CHAPTER II
EXPERIMENTAL ARRANGEMENT

The specific objective of the experiment, as defined earlier was the study of single particle behaviour in magnetic mirror geometry, with slow spatial variation. The particle field interaction manifests itself in modification of particle trajectories and ultimately in loss of particles from the trap. Hence, the processes such as interparticle collision, which would also result in particle loss have to be minimised in this experiment. The primary experimental requirements could thus be defined as low particle densities, ultra high vacuum, high particle energy, adiabatic mirror magnetic field and fast electronics.

This chapter describes an experimental system designed and constructed to fulfill the parameter constraints as defined above. The experimental set up can be broadly divided into the following sub systems:

i) Vacuum system
ii) Magnetic field system
iii) Source of charged particles (Electron gun)
iv) Diagnostics and data acquisition system

2.1. Vacuum System:

With a mirror separation of 120 cm and an additional length of 30 cm for diagnostic instruments etc a vacuum chamber of 150 cm in length and 15 cm diameter is used for the experiment.
The vacuum system is constructed entirely from 304 stainless steel. The vacuum system along with the magnetic field system is depicted schematically in fig.3. The main experimental region of the chamber was made up of a seamless stainless steel tube. The whole system was evacuated with the help of a LN$_2$ trapped oil diffusion pump upto a pressure of $\sim 10^{-5}$ torr. After attaining this pressure, the system was further evacuated to a pressure of $\sim 5 \times 10^{-8}$ torr with the help of a sputter ion pump which has a speed of 300 liters/sec. While pumping was continued with the help of the sputter ion pump, the oil diffusion pump along with the backing system was isolated from the experimental chamber with the help of a mechanical valve.

An isolation valve of 4" diameter was designed and fabricated for use between the ion pump and the experimental apparatus. The isolation valve consisted of a piston placed at 45° with a spring attached to it. The piston was pulled out with the help of a solenoid, thus connecting the pump to the system. This was possible since the stem of the piston was constructed out of magnetic stainless steel.

To attain ultra high vacuum (UHV) the system was baked to a temperature of 150°C for a period of 10-12 hrs. This was done with the help of tape heater wrapped on the main experimental system. The ion pump was also baked at the same time.

For any modifications necessitating the opening of vacuum system, the system was filled with nitrogen by continuously
Fig. 3. Schematic of the experimental apparatus.
flushing dry nitrogen gas through the system at a pressure slightly higher than the atmospheric pressure. During this period the ion pump was isolated with the help of the isolation valve. This helped greatly in regaining the UHV conditions in the system within a short time.

2.2. Magnetic Field System:

For electron energy of ~6 KeV and a midplane magnetic field of 200 gauss, the electron Larmor radius turns out to be ~1 cm. For a minimum angle of injection of 30° the required mirror field was 800 gauss. For flexibility in the experiment, a maximum field of 1000 gauss was desired.

The required magnetic field profile was obtained with the help of a set of 12 pancake coils, placed symmetrically on either side of the central plane. The pancake coils were made of 8 mm O.D and 5 mm I.D. copper tubing and all the coils had inner radius of 10 cm. Maximum constant current of 260 amps could be fed into them. To dissipate the heat generated, cold water was circulated through the coils. Five different magnetic field configurations were generated by varying the axial positions of the coils. For certain cases, current was also varied to obtain the desired field configurations. In these cases, to reduce the current through certain coils, shunts of low resistance and high current rating in the form of stainless steel strips of different thickness, width and length were used. The field configurations were numerically calculated following the method outlined in Appendix A.
A rectified power supply (300 V, 300 Amp), which could be operated in constant current or constant voltage mode with ripple content of 0.03 % was used to feed the coils for generating the desired static magnetic field.

For effective confinement of the charged particles, the injected particles must be made to feel some change in the parameters of the experimental system. For this purpose, the magnetic field value at the mirror throat near the injection point was lowered during injection. After travelling along the mirror system, the charged particles (electrons) were reflected from the opposite mirror and approached the first mirror. To confine the electrons, the magnetic field value at the mirror throat at injection end was raised to its initial value equal to the value at the other mirror point. This was achieved by means of a pulsed magnetic field superimposed on the static magnetic field at the mirror throat. Pulsed current was fed to a four turn stainless steel coil of 4 cm diameter. Stainless steel was chosen for its UHV compatibility. Since the fast magnetic field pulse could not penetrate through the 3 mm thick vacuum chamber wall, the small coil was placed inside the vacuum chamber and was fed through high voltage vacuum feed through.

