Chapter 1

General Introduction

1.1 Introduction

The advent of Industrial Revolution in Europe and its gradual expansion on the global scale lead to an aggressive competition amongst the countries to invent newer equipment for laying the foundation of a technologically superior modern world. The bliss of science compounded with high skilled technological innovations has rewarded the humanity with unthinkable material comfort. In achieving this, electric power had played its cardinal role as an indispensable entity in running of industries and in revelation of industrial finished products. The demand for goods in the society and competitive aggressiveness witnessed in industrial world has created a huge gap in the demand and supply need of electrical power in global context. Therefore, the hunt for creation of newer energy sources and their successful exploitation has been a matter of great challenge to the scientific community. Thermal power, the power from renewable natural sources like solar, wind, tidal, hydel and power from nuclear fission reactors taken collectively lacks sufficiently behind in fulfillment of actual power need. Moreover, environmental pollution arising out of thermal power plants, deficiency of nuclear fission fuel and the possibility of nuclear radiation hazard from nuclear power plant poses question mark on their long-term use.

This precarious energy scenario coupled with ever growing demand of electric power lead scientists to think harnessing of electric power out of nuclear fusion process which is largely pollution free and can guaranty for a long term energy solution.
If energy liberated in a fusion reaction is to be utilized for useful purposes, then like nuclear reactors where fission takes place in a controlled manner. Once fusion reactor becomes feasible then only the energy can be put to use. We have seen that three basic conditions must be satisfied before a fusion reactor can be made successfully operative. The number one is the high temperature. The cross-section or the probability for fusion is large for deuteron (D) or tritium (T) energies around 100 to 1000 keV, which corresponds to temperature around $10^7-10^8$ K. The second is high density of nuclei, so that in a given time interval, the number of collisions between nuclei may be large enough and third condition is fusion should be self sustained so that the system of reacting nuclei may be able to stand the time till the nuclear fusion takes place and also able to give out more energy than what is spent on the system.

In order to obtain a net yield of energy from a fusion reaction one need to supply sufficiently high temperature to enable the particles to overcome the coulomb barrier and that would be maintained for a sufficient confinement as well as higher ion density. The overall conditions, which must be met for a yield of more energy, than is required for the heating of the plasma are usually understood in terms of the product of ion density and confinement time, a condition called Lawson's criterion. There is a balance between the invested energy producing the plasma and the output fusion energy. The 'break-even' condition known as the Lawson criterion describes the equality between the invested energy and the recovered fusion energy.

For D–D fusion the Lawson number is one hundred times larger, and the temperature is larger by a factor of five, than in the D–T case. This is the reason why D–T fusion appears to be the easiest to achieve among all the other nuclear fusion possibilities. Thus the nuclear fusion reaction which is the least difficult to produce under laboratory conditions is one between D and T.
If deuterium and tritium is taken for fusion reaction, then the nuclear reactions are

$$\begin{align*}
D + T &\rightarrow ^{4}\text{He} \ (3.50 \text{ MeV}) + n \ (14.1 \text{ MeV}) \quad (1) \\
D + D &\rightarrow ^{3}\text{He} \ (0.82 \text{ MeV}) + n \ (2.45 \text{ MeV}) \quad (2) \\
D + D &\rightarrow \text{T} \ (1.01 \text{ MeV}) + \text{H} \ (3.02 \text{ MeV}) \quad (3)
\end{align*}$$

However, this reaction requires particle energies of about 10 keV and this corresponds to 100 million degrees centigrade. This is seven to ten times larger than the temperature of the core of the sun (15 million degrees centigrade). There are two practical problems in attaining the desired goal namely achieving of high temperature as well as the confinement of gaseous medium in such a high temperature. Equation (1) is more probable because of high yield than the rest of the reactions.

Now overall aim of these reactions is to gain more energy as a compensation of less energy in the input. This ratio may be estimated by Q-values of the reactions. Q is the ratio of fusion alpha heating power to input heating power. With the intention to solve out energy problem the many around the globe have tried with various experimental investigations. One of the largest experiments is the Joint European Torus (JET). In 1997, JET produced a peak of 16.1 MW (21,600 hp) of fusion power (65% of input power), with fusion power of over 10 MW (13,000 hp) sustained for over 0.5 sec. In June 2005, the construction of the International thermonuclear experimental reactor (ITER) is commissioned and designed to produce several times more fusion power than the power put into the plasma over many minutes. ITER (Caderache, France) is proposed to produce 500 million watts of fusion power, 10 times greater than the external power delivered to heat the plasma.

