Energetic ion beam sources have become a subject of interest for their applications in ion implantation [1-3], surface modification [4-6], thin film deposition [7, 8], semiconductor doping [9], ion-assisted coating [10] and fusion material testing [11]. As per the requirements, there are number of ion sources developed so far as described in chapter 1. For an effective application of a particular ion beam source, one needs to obtain the reliable source characteristic parameters such as ion flux as well as ion energy spectrum and their dependence on the various experimental parameters. Therefore, the characterization of those ion sources has been a subject of paramount importance. Various attempts were made in that direction using several diagnostics such as a solid-state nuclear track detector (SSNTD), Silicon surface barrier detector (Si-SBD), magnetic analyzer, Thomson spectrometer and Faraday cup (FC). Among these diagnostics, the FC and SSNTD are promising candidates for the detection of ion energy with sufficiently high resolution over a wide energy range. Besides, the FC is a simple and cost-effective diagnostic that gives the time history of ion evolution. Its advantages are fast signal processing time, low E.M. noise and low energy ion detection [12]. The detection of ion beam through SSNTD is also a promising technique as the SSNTD is small in size and easy to handle [13] at any environment, high efficiency and need no electronics [14]. Therefore, it is widely utilized to characterize ion beam of various
sources, particularly in PF device since last several decades [12, 15-17]. The details of the detectors are discussed in section 3.2.

In the present work, an attempt has been made to characterize the neon ion beam emitted from plasma focus (PF) device in order to have information on ion beam energy, distribution and composition so that the device can be utilized for the study of physiochemical changes on some materials of interest in future generation tokamak reactor using multi FC assembly and SSNTD which are discussed in section 3.2.

It is noteworthy to mention that the PF devices of energy ranges from few kJ to MJ can generate ions with energy more than few hundreds of keV to tens of MeV [12, 15-17, 18]. In the past, several theoretical and computational models on ion production and acceleration mechanism have been developed. Among those models, moving thermal plasma model [19], generalized beam-target model with cross-field acceleration [20] and converging ion model [21] have explained the production-mechanism up to some extent. But, each individual model is best suited for a particular energy range of PF device. However, none of the model is in satisfactory agreement with the experimental measurements carried out on the different range of PF bank energies [17].

General characteristics of the ion beam in terms of their angular distributions and energy spectra were studied in different laboratories [12-17]. Earlier efforts on the ion study were mainly carried out in the deuterium-filled PF device to know the general characteristics of the ion beam emission, the acceleration mechanism of deuteron as well as their correlation with the neutron emission [22-25]. But, later on, the ion beam emission from the PF device was observed in other filling gases. Gribkov et al. [26] were first carried out a very systematic study on ion and electron beam dynamics of PF-1000 facility at its upper energy limit in relation to the neutron emission, the pinch characteristics and some other parameters. Their results favor the neutron emission model based on ion beam plasma interaction.
Sadowski et al. [27] described that the intensity of the ion beams depend upon the electrode geometry, bank energy and working gas type as well as pressure. Wong et al. [28] modified their PF to produce high-energy ion beam of nitrogen, argon and hydrogen in a low pressure mode and they suggested that the generation of a high local electric field due to the rapid increase in the plasma resistivity accelerates the ion beam to high energy. Zakaullah et al. [29] observed a good agreement on time evolution of the x-ray, electron, ion and voltage probe signals in an argon filled 3.6 kJ PF device. They measured ion energy by comparing the delay of ion signal with respect to the voltage probe signal and observed that the average energy of the argon ion beam is found to be pressure dependent. The average beam energy as measured by them, about 2.7 MeV at 0.25 mbar and the same increased up to 4.8 MeV at higher pressure, is expected to be a bit of either higher or lower value because of the ion energy extrapolation methodology. On the other hand, Heo and Park studied the argon ion emission from a low energy PF device by employing some more accurate diagnostics, which was a combination of capacitive current monitor and FC [30]. They reported that the maximum energy of the argon ions was over 1 MeV and the most common energy was about 200 keV. They speculated that the hybrid model describing the electric field induced by the moving current distribution, an anomalous resistivity and the Hall effect [30] is responsible for the acceleration of the ions to such a high energy. Takao et al. studied the characteristics of hydrogen ion beam emission from a PF device and they observed that the proton beam energy is distributed from 0.15 to 2 MeV [31].

The angular distributions of the ion beam emission from the PF device with different experimental conditions were also investigated to some extent. Kelly and Marquez [32], while investigating the ion emission from a 5 kJ PF device, that the measured ion number at 0° (anode axis) direction is approximately twice that of at 90° direction. Similarly, a high anisotropy of the ion emission was reported by Sadowski et al. with minima at 0° [33]. While
investigating the angular distribution of the proton beam emission from a 8 kJ PF device using LR-115 detector, Antanasijevic et al. [34] have also established that the protons are emitted dominantly at the axial direction. Their results are considered to be in good agreement with the theoretical studies of fast ion dynamics [35], which predict a strong anisotropy of the ion emission. Experiment performed in PF-1000 facility reveals that intense flux of several dozen keV deuterons is mainly accelerated in the electrode axis [36]. Zakaullah et al. [37] showed that the deuteron flux is maximum for the pressure range of 2.5–3.0 mbar with high fluence anisotropy, which is also the optimum pressure for the high neutron emission with low fluence anisotropy. The energy spectra and space resolved measurements of fusion reaction protons of the D(d,p)T reaction were studied by Sadowski et al. [38] in two PF devices (having bank energy 28 kJ and 280 kJ) by using LR-115A, CR-39 and CR-39/PM-355 covered with Al-filters. By putting appropriate Al filters in front of SSNTD detectors, they succeeded to distinguish protons of $E_p \geq 2.5$ MeV from deuterons and other fusion products. Moreover, they measured the reaction proton yield of $10^{11}$ by employing their 2 mm spatial resolution pinhole camera. The ion angular distributions, spatial distribution of sources, ion mass and energy spectra have been investigated by Szydlowski et al. employing a host of diagnostics such as SSNTD, ion pinhole camera and Thomson spectrometer [39].

