Design, Fabrication, and Data Analysis of a High-Temperature Single Langmuir Probe

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15 September 2016

Abstract

This summer project consisted of the design, fabrication, and testing of a high-temperature Langmuir probe for use in studying the plume of the high-current density cathode project. This paper consists of probe theory, design justification, and data analysis.

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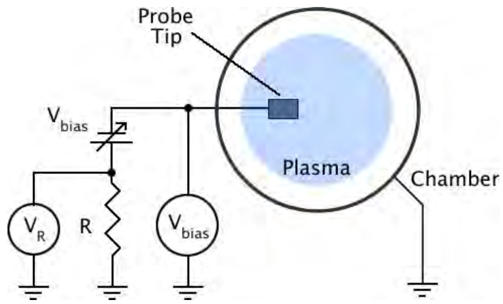

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Figure 1: A very basic Langmuir probe schematic. [4]

1 Overview

A Langmuir probe is a plasma diagnostic tool that allows for the accurate measurement of several plasma parameters, including electron temperature, plasma potential, and ion density. Langmuir probes are powerful tools because they represent one of the few ways to reliably get local measurements inside a plasma without causing disturbances to propagate through the plasma. [1] They are also very simple and relatively easy to implement. However, data analysis is very difficult, and numerous theories have been proposed to model the probe's behavior.

In its most simple form, a Langmuir probe consists of a very thin wire inserted in the plasma to which a bias voltage is applied. The resulting electron current that flows through the wire (and thus, the plasma) is then measured and plotted against the bias voltage; from this, various parameters can be computed through a well-developed probe theory. More complex Langmuir probes can have several wires, with various combinations of voltages providing more detailed information about the plasma, or alternate tip geometries, such as a plate or a sphere, but a single, cylindrical-wire Langmuir probe is often all that is needed for useful data. Moreover, it is the simplest of the three geometries to manufacture, as one can use a very thin wire as the probe collecting surface.

2 Probe Theory

This section will be brief, and focus mainly on the equations and physics necessary to understand a very simple single probe. For a much more thorough explanation and derivation of Langmuir probe theory, see Francis Chen's notes on Langmuir probes.

2.1 Debye Sheath

The Debye sheath is the name given to the region of a plasma which feels the effect of an introduced electric charge. Because a plasma consists of a quasineutral mixture of ions and electrons moving in space, the introduction of a negatively charged particle or object into the plasma will cause electrons within several Debye lengths to flee the region surrounding the object, creating a net positively charged sheath and the breakdown of the quasineutral assumption. Unfortunately, probes create sheaths by virtue of being charged objects in a plasma, so understanding their properties becomes necessary to understanding the probe's operation.

2.2 I-V Curve

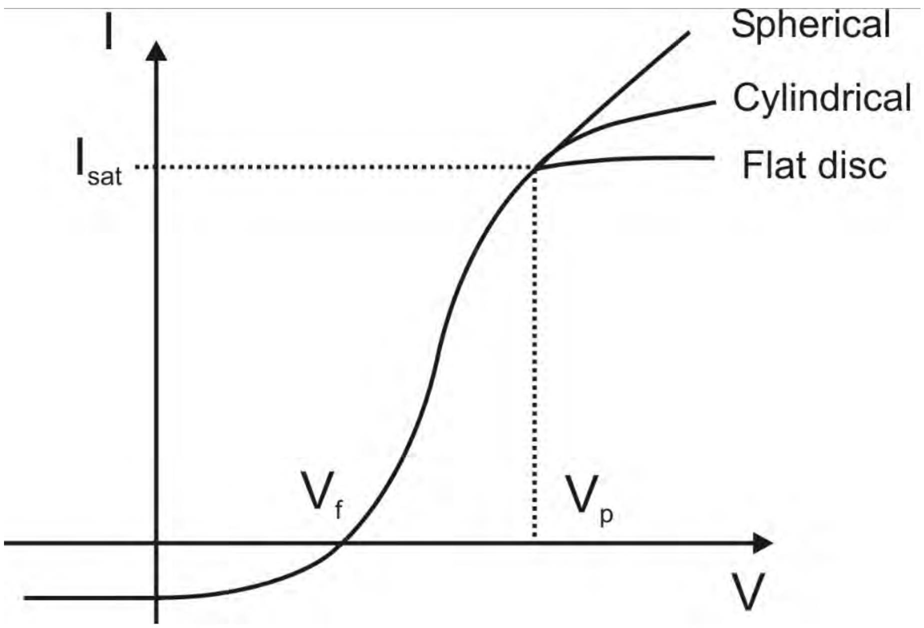

Figure 2: I-V trace for an ideal Langmuir probe. [5]

