Chapter 7

7 Ion optics and focusing column design

7.1 Introduction

The criteria for getting a focused ion beam, of very small beam size with as high current as possible, demands a highly efficient focusing column. To meet these challenges, the focusing column has to be optimized under limitations of having a large virtual source, constraints of electrostatic lenses and complexity of mechanical constructions. An understanding on the accurate lens properties, aberrations, ion beam optical characteristics etc are necessary to reach the final goal of high current focused heavy ion beam. Simulation codes can be used to design a proper focusing column and after the design, it is very essential to fabricate the mechanical parts of the column with precision. Problem arises again while measuring the beam size as it has very small beam size, normal wire scanners cannot be used and also since it has very high current density, the measuring system gets damaged due to sputtering and erosion. Thus while focusing the beam, each step is challenging. This chapter describes about the design and construction of the focusing column and beam profile measurement system. Also details are presented about the experiments carried out for optical column optimization for the high current mode operation of the column at an energy range of 7 – 10 keV.

7.2 Basics of Electrostatic optics

Generally, to control the trajectories of charged particle, either an electrostatic field or a magnetic field or combination of both is used. At low energies of the charged particle, electrostatic force is more efficient as magnetic force is proportional to the velocity of the particle. Moreover, the optical column making use of the magnetic lenses cannot be generally compact and hence cause the deterioration of the beam quality. Considering all these, the optical column of FIB described in this thesis consists of purely electrostatic lenses. Electrostatic
lenses have many advantages in many applications since they are easy to construct and operate, and unlike magnetic lenses, stray magnetic fields are not present in such systems.

Axially symmetric electrodes that, when electrically biased, will produce axially symmetric equipotential surfaces. A charged particle passing across these surfaces will be accelerated or decelerated and its path will be deflected so as to produce a focusing effect. The equation of trajectory of charged particle which experiences a radial force from the focusing lens can be written as follows [83][85].

\[ r'' + \frac{1}{2} \frac{V'}{V} r' = -\frac{r V''}{4} \]  

(1)

To take the advantage of rotational symmetry, cylindrical coordinates are generally used to represent such systems. In equation 1, \( r \) is the radial position of the particle \( V \) is the electric potential, where as ‘ and “ denote single and double derivative of the parameters as a function of distance on beam axis. This equation is known as paraxial ray equation which is valid only for paraxial rays those having very low diverging angle from the symmetry axis of lens. Most important point in the equation 1 is that it does not contain any term including charge and mass and thus charged particle of any mass and charge will follow the same trajectory. So, with the appropriate polarity of the applied voltages an electrostatic lens system may equally well be used for particles of any charge or mass, e.g., electrons, positrons, and negatively or positively charged ions. The only constraint is that the potential should have a sign opposite from that of the particle to ensure a positive total energy. Most essential thing in the design of the optics is that second derivative of the potential of the lens cannot vanish and in such case charged particle won’t be able to change the direction of motion. Means, if a particle is moving away from the axis, it will never come back to the axis.

7.2.1 Refraction at spherical surface - Snell’s Law

The trajectory of the particle traveling through a field depends on the angle of incidence on the equipotential surfaces of the field. This effect is analogous to the situation in optics when a light ray passes through a medium in which there is a change of refractive index. Figure 7-1 illustrates the behavior of a charged-particle beam as it passes through two different region
of uniform potentials \( V_1 \) and \( V_2 \). The initial and final kinetic energies of a particle of charge \( q \) that originates at ground potential are \( E_1 = qV_1 \), and \( E_2 = qV_2 \), respectively. \( \alpha_1 \) and \( \alpha_2 \) are the angles of incidence and refraction with respect to the normal to the equipotential surfaces that separate the field-free regions. The quantity in charged particle optics that corresponds to the index of refraction in light optics is the particle velocity, proportional to the square root of the particle energy. Thus, the charged-particle analog of Snell’s law is \([83][85]\),

\[
\sqrt{E_1 \sin \alpha_1} = \sqrt{E_2 \sin \alpha_2} \tag{2}
\]

Clearly, this property can be exploited in charged-particle optics, as in light optics, to make lenses by shaping the equipotential surfaces. This is equivalent to varying the refractive index and shape of lenses for light.

![Figure 7-1 Deflection of trajectory of charge particle while crossing a potential gradient](image)

7.2.2 Helmholtz Lagrange Law

Apertures are used in electrostatic lenses to define the beam. A window aperture defines the radial size of the beam and a pupil aperture defines the angular extent of the beam. Figure 7-2 shows a schematic of an electrostatic lens produced by the different potentials \( V_1 \) and \( V_2 \) illustrating the definition of the beam by the window and pupil apertures. The lens produces an image of the window. The radial size of the image is determined by the magnification, \( M \), of the lens. \( M = r_2/r_1 \), where \( r_1 \) and \( r_2 \) are as shown in Figure 7-2. As the particle travels from potential \( V_1 \) to \( V_2 \), its energy changes. The angular extent of the beam is minimized by placing
the pupil at the focal length of the lens. This produces a zero beam angle and hence the angular extent of the beam is solely defined by the pencil angle ($\theta$). The quantities $r$, $\alpha$, and $V$ in the object (window) and image plane are related by the law of Helmholtz-Lagrange [83]:

$$r_1 \alpha_1 \sqrt{V_1} = r_2 \alpha_2 \sqrt{V_2}$$

(3)

