THE LANGMUIR PROBE

Last Edited: June 26, 2007

QUESTION TO BE INVESTIGATED:

How is discharge current related to the standard plasma parameters?

INTRODUCTION:

The Langmuir probe is a diagnostic device used to determine several basic properties of a plasma, such as temperature and density. A plasma is a state of matter which contains enough free (not bound to an atom) charged particles (electrons and ions) so that its dynamical behavior is dominated by electromagnetic forces. The subject of plasma physics is concerned mainly with ionized gases although very low degrees of ionization (@ 0.1%) are sufficient for a gas to exhibit electromagnetic properties.

A method, first used by Langmuir about fifty years ago, can be used to determine the ion and electron densities, the electron temperature, and the electron distribution function. These are commonly known as the *plasma parameters*. Langmuir's method involves the measurement of electron and ion currents to a small metal electrode (or Langmuir probe) as different voltages are applied to the probe. This yields a curve called the *probe characteristic* of the plasma. In general since the electron and ion masses are significantly different they respond to forces on different time scales, however the requirements of overall charge neutrality gives $n_e = n_i$.

In this experiment we make use of a sample gas tube, the OA4-G which possesses a built-in Langmuir probe. The tube is filled with argon gas at 10^{-3} atm. The tube contains three electrodes: A voltage is applied across two electrodes in order to create an electrical current in the gas while the third electrode is used as the Langmuir probe. This "discharge" current then continuously creates the plasma. Before discussing the experimental apparatus we will now consider the basic theory of the Langmuir probe.

THEORY:

The fundamental plasma parameters can be determined by placing a small conducting probe into the plasma and observing the current to the probe as a function of the difference between the probe and plasma space potentials. The plasma space potential is just the potential difference of the plasma volume with respect to the vessel wall. It arises from an initial imbalance in electron and ion loss rates and depends in part upon anode surface conditions, and filament emission current.

Referring to the probe characteristic, Figure 1, we see that in region A when the probe potential, V_p, is above the plasma space potential, V_s the collected electron current reaches a saturated level and ions are repelled, while in region B just the opposite occurs. By evaluating the slope of the electron I-V characteristic in region B the electron temperature T_e is obtained, and by measuring the ion or electron saturation current and using the T_e measurement, the density can be computed.

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

$$I = \sum_i n_i q_i v_i \tag{1}$$

where *A* is the total collecting surface area of the probe; v_i= the average velocity of species *i*, and $\langle v_i \rangle = \frac{1}{n}\int v f_i(\vec{v}) d\vec{v}$ for unnormalized $f_i(\vec{v})$. It is well known in statistical mechanics that collisions among particles will result in an equilibrium velocity distribution f given by the Maxwellian function:

$$f_\alpha(\vec{v}) = n\left(\frac{2\pi KT}{m_\alpha}\right)^{-3/2} Exp\left(\frac{-\frac{1}{2}m_\alpha|\vec{v}|^2}{KT_\alpha}\right) \tag{2}$$

This distribution function is used to evaluate the average velocity of each species.

We will first consider a small plane disc probe which is often used in our experiments. Then it is placed in the yz plane, a particle will collide with the probe and give rise to a current only if it has some v_x component of velocity. Thus, the current to the probe does not depend on v_y or v_z. The current to the probe from *each* species is a function of $V \circ V_p - V_s$.

$$\begin{aligned} I(v) = nqA\int_{-\infty}^{\infty} dv_y \left(\frac{2\pi KT_\alpha}{m_\alpha}\right)^{1/2} Exp\left(\frac{\frac{1}{2}m_\alpha v_y^2}{KT_\alpha}\right) \\ \bullet \int_{-\infty}^{\infty} dv_z \left(\frac{2\pi KT_\alpha}{m_\alpha}\right)^{1/2} Exp\left(\frac{\frac{1}{2}m_\alpha v_z^2}{KT_\alpha}\right) \\ \bullet \int_{v_{min}}^{\infty} dv_x v_x \left(\frac{2\pi KT_\alpha}{m_\alpha}\right)^{1/2} Exp\left(\frac{\frac{1}{2}m_\alpha v_x^2}{KT_\alpha}\right) \end{aligned} \tag{3}$$

The lower limit of integration in the integral over v_x is v_{min} since particles with v_x component of velocity less that are $v_{min} = \left(\frac{2qv}{m_\alpha}\right)^{1/2}$ repelled, Figure 2.