The I-V curve is the basis for Langmuir probe theory. From this curve, it is possible to back out the above-mentioned plasma parameters. There are three main regions in the curve: the ion saturation region, the transition region, and the electron saturation region. The leftmost region of the plot where the I-V curve is nearly horizontal corresponds to the ion saturation region. At this point, the current is negative and unchanging, which means that the ion flux towards the tip is saturated, and no electrons are reaching the tip. This is the ion saturation current, I_{sat}. As the voltage increases, the curve crosses the I = 0 point. This potential, the floating potential (V_f), is the potential that an ungrounded, unbiased probe would arrange itself to so as to draw no current from the plasma. At this point, the ion current must be exactly equal to the electron current.

Further increasing the voltage, the curve enters a transition region in which ions start to be repelled from the probe. Electrons are repelled less and less as the probe potential nears the space potential $\mathrm{V_s}$ of the plasma at large. The assumption of a Maxwellian plasma means that the current in this section has an exponential dependence on the voltage. When the probe potential exactly matches the space potential, the probe is attracting all the electrons that randomly enter the sheath around the probe. Beyond this potential, the sheath expands, and depending on geometry will either continue to grow or remain more or less constant. The three curves beyond that point, corresponding to the three potential probe geometries, show the diversity in sheath growth.

2.3 Plasma Temperature

Plasma temperature information can be gained from the transition region of the I-V curve. If we assume that the electron distribution is Maxwellian and follows the Boltzmann law, then the electron current is given by Equation 1: [1]

$$I = A_a n_0 \left(\frac{kT}{2\pi m}\right)^{0.5} e^{-\left|\frac{eV}{kT_e}\right|} \tag{1}$$

Comparing the bias voltage and current (V and I) to the space potential and electron saturation current ($\mathrm{V_s}$ and $\mathrm{I_{e,sat}}$), and taking the logarithm of both sides, we find that

$$\log(I - I_{e,sat}) = -\left|\frac{e(V - V_s)}{kT_e}\right| + \log\left(A_a n_0 \left(\frac{kT}{2\pi m}\right)^{0.5}\right) \tag{2}$$

which is linear with slope $1/\mathrm{T_e}$ in eV. Therefore, by plotting log(I) against V, and then computing the reciprocal of the slope of the transition section, we can compute the electron temperature of the plasma. Hutchinson recommends taking the derivative instead and plotting V vs $\frac{dI}{dV}$, which he claims gives a more accurate method of locating $\mathrm{T_e}$. [2] Both methods work, and both will be explored in further data analysis.

2.4 Plasma Density

The plasma density is often approximated by linearly fitting a curve to both the electron saturation and the transition regions and then finding their intersection. The intersection point is a good approximation of the plasma density if the I-V curve has a sharp bend between the electron saturation and transition regions. A bit of manipulation of Equation 1 gives us the following equation for the plasma density: [2]

$$n_e = \frac{I_s at}{qA_s \exp(1/2)}\sqrt{\frac{M}{kT_e}} \tag{3}$$

where $\mathrm{A_s}$ is the sheath area and M is the mass of an ion. For a cylindrical probe, the sheath area needs to be modified by the following expression: [2]

$$A_s \approx A_p \left(1 + \frac{x_s}{a}\right) \tag{4}$$

where x_s is an empirically derived function of temperature [2] and a is the probe radius. With this in mind, the plasma density can be computed relatively accurately via iteration.

3 Design & Apparatus

A successful Langmuir probe design requires several parameters to be optimized.

First, the probe needs to be resistant to incredibly high temperatures. As such, material selection requires heat resistance to be a primary concern.

Second, the only part of the wire that can be unshielded is the very tip that's exposed to the plasma; otherwise, the changing voltage will create oscillations, both electrical and magnetic, in the plasma that will distort the probe's measurements.

Lastly, the probe must be thin enough not to disturb the plasma but large enough to be much greater than the Debye length so that the thin-sheath approximations that are made in the theory can hold.

3.1 Probe

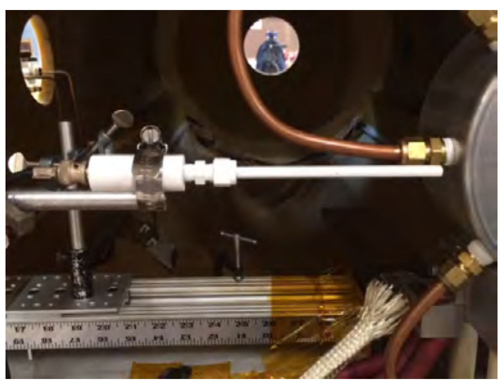

Figure 3: Probe mounted in experiment.