The product of $r$, $\alpha$, and $V^{\frac{1}{2}}$ is conserved. So, as the retarding ratio ($V_1/V_2$) is increased, the linear and/or angular magnification must also increase. This is also evident from equation 7. Current $I_1$ through the object window is same as the current $I_2$ through the lens. i.e, $I_1=I_2$. Then equation 3 can be rewritten as

$$\frac{I_1}{r_1 \alpha_1 \sqrt{V_1}} = \frac{I_2}{r_2 \alpha_2 \sqrt{V_2}}$$

(4)

Where $\sqrt{V}$ can be written as energy, and brightness $\beta = \frac{I}{r \alpha}$, then equation 4 becomes

$$\frac{\beta_1}{E_1} = \frac{\beta_2}{E_2}$$

(5)

Thus Helmholtz-Grange states that ratio of Brightness to energy is invariant in the system.

Figure 7-2 Beam defining apertures and image formation by lens
7.2.3 Image formation

Charged-particle lenses are “thick” lenses, meaning that their axial dimensions are comparable to their focal lengths. Thus they have two principle planes namely $H_1$ and $H_2$. Thus focal lengths of the lens have to be measured not from the axis but from the two principle planes. Figure 7-3 shows how the image is formed in a thick lens. M is the mid plane. As in light optics, it is possible to graphically construct the image produced by a lens if the cardinal points of the lens are known. It is only necessary to trace two principal rays. From a point on the object draw a ray through the first focal point and thence to the first principal plane. From the point of intersection with this plane draw a ray parallel to the axis. Draw a second ray through the object point and parallel to the axis. From the point of intersection of this ray with the second principal plane, draw a ray through the second focal point. The intersection of the first and second principal rays gives the location of the image point corresponding to the object point. A number of important relationships can be derived geometrically from Figure 7-3. The linear and angular magnifications, $M$ and $m$, respectively, are given by:

$$M = -\frac{f_1}{p} = -\frac{q}{f_2} \quad \text{and} \quad m = \left(\frac{-r_1}{r_2}\right)\left(\frac{f_1}{f_2}\right) \quad (6)$$

$$Mm = -\frac{f_1}{f_2} = \left(\frac{V_1}{V_2}\right)^{1/2} \quad (7)$$

Figure 7-3. This diagram illustrates the construction of image of a given object by using asymptotes to the principal rays [39]
7.2.4 Aberrations in image forming system

Ideally speaking, the rotationally symmetric lens shall produce an image of same shape as that of the object and the size depending on the magnification of the lens. But practically, optical systems are far from ideal and the size and shape of the focused ion beam are strongly influenced by imperfections in the focusing column. This section gives a note on the three most important defects that can occur in focusing lenses [83].

7.2.4.1 Spherical aberration:

This defect is caused by the focusing fields that are invariably stronger away from the beam axis which makes the marginal rays to cross nearer to the lens and paraxial rays farthest from the lens[86]. This is depicted in Figure 7-4. The minimum diameter of the beam occurs much ahead of the Gaussian plane which is called as the disc of least confusion. The diameter of the beam at Gaussian plane can be four times bigger than the beam diameter at disk of least confusion. The spherical aberration is characterized by the third-order coefficients, $C_s$ given by the equation 3. Where $\Delta r$ is the radius of the disc formed in the Gaussian image plane by non-paraxial rays starting from an axial object point with a maximum half angle $\alpha_0$ and $M$ is the linear magnification [83].

![Figure 7-4 Blur due to spherical aberration at focal point](image-url)
\[ \Delta r = -MC_s\alpha_0^3 \]  

(8)

It is impossible to eliminate spherical aberration from a beam by any subsequent ion optical action. Thus it is very important to design the ion optical system with as less spherical aberration coefficient \((C_s)\) as possible.

### 7.2.4.2 Chromatic aberration:

The chromatic aberration in a lens refers to the sensitivity of the focal properties to the energy with which the particle enters the lens\[86\]. A higher energy particle will come to a focus farther from the lens than a particle with lower entrance energy. This effect is illustrated in Figure 7-5. It is seen that a disk of confusion exists as in the case of spherical aberration. The disk at Gaussian plane will be

\[ \delta r = -MC_c\alpha_0 \frac{\delta E}{E_0} \]  

(9)

It is seen that chromatic aberration is not only a function of the lens characteristics but also of the incident ions. Since the lens characteristics are dependent on the applied voltage, the focused spot can exhibit a form of chromatic aberration if these voltages vary because of power supply ripple or drift.

