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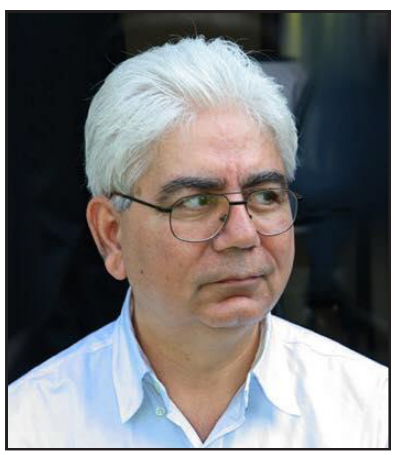

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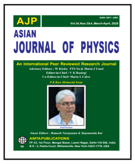

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Influence of discharge conditions on dynamics of plasma parameters in a double plasma device

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Dedicated to Prof P K Kaw

Double plasma devices are known to produce uniform and quiescent plasma which makes it very convenient to study phenomena on basic plasma physics. The device is also used to produce a well-controlled plasma and ion beams with a simple DC discharge mechanism. Enhancing the control of plasma contributes to the improvement of material processing and advancement of plasma techniques. In this work, a steady state Argon discharge was studied through a series of experiments in a double plasma device to investigate the influence of different parameters, e.g. discharge voltage, chamber pressures, source chamber bias etc. on the plasma parameters measured across the device. It was observed that by changing the discharge voltage, plasma density inside the source chamber could be controlled without affecting the electron temperature, while outside the source chamber, the electron temperature could be controlled without affecting the plasma density. The overall plasma density enhanced significantly when the gas pressure was increased. The plasma potential was relatively unaffected by the variation in discharge voltage and gas pressure, but changes significantly when the source chamber was grounded from the floating condition. Manipulating the plasma potential can help to control the ion bombardment energy, while a controlled electron temperature is always desirable in many plasma-based material applications. It was also observed that under the grounded source chamber configuration, a low quiescence level ($(\delta I_{is}/I_{is}) < 0.5\%$) could be maintained in the plasma compared to the floating source configuration.

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Keywords: Hot filament DC discharge, Discharge voltage, Plasma parameters, Double Plasma Device.

1 Introduction

In 1969, Taylor *et al* first introduced the Double Plasma Device (DPD) to produce large cross section beams and waves [1]. Since then, the DPD has contributed significantly to our understanding of plasma dynamics, instabilities, wave propagation, and particle interactions in controlled low pressure laboratory plasmas [2-4]. The device is also known to produce uniform and quiescent plasmas, making it highly suitable for conducting experiments in fundamental plasma physics as well as for specific plasma-based applications. The device consists of two plasma zones (source and target) separated by a negatively biased grid placed in a common vacuum chamber. Plasma is generated by hot cathode DC discharge where tungsten filaments are used as a cathode for electron emission. By manipulating discharge parameters such as, filament heating current I_h, discharge current I_d, and discharge voltage V_d, source and target chamber biasing, plasma parameters can be controlled at remote region. The versatility of DPD lies in the selection of different modes of operation viz, choosing the desired plasma source, grounding, and biasing scheme for source and target chambers, using grids of different transparencies. These features enable generation of two distinct plasma regions within the same system and control them independently for different applications.

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By inducing a potential difference between these two plasma volumes, an ion beam can be introduced into the target chamber. This feature makes DP devices widely utilized for exploring various ion beam-related phenomena [5-7] such as beam-driven instabilities [8], solitons in an ion-beam–plasma system [9] etc. Despite DPD's use for fundamental studies of wave and beam phenomena over the years, controlling the plasma parameters has currently emerged as a new area of study due to its popularity in many applications involving plasma-based materials [10,11].

In the present work, experiments were carried out to investigate effect of different parameters, e.g. discharge voltage, chamber pressures, source chamber bias and neutral gas pressures on the steady state spatial profile of plasma parameters in a DP device where plasma is ignited in source chamber only and allowed to diffuse to far region in absence of separation grid. A detailed description of the experimental setup is provided in Sec 2; the experimental results and discussions are presented in Sec 3 and concluded in Sec 4.