Precise information on the energy spectrum and the angular distribution of ions leaving the pinch plasma in the background gas medium and their dependence on the PF parameters are the center of attention. This information would help in achieving the goal of usage of PF for the development of future key technologies. Till now no detailed studies have been carried out about the neon ion spectrum in the background gas medium that has strong bearing on plasma processing work using PF device. Interactions involving noble gas ions such as neon or argon and plasma facing components (PFC) are very much connected
with the radiative cooling of the plasma edge [11]. The concept aims at the uniform distribution of heat loads onto the first wall, i.e., at the reduction of power deposition on localized areas such as limiter or divertor tiles of the reactor like ITER. This is accomplished by injecting certain impurity species predominantly noble gases into the plasma edge in order to decrease the heat flow from the plasma by line radiation from excited states of seeded impurities [11, 40]. The resultant energy radiation leads to a uniform power distribution onto the entire wall of the reactor. Moreover, the seeding of the neon gas in tokamak reactor is a significant feature that can reduce the erosion of the PFCs.

The neon ions of tokamak reactor normally interact with the materials that are at the divertor region. Therefore, it is interesting to study the physical and chemical changes on divertor materials due to neon ion exposure which is described in the last chapter of this thesis. Understanding various issues such as energy spectrum, flux, angular variation, etc., of the neon ion emission from our PF device is quite essential before employing it for the material testing.

### 3.2 Apparatus and diagnostic technique

The apparatus used to investigate the ion emission from PF were a set of FCs as well as SSNTD assembly. The following subsections provide the principle and design consideration of FC and SSNTD along with estimation methods of ion velocity, ion energy and ion number density.

#### 3.2.1 Faraday cup

Faraday cup is a simple charge collector, cost effective and easy to handle [41, 42]. It consists of two conical electrode geometry; the inner electrode is made of graphite cup that encircles by a conical brass shielding. The two electrodes are separated by insulating...
material Teflon. With the conical shape, it has a small aperture at the entrance of ions and a
deep graphite collector biased at a negative potential. The entrance pinhole of the FC was
typically 300 µm in diameter. The bias applied to it is kept somewhat higher for the incoming
beam energy [43]. The negative potential is due to remove any electrons accompanied with
the incoming ion beam. The negative voltage also removes the secondary electrons from the
surface of the collector. Thus a suitable biasing voltage on the collector is essential for
proper interpretation of the collector signal. Regarding the proper biasing of FC in details can be
found in Ref. [44]. FC has been applied to several PF experiments to infer the ion spectrum by
time of flight techniques. Despite its several advantages, it has the following disadvantages: a low
signal-to-noise ratio and the emission of secondary electrons by the energetic ions impinging on
the collector. In order to overcome the above-said disadvantages an appropriate designing of the
detector and a collector material were employed which minimizes the emission of secondary
electrons.

The dimensions of inner and outer electrodes are typically estimated so as to get characteristic impedance of the FC as 50 Ω
using a simple equation [45],

\[
Z = \frac{138.2}{\sqrt{K}} \log_{10} \frac{D}{d_o}
\]  

(3.1)

Where \(D\) is the inside diameter of the outer electrode, \(d_o\) is the
outside diameter of the inner electrode and \(K\) is the dielectric
constant. To achieve the impedance of the FC as 50 Ω one
should be taken care. The graphite was chosen as the inner
electrode because of its low Secondary Electron Emission (SEE) effect [16]. A negative bias
voltage was applied to the inner electrode while the outer electrode was grounded. The electrical
insulation between the electrodes was accomplished by inserting a Teflon cup. The schematic of
FC along with the biasing circuit is shown in Fig. 3.1. When an incoming ion beam strike the graphite collector surface that is biased negatively with respect to the aperture, a current is generated in the circuit and a corresponding voltage \( V_R \) is developed across the resistor \( R \), value is 5-10 kΩ. This voltage \( V_R \) is proportional to the incoming ion flux and can be recorded on the oscilloscope. 'C' is the blocking capacitor, value is 10-20μF. When ion strikes the graphite cup which is negatively biased with respect to the aperture, current is generated through the circuit and voltage is developed across the resistor. This voltage is proportional to incoming ion flux. The size of aperture limits the amount of ions reaching the graphite collector and hence controls the magnitude of the ion pulse. In the multiple FC assembly, we have used five FCs whose design and dimensions are same as that explained above and were deployed at different angular positions to study the ion anisotropy. The results of the ion beam characteristics using FCs are discussed in section 3.4.

