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A comparative study of sheath potential profile measurements with laser-heated and current-heated emissive probes

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Emissive Langmuir probe is one of the most efficient diagnostic tools available for plasma potential measurements. Extensive studies have been carried out in designing different kinds of conventional (electrically heated) emissive probes (CEPs) to estimate the plasma potential. Laser heated emissive probe (LHEP) has been developed with certain advantages over the conventional probes such as low evaporation rate of the probe material, high lifetime, and high emission levels. Most importantly, the LHEP uses laser to heat the probe-tip and does not require electric current to heat the probe-tip like in CEP. The heating current in CEP substantially affects the plasma potential measurements, especially in the regions of plasma where high electric and magnetic field gradients are present. In this paper, we studied the plasma potential structures in sheath-presheath region using both LHEP and CEP in an unmagnetized dc-filament discharge plasma. Measurements of sheath spatial potential profile using laser heated emissive probe are compared with those obtained using conventional emissive probe. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4945693]

I. INTRODUCTION

Sheath and presheath potential structures determine the confinement of charged particles and energy loss to the physical boundary in plasmas by controlling the plasma drift velocities. Enormous theoretical and simulation models were presented to determine the sheath structure and plasma drifting in the sheath-presheath region.[1–3] Several experiments were also carried out for determining the Sheath-Presheath potential profile[4,5] and charged particle flow velocities[6,7] in the Sheath-presheath region. However, the sheath profile and flow velocities in the complex cases like in magnetized plasma, in multi ion species plasma, and in presence of oblique magnetic fields are still not completely understood and require further experimental studies.

Emissive probes are widely used for space/plasma potential measurements in variety of plasmas ranging from RF discharges to tokamaks.[8–16] The idea of emissive probe was given by Langmuir[17] and it works on the simple principle of electron emission when the probe is biased below plasma potential. The probe ceases to emit electrons when biased above the plasma potential. The emissive probes are required to be heated for emitting electrons. The conventional or the widely used emissive probes are generally a miniature filament made up of tungsten and are heated by passing electrical current through them. Laser heated emissive probe is a recent advancement in emissive probes proposed by Schrittwieser *et al.*,[18] which are heated by high power Lasers. Laser-heated emissive probes (LHEPs) are successfully used for plasma potential measurements in RF as well as fusion plasmas.[19,20] However, in order to establish its effective usage, the LHEPs has to be exposed to a wide range of plasma densities and in the plasma regions where high electric and magnetic gradients are present. In this present work, laser heated emissive probe has been used for sheath potential measurement for the first time where high electric field gradients are present.

LHEP delivers several advantages over the conventional emissive probes (CEPs). For example, since there is no heating current required to be passed though the probe material, there is no effect of potential drop across the probe material on the plasma potential measurement and the whole laser-heated probe surface remains at the same potential. Whereas, in CEP, since a potential drop is required across the probe material to pass the heating current, this potential drop is added to the measuring spatial potential in case of a continuously glowing probe. Hence, proper care has to be taken in order to measure absolute plasma potential in CEPs.[21,22] Furthermore, in CEPs, the mechanical contacts at the probe end terminals lead to reduced temperatures at the ends, which result in non-uniform emission over the entire length of the probe. The sheath produced around supporting holders also hampers the emissions from the probe end terminals through the development of relative negative potentials near the end terminals. These issues with CEPs become more significant in measurement of plasma or space potential profiles in presence of strong potential gradients such as in the sheath region as well as in the presence of magnetic fields. In presence of magnetic field, the $\mathbf{j}_{\text{filament}} \times \mathbf{B}$ forces on the filament emissive probes (CEPs) restrict the orientation of CEPs inside the plasma and also affect its lifetime. Last but not least, the filament burn outs severely hinder the CEPs lifetime and replacing them in evacuated plasma devices frequently leads to the loss of valuable experimental time. By heating a small probe head made up of LaB_6, tungsten or graphite using a suitable Laser beam, all the above mentioned issues with CEPs can be effectively eliminated. Hence, plasma potential measurements with LHEPs need to be consolidated by carrying out experiments with LHEPs in different plasma devices.

The paper is organised as follows. In Section II, methodology of plasma potential estimation using emissive probes has been described. The experimental setup along with construction of CEP and LHEP is presented in Section III. The experimental results containing measurements of space potential profile in the sheath region with CEP and LHEP and their comparison are given in Section IV. The paper is summarised in Section V.