2 Experimental Setup

The experiments were carried out in a double plasma (DP) device that was designed and developed at Plasma Lab, IIT Delhi. The detailed description of the experimental setup is given in following Sub Sec (a), including a schematic diagram (Fig 1) and an actual photograph of the device (Fig 2). Details on the scheme of plasma production in this device are given in following Sub Sec (b).

(a) *Description of the device*

The device is a cylindrical non-magnetic Stainless-Steel (SS304) chamber of length 111 cm and diameter 40 cm. Two identical hollow cylinders (length and diameter ≈ 35 cm), namely the source and the target chamber, can be placed coaxially inside the main vacuum chamber. However, in the present experiments only the source chamber was installed to investigate the influence of different discharge conditions on plasma parameters inside and away from the source chamber. The device is connected to a diffusion pump (pumping speed of 750 l/s) backed by a rotary pump to evacuate the chamber. A base pressure of 4×10^{-6} mbar was achieved inside the chamber. Two Pirani gauges and an ionization gauge are installed in the chamber to monitor the pressures. Argon (Ar) gas was introduced into the vacuum chamber through an inlet on the end plate, defined as $z = 0$ cm. As shown in Fig 1(a) one end of the source chamber was placed at $z = 10$ cm.

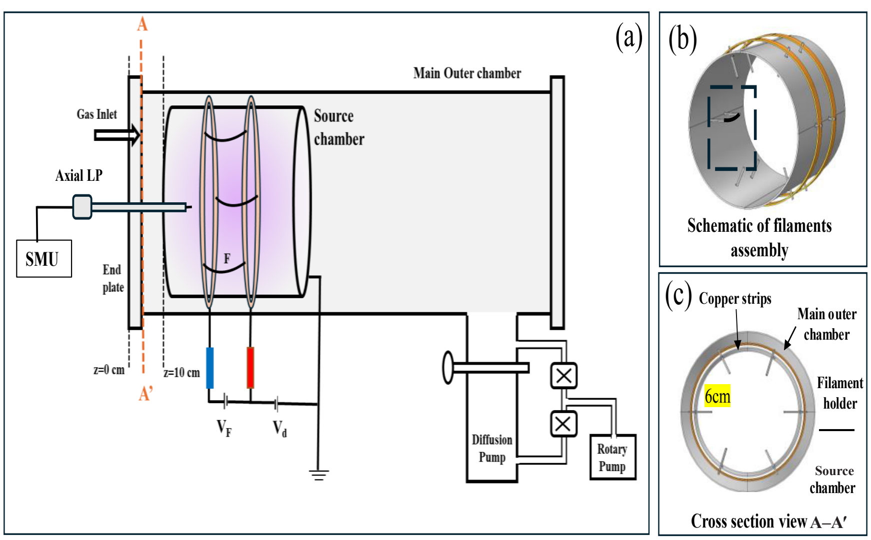
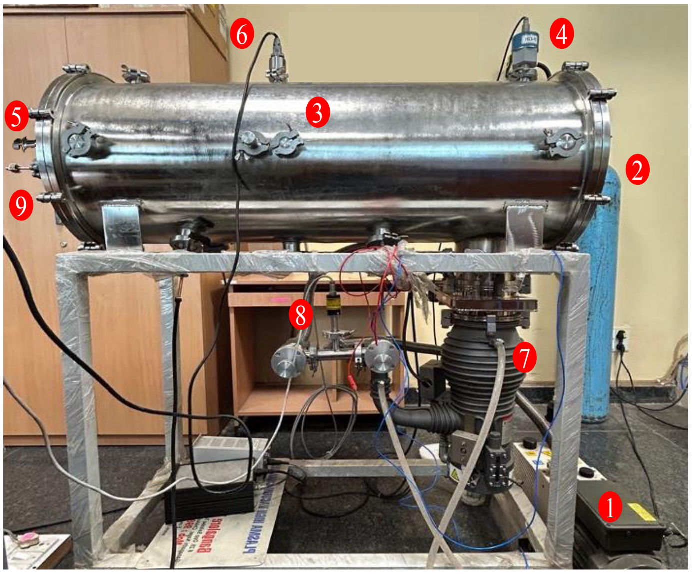


Fig 1. (a) Schematic of experimental setup (DPD). F is the Thoriated Tungsten filament, V_F is filament heating power supply, and V_d is the discharge voltage power supply. (b) arrangement of filaments using two circular copper rings at a gap of 10cm. (c) the cross-section view A-A′.