The required pulse duration and the magnitude of the field value used were dependent on the energy of the electron beam. Since minimum dispersion in the beam energy was desired,
sufficient care was taken while constructing the pulse forming net work. The pulse forming ne-work used for this purpose is described in section 2.4 of this chapter. The fall time of the pulse should be less than twice the transit time of the beam pulse through the system. Since the magnetic moment of the electrons was kept constant, the pulsed magnetic field should be homogeneous. For this purpose, the current pulse used to produce the magnetic field had to be made ripple free and with a short fall time. Thus a 100 amp current pulse of 150 nsec duration with a fall time of 30 nsec was used to produce the pulsed magnetic field. The value of the pulsed magnetic field was directly proportional to the current. By varying the current amplitude, the magnetic field value required for the experiment was selected. Fig. 7(1) shows the trace from an oscillogram of the current pulse registered with the help of a current transformer (Pearson model No.411). The magnetic field produced by this current was measured with the help of a magnetic probe, specially constructed for this purpose. The construction and the characteristics of the magnetic probe are described in section 2.5 of this chapter.

2.3. Electron Gun:

A low current electron gun was used during the experiment. The maximum beam current used was \( \sim 6 \mu A \) during the single reflection experiment with an energy of 250 - 300 ev. While conducting the confinement experiments, the beam energy was
varied upto 5 kev with a beam current of 0.2-0.4 \( \mu \)A. Since the experiments dealt with single particle phenomenon, the density of the beam was kept low, typically of the order of \( 10^4 \) particles/cc. The beam pulse duration was 50 \( \mu \) sec during the single reflection experiment, while the pulse widths used for the confinement experiments were 30 nsec & 500 nsec.

Since a distribution in the electron energy leads to a distribution in the magnetic moment, one should try to have a beam with as small an energy spread as possible. As it was difficult to define a critical parameter for this, the effort was to reduce the major causes which gave rise to beam dispersion. Some of the major causes are the following:

a) the velocity distribution with which electrons are thermionically emitted.

b) Fluctuations in the accelerating voltage in time scales short compared to the beam switching time.

c) Beam forming optics.

d) Geometric factors: Finite dimensions of the filament and anode causes the space charge cloud to have potential gradients especially when the beam switching takes place in a short time.

Therefore, an electrostatic electron gun was designed to give a well focussed beam. Strong focussing i.e. the use of distribution of electrostatic einzellinsen, was used. Three cylindrical electrodes were used to focus and accelerate
the beam. The central electrode was kept at a lower voltage than the other two electrodes. In certain region of small ratios of $a/L$, the gap region of the system would be a lens with a long focal length $37$. Here $2a$ is the diameter of the cylindrical lens and $L$ is the total length of two consecutive lenses along with the gap between them. The ratio of the diameters and voltages were calculated from the perveance for the particular specifications. For simple multielectrode systems, the perveance is approximated by

$$ P = 61 \times 10^{-6} \left( \frac{V_f}{V_0} \right)^2 \left( \frac{2a}{L} \right)^2 $$

(2.3.1)

Perveance $P$ is expressed in microperms. A gun with a perveance of one microperm gives $1 \mu A$ at $10$ KV. In the above formula $V_1 = V_{\text{High}} - V_{\text{Low}}$ and $V_0 = (V_H + V_L)/2, V_1 \ll V_0$ and $2a \ll L$. In the derivation, the charge density was assumed uniform as it should be when the beam originates from a well designed gun.

A grid was placed in front of the cathode aperture at a distance of $3$ mm. Both the cathode and the grid were kept at negative potential with respect to the accelerating electrode. A $300$ V pulse with desired pulse duration was applied to the cathode making the grid $300$ V positive with respect to the cathode. During this time a pulse of electrons escaped through the grid and was accelerated through the cylindrical electrodes. It should be noted that, for the short pulse width
operation, care had to be taken in the electrical connections to the cathode. The connecting cable length etc were minimized as stray inductance and capacitance affected the pulse shape considerably. The pulse forming network is discussed in a subsection later in this chapter.

Focussing of the beam was considerably simplified as the gun was placed in a magnetic field. Besides, the electrostatic focussing, the magnetic field also gave a focussing effect. A zinc sulphide coated screen was employed to estimate the beam diameter along the length of the system. The pencil beam that was formed gave a spot size of 2 - 4 mm on the screen.