II. MEASUREMENT OF SPACE POTENTIAL USING EMISSIVE PROBES

A. Conventional emissive probes

Emissive probes are being used for last eight decades to measure plasma potential and well-established methods exist for interpreting the probe data.[23] Construction and heating methods of conventional current-heated probes are reviewed extensively by many authors[24–26] to showcase their various strengths and limitations. Emissive probes measures the space potential more accurately than their collecting counterpart.[24] Even though, Langmuir introduced the concept of emissive probe in 1920s,[17] its significant usage in the plasma potential measurement came after the reports by Kemp and Sellen in 1966.[25] They found that the floating potential of the emissive probe tends to saturate as probe temperature increased and interpret saturating potential as plasma potential. However, if the probe is heated to large enough temperatures, as observed in several experimental investigations,[26] the emitted current will not saturate at plasma potential but will continue to increase due to space charge effects. And for that very reason, careful interpretation is required while using at the emissive probes in plasmas with very high or very low densities. In general, this method is valid in the density range 10^{11}–10^{18} m^{-3}.[23] Smith *et al.* developed a method in an attempt to reduce space charge effects, which do not depend on strong emission and hence can be adapted in plasmas with higher densities.[27] The emissive probe emits electrons in the plasma when biased more negatively than the space potential and ceases to emit electrons, except for a small number due to the tail of emitted electron distribution, when the bias becomes more than the space potential. In the current-voltage (I–V) characteristics, the emissive probes have a wire-temperature (T_w) dependent exponential region, whereas the exponential region in case of collecting probes directly depends on the electron temperature (T_e). Since the probe wire temperature remains much less than plasma electron temperature ($T_w \ll T_e$), in most of the low temperature laboratory plasmas, where $T_e \geq 1$ eV, emissive probes can measure the plasma potential more accurately. When inserted inside the plasma and biased externally, the I–V curve of emissive probe contains two components of current: the collected current and the emitted current. The calculations remain simpler till the space charge effect are neglected and the simple basic equations of collecting current and emitting currents describe the qualitative working principle of emissive probes.

The collected current by the emissive probe is similar to the collecting Langmuir probes and given as[23]

$$I_c(V_b) = \begin{Bmatrix} I_{es}\exp(\frac{-e(V_p - V_b)}{T_e}) & \text{for } V_b \leq V_p \\ I_{es}g'(V_b - V_p), & \text{for } V_b > V_p \end{Bmatrix}. \quad (1)$$

Where I_{es} is the electron saturation current, V_b is the probe bias, V_p is the plasma potential, T_e is the electron temperature, and $g(V_b - V_p)$ is a function accounting for the angular momentum of the collected current, $g'(V_b - V_p)$ is its first derivative.

The additional emitted current present in emissive probes is given by

$$I_e(V_b) = \begin{Bmatrix} I_{eo} \quad \text{for } V_b < V_p \\ I_{eo}\exp(\frac{-e(V_b - V_p)}{T_w})g(V_b - V_p), \\ \text{for } V_b \geq V_p \end{Bmatrix}. \quad (2)$$

Where T_w is the wire temperature and I_{eo} is the temperature limited emission given by Richardson-Dushman equation

$$I_{eo} = AT_w^2 S \exp\left(\frac{e\Phi_w}{T_w}\right). \quad (3)$$

Where A is Richardson's constant, T_w is the probe wire temperature, S is the surface area of the probe wire, Φ_w is the work function of the material of the probe. Probe emits the emission current when bias voltage less than plasma potential but not above.

After obtaining the I-V characteristics of emissive probes experimentally, different methods are being implemented for estimating the plasma potential using I–V characteristics. The well-known methods are (1) separation point method,[28] (2) floating point method,[25] and (3) inflection point method in the limit of zero emission.[27] Out of these three, the floating point method given by Kemp and Sellen[25] is relatively simple and convenient technique to estimate the space potential. Although the most accurate, the inflection point method is lengthy and time consuming method, while separation point method mostly is an inadequate method.[8] Detailed information regarding comparison and choice of the technique that may be suitable to a particular plasma discharge system is thoroughly reviewed by Sheehan and Hershkowitz.[23] For the sake of completeness of this paper, a brief description of the estimation techniques are given below.

