CHAPTER 3
DIAGNOSTICS AND INSTRUMENTATION

Methods for determining the temperature, density and composition of plasmas are important in experimental plasma physics. Many types of diagnostics have been developed. Basically, there are two types of x-ray spectroscopy. One is the high resolution spectroscopy using crystal and grating. This type of spectroscopy is used to study the line widths and line ratios which give information on density and temperature. The other one is the low resolution spectroscopy using absorbing filters. This type of spectroscopy is used to measure the emission in different wavelength regions to calculate the plasma temperature.

Another type of diagnostic used frequently is x-ray imaging. Information such as the size of the plasma and the spatial origin of the x-ray emission can be obtained from x-ray images. Even information such as x-ray energy emitted from the plasma source can be obtained by using multiple apertures filtered with different absorbers.

In this thesis, the plasma x-ray emission is studied using the x-ray foil absorption technique, x-ray imaging and $dl/dt$ measurement. Also, the probable x-ray emission from the plasma is studied using a convex crystal x-ray spectrometer.

3.1: Measurement of the $dl/dt$ signal

The electrical current from the discharge of the vacuum spark is both large and rapidly varying. This results in rapidly varying magnetic field. A magnetic
probe placed near the system can be used to measure the current due to this varying magnetic field.

The probe used in this work consists of a single-layer coil of 10 turns 0.0813 mm enamelled copper wire wound on a PVC wire sleeve. The average diameter of the coil is 1.25 mm. The leads from the coil are twisted together and inserted in a glass tube with the terminating ends of the leads soldered to a BNC connector. The glass tube and the BNC connector are then glued. The whole assembly is inserted in a brass tube and placed radially in the space below the earth return plate. This is illustrated in Figure 3.1.

The azimuthal magnetic field generated by the discharge is picked-up by the coil. The voltage induced in the coil, which is fed into an oscilloscope, is proportional to the rate of change of current. From the $dl/dt$ signal, the period of oscillation is 1.84 $\mu$s, giving the frequency of discharge as $3.408 \times 10^6$ rad s$^{-1}$. Therefore, the calculated loop inductance and resistance are approximately 46.5 nH and 17.3 m$\Omega$, respectively. The current peak is calculated to be about 126 kA and the calibration constant for the probe is $2.2 \times 10^{10}$ A/s/V.

3.2: PIN diode as an x-ray detector

X-ray PIN diodes are used for the detection of hard x-ray from the UMVS. It has fast response and high sensitivity which makes it suitable for measurements of pulsed radiation between 1 and 20 keV [van Paasen, 1971]. A PIN diode consists of a layer of $n$ type silicon separated from a $p$ type silicon by an intrinsic silicon [Corallo et al., 1980]. The $n$-layer is maintained at ground
Fig. 3.1: The schematic diagram showing the mounting of magnetic probe.
potential and is called the 'dead layer'. The entrance window of the diode is the \( n \)-layer. Figure 3.2 shows the biasing circuit used to bias the \( p \)-layer at negative potential.

Quantrad model 100-PIN-250 with the following specifications is used

\[ \text{Quantrad Corporation, L. A., C. A., U. S. A.} \]

- Thickness of Si entrance window \( = 0.8 \text{ \( \mu \)m} \);
- Depletion depth of intrinsic layer \( = 250 \text{ \( \mu \)m at reverse biased voltage of -300 V} \);
- Effective area of detection \( = 100 \text{ mm}^2 \);
- Saturation occurs when output current \( = 2 \text{ A} \);
- Rise time \( = 2 \text{ ns (factory tested)} \).

