Handout for Plasma Physics: Plasma Probes*

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June 27, 2014

This document is intended to be a short reference for the *Plasma Physics: Plasma Probes* ALPhA Immersion that was held at the Princeton Plasma Physics Laboratory from June 24 - 26, 2014. This document includes:

1. Parts list for two different experimental setups
2. Detailed description of the analysis process.
3. Representative results
4. List of potentially useful references.

If you have any questions on these materials or would like additional information, you can reach me by e-mailing me at jwilliams@wittenberg.edu.

*This document was prepared as part of the ALPhA Immersion *Plasma Physics: Plasma Probes* held at the Princeton Plasma Physics Laboratory from June 24 - 26, 2014. An updated version of this material will be maintained on my lab webpage: http://wupl.wittenberg.edu/curricular/ALPhAImmersion2014.html

†This material is based upon work that is partially supported by the National Science Foundation under Grant No. PHY-0953595.

Equipment List*

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June 27, 2014

1 Simple Langmuir Probe Experiment

This version of the experiment is built around an older vacuum triode, OA4G, and is based off of an article in the American Journal of Physics[1]. The plasma is ignited by applying a bias across two of the electrodes within the tube, while the third electrode serves as a Langmuir probe. While this version is more limited, it has the advantage of being relatively simple, self-contained and inexpensive.

- OA4G Tube (2)
  - This item is no longer manufactured, but it can be found on *e-Bay* for (typically) under $20 per tube. You will want to get one of the earlier versions of this tube where you see the inside of the tube (manufactured by either RCA and Sylvania), not the ones that are enclosed in a black metal case. The new version (in the black metal case) has a slightly different internal geometry that does make them well suited for this experiment.
  - Different manufacturers used different sized wires for the trigger anode, which is used as a Langmuir Probe . As such, you may want to buy two tubes, one for the experiment and one to break open to measure the size of the probe. In the immersion, we used the RCA tube with $\phi = 0.76 \pm 0.02$ mm and $l = 2.54 \pm 0.02$ mm.
  - You will need a collection of wires to connect everything. To make things simpler, we constructed a small project box with three banana plugs to connect to the three pins on the OA4G tube. This is not necessary but it does make things easier.
- Power Supply to generate a discharge (1)
  - Any power supply will work, but you will want it to be current limited and will need ∼100V to ignite the plasma. In the immersion, we used an Agilent DC Power supply (Model # E3612A), which can provide 0 - 120V at 0 - 250 mA. If your power supply is not current limited, a high power resistor (∼75 - 100 kΩ) in series with your power supply will limit the discharge current. The discharge current should be limited to under 120 mA to extend the life of the tube.
- To measure a Langmuir trace, you will need to vary the voltage applied to the probe and then measure the current collected by the probe. For the OA4G tube, you will need to vary the voltage over a range of $\sim \pm 15$V. In the immersion, we used a regulated, linear power supply from International Power (Model#IHAD15-0.4), which provides an output of ± 15V. This output was connected across a 10 turn potentiometer to provide a variable voltage. A pair of multimeters can be used to measure the probe bias and current collected. Alternatively, you can measure the I-V trace directly using source meter. In the immersion, we used a Keithley 2400 source meter.

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[1] I. Alexeff, J. T. Pytlinski and N. L. Oleson, Am. J. Phys. **45**, 860 (1977).

The figures below should help clarify the setup.

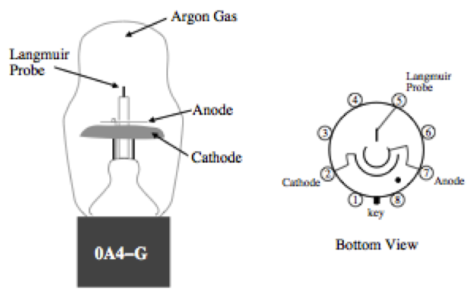

Figure 1: Geometry of the OA4G tube.

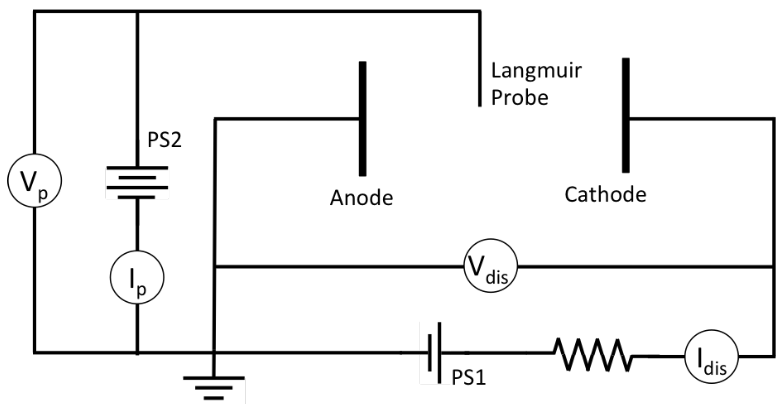

Figure 2: Schematic of the experimental circuit. PS1 is used to ignite and maintain the discharge plasma, while PS2 is used to measure the I-V trace.

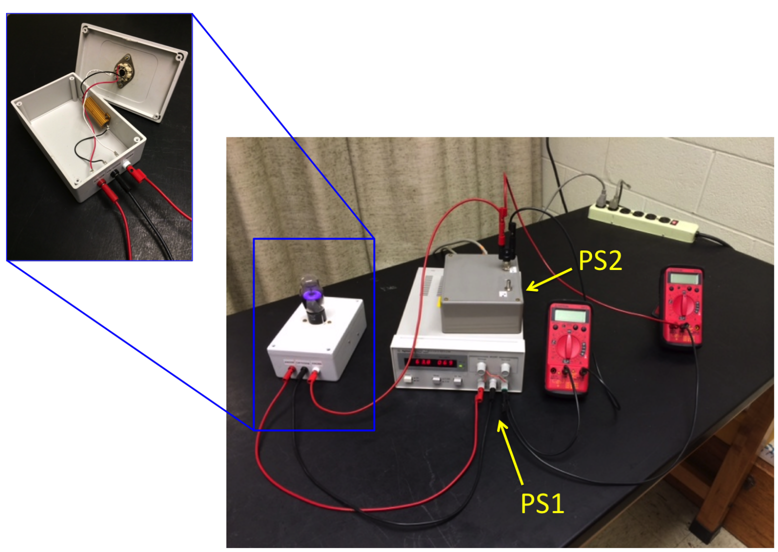

Figure 3: Photograph of the simple Langmuir probe experiment. PS1 is used to ignite and maintain the discharge plasma, while PS2 is used to measure the I-V trace. The inset shows the interior of the box that holds the OA4G tube.

Figure 4: Photograph of interior of the OA4G tube.

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OA4G

MECHANICAL DATA

Bulb	ST-12
Base	B6-3, Small Shell Octal, 6-Pin
Outline	12-7
Basing	4V
Cathode	Cold
Mounting Position	Any

ELECTRICAL DATA

RATINGS (Absolute Values)

Peak Cathode Current	100 Ma Max.
DC Cathode Current	25 Ma Max.

CHARACTERISTICS

Peak Anode Breakdown Voltage, (Starter Anode Tied to Cathode) Minimum	225 Volts
Peak Positive Starter Anode Breakdown Voltage	
Minimum	70 Volts
Maximum	90 Volts
Starter Anode Current (For Transition of Discharge to Anode at 140 Volts Peak) Maximum	100 μa
Starter Anode Voltage Drop, approx.	60 Volts
Anode Voltage Drop, approx.	70 Volts

TYPICAL OPERATION[1]

Relay Service — With AC Supply

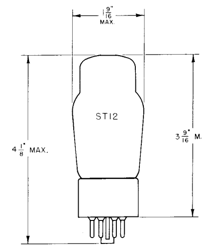
Anode Supply Voltage, RMS	105-130 Volts
Peak AC Starter Anode Voltage	70 Volts
Peak RF Starter Anode Voltage	55 Volts

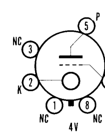
NOTE:

1. To assure stable operation, the OA4G should be shielded from external light sources.

QUICK REFERENCE DATA

The Sylvania Type OA4G is a cold cathode, gas-filled triode designed for use in the remote control of various line operated devices. The OA4G may also be used in relaxation oscillator circuits and as a voltage regulator.