Separation point method compares the I-V characteristics of non-emitting and emitting modes of the same probe from below the plasma potential. The plasma potential is the lowest potential at which the collected current is same for the emitting and non-emitting modes. The point of separation in the superimposition of I-V characteristics from emitting and non-emitting modes reflects the plasma potential. The accuracy of this method is $\sim T_w/e$, though the uncertainty is much larger than T_w/e.

For a sufficient electron emission current from the probe material surface, the sheath potential around the probe surface will decrease and the floating potential approaches the plasma potential. So, when the probe is heated from no emission regime to high emission regime, the floating potential rises rapidly and became saturated at higher emission levels. This saturated floating potential is the plasma potential. Floating potential method determines the plasma potential with accuracy of the order of T_e/e and is suitable for measurements in lower electron temperature plasma and does not depend on plasma density. From the ease of measurement point of view, this method is the most apposite as it can directly measure the plasma potential by measuring the saturated floating potential for higher emission, rather than reading multiple floating potentials at different emission currents.

Inflection point method is developed by Smith *et al.*, to account for space charge effects associated with floating point method. Inflection point technique depends on the fact that inflection point of I-V traces of emissive probe approaches plasma potential in the limit of zero emission. As emission increases, the inflection point is shifted slightly towards the negative potential because of space charge effects and this shift varies almost linearly. Hence, to obtain the space potential, numbers of I-V characteristics are recorded while heating the probe slowly to moderate emission levels, i.e., emission current is of the order of electron saturation current. These inflection points are then extrapolated to zero emission where space charge effects are absent, which gives the plasma potential.

B. Laser heated emissive probes

Laser heated emissive probes are different from their conventional counterpart in terms of method of heating. The tip of LHEP is heated by high power lasers instead of electrical current, which is used to heat the conventional emissive probes. Heating the probe tips with lasers provides several advantages over conventional heating using currents as it neither requires potential drop across the tip to carry heating current nor any pulsed circuit to avoid issues with uneven potential drops across the probe. So LHEP gives accurate space potential with simple circuitry. LHEP avoids the above problems simply by its nature. Since there is no heating current required to pass though the material, its entire surface always stays at same potential and hence the potential drop issues across the probe material with CEP are effectively eliminated. Again, as no heating current passes through the LHEP probe tips, they are not subjected to any $J \times B$ forces when used in presence of magnetic fields. Hence, no deformation of LHEP probe tip occurs in strong electric and magnetic fields. The CEP suffers from frequent breaking of its current carrying element, which limits its usage in high vacuum systems where changing of filaments of CEPs is always irksome. Furthermore, proper design of holding structures of LHEP reduces the effect of support material on emission as well. Note here that LHEP differs from the conventional emissive probes only in terms of heating methodology and the plasma potential estimation mechanism remains same for the both. All the techniques described in Sec. II A for estimation of plasma potential remain same for LHEP and can be implemented on the LHEP I–V characteristics. LHEPs have been successfully used in many plasma devices to measure the plasma potential.[18–20]

III. EXPERIMENTAL SETUP

Experiments are carried out in a cylindrical stainless steel (SS) chamber having length of 50 cm and inner diameter of 20 cm. Base pressure of 1×10^{-5} mbar is achieved using a diffusion pump backed up by a rotary pump. The schematic diagram of the setup is as shown in Figure 1. Plasma is produced by filament discharge method, using two tungsten filaments of diameter 0.25 mm and length 5 cm, which are placed at the one end of the chamber and biased negatively with respect to the chamber.

Single Langmuir probe made up of tungsten wire of 0.5 mm diameter and 4 mm length is used to estimate the plasma parameters. The typical plasma density and electron temperature are $\sim 1 \times 10^{14}$ m^{-3} and 2–4 eV, respectively, for the plasma produced with helium at 1×10^{-3} to 5×10^{-3} mbar working pressure, discharge current of 250 mA–600 mA, and discharge voltage of -60 V. Sheath to be studied is produced in the vicinity of a SS plate of diameter 5 cm immersed in the plasma has been studied with emissive probes. This SS plate placed at the centre of the chamber is covered with Teflon cap on the backside and biased with negative potential of -30 V with respect to chamber to produce sheath.