3.2.2 Estimation of ion velocity, energy and density

The estimation of velocity, energy and density of neon ion registered in FCs are carried out using Time-Of-Flight (TOF) technique. This technique deals with the finite time extension \( t_f \) of the ion source through a choice of experimental conditions such that \( t_f \) is small compared to the ion time-of-flight, i.e. through a choice of the distance \( S \) between the ion source and the detector (that is sufficiently high such)

![Fig. 3.2: A typical FC signal showing ion evolution with corresponding ion energy in keV [1]](image)
where $v$ is the velocity of the ion. On the other hand, the drop of the beam signal amplitude with increasing $S$ may reduce the signal amplitude to such levels that are not detectable for some of the less populated regions of the ion spectrum. Thus care should be taken while choosing the $S$.

The FC signal has two distinct components, first one (a little hump like structure) is generated due to other radiation namely X-ray where as second strong spike/peak is due to only ions [1]. Therefore, the flight time of ion for a fixed distance of the FC from source is determined by measuring the time delay between one point on the X-ray signal and the equivalent point on the ion signal [1,15] as shown in Fig. 3.2. It delineates FC signal, obtained for a typical PF shot, with corresponding ion energy estimated by the TOF measurement. Here the delay time ($t_f$), between the rising time (or falling time) corresponding to X-ray peak and subsequent rising time (or falling time) ions peak are measured. By knowing $S$ (in our case it is 6 cm) and $t_f$ one can easily calculate $v$ ($=S/t_f$).

The velocity ($v$) thus obtained can be used to calculate the energy associated with the ions, which are reaching the FC at different instants, by the simple formula

$$E = \frac{1}{2} M v^2$$

(3.3)

where $M$ is the mass of ion. Therefore, the lower value of delay time corresponds to higher value of kinetic energy of the ions and vice-versa. The estimated FC signals arises due to the ions correspond to kinetic energy ranging approximately from 18 to 1000 keV. Also, the number density of ions having velocity $v$ and charge $q$ is given by [44]

$$n_i = \frac{V}{R q A v}$$

(3.4)
where $V$ is the maximum voltage of ion pulse, $R$ is the resistance across which the output of the ion pulse is taken, $A$ is the area of the aperture and $v$ is the velocity of the ion.

### 3.2.3 Solid state nuclear track detector (SSNTD)

A solid-state nuclear track detector (SSNTD) is a sample of solid material (Photographic emulsion, crystal, glass or plastic) exposed to nuclear radiation such as neutrons, charged particles occasionally also gamma rays. It is a passive detector where any particle while passes through this medium gives out permanent track of particles after etched one can examined microscopically. In spite of the remarkable diversity of SSNTD applications that have emerged over the years in different fields, its potential is by no means saturated. SSNTD has so many applications in diversified fields of science and technology. Taking into account sensitivity, resolution, and variability of their response, the best SSNTD materials appeared to be optically clear amorphous, thermo set, plastics (polymers), which have high homogeneity and isotropy, high optical transparency and uniformity. A plastic material fulfilling those requirements was synthesized in 1978, and it was called CR-39 (Columbia Region) [46]. Others, more sensitive SSNTDs were manufactured in the eighties and they are commercially available as PM-355, PM-500, and PM-600 plastics. In our experiments we have used PM-355 type of SSNTD having thickness 1000 $\mu$, which was procured from International Environment Consulting, New Delhi.

(i) Track formation mechanism

The starting point of track formation mechanism is the transfer of energy from the projectile ion to the target electrons and nuclei in binary encounter. The basic block diagram of track formation between ions and target (or detector), their revealing by chemical method and observation is depicted elegantly in Fig. 3.3 and those will be discussed categorically.
There are three processes by which the charged particle can transfer their energy to the stopping medium. They are:

1. Coulomb electrostatic force between the particle and electron of the target atom may cause excitation or ionization.
2. When particles are decelerated they lose their energy by emitting radiation (Bremsstrahlung).
3. A direct electrostatic force between the moving charge particle and target nuclei can result in the ejection of target from the lattice site or molecular chain.

![Diagram of track formation mechanism]

Fig. 3.3: Three steps of track formation mechanism

(ii) Ion explosion spike

The passage of heavily ionizing nuclear particles through most insulating solids creates narrow paths of intense damage on an atomic scale. These damaged paths are called tracks. The damage along the tracks in inorganic solid consists mainly of displaced atoms; yet the damage results from interactions with the electrons in detector, not from direct atomic scattering. The escape from this dilemma has been suggested, termed the ion explosion spike. This process meant to use the burst of ionization along the path of a charged particle to create an electro-statically unstable array of adjacent ions, which eject one another from their normal sites into interstitial positions. Following the primary ionization, an array of interstitial ions and vacant lattice sites is produced by the Coulomb energy of ions, after
which elastic relaxation diminishes the acute, local stresses by spreading the strain more widely. It is the creation of long-range strains in this third step that makes possible the direct observation of unetched tracks in crystal by transmission optical microscope [47]. The ion explosion mechanism of track formation is shown schematically in Fig. 3.4.

