Response of the low-pressure hot-filament discharge plasma to a positively biased auxiliary disk electrode

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Abstract

In a steady-state plasma, the loss rate of plasma particles to the chamber wall and surfaces in contact with plasma is balanced by the ionization rate of background neutrals in the hot-filament discharges. The balance between the loss rate and ionization rate of plasma particles (electrons and ions) maintains quasi-neutrality of the bulk plasma. In the presence of an external perturbation, it tries to retain its quasi-neutrality condition. In this work, we studied how the properties of bulk plasma are affected by an external DC potential perturbation. An auxiliary biased metal disk electrode was used to introduce a potential perturbation to the plasma medium. A single Langmuir probe and an emissive probe, placed in the line of the discharge axis, were used for the characterization of the bulk plasma. It is observed that only positive bias to the auxiliary metal disk increases the plasma potential, electron temperature, and plasma density but these plasma parameters remain unaltered when the disk is biased with a negative potential with respect to plasma potential. The observed plasma parameters for two different-sized, positively as well as negatively biased, metal disks are compared and found inconsistent with the existing theoretical model at large positive bias voltages. The role of the primary energetic electrons population in determining the plasma parameters is discussed. The experimentally observed results are qualitatively explained on the basis of electrostatic confinement arising due to the loss of electrons to a biased metal disk electrode.

Keywords: hot-filament discharge, plasma response, plasma parameters, positively biased electrode

(Some figures may appear in colour only in the online journal)

1. Introduction

In the plasma, charged particles (electrons and ions) are not free but strongly affected by the electromagnetic field from the neighbouring charged particles, and hence shows a collective response. The plasma is resulting from the ionization of neutral atoms; therefore, it generally contains nearly equal numbers of electrons and ions ($n_e \approx n_i$) which is called a quasi-neutral plasma. Here $n_e$ and $n_i$ are electron and ion density respectively. In laboratory hot-filament discharges, the primary energetic electrons emitted from heated filaments are the source of energy to initiate the gas ionization and the chamber wall is a sink for the plasma particles (electrons and ions). In steady-state hot-filament discharge, ionization rate of neutrals (or plasma formation rate) is balanced by the plasma loss rate (ambipolar diffusion) to maintain the quasi-neutrality condition [1–3].

The response of weakly ionized hot-filament discharge plasma to a biased auxiliary metal electrode above the plasma potential gives some very interesting features such as formation of fire ball [4, 5], excitation of solitary electron hole [6, 7], electrostatic confinement [8, 9], plasma potential locking [10, 11] etc. At a given discharge condition, the strength of plasma perturbation depends on the net electron current to the positively biased disk. The flux of drifted electrons to biased disk mainly
depends on the amplitude of the external potential/electric field strength and area of it. Therefore it can be stated that the size of an auxiliary metal electrode (diameter in case of disk electrode) and bias voltage above the plasma potential mainly determine the plasma characteristics.

According to the theoretical model, the ratio of area, \( A_d/A_w \), determines whether an electron sheath (\( A_d/A_w < \mu \)) or a double sheath (\( A_d/A_w \approx 1.7\mu \)) or ion sheath (\( A_d/A_w > 1.7\mu \)) will form around or in front of a positively biased \( V_b > V_p \) auxiliary disk electrode in low pressure filament discharge plasma \[9-11\]. Here \( A_d \) is area of disk electrode, \( A_w \) is the plasma-facing area of the vacuum chamber, \( \mu = \sqrt{2.3m_e/M_i} \) and \( V_b \) is the disk bias voltage. The characteristics of bulk plasma at different values of \( A_d/A_w \) to \( \mu \) have been reported experimentally in double plasma device (hot-filament discharge) \[11\] and cylindrical MacKenzie bucket \[9\]. In these experiments, authors have reported the increase in plasma potential and decrease in bulk plasma density in presence of an auxiliary positively biased disk electrode \[9, 11\]. The observed bulk plasma parameters in these experiments were compared to the plasma parameters obtained from the theoretical model and validated the proposed theoretical model \[9, 10\] for hot-filament discharges.