2.4. Pulse Forming Network for Trapping B-field:

To form a high current rectangular pulse, a transmission line (coaxial cable) terminated with its characteristic impedance $Z_0$ was used. Schematic of the line is shown in fig.4. An open ended length of coaxial cable was charged through a high resistance to a dc potential $V$. The line was discharged into a load resistance $R_L$, equal to the characteristic impedance $Z_0$ ($50 \Omega$) of the cable, through an air spark gap. The spark gap opened after each closure to allow the line to recharge, thus enabling repetitive pulses to be produced. The pulse repetition rate could be adjusted by changing the value of the charging resistors.

Let the voltage be written as a function of time in the form $V = V_0 e^{-t/t_0}$, the spark gap being operated at time
Fig. 4. Coaxial pulse forming line to generate 100 amp. current pulse of 150 nsec duration.

Fig. 5. Schematic of the magnetic probe circuit.
t = 0^20. The laplace transform of this voltage was then \[ \mathcal{V} = V/p. \]

On looking into the line A a certain impedance \( Z_{\text{in}} \) was seen. The signal voltage \( V_B \) which appeared across the load \( Z \) was given by the simple potential divider formula as

\[
\overline{V}_B = \frac{Z}{Z + Z_{\text{in}}} \mathcal{V} \tag{2.4.1}
\]

Since the line was open circuited at the end remote from A, it followed

\[
\overline{V}_B = \frac{Z - Z_o}{Z + Z_o} e^{-2\rho T l} \mathcal{V} \tag{2.4.2}
\]

where \( T \) was the transit time of the pulse and \( l \) was the length of the line. For the case \( Z = Z_o \), this reduced to

\[
\overline{V}_B = (1 - e^{-2\rho T l}) \mathcal{V} / 2 \tag{2.4.3}
\]

and when the inverse laplace transform was taken, it was found that the output pulse was rectangular in shape, had an amplitude \( V/2 \) and lasted for a time \( 2T \) i.e. twice the transit time of the pulse in the line.

To form a pulse of 150 nsec, the length of the coaxial cable needed was

\[
L = \frac{V t}{2} ; \quad \text{where} \quad V = \frac{e}{\sqrt{\varepsilon_o}}
\]

\( \sim 14 \) mts.
where $\varepsilon$ is the dielectric constant of the medium. To get a current amplitude of 100 amp, the voltage required to charge the cable was 10 kV. The four turn coil to produce the magnetic field was put in series with 50 $\Omega$ resistance. The current pulse was picked up by a current transformer and is shown in fig. 7 (1). The magnetic field pulse shape was monitored and the magnitude was measured with the help of magnetic probe, described in the next section.

2.5. Fast Response Magnetic Probe

Fig. 5 shows the schematic of the magnetic probe used for measuring time varying magnetic field. When a coil of effective area $A_{\text{eff}}$ was placed in a time varying magnetic field $B$, induced voltage $V_i(t)$ across the terminals was

$$V_i(t) = A_{\text{eff}} \frac{dB}{dt} \quad (2.5.1)$$

where $A_{\text{eff}} = nS$; $n$ is the number of turns in the probe and $S$ is the cross section $1/4 \pi d^2$.

From equation (2.5.1), it is seen that magnetic field $B$ is directly proportional to $\int V_i(t) \, dt$. This integral could be directly measured by coupling the probe to an integrating circuit as shown in fig. 5. For pulse duration smaller than the integration time $RC$, the following relation could be easily obtained$^{13}$. 
It is clear from (2.5.2) that the magnetic field was directly proportional to the voltage drop $U$ across the capacitor $C$, which could be measured directly on the oscilloscope.

The main requirements for such a probe were:

i) Minimum size to obtain good resolution in time and space.

ii) Fast electrical response $\lesssim 10$ nsec.

iii) Correct matching of the circuit impedance, particularly between the cables connecting the coil to the scope, thus avoiding ringing.

iv) Alignment of the probe coil with respect to the field component to be measured.

v) Shielding of the probe against electrostatic noise.

When there was no integrating element, resistance $R_T = 50 \, \Omega$ was connected in series with the probe to match its impedance with the characteristic impedance of the coaxial cable.

The frequency response of the coil was given by the ratio $L/R_0$, $L$ was the inductance of the coil and $R_0$ was the resistance across it. The inductance value was found to be 152 n Henry and the corresponding response time $T$ was $0.152$ nsec for a total resistance value of $1000 \, \Omega$. 

$$B = \frac{RC}{A_{eff}} U = 10^8 \frac{RC}{A_{eff}} U \left[ \text{gauss} \right]$$ 

(2.5.2)
The constructed coil had 20 turns with a diameter \( d = 16 \text{ mm} \), length \( l = 4 \text{ mm} \) and \( K \frac{d}{L} = 3 \) where \( K \) was a damping constant.