The integrals over v_y and v_z in (3) give unity so the current of each species is just

$$I(v) = nqA\int_{v_{min}}^{\infty} dv_x v_x \left(\frac{2\pi KT_\alpha}{m_\alpha}\right)^{1/2} Exp\left(\frac{\frac{1}{2}m_\alpha v_x^2}{KT_\alpha}\right) \tag{4}$$

a) <u>The electron saturation current</u>, I_{es}: In this region all electrons with v_x component toward probe are collected. We obtain the electron saturation current

$$I_{es} = neA\int_{0}^{\infty} dv_x v_x \left(\frac{2\pi KT_e}{m_e}\right)^{1/2} Exp\left(\frac{\frac{1}{2}m_e v_x^2}{KT_e}\right) \tag{5}$$

$$= -neA\left(\frac{KT_e}{2\pi m_e}\right)^{1/2}$$

Similarly, in region B and C were $V_p < V_s$ and electrons are repelled, the total current is

$$I(v) = I_{is} - neA\int_{v_{min}}^{\infty} dv_x v_x \left(\frac{2\pi KT_e}{m_e}\right)^{1/2} Exp\left(\frac{\frac{1}{2}m_e v_x^2}{KT_e}\right) \tag{6}$$

Substituting $\frac{1}{2}m_e v_{min}^2 = -eV$, (6) becomes

$$I(v) = I_{is} - neA\left(\frac{KT_e}{2\pi m_e}\right)^{1/2} Exp\left(\frac{eV}{KT_e}\right) \tag{7}$$

since V < 0 in region B and C. Equation (7) shows that the electron current increases exponentially until the probe voltage is the same as the plasma space potential ($V = V_p - V_s = 0$).

b) <u>The ion saturation current</u>, I_{is}: The ion saturation current is not simply given by an expression similar to (5). In order to repel all the electrons and observe I_{is}, V_p must be negative and have a magnitude near KT_e/e as shown in

Figure 3. The sheath criterion requires that ions arriving at the periphery of the probe sheath be accelerated toward the probe with an energy ~KT_e, which is much larger than their thermal energy KT_i. The ion saturation current is then approximately given as

$$I_{is} = neA\left(\frac{2KT_e}{m_i}\right)^{1/2} \tag{8}$$

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.

c) Floating potential, V_f: Next we consider the floating potential. When $V = V_f$, the ion and electron currents are equal and the net probe current is zero. Combining equations (7) and (8), and letting $I = 0$, we

$$V_f = -\frac{KT_e}{e}\ln\left(\frac{m_i}{4\pi m_e}\right)^{1/2} \tag{9}$$

d) The electron temperature, T_e: Measurement of the electron temperature can be obtained from equation (7). For $I_{is} << I$ we have

$$I(v) = -neA\left(\frac{KT_e}{2\pi m_e}\right)^{1/2} Exp\left(\frac{eV}{KT_e}\right) = I_{es}Exp\left(\frac{eV}{KT_e}\right) \tag{10}$$

$$\frac{d\ln|I|}{dV} = \frac{e}{KT_e} \tag{11}$$

By differentiating the logarithm of the electron current with respect to the probe voltage V 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 Maxwellian.

e) Measurement of the electron distribution function, $f_e(v_x)$: The electron current to a plane probe could be written in a more general expression as (again neglecting the ion current)

$$I = nqA \int_{v_{min}}^{\infty} v_x f(v_x) dv_x = \frac{nqA}{m_e} \int_{qV}^{\infty} f(qV) d(qV) \qquad (12)$$

$$\frac{I}{d(qV)} \propto f(qV)$$

where $q = -e$, the electron charge. This is a very simple way of obtaining the electron energy distribution function.

This discussion of the Langmuir probe theory applies when the probe radius is large compared to the sheath distance or shielding distance that is given by the Debye length

$$\lambda_D = \left(\frac{KT}{4\pi n e^2} \right)^{1/2} \qquad (13)$$

The Debye length is a measure of the distance over which charge neutrality may not be valid near a boundary of a plasma, or in this case near the probe. It is also a measure of the effective range of the shielded Coulomb potential. The requirement $r_p >> l_D$ insures that edge effects may be neglected.