As mentioned earlier, two different types of emissive probes are used to investigate the spatial potential profile, namely, conventional emissive probe and laser heated emissive probe. Conventional emissive probe of loop length 3 mm is made with tungsten wire of diameter 0.125 mm and length 7 mm. The tungsten wire is electrically connected to bunch of fine copper twisted wires in two single-bored ceramic tubes.[29] The electrical connections are brought outside the vacuum using two vacuum BNC connectors. The schematic diagram of the probes construction is shown in Figure 2. Laser heated emissive probe tip is made up of lanthanum hexaboride (LaB_6), which has low work function ~2.5 eV. The LHEP probe tip is of a tablet shape with diameter ~2 mm and thickness ~1.5 mm and is being held by one single-bored ceramic tube. The electrical connection is brought out through this ceramic tube. CO_2 laser of wavelength 10.6 μm has been used to heat the probe tip. The 2 mm diameter laser beam is focused on to the probe tip using a zinc selenide (ZnSe) lens. The details of LHEP used along with the measurements of emission current and temperature profile of LaB_6 material are presented elsewhere.[30] Spatial resolutions of LHEP and CEP are ~2 mm and ~3 mm, respectively; however, the shaft of CEP is bigger than that of LHEP as it has to accommodate two ends of curved tungsten wire. Usage of single ceramic tube to hold LHEP tip makes the probe shaft of LHEP smaller than the CEP shaft and hence disturbs the plasma less compared to CEP.

The schematic of the electrical circuitry for both the probes is shown in Figure 3. The two terminals of the filament probe are connected to the heating power supply through vacuum BNC and biasing power supply is connected to either positive or negative leg of the heating supply. The current flowing through the biasing circuit is measured by potential drop across the 500 Ω resistor. Floating potential method is adopted for sheath potential profile measurement using both the probes. In order to measure the floating potential accurately, the input impedance of the measuring device must be sufficiently high so the current drawn is as small as possible.[25] In the reported measurements, the floating potential is measured across a 1 MΩ resistor for both the CEP and LHEP.

Different techniques are compared to estimate the plasma potential for both conventional and laser heated emissive probes.

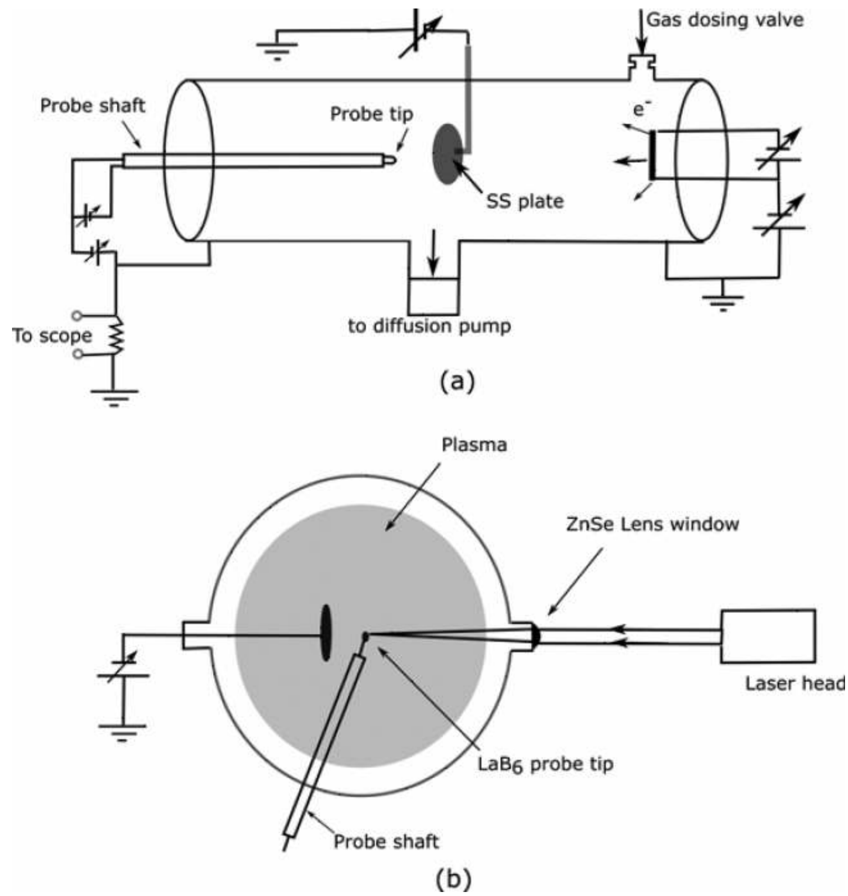

FIG. 1. (a) Schematic diagram of experimental setup. (b) Cross section through the device with Laser-heated probe setup.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experiments are carried out in two parts. The first set of experiment is to measure the plasma potential in the bulk region using both CEP and LHEPs. These experiments are carried out with working pressure $\sim 5 \times 10^{-3}$ mbar, discharge current ~300 mA, and discharge voltage of −60 V. Electron density and temperature in these plasmas are $\sim 5 \times 10^{14}$ m^{-3} and ~2.5 eV, respectively. The second set of experiment is carried out for measurement of sheath potential measurement, which is carried out in different parameter regime of plasma, i.e., working pressure $\sim 1 \times 10^{-3}$ mbar, discharge