The sensitivity, \( S(\lambda) \), of the PIN diode is described by a two-thickness model and is expressed as \[ \text{Corallo et. al., 1980} \] :

\[
S(\lambda) = 0.282 e^{-\mu_{ti}} (1 - e^{-\mu_{ti}}) \quad A/W
\]  

(3.1)

where the first exponential term is the transmission through the \( n \)-type dead layer and the second exponential term in brackets is the absorption in the intrinsic layer. The constant 0.282 is the coulomb of charge generated for each joule of x-rays absorbed. This is the reciprocal of the average energy needed to form an electron-hole pair which is 3.55 eV \[ \text{Siegbahn, 1966} \]. Figure 3.3 shows the calculated sensitivity. The \( K \)-absorption edge of silicon is represented by the singularity at about 6.7 Å.
Fig. 3.2: The biasing circuit for PIN diode.
Fig. 3.3: The sensitivity curve for PIN diode.
3.3: Soft x-ray detector

A common detector for soft x-ray is the x-ray diode (XRD). An x-ray diode consists of an x-ray sensitive photo-cathode and an anode. The photo-cathode acts as a transducer to convert x-ray photons into photo-electrons which are accelerated to the anode under the influence of an applied electric field. This produces a current which depends on the x-ray flux and is recorded by an oscilloscope. Thus, the output of the oscilloscope gives information on the x-ray flux.

In this project, the XRD used, consists of a thick aluminium as photo-cathode and a brass wire mesh anode that is transparent to the radiation. The bi-planar XRD with the biasing circuit is shown schematically in Figure 3.4. A 2.5 μm aluminized mylar foil was used as filter.

The spectral sensitivity of the XRD used in this work is shown in Figure 3.5. This figure shows that at higher energies the response of the diode decreases. This is because the higher energy x-rays are absorbed at depths where the electrons cannot be extracted. On the other hand, the work function of the cathode material would produce a lower limit for the sensitivity of the aluminium photo-cathode. From the output of the XRD, the temporal evolution of the soft component of the x-ray emitted by the plasma can be deduced.
Fig. 3.4: The schematic diagram of the biasing circuit for the bi-planar XRD.
Fig. 3.5: The response curve for an aluminium photo-cathode XRD filtered with 2.5 μm aluminized mylar.
3.4: X-ray imaging

3.4.1: X-ray pinhole camera

X-ray pinhole images give spatial information on the origin of the x-ray emission. However, the size of the pinhole limits the spatial resolution. The image recorded on the film depends on the size of the source with respect to the pinhole size. A source smaller than the pinhole would produce an image of the pinhole. For a source smaller than the pinhole but still finite in size, a penumbra would be formed around the pinhole image and a source very much larger than the pinhole would produce a magnified image. These are shown in Figure 3.6.

The pinhole camera used is shown in Figure 3.7. It is a single pinhole camera with pinhole size of 300 μm and magnification of 1.0. The pinhole camera is isolated from the vacuum chamber by a pinhole filtered with either a 12 μm or 24 μm aluminized mylar which also acts as a visible light filter. The transmission curves of these filters are shown in Figure 3.8. Since the x-rays reaching the film traverse a few centimetres of air and the foil, the response of the pinhole camera can be taken to be below 5 Å.

A maximum of six discharges can be recorded on a single film. After every discharge, the film is turned 60° so that the image from the next discharge is recorded at a new position. Kodak DEF film is used to record the images.
Fig. 3.6: X-ray pinhole imaging.
Fig. 3.7: The schematic diagram of the pinhole camera.
Fig. 3.8: The transmission curves for aluminized mylar foils of 12 μm and 24 μm.
3.4.2 : X-ray slit-wire camera

The hot spot size is estimated using a newly developed slit-wire camera which is a derivative of the classical filtered x-ray pinhole camera [Dumitrescu-Zoita & Choi] [Choi et. al., 1994]. This camera uses slits instead of pinholes as apertures. The widths of the slits are tens of μm with lengths proportional to the size of the camera. The use of slits instead of pinholes increases the solid angle along the plane of the slits which subsequently increases the number of photons reaching the film. Therefore, the detection of very small and weak hot spots are enhanced and allows the determination of the size of these spots.

The slits, which are orientated orthogonally to the axis of the plasma column, acts as a 1-D imaging aperture to provide spatial resolution in the axial direction. To study different energy regions, the slits are separately filtered. Also, the slits have to be sufficiently far apart so that the images of the plasma column do not overlap.

A number of thin wires, which are opaque to the radiation of the emitting source, are mounted across the slits. These wires act as an obstacle rather than as an aperture to provide spatial resolution along the radial dimension of the plasma. The diameters of the wires range from a few μm to 100's of μm. Both the wires and the filters are mounted on the same side as the x-ray film.