EXPERIMENT

A sketch of the gas tube is shown in Figure 4. This tube consists of a metal disc cathode (labeled as pin 2), a wire tip anode (used as a probe and labeled pin 5), and a trigger anode ring (labeled as pin 7). We will run the discharge current from the metal disc cathode to the trigger anode ring and use the wire tip anode as a Langmuir probe.

The circuit schematic for this experiment is shown in Figure 3. Pin 2 is the cathode, pin 5 the anode, and pin 7 the trigger anode. Do not connect a wire along the dashed line at this time. A supply voltage of 100–200 volts is used to run the discharge. The protective resistor (4KW) is used to limit the current because a gas filled tube tends to draw large currents if not stabilized. Identify these components if you have not yet done so.

This experiment has been automated using LabVIEW, which will control a variable voltage source (Keithley 228 voltage/current source) as connected in Figure 3. While varying this voltage source, LabVIEW will record readings from a picoammeter (also by Keithley). The floating variable (±30V) voltage source is used to bias the probe. At some voltages you may see extremely small currents. A picoammeter has been provided for these measurements.

Take all of your data for each part using a single range for the meter, otherwise LabVIEW may become confused. The ammeter's scale is set using LabVIEW. Choose the scale so that the data just fits within that range without overflowing. 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 meter. The LabVIEW program automatically stops taking data if the data overflows the meter scale. If this happens, you may need to adjust the range of voltage applied or the picoammeter scale before you take the next data set. *Due to these restrictions* *you will need to take several data sets with different scales spanning only portions of the entire curve that you wish to observe.* Setting the scale to “0” allows the picoammeter to auto scale, which you do not want. Otherwise, the lower the number the finer the scale.

At this point you should set up the device in accordance with Figure 3. Take time to understand what goes where and why.

A. <u>Preliminary Measurements</u>

In this experiment you will obtain and interpret the Langmuir probe characteristic for the plasma (e.g., Figure 1). 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 (LabVIEW has taken care of this). Set the picoammeter scale to something rather coarse (i.e., 7) and scan the range of between -30V and +30V (This is the process that has been automated for you using LabVIEW). Note how the probe current rapidly reverses polarity albeit the negative currents were quite small. These preliminary measurements should give you an indication for the general nature of the probe characteristic (Figure 1) so that you may vary the voltage, scale, and resolution of measurement accordingly when moving through the regions of your curves.

B. <u>Data Taking</u>

Remember, you wish to understand how the discharge current is related the standard plasma parameters. Therefore, you will be measuring the current on the Langmuir probe as you change the probe’s bias voltage (between -30V and +30V) at varying values of the discharge current. Do this for discharge currents of 40mA, 30mA, and the lowest discharge current that still creates a plasma. For each value of the discharge current you will want to know the potential between the cathode and the trigger anode ring.

Finally, you should rearrange the apparatus so that the probe voltage source rides atop the cathode (pin 5) instead of the trigger anode ring. This is shown by the dashed line in the figure. Create a curve of Probe Current vs. Probe Voltage for this arrangement at a discharge current of 40mA.

Estimate the length and diameter of the exposed tip of the Langmuir probe.

You should now reassemble your data in Excel for each of your discharge current runs. It should look vaguely like Figure 1.

C. Data Analysis

Reconstruct your data within Excel. Create a plot of Probe Current vs. Probe Bias Voltage for each of the discharge currents that you used. Overlay them on the same plot so that you may compare.

1. Plot the probe curves on a semi-log plot. N.B. The ion saturation current must be plotted with the sign reversed to fit on the same plot. Plot the results of data sets 1, 2, and 3 on the same plot.
2. Fit straight lines to the curves in the exponential region and from these determine T_e (in °K and eV). Hint, take the logarithm of the current and then plot that on the y axis before fitting.
3. Identify the plasma potential in each case. What is the voltage drop between the cathode and plasma

potential? This plasma potential - cathode drop accelerates ions into the cathode and sputters the material onto the glass. Did you observe any sputtering from the probe? What energy would these accelerated ions have in °K (in eV)?