(iii) Criteria for the atomic displacement of the atom

According to this criterion, the Coulomb repulsive forces within the ionized region be sufficient to overcome the lattice bonding forces in terms of a local electrostatic "stress" being greater than the local "mechanical strength" or bonding strength. If two ions in material of dielectric constant $\varepsilon$ and average atomic spacing $a_0$ have received an average ionization of $n$ unit charges $e$, the force between them is $n^2e^2/\varepsilon a_0^2$ or a local force per unit area (the electrostatic stress $\sigma_e$) of $n^2e^2/\varepsilon a_0^4$. The inter-atomic bonding force is a macroscopically measurable quantity, by noting that the theoretical mechanical tensile strength ($\sigma_M$) of young’s modulus $Y$ is approximately $Y/10$. Now in order to measure the relative sensitivity of various track-storing materials the mimic condition to be restored is,

$$\sigma_e > \sigma_M$$

$$n^2 \frac{e^2}{\varepsilon a_0^4} > \frac{Y}{10}$$

$$n^2 > R \equiv \frac{Y \varepsilon a_0^4}{10 e^2}$$

This relation indicates that tracks should be formed most easily in materials of low mechanical strength, low dielectric constant, and close interatomic spacing. After formation

---

**Fig. 3.4:** Ion explosion mechanism for track formation
of the track the sample should be etched using 6.25N NaOH solution at 70 (±2) °c [48]. To maintain the constant etching condition such as temperature and concentration it was mechanically stirred. The main aim of the etching purpose is to visualize the tracks more clearly under the optical microscope. Hence after etching the tracks can be observed using optical microscope.

Fig. 3.5: (a) SSNTD sample before irradiation, (b) SSNTD sample after irradiation

(iv) Track etching process

Latent tracks produced by neon ions on the CR-39 (PM-355 type) are very small. Therefore, only a optical microscope can "see" these tracks. For the enlargement of the tracks so that an optical microscope may "observe" them, a technique called etching is used. For instances, we have shown two micrographs in Fig. 3.5 where one is unexposed sample (a) and other one is exposed by Ne-ions (b). When SSNTDs are treated with some chemical etching solution, in our case 6.25 N NaOH solution at a constant temperature of 70±2°C, the material around the latent track is attacked preferentially and a cylindrical or a cone-shaped hole is formed. The observed tracks appeared to be circular or partly elliptical depending upon the incident angle of ions. For normally incident ions the track geometry is shown in Fig. 3.6. When a detector is placed in an etching solution and is heated to a suitable fixed temperature, the undamaged material is etched with a rate \( v_m (\mu m/h) \). The damaged material around the track is etched at a much faster rate \( v_d (\mu m/h) \). The material etching rate \( v_m \)
depends on the plastic type, etchant normality and the temperature of the solution. The track-etching rate $v_t$ depends, along with these factors, on the energy loss of the ions as well.

\[ \theta_c = \sin^{-1}\left(\frac{v_b}{v_t}\right) \]

where $v_b$ is bulk etch rate and $v_t$ the track etch rate.

**Fig. 3.6: Track etching geometry for normally incident ions.**

During etching, the undamaged material is etched isotropically at the rate $v_m$ where as the track etching is in action with the same rate $v_t$ and the material is continuously etched also with the rate $v_m$. The simultaneous actions of the two processes develop cones at the track sites. Their shape depends on the angle of the track with the surface of the detector. For obliquely incident ion tracks (shown in Fig. 3.7), if the angle of the track is less than a critical angle $\theta_c$ [49], the track would not be visible after etching treatment. This is due to the fact that the component of track etching rate is perpendicular to the detector surface $v_{t\perp}$ becomes smaller than the bulk etch rate $v_b$ if the angle is less than $\theta_c$. 

![Diagram showing track etching geometry](image)
Fig. 3.7: Side view of an etched track to explain the phenomena of critical angle

Different etchants can be used for enlargement of the tracks for different detectors, but for plastics, the aqueous solution of NaOH with concentration of 6 N is most frequently used etchant. The temperature range employed for it 40°C to 80°C. It is necessary to control the temperature of the etchant (±2°C) in an accurate measurement. The time for etching varies from a few hours to many hours, but for high efficiency and accuracy long etching time is preferable.

For CR-39 (PM-355 type) SSNTDs 6.25N solution of NaOH as an etchant has been found to be very effective. The etching time for CR-39 may varies 2-8 hours. However, this period may be prolonged to increase the track size even further. The corresponding temperature of the solution should be maintained at 70 °C (±2°C) [48, 50].

In order to etch the exposed CR-39 detector we have used a hot air electric oven as a etching chamber. It is procured from Ikon, Delhi having volume of 95 liters and shown in Fig. 3.8. It has a digital temperature controller cum indicator and the temperature of the oven can be varied from ambient to 250±1 °C. During the etching time we mixed 6.25N NaOH solution in a beaker and then put inside the oven. Gradually the temperature is given to rise up and reading was observed using thermocouple. The etching solution is mechanically stirred in order to achieve the constant etching condition such as temperature and concentration of the solution during the process.
In our experiment after irradiation by neon as well as proton beam tracks left on the CR-39 material, which were etched by 6.25N NaOH at 70±2 °C for a range of etching time 2 to 8 hours. After etching the samples are rinsed using a ultrasonic bath and then ready to view under optical microscope (OM). The OM which is shown in Fig.3.9, is an Olympus make (model BX51) [51] with CCD camera, motorized microscope stage (x, y axes), focusing knob etc. The microscope and CCD camera are interfaced to a computer running commercial image processing software. Importantly the controller unit has facility to perform 'autofocus' by adjusting the focus position to maximize the image contrast. The image processing software incorporates so many parameters which we used to control the stage movement, focusing and counting etc. Also the objective of the OM can vary from 5x to 100x. From the track images we also quantitatively measured the various parameters with different experimental conditions by selecting different areas using image analysis software.
Fig. 3.9: Photograph of Optical Micrograph with online computer system.

