THE LANGMUIR PROBE

Last Edited: June 25th, 2012 by Alex Strieder

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QUESTION TO BE INVESTIGATED:

How is *discharge current* [1] related to the standard *plasma parameters*?

SYMBOLIC NOTATION

A_p – current-collecting surface area of the entire probe
A_d – current-collecting surface area of the flat disc top of the probe
e - elementary charge
ϵ_0 - permittivity of free space
K_B – Boltzmann constant
r – distance between charges
r_p – probe radius
V_p – probe voltage/potential
V_f – floating potential
V_s – plasma space potential/electrostatic potential
n_α – number density of species α
m_α – mass of species α
v_x – x component of the thermal velocity
$\vec{v}_\alpha$ – thermal velocity of species α
$\langle \vec{v}_\propto \rangle$ - average thermal velocity of species α
α=*e, i, n, 0* (for electrons, ions, neutral atoms, or a selected reference density respectively). Without a subscript the meaning depends on the context.

I. INTRODUCTION:

The *Langmuir probe* is a diagnostic device used to determine several basic properties of plasma[2], such as temperature and density. Plasma is the most prevalent form of ordinary matter. Plasma is a state of matter which contains enough free (not bound to an atom) charged particles (electrons and ions) so that its dynamical

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[1] Terms defined more precisely in the glossary will be italicized at first occurrence.
[2] The term "plasma" was first coined by Irving Langmuir and means from the Greek: 'something molded or fabricated'. Unfortunately, the Greek is not representative of plasma's meaning in physics. Our definition of plasma is a medium which exhibits *Debye shielding*.

behavior is dominated by electrostatic shielding or, more specifically, Debye shielding. If a collection of charged particles is sufficiently large, then shielding can occur and one can expect to observe plasma behavior. If the typical kinetic energies of the particles is greater than their typical electrostatic energies then the plasma is *weakly coupled* meaning that it will behave very much like a fluid (in the opposite limit plasmas can crystalize).

As an example of plasma behavior let us think about the situation of a Langmuir probe suspended in plasma (of test charge q). This situation can be described by looking at the Poisson equation in three spatial dimensions:

$$\nabla^2 V_s = -\frac{e}{\epsilon_0}(n_i - n_e) - \frac{q}{\epsilon_0} \text{ [Eq. 1]}$$

Notice that if the *ion and electron densities* are the same in [Eq. 1] the equation reduces to the Poisson equation for a typical electrostatic potential. For this simple model we can assume that the ions are colder and more massive than the electrons so that they do not move and have a constant density $n_i = n_0$ (in general they can also contribute to the shielding). We furthermore assume a Maxwell-Boltzmann distribution for the electron density as they rapidly move in the average *space potential*, $V_s(x)$: $n_e = n_0 e^{eV_s/K_B T_e}$. Putting this together and assuming that the density variation is not too large we obtain:

$$(\nabla^2 V_s) = \frac{n_0 e^2}{\epsilon_0 K T_e} V_s - \frac{q}{\epsilon_0} \text{ [Eq. 2]}$$

We define the *Debye length* as:

$$\lambda_D \equiv \left(\frac{\epsilon_0 K_B T_e}{n_0 e^2}\right)^{1/2} \text{ [Eq. 3]}$$

The solution to Eq. 2 is then:

$$V_s(r) = \frac{q}{4\pi\varepsilon_0 |r|} \cdot e^{-|r|/\lambda_D} \text{ [Eq. 4]}$$

[Eq. 4] is the Debye-Hückel potential. Near the charged probe, the potential is similar to what you obtain from a free charge q, but the presence of free charges in the plasma causes an additional exponential shielding over Debye length scales. The Debye length is a measure of the distance over which charge neutrality may not be valid near a boundary of the plasma, or in this case near the probe. It is also a measure of the effective range of the *screened (Coulomb) potential*. The requirement $r_p \gg \lambda_D$ insures that edge effects may be neglected. Provided that the radius (spherical symmetry) of the collection of particles is larger than the Debye length, shielding can occur. Physically, the positively charged probe attracts a “cloud” of electrons that has an equal and opposite charge to the probe causing the electric potential modification to be confined to a small sphere with a radius on the order of a Debye length. It is an amazing fact that a weakly coupled plasma, despite all of its free charges moving about, is very nearly electrically neutral (that is, they are *quasi-neutral*). So the electric fields are small and the field of a charged probe will be shielded over a small distance (the Debye length). Plasmas often exist along with the presence of neutral gas because, usually, even a low percentage of ionization is sufficient to produce plasma behavior but if the *mean-free-path* for collisions between the charged particles and the neutrals is short enough (comparable to the Debye length) then the theory must be modified.

A technique, first used by Irving Langmuir, can be employed to determine the ion and electron densities, the *electron temperature*, the *electrostatic potential* (also called the *plasma space potential*), and the electron distribution function. These quantities are commonly known as the plasma parameters. Langmuir's technique involves the measurement of electron and ion currents to a small metal electrode (the Langmuir probe) as different voltages are applied to it. This yields a curve called the *probe characteristic* for the plasma. From the probe characteristic it is possible to determine the plasma parameters.