Experiments were conducted at two different modes of operations; (a) when the source chamber is kept grounded (along with main chamber) called SG configuration; and (b) when source chamber is kept floating (with the main chamber grounded) called SF configuration.



1. Rotary pump
2. Argon gas
3. Main outer chamber
4. Penning gauge
5. Gas inlet
6. Pirani gauge (chamber)
7. Diffusion pump
8. Pirani gauge (backing line)
9. Axial LP

Fig 2. Photograph of DPD at Plasma Lab IITD.

(*b*) *Plasma production*

The plasma was produced by thermionic emission in DC discharge mode. 1% Thoriated tungsten filaments of diameter 0.38 mm were used as source of primary electrons in this device. A two-dimensional arrangement of 3 parallelly connected filaments (each 0.38 mm diameter and 12 cm long) from z = 22 to 33 cm was mounted on two circular copper rings around the periphery of source chamber as shown in Fig 1(b). Figure 1(c) presents the cross-sectional view along line A-A′, showcasing the internal structure of the system. Tungsten's extremely high melting temperature (3683 K) makes it a desirable material for thermal electron emitters. When heated above 2000K, it emits a copious amount of electrons [12]. The required current to heat a single filament at temperature T was calculated using the balance equation (1), where the left-hand side represents the power generated due to the ohmic heating and the right-hand side shows the power radiated (Stefan-Boltzmann law)

$$I^2 R = A_f \epsilon \sigma T^4 \tag{1}$$

where I is the filament heating current in amperes, R is the resistance of thoriated Tungsten in ohms, A_f is the surface area of the filament, $\sigma = 5.67\times10^{-8}$ Wm^{-2}K^{-4} is the Stefan-Boltzmann constant, $\varepsilon = 0.35$ is the emissivity of thoriated tungsten and T is the filament temperature in Kelvin. Figure 3 displays the theoretically calculated required current to heat a tungsten filament (diameter 0.38 mm) at 2000K or more.

A DC regulated power supply of 30 V-100 A was used for heating the filaments. A total DC current of 28 Amp was provided to the filament to get sufficient electron emission at a constant voltage drop of 7.5 V. The maximum emitted electron current density, (J_{max}) is given by the Richardson (or Richardson–Dushman) equation,

$$J_{max} = A_0 T^2 \exp\left(-\frac{eW}{kT}\right) \tag{2}$$

Here, $A_0 = 3\times10^4$ A/m^{2}K^2 is the Richardson constant, T is the temperature of the thoriated Tungsten in Kelvin, W is its work function i.e. 2.6 eV, k is the Boltzmann constant. The filaments are biased negatively using a discharge power supply (100 V, 5 A) to accelerate the emitted electrons away from the filaments as these electrons initially possess low energy. The negatively biased filaments function as cathode with respect to grounded source chamber and main chamber (anode). As primary electrons travel to the anode, the plasma is ignited by the electrons impact ionization with neutral Ar atom.

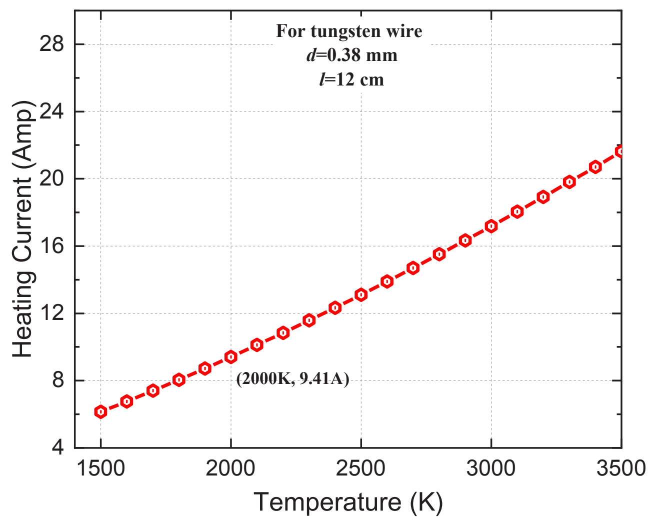


Fig 3. Plot of required filament heating current vs temperature for thoriated tungsten of diameter 0.38mm and length 12 cm.