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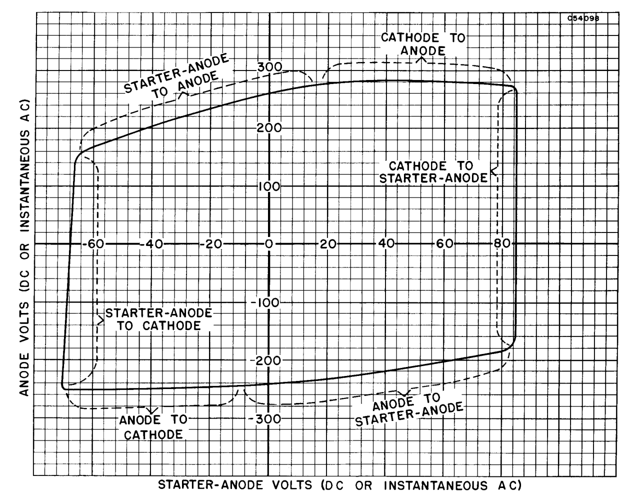
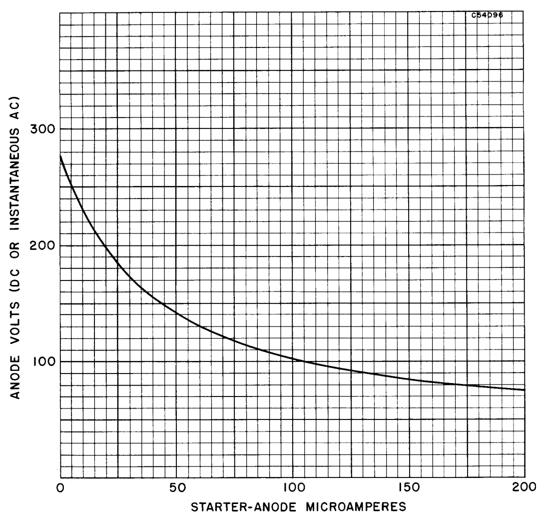
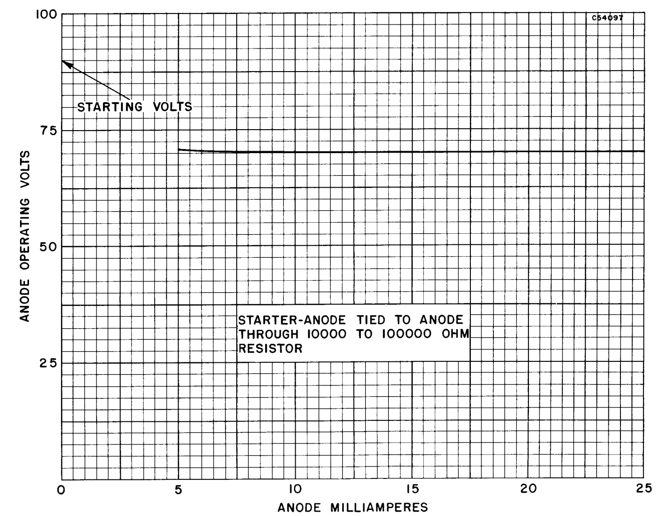
TYPICAL BREAKDOWN CHARACTERISTICS



AVERAGE TRANSITION CHARACTERISTICS



AVERAGE ANODE-DROP CHARACTERISTICS



2 Less Simple Langmuir Probe Experiment

This approach makes use of a vacuum system. In addition to the ports for the gas system (vacuum pump and gas inlet) and electrodes (to generate the plasma), you will need one additional port to provide access for the Langmuir probe. The attached part lists on the pages that follow assumes that this additional port is a KF (or NW) 25 connector. While we include parts lists from the Kurt J. Lesker company (for vacuum components) and McMaster-Carr (for the probe), the necessary parts can be found from other vendors.

1. In terms of the items on the parts list from the Kurt J. Lesker company, the following items are optional but may make things easier to assemble.

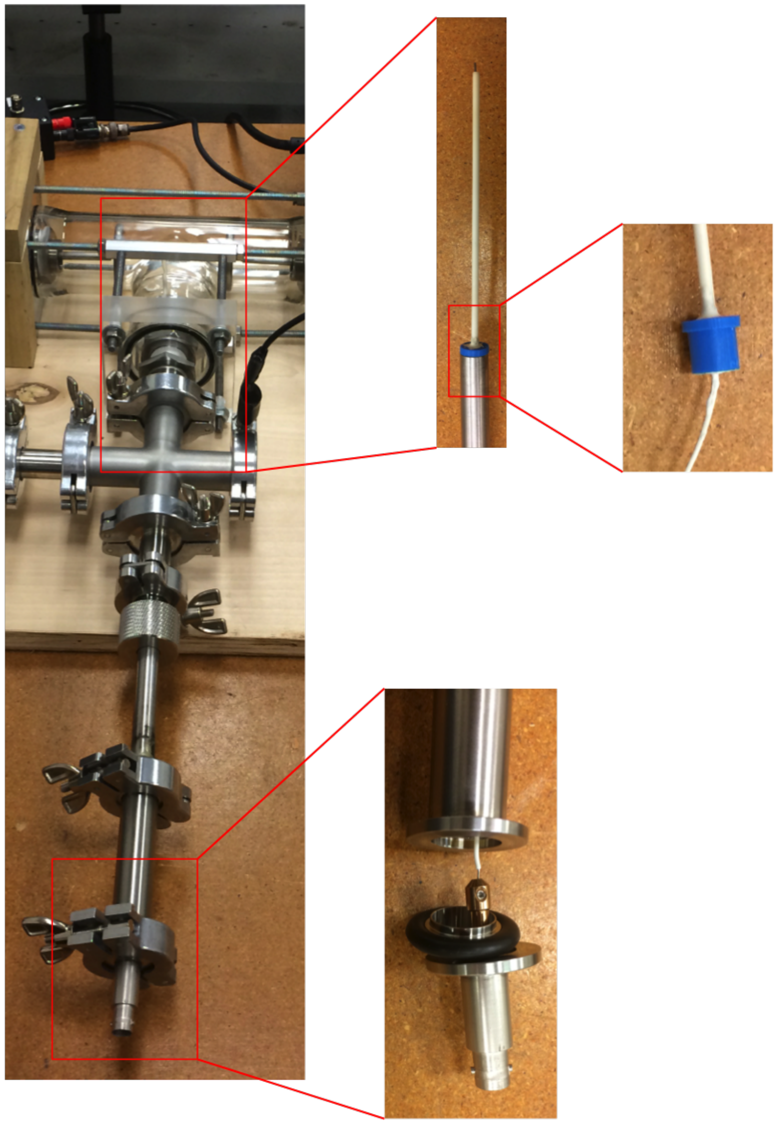
   - (1) KF16 Full Nipples (304L SS), Part Number QF16-075-N $41.20
   - (1) KF16 Cast Clamps (Aluminum), Part Number QF16-075-C $6.20
   - (1) KF16 Centering Ring (SS with Fluorocarbon O-Ring), Part Number QF16-075-SRV $6.20
   - (1) Torr Seal Low Vapor Pressure Epoxy, Part Number V9530001 $52.00

2. To do this on the chromatography setup that was used in the plasma immersion experiments, you will need to have a chromatography tube with (at least) one port in the middle region of the chromatography setup and the $\frac{1}{2}$ stainless steel tube would need to be replaced with the appropriate sized tube (this would have been a $\frac{1}{4}$ stainless steel tube if you used the chromatography tube that was used in the spectroscopy experiment). This would require a different adapter than the Braze KF (QF) Flanges (Brass) [Lesker Part No QF16-050-BF].

3. You will need to have brazing equipment, which can be obtained at a modest cost at retailers such as Lowe's.

4. To measure a Langmuir trace, you will need to vary the voltage applied to the probe and then measure the current collected by the probe. The range of voltages that you will need will depend on the plasma that you are looking at. For the DC discharges that were looked at in the immersion, a power supply that can provide $\sim \pm 100$V should cover most of what you need. The probe measurement is made around the floating potential (this can be found by measuring the voltage on the probe while it is sitting in the plasma), so it may be necessary to have a second power supply to provide an offset. A pair of multimeters can be used to measure the probe bias and current collected. Alternatively, you can measure the I-V trace directly using source meter. In the immersion, we used a Keithley 2400 source meter.