![Figure 7-5. Blur due to Chromatic aberration. Both red and blue trajectories denote trajectories of particle launched at same angular distribution, but with different energy.](image-url)
7.2.4.3 Astigmatism:

A potentially serious form of astigmatism can result if the apertures of electrostatic optical elements are not circular, or are displaced or tilted with respect to the optical axis. The disk of confusion in this case will be

\[ \delta = C_e \alpha_i \]  

(10)

\( C_e \) is the ellipticity constant in the case of non circular aperture. This general form of aberration is quite common in charged particle optical system and it can be identified by the observation of two line or elliptical foci which are 90° apart on the observation screen and are of different focal length. Astigmatism basically originates from the mechanical imperfections and the optical design can become meaningless if not implemented with high degree of mechanical fabrication and assembly precision. Astigmatism can be corrected to a great extent by implementing a stigmator which is an n-pole element of opposite electric field arranged around the beam.

Coma is generally encountered with off-axis rays arriving on lens and is most severe when lenses are misaligned. When these aberrations occur, the image of a point is focused at sequentially differing heights producing a series of asymmetrical spot shapes of increasing size that result in comet-like shape.

In the work mentioned in the thesis, Spherical and chromatic aberrations are most serious and thus included in the lens design in detail. However, the alignment of all the electrodes of lenses to the ion beam extraction system is made as good as possible. Ion source parameters are adjusted to minimize energy spread and thus chromatic aberrations are minimized. The angular current density is much higher as compared to that of LMIS based FIB systems and hence a fine aperture is placed to limit the beam with large divergence. In spite of using small aperture, high current operation could be achieved due to high angular current density. This small aperture minimizes both the spherical and to some extent chromatic aberrations also. The simulations are carried out on the optical column under considerations as
will be explained in the following sections. Finally, various contributions are then generally summed in quadrature using the following formula [15].

\[ d = \sqrt{d_g^2 + d_C^2 + d_S^2} \]  

(11)

Where \( d_g = M d_v \), \( d_C = M C_S \frac{\Delta E}{E} \), \( d_S = \frac{1}{2} M \alpha^3 C_S \), \( M \) is magnification and \( d_v \) is virtual source size. \( C_S \), \( C_c \) are calculated from equation Error! Reference source not found. and Error! Reference source not found. respectively.

7.3 Two lens optical column for ICP- FIB

Electrostatic lenses are generally made by two or more electrodes operated at different potentials. Electrodes can be cylinders, disc having aperture or counter bored cylinders. For the work mentioned in this thesis, disc electrodes with apertures have been used. In our design, each lens has three electrodes with end electrodes at ground potential which makes it an Einzel lens. In the focusing column described in this thesis, we have used two such Einzel lenses, a pair of deflectors, beam limiting apertures and drift spaces. This compact focusing column is designed using the code OPTICS by Munro’s Electron Beam Software Ltd [87] [88][89]. OPTICS relies on the First order finite-element method (FOFEM) for calculating the field of any rotationally symmetric lenses. The code executes three main tasks.

1. Computing field distribution in individual lenses and deflectors.
2. Computing the optical properties and aberrations of any combination of such elements.
3. Graphical display of the effects of the aberrations.

First task in the process of design of the optical column is to calculate the field distributions inside the individual lenses that are used in the optical column are calculated. These fields are used in calculating the optical properties of the column. The shapes of the electrodes are optimized to obtain the required field distribution along the axis. The first lens in the column is a simple Einzel lens having symmetry in both radial and longitudinal directions while the second
lens is mechanically asymmetric in longitudinal direction keeping the radial symmetry. Electrostatic lenses with physical asymmetry are known to have lesser spherical and chromatic aberrations. This is shown in the schematic Figure 7-7. Next phase of the analysis is to assemble these individual components into a complete electron optical column, in order to compute the optical properties and aberrations. \( V, V', \) and \( V'' \) are plotted along beam axis and then the paraxial ray trajectories are drawn. First order optical properties are determined by numerically solving the paraxial ray equation and the third order geometric and first order chromatic aberrations coefficients are computed by evaluating the appropriate aberration integrals. Iterations in the geometrical features of the lens and the position of the aperture are varied to get the minimum aberration and beam size at target position.

Since the goal of the work is to have high throughput milling, apart from aiming at low aberration, the main focus on the design is low beam size at target plane with highest possible current. In two lens optical column, there is flexibility to choose either high resolution mode or high current mode. By varying the strength of the first lens which is also known as condenser lens, various modes of operation are possible. There are merits and de merits of each of these modes and many authors have reported works on optimization of the focusing column for these modes to obtain desired probe features.