In ITER like machine where the plasma durations are long and its interaction with the surface is also for a long period, there are serious issues related with plasma sputtering of carbon based surfaces, contamination of plasma and subsequent entrapment of tritium. Disruption generates runway electron, which interact with plasma facing components.
Plasma interaction with graphite surfaces, carbon sputtering and redeposition sometimes results in the hydrogenated thin films. These films can remove significant amount of hydrogen from the reactor and will affect fuel inventory inside the machine. Carbon-based materials such as isotropic graphite and carbon fiber composites (CFCs) have been widely employed for protection of inner walls of existing tokamaks [1, 2]. Although carbon-based materials have a superior thermal shock resistance than metals, the affinity for hydrogen isotopes creates a concern about the particle inventory in the wall and control of hydrogen plasma density. In addition, the anticipated erosion rate of low Z plasma facing components such as beryllium and carbon is much larger than that of high Z materials, and associated issues of erosion lifetime and tritium co-deposition are therefore worse. In order to reduce the erosion rate of the plasma-facing wall in a fusion reactor, the use of typical high Z material, tungsten, has been proposed [3-5] due to high thermal conductivity, high chemical inertness, low sputtering yield, better stability at high temperature. Therefore it is quite essential to understand the physiochemical properties of those plasma-facing components for fusion environment for the better operation and safety of the reactor. Due to these well mentioned properties previous investigations of plasma facing components were focused using various energetic ions with different energy ranges in various types of experimental facility such as linear magnetized plasma facility (PISCES-B) [6], Material Irradiation Experiment (MITE-E) [7], magnetized coaxial plasma gun [8], inertial electrostatic confinement [9], High Average Power Laser (HAPL) [10], and PF-1000 with MJ energy [11] etc. Ion sources also play a vital role for the investigations of the physiochemical changes of those plasma-facing components in a harsh environment.

1.2 ION SOURCES

An ion source is an electromagnetic device that is used to create charged particles. As per the requirements, there are number of ion sources developed so far. Some typical
examples of common ion sources are thermo-ionic ion source, electron beam ion source, radio frequency ion source, electron cyclotron resonance, laser ion source, Duoplasmatron, Penning etc. These ion sources have their merits and demerits in various application fields which are discussed hereafter.

1.2.1 Thermo ionic ion source

The operation of a thermoionic ion source is based on the effect of thermoionic emission of alkali ions (Li⁺, Na⁺ and K⁺) from the corresponding aluminosilicate. The ionic beams are injected into the plasma, and the secondary fluxes of ions of higher charge states or excited light radiation created during collisions with plasma particles are detected outside the plasma device. The injectors of probing beams should provide the beams of high intensity for clear discrimination of secondary signals. The ion source is the heart of any diagnostic injector. For example, the thermo-ionic ion source is highly efficient with small emittance source, but it is limited for alkali, earth alkali and some rare earth elements. Other disadvantages are low ion current, extensive heat dissipation to the environment. Kuncser et al. [12] observed simultaneous discharges of Fe-Cu metal sources using thermo ionic ion source. This is the new procedure for preparation of granular Fe-Cu thin films with sensibly enhances room temperature giant magneto resistive effects.

1.2.2 Electron beam ion source

In the Electron Beam Ion Source (EBIS), a fast, dense, electron beam interacts with cold ions trapped in an electrostatic well. Ions are confined radially by the potential well in the electron beam and axially by electrostatic mirrors. Ions accumulated in the trap can be expelled by lowering the potential of one end of the trap. As the interaction time between hot electrons and ions depends on the electron energy and the source length, for highly charged ions this time is necessarily short. Thus high density, and hence high current density,
electron beams are required, electron beam ion sources produce highly charged state ion and can be operated in pulse mode for long period. The main disadvantage of this source is that it needs a very high-density electron beam, which generates instabilities and usually needs ultra-high vacuum to reduce the impurities.

1.2.3 Electron cyclotron resonance (ECR)

The electron cyclotron resonance ion source is highly efficient with very high output current and large emittance ion source that can be operated in continuous as well as pulsed mode. It can be used as metallics as well as gas ion source. The disadvantage of this device is that it needs very high microwave frequency and high magnetic fields from the resonance condition. Also this source has very low efficiency for refractory elements. An ECR ion source using a selected circular mode microwave is studied for material processing by Aseji et al. [13]. The results of film deposition of pure tungsten as well as intermetallic compound substrates using planar ECR plasma source are studied by Tereshin et al. [14].

