Design and Implementation of a Double Langmuir Probe for an RF Plasma

Jordan Brown

August 14th, 2017

The report describes the design process of an adjustable mount capable of horizontally moving two double Langmuir probes through an RF plasma. It details not only the refinement of the design but also the probes, wiring, and circuitry. Engineering drawings are provided for every part, and photos are included featuring multiple steps in the design process. The probes and mounts are tested within several RF plasmas of varying power and magnetization. I-V Traces are created for each of these plasmas and the plasma temperatures and densities are calculated. The temperatures and densities for the unmagnetized, low-power plasma were 4 eV and 2.53e+22 $/m^3$ respectively. The temperatures and densities for the magnetized, low-power plasma were 9 eV and 4.33e+22 $/m^3$ respectively. The probe mount will continue to be used in the Electric Propulsion and Plasma Dynamics Lab (EPPDyL). It will provide a cost-benefit analysis against interferometric plasma dispersion relation measurements in order to determine if the later provides a significants increase in the quality of measurements.

Contents

1. Overview

To measure the key characteristics of a plasma, one must rely on using various types of probes. One of such probes is the Langmuir probe, which can be used to measure the temperature, density, and electric potential of a plasma. A Langmuir probe works by inserting an electrode into the plasma and applying an electric potential to it. In a double Langmuir probe, two electrodes are inserted into the plasma. These electrodes are electrically isolated from any ground or shielding, and the voltage is applied across the two probes. This in turn biases a current between the two probes. This current can be measured against various voltages, and the resulting data can be analyzed to find values for the plasma temperature and density.

The goal of this project is to design and create an inexpensive double Langmuir probe mount. The measurements acquired from this mount will be compared to interferometric plasma dispersion relation measurements obtained through using a Laser-Induced Florescence (LIF) technique. Ultimately, waves will be excited in the plasma using an RF antenna, and the characteristics of these waves will be measured using Langmuir probes. As such, the experiment requires that there be at least two Langmuir probes, each capable of independent linear motion along the sight of the laser.

2. Probe Theory

The following offers a summary of pertinent probe theory concepts. For a more comprehensive source, please reference Francis Chen's book on plasma physics [2].

2.1. Plasma Sheaths

Plasmas are composed of charged particles. As a result they are highly sensitive to the presence of any charged body or conductor. When a charged body enters a plasma it creates a Debye sheath. Oppositely charged particles will move toward the body. These particles partially shield other particles from the body's charge, resulting in fewer charged particles at greater distances from the body. At the Debye length the effect from the electric potential is equal to the that of thermal motion. Therefore the potential is negligible beyond the Debye length [3].

In conductors a similar process occurs. If a conductor is inserted into a plasma while it is not grounded it will begin absorbing particles. Electrons have higher mobility than ions, which causes them to be more easily absorbed. The conductor will gain a net negative charge and a negative potential sheath will form to repel electrons. Eventually the potential will become strong enough so that an equal number of ions and electrons are absorbed by the conductor.

A Langmuir probe has the conductor grounded or otherwise allows current to flow. As charge can no longer build on the conductor the electrons will form a current. This current is limited by the size and shape of the probe as well as the speed at which the electrons can move through the plasma. Applying a voltage to the conductor will alter the amount of electrons entering the conductor. Increasing the voltage will increase the electrons, while decreasing will accomplish the opposite. If the voltage is lowered enough, ions will become the dominant charge carrier entering the conductor and the current will change sign.

2.2. I-V Trace

Taking measurements with any Langmuir probe consists of recording current values over a range of voltages. When plotted, a graph of voltage versus current will look similar to Figure 1. As one can see, the I-V traces are divided into three regions by two locations called "knees". These regions are the ion saturation region, electron retarding region, and the electron saturation region.

