Understanding Langmuir probe current-voltage characteristics

Robert L. Merlino[a)]
Department of Physics and Astronomy The University of Iowa, Iowa City, Iowa 52242

(Received 26 February 2007; accepted 14 July 2007)

I give several simple examples of model Langmuir probe current-voltage (I-V) characteristics that help students learn how to interpret real I-V characteristics obtained in a plasma. Students can also create their own Langmuir probe I-V characteristics using a program with the plasma density, plasma potential, electron temperature, ion temperature, and probe area as input parameters. Some examples of Langmuir probe I-V characteristics obtained in laboratory plasmas are presented and analyzed. A few comments are made advocating the inclusion of plasma experiments in the advanced undergraduate laboratory.
[DOI: 10.1119/1.2772282]

I. INTRODUCTION

Plasma physicists use Langmuir probes in low temperature plasmas[1] (approximately a few electron volts) to measure the plasma density, electron temperature, and the plasma potential. A Langmuir probe consists of a bare wire or metal disk, which is inserted into a plasma and electrically biased with respect to a reference electrode to collect electron and/or positive ion currents. Examples of the use of a cylindrical (wire) probe in a gas discharge tube and a planar disk probe in a hot filament discharge plasma are shown in Fig. 1. Probes, initially called "sounding electrodes," were first used in the late 19th and early 20th centuries in an attempt to measure the voltage distribution in gas discharges. A gas discharge [Fig 1(a)] is produced in a glass tube of about 2–5 cm diameter and 20–40 cm long, which contains metal disk electrodes (anode and cathode) at both ends. The tube is first evacuated and then refilled with a gas at low pressure (about 1 Torr or less) and an electrical discharge (ionized gas or "plasma") is formed by applying a DC voltage of 300–400 V across the electrodes. A common example of a discharge tube is an ordinary fluorescent light. Probes are inserted at one or more locations along the length of the tube, with the exposed tips protruding into the plasma column. The early users of probes naively assumed that the potential of the plasma at the location of the probe (known as the *plasma potential* or space potential and designated as V_P) could be determined by measuring the potential on the probe relative to one of the electrodes. However, this procedure determined the *floating potential* V_f of the probe which is generally not the same as the plasma potential. By definition, a probe that is electrically floating, collects no net current from the plasma, and thus its potential rises and falls to whatever potential is necessary to maintain zero net current.

In a typical plasma, the electrons, because of their smaller mass, have significantly higher thermal speeds than the positive ions, even if the electrons and ions are at the same temperature. Usually the electrons have a higher temperature than the positive ions. Although a plasma is electrically neutral, and the electron and ion densities are very nearly equal, a floating probe will tend initially to draw a higher electron current because the electrons reach the probe faster than the more massive ions. Because the net current to the floating probe must be zero, the probe floats to a negative potential relative to the plasma so that further collection of electrons is retarded and ion collection is enhanced. Thus, the floating potential is less than the plasma potential. The plasma potential is the potential of the plasma with respect to the walls of the device at a given location in the plasma. V_P is generally a few volts positive with respect to the walls, again because the swifter electrons tend to escape to the walls first, leaving the plasma with a slight excess of positive space charge. The bulk of the plasma, however, is "quasineutral" (electron density ≅ ion density), and the potential difference between the bulk of the plasma and the wall is concentrated in a thin layer or sheath near the wall. The gradient of the plasma potential determines the electric field that is responsible for energizing the electrons, which maintain the discharge through ionization.

Although physicists knew that V_f and V_P were not the same, they thought that the difference was probably small, and in any case, they had no way of either estimating the difference or of measuring the actual plasma potential. Irving Langmuir and Harold Mott-Smith of the General Electric Research Laboratory in the 1920s were the first to provide a quantitative understanding of the difference between V_f and V_P. They developed an experimental method for determining the plasma potential and also showed how it was possible to use the probe (now known as a "Langmuir" probe) to determine the plasma density and the electron temperature as well.[2] Langmuir's method consists of obtaining the current-voltage (I-V) characteristic of the probe as the applied bias voltage V_B, is swept from a negative to a positive potential.

Many students of experimental plasma physics are given the task of constructing and implementing a Langmuir probe in a plasma. They quickly realize that building the probe and obtaining a I-V characteristic is much easier than extracting accurate values of the plasma parameters from the data. The literature dealing with the theory of the Langmuir probes is extensive, and new papers appear regularly. My purpose here is not to discuss the complexities of probe theory, which is treated in a number of excellent monographs,[3–9] but to provide a method to help students understand why a Langmuir characteristic looks the way it does. The difficulty with understanding probe I-V characteristics stems from the fact that the electrons and ions are not monoenergetic and often have very different temperatures. As a result, the probe sometimes collects only ion current, sometimes only electron current, and sometimes both. It is easier to understand and analyze the full I-V characteristic if the ion and electron current contributions are separated.

In Sec. II we discuss the most basic aspects of probe theory needed to calculate the individual electron and ion currents, and then construct an ideal probe I-V relation using