The capacitance value used was 5 pf. However, the total capacitance of the circuit was 175 pf. This value included the 20 pf input capacitance of the oscilloscope and 150 pf was the approximate capacitance of the coaxial cable having a length of 1.5 m. Therefore, the integrating time \( RC \) was found to be 175 nsec. Since the pulse duration was 150 nsec, the magnetic field could be related to the observed voltage with the help of (2.5.2).

Fig. 6 shows the construction of the probe. The glass cover over the probe coil was coated with a thin layer of silver to avoid electrostatic pick up during the measurements. Fig. 7 shows the simultaneous traces of the magnetic probe and the current pulse from the current transformer. For calibration of the magnetic probe, the current through the magnetic field production coil was varied by varying the input voltage, used for charging the pulse forming line. The probe output voltage as a function of the magnetic field is shown in fig. 8.

2.6. Electron Beam - Pulse forming Network:

It has been already mentioned that the shape of the electron beam pulse was very important. Therefore to form a 30 nsec, -300 V rectangular pulse, a three stage lumped LC circuit was used.
FIG. 6. Magnetic Induction Probe.
Fig. 7. Curve 1 represents the current transformer output. Curve 2 - The magnetic field produced by the same current pulse as registered by the magnetic probe.
Fig. 8. Calibration curve for the magnetic probe.
The final shape of the pulse obtained with the help of a lumped circuit is made up of the sum of the individual currents in the resonant circuits. As suggested by Guillemin, the Fourier series representation of an alternating current with the wave shape of each half period approaching that of the desired pulse was calculated. The alternating current could be written in the form of

\[ i = \sum_{n} i_n \left( n = 1, 3, 5, \ldots \right) \quad (2.6.1) \]

where \( i_n = k_n I \sin \omega_n t \); \( \omega_n = \frac{n\pi}{T} \), \( T \) is the total pulse duration.

Because of symmetry the even harmonics of the Fourier series do not contribute to the total current \( i \). From the equivalent form of Guillemin Voltage fed network, the \( I_n \) and \( C_n \) were calculated. The values of the inductances of the equivalent form were multiplied by \( Z_0 \) \( T \) and the values of the capacitances by \( T/Z_0 \). \( Z_0 \) was the characteristic impedance of the network, given by the ratio of the initial capacitor voltage to the current amplitude \( I \). The discharge current of the circuit was very similar to \( i \) of eq. (2.6.1) and switched by SCRs, it was similar to the single pulse of the desired shape. In such a lumped circuit, the shape generally depends on the number of elements and losses in the circuit. As the pulse width was increased, to form a better pulse, the number of lumped
circuits needed increased. For a very short pulse, the wiring of the circuit had to be carefully done to reduce losses in the circuit and also to reduce the effect of stray capacitance and inductance on the pulse shape.

In practice, to form the pulse, the capacitors of the storage network were charged up to the required voltage of -300 V. Then the charging unit was disconnected and the storage network was discharged through a series of SCRs. Fast response SCRs (GB 30 I A) were used for producing the short duration fast rising pulse. Since each of these SCRs could accommodate a voltage of 150 V, three SCRs in series were used. The SCRs were triggered with the help of a voltage pulse derived from the current pulse for the production of the pulsed magnetic field. The triggering of the SCRs was delayed by 100 nsec with respect to the magnetic field pulse, so as to synchronize the entrance of the electron beam with the applied magnetic field.

As shown in fig 9, in series connection of SCRs, difference in delay and fall time could result in voltage imbalance during the turn on period. This would mean that if all the devices have different time delay in turning on, then the full voltage drop would appear across the device which has the largest delay. The trigger pulse was applied to SCR\textsubscript{1}, it turned on and the voltage across it dropped from 100 V to 0.8 volts. Then C\textsubscript{1} discharged through SCR\textsubscript{2} gate and it turned on. Similarly SCR\textsubscript{3}
Fig. 9. Circuit diagram for the 30 nsec pulse forming network. 
$L_p$, $C_f$, and $L_u$, $C_u$ correspond to $L_1$, $C_1$ and $L_3$, $C_3$ of Guillemin voltage fed network respectively.
was also turned on. The 1.5 MΩ resistances were used to ensure similar voltage drop across the three SCRs. The final voltage drop across the load due to the current pulse gave the voltage pulse which was fed to the cathode of the electron gun as described earlier in this chapter.

Longer duration pulse (500 nsec) was also used during the experiment. In that case, care was taken to synchronize the magnetic field pulse with the voltage pulse in such a way that the field pulse was always within the voltage pulse duration. The number of electrons trapped in the system did not change as only a part of the electrons would see the change in the magnetic field. The electrons, not trapped in the system, anyway, did not contribute to the decay current.