The figure below shows an expanded view of the probe that was constructed/used at the immersion.



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QF25XVC050	KF (QF) Flange to Quick Connect Fitting Adapter	In Stock	$70.00	1	$ 70.00
IFTBG012038	INST F/T,BNC,GRNDED,500V,(1) .094"SS COND,3A,QF16	In Stock	$100.00	1	$ 100.00
FTASSC094	CONNECTOR,PUSH ON TO .094" PIN 15A,UP TO .050"WIRE,10/PKG	In Stock	$48.50	1	$ 48.50
QF16-075-N	KF (QF) Full Nipples (304L SS)	In Stock	$41.20	1	$ 41.20
QF16-075-C	CLAMP,ALUMINUM,QF16,CAST 1/2" & 3/4"	In Stock	$6.20	2	$ 12.40
QF16-075-SRV	CENTERING RING,SS,QF16,VITON O-RING,3/4"	In Stock	$6.20	2	$ 12.40
QF25-100-SRV	CENTERING RING,SS,QF25,VITON	In Stock	$8.25	1	$ 8.25
V9530001	Torr Seal Epoxy Resin Leak Sealant	In Stock	$52.00	1	$ 52.00

Sub Total: **$352.00 (US Dollars)**

Prices are F.O.B. Jefferson Hills, PA (sales taxes for PA, CA, AZ, GA, IL, NC & NJ added as appropriate). Availability of items are quoted with the most current information, however, changes in availability may occur

*** Sub Total does not include shipping / handling or any applicable fees**

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If you have any questions, please reply to this email and let us know how we can help.

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3 Langmuir Probe Circuit

Figure 5 depicts three different approaches to measuring a Langmuir trace. In the simplest (both conceptually and in practice) approach, Fig. 5(a), a variable power supply is used to vary the probe bias voltage and the probe current is measured using the voltage drop across the resistor (typically, 10 - 1000 Ω). A more complex version involves applying a variable voltage (*i.e.* the triangle/ramp output of a function generator) to the probe tip, Fig. 5(b). The current is again measured across a resistor to ground. This circuit can be a simple as a 555 wired to generate a triangle wave and an op-amp wired as a voltage follower to the circuit seen at the end of this document.[2] The final approach, Fig. 5(c), involves using a source meter. This is perhaps the most flexible (and expensive) approach to measuring a Langmuir trace.

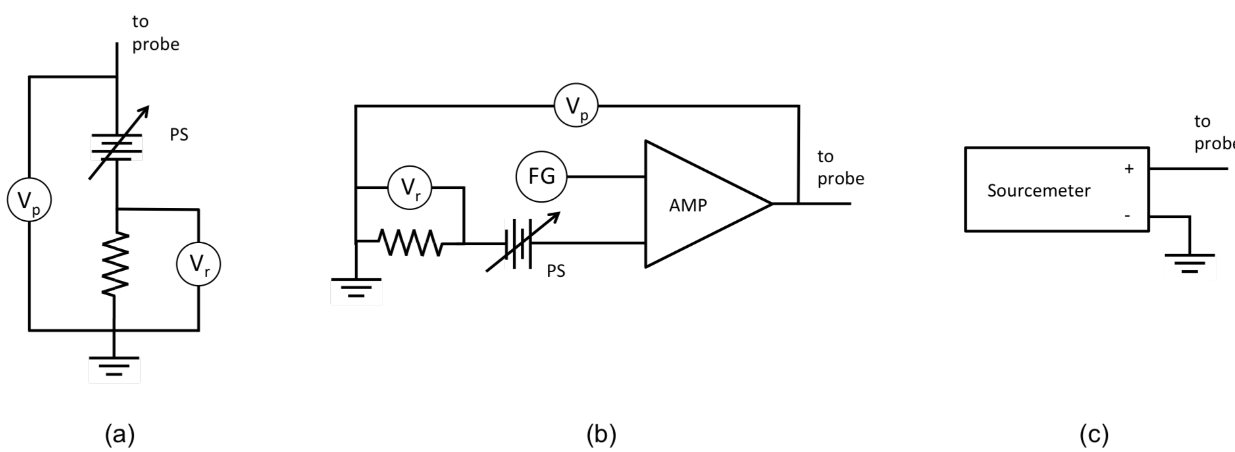

Figure 5: Schematic of three circuits of increasing complexity to measure a Langmuir trace . The probe bias voltage, V_p, is measured using a multimeter and the current collected by the probe is found by measuring the voltage drop across a resistor, V_r.

[2]This circuit comes from Ruzic, D. N., *Electric Probes for Low-Temperature Plasmas*, (AVS Monograph Series, New York, 1994).

2.3 Active probe circuits

An active circuit is one that contains op-amps or other elements which are powered. The most important active element for a Langmuir probe analysis is a differential amplifier which will subtract V_{probe} from V_1 and amplify the difference. Figure 10 shows a diagram of a successful active analysis circuit.[8] This circuit can operate with dc bias voltages of more than ±1000 V, can source or sink hundreds of milliamps and can accurately measure probe currents at the microamp level and probe voltages at the tens of millivolt level. The accompanying table on page 29 gives the exact specifications of every component. The little inverted triangles are connected to each other. Those points all sit at the dc bias voltage. The basic function and rationale for each element is described next.

The first element is the "sensing resistor", shown as four parallel R_s resistors and a switch. A small value for the resistor should be used when the current is very small. This produces a larger voltage which can be digitized. Too small a resistor however, will allow too large a current to be drawn from the plasma when the probe is biased near the plasma potential. For that range of bias voltage a larger resistance is needed. A switch is provided for easy changes between several values of resistance depending on which portion of the I-V characteristic is to be measured. For the prototype circuit [8], resistors of 25, 100, 500, and 2500 Ohms were used. If the whole I-V trace is to be mapped out at one time, the largest R_s should be used. However, much more accurate measurements of the ion saturation region will be obtained with the lower R_s values.

The second element is the "differential amplifier" which measures the current across the sensing resistor, shown as OA3 in figure 10. The amplifier's power supplies are floating on top of V_B and are shown as the $\pm V_{s1}$ and $\pm V_{s2}$ sources on the side of the figure. In other words, the two power leads to the amplifier are at V_B +15 V and V_B -15 V. The resistor, R, is added to