4. Identify the electron saturation current and compute the electron density. What is the uncertainty in the density due to the uncertainty in determining the probe area? Is the electron density proportional to the current in the main discharge?
5. Identify the ion saturation current and using equation (8) compute the density. How does this compare with the previous determination of n? Assuming that an expression similar to (5) is valid for the in saturation current, compute a temperature for the ions. Does this temperature correspond to that of the electrons, or that of the gas atoms? (Gas atoms are at room temperature $\sim\frac{1}{40}\,\mathrm{eV}$.) Why is this so? (Gas pressure is about 1/1000 atmosphere in the tube.)
6. Identify the point at which the positive probe begins to break down. At this point some of the electrons may acquire enough energy to ionize the background gas. How far is this potential in volts, from the tip of the electron current distribution? Compare this voltage with the ionization potential for argon.
7. What is the floating potential of the probe? The value of the floating potential can be computed theoretically, with reference to plasma potential, V_s

$$v_f - v_s = \frac{1}{2} T_e \ln \frac{T_e m_i}{T_i m_e} \tag{14}$$

Compute this value for all runs, and compare with the experimental values.

8. Compute the Debye radius for all runs, and compare with the observed probe radius.
9. Compute the percentage ionization for the various discharge current, i.e., the ratio of electron density to neutral gas density in the tube.

REFERENCES

1. Plasma Dynamics, T.J.M. Boyd and J.J. Sanderson, Barnes and Noble, New York, 1969.
2. Plasma Diagnostic Techniques, R.H. Huddlestone and S.L. Leondard, editors, Academic Press, New York, 1965, Ch. 4.
3. Plasma Diagnostics, W. Lochet-Holtgreven, ed., North Holland, Amsterdam, 1968, Ch. 11.
4. Introduction to Experimental Plasma Physics, A.Y. Wong, UCLA report, 1977.
5. The Taylor Manual, T.B. Brown, ed., Addison-Wesley, Reading, Mass., 1961, p. 450.

APPENDIX: Figures

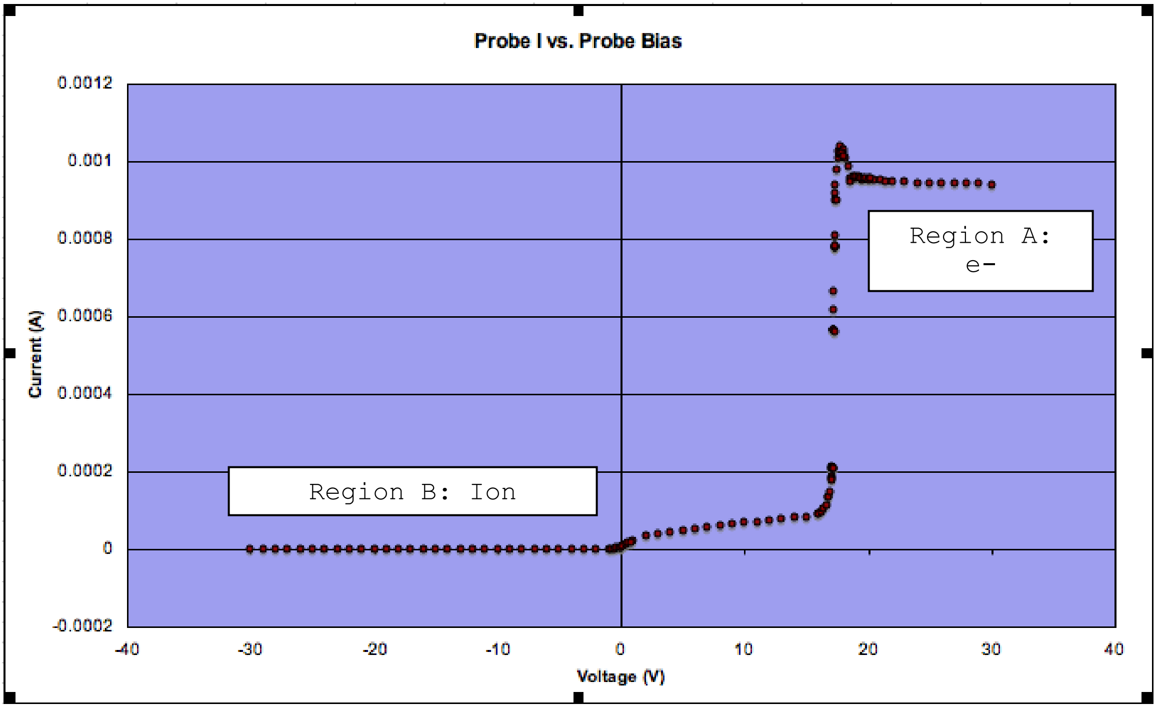

Figure 1: A typical probe characteristic (i.e., data set) at a discharge current of 40mA. This curve has been reconstructed from several runs' worth of data using Excel.