In this experiment we make use of an argon gas tube, the OA4-G, which possesses a built-in Langmuir probe. The argon gas is at 10^{-3} atm. The tube contains three electrodes: In order to create plasma voltage is applied across two electrodes (a *cathode* and an *anode*) producing an electrical discharge current in the gas while the third electrode is used as the Langmuir probe. Plasma is generated when the potential between the cathode and the anode causes the electrons emitted from the cathode to be accelerated to energies sufficient to produce atomic excitation and ultimately *collisional ionization* of the gas. Once a few electrons have been liberated they will collide with other atoms knocking more electrons off and producing an "avalanche" or "discharge". This discharge current then continuously creates plasma and is self-sustaining despite the fact that in some of the plasma electrons and ions will hit the walls of the tube and recombine into neutral gas atoms.

II. THEORY:

Langmuir probe theory consists in predicting by use of the plasma parameters, what the electrical current to a conducting probe should be as a function of the probe voltage. A typical probe characteristic is shown in Figure 1.

Referring to Figure 1 we divide the problem into four regions labeled A-D. In region A the *probe potential* is so large that a plasma discharge is established between the probe and the cathode (in parallel with the discharge between the anode and the cathode). This means that the probe is a large perturbation to the plasma and will actually change the plasma parameters – you do not want to operate the probe in this region because it may damage the probe. In region B which covers the region where probe potential is comparable to the space potential to the point where the probe discharge starts; the probe collects all the electrons that hit it (and repels none) while it repels all of the positively-charged ions. This is the *electron saturation current*. Region C is a transition region where the characteristic satisfies an exponential dependence (described later). Finally, in region D the electrons are all repelled and only ions are collected by the probe. This is the *ion saturation current*. Most of the information on the plasma parameters is obtained from the transition region (C) although the plasma density can be obtained from the saturation currents (although these currents also depend on the electron temperature). We will give a derivation in the appendix, but here we will summarize the results in the three regions that are useful for analysis. From this point on refer to Figure 2 when there is need to reference a probe characteristic as Region A will be ignored.

The current of each species to the Langmuir probe as a function of velocity is:

$$I_\alpha = n_\alpha q_\alpha A_p \iiint_{v_{min}}^{\infty} \vec{v}_\alpha \left(\frac{2\pi K_B T_\alpha}{m_\alpha}\right)^{-3/2} \exp\left(\frac{-m_\alpha |\vec{v_\alpha}|^2}{2K_B T_\alpha}\right) d\vec{v}_\alpha \qquad \text{[Eq. 5]}$$

where $v_{min} = \left(\frac{2|q_\alpha V_p|}{m_\alpha}\right)^{1/2}$. The height of the probe is 3.4 mm and the probe diameter is 0.8 mm. Eq. 5 is solved for the electron saturation current and the ion saturation current.

The <u>electron saturation current</u> (Region B) is given by[3]:

$$I_{es}(V_p) = -n_e e A_p \left(\frac{eV_p}{2\pi m_e}\right)^{1/2} \text{[Eq. 6]}$$

The <u>ion saturation current</u> (Region D):

$$I_{is} \approx n_i e A_p \left(\frac{2K_B T_e}{m_i}\right)^{1/2} \text{[Eq. 7]}$$

The <u>transition current</u> (Region C) where $I_{is} < I < I_{es}$ is:

$$I_t(V_p) \approx eA_p \left[n_i \left(\frac{2K_B T_e}{m_i}\right)^{1/2} - n_e \left(\frac{K_B T_e}{2\pi m_e}\right)^{1/2} \exp\left(\frac{eV_p}{K_B T_e}\right)\right] \text{[Eq. 8]}$$

The floating potential, V_f, is the potential when the ion and electron currents are equal and is given by:

$$V_f \approx \frac{K_B T_e}{e} \ln\left[\frac{n_i}{n_e}\left(\frac{4\pi m_e}{m_i}\right)^{1/2}\right] \text{[Eq. 9]}$$

[3] Mathematical derivation is provided in the appendix.

You will need to know the electron temperature and the ion and electron densities in order to solve for the current values and the floating potential. The electron temperature is obtained from the slope of the probe characteristic:

$$\frac{d\ln|I|}{dV_p} = \frac{e}{K_B T_e} \text{ [Eq. 10]}$$

where the probe characteristic is semi-logarithmic. Once the electron temperature has been obtained the ion and electron densities can be found by solving [Eq. 6] and [Eq. 7]. Keep in mind that these equations work because we have a weakly-coupled plasma.

III. EXPERIMENT

Before we begin I need to make aware a precaution that one must observe while operating the equipment, namely, please do not exceed 150 V on the Heathkit regulated power supply or a probe voltage of 8 V this may damage the equipment by causing discharge on the probe (Region A of Figure 1). Also, do not attempt to edit the LabVIEW program in any way.

A sketch of the gas tube is shown in Figure 5. This tube consists of a metal disc cathode (pin 2), a Langmuir probe (pin 5), and an anode (pin 7). We will run the discharge current from the cathode to the anode. The circuit schematic for this experiment is shown as Figure 4. A supply voltage of 100–150 volts is used to run the discharge. The protective resistor (4kW) will limit the current because gas filled tubes tend to draw large currents if not stabilized. Identify these components if you have not yet already done so.