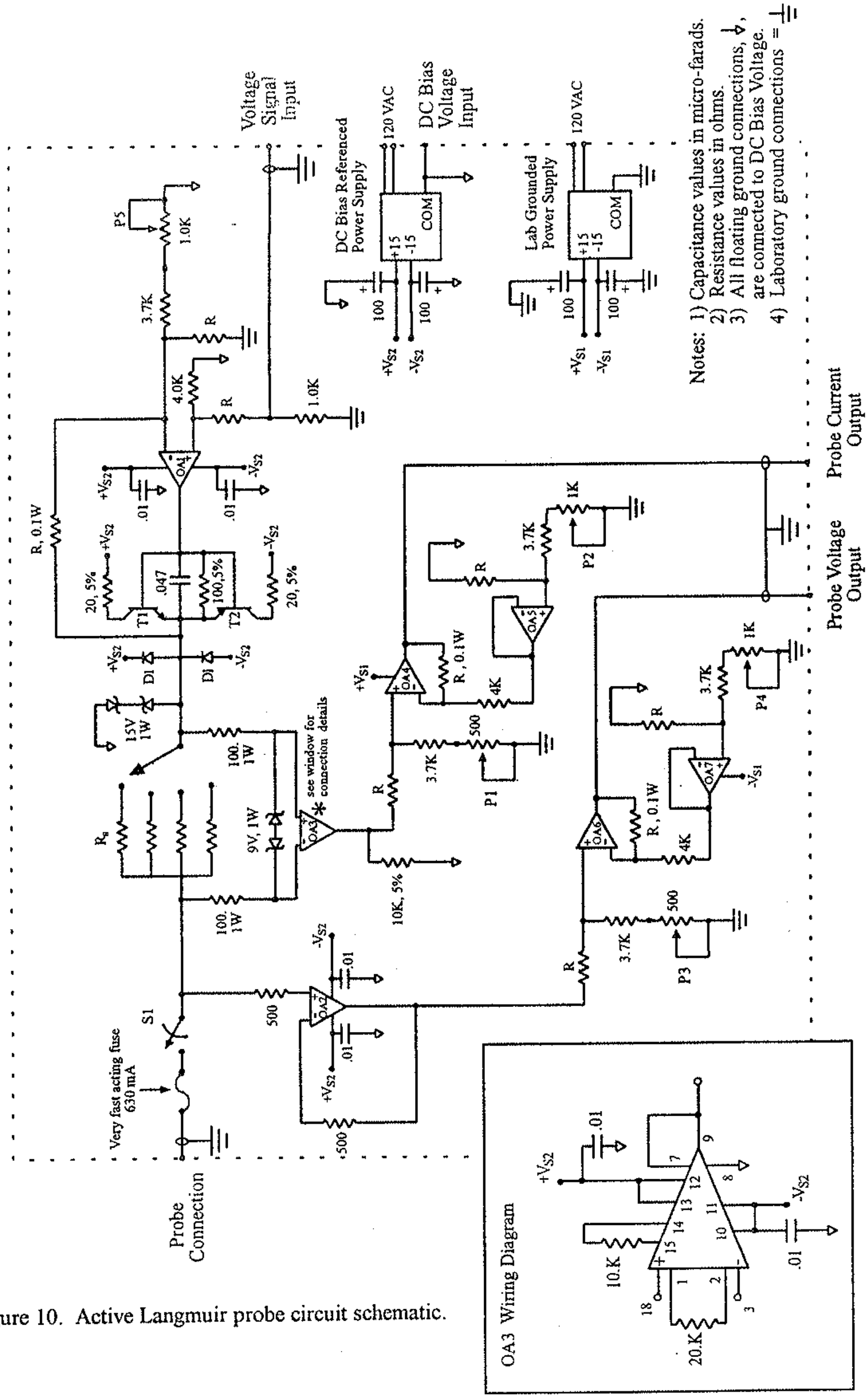

Figure 10. Active Langmuir probe circuit schematic.

give the proper output impedance for the device. The gain of this amplifier is 10. A Zener diode is placed between the inputs of the differential amplifier to prevent its destruction during an over-voltage from the plasma. The third element provides a "high-input impedance" for measuring V_{probe}. It provides over current protection for the amplifier and the scope and is powered by the floating ±15 V power supply. Between these two elements of the circuit and the outputs are output amplifiers (OA4 through OA7) that subtract the dc bias voltage from the signal and reamplify the remaining signal.

The fourth element in the circuit is a "probe driver" which includes OA1, T1, and T2 in figure 10. The feedback resistor has the same value as the input coupling resistor to maintain a similar magnitude of the voltage ramp. The voltage signal input can be a function generator or any ±V ramp or triangle wave generator.

The value of R depends on the maximum dc bias voltage, VDCmax, applied to the system. R should be greater or equal to VDCmax x 400, but at least 40kOhms. The wattage of the R resistors (and the 4kOhm resistors) should be two or three times greater than VDCmax / 400. The resistors, R, should have 1% or better tolerances.

Okay, I can build this circuit; how do I set it up?

Figure 11 shows how a function generator, oscilloscope, DC bias power supply, DC bias voltmeter and the probe are connected. A data acquisition and storage system can be attached to the scope if you want to record the data. There is some calibration to be done to the system. Details are contained in [8], but the basics are straight-forward:

1) Connect the dc bias supply and scope as shown in figure 11 and connect the voltage signal input to ground. The probe connection should be left floating.
2) Turn on the dc bias supply with its output at 0 V. Then turn on the two +/- 15 voltage supplies for the opamps.
3) Put 10 volts on the dc bias supply and adjust the variable resistor, P2 until the probe current output gives 0 V.
4) Connect the probe connection to the 10 volts of the dc bias supply as well. Adjust P4 to give 0 V at the probe voltage output.
5) Connect a voltmeter to the probe connection instead of having the dc bias supply attached there. Adjust P5 until the probe voltage read on that voltmeter is the same as the dc bias supply voltage. Adjust the dc bias voltage higher and check that the voltmeter always reads the same. The P5 variable resistor is floating at dc bias voltage so the dc bias voltage should be reduced to a safe level when adjusting the resistor.
6) Turn the DC bias voltage supply back down to 0 V. Remove the voltmeter from the probe connection and connect one channel of the oscilloscope there. Connect the other channel of the scope to the probe voltage output. Connect the function generator to the voltage signal input and set it to give a 20 V peak-to-peak signal. Set R_S at its lowest value. Adjust P3 until the two channels of the scope give the same reading.

7) Remove the oscilloscope from the probe voltage output and connect that channel to the probe current output instead. Leave the other channel connected to the probe connection. Find a resistor, $R_{calibration}$, that has the following value:

$$\frac{R_s}{R_s + R_{calibration}} = \frac{1}{OA3\ gain} = \frac{1}{10} \text{ using the op-amp listed in the table}$$

Connect that resistor between the probe connection and ground. Adjust P1 until the two signals on the scope are equal.

Calibration is now complete. Connect the remaining components as shown in figure 11. Always be sure the dc bias voltage supply is on and set to 0 V before turning on the ±15 V opamp power supplies. A positive-going voltage ramp of 20V per msec or slower is recommended for the function generator.

When increasing the frequency of the ramp, care must be taken lest the common mode rejection ratio of the differential amplifier be exceeded. For a R_S = 2000 Ohm, 1 ms is the fastest possible sweep period. For smaller values of R, say 200 Ohms, the time for a sweep can also be divided by 10. Speeds faster than 10 μsec with an R=20 Ohm seem to be the limit for this particular circuit.

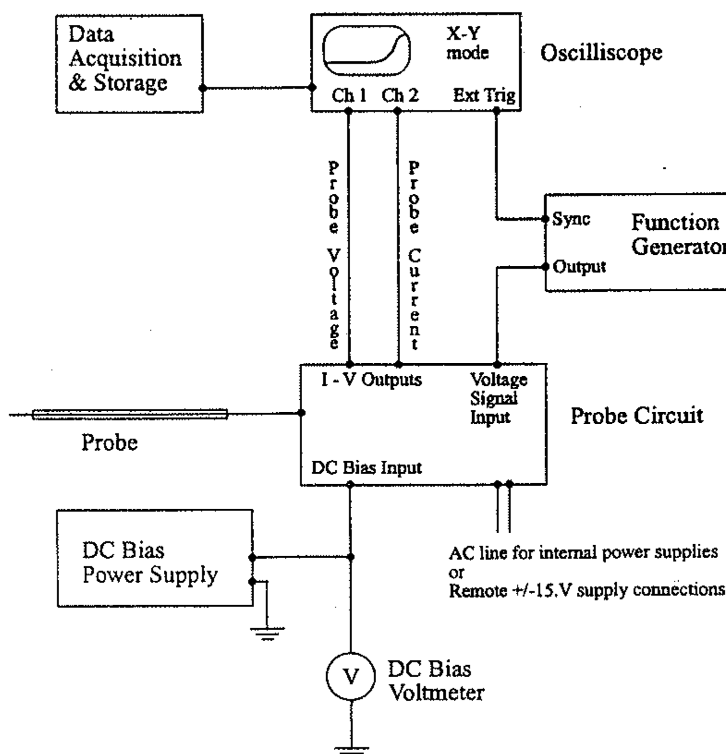

Figure 11. Schematic of the active Langmuir probe circuit overall set-up.

How do I use the circuit?

Place the probe in the plasma chamber but do not connect it to the probe connection. Turn on the circuit and the plasma. Measure the approximate floating potential of the plasma by connecting a voltmeter from the probe to ground. Adjust the dc bias voltage to this level and then connect the probe to the probe connection of the circuit. Place the scope in the X-Y mode and dc coupled. Traces like those in figure 12 should appear. The dc bias voltage can be adjusted to capture different portions of the curve. Adjusting R_S can give you higher sensitivity for the lower voltage regions.