These regions are slightly different with respect to single and double Langmuir probes. In a single Langmuir probe the ion saturation region is where the voltage on the probe has become so negative that all electrons are repelled. The current is then dominated by ion flow. The region to the right is the electron retarding region. In this region, the electrons are partially repelled by the probes voltage. Lastly, the electron saturation region is the region where the probe physically cannot absorb any more electrons. Current only increases slightly in this region. This is due to the sheath surrounding the probe increasing in size and thereby increasing the electrons' velocities and saturation current [1]. This will occur much more slowly in the ion saturation region, as the Ions are much less mobile than the electrons.

In a double Langmuir probe the I-V trace is symmetric. When a voltage is applied across the two electrodes in a double Langmuir probe, they each obtain voltages of the same magnitude, but of opposite sign. Electrons and ions are absorbed by the positive and negative electrodes respectively, causing a current from the positive electrode to the negative electrode. Any electron contribution from the positive probe is accompanied by an ion contribution from the other. For example, when one electrode is in the electron saturation region, the other probe is able to increase the total current by absorbing more ions. I-V traces for double Langmuir probes do not level off as quickly as single Langmuir probes'. A double Langmuir probe is the superposition of two single Langmuir probes; therefore they must satisfy the following equations:

$$i_1 + i_2 = 0 \tag{1}$$

$$V = V_1 - V_2 \tag{2}$$

where V is the applied voltage between the two electrodes.

Additionally, since the regions described above are with respect to one probe, for simplicity, the electron saturation region for a double Langmuir probe is the region where a positive voltage results in a positive current between the probes.

2.2.1. Plasma Temperature

Since the I-V trace for a double Langmuir probe is the superposition of two single probes, one must combine equations from both probes and those listed in Section 2.2 in order to solve for the plasma temperature [5]. Assuming that the plasma follows a Maxwellian distribution and that the probes are similarly sized, the currents for the probes are as follows:

$$i_x = i_0(e^{q(V_x - V_F)/kT} - 1) \tag{3}$$

where i_0 is the current in the line, k is the Boltzmann constant, and V_F is the voltage at which no current flows. Combining this with Equations 1 and 2 and substituting the result

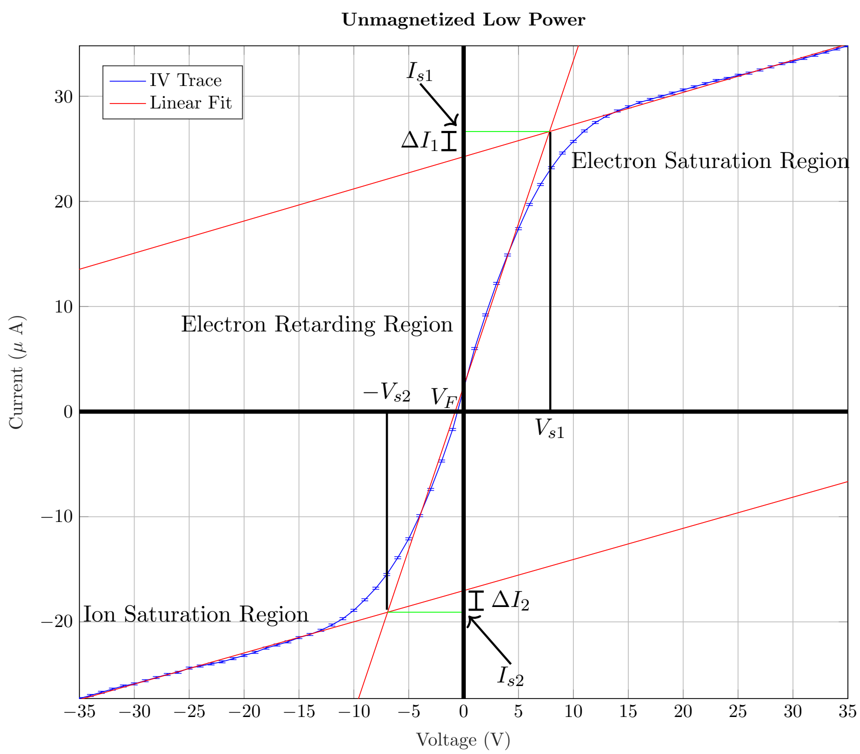


Figure 1: Regions and important variables labeled on an I-V trace.