1.2.4 Laser ion source

The laser ion source is a highly efficient device for around 90% of the elements ion production with low emittance. The advantage over the other devices are that it is a simple structure at high voltage level with less insulation problem and need not required confinement systems. It is ideal for the refractory materials. The main disadvantage of this device is that it requires high power laser system short pulse height and low repetition rate. In addition, it is not suitable for the gases. Freinkman et al. [15] proposed a laser ion source for nanotechnology. The shape and size distribution of supported Au clusters on highly oriented pyrolytic graphite prepared by two kind of clusters beam techniques, liquid metal ion source and pulsed laser ablation were studied by Hu et al. [16].
1.2.5 Penning

A penning ion source works with cold or heated electrodes that generates a high-voltage, low-pressure plasma discharge. In a typical configuration, electrons oscillate between two cathode electrodes inside an anode ring. An axial magnetic field increases the path length of ionizing electrons, making plasma production more efficient. Penning discharge is used in a number of sources with either cold or hot thermionic emitter and can be used for low-charge-state light ions. This ion sources have been used for a variety of applications, such as sputtering and evaporation of surfaces, electromagnetic separation of isotopes, and fusion applications [17].

1.2.6 Plasma based ion source

(a) Low pressure

Low pressure ion sources include the studies by using magnetron, DC, RF and glow discharge etc. There are several interesting investigations reported in the literature. The characteristics of diamond-like carbon (DLC) films deposited on a 4-in. Si (100) substrates using a magnetron sputter-type negative ion source (MSNIS) were investigated using Raman spectroscopy and X-ray photoelectron spectroscopy (XPS) method by Paik [18]. High power impulse magnetron sputtering (HIPIMS) and related self-sputtering techniques are reviewed from a viewpoint of plasma-based ion implantation and deposition (PBII&D) by Anders [19]. Ion implantation is a surface modification process in which a solid surface layer is irradiated by beam of energetic ions emitted from an ion source. The implanted ions penetrate to a depth and modify the solid surface layer depending on the ion energy, ion type and nature of the solid surface. The modification of solid surface layer may cause either due to physical changes induced by ion beam damage or due to chemical change arising from bonding of the irradiated ions with constituents of the surface layer. An RF electric field
coupled into the plasma chamber maintains a low pressure ($10^2 - 10^3$ Torr) discharge. Positive ions are expelled from the discharge by a negatively biased repeller electrode. The operation and characteristics of radio frequency (RF) plasma beam sources based on the expansion of the discharge outside of limited spaces with small interelectrode gaps are studied by Dinescu et al. [20]. The appropriate electrode configuration, combined with high mass flow values and appropriate power levels, leads to small- or large-size plasma jets, working stably at low, intermediate, and atmospheric pressures. Similarly, Konstantinidæs et al. [21] studied the titanium oxide deposition using an efficient RF amplified magnetron source. The sources are promising tools for a wide range of applications in thin film deposition, surface modification, and cleaning, including the case of temperature-sensitive substrates. The glow discharge plasma is luminous and can be produced by applying a potential difference between two electrodes in a gas. Farouk et al. [22] studied the thin film deposition at atmospheric pressure using methane-hydrogen dc micro-glow discharge technique. They studied the gas-phase discharge, the surface reactions, deposition characteristics and its growth rate. The opto-electronic polymer thin film depositions on materials which can be used for preparation of highly integrated microships are also studied by Zhao [23] using glow discharge plasma technique.

(b) High pressure

A high-pressure ion source includes plasma torch and dielectric barrier discharge. Inductively coupled plasma (ICP) sources typically used for trace elemental determination and speciations were investigated with infrared (IR) thermography to obtain spatially resolved torch temperature distributions. Dielectric barrier discharges (DBDs) at atmospheric pressure are obtained using mixtures of He and Ar as carrier gases and various reacting additives such as hydrocarbons, hydrogen and nitrogen by Goossens et al. [24]. These DBDs are used in three applications: deposition of polymer films, cleaning of Ag and Cu substrates...
and activation of polyurethane and steel surfaces. In the case of the film deposition, several process conditions are investigated.

(c) **High density and high temperature**

High density and high temperature plasma include such as capillary discharge, plasma focus (PF) discharge. Bhuyan et al. [25] studied about the formation of sub-micron size carbon structures using a pulsed capillary discharge from a methane operating gas medium. They characterized the carbon substrate using scanning electron microscope, energy dispersive X-ray analysis and Raman analysis etc and thereby confirmed the submicron size carbon structure. Also this discharge has potential application in microscopy; holography, biological imaging and the diagnostics of very high density plasma [26]. At present, there are few numbers of plasma producing devices that can be used for material processing. Among them PF with some salient properties with respect to magnetic fusion applications is one of the potentially suited devices in material processing due to its improved process efficiency and economy [27,28]. The genesis of the PF device is discussed in the later section.

