Chapter 5

Influence of electron beam on plasma parameters and sheath in dc discharge plasma

5.1 Introduction

Low pressure, high-density direct current cold plasma sources have recently attracted increased interest for its applications in plasma-based technologies. The plasma parameters and the sheath conditions determine the processing performance. The electron energy distribution function is of fundamental importance in gas discharges since the excitation and ionization of gas atoms is, to a large part, caused by electrons [Li et al 1999b, Gudmundsson 2001, Bazhenov et al 2001, Matveyev and Silakov 2001]. In case of non-equilibrium electrical discharges, special attention has been paid to study the electron energy distribution function since electron heating in a steady electric field and electron collisions with heavy particles accompanied by energy transfer cause the main primary mechanism of energy input into the discharge plasma. The behaviour of high-energy

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section of the distribution function is very sensitive to the variations of the whole set of
cross-sections of the processes of electron interaction with heavy particles. Normally,
electrons in dc discharge plasma show a Maxwellian energy distribution. In some
discharges, plasma electrons have two separate energy distributions [Sheridan et al 1991].
In many cases the electrons in a discharge are not in equilibrium whereas the Maxwellian
distribution applies to an assembly of particles in complete thermal equilibrium. The
Druyvesteyn energy distribution can be used as an approximation for the electron energy
distribution that is depleted at high energy, which corresponds to many laboratory cold
plasma discharges. In a recent theoretical study by Gudmundsson (2001) shows that the
effective electron temperature increases and the electron density decreases as the electron
energy distribution is varied from being Maxwellian to become Druyvesteyn like and the
sheath voltage decreases at low pressures (< 2 mTorr) for similar changes in the
distribution function, but the sheath voltage is found to increase for higher pressure.

The energetic electrons injected into plasma from an auxiliary source, play a
significant role in modifying the ion and electron energy distribution functions and the
electron energy distribution function alters the structure and behaviour of the plasma
boundary, which in turn influences the ion dynamics inside the sheath. Another important
area for study of the beam plasma interaction is to optimize the parameters in plasma
processing e.g. controlling the ion bombardment characteristics. Recently, theoretical
investigations have been made to determine the sheath edge behavior in discharges
containing mono-energetic beam electrons with finite temperature [Takamura 1988,
Ingram and Braithwaite 1990]. Considering that the beam distribution is a drifting
Maxwellian, Bradley and Amemiya (1994) has found out that the influence of an electron beam temperature on the sheath-edge behaviour is not very significant except in the case when the beam temperature is very much larger than the thermal electron temperature. It was also predicted that the floating potential increases from the usual value as the beam density ratio increases and tends to a value above the potential equivalent of the beam energy. Theory has also been extended to determine the sheath edge behavior in complex discharges such as multi-component plasmas with negative ions containing an electron beam [Amemiya 1995], where it has been found that at a constant negative ion density ratio, the sheath edge potential and the positive ion flux increase with the relative electron beam density. It has also been found from that study that the floating potential of an insulating substrate varies with the relative electron beam and negative ion densities in plasma for a wide range. Studies on electron beam excited plasma discharges reveal that the thermal electron beam component has a significant role in determining the process conditions [Ryoji et al 1992, Bradley and Kato 1993, Hamagaki and Hara 1994]. In an experiment by Griskey and Stenzel (1999), the effect of a 200 eV electron beam incident on an electrode and the secondary-electron-emission instability in unmagnetised dc discharge plasma has been investigated. The electron beam provides the free energy for such instability. The relation between the sheath potential and the electron energy distribution function in an electron beam excited plasma has been determined by Miyano et al (1996), where the measured sheath potentials are compared with those calculated using a theoretical current balance equation and found that the profile of the sheath potential depends on the beam potential at the sheath edge in the plasma.
In this chapter, the production of an electron beam in a double plasma device and its influence on the plasma parameters and sheath characteristics has been discussed. When a low energy electron beam ($E_b = 10 \cdot 50$ eV) is injected into the target section, the density as well as the positive ion fluxes into the sheath formed in front of a negatively biased plate increases. As a result, sheath contraction takes place. It is also observed that the floating potential of the plate can be controlled with the help of an electron beam.