back into Equation 3 results in the following:

$$i_1 = i_o \tanh(\frac{eV}{2kT}) \tag{4}$$

At this point, this equation form looks similar to the trace shown in Equation 1. Taking the slope of this equation at $V = 0$ provides the electron temperature of the plasma at its rest state. The form of Equation 5 is quite convenient. The slope at $V = 0$ can easily be approximated by breaking a trace into the three regions discussed in Section 2.2. $\frac{di}{dV}$ can simply be approximated as the saturation current over the "knee" voltage, both of which are easily readable from a graph. As the i_0 terms cancel, the final result is only in terms of V_s, which can easily be found through the intersections of fit lines [5].

$$T = \frac{i_0 q}{2k}\left[\sec^2(\frac{qV}{2kT})(\frac{di_1}{dV})^{-1}\right]_{V=0} = \frac{i_0 q}{2k}\left[\frac{di_1}{dV}\right]^{-1}_{V=0} \approx \frac{i_0 q}{2k}\frac{V_s}{i_0} = \frac{qV_s}{2k} \tag{5}$$

2.2.2. Plasma Density

The plasma density can be determined from the saturation regions. For a given probe, the maximum amount of current that can enter the probe is the amount that can enter due to their own thermal velocities:

$$i = qn_e Av = qn_e A\sqrt{\frac{kT}{m_i}} \to n_e = \frac{i}{qA}\sqrt{\frac{m_i}{kT}} \tag{6}$$

In order to determine i, one must combine the contributions from both ions and electrons. Approximating these equations for large V and similar probe sizes results in the following:

$$I_1 = -i_0(1 - SV_1) + i_0 e^{\frac{qV_1}{kT}} \approx i_0(S + \frac{e}{kT})V_1 \tag{7}$$

$$I_2 = -i_0(1 - SV_2) + i_0 e^{\frac{qV_2}{kT}} = -i_0(1 - S(V_1 - V)) + i_0 e^{\frac{q(V_1 - V)}{kT}} \approx -i_0(1 - S(V_1 - V)) \tag{8}$$

where S is a constant. Combining these results with Equation 1 results in the asymptotic behavior of the saturation current. This equation is useful as one can set measurable values in Figure 1 against intercepts and slopes. In line 10 a value for S is found, which is substituted into line 9 to determine i.

$$I_1(V>0) = i_0(1+SV)\frac{S+\frac{q}{kT}}{2S+\frac{q}{kT}} \rightarrow I_1(V=0) = i_0\frac{S+\frac{q}{kT}}{2S+\frac{q}{kT}} = i_s - \Delta i \tag{9}$$

$$\frac{dI_1(V>0)}{dV} = \frac{\Delta i}{V_s} = i_0 S\frac{S+\frac{q}{kT}}{2S+\frac{q}{kT}} = S(i_s-\Delta i) \rightarrow S = \frac{\Delta i}{V_s(i_s-\Delta i)} \tag{10}$$

$$i_0\frac{S+\frac{q}{kT}}{2S+\frac{q}{kT}} = i_0\frac{\frac{\Delta i}{V_s(i_s-\Delta i)}+\frac{2}{V_s}}{2\frac{\Delta i}{V_s(i_s-\Delta i)}+\frac{2}{V_s}} = i_0\frac{2i_s-\Delta i}{2i_s} = i_s-\Delta i \rightarrow i_0 = 2i_s\frac{i_s-\Delta i}{2i_s-\Delta i} \tag{11}$$

Finally, substituting this value into Equation 6 gives a definition for density that can be solved with measurable quantities on the I-V trace [5].