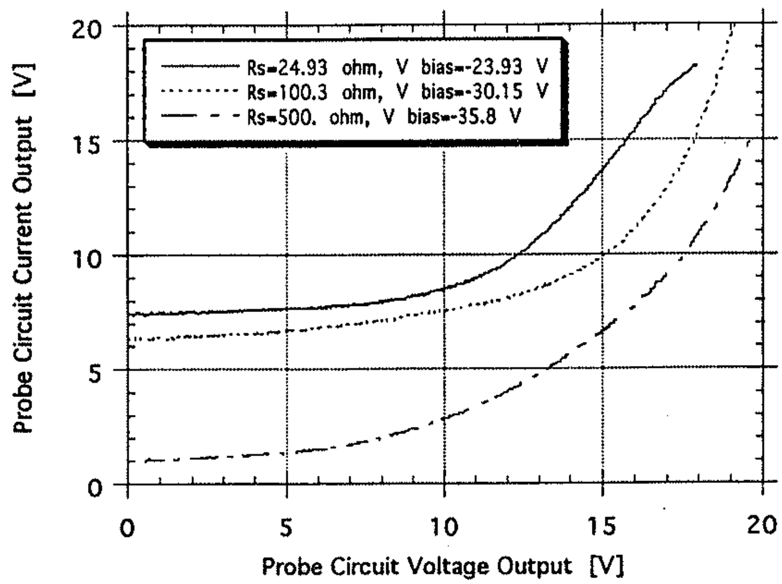

Figure 12. Three raw I-V data traces, each as displayed originally on the oscilloscope screen. The three traces were measured with different values of R_S and dc bias as indicated, but with identical plasma parameters. Note that the raw probe current data has units of volts.

By recording the bias voltage, R_S value, and the dc offset of the scope for both inputs, the voltage traces can be pieced together. To measure the scope offsets change the coupling switch on both oscilloscope channels from dc to "ground" while still in the X-Y mode. The difference between the dot on the screen and the vertical y axis is the Scope Voltage offset. the distance between the dot and the horizontal axis is the Scope Current offset (in Volts). Once these offsets are measured the absolute probe currents and voltages can be determined by:

Absolute probe voltage = Output probe voltage + dc bias voltage - Scope Voltage offset

Absolute probe current = (Output probe current - Scope Current offset) / (10. x Rs)

The factor of 10 is from the gain of the OA2 component.

These data should match extremely well. Figure 13 is the data from figure 12 plotted as an actual current vs voltage. For this experiment, a 250mTorr He dc glow discharge, the scope voltage offset was 10.20 V and the scope current offset was 7.60 V.

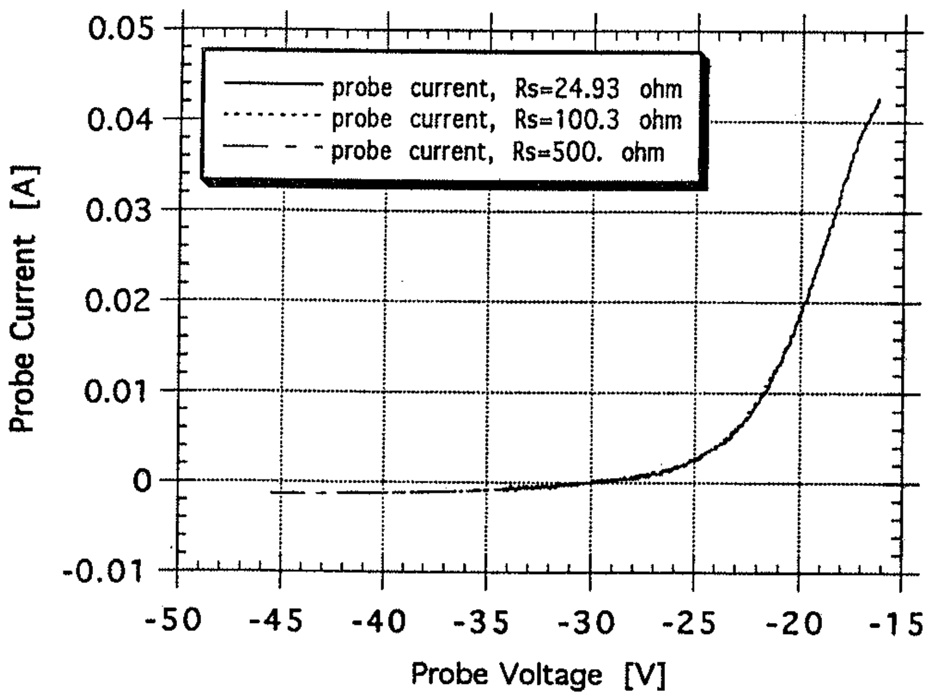

Figure 13. The three I-V traces shown in figure 12 put on a laboratory-referenced voltage scale, and the raw probe current data have been converted to amperes. Note the excellent match-up and overlap of the three data sets. Because both small and large values of R_S were employed to acquire the data, the portion of the curve with negative current has approximately the same fine resolution as the portion above the axis.

When do I have to use this? When can I use the passive circuit instead?

The active circuit shown here produced the data that will be shown in the examples. It allows a high degree of precision and simplifies the data collection. At the touch of a button on the frequency generator, a thousand pairs of (V_{probe}, I_{probe}) can be stored in a file. Exactly how many pairs depends on the specific computer interface and digital scope, of course, but a great deal of data can be taken with minimum effort using the active probe circuit. To ensure high precision in regions with differing signal magnitudes (the ion saturation region, the electron retardation region and in the electron saturation region --- all described in chapter 3) simultaneously is not possible with a simple circuit. The passive circuit is easier to build and understand, but acquiring and analyzing the data are much more problematic.

Table 3. Circuit component, model, and manufacture for the active Langmuir probe circuit shown in figure 10.

Component	Model	Manufactures
OA1	AD845JN	Analog Devices
OA2	OP-27 FP	Analog Devices, PMI
OA3	AMP-01EX	Analog Devices, PMI
OA4-OA7	OP-471 EY	Analog Devices, PMI
T1	2N2222	Motorola, various
T2	2N2905	Motorola, various
D1	1N4934	Motorola, various
Very fast-acting fuse	GDA 630MA	Bussmann

Analysis of a Langmuir Probe Trace*

Jeremiah Williams†
Physics Department, Wittenberg University.

June 27, 2014

The Langmuir probe is a common diagnostic technique in low temperature plasmas (*e.g.* plasmas with $T_e \sim$ a few eV [1]) and is used to measure the plasma density, electron temperature and the plasma potential. Typically,a Langmuir probe consists of a bare wire (or metal disk/sphere) that is inserted into a plasma. When a bias is applied to the probe, the probe will collect electrons and ions from the plasma in the area surrounding the probe. At negative (positive) biases, protons (electrons) and only the electrons (protons) with sufficient energy to overcome the potential barrier of the probe are collected. As the probe bias is varied, the fraction of the electron and ion distributions that are collected varies. The resulting I-V trace will resemble what is seen in Fig. 1.

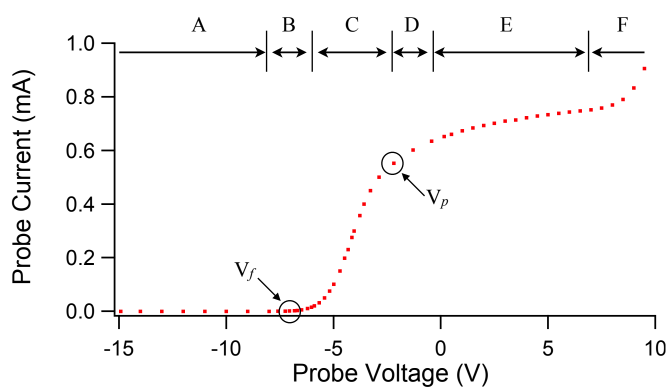

Figure 1: A representative Langmuir probe trace with different regions of interest indicated.

