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Experimental studies of the difference between plasma potentials measured by Langmuir probes and emissive probes in presheaths

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Abstract

The plasma potential measured by cylindrical and planar Langmuir probes has been shown to differ from the plasma potential measured by emissive probes in the neighborhood of the presheath near a negatively biased electrode immersed in a weakly collisional low temperature argon plasma. There are two principal results demonstrated in this paper. First, while it is well known that Langmuir probes cannot reliably measure plasma potentials inside of sheaths, results presented here demonstrate that the problem persists in presheaths, the quasineutral plasma bordering sheaths. It is known that emissive probes analyzed in the limit of zero emission accurately measure the plasma potential in the sheath. It is now clear that they are the only known electrostatic probe technique able to measure the plasma potential accurately throughout the presheath. Second, it is shown that the difference between potential measurements made by Langmuir probes and emissive probes in the body of the plasma, farther than a presheath distance from the boundary, is not proportional to T_e, as has been previously claimed.

Keywords: Langmuir probes, emissive probes, plasma sheath, Bohm's criterion, plasma boundary layers, electrostatic probe diagnostics

1. Introduction

Langmuir probes have been one of the most important diagnostics of particle flux in the field of plasma science for almost a century [1]. Used aboard satellites [2–4], in plasma processing experiments [5–8], at boundaries in tokamaks [9–11], and in a host of fundamental plasma physics experiments past and present spanning the range of plasma densities and temperatures represented by these applications ($10^2 \leqslant n_e \leqslant 10^{13}$ cm $^{-3}$, and $10^{-3} \leqslant T_e \leqslant 10^2$ eV), Langmuir probes have been useful over a very wide range of plasma parameters. At the same time Langmuir [12] invented the probe that bears his name (circa 1923), he also invented the emissive probe, now primarily used as a diagnostic of plasma potential, the accuracy of which has been improved by refinements in technique [13–16]. It is a diagnostic of utility in an even wider variety of environments (for example, it can be used to measure space potentials in a vacuum [17]). The focus of this paper is the comparison of these two principal diagnostics in the measurement of plasma potentials near boundaries in low temperature, low pressure ($P_n \leqslant 1$ mTorr, and therefore weakly collisional) plasma, where it has been assumed that the two types of measurement agree [18].

It is conventional wisdom that Langmuir probes do not reliably measure plasma potentials inside of sheaths. It is also well known that emissive probes, analyzed using the inflection point technique in the limit of zero emission [14, 19], give accurate measurements of the plasma potential even inside of sheaths, *and that is the method used in this paper*. In this work we present results demonstrating that the problem with Langmuir probes persists in presheaths, that is, in the quasineutral plasma bordering sheaths. It is also shown that differences between measurements of plasma potentials by emissive probes and Langmuir probes exist in the body of the plasma, farther than a presheath distance from the boundary. This is well known and consistent with previous work, for example, that of Knappmiller and Robertson [20]. However, we show that these differences are not proportional to T_e, as has been previously assumed [15, 21]. These two findings are the principal results of this paper.

The layout of the paper is as follows. In section 2, the basic design of the experiments and the diagnostics are described. In section 3 we present the principal results of the work, and we discuss these results in section 4.

2. Experimental configuration and design

The basic design of the experiment was to set up a presheath-sheath structure using a negatively biased electrode immersed within a large plasma volume, well known to produce directed ion flow toward the electrode, ranging from zero to the ion acoustic speed [22, 23]. We wished to observe if under those conditions, the usual determination of the plasma potential in the neighborhood of the sheath using Langmuir probe current–voltage (I–V) characteristics still hold valid, calibrated by emissive probe measurements. Both probe methods involved calculating derivatives of the I–V characteristics, and we note that the dI/dV curves were smoothed using a Savitzky–Golay algorithm with a second order polynomial and a 20 point window.

Our work was motivated by potential profile measurements made in a multidipole chamber at the University of San Diego [24], with a Langmuir probe. The multidipole chamber is similar to the one at the University of Wisconsin, Madison, to be described presently. Near a negatively biased electrode (-100 V) we made routine plasma potential profile measurements with an emissive probe followed by a non-routine plasma potential profile measurement using a planar Langmuir probe. It was observed that plasma potentials obtained from Langmuir probe I–V (current voltage) characteristics never went negative; indeed, they became more positive as the probe approached the electrode, demonstrating a clear disagreement between the two methods of measuring plasmas potentials. This was not surprising for measurements taken within the sheath, however, the beginning of the difference occurred well before the Langmuir probe entered the sheath. We were prompted by these results to study the Langmuir probe results in much more detail. The experimental results presented here confirm and significantly extend those results, demonstrating that the disagreement extends into the quasineutral presheath.