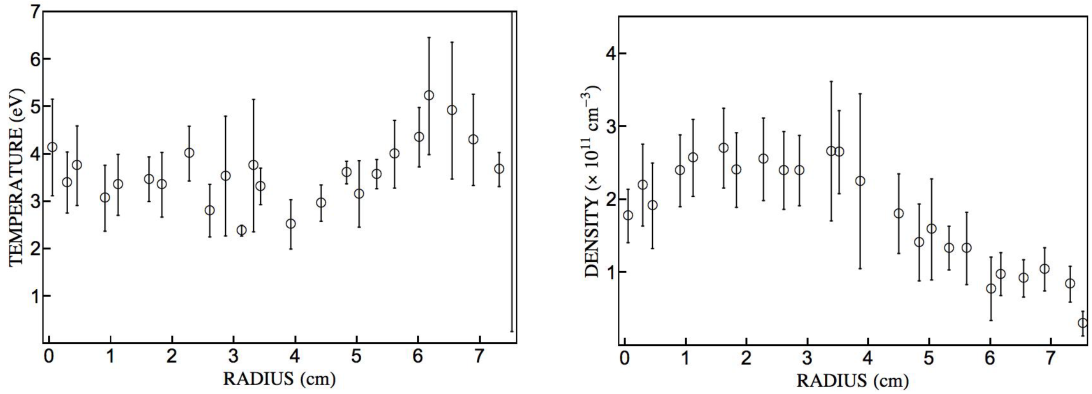
$$n_e = \frac{2}{.61A_p q} i_s \frac{i_s-\Delta i}{2i_s-\Delta i}\sqrt{\frac{m_i}{kT}} \tag{12}$$

The area in the equation is the effective area of the probe. This value is the region on the probe where the ions and electrons may be freely absorbed. For an unmagnetized plasma this is merely the surface area of the probe. For a magnetized plasma, the result is not so simple. The particles will roughly flow along field lines [3]. The particles will primarily enter through only one side of the probe, and thus the effective area is the cross-sectional area of the wire.

3. Design

In order to compare the measurements found using the LIF method and the Langmuir probes, the Langmuir probes must collect data along the sight of the laser. To accomplish this, the probes must be mounted on a device that can move them horizontally without significant vertical displacement. This mount must be inserted into the existing RF plasma source, shown in Appendix A. The device is a cylindrical quartz glass tube that is open on each end. One end is capped with a quartz window and the other is attached to a four-directional aluminum pipe fitting. This fitting then connects to the pumps, the pressure sensor, and an aluminum plate. This plate is the only location where diagnostics could be mounted and accessible from the outside.

Before making any alterations, the plate already had two holes in it. One was for the argon gas intake valve and the other was for a feed-through for the antenna. The mount could only be attached through one of feed-through holes, which allowed it rotational motion and longitudinal translation. The laser's sight is roughly 65 cm from the area of attachment. The probe must extend to that distance without any significant static or dynamic bending.



(a) Temperature within tank

(b) Density within tank

Figure 2: Ben Jorn's measurements of the plasma parameters within the RF plasma source [4]

According to Ben Jorn's previous experiments on the RF plasma source, the plasma has relatively uniform temperature and density within the inner 6 cm diameter region [4]. The probes should be able to move within this area freely without vertical displacements over 5 mm.

The constraints of the mount are listed below:

- The mount must independently move two Langmuir probes along the sight of the laser
- The mount must be able to move the probes within the inner 6 cm diameter of the tank
- The mount must attach through the aluminum plate at the far end of the tank
- The mount must not bend significantly under its weight or while under motion
- The probes and wiring must be electrically isolated from the plasma and any ground, with the exception of the probe ends
- The probes must be shielded from any EM signals from the plasma

3.1. Mount

3.1.1. Brainstorming and Refinement

The design underwent numerous charges during its development. While the base design was developed relatively quickly, many adjustments were made. A catalog of the major design steps can be found in Appendix B.