1.3 **Genesis of plasma focus (PF) device**

PF device is a machine that can produce a short-lived plasma, by electromagnetic acceleration and compression. This short-lived plasma is so hot and dense that it can emit energetic ions, electrons, neutrons (when operated in deuterium gas) and intense X-rays etc. The electromagnetic compression of the plasma is called a pinch. It was invented in the early 1960s by J.W. Mather (USA) and also independently by N.V. Filippov (USSR). The devices investigated by these two pioneers have significantly different geometries, though they are similar in many aspects and results. Many PF devices have since been built by other investigators, but all broadly confirm to one of the two original geometries, and can be classified as either of Mather- or Filippov-type.
In the last century (from 1960-80), the PF was studied as a possible device for controlled thermonuclear fusion. However, the main mechanism for producing neutrons was found not to be thermonuclear origin rather and beam target origin [29]. If the fusion mechanism is thermonuclear origin then emission of neutron should be anisotropy. But experimentally it was not possible. So this measurement of anisotropy is attributed to a non-thermal process of the ion beam-target between the deuterons with the plasma and with the neutral gas. Hence it is worth worthy to mention that it fails to explain that all neutrons are coming from thermonuclear origin. Therefore during 80's researchers were thinking as the PF is an intense pulsed of alternative radiation sources like X-ray and charged particles.

Besides being a ready source of hot dense plasma and fusion neutrons, the focus also emits copious amount of charged particles, X-rays (soft and hard), from the plasma column and hot-spots in discharges operating with gases with atomic number higher than hydrogen (neon, argon, xenon, etc) [30] and mixtures of gases [31]. Various groups characterized the X-rays from PF device. Wang et al. investigated the X-ray emission from anode region using PF device [32] and Sofield et al. studied the radiations over a wide range from infrared light to hard X-ray [33]. Pavez et al. demonstrated the evidence of X-ray emission from this ultra miniature pinch PF device that operates at only 0.1 J shot using H₂, Ar, and Ne [34]. These powerful X-ray sources particularly suitable in different field of applications such as lithography [35], X-ray microscopy [36] and radiography [37] etc.

In addition, the last few decades, the above-mentioned radiation draws attention of researchers that this low bank energy PF device can be used in material science. Ion beams emitted from the PF devices can be used as different purposes such as ion implantation, energetic ion irradiation, surface modification and coating production etc. [38-42]. Applications of fast ions for the production of isotopes useful in nuclear medicine have also been suggested [43]. During these days there is a renewed interest in the development of
transportable and portable plasma foci for industrial and field applications in different manner.

During the last three decades, substantial efforts and resources have been invested in PF devices [11, 44-47]. A large range of investigations have been performed on both types of PF geometries with stored energies varying from a few Joules to ~ M.J. Some of the different bank energy PF devices are incorporated in a table 1.1.

With the background and range of several PF energies all over the world as quoted in the following table many groups are trying level best to extract good information for the scientific community. In that context, CPP-IPR is working with a Mather type device and therefore, it needs a brief discussion to understand it. Therefore the discharge dynamics of this device is discussed in the following section.

**Table 1.1: List of PF devices in various energy ranges all over the world**

<table>
<thead>
<tr>
<th>Device/laboratory</th>
<th>Energy (kJ)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PF-1000</td>
<td>1200</td>
<td>[11]</td>
</tr>
<tr>
<td>PF-1000</td>
<td>1000</td>
<td>[44]</td>
</tr>
<tr>
<td>SPEED 2</td>
<td>100</td>
<td>[45]</td>
</tr>
<tr>
<td>AAAPT</td>
<td>3</td>
<td>[46]</td>
</tr>
<tr>
<td>ILT-LLT</td>
<td>2-5</td>
<td>[47]</td>
</tr>
<tr>
<td>SRL</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
1.4 Discharge Dynamics of PF device

The dynamics of the PF can be divided into three stages: the breakdown or inverse pinch phase, the axial acceleration phase and the radial collapse phase as shown in Fig. 1.1. The PF device is usually operated with the inner electrode as anode and the outer electrode as cathode. The operation of the device with the reverse polarity decreases the neutron and X-ray output [51]. The gross dynamics of the three distinct regions or phases is described in the following sub-sections.