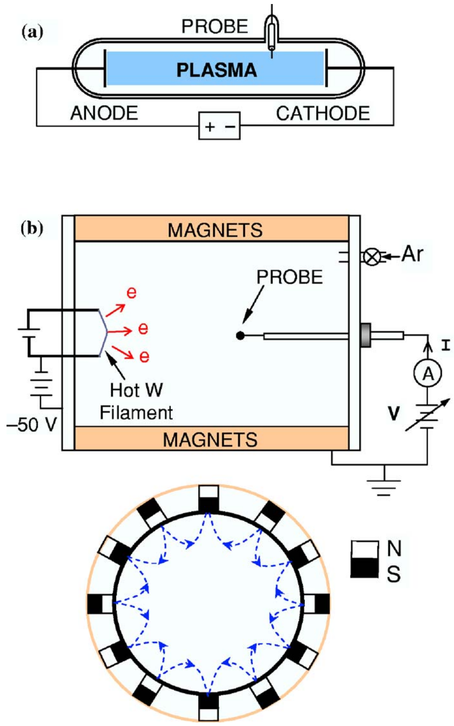

Fig. 1. Schematic of basic devices for producing a plasma. (a) A discharge tube in which a plasma is formed in a low pressure gas (<1 Torr) by applying several hundred volts across the cathode and anode. A cylindrical (wire) probe is inserted into the discharge to measure the properties of the plasma. (b) Schematic of a multidipole hot filament plasma device with a Langmuir disk probe. The plasma is produced by electron impact ionization of argon atoms by electrons that are thermionically emitted and accelerated from a hot tungsten (W) filament. To enhance the ionization efficiency, the walls of the chamber are lined with rows of permanent magnetic of opposite polarity. The lower diagram is an end view showing the arrangement of magnets. The magnetic field lines are sketched as the dotted curves. In this magnetic cusp configuration, the bulk plasma is essentially magnetic field-free.

a set of model plasma parameters. A link is provided to a program that allows the user to input the plasma and probe parameters (density, temperature, plasma potential, and probe dimension) and plot the resulting Langmuir I-V characteristic. Section III provides two examples of real Langmuir probe I-V characteristics obtained in laboratory plasmas. I close in Sec. IV with comments advocating the inclusion of plasma experiments in the undergraduate advanced laboratory course.

II. MODEL LANGMUIR PROBE CURRENT-VOLTAGE CHARACTERISTICS

In this section I discuss some of the basic aspects of Langmuir probe theory that are needed to construct model probe I-V characteristics. Two examples of ideal probe I-V characteristics are then given. Finally, a discussion of how the ideal characteristics must be modified to account for real probe effects is presented.

A. Ion and electron currents to a Langmuir probe

1. The ion current

When the bias voltage V_B, on the probe is sufficiently negative with respect to the plasma potential V_P, the probe collects the ion saturation current I_{is}. Positive ions continue to be collected by the probe until the bias voltage reaches V_P, at which point ions begin to be repelled by the probe. For $V_B \gg V_P$, all positive ions are repelled, and the ion current to the probe vanishes, $I_i=0$. For a Maxwellian ion distribution at the temperature T_i, the dependence of the ion current $I_i(V_B)$ (usually taken to be the negative current) on V_B is given by[10]

$$I_i(V_B) = \begin{cases} -I_{is} \exp[e(V_P - V_B)/kT_i], & V_B \geq V_P, \\ -I_{is}, & V_B < V_P, \end{cases} \tag{1}$$

where e is the electron's charge, and k is the Boltzmann constant. When T_i is comparable to the electron temperature T_e, the ion saturation current, I_{is} is given by[4]

$$I_{is} = \frac{1}{4} e n_i v_{i,th} A_{\text{probe}}, \tag{2}$$

where, n_i is the ion density, $v_{i,th} = \sqrt{8kT_i/\pi m_i}$ is the ion thermal speed, m_i is the ion mass, and A_{probe} is the probe collecting area. When $T_e \gg T_i$,[11] the ion saturation current is not determined by the ion thermal speed, but rather is given by the Bohm ion current[3,4,12]

$$I_{is} = I_{\text{Bohm}} = 0.6 e n_i \sqrt{\frac{kT_e}{m_i}} A_{\text{probe}}. \tag{3}$$

The fact that the ion current is determined by the electron temperature when $T_e \gg T_i$ is counterintuitive and requires some explanation. The physical reason for the dependence $I_{is} \sim (kT_e/m_i)^{1/2}$ has to do with the formation of a sheath around a negatively biased probe.[12,13] If an electrode in a plasma has a potential different from the local plasma potential, the electrons and ions distribute themselves spatially around the electrode in order to limit, or shield, the effect of this potential on the bulk plasma. A positively biased electrode acquires an electron shielding cloud surrounding it, while a negatively biased electrode acquires a positive space charge cloud. For a negatively biased electrode, the characteristic shielding distance of the potential disturbance is the electron Debye length[14]

$$\lambda_{\text{De}} = \left(\frac{\varepsilon_o k T_e}{e^2 n_e} \right)^{1/2}. \tag{4}$$

In the vicinity of a negatively biased probe, both the electron and ion densities decrease as the particles approach the probe, but not at the same rate. The electron density decreases because electrons are repelled by the probe. In contrast, the ions are accelerated toward the probe, and due to the continuity of the current density, the ion density decreases. A positive space charge sheath can form only if the ion density exceeds the electron density at the sheath edge, and for the ion density to decrease more slowly than the electron density, the ions must approach the sheath with a speed exceeding the *Bohm velocity* $u_B = (kT_e/m_i)^{1/2}$.[13,15] To achieve this speed, the ions must acquire an energy corresponding to a potential drop of $0.5(kT_e/e)$, which occurs over a long distance in the plasma. The factor of 0.6 in Eq. (3) is due to the reduction in the density of the ions in the *presheath*, which is the region over which the ions are accelerated up to the Bohm speed.

Table I. Parameters of a typical laboratory plasma used to construct an ideal Langmuir probe volt-ampere characteristic.

