-5 because the applied voltage is not sufficient to shift the crossover up inside the extraction system. Characteristics of 3 mm aperture extraction system shows increased extracted current and greater saturation points than the cases of electrodes with 2 mm and 1 mm apertures. It is seen that up to a certain voltage, the V-I characteristics follow C-L equation. For example in Figure 3-7, for 1 mm aperture, up to about extraction voltage of 1 kV, the extracted ion current follows the Child-Langmuir law with perveance of $6.32 \times 10^{-9} \text{ A}/\text{V}^{3/2}$ which is very close to theoretically calculated perveance of $6.8 \times 10^{-9} \text{ A}/\text{V}^{3/2}$ (for argon) [45] [46]. With increase in the extraction potential, plasma meniscus starts to become concave increasing the area of emission as well as moving away from the anode and thereby deviated significantly from Child-Langmuir curve. From about 1 kV, there is a sharp change in the characteristics and the extracted current linearly increases at a rate of $45 \mu\text{A} / \text{kV}$.

Characteristics show that the rate of increase of current is same up to 8 kV extraction potential, showing that plasma is still capable of providing larger currents at higher extraction potentials. It is experimentally seen that at about 2-2.5 kV extraction potential, the divergence of ion beam is least and hence one can assume that the plasma meniscus is about flat. At these potentials, the extracted argon current is about $250 \mu\text{A}$. Substituting the ion current ($I_i$), extraction
aperture radius \( r \), mass of argon \( M_i \), and mean electron energy \( T_e \) of 4 - 5 eV into Bohm’s relation (23) which is same as equation (2), the plasma density \( n_i \) at the extraction aperture is calculated to be \( \sim 1 \times 10^{12} \text{ cm}^{-3} \).

\[
n_i = \frac{I_i}{0.6q\pi a^2 \sqrt{\frac{KT_e}{M_i}}} \tag{9}
\]

This high plasma density is possible due to the coupling of high RF power to plasma of small volume. The plasma chamber has volume of 25 cm\(^3\) and with applied RF power of 160 W the RF power density in the plasma is 6.4 W/cm\(^3\) [47]. Figure 3-8 shows the variation of Extracted current from Krypton plasma at 150 W for two different pressures.

This experiment is carried out with 2 mm extraction aperture. As comparing with Figure 3-7, Krypton currents are less. Though plasma density for krypton plasma is higher, the extracted current is less because of the low velocity of the krypton ions at same energy as compared to that of the argon ions.

Here, after the knee point, the slope for both the cases was similar 17-18 V for increase of 1 µA which is less steeper than that of Argon’s case. \( V_{\text{knee}} \) also shifted from 2kV to 2.4 kV while increasing the pressure. Figure 3-9 Glow through the ion beam path after extraction shows the
glow in the beam path, just after the extraction system. Here about a mA of Ar current is extracted.

3.6 Conclusion

Extraction system is simulated and designed using IGUN code to get a low divergence high current beam. Extraction system consisting of simple two electrode geometry has been employed to extract high current ion beams of various gaseous elements from the plasma source. The experimental results closely match with the simulations. With low aspect ratio (0.5) extraction system, ion beam with least divergence has been obtained. At 100 W, 500 µA of argon beam could be extracted for 3 mm extraction aperture. By increasing power to 150 W, 800 µA can be extracted from a large plasma volume. Still higher extracted current could be obtained by increasing the power. But at higher RF power it is observed that the energy spread is higher and hence the RF power is kept low. Keeping the RF power same, the power density coupled to the plasma is reduced by simply reducing the plasma volume and found significant improvements in the extracted current. Just by reducing the plasma volume to half, much higher current was extracted. The increase in current by changing power from 100 W to 150 W could be obtained just by reduction in plasma volume and RF power of 100 W. This is an important achievement that just by changing the plasma chamber size; increase in current density was obtained. Improvement in angular current density of the ion beam by changing the plasma chamber volume (one of other important parameter for high current FIB) is studied and described in Chapter 6.

For generating focused ion beam, higher brightness is required and hence the extraction system is design to generate ion beams with minimum divergence. Although increase in the extraction aperture increases the extracted current, the emittance deteriorates and hence the in all the works in this thesis, larger size apertures are avoided. Thus the extraction apertures of 1 mm and 2 mm were employed for all the experiments. For all the focusing experiments, to obtain higher plasma density with low energy spread, small plasma volume with low power operation is opted. Current extracted from ion source was found stable for long hour operations