Chapter 2

Experimental set-up and diagnostics

2.1 Introduction

Ion beam sources have been playing a crucial role to meet the requirements of testing plasma facing components in fusion environment, which demands a conceptually high and technically sound setup. One of such ion source is plasma focus (PF), which is mainly an ingenious source of X-rays, neutrons, energetic ions and electrons [1, 2]. The suitability of producing various types of beams and solely depends upon the type of filling gas makes this device an extremely versatile machine. Moreover, this ion source produces a wider broad band of energy for a very short duration having high fluence of ions. Of course there are many successful machines in worldwide among them in India like PF device (Delhi University) [3], plasma gun (IPR, Ahmadabad) [4] or mini-accelerator (BARC) [5]. The PF device which has been used in this present experimental work at Centre of Plasma Physics-Institute for Plasma Research (CPP-IPR), India is a 2.2 kJ Mather type device [6], which was designed in collaboration with Bhabha Atomic Research Centre, Mumbai. In order to run this device successfully we need to understand the basic principle and working procedures of some of major components. This chapter is devoted to the description of different subsystems of our PF device and electrical diagnostics which are used to visualize discharge dynamics. The photograph of CPP-IPR, PF device with different subsystems is shown in Fig. 2.1. The various subsystems, which are related with PF device, are described hereafter.
2.2 High power injector system

The high power injector system is a pulsed power system (PPS) that delivers power to the electrode assembly in the form of mono-pulse, repetitive pulses or a single burst of multiple pulses for a short duration of time. The main aim of pulse power technique is to transform the low power electrical energy to high power (~MW to TW) by compressing the time duration (~seconds to microseconds) in the form of mono-pulse.
The simplest of a PPS is a primary energy storage device, comprising of a capacitor bank, a high power low inductive switch and a low impedance transmission line connected to the load. This system has the advantage of low cost and small size. A simplest type of PPS having low cost is used for running the PF device in our laboratory. The system consists of a high-energy storage capacitor, transmission line, high voltage capacitor charger and high voltage switch. The description of the components of the PPS is discussed in the following sub sections.

2.2.1 High-energy storage capacitor with spark gap

The energy storage capacitor possesses the characteristics of low inductance, high peak current, large $dl/dt$, good fault tolerance, good life and excellent reliability. The capacitor elements, made up of alternative layers of metallic foils and dielectric film, are impregnated with dielectric fluid and assembled in a metal or plastic can [7]. As per the requirement at the time of choosing a capacitor one has to note the specification such as voltage stress of dielectric, capacitance, internal series inductance, longevity etc. In PF device to satisfy a number of requirements like maximum storage energy transfer to plasma, a high voltage input power and high current generation is essential to produce the plasma within the some micro or nanosecond of time. In order to achieve such type of current and voltage the convenient way is by discharging a capacitor it is charged to a high voltage through the desired load. So while choosing a capacitor, one has to note that the capacitor

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Fig. 2.2: Photograph of high energy storage capacitor
should have low internal inductance and it should connect through a path of low circuit
inductance [8]. The energy stored in the capacitor is given by,

\[ E = \frac{1}{2} CV_0^2 \]  

(2.1)

Where \( C \), the storage capacitance and \( V_0 \) is the peak charging voltage. But the increase in
voltage above a certain limit will create insulation problem. Again, higher capacity
capacitors with lower inductance are costly and use of more capacitors (in parallel
connection) to get desired results (low inductance) creates design difficulties [5]. In view
of the above-mentioned constraints and limitations, we have chosen an oil filled
capacitor of capacitance 7.1 \( \mu \)F; having charging voltage 40 kV with inductance of the
order of 40 nH for the present experiment. For the operation of PF device, the capacitor is
charged to a voltage of 25 kV. The various specifications of the storage capacitor (procured
from Passoni and Villa, Millano, Italy) are given in the Table 2.1. The photograph of the
high energy storage capacitor has been shown in Fig. 2.2.