For clarification, CR-39 is an organic polymer and its chemical name is Poly Allyl Diglycol Carbonate (PADC), with chemical formula of $\text{C}_{12}\text{H}_{24}\text{O}_6$ and density of 1.31 g/cm$^3$.

The chemical structure of CR-39 is shown in Fig. 3.24. The thickness of the samples is 1000 $\mu$m supplied by Page Mouldings, UK.

```
CH_2-CH_2-O-C-O-CH_2-CH=CH_2
\ \ \ O
CH_2-CH_2-O-C-O-CH_2-CH=CH_2
```

Fig. 3.10: Chemical structure of CR-39
3.3 Experimental setup for characterization of neon ion using FC

The experiments were conducted using our 2.2 kJ PF device. The details of the PF device are presented in chapter 2. The experimental parameters that were varied in the present work were filling gas pressure and FC positions at different heights and angles. The schematic diagram of the experimental setup is shown in Fig. 3.11. As explained in chapter 1 section 1.5, disruption of the hot and dense plasma takes place due to the growth of $m = 0$ instabilities. Immediately after the disruption, ions and electrons are accelerated in opposite direction i.e. ions rush towards the top of the chamber and electrons move towards the electrode assembly due to the high electric field generated by $m = 0$ instabilities [5, 10, 16]. These accelerated ions are detected by putting the FC along the electrode axis and

![Fig. 3.11: Schematic of PF device with FC assembly](image)
off axis at a height of ≥ 60 mm from the top of the focus region. In order to study the time history of the ion emission, we have taken current probe (Rowgowski coil) and PIN diode signals as reference. The signals from current probe, PIN diode and FC are simultaneously recorded on the oscilloscope for each PF discharge. For angular measurement of ion emission the Faraday cups were placed inside the PF chamber at a distance of 60 mm from the top of the anode and at five different angles (0, 20, 25, 50, 90°). The output of each FC’s was fed to a digital oscilloscope through an appropriate biasing circuit for monitoring ion beam signal. The FCs were biased at approximately -200 V throughout the experiments and the signals of FCs were recorded and analyzed for extrapolation of the ion flux, energy and number density.

3.4 Results and discussion

The typical FC signals along with PIN diode and dl/dt signals are shown in Fig. 3.12. Two distinct features are clearly marked in the FC signal. The first one (a little hump like structure) is generated due to EM radiation namely X-ray as it’s appearance matches with the PIN diode signal. This is because the velocity of EM radiation always faster than all other radiation. Therefore, the first peak cannot be recognized.
as ion peak. So, the second strong spike/peak is only due to the ions of PF device. The ion beam signals with similar type of characteristics were also reported by earlier workers [2, 16] where the small hump is identified as due to EM radiation rather than ion beam. In order to substantiate this fact, another simple technique was employed [17], i.e., by applying a transverse magnetic field of 2 kG (using permanent magnets) in between the entrance pinhole of FC and ion source and found that the first peak remained unchanged whereas the intensity of the second peak was drastically reduced. We believe that the first peak in FC signal is not at all due to ions, which is appeared due to X-ray namely hard X-ray. We have carried out experiment by blocking the pinhole of FC in order to check the response of x-ray radiation onto the part of transmission line that is inside the PF chamber. The upper trace of the figure clearly indicates that a small noise is picked by the FC assembly, which occurs at the same time as of dip of dl/dt signal and middle one is FC signal. Hence, it is obvious from the present investigation that EM radiation does not affect much to the part of transmission line that is inside the

Fig. 3.13: FC signals with block and with pinhole along with dl/dt signal
PF device [52]. The noise, FC and dl/dt signals all are shown in Fig. 3.13. The results obtained in investigations at axis only are presented next section.

3.4.1 Study of axially emitted neon ion

To study the dependence of neon ion beam intensity with filling gas pressure, the ion beam signals were recorded by varying the filling gas pressure from 0.1 to 1 Torr by keeping FC at height of 6 cm from the anode top. Fig. 3.14, the plot of ion beam intensity versus operating pressure indicates that the ion beam intensity strongly depends upon the filling gas pressure. The maximum ion beam intensity is obtained at a pressure of 0.3 Torr. At this pressure, the device favours a proper discharge dynamics so as to form a strong pinching [52, 53]. Again, at this pressure the pinching time is seen to be occurring near the maximum of discharge current and thereby transferring maximum energy into the plasma. Therefore, the ion beam emission is optimum at this pressure and, hence, maximum beam intensity is obtained. Below 0.3 Torr, the beam intensity decreases and this may be the consequence of weak current sheath dynamics at low filling gas pressures. As the pressure increases beyond the optimum pressure (0.3 Torr), the current sheath velocity decreases due to the increase of sheath mass. Therefore, the focus formation becomes weaker which yields low emission of ion beam. This type of observation on pressure variation on ion beam intensity is also reported by Heo and Park [30].