Choudhary et al \[12\] have reported the plasma density enhancement rather than reduction after application of transient high voltage positive pulses to the auxiliary electrode (metal disk) in low pressure hot-filament helium plasma. This study suggests that there should be a plasma density increment instead of reduction which was observed in the double plasma device \[11\] when a positively biased \( V_b > V_p \) disk electrode is immersed in the hot-filament discharges. Here \( V_p \) is plasma potential with respect to the grounded chamber wall. Another concern is related to the experimental devices used in earlier study of plasma responses to an auxiliary biased electrode \[9-11\]. Therefore, we expect a slight different characteristics of bulk hot-filament helium discharge \[12\] if an external DC electric potential (or positive voltage) is applied to an auxiliary metal electrode (disk). Some of these open questions motivate us to perform experiments in the hot-filament helium discharge to investigate the effect of positively as well as negatively biased auxiliary disk electrodes on the plasma characteristics.

In the present work, the response of bulk helium plasma to a biased (positive and negative) disk electrode is investigated. The characteristics of plasma in presence of DC electric potential perturbation due to the biased electrode is recorded by measuring the plasma parameters using the planar Langmuir probe and emissive probe. We have observed an increase in plasma potential, electron temperature, and plasma density with an increase in the bias voltage above the plasma potential to the metal disk. The observed results are explained based on the loss of plasma electrons to the positively biased disk electrode and the role played by primary electrons in enhancing the gas ionization rate (plasma formation rate). A detailed description of the experimental setup and plasma production is given in section 2. The variations of plasma parameters with bias voltages on the disk electrode and with filament heating currents (primary electron population) are discussed in section 3. The experimentally observed results are discussed in section 4. A brief summary of the work along with concluding remarks is provided in section 5.

2. Experimental setup

The experiments were conducted in a grounded cylindrical chamber of stainless steel (SS) having an inner diameter of 29 cm and length of 50 cm (see figure 1). The vacuum chamber was evacuated with the help of a pumping assembly consisting of a combination of rotary pump and diffusion pump. The chamber was evacuated to base pressure of \(~1 \times 10^{-5}\) mbar. The pressure inside the vacuum chamber was measured by a Penning gauge. A needle valve attached to the chamber was used to regulate the gas pressure inside the vacuum chamber. The plasma is generated by electron impact ionization of helium atoms at a working pressure of \(1 \times 10^{-3}\) mbar by primary energetic electrons (\(\sim 65\) eV in absence of disk) emitted from four DC biased hot thoriated tungsten filaments of radius 0.125 mm each. These filaments were mounted on two SS rings of 12 cm radius. The filaments were heated by using a direct current (DC) power supply (32 V, 30 A) and then biased to a negative potential of 65 V with respect to the grounded chamber by using a discharge power supply (300 V, 5 A). Since electrons emitted from the heated filaments (thermionic emitted electrons) have very low energy (0.2–0.3 eV), an external negative biasing is required to accelerate the thermionic emitted electrons above the ionization potential of helium gas (\(\sim 24.58\) eV). A one-sided SS disk (auxiliary electrode) of diameter 3 cm or 8 cm was used to introduce the external potential perturbation to the steady-state plasma. The metal disk was biased ranging from \(-50\) V to \(+50\) V using a DC power supply. A one sided-planar Langmuir probe \[13–15\] of radius 4 mm was used to measure the plasma density \((n)\) and electron temperature \((T_e)\). The plasma potential at a given experimental condition was measured using the emissive probe (floating point method) \[16\]. It should be noted that the purity of disk electrode,
probe, and filament materials is approximately 99.9%. High purity helium gas (99.9%) was used to perform the experiments. The experimental chamber, disk electrode, probe, and filaments were cleaned before carrying out the experiments. Schematic diagram of the experimental setup used in the present study is given in figure 1.

3. Experimental results

To investigate the effect of positively or negatively biased auxiliary (additional) metal electrode (disk) on the characteristics of low-pressure filament discharge, plasma parameters such as plasma density (n), electron temperature (T_e) and plasma potential (V_p) were measured using the electrostatic probes. A SS metal disk of diameter, D = 3 cm or 8 cm and thickness of 0.5 mm was placed at a fixed position along the discharge axis (see figure 1) to introduce electric potential perturbation. The backside of the disk was covered by a thick insulator material and only the front side was exposed to helium plasma. A planar probe at z = 10 cm from the biased metal disk (at z = 0 cm) on the same axis was used to obtain the current-voltage characteristics (I–V curves) after applying a voltage ramp in the range of −50 to +50 V. The plasma potential at the same place (at z = 10 cm) was measured by a radially movable emissive probe. Since probes are located 10 cm away from the biased disk, they characterize bulk plasma rather than the sheath or presheath region. We also measured the plasma potential using the cold probe technique (first derivative of I–V curve of planar probe) for the given experimental conditions. The difference in measured plasma potential with both hot and cold probe techniques was <5%.