The multidipole chamber used in our experiments is described elsewhere [25] and is shown in figure 1. All discharges were argon discharges. Briefly, impact ionization of argon gas was achieved with energetic electrons emitted

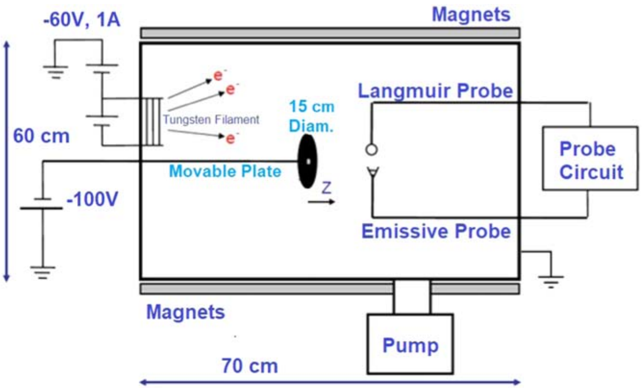

Figure 1. Multidipole plasma chamber and probe diagnostics.

thermionically by hot tungsten filaments biased negatively with respect to grounded chamber walls. The bias voltage was much greater than the ionization potential of the neutral argon atom (15.8 V). The base pressure of the chamber was approximately 2.5 μTorr. The neutral pressure P_n was varied from 0.1 to 1 mTorr. A movable 15 cm diameter plate was positioned on the axis, and was biased at -100 V with respect to the ground to create a sheath and presheath in the plasma. Movable planar Langmuir probes with a 6.4 mm diameter probe tip were inserted from one of the end walls with surfaces parallel to the plate, opposite to the one on which tungsten filaments were installed, to measure the plasma density n_e, electron temperature T_e, and plasma potential, V_p. Standard techniques described in the next section were used to measure plasma potentials, V_p. An emissive probe was inserted from the same end wall as the Langmuir probe. Both probes could be rotated or positioned on the axis of the plate. The filament of the emissive probe was parallel to the plate and was made of a thoriated tungsten wire 0.025 mm in diameter and approximately 7 mm in length.

3. Principal measurements and results

Plasma potentials were measured with an emissive probe and four different Langmuir probes: a cylindrical Langmuir probe (10 mm length, 0.025 mm diameter, tungsten), a double sided planar, circular disk, Langmuir probe (6.4 mm diameter, tantalum), and two variants, one that was coated with ceramic paste on the side facing the boundary plate, and one that was coated on the side facing the bulk plasma. In the following, Langmuir probes are indicated by the notation, LP_k, where k is an integer from 1 to 4, with 1 referring to the cylindrical Langmuir probe, or LP_1, 2 referring to the planar Langmuir probe, 3 and 4 referring to the Langmuir probe with coating on the side facing the boundary plate, or on the side facing the bulk plasma, respectively. Plasma parameters, including the Child–Langmuir sheath thickness, derived from the uncoated planar Langmuir probe measurement (LP_2) in the bulk plasma, are listed in table 1. The diameter of both emissive probe and cylindrical Langmuir probe filaments are at least 5 times smaller than the Debye length for all cases. For planar electrodes such as for the boundary plate depicted in figure 1,

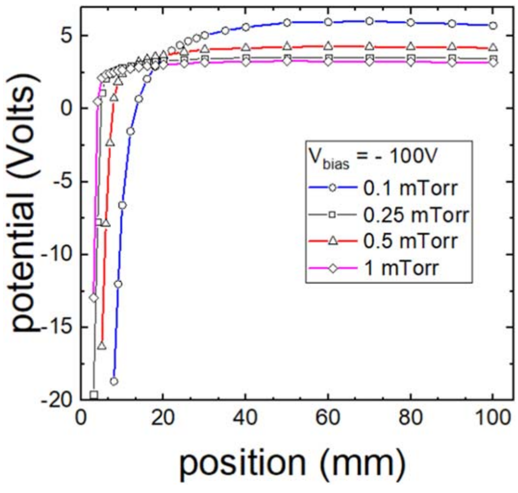

Figure 2. Plasma potential profile by emissive probe for different neutral pressures.

Table 1. Plasma parameters for these experiments, neutral pressure, electron temperature and density, Debye length, and Child–Langmuir length.