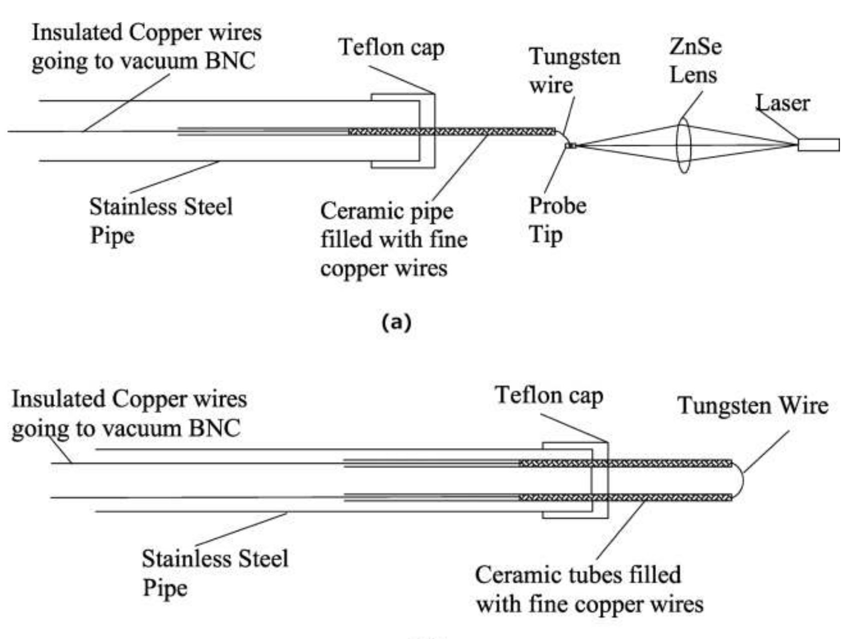

FIG. 2. (a) Schematic diagram of LHEP. (b) Schematic diagram of CEP.

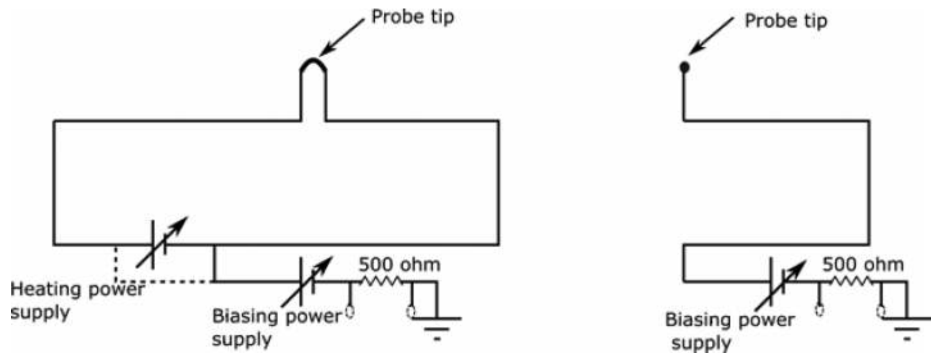

FIG. 3. Measurement circuit diagram of (a) CEP and (b) LHEP.

current ~600 mA, and discharge voltage of −60 V. Electron density and temperature in these conditions are $\sim 4 \times 10^{14}$ m^{-3} and 3 eV, respectively.

A. Estimation of space potential using CEP

In the experiments, the conventional emissive probe is operated as continuous emissive probe with DC current heating. After obtaining stable plasma in the system, the CEP is biased from −30 V to +30 V for obtaining the I-V characteristics in both cold and emitting conditions for different heating currents. Analysing the I-V characteristics, the plasma potential has been estimated using floating point method and inflection point method as described in Section II. The space potential values estimated from the separation point method are found to be erroneous as the I-V characteristics of cold and emitting probe do not match above crossing point and crossing point is also found to be sensitive to emitting current. Floating point method produced much better and consistent results. I-V characteristics of CEPs are plotted for different emission levels are plotted in Figure 4. From Figure 4, as the emission level increases, the floating potential shifts to more positive values initially and saturates at ~2.5 V at higher emission levels more than 4×10^{-4} A, giving the plasma potential. Plasma potential also estimated with the inflection point method, which is in good agreement with the floating point method. Because of the simplicity, we adopt floating point method throughout in this experiment.