Parameter	Symbol	Value	Units
Ion species	Ar^+		
Ion mass	m_i	6.7×10^{-26}	kg
Electron density	n_e	1.0×10^{16}	m^{-3}
Ion density	n_i	1.0×10^{16}	m^{-3}
Electron temperature	T_e	2.0	eV
Ion temperature	T_i	0.1	eV
Plasma potential	V_P	1.0	V
Probe diameter	d_{probe}	3.0	mm

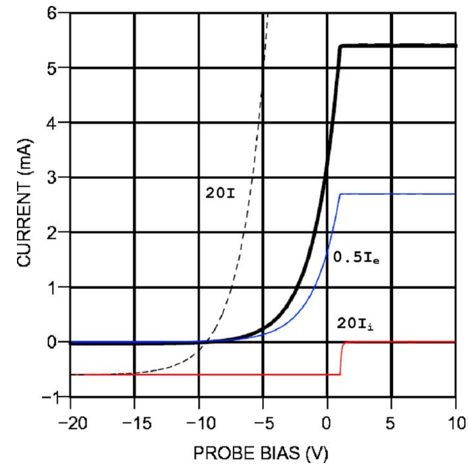

Fig. 2. Ideal Langmuir probe current-voltage characteristic (heavy line) for a model plasma with the parameters listed in Table I. The individual electron and ion currents that are used to construct the full characteristic are also shown. The dotted line is the full probe characteristic magnified by a factor of 20 so that the probe floating potential, V_f (the probe voltage where $I=0$) can be easily determined.

2. The electron current

For $V_B \gg V_P$ the probe collects electron saturation current I_{es}. For $V_B < V_P$ the electrons are partially repelled by the probe, and for a Maxwellian electron velocity distribution, the electron current decreases exponentially with decreasing V. For $V_B \ll V_P$ all electrons are repelled, so that $I_e=0$. The electron current as a function of V_B can be expressed as

$$I_e(V_B) = \begin{cases} I_{es}\exp[-e(V_P - V_B)/kT_e], & V_B \le V_P, \\ I_{es}, & V_B > V_P. \end{cases} \tag{5}$$

The electron saturation current I_{es} is given by

$$I_{es} = \frac{1}{4} e n_e v_{e,th} A_{\text{probe}}, \tag{6}$$

where n_e is the electron density, $v_{e,th} \equiv \sqrt{8kT_e/\pi m_e}$ is the electron thermal speed, and m_e is the electron mass. We see from Eqs. (2), (3), and (6) that because $n_e=n_i$ and $m_e \ll m_i$, the electron saturation current will be much greater than the ion saturation current. For example, in an argon plasma for $T_e \gg T_i$ we see from Eqs. (3) and (6) that $I_{es}/I_{is} = \sqrt{m_i/m_e}/(0.6\sqrt{2\pi}) = 271/1.5 = 180$.

B. Examples of Langmuir probe characteristic

1. The ideal Langmuir probe characteristic

For the values in Table I, with $A_{\text{probe}} = 2\pi(d_{\text{probe}}/2)^2 = 1.41\times10^{-5}\ m^2$ for a planar disk probe that collects from both sides, we find from Eqs. (3) and (6), $I_{is}=0.03$ mA and $I_{es}=5.4$ mA, so that $I_{es}/I_{is}=180$. The I-V characteristic corresponding to these parameters is shown in Fig. 2. The calculations of the ion current, Eq. (1), the electron current, Eq. (5), and the total current $I(V_B)=I_e(V_B)+I_i(V_B)$ for the I-V curve in Fig. 2 were performed using the Maple *procedure* function and the standard plotting command.[16] Alternately, the data for the I-V curve could be computed and plotted in a spreadsheet program. The heavy solid curve in Fig. 2 is the total probe current; the electron current (positive) and ion current (negative) are also indicated. The ion current is magnified by a factor of 20 in order to see its contribution to the total current. Because the electron current is much larger than the ion current, it is necessary to bias the probe to very negative voltages to even see the ion current. The total current is also displayed on a magnified scale ($\times 20$) to show the probe bias at which the total current is zero. The probe bias for which $I(V_B=V_f)=I_e+I_i=0$ is the probe's floating potential, which occurs at $V_f \approx -9.5$ V. The floating potential can be calculated from Eqs. (1)–(5), as the bias voltage at which $I_i(V_f)+I_e(V_f)=0$,

$$I_{es}\exp[e(V_f - V_P)/kT_e] = I_{is}, \tag{7}$$

or

$$V_f = V_P + \left(\frac{kT_e}{e}\right)\ln\left(0.6\sqrt{\frac{2\pi m_e}{m_i}}\right). \tag{8}$$

If the appropriate parameters are inserted into Eq. (6), we find that $V_f = V_P - 5.2T_e$, or $V_f = -9.4$ V for $(kT_e/e)=2$ V, corresponding to an electron temperature of 2 eV.

The nature of the Langmuir probe I-V characteristic of the type shown in Fig. 2 is dominated by the fact that the speed of the electrons is considerably higher than that of the positive ions. As a consequence, it is impossible to use the probe to determine the ion temperature, whereas the electron temperature can be easily found from the portion of the characteristic corresponding to electron repulsion, that is, for $V_B < V_P$.

2. Probe I-V characteristic for a positive ion (+)/negative ion (−) plasma with $m_+=m_-$ and $T_+=T_-$

Consider constructing the I-V characteristic in a plasma consisting of positive and negative ions of equal mass and temperatures, for example. In this case because the thermal speeds of the positive and negative plasma constituents are identical, we expect that $V_P=V_f=0$, and $I_{+s}=I_{-s}$. An example of such an interesting plasma would be an electron-positron plasma.[17] The probe I-V characteristic for this case is shown in Fig. 3, where arbitrary (but equal) values of the saturation currents are used. An important point to take from a consideration of the I-V plot in Fig. 3 is that the part of the curve where the negative ions are repelled ($V_B < V_P$) occurs at $-10\ \text{V} < V_B < 0$ V, and the portion corresponding to positive ion repulsion is $0\ \text{V} < V_B < 10$ V. To find the negative ion current the positive ion saturation current must be used as the baseline (and not the $I=0$ line) and vice versa to obtain the positive ion current. The line extrapolated from the ion cur-