The experiment has been automated using LabVIEW, which will control a variable voltage source (the Keithley 228) as connected in Figure 4. The Keithley 228 is used by LabVIEW to bias or increment the voltage to the probe. As LabVIEW biases the probe, it will record readings from a picoammeter (the Keithley 485). A picoammeter is required because ion currents tend to be very small. Take all of your data for each part using the auto-scale function of the ammeter. The ammeter's scale is set using LabVIEW. You may choose the scale to be other than "auto-scale" but to do so you must choose a scale such that the data fits within that range without overflowing. I do not recommend this. At the higher bias voltages the currents may exceed the maximum range of the picoammeter in which case you will need to change the scale on the ammeter or turn down the maximum bias voltage. The LabVIEW program automatically stops taking data if the data overflows the ammeter scale. The input values for the scale on LabVIEW correspond to current increments in this way: 0=auto-scale, 1= 2nA, 2= 20 nA, 3= 200 nA, 4 = 2 μA, 5= 20 μA, 6= 200 μA, 7= 2 mA.

At this point you should set up the device in accordance with Figure 4. Take time to understand what goes where and why keeping in mind that the ion and electron currents flow in opposite directions.

IIIA. Measurements

In this experiment you will obtain and interpret the probe characteristic for the plasma (e.g., Figures 1, 2). As the probe voltage is varied the current may vary over many orders of magnitude and thus it is convenient to use a *semi-log plot*. Set the discharge current to 10 mA on the Heathkit Regulated Power Supply. In LabVIEW set the picoammeter to autoscale, the minimum voltage to -12 V, the maximum voltage to 8 V, and the voltage increment to 0.1 V. Now run the program for the first time. Note how the probe current rapidly reverses polarity even though the negative currents were quite small. This is when the ion current switches to electron current where the several magnitudes of difference between the two is accounted for by the difference in mass between the ions and electrons. Run a few more times if you see fit. When running LabVIEW you will be prompted to specify a file name to save your data as make sure to save the file as "*.xls" in order to save it as an Excel spreadsheet otherwise it will save as an *ASCII file*.

You wish to understand how the discharge current is related the standard plasma parameters. Now that you have a good handle for how a probe characteristic should look repeat the process above with all the same values except for the discharge current. Instead use these values for the discharge current: 10 mA, 15 mA, and 20 mA. Take several measurements until you are satisfied with the probe characteristics for each of these discharge currents. Oftentimes the plasma will not be visible unless the lights are off so please check before feeling the need to increase the discharge current. Assuming that the flux of electrons and ions are the same to the sides of the wire as they are to its flat disk top, by calculating the surface area of the sides, the current to the entire probe can be estimated.

IIIB. Data Analysis

LabVIEW should automatically create a plot of your data in Microsoft Excel. In Excel your data points should be accessed by right clicking on the plot and going to "Chart Object" then hitting "Open". When you exit LabVIEW make sure to click to option "Do not save all".

1. Take your data for your best runs at 10 mA, 15 mA, and 20 mA and overlay them on the same plot to see how discharge current affects the probe characteristic. When plotting make sure that your graphs have a logarithmic current scale and that your ion current is plotted with its sign reversed.

2. Fit straight lines to the curves in Region B (by right clicking on the data points and pressing "add trendline") and from them determine T_e [Eq. 10] in both ^oK and eV (1 eV/K_B = 11604.5 K).
3. In the probe characteristic the electron saturation current will be the current produced by the interaction between the plasma and the entire surface area of the probe. Compute the electron density by use of [Eq. 6]. Is the electron density proportional to the discharge current?

4. Use equation [Eq. 7] to compute the ion density. How does this compare with the electron density?

5. What is the floating potential of the probe? Compute this value for your best runs and compare with the experimental values.

6. Compute the Debye radius [Eq. 3] for all runs, and compare with the probe radius. Is the Debye radius much smaller than the probe radius?

7. Using [Eq. 8], create curves of the transition region and lay them with your best runs to see if the theory approximates well with what is there. Show error bars and compute chi-reduced square.

8. Compute the percentage ionization for the various discharge currents ($\frac{n_i}{n_n} \times$ 100% where n_i is the number ion density and n_n is the number neutral atom density). You will need the ideal gas law and the knowledge that the neutral gas temperature is roughly room temperature. Does your calculation agree with our statement that we do not need a large level of ionization for plasma to exist?

9. Does the theory of our experiment work well as an approximation of stellar plasma? Why or why not?

10. Qualitatively, how do the plasma parameters depend on discharge current?

IV. REFERENCES

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7. "New Elementary Experiments in Plasma Physics", I. Alexeff, J. T. Pytlinski, N. L. Oleson; American Journal of Physics, Vol. 45, No. 9, September 1977
8. "The Use of Electrostatic Probes for Plasma Diagnostics-A Review", B.E. Cherrington, Plasma Chemistry and Plasma Processing, Vol. 2, No. 2, 1982