We note here that as CEP carries the heating current, there exists a potential drop across the probe tip, which is exposed to the plasma. Therefore, the measured potential includes this potential drop in addition to the plasma potential. Further, the measured potential also depends on which leg of the probe has been connected to the measuring circuit. It has been observed that the measured floating potential differs by up to a maximum of ~3 V in these experiments for positive and negative probe leg connections of the heating circuit to the biasing-cum-measuring circuit as shown in Figure 5. This floating potential difference is proportional to applied heating voltage. This feature is quite common and has been studied in detail by Mravlag and Krumm.[21] As suggested in that Ref. 21, the floating potential is taken as average of these two values in this experiment. There is another method using two equal resistors in parallel with the CEP heating loop. From the point between the two resistors, the exact value of the plasma potential can be determined.[31] Hence, this choice of connection also results

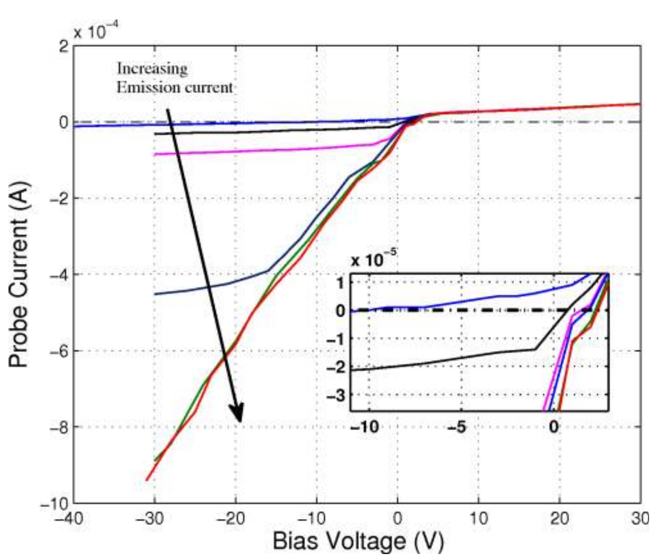

FIG. 4. CEP I-V traces for various emission levels in bulk plasma. It is clear from figure that floating point saturates for emission current is of the order of electron saturation current. Electron density and temperature are $\sim 5 \times 10^{14}$ m^{-3} and ~2.5 eV, respectively.

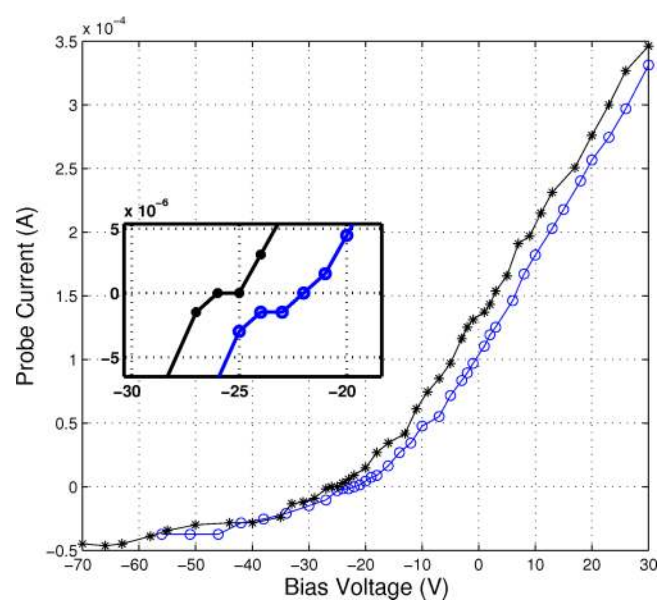

FIG. 5. CEP I-V traces for bias circuit connected to different legs of the probe; (-o-) for connection to positive leg and (-*-) for negative leg.

in substantial errors in plasma potential measurements with floating point technique with CEP. The pulsed (AC) emissive probe can avoid this problem by measuring I-V characteristics in the non-heating cycle and will give accurate plasma potential, but it requires a sophisticated electronic setup, which is very sensitive to stray signals. In absence of the sophisticated electronic circuitry, the CEP measurements are carried out as simple continuous emissive probe.