The experiments were performed in the gas pressure range of 1×10^{-4} mbar to 1×10^{-3} mbar. A cylindrical Langmuir probe of tungsten tip of diameter 0.25 mm and length 8 mm was inserted into the chamber through an axial port that enables measurement of the plasma parameters far away from source region. To obtain the I-V characteristics of plasma, a Keithley source meter unit-2450 was employed that provides probe biasing voltage from –150 V to 30 V and measures the probe current simultaneously. By changing the discharge voltage, experiments were performed to study the plasma behaviour and characteristics and are discussed in next section.

3 Results and discussion

The experimental results depicting the effects of different discharge parameters, viz. discharge voltage, gas pressure and source chamber bias on the plasma profile are presented in the following subsections. Average plasma density $n_i \sim 5\times10^9$–10^{10} cm^{-3} and electron temperature $T_e \sim 5$ eV were produced with a total absorbed power of ~ 50 Watts ($I_d = 0.7$ A and $V_d = 70$ V) which was found to be consistent with the values theoretically predicted by the uniform density discharge model [13].

(*a*) *Variation with discharge voltage in case of source chamber grounded configuration*

Argon gas was injected into the chamber at a pressure of 5×10^{-4} mbar. Plasma was produced at discharge voltage in the range of 60–90 V with a discharge current of 0.4 – 0.6 amp. In this configuration, discharge voltage was applied with respect to the grounded source chamber and main chamber (both working as anode). Figure 4 represents the axial profiles of plasma parameters for different discharge voltages. The plasma density peaks sharply near the filaments at z = 30 cm at all applied discharge voltages (V_d) and reaches a maximum $n_i \sim 1.5\times10^{10}$ cm^{-3} when V_d is set at 90 V. The plasma density then rapidly decreases after 30 cm, indicating that this was the primary ionization region in the source chamber. Higher discharge voltages enhances the rate of ionization by accelerating electrons and lead to higher plasma densities as can be seen in Fig 4(a) with negligible drop in electron temeprature in source chamber region (Fig 4b). Whereas in a region away from the filaments (z > 50 cm), a nearly constant plasma density profile was observed with increased electron temperature. This could be due to a reduced collision rate, as electrons moving through the outer chamber lack sufficient energy to induce further ionization.

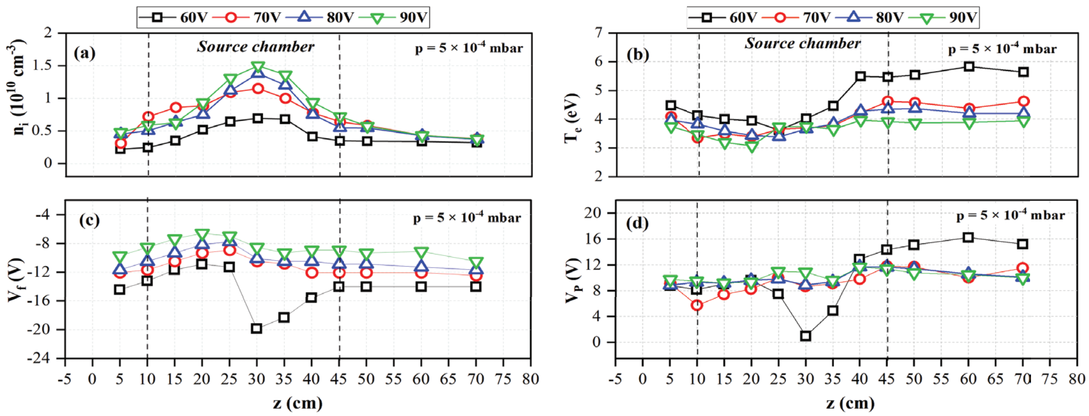


Fig 4. Axial variation in plasma parameters (a) plasma density (n_i), (b) electron temperature (T_e), (c) floating potential (V_f) and (d) plasma potential (V_P) for different discharge voltages, V_d = 60 V, 70 V, 80 V, 90 V at neutral Ar pressures, $p = 5{\times}10^{-4}$ mbar in case of source chamber grounded configuration.