For getting the aimed data (I–V characteristics at different disk biases), the metal disk was biased with a DC potential ranging from −30 V to +50 V and the corresponding probe current was measured to construct the I–V characteristics for a given disk bias voltage. According to the probe theory [17–19], probe does not perturb plasma outside the sheath region if it satisfies the conditions (i) probe radius (r_p) should be higher than the Debye length (λ_D). In our experiments, r_p = 4 mm and λ_D ≈ 0.4 mm to 0.5 mm which gives r_p > λ_D, (ii) electron and ion collisional mean free paths should be greater than the probe size. In present experiments, λ_e−a > 100 cm and λ_i−a > 4 cm which gives λ_e−a and λ_i−a > r_p, (iii) mean free path of plasma particles should be greater or higher than the Debye length. All the criteria are fulfilling for the low pressure helium plasma in the presence of biased disk [17]. Therefore, the plasma parameters outside the sheath region are considered to be unperturbed. Hence the perturbation to bulk plasma by a biased probe is ignored or not calculated in the present sets of experiments.

For the first set of experiments, helium gas pressure and discharge current were kept fixed at 1 × 10^{-3} mbar and 0.05 A respectively. The discharge current depends on the filament heating current (or thermionic emitted current flux) and negative DC bias voltage applied to heated filaments at a fixed pressure. In other words, it depends on the input power of the filament emitted electrons. In this case, filaments were heated by passing a current of 24 A, and thermionic emitted electrons were accelerated by applying a negative bias of 65 V to the filaments. The I–V characteristics of planar probe while the metal disk of diameter, D = 3 cm was kept at −3.5 V, 30 V, and 45 V are depicted in figure 2. It should be noted that selection of these three disk bias voltages is just for highlighting the change in I–V characteristics at a negative bias (−3.5 V), intermediate positive bias (+30 V), and large positive bias (+45 V) voltages respectively on the disk. These I–V characteristics at fixed discharge conditions indicate a change in the plasma characteristics after introducing the electric potential perturbation by placing a positively biased auxiliary metal disk in the plasma column. For getting the variation of plasma parameters against metal disk biasing at a given discharge condition, the I–V curves taken at various disk bias voltages were analyzed to obtain the plasma parameters [15, 20]. In calculations, three sets of data (I–V curve) at a given disk bias voltage have been analyzed. The plotted values in the respective figure are the average value of the calculated plasma parameters. The error over the average value is between 3% and 7%. The error over the averaged calculated value of plasma parameter is mentioned in the caption of the respective figure.

In figure 3(a), the plasma potential variation against disk bias voltages has been plotted. The plasma potential varies slowly at low positive bias voltages (< ± 20 V) and has an approximate linear growth above bias voltage of ± 20 V. It is clear from figure 3(a) that measured plasma potential is always found to be lower than the disk bias voltage. The negative value of plasma potential in the presence of floating or negatively biased disk is expected due to a significant low density of primary energetic electrons (beam electrons) in the plasma volume [21]. At low disk bias voltage (V_b < 50 V), it is difficult to determine the population of these beam
electrons using the probe but can be possible at large positive bias voltage on the disk electrode [12]. The increase in plasma potential (towards more positive) is expected due to loss of confined as well as energetic electrons to positively biased disk [3, 11, 22]. The rate of change of \( V_p \) with disk bias voltage depends on the background plasma density, population of energetic electrons, and size of the auxiliary disk electrode. It is discussed in the subsequent section of the report. Similar to the plasma potential, the plasma density (\( n \)) and electron temperature (\( T_e \)) were also calculated using the recorded \( I-V \) data at various metal disk bias voltages. The \( T_e \) variation with the disk bias voltages is given in figure 3(b). We observe an increment in \( T_e \) with increasing the bias voltage on the metal disk. The electron temperature increases with a higher rate up to bias voltage of +20 V and above that it shows only a slight variation. The increase in \( T_e \) with a positively biased disk is expected due to loss of low energy electrons and better confinement of energetic electrons (emitted from heated filaments and hot plasma electrons) [3, 11, 22, 23]. The plasma density variation against disk bias voltages is shown in figure 3(c). In figure 3(c), we observe that \( n \) increases with an increase in the disk bias voltage above the plasma potential. The plasma density increases slowly up to +25 V and has a nearly linear growth above the disk bias voltage of +25 V. At large positive bias voltage (+50 V), the plasma density is observed to be maximum. Thus, we observed a plasma density enhancement from its equilibrium (initial) value in the presence of a constant (DC) potential perturbation applied by a positively biased metal disk electrode.