Each of the regions indicated in Fig. 1 corresponds to unique populations being measured. At large negative biases (region A), only ions are collected by the probe. This is known as the *ion saturation current*, I_{is}. In region B, the ion saturation current plus a small amount of the electron distribution is measured. The voltage when the net current collected is zero is known as the floating potential, V_f. In region C, an increasing fraction of the electron distribution is measured. At the knee of the curve, known as the *plasma potential* (V_p), you are now measuring the entire electron distribution and some of the ion population is being repelled (region D). In region E, only electrons are collected by the probe and this is known as the *electron saturation current*, I_{es}. In region F, the probe is beginning to act as a source of electrons. The electron temperature and density can be found from region C and E respectively, while the plasma potential can be found from the intersection of these regions. It should be noted that under some experimental conditions, it is possible to not observe Regions D and E. In this case, you can only find the electron temperature from the I-V trace obtained with a Langmuir Probe.

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†This material is based upon work that is partially supported by the National Science Foundation under Grant No. PHY-0953595.

[1] It is common practice in the area of plasma science to report the temperature in the energy unit, eV, where 1 eV is 11,600 K.

1 Analysis Procedure

The I-V trace obtained from a Langmuir probe can be analyzed using the following recipe.[2] You should refer to Merlino, Am. J. Phys, **75** (2007) for details on the mathematical representation of a Langmuir Probe trace.

1. Perform a linear fit to the ion saturation region to find the ion saturation current and then subtract the ion current from the total current in the I-V trace to obtain the electron current.

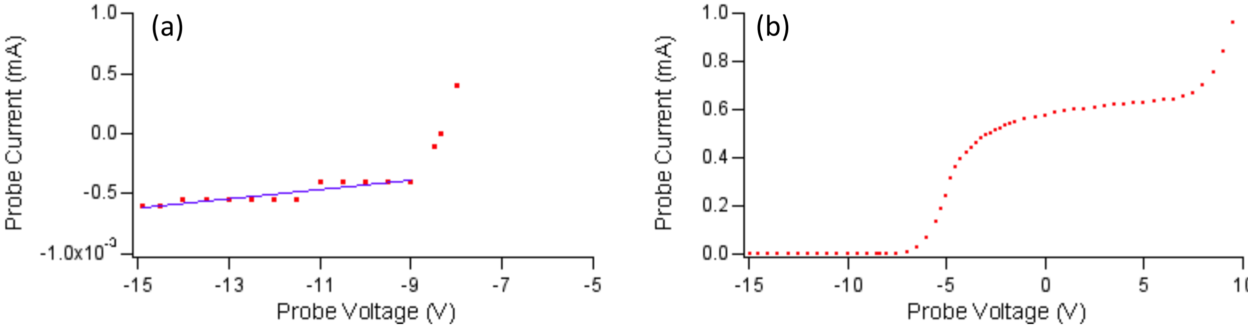
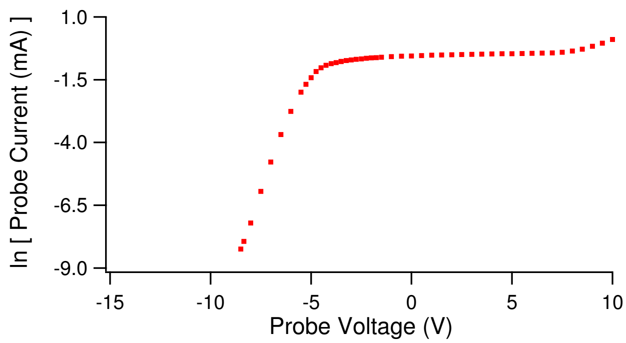
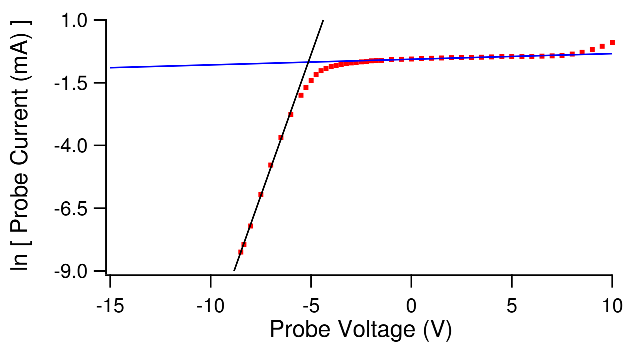


Figure 2: (a) Plot of the I-V trace and fit to the ion saturation current region (b) Plot of the electron current.

2. Take the natural logarithm of the electron current and plot this as a function of the probe voltage.



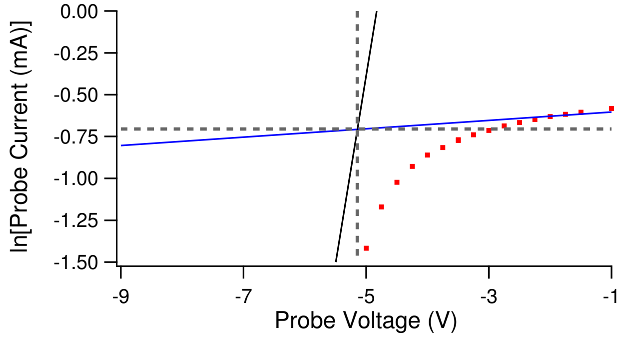
3. Perform a linear fit to the electron retardation (Region C, black curve) and electron saturation (Region E, blue curve) regions. The electron temperature, kT_e (in eV, 1eV =11600 K), is found from the inverse of the slope from the linear fit to the electron retardation region.[3]



[2] The sample data that is used to illustrate each step was taken using an OAG4 vacuum triode with $V_{dis} \sim 63$ V, $I_{dis} = 60$ mA. The original data will posted on my lab webpage: http://wupl.wittenberg.edu/curricular/ALPhAImmersion2014.html.

[3] see Equation 5 in Merlino, Am. J. Phys, **75** (2007).

4. The plasma potential and electron saturation currents are found from the intersection of the two straight-line fits to the electron retardation and electron saturation regions, as seen in the dashed lines below



5. The electron density can be found from the electron saturation current and electron temperature using Eq. 1.[4]

$$n_e = \frac{I_{e,sat}}{A_{probe}\sqrt{\frac{kT_e}{2\pi m_e}}} \tag{1}$$

The resulting plasma parameters are summarized in the table below.

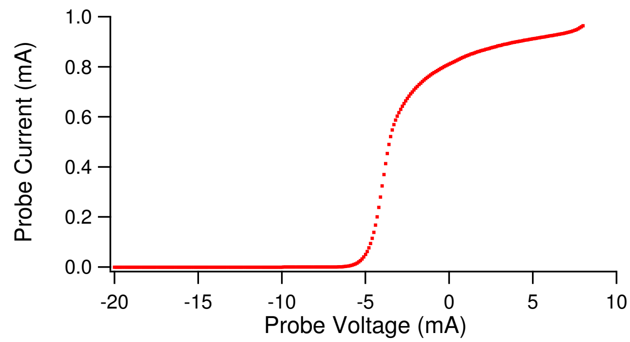
Table 1: Plasma Parameters

T_e	0.45 ± 0.01	eV
V_p	-5.1 ± 1.5	V
I_{es}	0.51 ± 0.02	mA
n_e	$(3.1 \pm 0.1) \times 10^9$	cm^{-3}

[4] see Equation 6 in Merlino, Am. J. Phys, **75** (2007).

2 Another approach

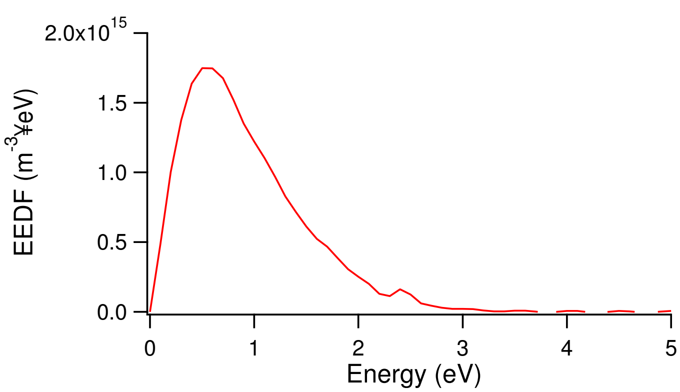
If you have sufficient data, it is also possible to reconstruct the electron energy distribution function (EEDF) from the measured I-V trace.[5]



1. Find the electron current as described in step 1 in Section 1 above.
2. The EEDF can then be found from the second derivative of the electron current with respect to the probe voltage using the Druyvesteyn method.

$$f_e(\epsilon) = \frac{2}{A_{probe} q_e} \sqrt{\frac{2m_e \epsilon}{q_e}} \frac{d^2 I_e}{dV_{probe}^2} \tag{2}$$

   where A_{probe} is the area of the probe, q_e is the electron charge, m_e is the electron mass, ϵ is the electron energy ($\epsilon = q_e$ (V_p - V_{probe}), V_{probe} is the probe voltage and I_e is the electron current. The reconstructed EEDF, $f_e(\epsilon)$ is seen below.