5.2 Experimental set up and procedure:

The experiment is carried out in a double plasma device equipped with multi-pole magnets for surface plasma confinement [Sarma 1996]. A schematic diagram of the experimental set up is shown in Fig. 5.1(a). The chamber consists of two identical cylindrical cage structures, which are made up of vacuum-sealed rectangular tubes containing small permanent magnets. The tubes are arranged in a cage structure (25 cm in diameter and 40 cm in length) with alternating magnetic pole orientation. The device is divided into source and target sections by placing two stainless steel mesh grids ($G_1$ & $G_2$) 0.5 cm apart. The base pressure of the chamber is $2 \times 10^{-5}$ Torr. Source and target plasmas are produced independently by electron bombardment of a neutral gas (Ar at $3 \times 10^{-4}$ Torr) applying dc voltage between hot cathode filaments and magnetic cages. The discharge voltage is kept at 70 V. The discharge current is controlled in the range $50 \sim 150$ mA in each section. The plasma parameters measured with a plane Langmuir probe (molybdenum disc) of 5 mm diameter are: electron density $n_e \sim 10^8-10^9$ cm$^{-3}$ and electron temperature $T_e \sim 1.5$ eV. The temperature of the ions measured with a retarding potential analyzer is nearly equal to $T_e/10$. 

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FIG. 5.1: (a) Schematic diagram of the experimental set up. S-source plasma, T-target plasma, E-emissive probe, F-Filament, L_1 & L_2-Langmuir probes, G_1 & G_2-mesh grids, P-SS plate, V, \( V_s \)-source bias voltage, \( A \)-Ammeter. (b) Scheme of the potentials at source and target plasma for the electron beam generation. \( \phi_p \)-plasma potential, \( V_s \)-source bias with respect to the grounded target.
In order to produce an electron beam, the target plasma potential is maintained positive with respect to the source plasma potential. To achieve this, the target anode and grid $G_2$ are grounded while the source anode and the grid $G_1$ are biased negatively. A schematic diagram of the potential structure in the plasma system is shown in Fig. 5.1(b). The electron beam energy $E_b$ is controlled by varying the source biasing voltage $V_s$ with respect to the grounded target. The electron beam density $n_b$ is varied by adjusting the discharge current. In this experiment, typical discharge currents are 60 mA and 100 mA in the source and the target plasma respectively.

The electron beam flowing from the source to the target plasma is detected by using a pair of disc-type Langmuir probes. The Langmuir probes consist of two identical molybdenum discs of 5 mm diameter glued back to back by a thin (~1.5 mm thickness) layer of ceramic paste. The probes are kept insulated from each other. The set of probes is placed in the target plasma in such a way that one probe faces ($L_1$ in Fig. 5.1(a)) the source plasma i.e. perpendicular to beam flow while the other ($L_2$) faces the opposite direction. Each of the probes has a separate electrical connection and voltage sweep arrangement to draw the $I-V$ characteristics. Differentiating the $I-V$ characteristics, the electron distributions are obtained. The distribution of the background plasma electrons is obtained from the probe $L_2$ while the combined distribution of the background plasma electrons and the beam is obtained from the probe $L_1$. By subtracting the background distribution from the combined beam and background distribution, the electron distribution in the beam is obtained.

A stainless steel plate of 4cm in diameter is placed in the target section facing the source plasma and hence the electron beam. The backside of the plate is covered with
ceramic paste. An ion rich sheath is formed in front of the plate when the plate is biased at a negative potential. The electron beam is allowed to flow towards the plate and the effect of this beam on the ion sheath is investigated.

An emissive probe is used to measure the axial potential profile in front of the plate. The emissive probe (diameter 0.005 cm and length 0.3 cm) is made up of 1% thoriated tungsten filament. A motor driving system is used to move the probe axially. The floating point of a strongly emitting probe technique \cite{Kemp and Sellen Jr. 1966, Hassal and Allen 1997} is used to determine the plasma potential $\phi_p$ spatially along the axial direction towards the plate. The resistance used with the probe for floating potential measurement is 11 MΩ and the measured value of the floating potential is calibrated accordingly. The inflection point technique \cite{Smith et al 1979} has also been employed to confirm the validity of the floating-point method and the difference in plasma potential measurement is found to be nearly 0.3 V between the two techniques.