1.4.1 Breakdown phase

When a high voltage pulse is applied between the two coaxial electrodes of the PF device filled with a working gas at an appropriate pressure, then gas medium starts to breakdown. In principle, the gas breakdown can take place anywhere between the electrodes. However, operation of the device demands that it should occur at the closed end of the electrodes assembly between the anode and the cathode plate of the focus chamber. An insulator sleeve, which is normally glass, is placed at the closed end of the electrode assembly. The image charges at this insulator surface helps in initiating the discharge. For a
symmetrical breakdown, the polarity of the inner electrode (anode) should be positive in order to concentrate these electrons at the insulator surface. The free stray electrons in the gas medium are accelerated towards the anode as well as insulator sleeve due to the appearance of high electric field. During the acceleration the electrons strike the insulator sleeve with sufficient kinetic energy and thereby producing secondary electrons. Now these secondary electrons further ionizes the ambient gas medium near the surface and glides towards the closed end of the electrodes. A gliding discharge develops along the insulator.

When the gliding discharge reaches the end of the insulator, both electrodes are connected by weak current filaments flowing just above the surface of the insulator between the anode and the cathode plate. These plasma filaments are then lifted off from the insulator surface in an inverse pinch manner, propelled by the self-generated $J \times B$ force (Fig. 1.1). When the current filaments reach the inner surface of the outer electrode (after 50 – 500 ns),

![Fig. 1.1: Schematic of PF with current sheath motion](image)

they blend to form a uniform current sheath due to the high conductance of the gliding discharge. In fact, it is a double layer structure consisting of an ionization front and the
magnetic piston [29, 52, and 53]. The frontal section of the sheath (attached to the inner electrode) remains temporarily immobile during the breakdown phase. When the uniform current sheath is formed, the focus formation process enters into the second phase.

1.4.2 Axial acceleration phase

The current sheath formed at the end of the breakdown phase is accelerated by self-generated $J \times B$ force towards the open end of the inner electrode in the inverse pinch phase. The radial component of $J \times B$ pushes the current sheath towards the outer electrode. The axial component of the force is stronger near the anode due to the $1/r^2$ dependence which leads to a higher velocity of the current sheath near the surface of the central electrode than near the outer electrode. The current sheath maintaining its axisymmetric character, acquires a paraboloid shape as it propagates down to the open end. If axisymmetry of the current sheath is not maintained, the quality of the focus is badly affected. Now because of radial component of the current sheath will push towards outer electrode. There are two important phenomena taking in this phase, namely the current shedding as well as mass loss. According to Lee et al. [54] all the current does not flow through the current sheath rather some current stays behind within the vicinity of the back wall insulator. In another paper by Chen et al. [55], reported from specially designed magnetic probe measurements, that only 50-70% of the total circuit current participates in the axial rundown phase. The mass loss which is indicated by the observation of the fact that the current sheath is not very thin (~20-30 mm thick), rather large due to inefficient

Fig. 1.2: X-ray pinhole image of pinch column showing sausage i.e. $m=0$ [58]
showprow action and also due to escape of the mass through the outer electrode resulting from pressure gradient in the canted current sheath.

Chow et al. [56] described that the current sheath is driven by a magnetic piston in a rest gas with super sonic speed; as a result a strong shockwave is generated in front of the sheath. The shockwave ionizes the rest gas on its passage. The current sheath is now composed of compressed hot plasma in between the moving shock and the magnetic piston. At the end of this phase, one end of the current sheath sweeps around the open end of the anode. The current sheath which is attached to the outer end continues to move along the tube, sweeping with it the greater portion of the accumulated plasma in the axial direction. Only a fraction of the plasma at the end of the axial acceleration phase contributes to the final focus.

1.4.3 Radial pinch phase

At the end of the axial rundown phase, the current sheath sweeps around the end of the inner electrode (usually anode) and finally collapses due to the inward $J \times B$ force. This collapse occurs within 50 – 200 ns, depending on the device characteristics. The radial collapse velocities range between 7 – 60 cm/μs, depending on the geometry of the electrodes, initial gas pressure, structure of the current sheath and electrical characteristics of the device. The other end attached to the cathode continues to move toward the open end of the electrode assembly. As a result the greater portion of plasma will be accumulated in axial direction. The remaining small part of plasma squeezes towards the axis of the anode as the inward radial component of $J \times B$ force become dominant. Now this force drags the current sheath towards the axis of central electrode and thereby compressing the plasma into a cylindrical plasma column. The magnetic piston was assumed to compress the shock heated plasma towards the axis resulting in the heating to such a temperature that bulk of the
radiation spectrum shifted out [57] of visible region. The plasma so produced is having temperature of the order of few eV to a few keV with a density $\sim 10^{25-26}/m^3$. The typical size of the plasma column length is 5-10 mm and with diameter of 1-2 mm respectively [58] which is shown in Fig. 1.2. The PF device not only provides high temperature and high-density plasma but also emits several energetic radiations such as neutrons, charged particles, X-rays etc which will be discussed in later on.