3. The electron density and effective electron temperature can then be found by taking moments of the distribution function.

$$n_e(\epsilon) = \int_0^\infty \frac{f_e(\epsilon)}{\sqrt{\epsilon}} \mathrm{d}\epsilon \tag{3}$$

$$T_e(\epsilon) = \frac{2}{3n_e} \int_0^\infty \epsilon^{\frac{3}{2}} f_e(\epsilon) \mathrm{d}\epsilon \tag{4}$$

[5] The sample data that is used to illustrate each step was taken using an OAG4 vacuum triode with V_{dis} $\sim$ 64.8 V, I_{dis} = 120 mA and ΔV_{probe} = 0.1 V. The original data will posted on my lab webpage: http://wupl.wittenberg.edu/curricular/ALPhAImmersion2014.html.

The plasma parameters found using the method described in Section 1 are summarized in the table below.

Table 2: Plasma Parameters

T_e	0.41 ± 0.01	eV
V_p	-3.9 ± 0.6	V
I_{es}	0.75 ± 0.01	mA
n_e	$(6.1 \pm 0.2) \times 10^9$	cm^{-3}

The values found from the reconstructed distribution function are summarized below.

Table 3: Plasma Parameters

T_e	0.49	eV
n_e	2.62×10^{10}	cm^{-3}

It is noted that the method used in Sections 1 and 2 are not the only model that can be used to analyze a Langmuir trace and that the reported error only includes the statistical error. The differences that are seen between these two methods is comparable to what one might find when using a different model. Additional information can be found in the references included.

3 Comment on Temperature

The analysis procedure that is described in Section 1 assumes that the entire electron population is at a single temperature. However, there are experimental conditions where there may be multiple electron populations at different temperatures. This can occur in plasmas that are created by an electron gun or cathode-anode pair.[6] As a result, the model that describes what is happening in Region C in Fig. 1 must be adapted to account for the additional population of electrons, Eq. 5, and is seen in your probe trace as a kink in Region C. This kink is seen in Fig. 3.[7].

$$I_e(V_B) = I_{es,cold}\exp\left(\frac{-e(V_p - V_B)}{k_B T_{e,cold}}\right) + I_{es,hot}\exp\left(\frac{-e(V_p - V_B)}{k_B T_{e,hot}}\right) \tag{5}$$

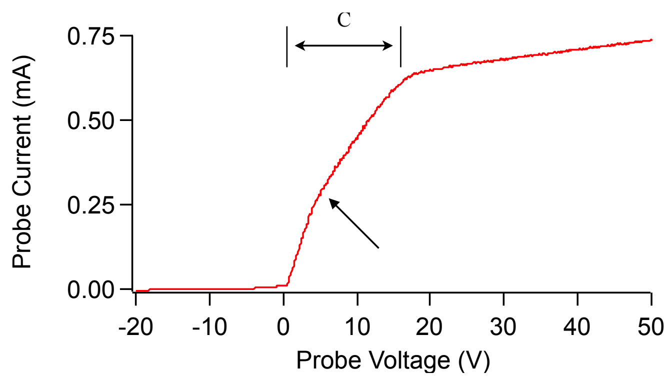
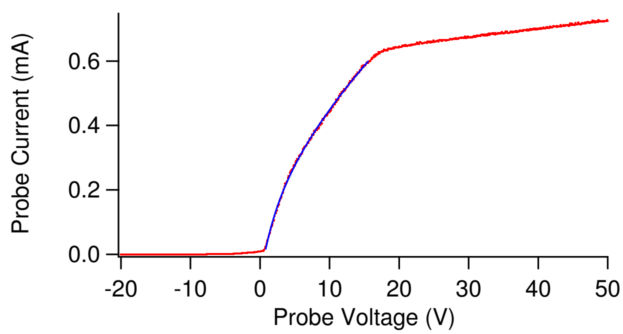


Figure 3: A representative Langmuir probe trace with two electron populations at different temperatures.

To properly account for this in the analysis, you need to fit Region C using Eq. 5.



From the fit, we find $T_{e,hot} = 29.657 \pm 0.004$ eV and $T_{e,cold} = 1.978 \pm 0.006$ eV.

[6]This is discussed briefly in Problem 1 of the Appendix in Merlino, Am. J. Phys, **75** (2007).
[7]This data was taken with the following experimental conditions: $p = 100$ mTorr, $V_{dis} = 550$ V and $I_{dis} = 0.14$ mA

Representative results*

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June 27, 2014

1 Typical Results using an (RCA) OA4G tube

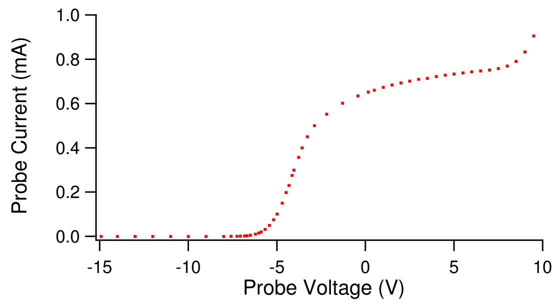

Figure 1: Representative Langmuir trace.

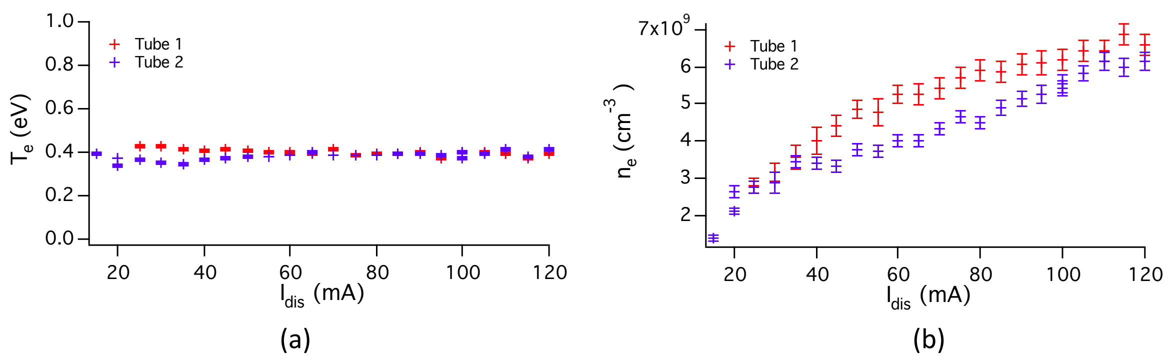

Figure 2: The plasma parameters appear to be relative independent of the tube used. The electron density increases with discharge current.

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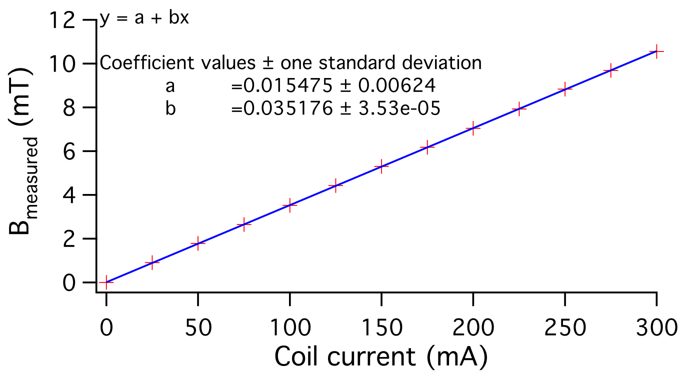
†This material is based upon work that is partially supported by the National Science Foundation under Grant No. PHY-0953595.

2 Magnetic field Experiment

To examine the effect that a magnetic field has on the measured I-V curve, we used a coil of wires (Heath Company, Part #40-694, dc resistance = 62.5 Ω, 3400 turns) and a dc power supply.