The design began as a single extending arm, shown in B.1. This idea used the antenna as a support to keep the entire mount from rotating with the moving probe. Unfortunately that design had two issues. The first was that the extending arm had no way to reliably contain the wire, so it would be exposed to the plasma. It also only moved one probe. This idea was then dropped in favor of the T-Slider design shown in B.2. Instead of the single extending arm, it had two small jointed arms supported by an opening spanning the base material. This opening would keep the probes from moving in the vertical direction, while guiding them horizontally. The arms would have two sections. The base arm would be rotated by the external pole, which would cause the probe to translate in the slit. The wire would be entrenched within the arms, running from the base arm and joint to the forearm and probe. While this design works in theory, there were a few small problems in its execution. First, the base arms were too long. This resulted in a lot of friction within the opening which made it difficult to move the probes. This also made the entire mount rotate about the center of the container. These complications made any reliable measurements or predictions of the probes' positions impossible. These problems were fixed in the final model.

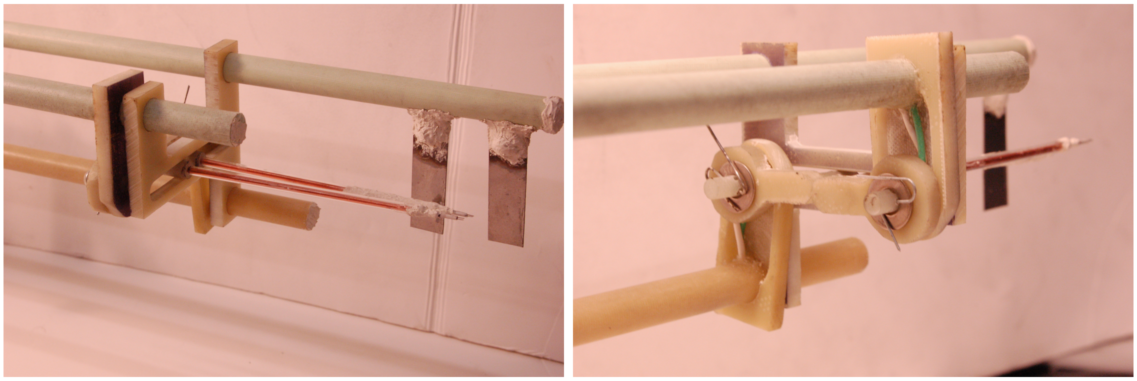
3.1.2. Final Design

The final design was named the 4-Slider, which is shown above. Its shape allowed it to brace the two pole-arms and antenna. Another brace was added to further resist deformation. Ultimately the error due to rotation in the probes' positions was within 2 mm. The base arms were also shortened so the arms could move more easily. Figure 4 shows a front-view picture with its parts labeled.

As the probes were moved, they deviated from the anticipated path. This equation can be found from simple trigonometry and is shown in Equation 13:

$$x = d_1 \sin(\theta) + \sqrt{d_2^2 - (h - d_1 \cos(\theta))^2} \tag{13}$$

In measuring the actual angles against the position, the results determined that the actual position differed slightly from the expected. Because the probes were not perfectly straight,



(a) Final Design Front View (b) Final Design Back View

Figure 3: Pictures of the final probe design

resulting in the positions of the tips being different from those of the base. There was also some play in the system, resulting in a hysteresis loop. These loops are shown in Figure 5, with errors due to both the mount rotation and measurement error. The expected result is between the base and tip measurements, and the measured results should be referenced when one wishes to use the mount.

3.2. Electronics

In order to take measurements, wires had to transfer current from the probes to outside of the container and the vacuum. The following sections detail these aspects of the design.

3.2.1. Probes

As mentioned in Section 2, a Langmuir probe works by absorbing electrons through one or two exposed electrodes. These electrodes take the form of two tungsten wires threaded through an insulating alumina tube. Surrounding the alumina tube is a copper sleeve, which shields the wires from electromagnetic interference. If the copper shielding were in contact with the plasma electrons would be absorbed by the shielding similarly to the wire tips. This would effectively eliminate the shielding and render the copper worthless. To prevent this the copper is inserted in a glass sleeve. Any remaining exposed copper is covered in zirconia, which insulates and isolates the copper from the plasma. These concentric layers make up the Langmuir probe, which is then mounted to the G10 base. The details of this design are shown in Figure 6. This design was based on double Langmuir probes create by Ben Jorns for similar tests within the RF plasma source [4].