The probe was designed with two goals in mind: one, to be as small as possible, and two, to be as heat-resistant as possible. Unfortunately, financial constraints led to some compromise on the first goal, but the second was well-achieved. The tip consists of .010" diameter tungsten wire, extending the length of the probe with .232" of wire protruding from the probe tip. This wire is connected to the center connector of a BNC terminal at the back of the probe.

Directly around the wire is a four-holed, .18"-diameter alumina tube, which acts as an electrical insulator separating the wire from the plasma, as well as

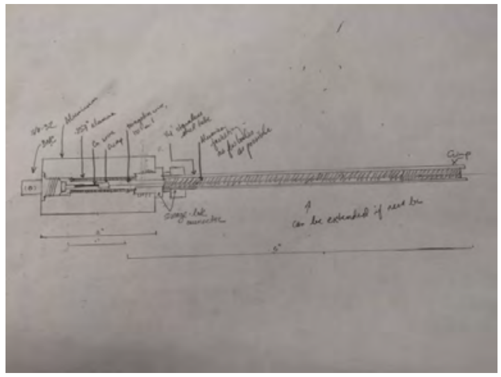

Figure 4: Cross-section diagram of probe.

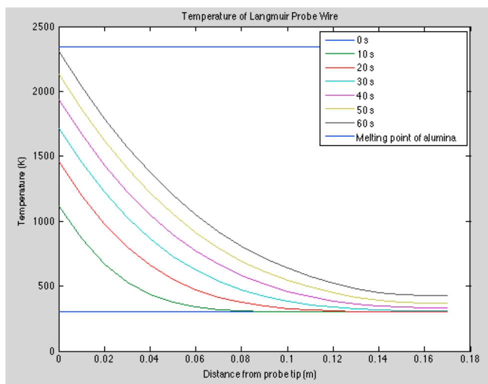

Figure 5: Finite difference heat equation solution for T = 3 eV, n = 10^{19} cm^{-3}

the metal jacketing. This piece abuts two more pieces in the body of the probe in order to preserve the insulation all the way to the BNC.

Surrounding these components are the shielding components. The tip is jacketed by a .25"-diameter stainless steel tube with gently crimped ends, while the body is formed by a .5"-diameter aluminum billet. The two are held together with a Swagelok connector. As the body is expected to get nowhere near the plasma, aluminum was selected for machinability; the stainless steel tube was a logical choice for the high-temperature probe tip as it melts at a higher temperature.

As the probe will be inserted between the cathode keeper and the anode, the entire outer layer is coated in a layer of boron nitride adhesive spray to prevent plasma grounding issues.

In order to ensure that the probe tip would not suffer extensive damage from the plasma, a finite difference solver was programmed in Matlab to solve the heat equation along the length of the wire. Using optimistic plasma temperature and density values of 3 eV and 1×10^{19} m^{-3}, the wire never gets above the melting point of its alumina jacketing, as shown in Figure 5.

3.2 Translation Stage

Figure 6: Translation stage. Potentiometer in back, with white marking.

The translation stage was salvaged from another experiment in the lab. It consists of a 12V motor geared to a long threaded rod, which engages with a tapped hole on the base of a plate. This plate is constrained to only be able to move in the direction of the rod, thus creating a mechanism by which the plate (and by extension whatever's on it) can move back and forth. To tell where the plate is on the track, there is a large potentiometer geared to the rod.

Chemistry stand clamps were used to hold the probe in the desired location. The joints between clamps were wrapped in Kapton tape for electrical insulation purposes, so that the ground that makes up the probe body would not try to go to the much larger ground that makes up the rest of the experiment.

Once the stage was placed and fixed down, it was possible to calibrate the translation stage to accurately place the tip of the probe to within 1/16". This is not incredibly precise, but is accurate enough for the purpose of testing the probe.

3.3 Probe Driver

The probe driver was built by Bob Sorenson as a general-purpose Langmuir probe driver. It takes a 15V, 2A power supply and a 1.5V DC input signal and outputs the current and voltage seen by the probe. Internally, the circuitry multiplies the input signal's voltage by 10x and supplies that as an isolated, floating voltage to the probe.