Figure 7-6 shows the different types of modes of operation. There are two major modes of operation: Crossover and non-crossover modes. By increasing the strength of the first lens, a crossover can be created anywhere in between the two lenses as shown in Figure 7-6(A). Non-crossover mode is further classified into parallel, diverging (semi-divergent) and converging mode as shown in Figure 7-6 B, C and D respectively. To operate the optical column under high current mode, the condenser lens needs to either converge the beam to focus between the two lenses or beyond the second lens as shown in Figure 7-6 A and D respectively. By converging the beam, the current passing through the aperture shown in the Figure 7-6 will increase until the crossover is just on the plane of aperture. Certain range of focusing strengths of the condenser lens, the cross over is between the two lenses, where the current passing through the aperture is reasonably high as well as the magnification mostly remains constant.
Further increase in the strength of the condenser lens decreases the probe current as the crossover shifts up towards the source and beam becomes divergent towards the second lens. In parallel and diverging modes of operation as shown in Figure 7-6 B and C respectively, the current passing through the aperture is less than that of the other two modes and also the magnification is low and hence these modes are suitable for low current high resolution applications.

Figure 7-6 Operational modes of a two lens FIB column: (A) crossover mode, (B) parallel mode, (C) diverging mode, and (D) converging mode where (B), (C), and (D) are the non-crossover modes.[90]

According to the calculations of Jiang [91], J Orloff [92] and Li Wang [90], the divergent mode (Figure 7-6 C) may be preferred to the crossover mode (Figure 7-6A) since it allows the best performances in ultimate resolution. On the other hand, the crossover mode, with beam defining aperture located between the lenses is capable of delivering much higher probe currents up to several microamperes making it ideal for quick and efficient micromachining. Generally the optimized probe size of the non-crossover modes is small than that of the crossover mode of a focused ion beam instrument over the full current range. The optimal
results show that the minimum probe sizes of the cross over mode are ~2 times larger than those of the non-crossover modes at the same probe current (3nA). This is valid for different beam energies and also applicable for electron beam instruments [91].

Figure 7-7 Schematic of the Ion beam focusing column and beam width measurement set up with potential profile across focusing column

Two lens focusing column in the thesis work operates in the high current modes and the distance between the lenses (L), Z₀, Zᵣ, position of aperture and its diameter are optimized for
high current and best resolution possible. Figure 7-7 shows the schematic of the two lens focusing column with the applied potentials on the Einzel lenses in the diagram on the right of the figure.

Table 2. Optical properties of focusing column under diverging and crossover mode for high resolution and high current modes respectively.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Diverging mode (High resolution mode)</th>
<th>Crossover mode (High current mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Angle</td>
<td>1.2 mrad</td>
<td>1.2 mrad</td>
</tr>
<tr>
<td>Beam energy</td>
<td>10 kV</td>
<td>10 kV</td>
</tr>
<tr>
<td>$dv$</td>
<td>15 μm</td>
<td>15 μm</td>
</tr>
<tr>
<td>$Cs$</td>
<td>1.22 m</td>
<td>5.4 m</td>
</tr>
<tr>
<td>$Cc$</td>
<td>$7.62 \times 10^{-2}$ m</td>
<td>$2.09 \times 10^{-2}$ m</td>
</tr>
<tr>
<td>$M$</td>
<td>0.146</td>
<td>0.467</td>
</tr>
<tr>
<td>$dg$</td>
<td>2.19 μm</td>
<td>10.76 μm</td>
</tr>
<tr>
<td>$d_{total}$</td>
<td>2.222 μm</td>
<td>10.76 μm</td>
</tr>
<tr>
<td>El1</td>
<td>8.8 kV</td>
<td>5.9 kV</td>
</tr>
<tr>
<td>El2</td>
<td>8.9 kV</td>
<td>9.6 kV</td>
</tr>
</tbody>
</table>

OPTICS code is used to simulate and estimate the properties of focusing column for high resolution and high current mode. The results are summarized in the Table 2. It can be seen from the table that the aberrations do not play important role in the focusing characteristics of the column since the aperture angle is too small. This is realized by providing 300 μm diameter aperture. Since the ion source has high angular current density, it is possible to push more current through small aperture. It is also worth noticing that the voltages calculated by OPTICS are close to the practical values. i.e, in crossover mode highest current could be obtained through the aperture for focusing voltages between 5.6 – 5.9 kV. The practically measured focusing characteristics of the first lens is shown in Figure 7-13. It can be seen from the table that the focusing characteristics are not greatly influenced by the aberrations, but influence only by magnification of the system. Since the virtual source size in 10s of μm, the
magnification should of the order of 0.01 to 0.1 to obtain micron to submicron beam sizes. However, aiming to produce the submicron beams, the lenses are designed to minimize both the spherical and chromatic aberrations. Since the working distance needs to be very small for realizing the high demagnification, the ion beam deflectors for scanning the beam are not used since they introduce large aberrations due to deflection. In this thesis, the aim is large volume milling at high speed and hence the sample to be milled is scanned across the beam.