V. APPENDIX:

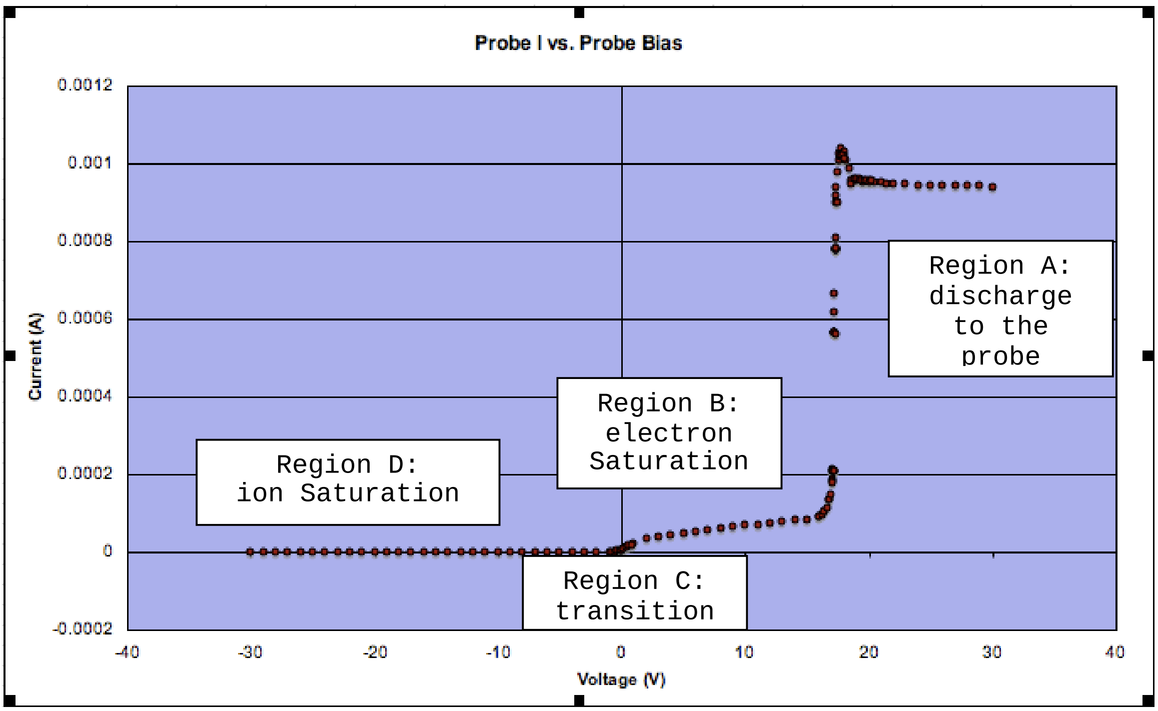

Figure 1: A typical probe characteristic (i.e., data set) at a discharge current of 40mA. This curve has been reconstructed from several runs' worth of data using Excel.

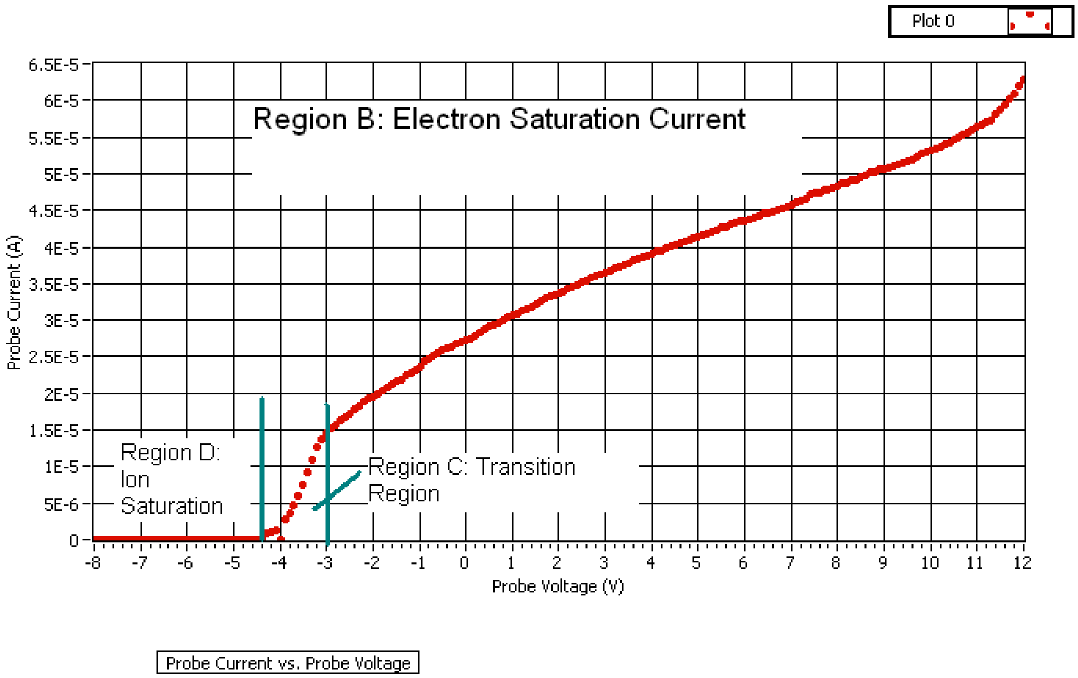

Figure 2: Probe characteristic created in LabVIEW without Region A.