Table 2.1: Specifications of energy storage capacitor

<table>
<thead>
<tr>
<th>Description</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
<td>7.1 ( \mu ) F ± 10%</td>
</tr>
<tr>
<td>Maximum charging voltage</td>
<td>40 kV</td>
</tr>
<tr>
<td>Energy</td>
<td>5.7 kJ ± 10 % (at 40 kV)</td>
</tr>
<tr>
<td>Voltage reversal</td>
<td>80 %</td>
</tr>
<tr>
<td>Series inductance</td>
<td>~110 nH</td>
</tr>
<tr>
<td>(Capacitor + Spark gap)</td>
<td></td>
</tr>
<tr>
<td>Charge-discharge life</td>
<td>5 ( \times ) ( 10^4 ) shots</td>
</tr>
<tr>
<td>Ringing frequency</td>
<td>( \geq 75 ) KHz</td>
</tr>
</tbody>
</table>
In high voltage pulsed power applications, to transfer energy from a driver to a load, special switches are commonly used. The closing switches employed in capacitor banks are: thyratrons, ignitrons, semiconductor switch, reed switches, spark gaps, solid dielectric switches etc. [9]. Among them most conversant, reliable and fast working switch at high current is spark gap. In addition, spark gap switches [9-11] are of low cost, simple and technically fast response with low jitter and long life. The voltages hold off can be in the order of MV and current produced in the order of MA when several gaps operated in parallel. In the present work a spark gap [5], in built with capacitor to hold off high voltage and switching is utilized. The spark gap employed in our case of two co-axial electrodes separated by dielectrics (generally air gap) as depicted in Fig. 2.3. The spark gap is housed inside an insulator casing of ceramic and is rigidly fixed to the top end of the capacitor. The electrodes are coated with an alloy of tungsten, molybdenum or tantalum for long life. The self-breakdown voltage of the spark gap

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC life</td>
<td>2000 hrs.</td>
</tr>
<tr>
<td>DC insulation</td>
<td>&gt; 1000 MΩ</td>
</tr>
<tr>
<td>Dielectric insulation</td>
<td>Paper</td>
</tr>
<tr>
<td>Dielectric oil</td>
<td>Phenyl Xylylethane</td>
</tr>
</tbody>
</table>

Fig. 2.3: Schematic of spark gap switch
having gap distance 9 mm is of the order of 21 kV at normal pressure and temperature \[8\]. To hold off voltage beyond that, the pressure inside the spark gap should be increased. It is pressurized up to three atmospheric pressures so that it can hold off the required operating voltage. This spark gap is triggered by releasing the pressure inside the gap. When the pressure goes down, at a certain pressure, the air inside the gap breakdowns and the switch is closed. This spark gap can also be operated in triggered mode by introducing a third electrode in between the main electrodes. The central electrode is a common point to the high voltage end and the capacitor. The outer electrode is connected to one side of the load (PF device). On application of a high voltage pulse in this electrode, the breakdown process occurs inside the gap, which helps in discharging the capacitor.

2.2.2 Transmission lines

The transmission lines are used to transfer the electrical power from the capacitor to the load in a short time. The line should possess low inductance so that the discharge phenomena become fast enough by reducing the loss of power. Depending upon its configuration and impedance, the discharge characteristics of the capacitor changes. In our experiment, the co-axial cables which are used in the form of coaxial geometry are used to drain the power from the capacitor to the load, 34 numbers of RG-56 co-axial cables are employed. One end of the transmission lines is connected to the high voltage terminal of capacitor and other end is connected to the cathode plate of PF device.

2.2.3 High voltage capacitor charger

The main aim of the high voltage capacitor charger is to charge the capacitor to its desired level. This charger assembly includes a high voltage transformer, rectifier chain, motorized and fixed variacs, isolation transformer and connecting and shorting switches. The
The high voltage step-up transformer (label 6) provides an output rating 33kV RMS, 50mA for 230 V RMS (AC). The fixed variac (label 4) is introduced to supply the required input voltage to the transformer. Our requirement is to charge the capacitor up to 25 kV for which the variac is maintained at 166.6 V. A half wave rectifier chain (label 8) of six diodes (15 kV, 500 mA each in series) is used to convert the A.C high voltage to D.C. For our convenience the whole rectifier chain is kept inside a U shaped PVC container filled with castor oil to reduce the excess heat that are produced in diode chain and also to prevent unnecessary corona discharge with air in the diode chain during the high voltage operation. The voltage divider (labels 15 and 16) composes of six numbers of 200 MΩ resistors in series of which one terminal is connected with the high voltage point of the capacitor. The other end of the divider is grounded through another 100 kΩ resistor (label 17). The voltage drop across this 100 kΩ resistor indicates the charging voltage of the capacitor, which is monitored by a voltmeter (label 18). Voltmeter is calibrated in such a way so that required voltage can be achieved. The half voltage produced in the third electrode helps properly in the switching of the spark gap. The other end of the rectifier chain is connected to the high voltage terminal through pneumatic valve operated "connecting/isolating switch" (label 9). Another pneumatic valve operated switch named as' shorting switch" (label 14) is used to the ground the high voltage terminal of the capacitor after each discharge to drain out the stray charges. For the smooth charging of the high voltage capacitor, the voltage needs to increase gradually from zero to the desired value. Therefore, one motorized variac (label 3) is connected in the input terminal of the fixed variac, which increases the input voltage from 0 to 220 V AC within 30 s. In addition to this, the input terminal of the motorized variac is connected to an isolation transformer (1:1, 1.5 kV) (label 2) to isolate the whole system from any back emf. In order to reduce any
unwanted shorting in the circuit, a miniature circuit breaker (label 5) is placed in between the fixed variac and the HV transformer. In the present work, the third electrode is connected to the midpoint of a voltage divider, which is coupled with the “connecting switch” (label 9). When the charging voltage becomes 25 kV, the voltage at the midpoint of the divider becomes its half (12.5 kV), and so the terminal is called as half voltage point. Lastly the required voltage flows to the load (PF device) through transmission line.