A typical image of a slit with wires across them is shown in Figure 3.9(i). By scanning the image using a microdensitometer, the different densities of the slit image are obtained. The microdensitogram for the image in Figure 3.9(i) is shown in Figure 3.9(ii). The dips in the microdensitogram corresponds to the part of the
Fig. 3.9: (i) A typical image from the slit-wire camera. (Shot #9501010: PH 23, #2) (ii) The microdensitogram of the image.
hot spot obscured by the wires.

The size of the hot spots are determined by using the following relation:

\[
\frac{\phi_1}{\phi_o} = 1 - \frac{d}{x} \left(1 + \frac{1}{m}\right)
\]  

(3.2)

where \(\phi_o\) is the total number of photons falling on the film through the slit, \(\phi_1\) is the number of photons falling on the film minus the amount obstructed by a wire with diameter \(d\), \(x\) is the size of the hot spot and \(m\) is the magnification of the camera. \(\phi_o\) is given by:

\[
\phi_o = \int_{x_1}^{x_2} f(x) \, dx
\]  

(3.3)

while \(\phi_1\) is given by:

\[
\phi_1 = \int_{x_1}^{x_2} f(x) \, dx - \int_{x_a}^{x_b} f(x) \, dx
\]  

(3.4)

In these integrals, \(x_1\) and \(x_2\) represents the beginning and end of the hot spot dimension in the considered \(x\)-dimension, while \(x_a\) and \(x_b\) represent the beginning and end of the part of the 'hot spot' which is obscured by the wire. This is illustrated in Figure 3.10.

Assuming in the first approximation that the source is emitting uniformly and considering the ray tracing geometry, equation (3.2) is obtained. Using this method, the size of the hot spot is estimated. The errors in this technique are mainly due to (i) the variation in the slit width which leads to variation on the
Fig. 3.10: A geometrical representation of the contribution from different regions of hot spot to the total number of photons falling on the film.
number of photons hitting the film, therefore, giving a background intensity which is not constant; and (ii) the 'trembling' of the microdensitometer pen as a result of grain noise on the film emulsion.

In this work, a ~500 μm wide single slit filtered with 36 μm aluminized mylar is used. The wires used are 98 μm (Ni), 50 μm (W), 25 μm (W), 18 μm (W) and 10 μm (W). The slit-wire camera's magnification is 1.4375.

3.5: Convex crystal x-ray spectrometer

A compact convex crystal x-ray spectrometer [Ong & Wong, 1991] is used to study the x-ray spectrum. Moderate quality mica sheets obtained from power transistor insulators are used as the crystal since only a preliminary scan of the probable x-ray spectrum is carried out.

In Figure 3.11 the schematic diagram of the spectrometer is shown. The smaller cylinder A is covered with the mica sheet and slotted into the slot of cylinder B. An x-ray diagnostic film which is placed on top of cylinder B will be exposed to the diffracted x-ray. Spectral lines recorded on the film can be identified by considering the geometrical setup of the spectrometer which is shown in Figure 3.12. From Bragg's relation,

\[ d \sin \theta = n\lambda \]  (3.5)

where \( \theta \) is the Bragg's angle for the diffracted x-ray with wavelength, \( \lambda \), \( d \) is the crystal constant and \( n \) is the order of Bragg's diffraction. The circle in Figure 3.12 is the circular cross section of cylinder A and is in the same vertical plane.
Fig. 3.11: The schematic diagram of the mica x-ray spectrometer.
Fig. 3.12: The geometry of the spectrometer. For the present setup, 
\[ D = 165.6 \, \text{mm}, \quad R = 7 \, \text{mm}, \quad W = 146 \, \text{mm}, \quad H = 18 \, \text{mm} \] and \[ A = 0 \, \text{mm}. \]
as the x-ray source. The position of a spectral line on the x-ray film is indicated by \( X \) and the relation between \( X \) and \( \lambda \) is given by

\[
X = D - R - W - [H - R(1 + \sin \alpha)] \times \tan[\sin^{-1}(n\lambda/2d) - \alpha] + 2R\sin^2(\alpha/2) \tag{3.6}
\]

where \( D, R, W \) and \( H \) are given in Figure 3.12. For calculation of \( \alpha \), the following equation is used

\[
\alpha = \cos^{-1}\left[ \frac{R}{2d} \left( \frac{4d^2 - n^2\lambda^2}{A^2 + D^2} \right)^{1/2} \right] - \sin^{-1}\left( \frac{n\lambda}{2d} \right) - \tan^{-1}\left( \frac{A}{D} \right) \tag{3.7}
\]