B. Estimation of space potential using LHEP

The complete exercise is repeated with the I-V characteristics obtained with LHEP. The probe is heated to different temperatures by varying the CO_2 Laser power. Figure 6 shows the I-V characteristics obtained with LHEP at different heating powers, i.e., at different emission levels. As the emission current is increased, the floating potential decreased and saturated at ~3 V at above the heating power of ~20 W giving space potential ~3 V in the plasmas produced with exactly same operational parameters where the CEP are used.

C. Sheath potential profile measurement using CEP and LHEP

As described in the Introduction, the study of plasma sheath is very important, since sheath plays an important role in most phenomena like confinement of charged particles, heat load to the physical boundary. The sheath thickness and its potential structure are measured by many authors[4–7] using the emissive probes to understand the nature and dynamics of sheaths. In this paper, an attempt has been made to measure the sheath potential structure formed in front of a stainless steel plate immersed in the plasma using a laser heated emissive probe for the first time. To compare the results obtained using the LHEP, a CEP is also kept alongside the LHEP. In this set of experiment, the helium plasma is produced at working pressure of 1×10^{-3} mbar, discharge voltage −60 V, and discharge current 600 mA. Plasma potential is estimated by

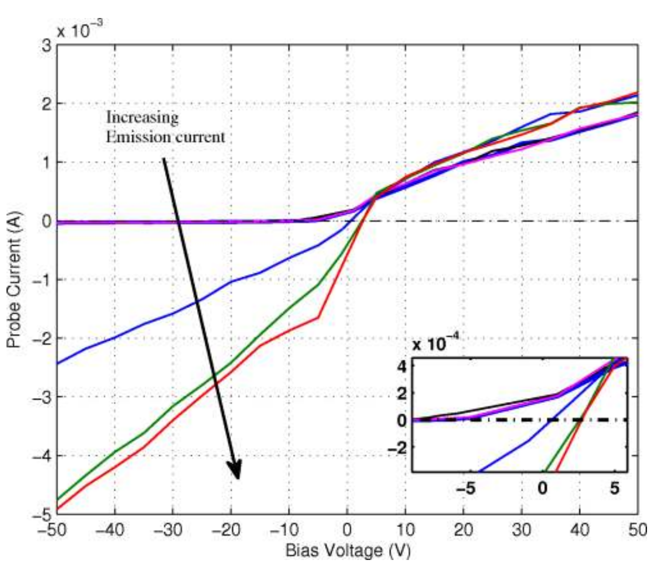

FIG. 6. LHEP I-V traces for various emission levels in bulk plasma. Electron density and temperature are $\sim 5\times10^{14}$ m^{-3} and ~2.5 eV, respectively.

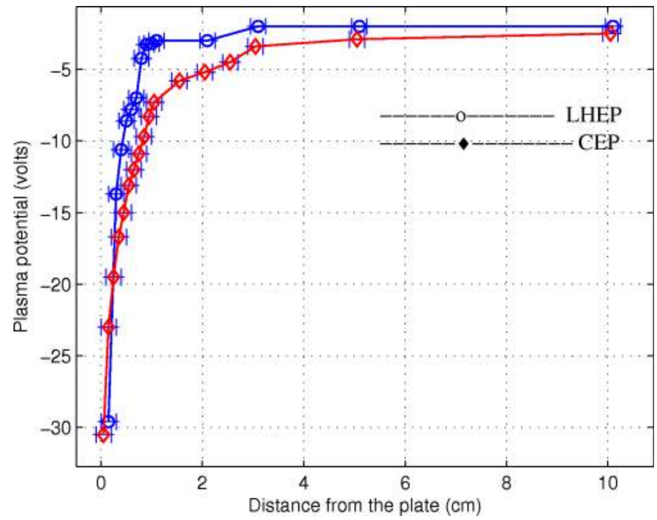

FIG. 7. Potential profile measured with LHEP and CEP for various distance from the plate surface. The error bar in distance (x-axis) is ±1.5 mm. Electron density and temperature are $\sim 4\times10^{14}$ m^{-3} and ~3 eV, respectively.

floating potential method using both the CEP and LHEP. The space potential measured with CEP and LHEP from sheath region to bulk region through presheath region and is plotted in Figure 7. Within the experimental uncertainties in the positions of both the probes, the LHEP always measured higher values of space potential at similar locations across the sheath and bulk plasma than that measured with CEP. The difference in measured space potential values by both the probes remains less (~0.5–0.7 V) in the bulk plasma, whereas differences up to ~5 V are observed in the region joining the sheath and bulk plasma, generally known as presheath. Further detailed studies are required to establish the cause of this large difference in the measured values of space potential in the presheath region by both the probes.