7.4 Mechanical Construction of focusing column

Electrostatic optical column designed and developed for the experiments consists of ion beam extraction system, two Einzel lenses, 300 µm aperture, two electrostatic quadrupole deflectors. Ion beam extraction system is described in Chapter 3. The two electrode extraction system is assembled along with the rest of the optical elements and all the electrodes are of the same outer diameter and are aligned precisely by using ceramic balls as spacers. Steel balls are used in place of ceramic ball wherever contact is required between two adjacent electrodes.
Perspex rod with screws is used for holding the electrodes together and to attach to the top flange. All the electrodes are 40 mm in diameter and when assembled one by one using ceramic ball or steel ball, they get aligned themselves automatically with the optical axis. Good vacuum inside the column is essential to keep the charge exchange of the ion beam minimum and the gap between the electrodes ensures a good vacuum. For providing connections to the electrodes from power supplies, push-in type pins are used.

Figure 7-8 shows the focusing column with typical arrangement of electrodes used in the experiments. The parts of the focusing column consisting of electrodes and the drift spaces are shown in Figure 7-9 (a). Quadrupole electrostatic deflectors are utilized between two lenses to have fine correction in the misalignment of the ion beam to the optical axis; Figure 7-9 (b) shows the picture of a deflector. This is slightly enlarged picture and the electrodes in figure and deflector has the same outer dia. The Al cylinder seen inside the deflector is used for the alignment and is removed when it is assembled to the focusing column. All the electrodes are buffed to for mirror finish on the surfaces to minimize sparking.

![Figure 7-9 (a) Disassembled view of the focusing column and (b) deflector with aligning rod in the center.](image)
7.5 Experimental set up to measure beam size

The experimental set up consists of an ion source, a focusing column, a knife edge mounted on a translation stage and a faraday cup. Ions are extracted through two electrode extraction system with 1 mm aperture in both the electrodes. After the extraction electrodes of ion source, 25 mm downstream of the extraction system, a 1 mm diameter aperture is used to cut down the beam current from nearly a mA to a few µA to chose the central bright core of the beam, to minimize the loading on power supplies and minimize the unwanted damages of electrodes due to sputtering.

![Figure 7-10 Assembly used in ion beam profile measurement](image)

For angular current density of about 20 mA/Sr this aperture offers angle of about 10 mrad. This aperture, for given angular current density, allows about 6 µA of current. Experiments show about 4.2 µA of current which is reasonably close to calculation. This reduction in the beam is due to spherical aberration caused by the first lens when the beam is focused down to another aperture placed at about 130 mm. Since the image distance is more and magnification is more than 2 spherical aberrations are quite large. This causes the reduction in the current passing
through the limiting aperture and through the second lens. The total length of the focusing column is about 170 mm and working distance is 2 mm from the last electrode. The focusing column has two einzel lenses, both working in decel (deceleration) mode, separated by field free space and an aperture. The beam limiting aperture with 300 µm diameter is used to eliminate the highly diverging ions and allow only near paraxial ions to pass through the second lens. In our experimental set up, the ions with divergence of ± 1.25 mrad are allowed to pass through the focusing lens. Focusing column ends with the last electrode of the second einzel lens. The knife edge for beam width measurement and the target for machining experiment are mounted on an X-Y stage and is assembled on a platform with the facility to move the stage in Z direction manually. The sharp knife edge is mounted on the X-Y translation stage that moves the knife across the beam in 50 nm steps.

For experiments with argon beam, a 38 mm long Gillette razor blade, having very uniform edge finish and edge radius better than 50 nm is used as knife edge [93][94]. In case of measurements on xenon ion beam, since the sputtering rate of xenon beam is very high and the knife edge gets milled very fast and hence the tantalum sheet which has less sputtering yield was sharpened at the edge and was used to measure the beam size. Ion beam profiles are obtained by moving the knife edge across the ion beam and recording the variation of ion beam current on the secondary electron suppressed Faraday cup as a function of the knife edge position. The working distance is adjusted manually to be 2-4 mm. Wherever measurements has to be taken with online variation of position of the knife edge in Z axis, i.e. the beam propagation axis or wherever adjustment of working distance is required, an X-Y-Z stage is used.

Actual experimental set up is shown in Figure 7-10. An application using LabVIEW is written for complete automation of measurement and analysis of the ion beam profile. Control panel of the same is shown in Figure 7-11. It is a user friendly GUI and has the facilities to control the extraction voltage and focusing voltage, movement control of the x-y stage etc. the program also stores the scanned data in to an excel file along with important parameters like Voltage, RF power, pressure etc for future reference. A part of the program does the analysis of the stored data. After recalling data for analysis, finding out beam width (both 20%-80% and
10%-90%), current density etc also can be carried out with this software. One of the typical profiles of focused Xe beam of 10 keV is shown in Figure 7-12. When the knife edge is out of the beam, full current is collected by the Faraday cup and as knife edge progresses through the beam, there is a steady decrease of collected current on the Faraday cup. The profile obtained by knife edge has step like feature where the slope of the profile gives the ion beam shape and size. Steeper the profile, smaller is the beam size. This profile is the integral of the radial current density distribution.