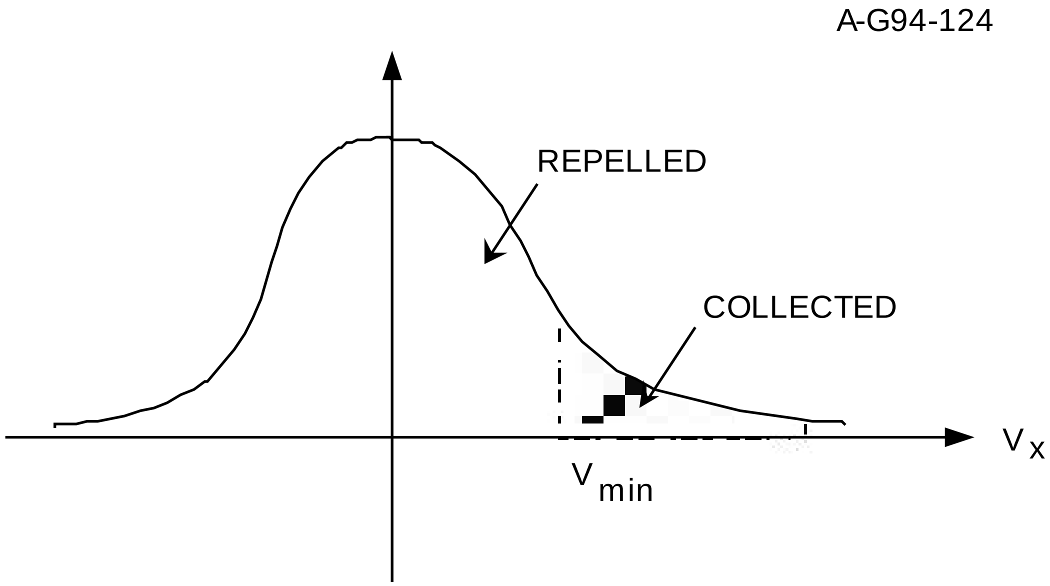

Figure 3: The region of integration from equation 4.

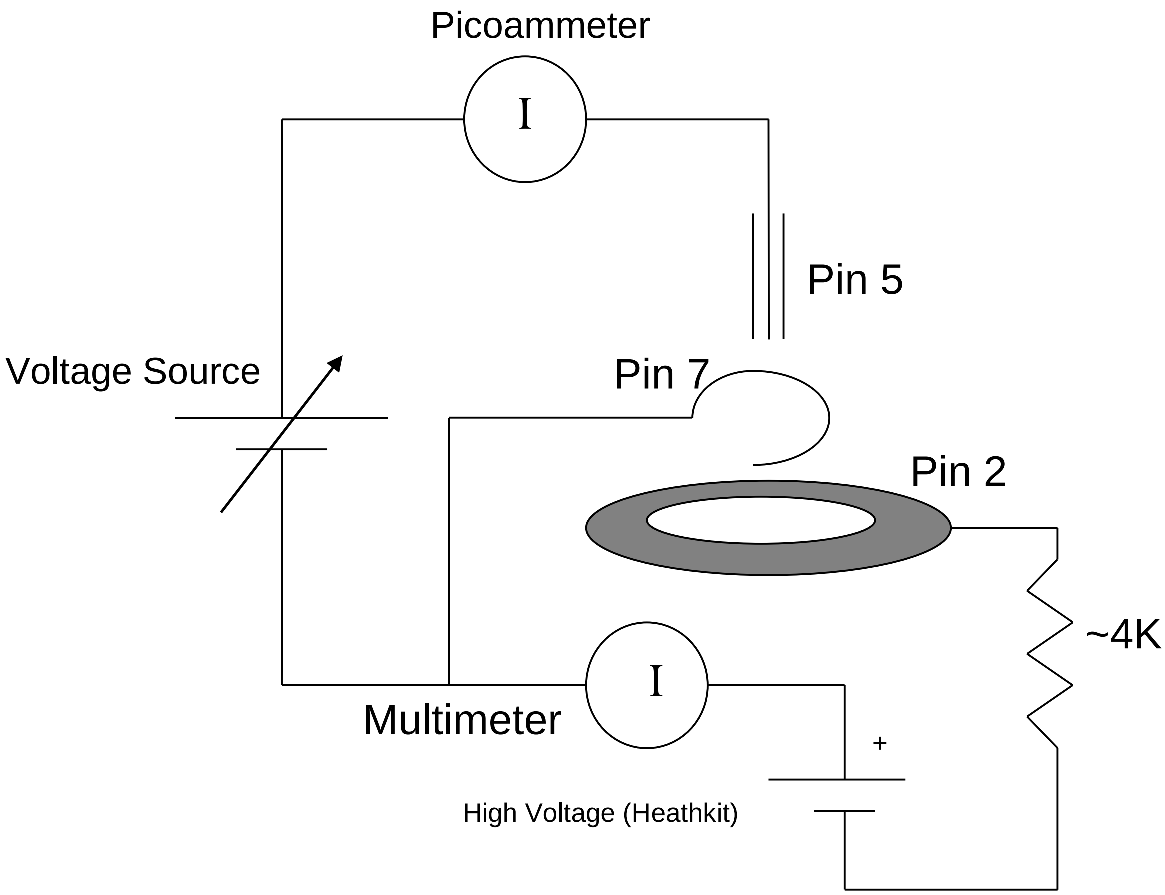

Figure 4: Circuit schematic.