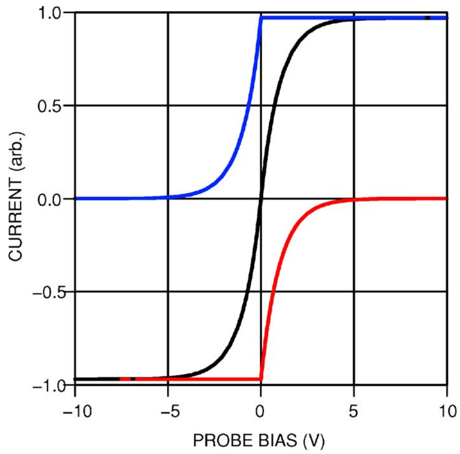

Fig. 3. Langmuir probe I-V characteristic for a plasma with positive and negative ions of equal mass and temperatures. The positive ion and negative ion currents are also shown.

rent should also be used as the baseline to determine the electron current for the case shown in Fig. 2, although in that case the positive ion contribution is negligible, and the $I=0$ line can usually be used to measure I_e. When the plasma contains a significant fraction of high energy (tens of electron volts) ionizing primary electrons in addition to the secondary electrons resulting from ionization, it is essential to first subtract the ion current from the total current to obtain accurate values of the electron current.

C. Effect of sheath expansion on probe characteristics

The sharp knee at the plasma potential ($V_P=1.0$ V) in the I-V characteristic and flat electron and ion saturation currents shown in Fig. 3 are ideal probe features that are rarely seen in practice. For this reason the I-V characteristic in Fig. 1 is ideal. Real Langmuir probe I-V characteristics have rounded knees and saturation currents that increase gradually with increasing voltage. The lack of saturation is related to the fact that a sheath[13–15] is formed around the probe, and this sheath expands with increasing bias voltage. Sheaths form around any electrode in a plasma if the bias voltage differs from V_P. The formation of a sheath is the plasma's way of maintaining charge neutrality in the bulk of the plasma. An electrode with a positive bias (relative to V_P) attracts an electron cloud to limit the penetration of the electric field into the plasma to a distance approximately equal to the electron Debye length, λ_{De}, defined in Eq. (4). If the plasma density is greater than $\sim 10^{16}$ m^{-3} and $T_e \approx 2$ eV, then the sheath width will be ≤ 0.1 mm. In this case the expansion of the sheath will produce only a negligible increase in current as the probe bias is increased. For lower plasma densities and small probes the sheath expansion produces an increase in the collected current because the effective area for particle collection is the sheath area and not the geometric probe area. Another way to think about the sheath expansion effect is to realize that for a finite probe, the collection of plasma particles is limited by fact that some particles that enter the sheath will orbit around the probe and not be collected. As the potential on the probe is increased, the minimum impact parameter for which particles are collected increases and thus more particles will be collected.

Sheath expansion occurs for both the ion and electron currents and must be taken into account in the interpretation of the I-V characteristics. The sheath expansion effect can be incorporated in the ideal probe characteristic so that we can learn how to deal with it when interpreting real Langmuir probe characteristics. An illustration of this effect is shown in Fig. 4. The parameters used to produce this I-V characteristic were $V_P=4$ V, $I_{es}=100I_{is}, T_e=4$ eV, and $T_i=0.1$ eV. The sheath expansion was modeled as a linear function of the bias voltage with $I_{is}(V_B)=-[0.2(V_P-V_B)+I_{is}]$ for $V_B<V_P$ for the ions, and $I_{es}(V_B)=0.7(V_B-V_P)+I_{es}$ for $V_B>V_P$ for the electrons. Figure 4(a) shows the full I-V characteristic. Real characteristics rarely show the sharp knee at the plasma potential; rather the knee tends to be rounded (as illustrated by the dotted curve) due to the presence of oscillations of the plasma potential[15] or averaging in the data acquisition or analysis process. The rounding of the knee complicates the determination of the electron saturation current, but the location of the knee is made more evident by replotting the current on a semilog scale, as shown in Fig. 4(b). Both I_{es} and V_p can now be easily determined as the coordinates of the intersection of two straight lines—one parallel to the curve above the knee and the other parallel to the sloping part. The slope of the straight line fit tothe electron current in Fig. 4(b) is used to determine T_e, as $T_e=(V_2-V_1)/\ln(I_{e2}/I_{e1})$, where 1 and 2 refer to any two points on the line. The electron current begins falling off the straight line due to the contribution of the ion current. An accurate measurement of the ion current in this case requires that I_i be obtained for a sufficiently negative probe bias so that the electron contribution is excluded. The procedure for measuring I_{is} is shown in Fig. 4(c). The ion current is plotted on an expanded scale and a straight line is fitted through the points; I_{is} is taken as the value of I_i at V_p. More accurate methods of dealing with the nonsaturation of the ion current are discussed in Refs. 5, 7, 9, and 18.

III. EXAMPLES OF LANGMUIR PROBE CHARACTERISTICS FROM LABORATORY PLASMAS

In this section I provide two examples of Langmuir probe I-V characteristics obtained in more realistic laboratory plasmas. These examples demonstrate how the basic principles presented in Sec. II are applied in the interpretation of real characteristics.