1.5 Instabilities in PF device

Increase in temperature in the plasma column, increases the kinetic energy of the charged particles but at the same time may induce fluctuations in the electric and magnetic fields. When a certain mode of perturbation grows, due to the growth of instabilities plasma will break into ions and electrons. These instabilities give disruptions of the focused column are caused by onset and occurrence of macroscopic type of instabilities such as Rayleigh-Taylor (RT) and magneto-hydrodynamics (MHD) origins. The RT is an instability of an interface between two fluids of different densities, which occurs when the lighter fluid is pushing the heavier fluid. It occurs when a heavier or denser substance is being pushed or accelerated by a lighter one [59, 60]. In regards of PF device in the radial compression phase of focus formation, the plasma is first accelerated towards the axis and then decelerated. The interface between the plasma and the magnetic field is found to be unstable during the radial compression [61]. Peacock et al. [62] using interferometric study has observed that the onset of the RT the growth time is about 30 ns before the end of this phase. Chen et al. also [63] studied the growth of RT instability in the spherical pinch column. Using interferometric technique Decker et al. [64] informed RT and radial density gradient during the compression phase. It is well known phenomena that the geometry of a plasma column confined by magnetic field is unstable subjecting the magneto hydrodynamic instability. This instability is of two types sausage ($m=0$) as well as kink ($m=1$); where 'm' represents the azimuthal
magnetic mode number in the MHD equation [65]. The details about the existence of the above two MHD instabilities are well explained in elsewhere [62, 66]. In view of (a) sausage (m=0) and (b) kink instabilities (m=1) of plasma focus column Rawat et al. [67] has clearly being explained and measured it by using the magnified soft X-ray (SXR) pinhole images which was shown in Fig. 1.3. They observed both the instabilities at pressures of 3 mbar and 4 mbar respectively. The insulator sleeve having length of 19 mm in neon filled PF device were used at the closed end of the coaxial electrode assembly for SXR emission. When plasma is confined in plasma column it will experience a radially inward Lorentz force by magnetic field (B) and current density (I). Now owing to any radial perturbation the magnetic field keeps on varying and therefore pinch column is squeezing at some places resulting bulging at other place. This because of inverse radial dependence of magnetic
pressure \( (B^2/2\mu) \) arising by the azimuthal component of magnetic field. The higher the magnetic pressure of the squeezing region puts further inward pressure on the plasma column and thus making a clear constriction on it. This constriction appears like a neck-like structure in the plasma column. The rapidly changing magnetic pressure at each neck induces a large electric field, in turn accelerates the ions and electrons of hundreds of keV.

Second possibility is that when a pinch column of plasma is bent or twisted due to any radial perturbation, then what happens that the magnetic lines of force becomes weaker in the outer edge of the bend and comparatively stronger at the inner edge of the bend. Because of this stronger magnetic field inside the plasma column, which causes the pressure in the bend, which leads to further bending and the consequence, is breaking of plasma column into ions and electrons. This phenomena is known to be kink \((m=1)\) instability and depicted in Fig. 1.3 (b).

The growth of sausage \((m=0)\) and kink \((m=1)\) instabilities were also observed by Peacock et al. using the image converter photographs in the most compressed phase [62]. In their measurements the growth time for the both type of instabilities is found to be less than 50 ns. Of course, the local break up of the plasma pinch column is mainly due to \(m=0\) instability whereas the \(m=1\) instability is a less often observed phenomena with much slower growth rate. There are ample evidence of occasional contributions due to break up in the pinch plasma column through \(m=1\) instability by Peacock et al. [62, 63]. On the other hand, the occurrence of \(m=0\) instability in the PF was predicted by Potter [68] in a manner of two dimensional MHD model. In another paper by Comisar [69] predicted that the lifetime of the resulting fountain like pinch column appears to be governed by the formation of sausage instability. Therefore, it established that the growth time of the instability is found to be at least 5-10 times shorter than the observed pinch lifetime (~50 ns).
1.6 Radiation emission from PF device

Considerable efforts have been concentrated from the discovery of the PF on the study of the emission of radiation like neutrons, X-rays (hard and soft) and charged particles. The general properties of the PF such as neutron emission, neutron energy spectra and X-ray emission were studied by Mather [29] and Bernstein et al. [70].