The presheath potential profile measured with LHEP is fitted with the formula[32] $\boldsymbol{\phi} = \boldsymbol{\phi}_0 + \boldsymbol{T_e}\sqrt{\frac{(x-x_0)}{\lambda}}$ as shown in Figure 8, where $\boldsymbol{\lambda}$ is the ion-neutral collision mean free path, $\boldsymbol{\phi_0}$ is the potential at the sheath edge $\boldsymbol{x_0}$. In case of LHEP, the potential drop ~4 V in the presheath region is of the order of T_e/e. The sheath-presheath boundary is determined by extent of the potential profile well-fitted with the Child's law. Hence, the plasma potential profile near the plate measured with LHEP is fitted with Child's law[32] (shown in Figure 8) to determine the sheath-presheath boundary. The experimentally measured potential profile with CEP fits well with Child's law up to 3 mm away from the plate, whereas the data obtained with LHEP fit the Child's Law well up to 4 mm away from the plate. Hence, both the probes measured almost same sheath thickness. The sheath thickness calculated using the formula,[32] $S = \frac{\sqrt{2}}{3}\lambda_{Ds}\left(\frac{2V_0}{T_e}\right)^{3/4}$ where, λ_{Ds} is the Debey length at sheath edge, V_0 is the potential on the plate, and T_e is the electron temperature. Sheath thickness comes out to be ~6 mm, which is closer to the value obtained with LHEP in comparison to CEP.

The measurements of plasma potential in the sheath, presheath, and in the bulk plasma region of filament produced plasma using LHEP match quite well with available theoretical models and also are comparable to those obtained with CEP.

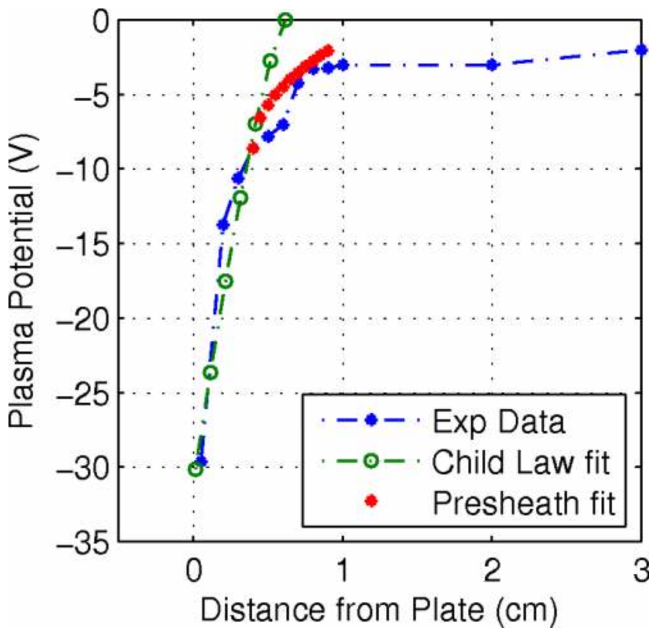

FIG. 8. Child law and Presheath potential fit to the LHEP experimental data. The measurement errors are within ±5%.

Therefore, the reported measurements with LHEP further establish its capabilities of plasma potential measurements in various regions of plasmas having different electric field gradients.

V. CONCLUSION

In order to establish the plasma potential measurements using the recently developed laser heated emissive probes, plasma potential profiles in sheath, presheath, and bulk plasma region have been measured. The plasma potential in the same regions has also been simultaneously measured with conventional current-heated emissive probes and the results are compared. Both the probes measure the almost same plasma potential in the bulk plasma region. The CEP measures the sheath thickness of ∼3 mm, whereas the LHEP measures the sheath thickness of ∼4 mm close to the theoretically estimated value of ∼6 mm. The measured values of plasma potential using both the probes differ significantly in the presheath region. Therefore, it can be concluded that with several advantages over CEP, the LHEP can be used effectively in measurements of plasma potentials in plasmas.

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