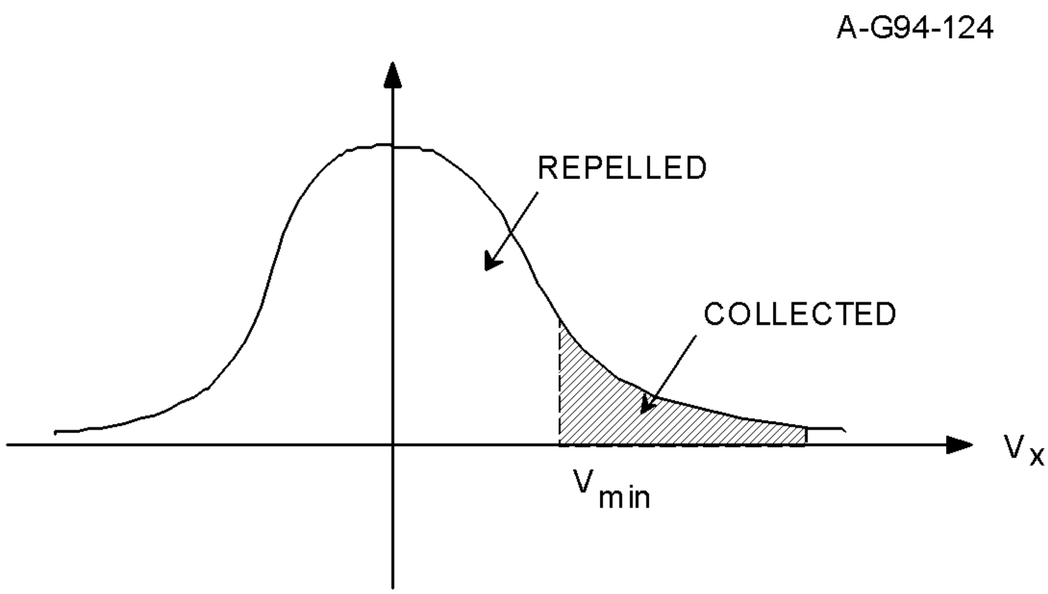

Figure 2. The region of integration from equation 4.