A. Multidipole plasma

A multidipole device[19–21] is a relatively simple setup for producing a plasma that can be used for basic plasma physics experiments. A schematic diagram of a typical multidipole device is shown in Fig. 1(b). It is essentially a large (about 20 l) stainless steel soup pot (sometimes literally) which is pumped down to a base pressure of $\sim 10^{-6}$ Torr, and then filled with a gas such as argon to a pressure of approximately $10^{-5}-10^{-3}$ Torr. The plasma is produced by electron emission from a set of tungsten filaments that are biased to a negative potential of approximately 50 V. The thermionically emitted primary electrons that are accelerated from the filaments ionize the gas producing the plasma. To enhance the probability that a primary electron will undergo an ionizing collision with a neutral atom, the walls of the device are lined with permanent magnets in rows of opposite polar-

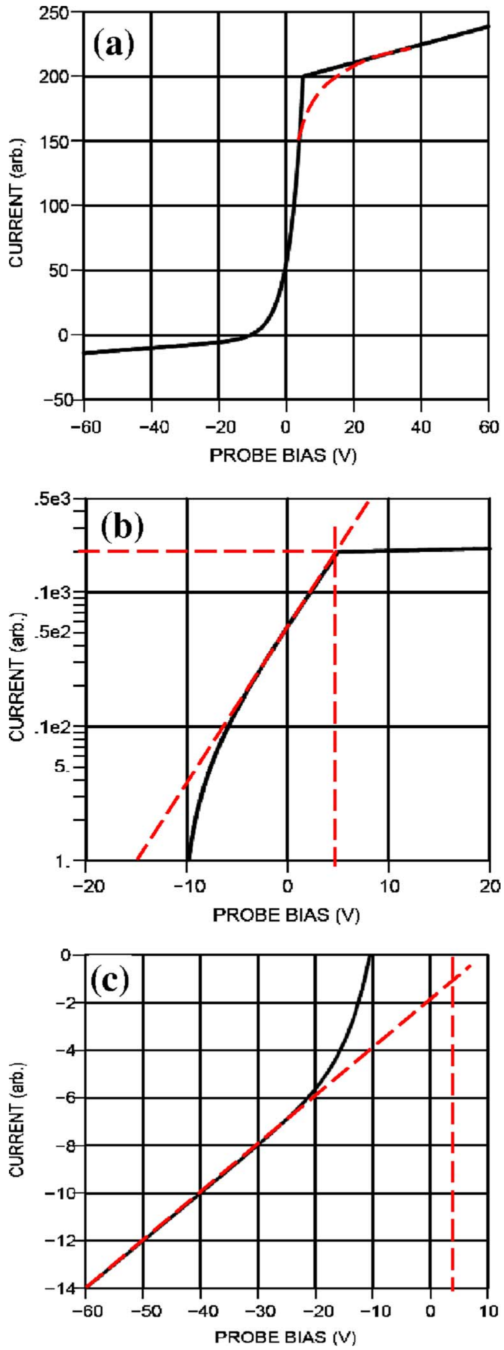

Fig. 4. Model Langmuir probe I-V characteristic including the effect of sheath expansion, computed with $V_P=4$ V, $T_e=4$ eV, $T_i=0.1$ eV, and $I_{es}/I_{is}=200$. (a) Total current. The dotted curve depicts the rounding of the knee due to plasma noise or averaging effects. (b) $\log I(V_B)$ versus V_B. The intersection of the horizontal and vertical dotted lines occurs at the coordinates (V_P, I_{es}). The electron temperature is obtained from the slope of the linear part of the downward sloping portion of this curve. (c) Expanded view of the ion current. The sloping dotted line is a linear fit to the ion current. The ion saturation current is found by extrapolating this line to the plasma potential.

ity creating a magnetic barrier, which inhibits the ionizing electrons from escaping. Due to the alternating polarity of the magnet rows, the magnetic field has substantial strength only very close to the walls, so that the main plasma region is essentially magnetic field free.

A typical Langmuir probe I-V characteristic obtained in

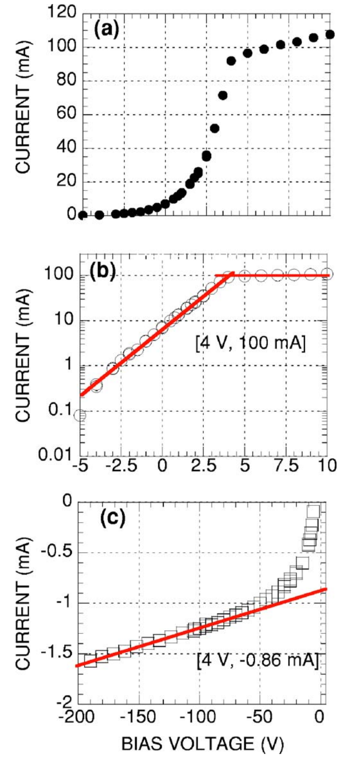

Fig. 5. Langmuir probe I-V characteristic obtained in a multidipole plasma in argon at a pressure of 0.5 mTorr. (a) Electron current. (b) $\log I(V_B)$ versus V_B. The semilog plot of the electron current provides a clear demarcation of the plasma potential and electron saturation current. T_e is found from the slope of the exponentially decreasing portion. (c) Expanded scale view of the ion current used to find I_{is}.