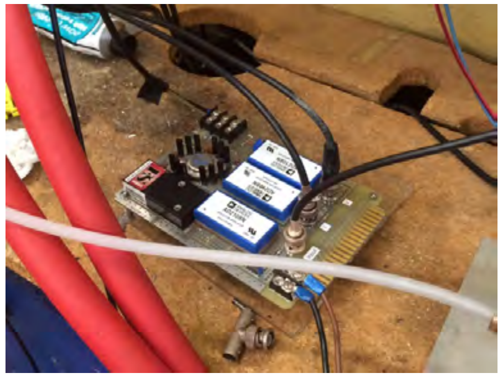

Figure 7: Probe driver, after all wiring done.

3.4 Data Collection System

Data collection was done in Labview using a Tektronix TDS 3034B oscilloscope interfaced with a computer. A script was written to collect and record data; other Matlab scripts were used to process the data and produce useful plots.

4 Results

Unfortunately, the day that data was supposed to be taken for the first time, the cathode to the high-current microwave experiment cracked and had to be repaired. The graduate students were very generous, however, and immediately set to building a simple microwave cathode so that the probe could at least be tested. As such, data was taken on this very simple cathode/anode system.

5 Analysis

Unfortunately, the sample rates of the data logger matched the harmonic frequency of the oscillator, so data points ended up only existing at certain points. Figure 8 illustrates this problem.

Notice how the data all seem to line up in vertical rows; this limits the accuracy of the acquired data. Averaging along those vertical lines, the data looks like the following:

This section of plot looks very much like a normal Langmuir probe trace, with some noise in the region around the floating potential. Subtracting off the ion saturation current, and taking the log of both sides, we find that the data looks something like Figure 10.

This figure is exactly what is needed in order to compute plasma density and temperature; however, the data is not in the right 'range' in order to find the necessary values. It was not possible in the time of the internship to apply a bias voltage to the voltage sweep in order to shift the operating window

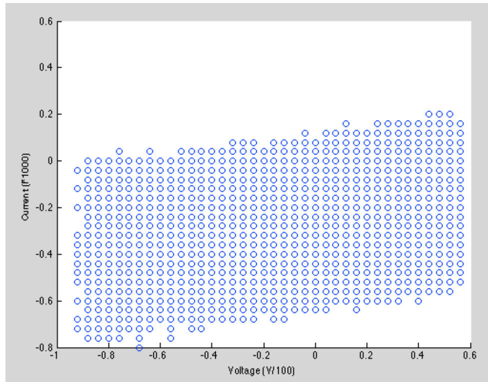

Figure 8: An example of raw data taken with the probe.

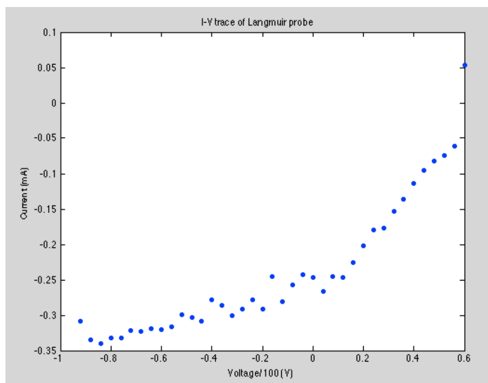

Figure 9: I-V trace after averaging.

of the probe to match plasma parameters. As such, the important sections (i.e. the exponential region of the transition, the knee for plasma density) are not contained within the voltages swept. Therefore, it is not possible from the data collected to compute plasma parameters. However, by showing a nonlinear response, it was shown that the probe does function, and more work is necessary to apply the correct bias voltage in order to take accurate data.

6 Acknowledgements

This summer has been a whirlwind of learning, and there are many people I would like to thank for their help and generosity. Will Coogan, for informing me about PPST; Prof. Choueiri, for offering me the opportunity to work in the lab; Pierre-Yves Taunay, for offering me a new project when my old one fell through and then mentoring me through its completion; Bob Sorenson, for his

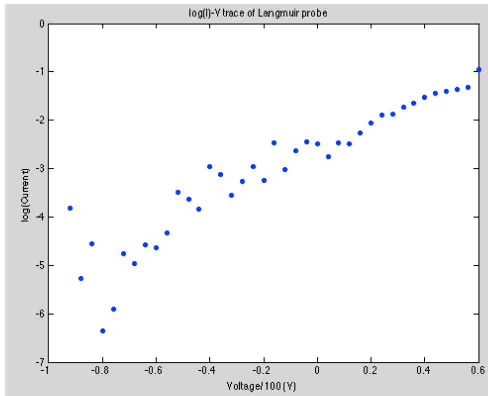

Figure 10: ln(I-Isat) vs V curve.

technical expertise; and the rest of the grad students in the EPPDyL and 3D3A labs, for their company, cheer, and optimism in the face of setbacks. Lastly, I'd like to thank PPST for offering the program and funding my research this summer.

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