In the present setup, \( D = 165.6 \text{ mm} \), \( R = 7 \text{ mm} \), \( W = 146 \text{ mm} \), \( H = 18 \text{ mm} \) and \( A = 0 \text{ mm} \). Using equations (3.6) and (3.7), a plot of \( X \) versus \( \alpha \) is obtained. The wavelength, \( \lambda \), corresponding to a spectral line at position \( X \) can be inferred from this graph, which is shown in Figure 3.13.

Since the intensity of the diffracted x-ray is low, multiple shots are required to observe the spectral lines. This would introduce errors in the interpretation of the lines because the position of the x-ray source is not fixed due to shot to shot variation. In addition, the overlapping of several orders of spectral lines would also introduce some errors in the estimate. However, the spectrum obtained still yields some information on the emission spectrum.

\[3.6: \text{x-ray transmission}\]

The x-ray filter transmissions are calculated using the mass absorption coefficients from the literature and extrapolated values from mass absorption
Fig. 3.13: The graph of $X$ versus $\alpha$. 
curves. The absolute transmission is then calculated using equation

$$T(\lambda) = \exp[-\mu(\lambda) \rho \, \ell]$$  \hspace{1cm} (3.8)

where $T(\lambda)$ is the transmission as a function of wavelength, $\mu(\lambda)$ is the mass absorption coefficient at $\lambda$ in $\text{cm}^2/\text{g}$, $\rho$ is the mass density in $\text{g/cm}^3$ and $\ell$ is the filter thickness in $\text{cm}$. The transmission of composite filters is calculated by taking the product of their separate transmissions.

### 3.7: Plasma x-ray emission

For a plasma source at a distance of $d$, the intensity detected by the PIN diode is given by

$$I = \frac{A}{4\pi d^2} \int_{0}^{\infty} P(\lambda) \, S(\lambda) \, T(\lambda) \, d\lambda \hspace{1cm} \text{A/cm}^3$$  \hspace{1cm} (3.9)

where $P(\lambda)$ is the rate of energy emission per unit volume per unit wavelength, $S(\lambda)$ is the sensitivity of the PIN diode, $T(\lambda)$ is the transmission of x-ray through filters and $A$ is the effective area of detection of the PIN diode. The emission of x-ray from plasma is through three processes which are:

1) **Bremsstrahlung or free-free transition.**

These are continuous radiation emitted by charged particles mainly the electrons as a result of deflection by the Coulomb fields of other charged particles. For electron temperature, $T_e$, less than 50 keV, the bremsstrahlung from
a plasma arises almost entirely from electron-ion interactions. The contribution of electron-electron collisions is significant only at high temperatures. This is found by comparing the ratio of electron-electron bremsstrahlung energy to that for electron-ion interactions which is estimated to be 0.06 at $T_e = 25$ keV, 0.13 at $T_e = 50$ keV and 0.34 at $T_e = 100$ keV [Wandel et al., 1959] [Post, 1959]. Since the electron is free before its encounter with an ion and remains free subsequently, the transitions are often described as 'free-free'. The rate of energy emission per unit wavelength is given by

$$P_{\nu}(\lambda) = 1.9 \times 10^{-28} \left[ \frac{n_e \sum n_i Z_i^2}{T_e^{1/2} \lambda^2} \right] \exp\left(\frac{-12431}{\lambda T_e}\right) \text{ W/cm}^2/\lambda$$  \hspace{1cm} (3.10)

where $n_e$ is the electron density in cm$^{-3}$, $n_i$ is the ion density in cm$^{-3}$, $Z_i$ is the effective nuclear charge, $T_e$ is the electron temperature in eV and $\lambda$ is the wavelength in Å. The spectrum peaks at $\lambda = 6200/T_e$ Å.

ii) Recombination or free-bound transition.