P_n (mTorr)	T_e (eV)	n_e (10^8 cm^{-3})	λ_D (mm)	d_{CL} (mm)
0.1	4.0 ± 0.1	3 ± 2	0.86	7.6
0.25	1.9 ± 0.1	10 ± 2	0.33	5.1
0.5	1.3 ± 0.1	22 ± 2	0.18	4.1
1	1.0 ± 0.1	39 ± 2	0.12	3.0

the planar Child–Langmuir sheath thickness [26] is a measure of how far from the biased electrode the space-charge layer persists in units of Debye lengths, $d_{CL} = 2^{5/4}(V_{bias}/kT_e)^{3/4}\lambda_D/3$. Our claim that differences between the plasma potential measured by Langmuir probes and emissive probes exist in the presheath (and not just the sheath) rest principally on whether or not it is noticed that differences between those measured plasma potentials occur at distances of multiples of d_{CL} from the biased electrode.

Plasma potentials were obtained by all five probes for four different neutral pressures. The emissive probe profiles shown in figure 2 were indicators of the true local plasma potential for each case. For relatively higher neutral pressures we observed a shorter presheath, consistent with the presheath scale length scaling with the ion-neutral mean free path, well known [27] to be inversely proportional to the neutral pressure.

Consider the intermediate pressure case, $P_n = 0.25$ mTorr, shown in figure 3. Compare the plasma potential profiles measured by the emissive probe Φ_{EP}, with those by Langmuir probes (Φ_{LP_k}) for all k. The first thing to notice is that the plasma potential in the bulk plasma measured by the emissive probe is higher than that measured by each LP_k, and other than a small offset, the profiles are relatively flat (not changing with position relative to the biased plate) and the same. However, by 20 mm, *between* 3 *and* 4 d_{CL}, the two Langmuir probes in widest use, the cylindrical Langmuir probe and the planar

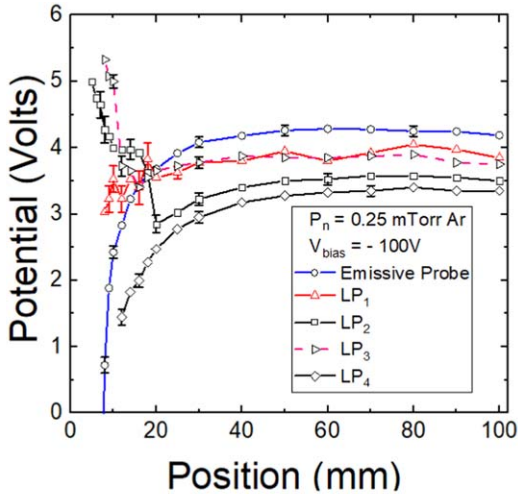

Figure 3. Plasma potential profiles measured by by emissive probe, cylindrical Langmuir probe and the three different planar Langmuir probes for $P_n = 0.25$ mTorr.

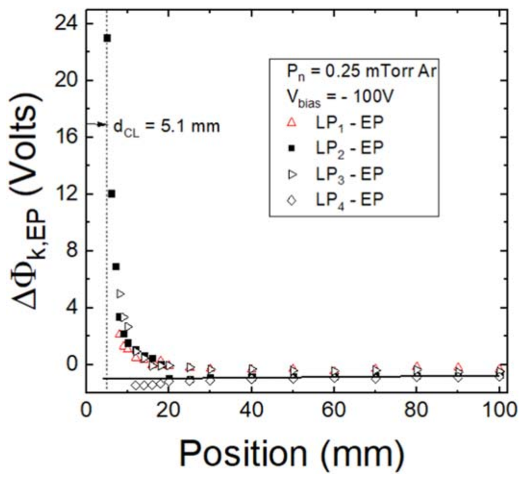

Figure 4. Plasma potential differences as a function of position relative to the biased electrode for all four Langmuir probe types. The pressure was $P_n = 0.25$ mTorr. The black line models the difference for the two sided planar Langmuir probe. The dotted vertical line marks d_{CL}, the calculated sheath edge.

Langmuir probe (uncoated), either remains flat (the cylindrical probe) or trends upward positively as the probes approach the sheath set up by the negatively biased plate, while the true plasma potential becomes quite negative. That is, $\Phi_{LP_{1,2}} - \Phi_{EP} > 0$ and becomes increasingly positive. However, these differences occur in the presheath. This is one of the main results of the paper.