Figure 4(c) illustrates the variation in the floating potential V_f, that became less negative as the discharge voltage V_d was increased. At lower discharge voltage of 60 V, V_f shows a dip around 25–35 cm, reaching values as low as –20 V. This indicates a region rich with primary electrons, where electrons can reach the probe without frequent collisions, thus creating a strong negative potential. Increased discharge voltages significantly reduce V_f, as higher voltage leads to more ionization and reducing the electron temperature and their energy. Plasma potential V_P which influences the particle confinement was determined using the equation, $V_P = V_f + 5.2\ T_e$. It was observed that increasing discharge voltage has a minimal impact on plasma potential possibly due to increased collisions that stabilize the energy distribution of electrons, preventing large changes in V_P despite of increasing discharge voltage V_d as shown in Fig 4(d).

(*b*) *Variation with gas pressure*

To study the effect of gas pressure, further experiments were carried out in the chamber at three distinct Ar gas pressures of $1{\times}10^{-4}$ mbar, $5{\times}10^{-4}$ mbar and $1{\times}10^{-3}$ mbar. At each pressure, plasma was produced at a discharge voltage of 70V, while the discharge current was varying from 0.5–0.6 A. As shown in Fig 5(a) at neutral pressure $p = 1{\times}10^{-4}$ mbar the plasma density peaks sharply near the filaments, reaching a maximum n_i ~$3{\times}10^{9}$ cm^{-3}. The plasma density then rapidly decreases after 30 cm. When the pressure was raised to $5{\times}10^{-4}$ mbar, the plasma density values were higher, reaching around $1{\times}10^{10}$ cm^{-3} at the peak. The increase in gas pressure provides more neutral particles for ionization, leading to higher plasma density. Furthermore, at $p = 1{\times}10^{-3}$ mbar, plasma density reaches even higher values, peaking at around $3{\times}10^{10}$ cm^{-3}. The peak plasma density region remains same around 25 cm, but the density drops more gradually after this point. A significant reduction in electron temperature from T_e ~ 8 eV to 4 eV was observed when the pressure was increased as shown in Fig 5(b). Increasing pressure leads to a shorter mean free path of ionization, as electrons undergo more frequent collisions with neutrals. This results in more energy losses and generally lower electron temperatures compared to the lower-pressure. Frequent collisions not only lowers the electron temperature but rapidly redistribute the energy of electrons, making the electron temperature profile more uniform across the plasma.

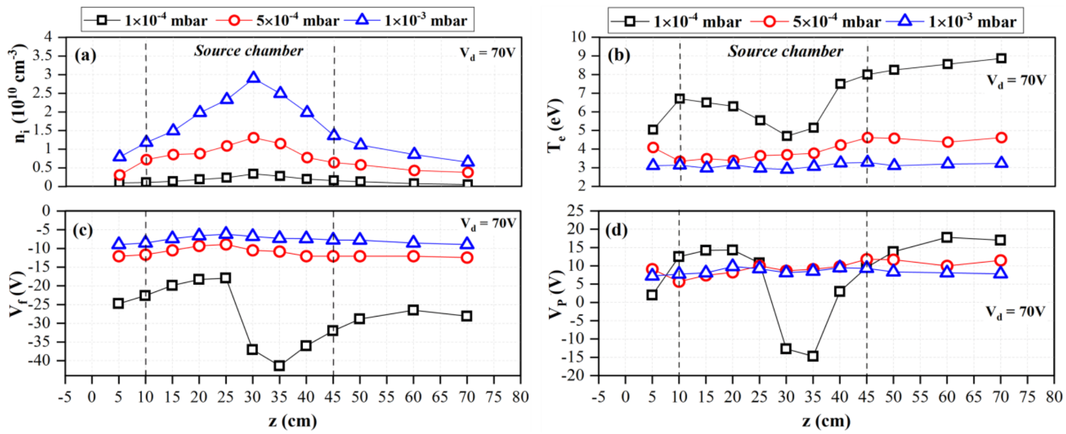


Fig 5. Axial variation in plasma parameters (a) plasma density (n_i), (b) electron temperature (T_e), (c) floating potential (V_f) and (d) plasma potential (V_P) at discharge voltages V_d = 70 V at three different neutral Ar pressures of p =1×10^{-4} mbar, 5×10^{-4} mbar and 1×10^{-3} mbar in case of source chamber grounded configuration.