![Fig. 3.14: Ion beam intensity versus operating gas pressure (Torr)](image1)

![Fig. 3.15: Ion beam energy versus ion flight time.](image2)
The neon ion energy emitted from the PF device is estimated from the ion beam signals obtained at different pressure by using time of flight technique as reported in Ref. [54]. The Fig. 3.15 shows the neon ion beam energies as a function of ion flight time, estimated from the ion beam signal obtained at optimum operating pressure (0.3 Torr). The curve shows that the PF device emits poly-energetic ion beam that ranges from 18 to 1000 keV. The maximum ion energy is calculated for each operating pressure and plotted as a function of pressure as illustrated in Fig. 3.16. The plot shows that the maximum ion energy increases as the pressure increases from 0.1 Torr and reaches a maximum at around 0.3 Torr. The further increase in pressure the maximum ion beam energy decreases. The physical phenomenon behind the variation of maximum ion beam energy with pressure may be explained as follows. It is known that the induced accelerating field during the pinching phase is responsible for the acceleration of the ions. Thus, higher is the accelerating field more is the ion beam energy. It is already mentioned that at optimum pressure (0.3 Torr) the PF shows strong pinching and thereby generates strong accelerating field. In case of other pressures, the pinching is weaker than that of optimum pressure and thus inducing a weaker accelerating field.

Fig. 3.16: Variation of maximum ion beam energy with operating pressure

Fig. 3.17: Ion beam density versus ion beam energy
while moving up. Measurements of neon ion emission at various angular positions are described hereafter.

Fig. 3.18: Ion beam intensity at different FC heights

![Graph showing ion beam intensity vs. time](image)

Fig. 3.19: Neon ion current density as a function of FC heights

![Graph showing ion current density vs. height](image)

3.4.2 Study of neon ion emission in various angular positions

A set of typical time resolved neon ion beam signals obtained from the FCs placed at different angular positions (0, 20, 25, 50 and 90°) is shown in Fig. 3.20. It is observed that the ion beam signals follow similar type of time resolved characteristics irrespective of the angular positions, i.e., a distinct high amplitude ion beam spike always follows with a small hump. The small hump prior to the ion beam spike is taken as the reference for ion emission time for further analyses of the ion beam signal. It is to be noted that the FC positioned at 90° angle also collects sufficient amount of ion flux and thus conforming the radial emission of ion beam from the PF device. Such evidence of the radial emission of the ion beam is also reported in Refs. [56, 57]. A plot of the full width at half maximum (FWHM) of ion beam signals versus the angular positions of the FCs is illustrated in Fig. 3.21. The FWHM of the ion beam signals of different angular positions are observed to be increasing from 0 to 90°.
this experiment, we could detect much lower energy ions (>10 keV) as compared to the previous reports. It is evident from the Fig. 3.23 that the density of the low energy ions is more in comparison to the high-energy ions. Similar type of ion energy spectrum is also reported in Refs. [1, 59]. At 0° angular position, the most probable ions is found to be around 57 keV, while it is around 20 and 12 keV in case of 20 and 25° angular positions, respectively. The observation of most probable value of neon ion energy within the 20 to 25° angular positions is by and large in consistent with the previously reported result on nitrogen ion beam emission from the PF device using different anode designs [1]. Bhuyan et al. [57] also observed most probable proton flux in the range of 15 to 40 keV while studying the ion emissions from methane filled PF device. The most probable ion densities at 0, 20 and 25° angular positions, in our study, are estimated to be around 9.7x10^{19}, 11.4x10^{19} and 15.5x10^{19}/m^3, respectively. This implies that the contribution of lower energy ions is more in the higher angular positions. The shifting of the most probable ions towards lower energy side as well as the increase of lower energy ions in higher angular positions may be

![Ion density as a function of ion energy](image)

**Fig. 3.23:** Ion density as a function of ion energy
explained in the light of ion Larmor radius. The Larmor radius of the lower energy ions is smaller than that of the higher energy ions. Thus, they deviated much in magnetic field and thereby increasing their contribution at higher angular positions. One may also view the contribution of the lower energy ions in the higher angular position in a different perspective i.e., the low energy ions may come from the segment of current sheath, which does not take part in the pinching process at the anode top and continues to move beyond the open end of the electrodes.

3.5 Characterization of neon ion using SSNTD

The space resolved and time integrated ion emission from our PF device was also carried out using SSNTD. Inside the vacuum chamber we placed the samples of SSNTD at the axial as well as at different angular positions namely 0, 10, 20, 30, 50, 60, 80 degrees. All samples are placed at same height 60 mm in the experimental arrangement from the top of anode as shown in Fig. 3.24. Before putting CR-39 of samples inside the PF device it is cut into small pieces with a size of 10x15 mm². After rinsed the samples with running tap water we have mounted them inside the PF device. The samples are first irradiated by neon ion and etched with NaOH solution. The overall effect is that the chemical solution etches the surface of the detector material, but with a faster rate in the damaged region. In this way, a ‘track’ of the particle is formed, which may be seen under an optical microscope. This procedure is called ‘detector etching’ or track visualization, and the effect itself is called the ‘track effect’.
Once the CR-39 detectors were exposed with neon ions, the next job is to be washed, rinsed and then etched in order to enlarge and develop neon tracks, so that they can be viewed under an optical microscope. The whole process in known as the phenomena of track development or simply the etching process.