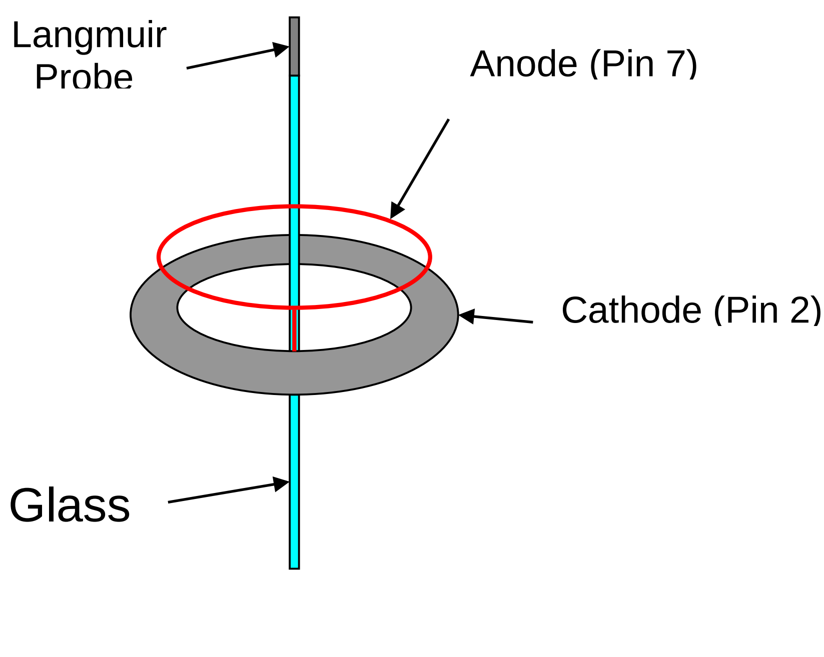

Figure 5: The tube.

Derivation of current incident on the probe and other plasma parameters:

A1) The Maxwell-Boltzmann Velocity Distribution

The current collected by a probe is given by summing over all the contributions of various *plasma species*:

$$I = A_p \sum_\alpha n_\alpha \, q_\alpha \langle v_\alpha \rangle \qquad \text{[A. 1]}$$

where $\langle v_\alpha \rangle = \frac{1}{n_\alpha} \int v \, f_\alpha(\vec{v}) d\vec{v}$ for unnormalized $f_\alpha(\vec{v})$. The species α takes values of either "electron" or "ion". It is well known in statistical mechanics that collisions among free particles like those in a "classical" gas will result in an average velocity given by the Maxwell-Boltzmann *velocity distribution function*, $f_\alpha(\vec{v})$. The distribution function may be used because we can safely ignore the electromagnetic forces between the electrons and ions due to the nature of low density plasmas:

$$f_\alpha(\vec{v}) = n_\alpha \left(\frac{2\pi K_B T_\alpha}{m_\alpha}\right)^{-3/2} \exp\left(\frac{-m_\alpha |\vec{v}_\alpha|^2}{2K_B T_\alpha}\right) \qquad \text{[A. 2]}$$

In order to get a general expression of the current to the probe in terms of velocity we combine Eq.? and Eq.?.:

$$I_\alpha(\overrightarrow{v_\alpha}) = n_\alpha q_\alpha A_p \iiint_{v_{min}}^{\infty} v_\alpha \left(\frac{2\pi K_B T_\alpha}{m_\alpha}\right)^{-3/2} \exp\left(\frac{-m_\alpha |\overrightarrow{v_\alpha}|^2}{2K_B T_\alpha}\right) d\vec{v}_\alpha \qquad \text{[A. 3]}$$

To simplify calculations we will first consider only the small disc top of the probe lying in the yz plane. Thus, particles will give rise to a current only if it has some v_x component of velocity. The current to the probe from *each* species is a function of $V \cdot (V_p - V_s)$. In Cartesian coordinates:

$$I(v_\alpha) = n_\alpha q_\alpha A_d \int_{v_{min}}^{\infty} v_x \left(\frac{2\pi K_B T_\alpha}{m_\alpha}\right)^{-1/2} \exp\left(\frac{-m_\alpha v_x^2}{2K_B T_\alpha}\right) dv_x \qquad \text{[A. 4]}$$

The lower limit of integration in the integral is v_{min} since electrons and ions with component of velocity less than $v_{min} = \left(\frac{2|q_\alpha V_p|}{m_\alpha}\right)^{1/2}$ are repelled due to the fact that at this point the particles lack the sufficient kinetic energy needed to push through the *Debye sheath*, Figure 3.

A2) The electron saturation current, I_{es}, (Region B):

In region B, when all electrons which interact with the probe are collected we obtain the electron saturation current for the disc:

Since $\int_0^\infty ve^{-Cv^2}dv = \frac{1}{2C}$ for the real part of C [A.8] we can show that

$$I_{es}(v_x) = -n_e e A_d \int_0^\infty v_x \left(\frac{2\pi K_B T_e}{m_e}\right)^{-1/2} \exp\left(\frac{-m_e v_x^2}{2K_B T_e}\right) dv_x = -n_e e A_d \left(\frac{K_B T_e}{2\pi m_e}\right)^{1/2} \quad [A. 9]$$

in terms of the probe potential and generalizing to the area of the entire probe:

$$I_{es}(V_p) = -n_e e A_p \left(\frac{eV_p}{2\pi m_e}\right)^{1/2} \quad [A. 10]$$

We are able to generalize to the entire surface area of the probe because the flux to the probe is isotropic.