In figure 4, we graph $\Delta\Phi_{k,EP} \equiv \Phi_{LP_k} - \Phi_{EP}$, for all k. Noticing that each curve is more or less flat in the bulk, and fitting a straight line to them (as shown for $\Delta\Phi_{2,EP} = \Phi_{LP_2} - \Phi_{EP}$), departures of the data points from a flat line for each curve locates where in the plasma differences occur between *the shapes of the plasma potential profiles*. As described above, for the two sided planar Langmuir probe, $\Delta\Phi_{2,EP}$ begins to depart from the straight line model approximately 20 mm from the boundary plate, or 4 times d_{CL}. The nominal thickness of the sheath in this case is 5.1 ± 0.5 mm and the difference $\Delta\Phi_{2,EP}$ becomes greater than

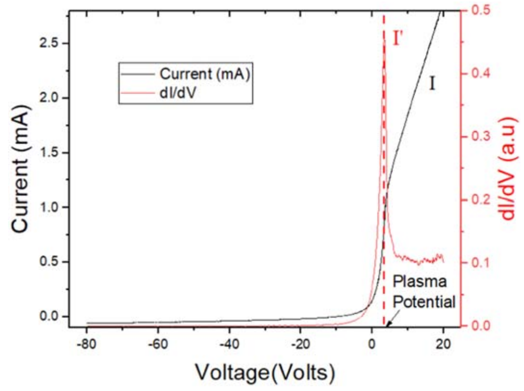

Figure 5. *I–V* characteristics and the first derivative of the single sided planar Langmuir probe that collects current on the plate side, LP_4, for $P_n = 0.25$ mTorr at 60 mm from the boundary plate.

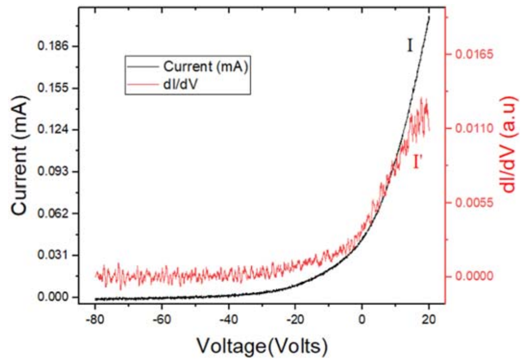

Figure 6. *I–V* characteristics and the first derivative of the single sided planar Langmuir probe that collects current on the plate side, LP_4, for $P_n = 0.25$ mTorr at 8 mm from the boundary plate.

20 V there, which is greater than $10T_e/e$, a significant difference. This observation holds for all of the Langmuir probes more or less, with exceptions that we will describe presently. But the most important observation is that the Langmuir probes used most commonly, LP_1 and LP_2, the cylindrical and uncoated two sided planar Langmuir probes, are significantly in error relative to the true plasma potential, large compared with T_e/e, well before the probe has reached the sheath edge.

It was observed that the inflection point method became less and less useful for measuring plasma potentials the nearer the Langmuir probes came to the sheath edge. The *I–V* characteristics were such that, in part due to increased noise, in part due to reduced signal, the first derivative of the current with respect to the voltage no longer possessed an extremum somewhere in the neighborhood of the appearance of space charge, as determined by the estimate of d_{CL}. The closest position for which we could still determine the plasma potential in this way varied with probe type; LP_2 (two sided planar disc probe) could get the closest, useful even in the space charge region to some extent, and LP_4 (single sided planar disc probe, collecting side facing the plate) the farthest, ceasing to be useful in the near (to the plate) presheath, with the others intermediate between these two types. The *I–V* characteristics for LP_4 are shown as a general example of this, along with the first derivative of the current with respect to the probe voltage, at two different positions, in figures 5 and 6, showing a very sharp maximum in current versus probe voltage in the bulk plasma, 60 mm from the biased plate, and the loss of the extremum when the probe is too close (8 mm) to biased plate. Also notable was that LP_4 best mirrored the potential profile of the emissive probe. The magnitude of the difference with the emissive probe profile, $|\Delta\Phi_{4,EP}|$, was the smallest overall compared with the other Langmuir probe types.