In the next set of experiments, we carried out the experiments with a large diameter disk electrode (\( D = 8 \) cm) at same discharge conditions. The plasma potential with disk bias voltages at three different locations from the disk (\( z = 0 \) cm) is shown in figure 4. For \( D = 8 \) cm disk electrode, the ratio \( A_d/A_w \) is less than to \( \mu \) (\( A_d/A_w < \mu \)) which suggests a slow variation of plasma potential with positive bias voltage above the plasma potential [9, 10]. However, the plasma potential increases at a higher rate above +10 V than that expected from the theoretical model [9] with increasing the bias voltage to the metal disk (see figure 4). Moreover, above +10 V the plasma potential increases approximately linear with increasing the disk bias voltages. The plasma potential is observed to be lower than the bias voltage at given

![Figure 3](image-url)
discharge condition. The difference between $V_p$ and $V_b$ for $D = 8 \text{ cm}$ disk is less than that measured for $D = 3 \text{ cm}$ biased disk. The plasma potential profiles are nearly same at different locations ($z = 4 \text{ cm}, 10 \text{ cm}$ and $20 \text{ cm}$) from biased disk which confirms that the effect of the positively biased electrode (or potential perturbation) is to the entire bulk plasma. It also confirms the proper shielding of external potential (or electric field) by the plasma up to a certain distance ($z < 4 \text{ cm}$) from disk surface. The plasma density and $T_e$ increase with increasing the bias voltage to disk electrode and a similar trend was observed for small sized ($D = 3 \text{ cm}$) biased metal disk (see figure 3). For the same experimental configuration and discharge conditions, we also measured plasma potential and plasma density radially from the discharge axis ($r = 0 \text{ cm}$) at $z = 10 \text{ cm}$, for which we see a slight change in $V_p$ and $n$ radially as shown in figure 5. From which we can infer that external electric potential perturbation introduced by a biased metal disk propagates throughout the plasma volume due to the collective response of plasma particles. The last set of experiments was conducted to explore the effect of primary energetic electron flux on the plasma parameters when an auxiliary positively biased metal disk is immersed in the plasma column (see figure 1). The $I$–$V$ characteristics of the probe were recorded for two disk bias voltages ($−3.5 \text{ V}$ and $+30 \text{ V}$) at different filament currents (or thermionic electron currents). The primary energetic electrons flux increases with increasing the filament current at a fixed DC bias voltage ($−65 \text{ V}$). Variation of plasma density with filament heating current for two different disk bias voltages is shown in figure 6(a). The plasma density increases if the flux of primary energetic electrons is increased by passing more current through filaments. The plasma density increment rate depends on the bias voltage of the metal disk (or perturbation strength), as can be seen in figure 6(a). More gas ionization is expected with increasing the energy of primary filament emitted electrons. The energy of emitted electrons can be approximated by $V_p$ and filament bias voltage. Apart from plasma density variation plots, we also plotted $V_p$ and $T_e$ variation against the filament currents in figure 6(b). It is clear from figure 6(b) that $T_e$ has different values for bias voltages of $−3.5 \text{ V}$ and $+30 \text{ V}$ for a given filament current but a slight increment in $T_e$ is observed with increasing the population of primary energetic electrons or filaments heating. A slight lower plasma potential is observed at $V_b = 30 \text{ V}$ when filament heating current is increased, as seen in figure 6(b). This in turn reveals that plasma potential decreases with an increase in the population of primary energetic electrons. A similar kind of behavior of $V_p$ against filament heating current is expected for other disk bias voltages above the plasma potential as well. The $V_p$ variation in figure 6 indicates the role of primary energetic electrons (beam electrons) on the characteristics of plasma in the presence of an auxiliary positively biased metal electrode (disk). A detailed discussion on the observed experimental results is provided in section 4.