Fig. 2.4: Circuit diagram of PF device
2.3 Discharge chamber

The discharge chamber employed in our experiment comprises of a co-axial electrode assembly housed inside a stainless steel (SS) vacuum chamber. The basic design of the electrode assembly the PF device is similar to reference [5]. The parameters such as the electrode length, insulator sleeve material and its effective length, the annular spaces in between the electrodes, the operating gas pressure are so chosen that the electrical power injected to the electrode assembly can efficiently be converted into the plasma energy. There are few important points to be kept in mind in designing an efficient PF device. At the time of designing the chamber, one should note that the working pressure should be optimized in such a way that a uniform and axisymmetric current sheath is formed for efficient conversion of the high energy density. In addition, the current sheath should enter into the radial compression phase at the instant, when the discharge current becomes a maximum so that large electrical energy transformed into plasma energy.

Various designs were reported earlier for efficient operation of a PF device [12-14]. Among them, the designing reported by Bernard et al. [12] seems to be best suited for a PF device. Their designing is based on the empirical relations among different parameters such as input energy, pressure, electrode length and inner electrode radius. The empirical relations are

\[
\frac{CV_0^2}{2lp} = \eta \tag{2.2}
\]

\[
\frac{CV_0}{2rlp^{1/2}} = \varepsilon \tag{2.3}
\]
Where, \( C \) the capacitance of the capacitor, \( V_0 \) the charging voltage, \( p \) the operating gas pressure, \( l \) the length of the electrode and \( r \) the radius of the inner electrode. \( \eta \) and \( \epsilon \) are two constants. In designing the PF device for best focus account are taken to the anode length, anode diameter or radius, length of the insulator, the annular space between the electrodes and pressure in order to meet right values \( \eta \) and \( \epsilon \) from the existing PF device. In some other cases Lee [13] also reported at the time of designing of the Mather type PF device, one should take care of the drive parameter in order to have a better focus performance namely \(( I_p / a ) / \rho_0^{1/2}\), where \( I_p \) is the peak current driving the plasma sheath, \( a \) the anode radius, \( \rho_0 \) ambient gas density. For our convenience we kept central electrode as anode and outer electrode as cathode. It is because electrode polarity dependence for magnetically accelerated plasma with sheared flow consistent with the observation that plasma foci generally have superior performance if the center conductor is the anode [15]. Both the electrodes are separated at the base end by an insulator sleeve made of borosil glass. Feagies et al. [16] used insulator sleeve made of glass in their experiment. They reported that the insulator surface material has played an important role in repeatable current sheath development, pinch instability and ion acceleration from discharge to discharge. Rout et al. reported that the output yield of the PF device exhibits the impurities mainly from central electrode and insulator. They studied the neutron production using insulator sleeve with different materials and among them the quartz or glass made insulator sleeve will provide the maximum yield and less impurity adhered to the insulator surface [17]. According to the requirement the annular spaces and between electrodes should be 25 mm and for a voltage of 4 kV an insulator of length 1 cm leads to symmetric and homogeneous current sheet formation around the insulator [18]. The length of the outer electrode is taken equal to the length of anode or just shorter than the anode, so that it cannot hinder to use the diagnostics. At the time of designing Mather et al. optimized the length of the outer electrode is 20-25 cm.
and inner electrode is provided with the sliding electrical seal so that length adjustment can be made for the optimization of the current sheath flight time as their convenience [19]. In our case the outer electrode is made of 12 equally spaced rods, so that it becomes transparent to gas inside and, thereby, reduces the plasma pile up near the outer electrode during the current sheath motion [20]. Mather et al. also reported that their device consists of two co-axial cylindrical electrodes and explained that the current sheath at the end of the centre electrode carries a maximum current with well defined thickness [19]. In the present setup the whole system is housed inside a stainless steel (SS) cylindrical chamber having length and diameter 24.8 and 15.2 cm, respectively. The total volume of the chamber is 6 litre. However the emission of the ion from PF device does not vary with the change of volume of the chamber as reported by Barnard et al. [12]. They reported that in their case for the neutron characterization the total chamber volume was 100 litre. By placing the target (LiD) further and further upstream in the device, they observed that the total emission did not vary very much but close to the target emission was increased. The dimensions, shape and materials of electrode assembly, insulator sleeve and vacuum chamber of our PF device are mentioned in Table 2.2. The value of $\eta$ and $\varepsilon$ are taken from an existing PF device of BARC, Mumbai. The coaxial electrode assembly consists of an anode surrounded by twelve cathode rods arranged in a squirrel cage fashion.