### 3.5.1 Energy loss calculation

It is well known that when the charged particle strikes the detector medium then it losses the energy through the interaction processes like ionization and excitation. The physical quantity that describes the slowing down of charged particles in materials is stopping power $-dE/dx$, where $dE$ is the energy at the distance $dx$. The energy lost by a particle in the distance $dx$ is energy transferred to the sample (material), so this quantity is called linear energy transfer (LET). The classical expression that describes the specific energy loss is known as the Bethe formula [60] and it can be written as
\[-\frac{dE}{dx} = \frac{4\pi e^4}{m_0 v^2} N Z \ln \left(\frac{2m_0 v^2}{I}\right)\]

In this expression \(v\) and \(z\) are the velocity and charge of the primary particle; \(N\) and \(Z\) are the number density and atomic number, \(m_0\) is the electron rest mass. The parameter \(l\) represents the average ionization and excitation potential of the absorber. The energy loss is inversely proportional to incident particle energy and directly proportional to atomic number. So energy loss and penetration depth are dependent on particle atomic number and particle energy. Higher atomic number, high-density materials will result in the greatest linear stopping power. Therefore, the stopping power \(S\) for a charged particle in a given absorber is defined as the differential energy loss for that particle within the material divided by the corresponding differential path length:

\[S = \frac{-dE}{dx}\]

Similarly, the range of any particle is defined as the maximum distance traverse within the absorber just before coming to rest. The energy range and stopping power of the neon ion are calculated using SRIM code [61]. The calculated values of energy loss and stopping range for Ne ion in CR-39 are shown in Figs 3.25 and 3.26, respectively.

**Fig. 3.25:** Energy loss of neon in CR-39

**Fig. 3.26:** Stopping range of neon in CR-39.
3.6 Results & discussion

The CR-39 detectors were exposed to the neon ion by varying the filling gas pressure as well as angular positions. A typical micrograph of neon exposed sample at the axial position is shown in Fig. 3.27. The micrograph shows the formation of ion tracks with different rim diameters and widths. The tracks are uniformly distributed on the detector and thus confirming an even spatial distribution of ions. The tracks resulted because of the normal and the oblique incidences of the ions are also noticed. Furthermore, overlapping of the tracks is also witnessed in the micrograph. The saturation/overlapping of CR-39 mainly depend upon the fluence of the incident particles. When the fluence of incident particles is larger than approximately $10^8$ particles/cm$^2$, then overlapped tracks are generally observed. The systematic study carried out by Gaillard et al. [62] on saturation of CR-39 detector reveals that the particle fluences above $\sim10^5$ particles/cm$^2$ turn the detector into the saturation regime so that direct track counting is not possible. There are quite a few literatures reported on saturation effect in SSNTD due to high fluence of ion. As far as our knowledge is concerned, as of now Ref. [63] only has reported the saturation effect on track detector while detecting the axially moving fusion protons (3.03 MeV) However, they have not reported any remedy for overcoming the saturation effect of SSNTD due to high fluence ion emission from PF device. We have used a simple technique to overcome the saturation or overlapping effect of CR-39 detectors by covering them with ion filters and thus overcome the saturation effect.
The estimation of neon ion energy is also carried out using CR-39 detectors covered with 0.8 μm Al filter at 0.3 Torr filling gas pressure. A typical optical micrograph of etched detector is shown in Fig. 3.28. The micrograph shows the formation of ion tracks with different diameters, which are uniformly distributed on the detector and thus confirming a regular ion distribution in a lower dimension scale length (500X500 μm²). The tracks resulted because of the normal and the oblique incidences of the ions are also noticed. SRIM code [61] indicates that 0.8 μm Al filter would pass neon ion energy of above 550 keV. Thus, the formation of tracks in the detectors covered with 0.8 μm Al filter is of indicative that the PF device emits neon ion having energy more than 550 keV. As mentioned earlier, the estimated value of neon ion energy by FC technique also reveals the energy up to 1 MeV. It is worthwhile to be mentioned that we had 0.4 μm foil of Al, and during experimentation we made it two fold resulting 0.8 μm foil which is the optimized one [53]. As a precaution we also tried with 2 μm Al filter in front of the detector, no tracks were observed. According to SRIM code the neon ion having energy more than 2 MeV can only pass through the 2 μm Al filter. This is evident from micrograph shown in Fig. 3.29 where no tracks are being

Fig. 3.27: Optical micrograph of exposed CR-39 with saturation

Fig. 3.28: Optical micrograph of exposed CR-39 detector covered with 0.8 μm Al filter.
observed. Hence we confirm that the neon ion emitted from our PF device having the maximum energy up to 1 MeV, which is also estimated by FC technique.

![Fig. 3.29: Optical micrograph of exposed CR-39 detector covered with 2 μm Al filter](image)

We have studied the ion emission characteristics with respect to filling gas pressure as well as angular positions by using CR-39 detectors covered with 0.8μm Al filter. The track number density was calculated from the micrographs for four different pressures. The plot of the pressure variation of the track counts per m² is illustrated in Fig. 3.30, which shows that the track counts/m² is the highest within the pressure range of 0.3-0.5 Torr. The trend of

![Fig. 3.30: Track counts as a function of pressure.](image)
variation of track counts with the filling gas pressure generally tallies with our earlier plot as illustrated in Fig. 3.22. The pressure dependence of track diameters and counts may be interpreted in terms of the pinch performance. It is well known that in the PF device, at the optimum pressure, the pinching is severe and, thus, one expects high fluence of energetic ions at this pressure than the others. Since the track size is ion energy dependent, hence one expects the variation in track diameter at different operating pressures. It is also stated that the track diameter obtained at optimum pressure (0.3 Torr) is higher than that of other pressures.