the multidipole device in the University of Iowa's undergraduate Advanced Physics Lab is shown in Fig. 5. This characteristic was taken with a 6 mm diameter planar disk probe in an argon plasma at a pressure of 0.5 mTorr. The top curve [Fig. 5(a)] is the positive probe current due to electron collection. As discussed in Sec. II (see Fig. 4), the electron current continues to increase slightly with increasing voltage above the plasma potential due to the sheath expansion effect. The determination of the electron saturation current and plasma potential is facilitated by replotting the current on a semilog scale as shown in Fig. 5(b). The break point occurs at $V_P \cong 4$ V, with $I_{es}=(100\pm5)$ mA. The slope of the downward portion of the line on the semilog plot gives $T_e \cong 1.5$ eV. The negative (ion) current is shown on an expanded scale in Fig. 5(c). Again we see the sheath expansion effect as the (negative) probe voltage increases. The ion saturation current is estimated by extrapolating the linear portion of the ion current to the plasma potential, where $I_i(V_P) = (0.85\pm0.05)$ mA. The floating potential is also found from Fig. 5(c) as $V_f(I=0) \cong -5$ V. The ion and electron densities can now be calculated using Eqs. (2) and (4) with $T_e = 1.5$ eV. We find that $n_i=(8.3\pm0.5)\times10^{16}$ m^{-3}, and $n_e = (5.5\pm0.55)\times10^{16}$ m^{-3}. Even taking into account the uncertainties involved in measuring the saturation currents from the plots, there remains a $\sim$25% difference between the plasma density obtained from the ion and electron currents. This difference is a typical occurrence with Langmuir probes measurements. In a magnetized plasma, the discrepancy in the densities obtained from the electron and ion saturation currents is considerably larger, but expected. The gyroradius of the electrons is typically much smaller than that of the ions so that the collection of electrons is affected more than the collection of ions. In that case, measurements of the plasma density using the ion saturation current are more reliable.

It is interesting to calculate the fraction of the neutral argon atoms that are actually ionized in the plasma using the measured value of the plasma density. This fraction is known as the percent ionization or ionization fraction. The density of the neutral argon atoms is $n_a = P/kT_g$, where T_g is the temperature of the neutral gas, and P is the neutral gas pressure. For $P = 5 \times 10^{-4}$ Torr and $T_{gas} \approx 300$ K, $n_a = 1.65 \times 10^{19}$ m^{-3}. With $n_i = 8 \times 10^{16}$ m^{-3}, we obtain $n_i/n_a = 0.005$. Thus, only 0.5% of the neutral atoms are ionized.

The fact that the neutral density is roughly 1000 times the plasma density might lead one to wonder about the role of these neutral atoms on the plasma and probe measurements. To access the possible effects of collisions of the ions and electrons with neutrals, we need to estimate a few typical collision mean free paths, $\lambda = (n_a \sigma)^{-1}$, where σ is the cross section[22] for the particular process considered. For ionization, $\sigma_{ionz} \approx 8 \times 10^{-20}$ m^2 (for 50 eV electrons on argon), so $\lambda_{ionz} \sim 75$ cm. Thus λ_{ionz} is on the order of the dimensions of a typical laboratory plasma device. The relatively long ionization mean free path explains, in part, the relatively low value of the ionization percentage—electrons that are energetically capable of ionizing atoms are more likely to make it to the wall before ionizing an atom.

The purpose of the magnets on the walls of the multidipole device is to reflect the ionizing electrons back into the plasma, thus increasing their chances of having an ionizing collision. Electrons can also make elastic collisions with neutral atoms; a typical cross section in this case is $\sigma_{en} \sim 10^{-20}$ m^2, giving $\lambda_{en} \sim 6$ m. For collisions between the ions and neutral atoms, the most important process to consider is charge exchange, $Ar^+ + Ar \rightarrow Ar + Ar^+$, in which an argon ion exchanges an electron with an argon atom, resulting in the production of very slow argon ions and argon atoms with an energy practically equal to the initial energy of the ions. The cross section for this process is $\sigma_{in} \sim 5 \times 10^{-19}$ m^2, giving $\lambda_{in} \sim 12$ cm.

We note that for all of the processes considered the mean free paths are much greater than the probe size and the shielding distance or sheath size, so that even though the neutral density far exceeds the plasma density, the neutral gas atoms produce negligible effects on the probe measurements.

B. A positive ion/negative ion plasma in a Q machine

Figure 3 is an example of a Langmuir probe I-V characteristic in a plasma in which the positive and negative particles have the same mass. This example might appear to be exotic, but it is not difficult to produce a plasma having almost equal numbers of positive and negative ions of comparable mass. We have produced positive ion/negative ion plasmas (also known as electronegative plasmas) in a device called a Q machine.[23] In a Q machine the plasma is produced by surface ionization, an effect discovered by Langmuir and Kingdon in 1923.[24] They found that cesium atoms that come into contact with a tungsten filament heated to 1200 K emerge as cesium ions. The reason is that the ionizing potential of cesium is 3.89 eV, and the work function for tungsten is 4.52 eV. Surface ionization is exploited in a Q machine[23] by directing an atomic beam of cesium or potassium atoms onto a hot (~2000 K) tungsten or tantalum plate, usually several centimeters in diameter. Both positive ions and thermionic electrons emerge from the plate forming a nearly fully ionized plasma that is confined by a strong (~0.1–0.5 T) longitudinal magnetic field. The relatively good thermal contact between the plasma and the hot plate results in a plasma in which both the electrons and positive ions are at roughly the plate temperature, typically 0.2 eV. The Q machine has been used mainly for studying the basic properties of magnetized plasmas, and in particular plasma waves. (The Q designation refers to the expectation that a thermally produced plasma would be quiescent, that is, relatively free of low frequency plasma instabilities.)

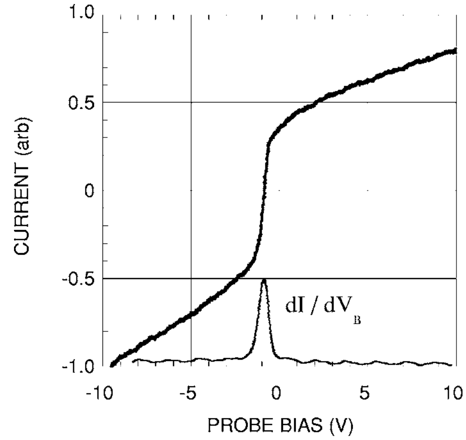

Fig. 6. Langmuir probe I-V characteristic obtained in a singly ionized potassium plasma produced in a Q machine. SF_6 gas was introduced into the plasma to form a negative ion plasma by electron attachment. A substantial fraction of the electrons became attached to the heavy SF_6 molecules resulting in a nearly symmetric probe characteristic with $I_{+s} \approx I_{-s}$. The lower curve is the derivative of the probe current, dI/dV_B. The plasma potential is the value of the V_B for which dI/dV_B is a maximum.