Table 2.2: Characteristics of the PF tube

<table>
<thead>
<tr>
<th>Components</th>
<th>Length</th>
<th>Diameter</th>
<th>Material (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode</td>
<td>115 mm</td>
<td>21 mm (O.D.)</td>
<td>Stainless steel, brass, tungsten, copper and aluminum</td>
</tr>
<tr>
<td>Cathode rod</td>
<td>110 mm</td>
<td>90 mm (O.D.)</td>
<td>Stainless steel, brass</td>
</tr>
<tr>
<td>Insulator sleeve</td>
<td>45 mm</td>
<td>21 mm (I.D.)</td>
<td>Borosil glass</td>
</tr>
<tr>
<td>Vacuum chamber</td>
<td>Volume~6 litres</td>
<td></td>
<td>Stainless steel</td>
</tr>
</tbody>
</table>
Fig. 2.5 indicates the schematic of PF device along with the central electrode which is usually a hollow cylinder made of SS. The photograph of the electrode assembly is also shown in Fig. 2.6. The outer electrode is made of twelve SS solid cylindrical rods fitted symmetrically on a SS base plate in squirrel cage fashion. Central electrode (anode) is taken as hollow cylinder instead of solid cylinder because of expecting ejection of less electrode materials due to the bombardment of electron beam on it. Thus by making so one can achieve pinch plasma column with less impurities. Since we will use ion of PF device for testing materials we need to avoid impurities in plasma column by taking hollow cylindrical shape anode [18]. The discharge chamber consists of six side ports, out of which five are used for diagnostic purpose and other one is for coupling the evacuation system.

![Schematic diagram of PF device](image_url)

**Fig. 2.5: Schematic diagram of PF device**
2.4 Vacuum pump and pressure gauges

The operating pressure regime of the PF approximately spans from 0.1-1 Torr in our experiments. Thus, a rotary pump is sufficient to evacuate the PF chamber to desired pressure level. As discussed in chapter 5 we have used our PF device for irradiation of ions on materials, therefore the evacuation of the chamber is needed to be evacuated up to $10^{-5}$ Torr base pressure level, and thus the plasma chamber gets rid of impurities by doing so. We used a rotary pump (ED-12, 200 lit/min, Hind hivac) for rough evacuation of the PF chamber. Also a 6" size diffusion pump capable of giving the vacuum of the order of
7.5x10^{-6} \text{ mm of Hg} \text{ procured from Vacuum Technique, Bangalore, is used to maintain high vacuum in PF chamber as well as drift tube assembly the pressure inside drift tube. The photograph of the diffusion pump is shown in Fig. 2.7. At the time of differential vacuum the operating pressure inside the PF chamber is monitored by a McLeod gauge and base pressure is measured by penning gauge. After attaining the base pressure, the operating gas is fed into the chamber through a needle valve, which is attached to the chamber through a side port. Basically, high purity neon as well as hydrogen gas (99.999\%) are filled inside the chamber. Generally, the PF could be operated in static as well as continuous pressure mode. The probability of formation of uniform current sheath is profound in case of static pressure mode than the later. Therefore, the device is operated in the static pressure mode for present experimentation. The refilling of gas inside chamber is maintained in such a way that in every discharge it reduces the impurities which are generated because of material erosion of the electrodes.}