A3) *The ion saturation current*, I_{is} (Region D)

The ion saturation current is not simply given by an expression similar to [A.10]. In order to repel all the electrons and observe I_{is}, V_p must be negative and have a magnitude near $K_B T_e/e$. The *Bohm sheath criterion* requires that ions arriving at the periphery of the probe sheath be accelerated toward the probe with energy $\sim K_B T_e$ which is much larger than their thermal energy $K_B T_i$. The ion saturation current is approximately given as:

$$I_{is} \approx n_i e A_p \left(\frac{2K_B T_e}{m_i}\right)^{1/2} \quad [A. 11]$$

Even though this *flux density* is larger than the incident flux density at the periphery of the collecting sheath, the total particle flux is still conserved because the area at the probe is smaller than the outer collecting area at the sheath boundary.

A4) *The transition current*, I_t (Region C)

Since it may be assumed that the current to the probe is isotropic the total current to the probe may be calculated by use of [A.3]:

$$I_{total}(v_x) = eA_p \left[n_i \int_{v_{min}}^\infty v_x \left(\frac{2\pi K_B T_i}{m_i}\right)^{-1/2} \exp\left(\frac{-m_i v_x^2}{2K_B T_i}\right) dv_x - n_e \int_{v_{min}}^\infty v_x \left(\frac{2\pi K_B T_e}{m_e}\right)^{-1/2} \exp\left(\frac{-m_e v_x^2}{2K_B T_e}\right) dv_x \right]$$

[A. 12]

Note that the energy $E = K_B T_\alpha = \frac{1}{2}mv^2 = -q_\propto V_p$ [A. 13]

A_p is the surface area of a cylinder with its bottom removed which may be substituted for A_d because flux to the probe is isotropic on all sides and all variables in [A.13] are magnitudes. In this region where probe potential < plasma space potential there is a Debye sheath and particles are repelled, the total current to the probe is given by the solution to [A.12]:

$$\text{Since } \int_C^\infty v * \exp(-Av^2)\, dv = \frac{\exp(-AC^2)}{2A} \text{ for Re(A)} > 0$$

$$I_t(V_p) = I_{is} - n_e e A_p \left(\frac{K_B T_e}{2\pi m_e}\right)^{1/2} \exp\left(\frac{eV_p}{K_B T_e}\right) \qquad [\text{A. }14]$$

since $V_p < 0$ in region C. [A.14] shows that the electron current increases exponentially until the probe potential is the same as the plasma space potential ($V = V_p - V_s = 0$). Substituting [A.11] into [A.14] yields our complete solution for the transition region in terms of probe voltage:

$$I_t(V_p) \approx eA_p \left[n_i \left(\frac{2K_B T_e}{m_i}\right)^{1/2} - n_e \left(\frac{K_B T_e}{2\pi m_e}\right)^{1/2} \exp\left(\frac{eV_p}{K_B T_e}\right)\right] \quad [\text{A. }15]$$

A5) *Floating potential*, V_f: Next we consider the floating potential. The probe potential equals the floating potential ($V_p = V_f$) when the ion and electron currents are equal and opposite thereby making the net probe current zero. Combining equations [A.10] and [A.11], and letting I = 0, we find that:

$$V_f \approx \frac{K_B T_e}{e} \ln\left[\frac{n_i}{n_e}\left(\frac{4\pi m_e}{m_i}\right)^{1/2}\right] \qquad [\text{A. }16]$$

A6) The electron temperature, T_e: Measurement of the electron temperature can be obtained from equation [A.14] if I_{is} can be approximated to zero in reference to the probe current:

$$I_t(V_p) = -n_e e A_p \left(\frac{K_B T_e}{2\pi m_e}\right)^{1/2} \exp\left(\frac{eV_p}{K_B T_e}\right) = I_{es} \exp\left(\frac{eV_p}{K_B T_e}\right) \qquad [\text{A. }17]$$

$$\frac{d \ln|I|}{dV_p} = \frac{e}{K_B T_e} \qquad [\text{A. }18]$$

By differentiating the logarithm of the electron saturation current with respect to the probe voltage V_p for $V < 0$, the electron temperature is obtained. We note that the slope of ln|I| vs. V is a straight line only if the distribution is a Maxwell-Boltzmann distribution.

A7) Measurement of the electron energy distribution function, $f_E(V_x)$: The electron current to the probe could be written in a more general expression as:

$$I = -n_e e A_p \int_{v_{min}}^\infty v_x f_v(v_x)\, dv_x = \frac{-n_e e A_p}{m_e} \int_{-eV_p}^\infty E f_E(-eV)\, d(-eV) \; [\text{A. }19]$$

GLOSSARY

Anode: The electron current from the cathode flows into the anode. The greater the potential between the anode and the cathode the greater discharge current will be produced in the plasma.

ASCII File: A column-delimited data file containing only the most basic characters i.e the digits, the alphabet, and some punctuation.

Bohm Sheath Criterion: An inequality which arises from the fact that electrons typically move magnitudes faster than ions in plasma (due to their mass). This limits the rate at which ions can be absorbed by the Langmuir Probe under the influence of Debye shielding, $v \geq \left(\frac{k_B T_e}{m_i}\right)^{1/2}$ where v is the speed of the ions; if the ion speed does not satisfy this inequality than it will not be absorbed by the probe.