Negative ions are readily formed in a Q machine plasma by leaking into the vacuum chamber sulfur hexafluoride SF_6 at a pressure $\sim 10^{-5}$–10^{-4} Torr. Electrons attach to SF_6 forming SF_6^- negative ions.[25] The cross section for electron attachment to SF_6 is energy dependent and peaks in the energy range that coincides closely with that of the Q machine electrons. Under these circumstances it is possible to produce plasmas in which the ratio of electron density to positive ion density is $n_e/n_+ < 10^{-3}$. A Langmuir probe I-V characteristic obtained in such a K^+/SF_6^- $(m_-/m_+ = 3.7)$ is shown in Fig. 6. Note that the negative ion (positive current) and positive ion (negative current) saturation currents are comparable. With such a characteristic the plasma potential is most easily determined as the voltage at which the first derivative of the characteristic is a maximum. In this case we see that $V_P \cong -1$ V. The characteristic is roughly symmetric about $I = 0$, with a floating potential $V_f \approx V_P$, a result that is to be expected in a plasma with $n_+ \approx n_-$ and $n_e \ll n_+$. When the negative ion and positive ion densities are comparable, it may even be possible to extract both the negative and positive ion temperatures from the Langmuir characteristic.

IV. COMMENTS

A Langmuir probe I-V characteristic becomes less confusing once we are able to see the individual current contributions as well as the total probe current. The procedure for constructing an I-V characteristic given an appropriate set of plasma input parameters has been presented. A MAPLE program that creates the I-V characteristic is available on EPAPS[16] and is also available on the author's website.

The inclusion of plasma physics experiments in upper level advanced laboratory courses for physics majors can provide students with much exposure to many important topics and methods in experimental physics including basic vacuum techniques, vacuum measurement methods, soldering, spot welding, brazing, electronic circuit design and fabrication, data acquisition methods, curve fitting techniques, and instrument design and construction (building a Langmuir probe). Students also experience using basic concepts in the kinetic theory of gases.

Plasma physics experiments also provide ideal research topics for undergraduate thesis projects. For instructors contemplating the inclusion of plasma experiments in advanced laboratory courses, my suggestion is to start with the basic multidipole plasma.[19–21] This device is relatively simple and inexpensive, with the most costly component being the vacuum pumping system. If money is not a concern, it is possible to purchase fully operational vacuum systems that are easily adaptable for plasma production. Although it is now possible to purchase off the shelf Langmuir probe systems, complete with probe and associated electronics, the experience of constructing probes from scratch is a valuable one that should not be avoided. Building a probe is often the first instance in which students are required to use their hands to create an experimental instrument. Far too often students are left with the impression that everything needed to perform a measurement can be found at manufacturers' web sites.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy Grant DE-FG02-04ER54795.

APPENDIX: SUGGESTED PROBLEMS FOR FURTHER STUDY

The following two problems are intended to extend the basic probe theory to include some other important effects often encountered in using Langmuir probes in realistic plasmas.

Problem 1. It is not uncommon to find in low pressure plasma discharges that there are two distinct Maxwellian distributions of electrons—a cold and hot distribution with temperatures T_{ec} and T_{eh}, respectively. Extend the analysis of Sec. II to include a two-temperature electron distribution. In this case the electron probe current is written as $I_e(V_B) = I_{ec}(V_B) + I_{eh}(V_B)$. Take the respective densities of the cold and hot components to be n_{ec} and n_{eh} with $n_e = n_{ec} + n_{eh}$. To simplify the analysis, introduce the parameter $f_{eh} \equiv n_{eh}/n_e$ as the fraction of hot electrons, so that $n_{ec}/n_e = 1 - f_{eh}$. An interesting issue arises as to what value of T_e to use in calculating the Bohm ion current. It was shown[26] that the appropriate T_e is the harmonic average of T_{ec} and T_{eh}:

$$\frac{1}{T_e} = \left(\frac{n_{ec}}{n_e}\right)\frac{1}{T_{ec}} + \left(\frac{n_{eh}}{n_e}\right)\frac{1}{T_{eh}}. \tag{A1}$$

After you have produced a Langmuir I-V plot, replot the electron current as a semilog plot to see more clearly the effect of the two-temperature electron distribution.

Problem 2. In plasmas produced in hot-filament discharges, the effect of the ionizing (primary) electrons on the probe I-V trace can be observed, particularly at neutral pressures below $\sim 10^{-4}$ Torr. Extend the probe analysis to include the presence of these energetic primary electrons, which can be modeled as an isotropic monoenergetic distribution. Express the total electron current as $I_{et}(V_B) = I_e(V_B) + I_{ep}(V_B)$, where $I_e(V_B)$ is the contribution from the bulk electrons, and $I_{ep}(V_B)$ is the primary electron contribution, which for an isotropic monoenergetic distribution is[3]

$$I_{ep} = \begin{cases} I_{ep}^* \equiv \frac{1}{4} e n_{ep} v_{ep} A_{\text{probe}}, & V_B > V_P, \\ I_{ep}^*\left[1 - \frac{2e(V_P - V_B)}{m_e v_{ep}^2}\right], & \left(V_p - \frac{m_e v_{ep}^2}{2e}\right) \le V_B \le V_P, \\ 0, & V_B \le \left(V_P - \frac{m_e v_{ep}^2}{2e}\right), \end{cases} \tag{A2}$$

where n_{ep} is the density of primary electrons, and $v_{ep} = \sqrt{2E_p/m_e}$ is the speed of the primary electrons with energy E_p. To produce an I-V plot, assume that the primary electrons are accelerated through a potential drop $\sim 50-60$ V, and the density is in the range of $(0.001-0.1)n_e$.