**2.5 Compressed air system**

As already discussed in section 2.2.3 to run the PF device various switches like spark gap, pneumatic valves that operate as the connecting and disconnecting switches are used. In order to pressurize the spark gap and various switches, the compressed as well as filtered air is very much essential. The output pressure should be increased to three times the atmospheric pressures with the aid of an air compressor that provides the compressed air. Before allowing the compressed air to fill inside the spark gap, it is dried by passing it through a pair of polycarbonate air filter (Shavo and Norgren) and a cylindrical dehumidifier containing silica gels. Also it can help to reduce the humidity and dust as the amount dust content in the atmosphere is also very high in Assam than other places.
2.6 Control panel

It is well known that PF emits several EM radiations along with some background radiations such as noise, pileup etc which are harmful for genuine measurement. In order to avoid those unwanted radiations emitted from the PF device during the experimentation period the control panel is kept in an isolated room. The control panel containing all the switches for operation that are fitted on a board inside a grounded steel cage, positioned at a few meters away from the plasma focus set up and the sketch of control panel transformer is shown in Fig. 2.8. The control panel contains all operations like charging/discharge the capacitor, allowing compressed air to the different units, shorting the high voltage side of the capacitor to the ground etc. A voltmeter fixed on the panel directly indicates the charging voltage of the capacitor. The data recorder system such as oscilloscope is also kept at the same room in a steel wardrobe mainly to reduce the electromagnetic noises and unwanted signals. Therefore, the wardrobe is grounded properly.

2.7 Data recorder and analysis

As PF is a pulse plasma-producing device, which produces very high temperature and high-density plasma, last for a few tens of nanoseconds [2]. In case of a sinusoidal pulse having time period ‘T’, the discharge current (I) of the device may be defined as the raising time of the pulse which corresponds to one quarter of that period i.e, T/4~I. Now in order to
collect these fast signals emitted within the nanosecond scale fast response sensitive tools is essential. In this work we employed ion diagnostics like multiple Faraday cups where we need to detect data online. Moreover, some basic diagnostics like current probe and voltage probe are also used to know discharge history. In order to register those signals from FC and basic diagnostics, we have used a Yokogawa make (model DL 9240) four channels digital storage oscilloscope (DSO) with 1.5 GHz frequency bandwidth and 10 GS/sec sampling rate. According to Nyquist criteria the sampling rate is chosen would be larger than twice the largest frequency component in the analog signal [21]. The photograph of Yokogawa make (model DL 9240) four channels digital storage oscilloscope [22] is shown in Fig. 2.9. The recorded data can be stored in a storage device. Then the stored data can be transferred to a computer for necessary analysis. The analysis is being carried out by the software provided by Yokogawa. The experimental data are plotted by using Microcal origin 7.0 and Microsoft excel.

2.8 Electrical diagnostics

Some basic diagnostics are designed and fabricated to study the discharge dynamics of the PF device. One of the diagnostics is current probe and the one is resistive Voltage divider (voltage probe). Brief discussions on the both diagnostics are discussed hereafter.

2.8.1 Current probe

Current probe is used to record the total discharge current signal [1-6]. Also it is a simple, cost effective and user-friendly diagnostics. This probe [23, 24] is a potential transformer. This is made up of multi turn solenoid bent into a shape of torus. It is used to
measure the current flowing through the inner surface of the torus. The voltage produced by a current probe is given by

\[ V = \frac{AN \mu_0}{l} \frac{dl}{dt} \]  \hspace{1cm} (2.4)

Where \( A = \pi a^2 \) is the area of one of the small loops, \( N \) is the numbers of turns, and \( l = 2\pi R \) is the length of the winding ('\( R \) and '\( a \) are major and minor radius of the coil). \( \frac{dl}{dt} \) is the rate of change of current threading the loop. This formula assumes the turns are evenly spaced and that these turns are small relative to the radius of the coil itself. The output voltage is proportional to \( \frac{dl}{dt} \).

The output can be integrated by using a suitable resistance, so that the L-R circuit so formed integrates the signal. The design of a typical current probe is shown in Fig. 2.10 where it is terminated with a low inductive resistor (R) i.e. 50\( \Omega \).

The circuit equation can be written as follows:

\[ L_c \frac{dl_c}{dt} + (R + R_c)l_c = k \frac{dl}{dt} \]  \hspace{1cm} (2.5)

If \( L_c \frac{dl_c}{dt} \gg (R + R_c)l_c \), then the equation (2.5) results \( l_c = \frac{k}{L_c}l \). Therefore, the output voltage is proportional to \( l \).

\[ V = R l_c = \frac{Rk}{L_c}l \]  \hspace{1cm} (2.6)
In this case, the current probe acts as a current transformer. The simplest way to achieve this situation is to make \( \frac{L_c}{(R + R_c)} \) much larger than the current pulse duration.