At low pressure (Fig 5(d), 1×10^{-4} mbar), the plasma potential V_P was observed to be higher, with sharp changes, possibly due to reduced particle collisions. High electron temperature allows the electrons to attain more energy, increasing V_P at lower pressures whereas high pressure creates a uniform V_P profile with minimal variation across the chamber. In essence, the high collisionality at increased pressures enforces a more uniform energy distribution in the plasma, leading to a uniform plasma potential.

(*c*) *Comparison between source chamber grounded and floating configuration*

To observe the behaviour of plasma inside a floating wall, experiments were conducted by applying the discharge voltage w.r.t. main chamber only (anode) and keeping the source chamber floating. The degree of plasma quiescence was also compared in both the configurations by measuring the fluctuations in ion saturation current ($\delta I_{is} / I_{is}$) through the Langmuir probe biased at – 90 V. The fluctuation is much higher in the floating case (($\delta I_{is} / I_{is}$) > 1%) compared to the grounded case (($\delta I_{is} / I_{is}$) < 0.5%) across all positions at pressure 5×10^{-4} mbar shown in Fig 6. This indicates that the plasma is more unstable or exhibits more pronounced fluctuations under the floating condition. This may enhance plasma instabilities and lead to stronger fluctuations. In contrast to the source chamber grounded configuration, this arrangement changes the direction of charged particles, which alters discharge current (I_d) flow through the opening into the main outer chamber. To study its influence on plasma parameters, experiments were carried out at a pressure of 1× 10^{-3} mbar at discharge voltage of 70 V and discharge current of 0.5 amps. A comparison of the experimental results for SF and SG configurations are presented in Fig 7. In case of source chamber floating configuration, a high density plasma was observed thoughout the chamber with a peak density of 3×10^{10} cm^{-3} at z = 35 cm. In contrast to the SG condition, which showed a steep decline in density profile, the SF configuration showed a spread in density as shown in Fig 7(a). The density variation is more significant at the right-hand side of the filament region (z > 40 cm) compared to the other side, where the end plate yielded a high diffusion loss. A uniform axial profile of electron temperature maintained at ~3eV was noticed at SG condition. However, it was reduced and produced a non-uniform profile when the biasing condition was switched to SF configuration as illustrated in Fig 7(b).

There was a noticeable shift in the plasma potential as can be seen in Fig 7(d) in the case of source chamber floating configuration. A negative plasma potential profile was observed throughout the axis of the chamber.

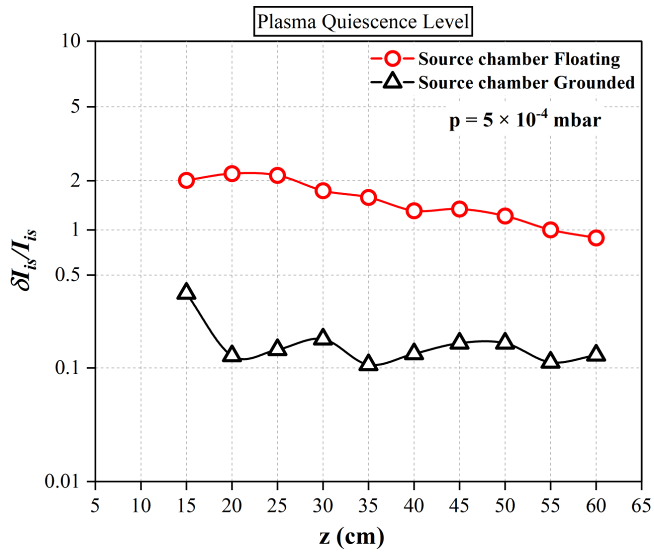


Fig 6. Axial variation of plasma quiescence level under source chamber floating and grounded configurations at the neutral gas pressure of $5{\times}10^{-4}$ mbar.