2.7. **Diagnostics and Data acquisition system:**

The conventional diagnostic methods applied in the experiments are as follows:

2.7.1. **Electrostatic Retarding Potential Analyser (RPA):** To measure the parallel energy of the charged particles, an electrostatic retarding potential analyser was used. The schematic of the device is depicted in fig.10. It consisted of three grids and a collector housed in a cylindrical casing with an aperture whose area could be varied. To measure the energy of the electrons, retarding potential was applied to the central grid. The remaining two grids on either side of the central grid were kept at the ground potential. This was done to reduce...
Fig. 10. Schematic of the electrostatic analyser.

Fig. 11. Sample collector current Vs. retarding voltage plot. Dotted line shows how data was interpreted.
the effect of the retarding potential on the electrons, which passed through the grids and were collected by the collector. The current due to the collected electrons gave a voltage drop across a resistance and could be displayed on the oscilloscope screen.

While designing the RPA, the field distortions such as capacitor fringe fields, field leakage through the aperture and retarding field perturbations from the grid were minimised and therefore assumed to be unimportant. There exist several mechanisms for electrons to be emitted from a surface, although most of the mechanisms involve only a small percentage of the electrons emitted. Since the effect of secondary emission was not significant on the observed signal, secondaries from particles with large incident angles were also ignored. The material used for the construction of the analyser was stainless steel.

Fig. 11 shows a typical curve of the collector current as a function of the retarding voltage. For a monoenergetic beam, the fall in the current value was abrupt near the cut off value of the retarding voltage. However, for certain values of applied voltage, small dips were observed probably due to small secondary emission. But, since these dips were never more than 5%, they were approximated by the dotted curve for all practical purposes. Fig. 12 shows the cut off retarding voltage as a function of the beam voltage. It is seen that the experimental curve falls slightly above the unit slope.
Fig. 12. Calibration curve for retarding potential analyser. Solid line shows the unit slope which is below the experimental curve.
While performing experiments with plasma stream, the same retarding potential analyser was used with one more grid on it to measure the directed ion energy. This grid was used to select the particles to be analysed. During the experiment, the number density was reduced with the help of a 30% transparent grid to avoid electrical break down between the grids in the presence of the plasma.

2.7.2. Electrostatic Probes: In one of the experiments, the reflected beam was measured at the mid plane of the system. For this purpose a single faced electrostatic probe in the form of a collector, made out of stainless steel was used. But it was observed, that when the beam impinged on the insulated surface of the collector, a small amplitude spurious signal due to capacitive coupling appeared. To avoid this, the collector was modified slightly. Two collectors with their insulated surfaces facing each other were employed to serve the purpose. Electrostatic Langmuir probes were employed to measure the directed velocity by measuring the time of flight of the pulsed plasma stream. For the measurement of the floating potential, high impedance electrostatic probes were used.

2.7.3. Data Acquisition System: During the trapping experiment, the RPA was placed outside the mirror throat and the current due to electrons leaking out of the mirror was measured. The data was digitized and recorded on a magnetic tape. Fig. 13 shows a block diagram of the system used for data acquisition.
Fig. 13. Block diagram of the data acquisition system.
The signal from the collector of the RPA was fed to the current to voltage converter. Op. amp. 8007 with high input impedance and low bias current (≈10⁻¹² amp) was used, since the signal level itself was small (≈10⁻⁶ amp). The collector signal was fed to the inverting end of the op. amp. Thus the output signal from the converter was inverted.

The signal from the current to voltage converter was fed to a log amplifier. Fig. 14 shows the circuit diagram of the log amplifier. The ratio \( \frac{R_1 + R_2}{R_2} \) was chosen such that the output voltage gain was 2.5 V/decade. It is wellknown, that a log amplifier, unlike an operational amplifier, cannot be adjusted by simply grounding the input. This is simply because the log of zero approaches minus infinity. It was therefore necessary to zero the off set voltage of \( A_1 \) and \( A_2 \) seperately and then to adjust the scale factor ²⁹.

To check the response of the log amplifier, the output voltage was plotted as a function of known input voltage. Fig. 15 shows the response of the circuit as a log amplifier.

The signal from log-amplifier was digitised by means of an A/D converter and was recorded on a digital tape recorder. Recorded data was analysed with the help of IBM 360 computer. The digitisation error for the signal was ≈1%. A detailed discussion of the data analysis method is given in chapter IV.
Fig. 14. Circuit diagram of the log-amplifier.
Fig. 15. Log-amplifier response over four decades.