Differential of this profile provides the actual ion beam profile [95][96]. Figure shows that the total current of 560 nA is focused to spot size of 12 µm (corresponding to 20% - 80% rise distance) with current density of 490 mA/cm². It is the current corresponding to 20%-80% rise distance of the knife edge profile contributes to the milling of surfaces. It can be seen from
the figure that it has a very good fit with Gaussian function and FWHM is measured to be 16.9 µm.

Figure 7-12 Knife edge characteristics, ion beam profile and Gaussian fit to the ion beam profile.

7.6 Experiments on focusing noble gas ion beam

Argon and Xenon beams were used for these experiments with energy ranging from 7 keV to 10 keV. RF power and pressure inside the plasma chamber is adjusted to obtain best ion beam quality, as learned from the result of experiments described in previous chapters. Depending on the extraction potential and from the knowledge of OPTICS simulation, focusing lens values were set. Focusing lens voltage and deflector voltages were adjusted to get best knife edge profile. Focusing column parameters need adjustments for different RF power and gas pressure since the plasma meniscus acts as a lens and changes the shape with change in power and pressure. Thus to complete the optimisation process and to get the best beam profile, involves search in an extended multiple parameter space.
7.6.1 Variation of current in the probe with strength of first lens

The first lens has control over the current passing through the focusing column and a test is carried out to estimate the maximum current focused through 300 μm aperture placed between first and second Einzel lens. Figure 7-13 shows the variation of faraday cup current with focusing voltage of the first lens. By varying the focusing voltage on the first lens, in principle, the real image position of the first lens can be moved from infinity till the last electrode of the first lens. While doing so, due to change in the cross over position, effective aperture angle on the objective side of the second lens changes giving rise to change in the available probe current. In addition, variation in crossover position also changes the overall magnification and hence resulting into variation of the probe size. The more downstream is the crossover from the aperture in the column, the larger is the overall magnification and is dominated by the magnification and aberrations of the first lens. By making the first lens stronger, the beam crossover can be moved upstream in the column reducing the column magnification. It is possible to adjust the magnification over the range of 0.08 - ~4 (calculated by OPTICS simulation code) by varying the voltage of the first lens. In both extreme positions of the crossover, the probe currents are minimum. The limitation of this two lens configuration with a fixed beam limiting aperture is that the change in the probe size is associated with a change in the probe current and vice versa.

By varying the strength of the first lens, the focusing column was optimized to obtain the best current density in the focused spot and found that the formation of crossover near the aperture produced a high current density in the focused spot. At each setting of focusing voltage on the first lens, it was required to carry out fine adjustment in the focusing voltage on second lens to obtain an optimal focusing of the beam. With finer adjustments in plasma parameters and the optical column parameters, operating the column in diverging mode, the minimum spot size of 1.8 µm could be achieved. The current density, under these condition was < 50mA/cm². This mode of operation is highly desirable for imaging applications where the damage to the sample is minimum.
Same spot size is also achieved by operating the focusing column in crossover mode. In this case the first lens strength is adjusted to create crossover just next to the first lens so that the combined magnification of the first lens and second lens is again less than 0.1. In this mode, more current is allowed to pass through the aperture while maintaining high demagnification. The results of this mode of operation have shown the minimum beam size of 2.5 μm with 110 nA of current which amounts to 2.13 A/cm² current density. Figure 7-14 shows ion beam profile obtained by scanning knife edge across the beam. The integrated profile shows a round edge indicating the milling of knife edge while scanning the edge across the beam. In practice the beam size is less than 2 μm and due to high current density the knife edge gets continuously cut while obtaining the profile, introducing the error in measurement. Thus by varying the first lens strength both low and high current regime can be realized while keeping the spot size mostly same.

7.6.2 Position of the beam divergence limiting aperture.

Aperture in a focusing column has much more importance than just limiting the beam current. The position and diameter of the aperture sets the beam divergence angle of the beam.
entering the second lens. Both spherical and chromatic aberrations depend on this angle and thus strongly influence the minimum achievable spot size.

![Graph showing beam profile](image)

**Figure 7-14** Beam profile showing 2.5 micron FWHM and 2.13 A/cm²

And the total current entering the second lens also is defined by this aperture diameter and position. In conventional LMIS-FIB systems, an aperture strip is used with several apertures with different diameters for varying the current in the probe. This is remotely movable to vary the current in the probe and can be centered or aligned with respect to the optical axis. We have used a single fixed aperture with diameter 300 micron. The position of the aperture along the column can be varied easily. As expected, the current and the size of the probe are strongly influenced by the position of the aperture in the focusing column.

Experiments were carried out with three different positions of the apertures. Figure 7-15 shows the beam profile at 6 keV argon beam. Here the beam limiting aperture is assembled just below the first lens. Since it is near to the extraction electrodes, ions with divergence of ± 15 mrad are allowed to pass through the lenses. This large divergence introduced large spherical aberrations and hence it was difficult to obtain the small spot size.
The lowest spot size was only 350 μm with current density of 63 μA/cm². Although several 10s of μA current was possible to focus, the size could not be brought down. The spherical aberrations are clearly seen in the form of large tails in the beam density distribution as shown in Figure 7-15.