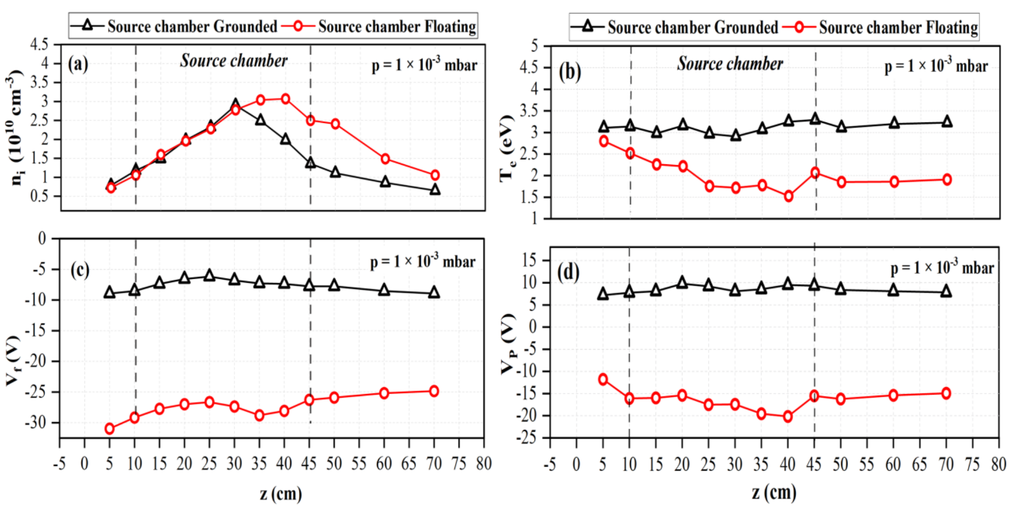


Fig 7. A comparison of plasma parameters (a) plasma density (n_i), (b) electron temperature (T_e), (c) floating potential (V_f) and (d) plasma potential (V_P) for SF and SG configurations at discharge voltage V_d = 70V and neutral Ar pressure $p = 1{\times}10^{-3}$ mbar.

The source chamber, in the floating case, is expected to be at a large negative potential. The voltage varies through the sheath region, transitioning asymptotically in the quasi-neutral bulk plasma. Therefore, the plasma potential in the bulk can remain relatively positive with respect to the floating boundary. The higher plasma density observed in the source chamber edge region during the floating configuration may be attributed to the discharge sustained between the filaments and the grounded main chamber. Additionally, the floated source chamber likely contributes to partial confinement of electrons and reduced loss to the chamber wall, thereby increasing the plasma density, which was not observed in the SG configuration. Further investigations are in progress to comprehend the underlying mechanisms and plasma dynamics in this experimental setup.

4 Conclusion

A quiet plasma with a low fluctuation $((\delta I_{is} / I_{is}) < 0.5\%)$ was produced by a hot filament DC discharge in this experimental setup. A peak plasma density of $n_i \sim 10^{10}$ cm^{-3} was found near the filaments, which diffuses towards the main chamber and drops to 10^9 depending on the pressure. Plasma density can be increased in source chamber region without affecting electron temperature whereas electron temperature can be controlled without affecting plasma density in the diffused region away from the filament by varying the discharge voltage. Increasing pressure from 1×10^{-4} mbar to 5×10^{-4} mbar, significantly increases the plasma denisty from 3×10^9 cm^{-3} to 1×10^{10} cm^{-3} and reduces the electron temperature from 7 eV to 4 eV. Discharge volatge shows minimal impact on plasma potential at high V_d but changing the source chamber biasing from grounded condition to floating condition can completely shift the plasma potential that can further help to control ion bombardment energy which is desirable in many plasma based material processing applications. Keeping the source chamber in floating configuration provides a confined plasma with higher denisty with and electron temperature with a negative plasma potential. Moreover, in the floating case, the fluctuation is much higher $((\delta I_{is} / I_{is}) > 1\%)$ compared to the grounded case $((\delta I_{is} / I_{is}) < 0.5\%)$ which indicates that plasma is more unstable and may lead to enhanced plasma instabilities.

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