The general features of the $P_n = 0.25$ mTorr case may be readily observed in the 0.1, 0.5, and 1.0 mTorr as well, and the plasma potential profiles for these pressures are found in figures 7, 8, and 9, respectively. As the pressure rises, the sheath thickness shrinks. The distance of separation between

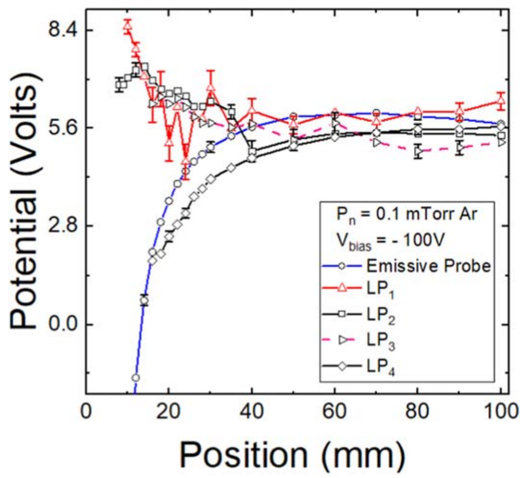

Figure 7. Plasma potential profile by emissive probe, cylindrical Langmuir probe and different planar Langmuir probes with $P_n = 0.1$ mTorr.

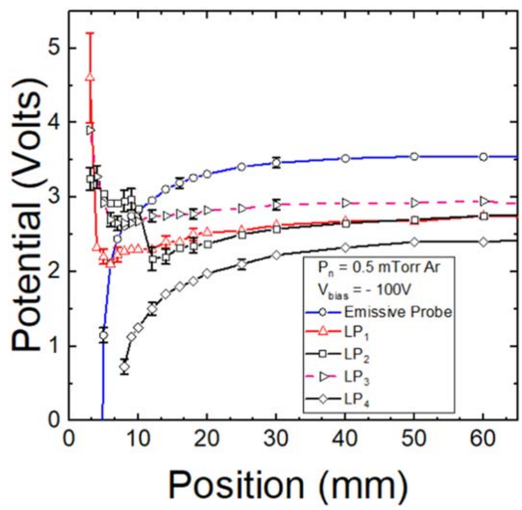

Figure 8. Plasma potential profile by emissive probe, cylindrical Langmuir probe and different planar Langmuir probes with $P_n = 0.5$ mTorr.

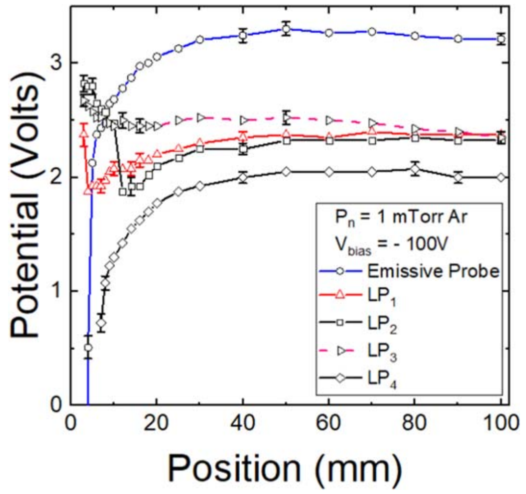

Figure 9. Plasma potential profile by emissive probe, cylindrical Langmuir probe and different planar Langmuir probes with $P_n = 1$ mTorr.

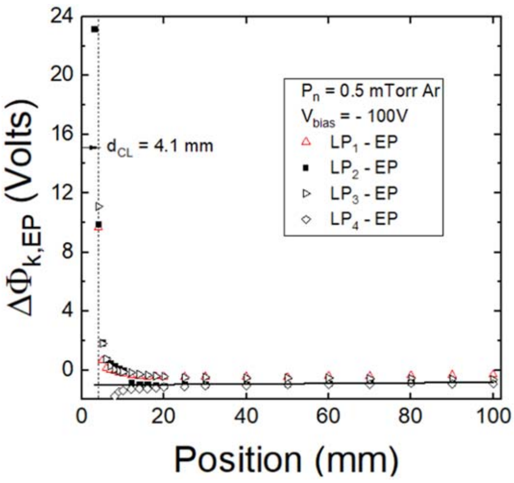

Figure 11. Plasma potential differences as a function of position relative to the biased electrode for all four Langmuir probe types, for the case, $P_n = 0.5$ mTorr. The black line models the difference for the two sided planar Langmuir probe.

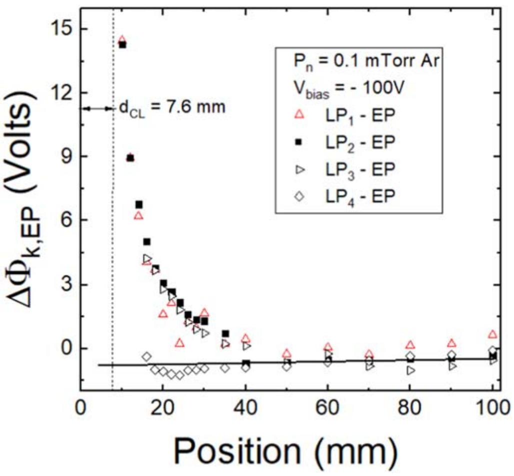

Figure 10. Plasma potential differences as a function of position relative to the biased electrode for all four Langmuir probe types, for the case, $P_n = 0.1$ mTorr. The black line models the difference for the two sided planar Langmuir probe.