![Figure 7-15 6 keV 6600 V, 5600 V aperture before the first lens. 350 micron 63 μA/cm²](image)

Second experiment was carried out with the aperture few mm from the first electrode of second lens which is the largest distance at which aperture can be placed in the focusing column. All three modes of operations were tried to characterize the focused beam over wide range of currents and the results are summarized in Figure 7-16. Initially, with the low focusing voltage on the first electrode to form the diverging or parallel beam between the lenses offered a minimum probe size of about 2 μm with current density of > 50 mA/cm². With an increase in the focusing voltage on the first lens, more current is passed through the aperture. Under this condition the increase in current is more than the increase in the probe size and ultimately resulting into higher current densities. Between 500 – 1000 nA, the current density is highest, measuring ~450 mA/cm² and the spot size remains between 8 – 10 μm. Further increase in the strength of the first lens, the focusing column enters into converging mode and magnified
source dominates the probe size thus reducing the current density in the probe. This can be seen from the figure that beyond 1000 nA the current density starts to fall rapidly even though a larger current is available in the probe.

Figure 7-16 Three modes of operation to characterize the focused ion beam over wide range of currents.

Third set of experiments were carried out for optimum position for high current operation of focusing column where the aperture is placed about 20 mm before the second lens. By doing so the magnification of the second lens is calculated to be about 0.08 for the beam that is focused at the cross over. By creating crossover at the aperture, high current could be obtained in the focused spot and at the same time, due to 0.08 magnification of the second lens, the demagnified image of the object could be produced at the focal plane of the second lens. With the object size of about 300 μm the spot size is 300 x 0.08 = 24 μm while measured spot size is 29 μm. Under these conditions, about 3 μA, 7 keV Ar could be focused to min of 40 μm. The same experiment was carried out with 10 keV Ar ion beam and found 3.5 μA could be focused to about 35 μm. Experiments on ion beam extraction have shown that much higher Xe ions with higher angular current can be extracted as compared to Ne, Ar, etc. Finally 10 keV Xe ion
beams were focused and with same focusing column, the maximum of 4.2 μA could be focused to spot size of 29 μm. The experimental results are summarized in the Figure 7-17.

![Graph](image.png)

**Figure 7-17** Variation of focused spot diameter and the current density as a function of current in the probe.

Left most regions in the graph are the diverging mode, middle portion is converging mode and right most portion is a crossover mode. Comparing the Figure 7-16 and Figure 7-17, it is seen that by shifting the aperture up in the column towards the ion source and increasing the energy of extracted ions the high current density could be achieved. This was partly due to easy ionization of Xe resulting into higher plasma density and higher extracted current. The current density has improved from 450 mA/cm² to 2000 mA/cm². In earliest case 2 μA could be focused to 30 μm diameter and in the last case the same 2 μA but Xe beam could be focused to spot less than 12 μm which a significant improvement in the performance. Figure 7-18 shows the knife edge profile of the highest beam current obtained at the target plane for 10 keV xenon beam. 4.12 μA was focused to 28 micron with a current density 670 mA/cm². The beam profile shows a strong deviation from Gaussian functions. As explained earlier this is due to the spherical aberration caused because of the large diverging angle of the beam. Figure 7-19 shows the beam profile for 2 μA beam current with current density of 1.8 A/cm². This has a very close fit Gaussian function.
7.6.3 Main challenges of the experiment

There were many challenges in order to achieve a fine focused beam and to characterize it. Many of them are solved and obtained the 2 A/cm² current density at target plane and many
of the problems still persists and need intense efforts to progress further. Some of the serious obstacles that we faced are described below.

Though at 10 kV extraction voltage, the operation of the ion source is very stable and smooth, problem exists if the extraction voltage has to be raised. This is due to the close proximity of the antenna and the faraday shield. Faraday shield is floating at extraction voltage and the lower end of the RF antenna is grounded. There is a requirement of air cooling for the plasma chamber and thus the faraday shield cannot be covered with insulator at present. Raising the voltage is certainly advantageous in achieving higher brightness. Accelerating ions to 30keV will increase the effective brightness by a factor of about 6 and hence there will be increase the current density in a given spot size (assuming chromatic blur is not the limiting factor) by a factor of 6.

The property of ion beam to sputter out surfaces has been exploited in micromachining and milling. But at the same time, sputtering of the electrodes used in extraction system and focusing column are highly undesired. First beam limiting aperture which is placed just after extraction system limits the ion beam current from mA to few hundred µA and this electrode gets damaged easily. And the fine apertures are generally made thin foil for the ease of mechanical fabrication and it also gets damaged quickly due to sputtering. Figure 7-20(a) shows a fine aperture eroded by beam sputtering. Right now the material used for fabricating the electrodes are S.S and instead of S. S, a material with low sputtering yield will be beneficial and this shall be implemented in future.