1.6.1 Neutron emission

The PF device is producing excellent neutron beam from the very beginning of its commission. The neutron emission from this device is thought to be similar to thermonuclear origin [29] after a few critical reports. With much experimental observation it has proved that neutron emission is anisotropy in nature (the flux in the axial direction being usually higher than that in the radial direction) [71]. Therefore, it was proposed that the beam-target fusion accounts for the most of the neutron production in the PF. Bernstein [70] proposed a crossed-field acceleration model to explain the generation of neutron in the PF. They mentioned that the high energy deuterons follow curved trajectories. Several models have been tried to explain the induced neutron emission and ion model [72], the beam target model [73] and the cross field model [74] are being successful in explaining them quite a bit. Depending on MHD calculation Potter [68], proposed that the neutron yield can be achieved upto $10^{12}$ per pulse from a 32 kJ Mather type PF device. The neutron scaling laws are also well established with different energy ranges and currents in the range of few kJ to MJ (or 100 kA-1MA). The most acceptable scaling law best explained on empirical relation is given in terms of discharge current ($I_0$) for the total neutron yields ($Y$) and it can be written as $Y = k I_0^3$, where $k$ is a constant [75].
1.6.2 Particle beams emission

The light ions namely proton, deuteron etc and heavy ions (mass number greater than $^4$He) are produced by PF device in the energy range of few tens of eV to MeV [76, 77]. Efforts are on to confine these energetic charged particles in accordance with high electric field strength in the radial compression phase. A number of works both in theoretical as well as experimental fronts have been carried out to understand the physical mechanism behind charged particles emission as well as their characteristics. Styger et al. [75] studied the ion beam using SSNTDs. They also monitored the neutron emission. They found out that the charged particle current was dependent on the discharge current of the capacitor bank. Bostick et al. [77] registered a band of deuteron energy beam ranges from 0.3 to 9 MeV in a 5.4 kJ PF. Their results show $10^{14}$ deuterons with an energy interval 0.3-0.5 MeV and $10^{12}$ deuterons with energy interval of 1-9 MeV. The uniqueness of the charged particle emission is that it produces pulse ion beams with highly charged states and wide range of energies. The electron beam energy spectra as well as ion beams spectra are found to obey power law dependence quite sometimes [78]. Moreover, the low bank energy PF devices are very compact ion source with low cost and provide excellent performance in terms of ion energy, fluency and exposure time. Similarly, Neog et al. [79] also reported the generation of electron using a 2.2 kJ PF device and studied the electron beam emission with various experimental conditions. They observed that electron beam current was found to be strongly dependent on the operating pressure and the average electron beam current. The highest value of electron beam charge and density were estimated at the optimum pressure as 7.5 mC and $4.5 \times 10^{16}$ m$^{-3}$ respectively. Johnson calculated the thick target electron beam X-ray spectra with a Monte Carlo electron beam transport programme by assuming a power law dependence of the electron beam emission [80]. Krompholz et al. [81] estimated the electron beam spectra from the X-ray observation and they found that the spectra obeyed Boltzmann
distribution at the energy 3 keV. They demonstrated the presence of non thermal electrons of above 100 keV energy and proposed a beam target model in PF device. Pouzo et al. [82] observed relativistic electron beam by employing fast response Rogowski coil in a 2 kJ PF device. Smith et al. [83] also studied the electron beam emission from a 3 kJ PF device using faraday cup (FC) and magnetic energy analyzer.

1.6.3 X-ray emission

Emission of X-rays from plasma takes place by three processes, namely Bremsstrahlung, recombination and line radiation. Processes in the plasma, which give rise to continuum emission, include Bremsstrahlung and recombination radiation. On the other hand, if an already bound electron loses energy by falling to a lower ionic energy state then a line spectrum is obtained. Different types of X-ray emission process are briefly described below.

In a free-free transition, radiation is emitted when a charged particle is accelerated or retarded in the field of another charged particle. When a free electron collides with another charged particle it decelerated, i.e., the electron loses some of its energy and makes a transition to a lower energy free state. This loss of energy appears as an X-ray photon with a continuum spectrum. The X-ray thus emitted is called Bremsstrahlung.

When a primary free electron is captured by a bound state of an ion, the ionic charge reduces by unity. The excess energy of the captured primary electron is emitted as a photon, giving free-bound or recombination X-radiation. The emission spectrum is a continuum for each bound state. The shape of the spectrum mainly depends on the free electron energy distribution. The continuum X-ray emission spectrum from plasma consists of both the free-free radiation and free-bound radiation [84].

Bound-bound radiation or line radiation is emitted as a result of transition between bound states of an ion. An electron bound in an ion may get excited to higher energy state either by
collision with primary particles or by absorption of photons that are created in the plasma by other means. When the excited electron makes a transition to another bound state of lower energy, an X-ray photon with well-defined energy is emitted. The intensity of X-ray emitted by this process is much higher than the other two above-mentioned processes.