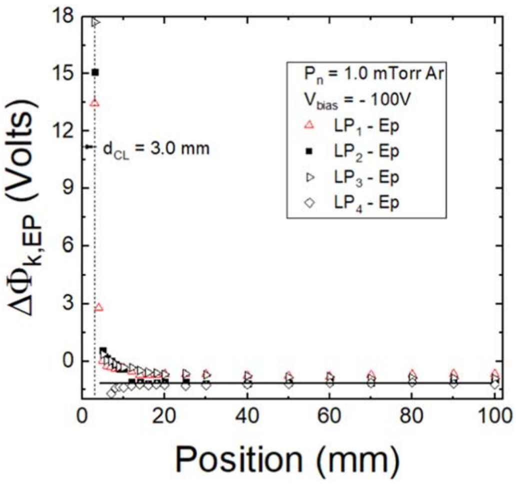

Figure 12. Plasma potential differences as a function of position relative to the biased electrode for all four Langmuir probe types, for the case, $P_n = 1.0$ mTorr. The black line models the difference for the two sided planar Langmuir probe.

the plasma potential profiles of LP_1 (cylindrical probe) and that of the emissive probe profile is greatest for the 0.1 mTorr case (about 40 mm) and least for the 1 mTorr case (about 10 mm), but in all cases the point of separation exceeds 3 to 4 $d_{\rm CL}$, and this was true also for the double sided planar Langmuir probe, LP_2. Again, in each case (for all pressures considered) it was LP_4, the single sided Langmuir probe collecting current on the side facing the biased plate that most closely followed the emissive probe profile (apart from a small offset) with the smallest magnitude of difference, $|\Delta\Phi_{k,EP}|$, of all of the probes. The graphs of plasma potential differences $\Delta\Phi_{k,EP}$, for the cases 0.1, 0.5, and 1.0 mTorr, respectively, are found in figures 10–12.

Next and finally, the offsets between the plasma potential profiles of the Langmuir probes and the emissive probe in the bulk plasma were examined for the different pressure cases. In low pressure discharges such as these, it is common that as the neutral pressure falls, the electron temperature rises, as shown in figure 13, for LP_1, the cylindrical Langmuir probe. Since the emissive probe profiles were relatively flat, we took as an estimate of the $\Delta\Phi_{1,EP}$, the average of $\Delta\Phi_{1,EP}$ at each position between 50 and 100 mm from the plate with an increment of 10 mm. Then, since the pressure was varied, the dependence of the offsets on the electron temperature could be assessed. It was observed that as the electron temperature diminished, the plasma potential difference increased. This is clearly seen in figures 13 and 14. Indeed, they diminished, even changed sign as the temperature increased, all clearly indicating that the differences between the two potential measurements were *not* proportional to T_e/e. This is second principal result of the paper.

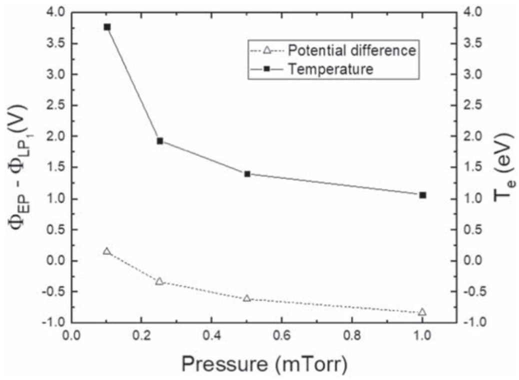

Figure 13. Plasma potential difference between LP_1 and EP, and electron temperature at different pressures.

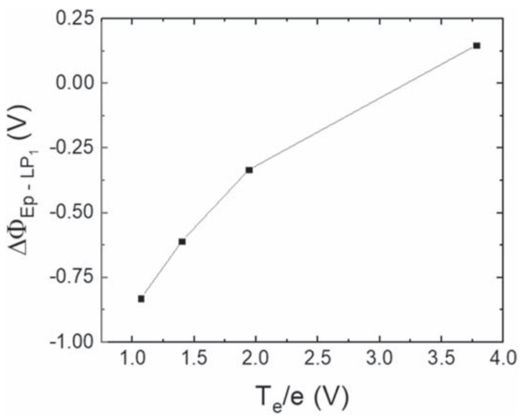

Figure 14. Plasma potential difference between LP_1 and EP, and $\Phi_{LP_1} - \Phi_{EP}$ as a function of electron temperature.