Any source of magnetic field will work - even permanent magnetic positioned around the discharge tube (this would allow you to create interesting magnetic topologies)

The calibration for the magnetic coils used was measured using a magnetic field sensor from Vernier and is given below. We used a slightly older mode of the magnetic field sensorl, which did not provide optimal access to the measurement volume. This measured value is slightly less than would be predicted by theory and we anticipate that the measured value of the magnetic field is slightly smaller than the actual value.



With increasing magnetic field, the electrons begin to orbit the magnetic field lines at the electron gyroradius, Equation (1). This results in a decrease in the measured electron saturation current, which results in a decrease in the measured electron density.

$$r_e = \frac{mv_\perp}{|q_e|B} = 2.38\frac{\sqrt{T_e}}{B} \tag{1}$$

where T_e is the electron temperature in eV, B is applied magnetic field in Gauss and r_e is the electron gyroradius in meters.

Typical results are seen below.

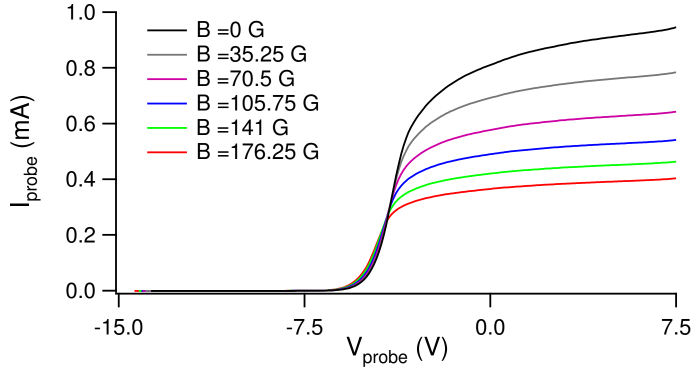


Figure 3: As the magnetic field increases, a decrease in the electron saturation current is measured.

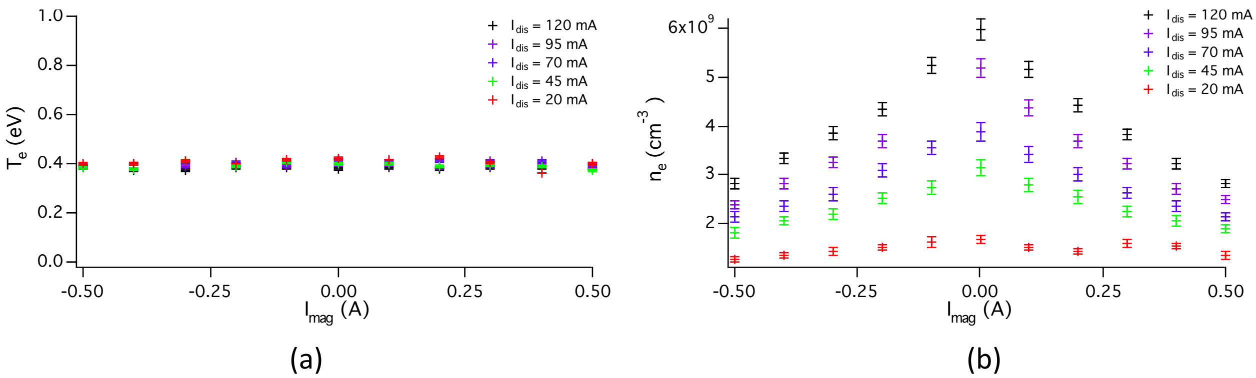


Figure 4: While the temperature is independent of the applied magnetic field, the density appears to decrease due to the smaller electron saturation current that is measured.

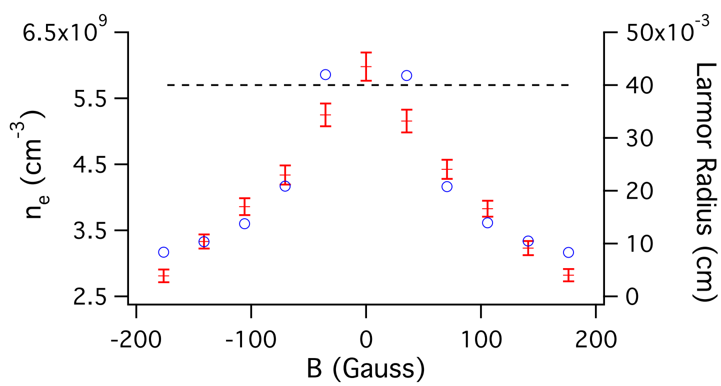


Figure 5: Plot of the electron density (crosses, left axis) and electron gyroradius (circles, right axis) as a function of the applied magnetic field. As the electron gyroradius becomes comparable to the probe size (indicated by the dashed line), the electron saturation current (and measured electron density) decreases.

Potentially Useful References*

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June 27, 2014

The following references should provide useful background and potential ideas for experiments suitable for the intermediate and advanced laboratory. When available, we have provided links to where these resources can be found online.

1. Stephanie A. Wissel, Andrew Zwicker, Jerry Ross and Sophia Gershman, *The use of dc glow discharges as undergraduate educational tools*, Am. J. Phys. **81**, 663 (2013). - Scitation link, Compadre link

    - This article provides a nice overview of several applications on how plasmas can be incorporated into the undergraduate curriculum using the device that you used during the summer immersion.

2. J. Williams, Andrew Zwicker, Stephanie Wissel, Jerry Ross, Sophia Gershman, *Initial work on Experimental Plasma Station for the undergraduate curriculum*, 2012 Conference on Laboratory Instruction Beyond the First Year of College, Philadelphia, PA (July 2012). - Compadre link

    - This poster provides a nice overview of several applications on how plasmas can be incorporated into the intermediate and advanced laboratory.

3. R. L. Merlino, *Understanding Langmuir probe current-voltage characteristics*, Am. J. Phys. **75** 1078 (2007). - Scitation link, Author's website

    - Provides a nice description on why a Langmuir probe trace looks the way that it does. MatLab/Octave code (based on the MAPLE code that the R. L. Merlino included with the publication of this article) to generate model Langmuir probe current-voltage (I-V) characteristics can be downloaded here.[1]

4. I. Alexeff, J. T. Pytlinski and N. L. Oleson, *New elementary experiments in plasma physics*, Am. J. Phys. **45**, 860 (1977). - Scitation link

    - Describes four plasma experiments that can be done using gas tubes. One of the experiments described in this paper was the basis for the experiment with the OA4G tube that was done at the immersion.

5. J. T. Pytlinski, H.J. Donnert and I. Alexeff, *Behavior of a single Langmuir probe in a magnetic field*, Am. J. Phys. **46**, 1276 (1978). - Scitation link

    - A nice experiment showing the effects of magnetic fields on Langmuir traces using the OA4G tube.

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†This material is based upon work that is partially supported by the National Science Foundation under Grant No. PHY-0953595.

[1] http://wupl.wittenberg.edu/curricular/ALPhA2014/GenerateLPTrace.m

6. O.K. Mawardi, *Use of Langmuir Probes for Low-Density Plasma Diagnostics*, Am. J. Phys., **34**, 112 (1966) - Scitation link

   - Provides a nice review on the theory of Langmuir probes and provides a sample calculation.

7. Ruzic, D. N., "Electric Probes for Low-Temperature Plasmas," (AVS Monograph Series, New York, 1994).

   - A short book that provides a practical level description of electric probe diagnostics.

8. Luis Conde, *An introduction to Langmuir probe diagnostics of plasmas*, available online.[2]

If you are interested in getting into the complexities of probe theory, the following references are an excellent starting point.

1. F. F. Chen , *Electric Probes*, in Plasma Diagnostic Techniques, edited by R. H. Huddlestone and S. L. Leonard (Academic, New York, 1965), Chap. 4.

2. I. H. Hutchinson, *Principles of Plasma Diagnostics, 2nd ed.* (Cambridge U.P., Cambridge, 2002), Chap. 3.

3. F.F. Chen provides a concise summary of Langmuir probe techniques *Lecture notes on Langmuir probe diagnostics* is available online at http://www.ee.ucla.edu/∼ffchen/Publs/Chen210R.pdf.

[2] http://plasmalab.aero.upm.es/ lcl/PlasmaProbes/Probes-2010-2.pdf