5.3 Probe response in plasma with drifting Maxwellian electrons:

The plasma under consideration consists of beam electrons (density $n_b$ and temperature $T_b$) along with the thermal plasma electrons (density $n_e$ and temperature $T_e$). In the target section of the double plasma device, the beam electron energy distribution is supposed to be drifted Maxwellian (since a negative potential $V_s$ is applied to the source anode with respect to the target to maintain electron drift into the target plasma). The electron drift energy $E_b$ (defined as $E_b = m_e v_b^2/2$, where $v_b$ is the beam electron speed) is much larger than $T_e$. The plane Langmuir probe is mounted perpendicular to the electron
FIG. 5.2: Ideal probe current $I_p$ versus probe bias voltage $V_b$ using equation (1). Contribution of electron beam ($T_b=0.03$ eV, $E_b=20T_e$ and $n_b/n_e=0.10$), bulk plasma electrons ($T_e=1$ eV) and ion current into the probe are considered. The first derivative $dI_p/dV_b$ versus $V_b$ is also shown.

$T_e = 1 \text{ eV}$
$T_b = 0.03 \text{ eV}$
$E_b = 20T_e$
$n_b/n_e = 0.10$
beam flow and at any bias voltage \( V_b \), the current to the probe \( I_p \) is represented by [Auciello and Flamm 1989]

\[
I_p = I_c + I_b - I_{i0} \tag{5.1}
\]

In equation (1)

\[
I_e = \frac{1}{4} e n_e \exp \left\{ - \frac{m_e v_{\text{min}}^2}{2kT_e} \right\} \tag{5.2}
\]

and

\[
I_b = e n_b \sqrt{\frac{T_b}{2\pi m_e}} \exp(-x_m^2) + \frac{e n_b v_b}{2} \left[ 1 + \text{erf} (x_m) \right] \tag{5.3}
\]

are the contributions of the plasma electrons and beam electrons respectively, where

\[
\text{erf}(x_m) = \frac{2}{\pi} \left[ \exp(-x^2) \right]_{0}^{x_m} \tag{5.4}
\]

\[
x_m = \sqrt{\frac{m_e}{2T_e}} [v_b - v_{\text{min}}] \tag{5.5}
\]

and

\[
v_{\text{min}} = \sqrt{\frac{2e}{m_e} \left( \phi_p - V_b \right)} \quad (\phi_p \text{ is the plasma potential}) \tag{5.6}
\]

The third term of equation (1)

\[
I_{i0} = \frac{1}{4} e n_e \sqrt{\frac{kT_e}{m_i}} \tag{5.7}
\]

is the positive ion current to the probe due to the plasma ions.
The prediction of equation (5.1) for an ideal situation where plasma consists of electron beam (with energy $E_b = 20\ T_e$) in addition to bulk plasma electrons (with temperature $T_e = 1\ eV$), is shown in Fig. 5.2. The beam to thermal electron density ratio ($n_b/n_e$) is considered to be 0.10 and temperature $T_b$ is considered to be 0.03 eV. It is found that two knee-like structures are present in the current-voltage characteristics, with the one on the right corresponding to the plasma potential $\phi_p$. It is noted that the second knee, which appears on the left, resembles an electron species at a potential close to $[\phi_p - (E_b/e)]$. It is apparent from equation (5.1) that in the case of one-dimensional beam the first derivative $dI_p/dV_b$ (as shown in Fig. 5.2) is proportional to the electron distribution function.