The capture of free electrons into a bound state of an ion, with the accompanying emission of radiation of energy $h\nu = mp^2/2 + \chi_n$, produces a continuous spectrum of radiation for $h\nu > \chi_n$. This results in a discontinuity (called recombination edge) in the free-bound spectrum.

The rate of energy emission per unit wavelength from recombination into the $n$th shell of a hydrogen-like ion of charge $Z_i - 1$ is given by
\[ P_{\beta}(\lambda) = 2.6 \times 10^{-27} \frac{n_i n_l^2 \varepsilon \sum (\tau_{\beta}/n)^{3/2} \exp (Z_{i}^{2} n_{l}^{2} n \lambda^{2} T_{e}^{3/2})}{T_{e}^{3/2} \lambda^{2}} \exp \left( - \frac{12431}{\lambda T_{e}} \right) \]  \( (3.11) \)

where \( Z \) is the effective charge number of the ions in final state, \( n_i \) is the recombining ion number density (with charge \( Z_i + 1 \)), \( n \) is the principal quantum number, \( \tau_{\beta} \) is the number of places in the \( n \)th shell which can be occupied by the captured electron, \( \chi_{II} \) is the hydrogen ionization potential (13.6 eV). This equation applies for \( \lambda < \lambda_{c} \) where \( \lambda_{c} \) is the recombination edge given by the following equation

\[ \lambda_{c} = \frac{12431}{(Z^2/n^2)\chi_H} \]  \( \AA \)  \( (3.12) \)

iii) **Characteristic line radiation or bound-bound transition.**

Absorption of energy can result in the formation of an electronically excited state. The excitation energy will subsequently be emitted as line radiation, called excitation radiation. Since the excited electron remains attached to the atom at all times, the transition leading to the emission of energy is referred to as 'bound-bound'. Assuming an optically thin plasma in a steady state coronal equilibrium condition, the rate of energy emission per unit volume for line radiation at a particular wavelength, \( \lambda_{o} \), due to ionic species \( i \) are given by \([McWhirter, 1965]::

\[ P_{i} = C_{nm} \frac{n_{n}^{2}}{T_{e}^{1/2}} \exp \left( - \frac{E_{u}}{kT_{e}} \right) \text{ W/cm}^3 \]  \( (3.13) \)

where \( E_{u} \) is the energy of the upper state of the ion, \( C_{nm} \) is a coefficient which
depends on the Gaunt factor, oscillator strength and transition energy of state from \( n \) to \( m \) and \( n \) to ground state.

In this thesis, it is assumed that the emitted spectrum is almost purely bremsstrahlung. Therefore, the absolute intensity and the spectral shape of the spectrum can be calculated exactly. The relative values of \( P_{\text{fr}}(\lambda) \) obtained from equation (3.10), for arbitrary electron and ion densities, have been plotted as a function of wavelength for electron temperatures of 1, 5 and 10 keV. These are shown in Figures 3.14 to 3.16. The emission spectrum detected by each PIN diode is also plotted on the same axes.

The electron temperature is estimated by using the two-foil absorption technique which is described in Chapter 5, while the volume and lifetime of the plasma are estimated from the slit-wire image and the hard x-ray signals recorded by the oscilloscope, respectively. For estimation of the effective nuclear charge, \( Z_{\text{eff}} \), an ionisation model is required. There are three models which are (i) Local Thermodynamic Equilibrium, (ii) Coronal Equilibrium and (iii) Collisional Radiative Equilibrium. The corona model is used for the condition of the vacuum spark plasma in this project. This is also described in Chapter 5. Using these values and the absolute measurement of the PIN diode(s), the electron density is estimated.
Fig. 3.14: Bremsstrahlung spectra and the spectrum detected by the PIN diodes for electron temperature of 1 keV.
Fig. 3.15: Bremsstrahlung spectra and the spectrum detected by the PIN diodes for electron temperature of 5 keV.
Fig. 3.16: Bremsstrahlung spectra and the spectrum detected by the PIN diodes for electron temperature of 10 keV.