An exhaustive study on X-ray characteristics from a PF of ~3 kJ has been conducted by the group of Zakaullah et al. [85, 86]. In Ref. [85] it is estimated that about 40 J of energy is radiated as X-rays, out of which 8 J is in the form of Cu-Kα lines in 4π geometry. The radiation yield represents a system efficiency of 1.7% for overall x-ray emission and 0.35% for the Cu-Kα line [86]. It is also found that with the same scaling law with the current peak, the Cu-Kα emission varies as $Y_{\alpha} [J] \sim [E(kJ)]^{3.5-4.5} \sim [I \times 100 \text{ kA}]^{3.5-4.5}$, whereas the total x-ray emission is found to follow $Y_{\text{tot}} [J] \sim [E(kJ)]^{1.5-5.5} \sim [I \times 100 \text{ kA}]^{4.5-5.5}$. The emission is dominated by the interaction of electrons in the current sheath with the anode tip. With a cut at the anode tip, the x-ray flux in the side-on direction is increased three times. Recently, studies of x-ray polarization from hot-spots have been conducted by Jakubowski et al. [87, 88]. Measurements of spectral lines using two spectrographs with perpendicular dispersion planes were performed. The most important results of the spectral measurements appear to be an evident difference between the relative intensities of the same lines, registered with the two perpendicular spectrographs. Such a difference could be explained by the x-ray polarization, caused possibly by the interaction of fast electron beams. Besides making the PF an intense X-ray source which is useful in many applications such as microlithography [35], X-ray microscopy [36] and X-ray radiography [37] the X-rays emitted also provide a convenient means for studying the plasma properties.
1.7 Layout of the thesis

Apart from the present chapter, general introduction of the thesis it contains another four chapters. The organization of the thesis is as follows:

Chapter 2 is fully devoted to the details of various subsystems of ion source (2.2 kJ PF device) \cite{29, 89} such as high power injector system (high-energy storage capacitor with spark gap, transmission line, high voltage capacitor charger), discharge chamber, vacuum pump and pressure gauges, compressed air system, control panel and data recording system etc. In order to evaluate the discharge dynamics of PF device we have employed the current probe and resistive voltage divider. The principle, design and performance of these diagnostics are discussed in this chapter.

The seeding of the noble gases such as neon and argon is very important in a fusion environment for the uniform distribution of heat loads throughout the first wall \cite{90}. Neon interaction with plasma facing components is very eminent. Therefore, one needs to check the physiochemical changes on reactor materials occurred due to neon irradiations. In chapter 3, an attempt has been made to characterize the neon ion beam emitted from PF device in order to have information on ion beam energy, distribution and composition so that the device can be utilized for the irradiation purpose. A multi FC assembly and solid state nuclear track detector (SSNTD) mainly CR-39 were employed at axial and different angular positions to characterize the neon ions which helps us to use this device for material irradiation application in a more controlled manner.

Chapter 4 is devoted for the characterization of proton from PF device. The proton retention and recycling properties of the first wall during and after the bombardment with proton from the plasma are important factors controlling the particle balance and isotropic composition of the plasma as well as the tritium inventory of the vessel wall of the reactor \cite{91}. Hence, proton interaction with reactor materials is also needed to be studied in depth.
So we characterized the protons emission from PF device using FC and SSNTD diagnostics and the details of the studies are incorporated in this chapter. Proton with the characteristics of energy and density seems to be effective for testing materials of interest in tokamak research.

For ITER, tungsten will be used at baffles and side-wall regions of divertor plates, carbon at strike points of divertor plates, and beryllium at first walls [92]. The testing of these materials has paramount relevance in fusion material research so we have exposed neon and proton on these materials. Chapter 5 reports detail of the motivation, experimentation and characterization of the materials. For surface morphological studies we have used a optical microscope (OM), scanning electron microscope (SEM) and atomic force microscope (AFM). In order to know the structural changes tungsten samples were carried out by employing X-ray diffraction at glancing angle (GIXRD). Compositional study was done using energy dispersive X-ray fluorescence (EDXRF) for tungsten samples. The Vickers hardness test is also carried out to find out the change in surface hardness. Similarly, for graphite samples the surface morphological analyses are characterized using OM and SEM. For structural analyses graphite samples were studied using X-ray Bragg diffractometer. While comparing the diffractograms of graphite, the crystalline structure of the unexposed slightly tends to amorphous structure in case of exposed samples are confirmed.
References


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