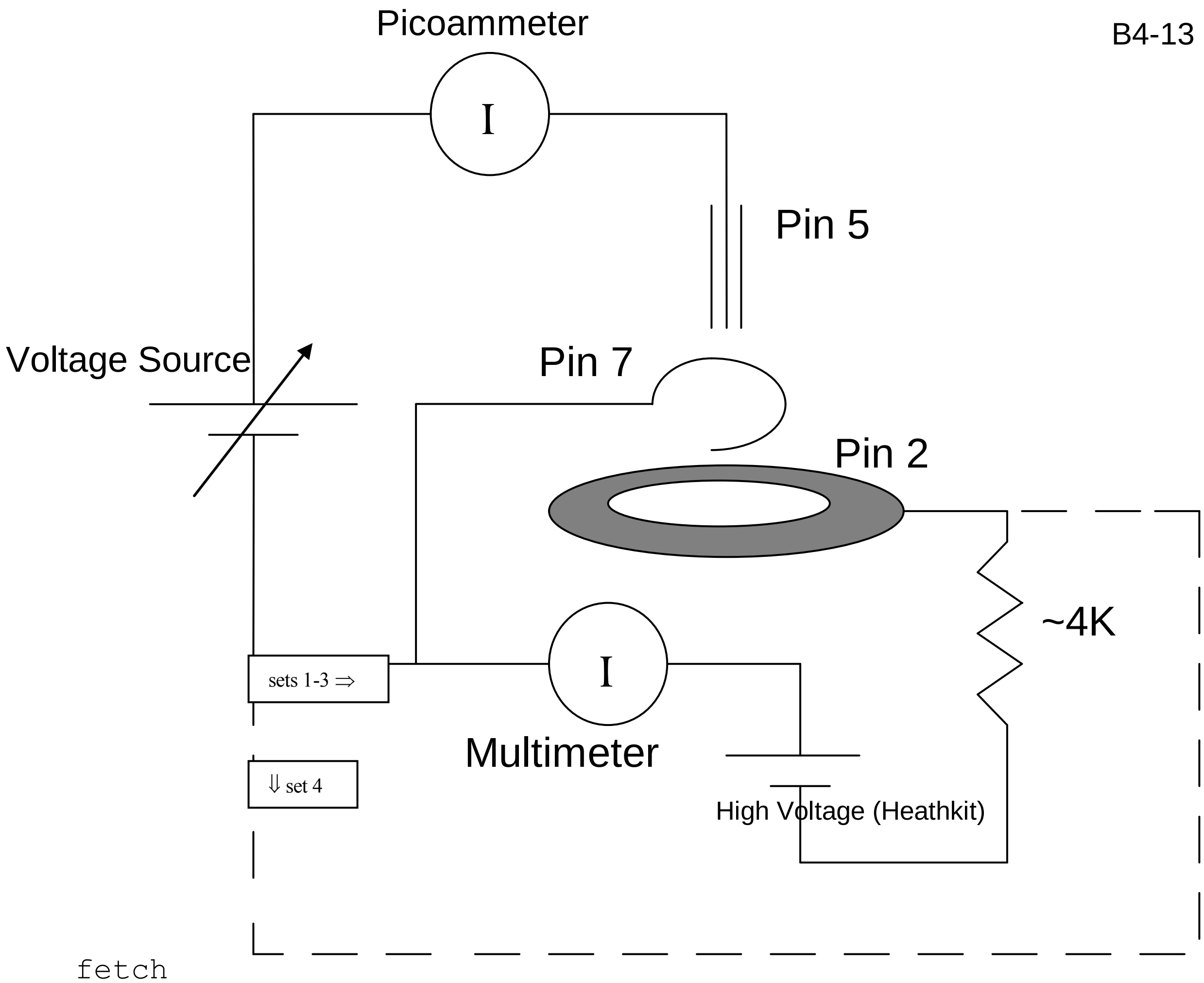

Figure 3: Circuit Schematic.

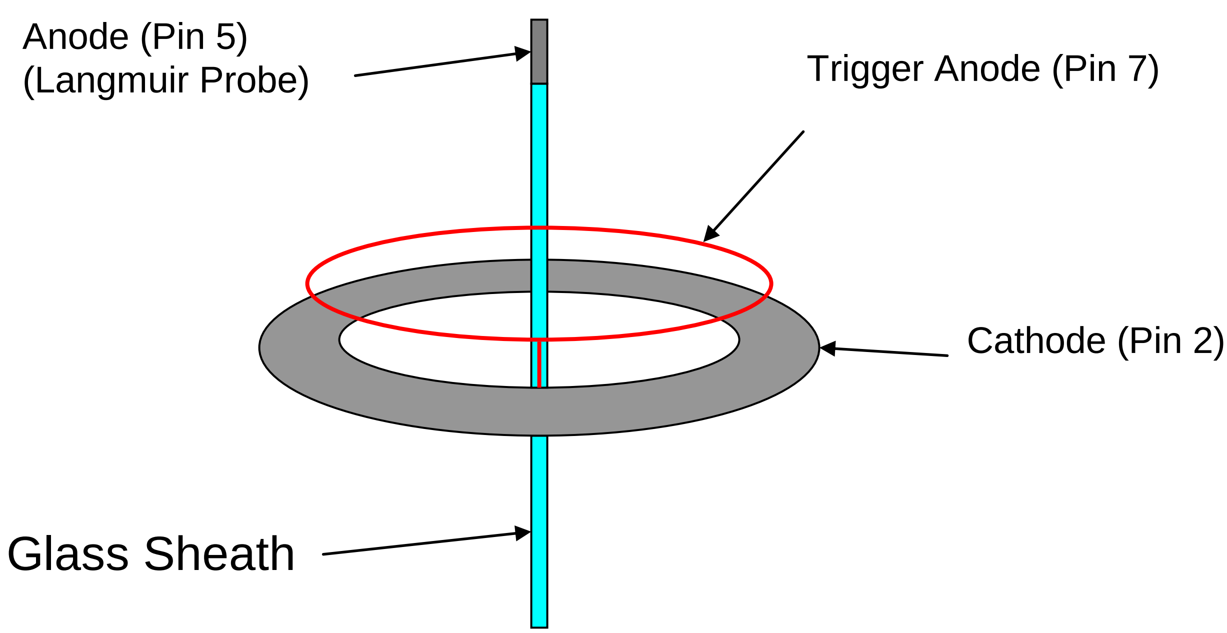

Figure 4 - Sketch of the vacuum tube's internals structures