[a]Electronic mail: robert-merlino@uiowa.edu

[1]It is common in plasma physics to give temperatures in equivalent energy units (eV). For example, we say that $T_e = 2$ eV, which means we are really giving kT_e converted to electron volts. The actual temperature corresponding to 1 eV is 11,600 K.

[2]I. Langmuir and H. Mott-Smith, "The theory of collectors in gaseous discharges," Phys. Rev. **28**, 727–763 (1926).
[3]I suggest that Langmuir probe novices start by reading Noah Hershkowitz's article, "How Langmuir probes work," in *Plasma Diagnostics, Discharge Parameters and Chemistry*, edited by O. Auciello and D. L. Flamm (Academic, Boston, 1989), Vol. 1, Chap. 3.
[4]B. E. Cherrington, "The use of Langmuir probes for plasma diagnostics: A review," Plasma Chem. Plasma Process. **2**, 113–140 (1982).
[5]F. F. Chen, "Electric Probes," in *Plasma Diagnostic Techniques*, edited by R. H. Huddlestone and S. L. Leonard (Academic, New York, 1965), Chap. 4. A concise summary of Langmuir probe techniques by F. F. Chen, "Lecture notes on Langmuir probe diagnostics" is available at ⟨www.ee.ucla.edu/~ffchen/Publs/Chen210R.pdf⟩.
[6]L. Schott, "Electrical probes," in *Plasma Diagnostics*, edited by W. Lochte-Holtgreven (North-Holland, Amsterdam, 1968), Chap. 11.
[7]J. D. Swift and M. J. R. Schwar, *Electrical Probes for Plasma Diagnostics* (American Elsevier, New York, 1969).
[8]I. H. Hutchinson, *Principles of Plasma Diagnostics*, 2nd ed. (Cambridge U.P., Cambridge, 2002), Chap. 3.
[9]J. G. Laframboise, "Theory of spherical and cylindrical Langmuir probes in a collisionless, Maxwellian plasma," Univ. Toronto Aerospace Studies Report No. 11 (1966).
[10]Reference 3, p. 118.
[11]It is common in discharge plasmas to have $T_i \ll T_e$ due to the fact that the ions are created from neutral atoms at room temperature, while the electrons are considerable hotter (by a factor of about 100) because they must

be energized to ionization energies to maintain the discharge. Energy transfer between the massive ions and light electrons is inefficient, so the ions remain relatively cold.

[12] Reference 3, p. 125; see also the review article by K.-U. Riemann, "The Bohm sheath criterion and sheath formation," J. Phys. D **24**, 493–518 (1991), and the recent article by G. D. Severn, "A note on the plasma sheath and the Bohm criterion," Am. J. Phys. **75**, 92–94 (2007).

[13] F. F. Chen, *Introduction to Plasma Physics and Controlled Fusion*, 2nd ed. (Plenum, New York, 1984), Vol. 1, p. 290.

[14] Reference 13, p. 8.

[15] M. A. Lieberman and A. J. Lichtenberg, *Principles of Plasma Discharges and Materials Processing*, 2nd ed. (Wiley, New York, 2005), Chap. 6.

[16] See EPAPS Document No. E-AJPIAS-75-009710 for a MAPLE program that can be used to produce Langmuir I-V curves. This document can be reached through a direct link in the online article's HTML reference section or via the EPAPS homepage (http://www.aip.org/pubservs/epaps.html). This program can also be accessed from ⟨www.physics.uiowa.edu/~rmerlino/⟩.

[17] See, for example, T. Sunn Pedersen, A. H. Boozer, W. Dorland, J. P. Kremer, and R. Schmitt, "Prospects for the creation of positron-electron plasmas in a non-neutral stellarator," J. Phys. B **36**, 1029–1039 (2003).

[18] D. Lee and N. Hershkowitz, "Ion collection by planar Langmuir probes: Sheridan's model and its verification," Phys. Plasmas **14**, 033507-1–4 (2007).

[19] R. Limpaecher and K. R. MacKenzie, "Magnetic multipole confinement of large uniform collisionless quiescent plasmas," Rev. Sci. Instrum. **44**, 726–731 (1973).

[20] A. Lang and N. Hershkowitz, "Multidipole plasma density," J. Appl. Phys. **49**, 4707–4710 (1978).

[21] R. A. Bosch and R. L. Merlino, "Multidipole confinement of argon and potassium plasmas," Rev. Sci. Instrum. **57**, 2940–2950 (1986).

[22] A good source for cross sections relevant to plasma physics is S. C. Brown, *Basic Data of Plasma Physics*, 2nd ed. (MIT Press, Cambridge, MA, 1967).

[23] R. W. Motley, *Q Machines* (Academic, New York, 1975).

[24] I. Langmuir and K. H. Kingdon, "Thermionic effects caused by alkali vapors in vacuum tubes," Science **57**, 58–60 (1923).

[25] Bin Song, D. Suszcynsky, N. D'Angelo, and R. L. Merlino, "Electrostatic ion-cyclotron waves in a plasma with negative ions," Phys. Fluids B **1**, 2316–2318 (1989).

[26] S. B. Song, C. S. Chang, and Duk-In Choi, "Effect of two-temperature electron distribution on the Bohm sheath criterion," Phys. Rev. E **55**, 1213–1216 (1997).