4. Discussion

In a steady-state low-pressure filament discharge, the plasma formation rate is balanced by the plasma loss rate to the chamber wall and other plasma-facing surfaces. The plasma production rate depends on the energetic emitted electron flux from the negatively biased heated filaments [3, 22, 23]. It was demonstrated in a previous study that plasma parameters get modified in the presence of a positively biased auxiliary metal electrode. For a negatively biased disk electrode in plasma, an ion sheath is formed in front of it which reduces the electron flux and increases the ion flux towards the disk surface. The E-field around the biased disk is localizing up to a few mm distance to maintain the plasma quasi-neutrality. Thus plasma parameters remain nearly unchanged in presence of the negatively biased disk at a given discharge condition. If we apply positive bias to the metal disk then, an electron or ion sheath is formed around the biased disk in the hot-filament helium discharge [9, 10]. A positively biased electrode draws a higher electron current which perturbs the bulk plasma but plasma tries to maintain the quasi-neutrality. Therefore, the external E-field/potential of the biased disk is shielded by the plasma particles up to a certain length. Outside the sheath region, bulk plasma is quasi-neutral. As disk bias voltage ($V_b$) is kept above the initial plasma potential, the confined, as well as energetic electrons, are lost to the surface of the metal disk. Due to the loss of plasma electrons, plasma potential becomes more positive to maintain the quasi-neutrality condition of plasma. However, the potential variation of bulk plasma with the disk bias voltage depends on the area of the biased metal disk ($A_d$) in order to maintain the current balance [9, 10]. The response of the plasma to a biased metal electrode above the plasma potential is mainly determined by the ratio of area $A_d/A_w$ and the ratio of ion-electron mass ($M_i/m_e$). The ratio of area $A_d/A_w$ determines whether an electron sheath or ion sheath or double sheath will be formed in front of a positively biased ($V_b > V_p$) auxiliary electrode to hold the plasma quasi-
The area ratio \( \frac{A_d}{A_w} \) for electron sheath should be \(< \mu \) (i.e. \( \frac{A_d}{A_w} < \mu \)), same for the double sheath should be \( 1.7 \mu \) (i.e. \( \frac{A_d}{A_w} = 1.7 \mu \)) and area ratio for ion sheath should be \( > 1.7 \mu \) (i.e. \( \frac{A_d}{A_w} > 1.7 \mu \)). These conditions were obtained after balancing the electron and ion currents to respective plasma-facing surfaces at given disk bias voltage [9–11]. For helium discharge, \( \mu \approx 2.3 \times 10^{-2} \). In the present experiment, the area of plasma-facing chamber wall, \( A_w \approx 6350 \text{ cm}^2 \) and area of disk electrodes of \( D = 3 \text{ cm} \) and \( D = 8 \text{ cm} \) are \( A_d \approx 7 \text{ cm}^2 \) and \( A_d \approx 50 \text{ cm}^2 \) respectively. So the ratio \( \frac{A_d}{A_w} < \mu \) for both disk electrodes \( (D = 3 \text{ cm} \text{ and } D = 8 \text{ cm}) \) which predicts the electron sheath near the positively biased disk [9]. Since the characteristics of bulk plasma depends on the type of sheath region around a positively biased electrode, plasma parameters \( (n, T_e \text{ and } V_p) \) should also vary according to that predicted in the theoretical model as well as in previous experiments [9–11].