Slight misalignment present in the focusing column causes decrease in the current introduces errors in the measurements. The problem is sever due to misalignment with the presence of a 300 µm aperture in the focusing column, since the central bright spot of the beam misses the aperture and only the peripheral, less bright beam is available for focusing. Misalignment of the beam is ascertained by the asymmetric ion beam profile in the focal plane and lateral shift in the focal spot with change in the strength of first lens.
Figure 7-20 Optical image of Damaged beam limiting aperture. Red circle shows beam impression and white circle shows actual aperture location (a) shows rupturing of aperture due to sputtering, (b) Beam misses out the aperture due to misalignment. Two circles are formed at two different focal voltages on the first lens.

Figure 7-20 (b) shows the two distinct beam impressions developed on the fine aperture electrode for two different focusing strength of the lens. It is also visible that the aperture lies on the periphery of the beam in both the cases. One way to get rid of this is to have a moveable aperture as in conventional system and align it online or use ion beam deflectors. In the focusing column two sets of deflectors are used to correct the misalignment in both x and y direction. With more precise alignment, it is expected to get more bright focused spot.

Sputtering also causes damage to the knife edge while beam width measurement. As the high density beam is scanned, the fine edge of the knife edge gets sputtered definite amount of beam passes through the slit produced in the knife edge, giving rise to artificial increase in the beam size as shown in the Figure 7-14. Figure 7-21 shows two consecutive scans, one with the damaged edge and the other one with fresh edge. This problem is severe with Xenon beam as its sputtering yield is much higher. So the steel knife edge is replaced by a tantalum sheet. It is planned to develop the fast beam scanning system to eliminate this problem.

Interestingly, with same focusing column, probe current can be changed to a large extent by changing the RF power. Hence RF power can be a fine control knob to control the probe current without employing the variable aperture and without changing the lens strengths.
However, at RF power greater than 160 – 180W, due to increase in the plasma density, plasma meniscus becomes convex. With increased RF power, there is also an increase in the energy spread. Hence beyond certain RF power, increase in the probe current is associated with rapid increase in the probe size.

Figure 7-21 Knife edge scan at a damaged edge and a fresh edge

To keep the system simpler as well as to minimize the use of a deflector so that the aberrations are minimum, the diverging mode and the limited converging mode with the crossover very near to the aperture are utilized in the experiments described in this article. By varying the gap between the lenses and the position of apertures, the characteristics in Figure 7-17 can be changed. In addition, by inserting one more lens, the focusing column can be easily operated over a range of magnifications with either high current mode or high resolution mode. In this thesis work, the geometry was kept simple to achieve only high current mode of operation of FIB.
7.7 Conclusion

A simple two lens focusing column is designed to operate the plasma based focused ion beam system in all the modes such as crossover, converging and diverging modes. The focusing column is designed by using OPTICS code and optimized the shapes to minimize the aberrations even though they are negligible. The experimental results at lower currents are mostly in good agreement with the simulated results. However, at high current operating modes, the simulated focused spot sizes are smaller than the measured ones, since the OPTICS code does not take the space charge into account. In order to achieve high current at moderately small beam spot sizes, the focusing lenses, their positions and the beam limiting aperture are optimized. Two sets of deflectors are also positioned between the first lens and the aperture to finely align the beam to the optical axis. Due to the slow processes of the large milling the ion beam deflectors are not utilized to scan the beam over the sample, but instead the sample is scanned across the beam. This eliminates the aberrations related with the deflectors. Experiments show that with the beam limiting aperture just before the second lens, nearly 0.5A/cm² of 7 KeV Ar ions could be easily focused onto the image plane at working distance of 2 mm, while by increasing the ion energy and using Xe ions and shifting the aperture up in column, Xe ion beams with 2.1 A/cm² could be focused. Since both the lenses are used in Einzel mode, there are only two control voltages to operate the optical column in all three modes with ease.

Conventional LMIS based system at currents > 100 nA at 20KeV energy, the spot size d α I^{3/2} where I is the current in the probe i.e, >250 µm for ~2.5 µA. While plasma ion source based FIB system designed in this work, the spot size is < 15 µm at 2.5µA of current in the probe. With this column configuration, the best spot size is < 1.8 µm and best current density is ~2A/cm² could be obtained. Plasma ion sources based FIB using Duoplasmatron ion source and ICP ion source similar to the one developed in thesis is compared by Smith et al [97]. This comparison shows 20 KeV Ar ion beam for 100 nA beam, the spot size is 2 µm and it would grow to about 5µm for current of 1µA. while the system developed in this thesis, at 7 KeV, 100 nA Ar ions could be focused to about 4 µm 1200nA could be focused to 9 µm diameter spot size.
There is a good scope to further improve the performance of the system by reducing the ion beam extraction aperture, using three lenses in a column and employing low voltage extraction and then accelerating the beam to higher energies such as 20-30 KeV would enhance the performance of this system significantly.