Cathode: The point of an electrical device where electron current flows out of it; by convention, the negative side of an electrical device. As stated above the anode-cathode pair in Figure 5 is what produces the discharge current in the plasma.

Collisional Ionization: Ionization of atoms by collisions where energies greater than or equal to the atom's ionization potential enter the system.

Debye Length (Sheath Distance): I. The distance at which charge carriers can begin to effectively reduce the strength of electromagnetic fields in the rest of the plasma (by *screening*). The Debye length will become smaller the denser the plasma. II: The distance in plasma over which significant deviations from charge quasi-neutrality can exist.

Debye Sheath: A relatively dense region of charged particles around the Langmuir probe. Debye sheaths decrease the probe potential in the surrounding plasma.

Debye Sphere: A sphere with the radius of the Debye Length.

Dielectric Limit (Dielectric Strength): The energy limit at which an insulating material (for instance, the neutral gas) becomes a conductor through ionization or some other process.

Discharge Current: The current of a plasma that is produced by the *drift velocities* of charged particles.

Drift Velocity: The average velocity that a group of charged particles obtains from an electric field. $v = \frac{I}{nAq}$ where v is the drift velocity, I is the current density through a cross sectional area A (like the surface area of the top of the probe), n is the number

density of charged particles (or charge carrier density), and q is the charge of each particle. We analyze the ion drift velocity and electron drift velocity in isolation from each other to simplify calculations.
Electron Saturation Current: The electron current is said to be saturated when the probe potential is equal to or greater than the plasma space potential. At this point there is no longer a negative sheath which can repel electrons away from the probe, so, the electron current reaches its maximum value.

Electron Temperature: The average kinetic energy of free electrons described by a Maxwell-Boltzmann distribution.

Electron/Ion Density: The number of free electrons or ions per unit volume; normally the electron density is equal to the ion density given the need for overall charge neutrality.

Flux Density: The density of field lines per given area. In this lab the flux density is the electron and/or ion density passing through the surface area of the probe per given time.

Ion Saturation Current: Analogous to the electron saturation current, the ion saturation is when there is no longer a positive sheath around the probe to repel the ions approaching the probe and, consequently, one will find the maximum (the saturated) ion current is produced.

Ionization Potential: The energies required to remove electrons from gaseous atoms or ions. There are typically several ionization energies for the same atom: singly ionized, doubly ionized, etc.

Langmuir Probe : The probe in our experiment is defined as the wire where electron current flows in from the plasma. By varying the voltage on the probe the probe characteristic may be found.

Laplacian Operator: The Laplacian operator, ∇^2, is an operator that modifies scalar fields and is equivalent to (in Cartesian coordinates):

$$\nabla^2 t(x,y,z) = (\nabla \cdot \nabla)t = \left[\left(\frac{\partial}{\partial x}\right)^2 + \left(\frac{\partial}{\partial y}\right)^2 + \left(\frac{\partial}{\partial z}\right)^2\right] t = \left(\frac{\partial t}{\partial x}\right)^2 + \left(\frac{\partial t}{\partial y}\right)^2 + \left(\frac{\partial t}{\partial z}\right)^2.$$

Mean-Free-Path: The average distance particles can travel before collision with other particles of that species. The mean free path is: $\ell = \frac{K_B T_e}{\sqrt{2}\pi d^2 P}$ where d is the diameter of the particle and P is the pressure of the "gas" of that species. In the experiment you will be primarily concerned with the mean-free-path of electrons, but the equation can be modified for ions as well.

Plasma Parameters: Fundamental parameters of plasma which characterize that plasma from others i.e. electron temperature, ion density, and electron density.

Plasma Species: A species is just a sub-classification of members in a group. In this experiment there are two charged species: ions and electrons.
Probe Characteristic: A plot of probe current vs. probe voltage which shows how the probe current varies with the probe voltage. The probe characteristic defines the plasma parameters.

Probe Potential: The potential of the probe's surface relative to the anode or the ground of the Earth.

Quasi-Neutrality: In the context of our experiment a collection of charges with size greater than the Debye length is quasi-neutral if it can be thought of as electrically neutral.

Screened Potential: Any diminishing of an electrostatic potential by external charges between that potential and a test charge. For example, in our experiment the probe potential is reduced by the screening effect of the Debye sheath around the probe. The greater concentration of charges there is around the probe the greater the effect of screening.

Semi-Logarithmic Plot: A two-dimensional plot with a logarithmic scale on one axis and a non-logarithmic scale on the other. In our probe characteristic, probe current should be on a logarithmic scale and probe potential on a non-logarithmic scale.

Space Potential (Electrostatic Potential): The voltage at any point in the plasma that is not inside or on the boundary of a Debye Sheath, that is, the region of plasma where the plasma may be considered to have a quasi-neutral distribution of charges.

Velocity Distribution Function: A function when integrated with respect to velocity gives the probability of finding particles with velocity between v and $v + dv$. [A. 2]

Weakly-Coupled Plasma: Plasma where the dominate motions of charged particles are determined by the thermal velocities of those particles and not the presence of electromagnetic fields.