The plasma potential variation with bias voltage to the metal disk (figures 3(a) and 4) does not follow the trend (sub-linear) that was predicted by theoretical model. Plasma potential strongly depends on \( T_e \) and plasma loss areas \( (A_w \text{ and } A_d) \). If the electron temperature of bulk plasma is \( T_e \) in case of positively biased electrode \( (V_b > V_p) \) then plasma potential is [9]

\[
V_p = \frac{T_e}{e} \ln \left( \mu - \frac{A_d}{A_w} \right)
\]

Here \( \frac{A_d}{A_w} < \mu \), a necessary condition for existence of a monotonic electron sheath in front of positively biased disk. The plasma potential increases with a higher rate (super-linear) when we apply more positive bias voltage \(+20 \text{ V}\) to the metal disk \( (D = 3 \text{ cm}) \) and \(+10 \text{ V}\) for disk of \( D = 8 \text{ cm} \). We finds difficulties in understanding such super-linear variation of plasma potential for the electron sheath \( (A_d/A_w < \mu) \) condition. The existing model considered only a single \( T_e \) in determining the total electron flux loss to chamber wall and electrode which determines the plasma potential. In the present setup, we can not ignore the role of primary energetic...
electrons (or energetic electrons of different $T_e$) when plasma potential is more positive than the negatively biased filaments. In figure 6(b), gap between potential measured at $V_b = -3.5$ V and $+30$ V is decreased by $\sim 2$ V if filament current is increased by 1.2 A (see figure 6(b)). It indicates that the beam electrons (primary energetic electrons) lower the plasma potential that was also observed in other hot-filament discharges [21]. The primary results (figure 6) indicate a significant role of the energetic electrons (filament emitted electrons and plasma electron) in determining the bulk plasma properties in the given condition ($A_d/A_w < \mu$).

The electron temperature of bulk plasma ($T_e$) also increases in the presence of a positively biased auxiliary metal disk. The variation of $T_e$ is somewhat similar to that predicted in theory and previous experiments [9, 11]. The positively biased disk ($V_b > V_p$) attracts more low-energy plasma electrons and provides better confinement to energetic electrons. In this way, the average energy of the bulk plasma electrons is increased [9, 11]. It is also expected to increase the average energy of bulk plasma electrons by Coulomb collisions of low energy electrons and high energy electrons in the potential well [22, 24, 25]. Hence we observe an increment in $T_e$ of the bulk plasma with increasing the disk bias voltage.

In the present experiment, there is a major difference in the plasma density variation with bias voltages above the plasma potential for the condition $A_d/A_w < \mu$. We observed the enhancement of plasma density (see figure 3(c)) instead of electron density depletion that was expected according to the theoretical model and previous experiments [9, 11] in the presence of a smaller sized positively biased auxiliary metal disk. However, it is possible qualitatively to understand the plasma density enhancement with the increase in the plasma potential [3, 10, 12, 22, 23]. Once the disk bias voltage is higher than the plasma potential ($V_b > V_p$), plasma electrons (bulk and energetic) loss rate to the metal disk increases, resulting in increasing the plasma potential. The plasma density follows the nearly same trend of the plasma potential for $V_b > +20$ V when $T_e$ has a slight variation. It is known that energy contained in the plasma mainly depends on the input power and it is proportional to the average energy of electrons ($T_e$) and density of electrons. In the hot-filament discharge, input power (energy) of filament emitted electrons depends on the plasma potential at a fixed DC filament bias. The energy of filament emitted electrons that enter the bulk plasma is approximately $e(V_p - V_d)$. Here $V_d = -65$ V, filament DC bias voltage. The plasma production rate (gas ionization rate) increases with the increase in the input power of the filament’s electrons. The increase in plasma potential due to loss of energetic as well as bulk plasma electrons to positively biased disk would ionize more helium atoms at given discharge condition. Hence plasma density increases with increasing the plasma potential and exhibits a similar trend above the disk bias of approximately $+20$ V. Apart from primary filament emitted electrons, secondary electrons (hot confined electrons) which are either released from the chamber wall or produced from the filaments emitted energetic electrons are confined in the potential well with respect to chamber wall [3, 22, 23, 25]. The secondary electrons of kinetic energy ($E > 25$ eV) above the ionization potential of helium gas ($\sim 24.5$ eV) may take part into the ionization process and increase the plasma density. As the density (population) of primary filament emitted electrons is increased, density growth rates are observed to be different for negatively ($V_b = -3.5$ V) and positively ($V_b = +30$ V) biased disk (see figure 6(a)). It confirms that the density of primary energetic electrons of the same energy plays a dominant role in determining the plasma formation rate (or ionization rate) in presence of a positively biased auxiliary metal disk.