5.4 Experimental Results and Discussion:

5.4.1 Detection of electron beam by Langmuir probe and measurement of beam density and energy:

The plane Langmuir probe $L_2$ does not collect the electron beams directly, so it gives the information about the plasma electrons only. Typical $I-V$ characteristics for different source-biasing voltages $V_s$ (0 V to -50 V) obtained by the probe ($L_2$) are shown in Fig. 5.3. The discharge current is kept at 60 mA and 100 mA in the source and the target plasma respectively. It is found that the electron saturation current increases with higher negative value of $V_s$ (i.e. with increasing beam energy). Since the probe $L_2$ is not facing the electron beam and therefore, the increment in electron saturation current is mainly due to
FIG. 5.3: Measured I-V characteristics drawn by the probe L₂ (not facing the electron beam) at different source biasing voltages $V_s = 0 \text{ V (no beam)}, -10 \text{ V}, -20 \text{ V}, -30 \text{ V}, -40 \text{ V} \text{ and } -50 \text{ V}$ for curves (a) – (f), respectively. Source and target discharge current are 60 mA and 100 mA respectively.
the enhanced ionization caused by the electron beam in the target chamber. The response of the probe $L_1$ that is facing the beam is similar for the electron saturation current increment but higher than that of $L_2$ by nearly 2%. The difference in the ion saturation current measured by the probes is clearly seen in presence of the electron beam. Examples of $I-V$ characteristics drawn by the probe $L_1$ are shown in Fig. 5.4 for different source biasing voltages $V_s$. Only the negative bias region of the $I-V$ characteristics is drawn with proper amplification to monitor the electron beam contribution. A knee is observed in the probe current (of $L_1$) signifying the presence of the electron beam at a probe bias voltage $V_b$ corresponding to the electron beam energy (determined by applied $V_s$). The measured $I-V$ characteristics showing the existence of an electron beam with a knee in the ion saturation current (Fig. 5.4), are similar to the theoretical curve (Fig. 5.2). The knee does not appear in the $I-V$ characteristics drawn by the probe $L_2$ (Fig. 5.3) because the electron beam is not coming into this probe. The electron beam density $n_b$ at particular $V_s$ is calculated from the difference in ion saturation current at the knee obtained from $I-V$ characteristics of probes $L_1$ and $L_2$. The electron beam distributions are obtained by subtracting the first differentials of the $I-V$ characteristics of $L_2$ from that of $L_1$ and are shown in Fig. 5.5(a) for different $V_s$. The set of probes are placed at the center of the target plasma and at an axial distance of 5 cm away from the grid $G_2$.

5.4.2 Beam temperature measurement:

It is observed that when source bias $V_s$ is made sufficiently negative, the electron drift into the target forms an energetic electron component in the tail of the Maxwellian distribution
FIG. 5.4: I-V characteristics drawn by the Langmuir probe $L_t$ (facing the electron beam) for different source biasing voltages $V_s$. Only the probe current for negative probe bias region (-10 V to -80 V) drawn with proper amplification to detect the electron beam are shown.
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FIG. 5.5: (a) Difference of first differentials of the measured I-V characteristics of probes (L₁ and L₂) representing the electron beam distributions at various source biasing voltages $V_s$. The beam energy $E_b$ is marked by the dashed line for each curve. (b) Radial profile of the measured electron beam distributions for $E_b = 20 \text{ eV}$
FIG. 5.6: Measured variation of beam current $I_b$ and $N_b (= I_b/E_0^{1/2}$ in an arbitrary scale) for different source bias voltages $V_s (0 \sim -50 V)$
and possesses separate distribution with a bump on the tail. The beam energy $E_b$ is obtained from the difference between the peaks of the Maxwellian electron distribution (which appears at plasma potential) and the beam distribution. It is found that the beam energy $E_b$ is almost equal to the applied source biasing voltage $|V_s|$ as shown in Fig. 5.5(a) by the dashed vertical lines. The spread in the beam energy $\Delta E_b$ corresponds to the half width of the energy distribution at e$^{-1}$ point. As seen from Fig. 5.5(a), the height of the distribution decreases and the spread in the beam energy increases with the increase of source biasing voltage $|V_s|$. Assuming that the beam velocity $v_b$ is much greater than the beam thermal spread in velocity $(2\Delta E_b/m_e)_{1/2}$, the beam temperature ($T_b$) is defined as

$$T_b = \left( \frac{\Delta E_b}{4 E_b} \right)^{\frac{1}{2}}$$  \hspace{1cm} (5.8)$$

Beam temperature measured from energy distributions for different $V_s$ are much lower than the beam energy spreads ($\Delta E_b$). Typical electron beam energy distributions measured for $V_s = -20$ V, -30 V, -40 V and -50 V indicate that the beam density $n_b$ and the temperature $T_b$ decrease with increasing beam energy $E_b$. The beam distribution functions are measured at different axial distances (1.5 cm to 13.5 cm) and shown in Fig. 5.5(b). It is found that the beam propagates efficiently in the axial direction. Furthermore, it is found that the beam energy spread increases, which is due to various types of instabilities [Yatsuzuka 1975, Dodo 1990].
FIG. 5.7: Measured variation of beam current $I_b$ with increasing source discharge current $I_{ds}$ at $V_s = -30$ V. The target discharge current $I_d$ is fixed at 100 mA.
5.4.3 Variation of beam percentage with source bias and discharge current:

The variation of the electron beam current $I_b$ with $V_s$ is shown in Fig. 5.6. It is found that the beam current initially increases rapidly but at higher beam energies, the increase is slow. We calculate a factor $N_b = I_b/E_b^{1/2}$ (where the beam energy $E_b$ is obtained from the differentiated curves of Langmuir probe $I-V$ characteristics (Fig. 5.5), at different source bias $V_s$ which is also presented in Fig. 5.6. The factor $N_b$ gives the indication of the beam density in an arbitrary scale. $N_b$ is found to increase with increasing beam energy (up to $V_s \sim -20$ V), and then it slowly decreases if the beam energy is further increased. As it is clear from this figure that the beam current tends to saturate at higher beam energies, hence the reduction of $N_b$ at higher beam energies is due to the conservation of beam flux.

Fig. 5.7 shows a typical curve representing the variation of beam current with the discharge current of the source for a particular source bias $V_s = -30$ V. It is found that by changing the discharge current of the source while keeping the target discharge current fixed at 100 mA, the beam current and hence the beam density can be controlled. The increase of the beam current with the discharge current of the source is due to the fact that with increasing the discharge current, the plasma density of the source increases and hence the electron flux coming from the source at a particular source bias also increases.

5.4.4 Variation of plasma density and temperature with electron beam:

The variation of plasma electron density with the source bias voltage ($V_s$) measured at the target plasma is represented in Fig. 5.8. It is evident that the electron density increases with increasing beam energies. This is due to enhanced ionization by the beam.
FIG. 5.8: Measured variation of plasma electron density $n_e$ and beam electron density $n_b$ with source bias voltages $V_s$. The plasma potential $\phi_p$ measured by the emissive probe at different $V_s$ are also shown.
FIG. 5.9: Measured electron temperature $T_e$ and beam temperature $T_b$ at different source bias voltages $V_s$. 
electrons in the target section. The measured beam density $n_b$ is also shown in Fig. 5.8 and is found to increase initially with increasing $V_s \ (V_s \leq -20 \ \text{V})$, and decreases when $V_s$ is made more negative. The maximum beam density in the present discharge condition is ~ 1.5% of $n_e$ when $V_s \sim -20 \ \text{V}$ and reduces to ~0.3% when $V_s$ is increased to ~50 V. At higher beam energies the beam density decreases due to conservation of electron beam flux from source to target, when the source plasma density remains constant. Another reason for a smaller percentage of beam density at higher $V_s$ is the increase in the background plasma density caused by enhanced ionization in the target plasma by the beam electrons. The plasma potential measured by the emissive probe in the bulk plasma region i.e far away from the sheath of the plate is also shown in Fig. 5.8. The target plasma potential is nearly zero, when there is no electron beam and it is found to decrease by 2 V or so when $V_s$ is varied from 0 to -50 V as shown in Fig. 5.8. An intrinsic property of plasma is that, it manifests its potential in such a way that it (plasma) remains quasi-neutral. In this case, with the injection of the electron beam the negative charged species increases in the target section and therefore plasma potential becomes more negative to reduce the loss rate of positive ions so that quasi-neutrality is maintained.

The plot of plasma electron temperature ($T_e$), beam temperature ($T_b$) versus $V_s$ is shown in Fig. 5.9. Electron temperature is calculated from $I-V$ characteristics drawn with the help of Langmuir probe $L_2$ while $T_b$ is calculated from the beam distribution function using equation (5.8) as described earlier. Measured beam temperature is much smaller than the plasma electron temperature. It is observed that both the electron temperature and the beam temperature in the target plasma decrease slightly with the increase of electron beam energy. This is due to enhanced collision and ionization with beam energy.
FIG. 5.10: Axial potential profiles in front of the stainless steel plate measured by the emissive probe at different source biasing voltages $V_s$. Plate bias is fixed at $-100$ V. Zero in the distance axis represents the position of the plate.
5.4.5 Sheath modification by electron beam:

The axial plasma potential profiles measured using the emissive probe in front of the plate biased at -100 V are shown in Fig. 5.10 for different source biasing voltages \(V_s\). The zero of the distance axis is the position of the plate. Far away from the plate the straight portion of the profile represents the potential of the bulk plasma. Toward the plate, the potential profile suffers a sharp fall, which indicates the plasma sheath boundary. The sheath-presheath edge is obtained from the measured potential profile curves. To obtain the sheath-presheath edge, a semi-logarithmic plot of \(\log \phi\) vs. distance \((x)\) of the potential profile is evaluated. Then two tangents, one along the sharp fall region of the sheath potential (near the plate) and the other along the slowly varying potential region towards the plasma, are drawn. The intersection of these two tangents is marked as the sheath-presheath edge. The distance between the sheath-presheath edge and the plate gives a measure of sheath thickness.

The measured variation of the sheath thickness \(d\) and the ion saturation current \(I_{is}\) at the plate with the source bias voltage \(V_s\) are shown in Fig. 5.11. It is found that the sheath thickness slightly decreases when electron beam \((E_b = 10 \sim 50 \text{ eV})\) flows towards the plate. Increase of ion saturation current at the plate is also observed when the electron beam is present. The increase of ion saturation current at the plate and the sheath contraction is attributed to the increase of plasma density. Although there is a direct flow of beam electrons towards the plate, the affect of the plasma density increment dominates since beam density is very low in the present case and as a result plate current increases.
FIG. 5.11 Dependence of ion saturation current \( I_s \), and floating potential \( \phi_f \) at the plate with source bias \( V_s \), Measured sheath thickness \( d \) versus \( V_s \), when the plate bias is fixed at \(-100 \, V\) are also shown.
5.4.6 Control of floating potential by electron beam:

The floating potential $\phi_f$ of the plate is measured from the $I$-$V$ characteristics drawn at the plate and is plotted with respect to the source bias voltage $V_s$ as shown in Fig. 5.11. It is clearly seen that the electron beam has influence on the floating potential of the plate. At the floating potential, the net current collected by the probe is zero i.e. $I_e + I_b = I$. In absence of electron beam, the measured floating potential of the probe is $-22$ V and becomes minimum ($-28$ V) when $E_b \sim 30$ eV. With further increase of $E_b$, however $\phi_f$ increases. This is due to the fact that in the present discharge condition, beam density increment is prominent only up to $E_b < 30$ eV (Fig. 5.8). The measured beam density in this experiment is maximum ($1.5\%$ of $n_e$) for $E_b \sim 20$ eV. With further increase of $E_b$, the beam density decreases in order to conserve the beam electron flux. On the other hand, the beam to thermal electron density ratio i.e $n_b/n_e$ reduces to a much lower value ($< 0.003$) when $E_b > 30$ eV due to the increase in bulk plasma density. It is evident from this experiment that the ion saturation current to the plate increases due to the increase in plasma density even for $E_b > 30$ eV, though the beam flux tends to saturate. Therefore, the beam current increment is smaller in comparison to ion saturation current increment at the plate for higher $E_b$ and hence, the control over the lowering of floating potential is limited to the beam energy range of 20 to 30 eV.

The importance of controlling the floating potential of the plate using the electron beam lies in the fact that this potential determines the bombarding energy of the plasma ions. It is found that a low energy and low-density electron beam is capable of lowering the floating potential to a value of the mean beam energy. Due to this effect, the bombarding
energy of ions at the surface is enhanced and it is influential in film deposition on a substrate. In this experiment, however, the ratio of beam to thermal electron density reduces to a much smaller value (~0.003) when $E_b \sim 30$ eV which limits further lowering of $\phi$ beyond $-28$ V (Fig. 5.11).

5.5 Conclusion:

It is found experimentally that a double plasma machine can be used to produce axially flowing low energy electron beam. Measured electron distributions in the target plasma, using plane Langmuir probes clearly show the existence of energetic electron beam in addition to the thermal plasma electrons. The experiment helps in understanding the basic physics of electron beam-plasma interaction in dc discharges. In this experiment, the maximum beam density of $\sim 1.5 \%$ of $n_e$ with $E_b \sim 20$ eV is produced. By controlling the discharge current of the source as well as the target, the beam density up to $\sim 5\%$ can be produced in this set up. By changing the discharge current, the electron beam density and consequently the floating potential of the plate can be controlled. One important application of this method is that the floating potential of an insulating surface can be controlled by this method.