4. Discussion

Both of these principal results are unexpected in some way, and we treat the second result having to do with offsets in the body of the plasma first. The accuracy of plasma potential measurements made using emissive probes vary according to technique, whether one uses the floating point method, inflection point in the limit of zero emission used in this work, or the separation method. It has been shown that of the three techniques, the inflection point technique is least susceptible to space-charge issues, the most important issue with emissive probes. In Sheehan's work [15], this accuracy has been subjected to model predictions based on Ye and Takamura's analytical work [30], showing that inflection point technique in the limit of zero emission is accurate to within $(T_e/10e)$ for the range of parameters considered. Moreover, Demidov [21] and others [1] cite the agreement of Langmuir probe (planar) measurements of plasma potential compared with that of emissive probes to be within T_e/e. Thus, one might reasonably expect that as the electron temperature rises, the average difference between Langmuir probe and emissive probe measurements of the plasma potential should also rise. It is found that this is not the case. This is an interesting result for which there exists at present no obvious model. We speculate that the difference could depend on factors such as degree of nonlocality, collisionality, and so forth, that is, the result could be plasma discharge dependent, something of critical importance to understand.

The principal result of greater importance however is the observed difference of the plasma potential *profiles* in the presheath as opposed to their offsets in the body of the plasma. The latter are relatively small and the former grow to be large compared with $T_e/$e. It is argued here that this is an effect of ion flow in the vicinity of the biased electrode that is inherent in the process of sheath formation. Emissive probes are not sensitive to this flow, but Langmuir probes are. For example, modification to Langmuir probe *I–V* characteristics due to drifting Maxwellian electrons, non-Maxwellian electrons, and energetic electron primaries present in hot filament discharge devices are known to occur in the ion branch [28, 29], i.e. that portion of the *I–V* characteristic for which the probe bias potentials are negative with respect to the plasma potential. These are not of concern in this work.

Before discussing work pertinent to the electron branch of Langmuir probe *I–V* characteristics, it is important to mention a result of interest to our study performed earlier by Knapmiller and Robertson, [20] in which emissive probe and cylindrical Langmuir probe potential profiles, in a weakly collisional low temperature plasma were compared. Their measurements included the region near wall of the vacuum chamber and penetrated into the sheath region. They observed that the plasma potential radial profile measured by the cylindrical Langmuir probe was flat in the body plasma and that in the sheath region closest to the wall, the plasma potential actually grew more positive. However they noted that the plasma potential measured by the emissive probe gradually became more negative radially, becoming parabolic downward in the presheath. Our results are consistent with their results in this regard.

Work conducted in the late 70s and early 80s by Weber *et al* [31] and Skøelv *et al* [32] examined effects of cold ion beams on the electron branch of *I–V* characteristics which are directly pertinent to this work. They showed that planar Langmuir probes, and *not* cylindrical probes, can be used as an effective indicator of local ion flow. Their experiment used a double plasma device to control the energy of an ion beam in the target chamber. They showed, surprisingly, that the signature of the ion beam in the electron branch of the *I–V*-characteristic was *not a decrease in the collected probe current, but rather a much larger than expected increase in the electron saturation current,* ΔI_b, indicated by a second knee, clearly visible when the beam energy E was sufficiently large compared with T_e and the beam temperature T_b was cold compared with T_e. This is seen clearly in figure 15, which was adapted from Skøelv *et al* [32], figure 1. Their modeling results also indicated, consistent with their measurements, that the addition of an ion beam caused an increase in the electron saturation current at probe voltages above the plasma potential by an amount corresponding to the beam energy, E, the sharpness of which depended on T_b. Their work supported the claim that the second knee was caused by sheath expansion arising from an alteration of the local space charge surrounding the probe, once the probe bias was positive enough

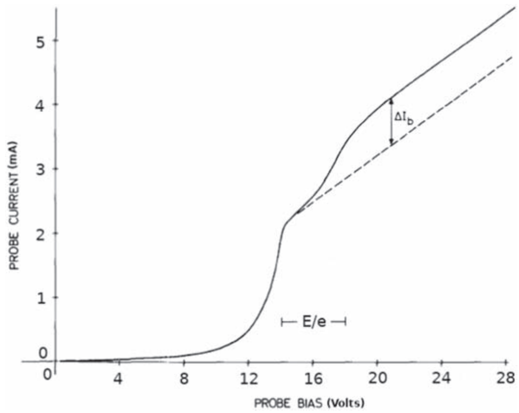

Figure 15. Ion beam contributes to an increase in the electron saturation branch.