On the other hand, if \( L_c \frac{dl_c}{dt} \ll (R + R_c)I_c \), then equation (2.5) gives

\[
V = Rl_c = \left( \frac{Rk}{R_c + R} \right) \frac{dl}{dt}
\]

In this case, \( \frac{L_c}{(R + R_c)} \) has to be very much smaller than the current pulse duration and the coil can be used to measure the derivative of the current (dl/dt). Due to their bare design the current probe is very sensitive to the electromagnetic noises. The simplest way to avoid such disturbances in the signal is to make use of an electromagnetic noise shielding, but this will add the distributed capacitances to the circuit, which will filter off the higher frequencies.

![Signal intensity (a.u.)](image)

**Fig. 2.11: dl/dt signal using current probe**

The current probe used in the present work is shielded by using aluminum foil. Only a small slit allowed the electromagnetic field to reach the solenoid. This probe, when used, as a current transformer is required to calibrate for absolute measurement. The PF device operated at high pressure resembles closely to a L-C-R discharge system. For known charging voltage (\( V_0 \)) and capacitance (\( C \)) the coil can be calibrated for absolute measurement from the relation [13, 25]:

46
\[ I_0 = \frac{\pi CV_0(1 + F_v)}{T} \]  

(2.8)

Where \( I_0 \) is the actual peak discharge current flowing through the circuit, \( T \) is the time period of discharge and \( F_v \) is a voltage reversal factor, which is the ratio of the voltage and can be expressed as:

\[ F_v = \frac{1}{4} \left( \frac{V_5}{V_4} + \frac{V_4}{V_3} + \frac{V_3}{V_2} + \frac{V_2}{V_1} \right) \]  

(2.9)

Where \( V_1 \) to \( V_5 \) are successive amplitudes of sinusoidal current damped waveform.

Once we know the \( F_v \) and \( T \) then we can calculate the value of current waveform \( I_1 \). Then the calibration factor (\( \delta \)) of the coil is expressed as:

\[ \delta = \frac{I_1}{V_1} \left( A/V \right) \]  

(2.10)

The current probe used in our experiments is a derivative type. The output of the probe used for the discharge current is first recorded directly as the current derivative (dI/dt) signal. A typical dI/dt signal obtained from current probe is depicted in Fig. 2.11. The dip in the negative side of the signal is directly related to the pinch compression, which is explained in chapter 1. Maximum dip in the signal is obtained for good focusing (maximum pinch compression). This variation in the dip of the signal occurs due to the rapid increase of the plasma inductance at the time of pinching.

Fig. 2.12: Discharge current waveform
The $\frac{dl}{dt}$ signal can also be integrated to give the discharge current waveform. The discharge current waveform is shown in Fig. 2.12 from where we measured the values of $f$ and $T$ and found to be 0.71 and 8.14 $\mu$s respectively. The value of the discharge current and external circuit inductance are 117 kA and 230 nH respectively.

### 2.8.2 Resistive voltage probe

The transient voltage developed across the plasma can be measured by using a simple resistive voltage divider [26]. The basic design of the voltage probes is either resistive or capacitive dividers or a combination of both. All designs have individual merits and demerits. Among them the resistive voltage is commonly used in case of frequency range (~few hundreds kHz) because of their easy design, fabrication and cost. The resistive voltage divider is connected at the lower end of the focus tube across the anode and cathode flanges.

The voltage attenuation factor ($A_v$) of this probe can be written as

$$A_v = \frac{r_s}{(r_s + R_t)}$$  \hspace{1cm} (2.11)

Where $R_t$ is the total series resistance of the chain and $r_s$ is the shunting resistance. If $r_s \ll R_t$, the equation can be written as

$$A_v = \frac{r_s}{R_t}$$  \hspace{1cm} (2.12)
The resistive voltage divider in our case attenuates the voltage signals approximately by 100 times. The output of this resistive voltage divider is connected to the oscilloscope through a $\pi$-attenuator, which attenuate the signal further by 22 times. Nevertheless, the performance of the resistive voltage probe is very much suitable for the frequent measurement of gross dynamics of the PF device. A typical discharge voltage in PF device monitored resistive voltage divider is shown in Fig. 2.13.
References