The optical micrographs of CR-39 detector keeping at different angular positions also show a clear difference in the track formation. A simple look at those pictures indicates that the diameter of the tracks is more in the case of higher angular positions. In addition, there is a distinct variation of the track number density with respect to the angular positions. The track number densities were estimated from each micrograph at five random places in order to have an average value for each angular position. The variation of the track density for different angular positions is shown in Fig. 3.31. It is to be noted that initially the track density increases towards higher angular positions and reaches a maximum at 30° angular position with a track density around $10.9 \times 10^9$ tracks/m². Further increase in the angular positions, the track density gradually decreases. Similar type of the observation in angular variation of the track density is also reported in Ref. [64] for deuteron beam. The reason behind obtaining the different track diameters for various angular positions can be
interpreted in terms of the ion Larmor radius. It is known that the ions with higher energy will have larger Larmor radii with respect to the system dimension and therefore, those higher energy ions move mainly either in the axial direction or in a smaller conical region along the axis. While the low energy ions having smaller Larmor radii moves mainly in larger conical region. This might be the reason behind obtaining different track diameters at different angular positions.

The trend of angular track distribution is quite similar with the variation of ion fluence estimated by FC measurements as illustrated in Fig. 3.32. Mohanty et al. also observed similar type of angular distribution of nitrogen ion beam emission by employing multiple FC assembly up to some extent and found maximum ion flux at 5° angular position [1]. The histogram, shown in Fig. 3.33, indicates the distribution of track counts as a function of the track diameters obtained for different angular positions. Over all, the tracks are distributed within a wide range of diameters from 2 to 13 μm having different track counts. The
populations of the lower diameter tracks (2-6 μm) are observed to be more at 0 and 10° angles. Even the tracks of diameter 2-4 μm are not seen in the higher angular positions. Furthermore, the histogram reveals that the most populated track counts are shifted towards the higher diameter as angular positions changes from 0 to 70°. Similar type of sifting is also observed by Szydlowski et al. [65]. The authors also reported that the number density of track of diameter 4-6 μm is more at 0° angle whereas at 90° angle the tracks having diameter in the range 8-10 μm are abundant.

We have also estimated the track diameters and counts by exposing CR-39 detector at two different axial positions. The histogram of track diameters/track density versus axial positions of the CR-39 detector is shown in Fig. 3.34. It is observed that the track diameter slightly increases as the height increases. The mean diameters of tracks are around 3.9 and

![Histograms of track counts as a function of track diameter](image)

Fig. 3.33: Histograms of track counts as a function of track diameter
4.5 μm for the detectors exposed at 5 and 10 cm, respectively. As height increases, certainly
the ions attenuates a fraction of energy due to the interaction with the background gaseous
medium and hence one may state that lower energy neon ions (> threshold energy) may
produce tracks of larger diameter. As expected the track counts reduces slightly as height
increases. Our investigation on the temporal and the spatial distributions of the ions predicts
that one can tailor the ion energy as well as flux inside the PF chamber by choosing proper
positions (axial as well as angular) and operating gas pressures. Hence, one may state that
lower energy neon ions greater than threshold energy, may produce tracks of larger diameter.
As expected the track counts reduces slightly as height increases. A rough estimation of neon
ion energy was also carried out by covering the CR-39 detectors with 0.8 μm Al-filter. SRIM
code indicates that 0.8 μm Al filter would allow to pass neon ion energy of above 550 keV.
The micrograph of detectors, in this case, show a lesser number of track counts than that of
the detectors exposed without Al filter. The formation of tracks in the detectors covered
with 0.8 μm Al filter indicates that PF device also emits neon ion having energy more than
550 keV. The estimated value of neon ion energy by FC technique also reveals energy upto 1
MeV.

![Fig. 3.34: Axial position of SSNTD versus track counts and diameter](image)

Fig. 3.34: Axial position of SSNTD versus track counts and diameter
3.7 Conclusion

By employing a multiple FC assembly and the CR-39 track detectors the temporal and spatial characteristics of the neon ion beam emissions from the PF device have been studied. The characterization of the neon ion has been made for different operating gas pressures as well as angular and axial positions. The FC analyses show that the ion beam fluxes strongly depend on the operating gas pressure as well as the angular positions. The ion beam fluxes are found to be highest at 25° angular position and 0.3 Torr operating pressure. The estimated ion energy measurements at the aperture of FC indicate that the PF device is a source of the polyenergetic ions ranging from approximately a few keV to a few hundreds of keV, irrespective of the pressures and the angular positions. The most probable ion energy at 0° angular position is around 57 keV whereas around 20 and 12 keV in case of 20° and 25° angular positions, respectively. It is marked that the most probable ion density at the aperture of FC for 0°, 20°, and 25° angular positions are around 9.7 x10¹⁹, 11.4 x10¹⁹, and 15.5 x10¹⁹ /m³, respectively. The optical micrographs of the exposed CR-39 show the formation of the ion tracks with different rim diameters and widths. It is to be noted that initially the track density increases toward higher angular positions and reaches a maximum at 30° with a track density of around 10.9 x10⁹ tracks/m². Further increase in angular positions, the track density gradually decreases. The tracks are found to be distributed over a wide range of diameters from 2 to 13 μm with different track counts. The populations of lower diameter tracks (2-6 μm) are observed to be more at 0° and 10° angles. It is also seen that the most populated track counts have shifted toward higher diameter as angular positions change from 0° to 70°. A clear picture of neon ion flux and energy distribution inside the PF chamber is obtained from this study, the neon ion was used for the testing of fusion materials to severe condition which is described in last chapter.
References