to stop the ion flow. The effect was directional, and led them to attempt measurements with planar probes with one side coated with an insulator, and oriented at various angles with respect to the beam direction. The modification of potential structure surrounding the probe was dramatic for planar probes, enhancing the effective electron current collecting area. This effect was minimal for cylindrical probes, even for $r_{\rm probe}/\lambda_D$ of the order of unity [32]. And they did not observe the second knee with a planar Langmuir probe oriented with the insulated side facing the ion beam.

Arguing qualitatively, using their results to predict what would happen in our experiment, two of our results appear to be immediately consistent. First, it seems plausible, as they did not see the second knee with the coated side facing the beam, that we might expect to observe the least difference between the plasma potential profiles (ignoring the offset) of LP_4 and that of the emissive probe, which in fact we do.

Secondly, and more importantly, their work focused on ion beam cases with the characteristic ratios, $20 < T_e/T_b < 70$, and $5 < E/T_e < 20$, trying to observe the second knee. We too have subjected Langmuir probes to ambient plasma conditions in which there is a drifting ion population, but with this difference, that $0 < E/T_e < 1/2$, the upper bound corresponding to Bohm's criterion, and $T_b \leqslant T_e$. This is the well known phenomenology [22, 23] of ion flow to the sheath edge in simple single ion species, low pressure, plasma. It seems plausible therefore, that the second knee would be no longer distinct from the knee of the plasma potential in our case, leading to an inaccurate measure of the plasma potential, even shifting the effective knee of the current voltage characteristic to values more positive than the true plasma potential, which is indeed what we observe.

Not everything in the cold ion beam model, of course, could be expected to model qualitatively our results. It is surprising, arguing analogically from the cold beam model, that the cylindrical probe plasma potential measurements are affected as much as the double sided planar Langmuir probe measurements in this regard. There are important distinctions between the work of Weber *et al* [31] and Skøelv *et al* [32], and the work reported in this paper. The ion flow in the experiments reported here is not a cold beam but a diffuse one, owing to the velocity dependence of the principal source of ion collisionality for single ion species plasma, charge-exchange collisions, which has a higher cross section for low speed ions than for fast ones [33]. This interaction is known to yield ion velocity distribution functions that are asymmetric about the peak value [23, 34], distended on the low velocity side as the ions accelerate toward the sheath edge. The ion speeds can stretch from zero to the Bohm speed in the presheath. That these collisions are important is reflected in the scale length of the presheath, which for the range of parameters for our experiment, is determined by the ion neutral collision mean free path [35, 36]. For the experiments reported here, the ion-neutral mean free path varied from 3 to 30 cm, as the neutral pressure varied from 1 to 0.1 mTorr. This is why the presheath was clearly shorter for the 1 mTorr neutral pressure case than the 0.1 mTorr, shown in figure 2. Another difference is that the ion flow in the case of sheath formation is not partial. In other words, in our experiment, there is not a stationary background (ion) plasma with the addition of a smaller population drifting cold ions into which the diagnostics were immersed. Near the biased electrode that sets up the sheath and presheath structure in the experiment described here, *all* the ions flow toward to the biased electrode.

The main contributions of this paper are phenomenological. We observe that planar and cylindrical Langmuir probe measurements of potential differ from the true plasma potential in the quasineutral presheath. The emissive probe potential measurement (analyzed in the limit of zero emission) is the only measurement that works in the sheath. It is also the only diagnostic that works throughout the presheath. Neither the cylindrical nor the planar Langmuir probe potential measurements agree with the emissive probe plasma potential measurements throughout the presheath, although in the case of the bulk sided coated Langmuir probe, there is markedly better agreement. These results are important where one attempts to use Langmuir probes to measure plasma potentials near boundaries where ion sheaths form. We also observe that the difference between the plasma potentials measured by emissive probes and Langmuir probes, both planar and cylindrical, are not found to be directly proportional to T_e. This is important because the difference could depend on factors such as degree of nonlocality, collisionality, the type of plasma source used, and so forth, and thus the assumption that the difference is proportional to T_e may not be generally true. We have not presented a model for these results, although we have shown that a step in the direction of successfully modeling them has been made with the help of experimental studies of cold ion beams diagnosed by Langmuir probes in double plasma devices performed by Weber *et al* [31] and Skøelv *et al* [32].

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