5. Summary

In this work, characteristics of hot-filament low-pressure helium plasma with an auxiliary (additional) biased disk electrode have been studied. The plasma parameters ($V_{pe}$, $T_e$, and $n$) were measured using the planar and emissive probe at various locations of the plasma column. For both sized metal disks ($D = 3$ cm and $D = 8$ cm), plasma potential, plasma density, and electron temperature are observed to increase with increasing the bias voltage to the metal disk above the plasma potential at given discharge conditions. However, the rate of change of plasma parameters with disk bias voltage depends on the size of the disk electrode and equilibrium plasma density (or population of primary energetic electrons). Such response of helium plasma is understood with the help of available theoretical models. The ionization rate (plasma production rate) and plasma loss rate to plasma-facing boundaries mainly determine the characteristics of bulk plasma. The discrepancy in the observed results (plasma parameters variation) from that predicted or observed in hot-filament discharge could be possible due to the presence of energetic primary electrons or energetic population of the bulk plasma. The present study is more focused on two different sized auxiliary electrodes to check the applicability of an available theoretical model for a particular case, $A_d/A_w < \mu$ in the hot-filament discharge. This work suggests a better theoretical framework taking into consideration of all electron groups (bulk plasma and energetic electrons) for better explaining the plasma characteristics at a higher plasma potential than the grounded chamber wall. A detailed study of plasma response to various diameters electrodes, has been a subject matter for the future. The present experimental results provide an insight into electrostatic confinement by using an auxiliary positively biased electrode in the plasma volume. It also motivates to study the transient response of hot-filament plasma at different electrostatics confinement strengths which depend on the depth (height) of the potential well. This primary study may help in exploring the physics of low pressure or collisional plasma in presence of auxiliary positively biased electrode.
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References

[1] Chen F F 1984 Introduction to Plasma Physics and Controlled Fusion 2nd edn (New York: Plenum Press)
[2] Bittencourt J A 2004 Fundamentals of Plasma Physics (New York: Springer)
[3] Cho M, Hershkowitz N and Intrator T 1990 J. Appl. Phys. 67 3254
[4] Stenzel R L, Ionita C and Schrittwieser R 2008 Plasma Sources Sci. Technol. 17 035006
[5] Stenzel R L et al 2012 Plasma Sources Sci. Technol. 21 015012
[6] Kar S et al 2010 Phys. Plasmas 17 102113
[7] Kar S and Mukherjee S 2013 Pramana 81 35
[8] Andreu J et al 1985 J. Phys. D: Appl. Phys. 18 1339
[9] Baalrud S D, Hershkowitz N and Longmier B 2007 Phys. Plasmas 14 042109
[10] Hopkins M M et al 2016 Phys. Plasmas 23 063519
[11] Barnat E V, Laity G R and Baalrud S D 2014 Phys. Plasmas 21 103512
[12] Choudhary M, Kar S and Mukherjee S 2016 Contrib. Plasma Phys. 56 878
[13] Cherrington B E 1982 Plasma Chem. Plasma Process. 2 113
[14] Chen F F 2003 Lecture notes on langmuir probe diagnostics http://www.seas.ucla.edu/ffchen/pubs/chen210r.pdf
[15] Choudhary M 2017 Experimental studies on collective phenomena in dusty plasmas PhD Thesis Homi Bhabha National Institute (HBNI) India
[16] Sheehan J P and Hershkowitz N 2011 Plasma Sources Sci. Technol. 20 063001
[17] Waymouth J F 1964 Phys. Fluids 7 1843
[18] Langmuir I and Mott-Smith H 1924 Gen. Elec. Rev. 27 616
[19] Sheridan T E 2000 Phys. Plasmas 7 3084
[20] Merlino R L 2007 Am. J. Phys. 75 1078
[21] Phukan A et al 2010 Pramana 74 399
[22] Robertson S and Sternovsky Z 2005 Phys. Rev. E 72 016402
[23] Robertson S, Knappmiller S and Sternovsky Z 2006 IEEE Trans. Plasma Sci. 34 844
[24] Knappmiller S and Robertson S 2011 Phys. Plasmas 18 100702
[25] Hershkowitz N et al 1982 J. Appl. Phys. 53 5330