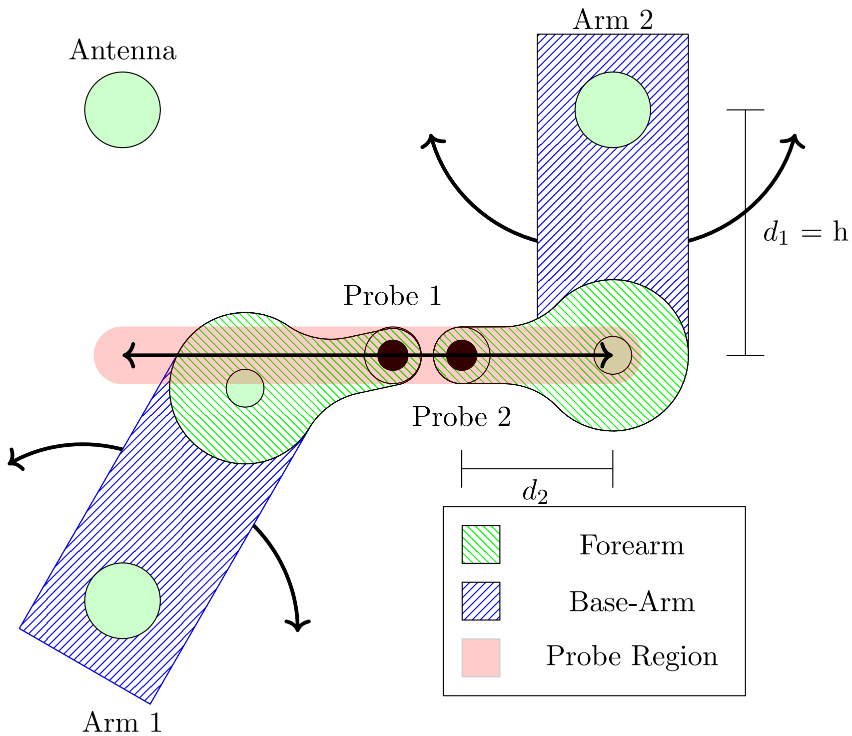
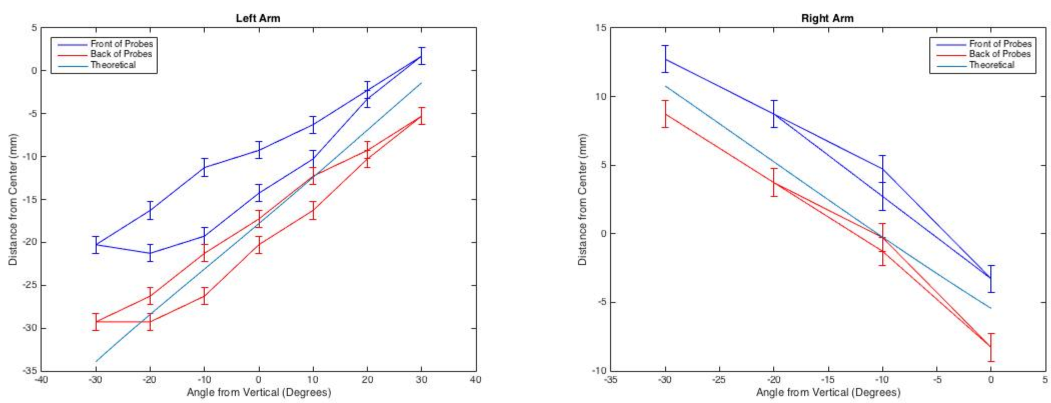


Figure 4: Front view of arms with range of motion



(a) Left Arm

(b) Right Arm

Figure 5: Calibration curves for front and back ends of each arm

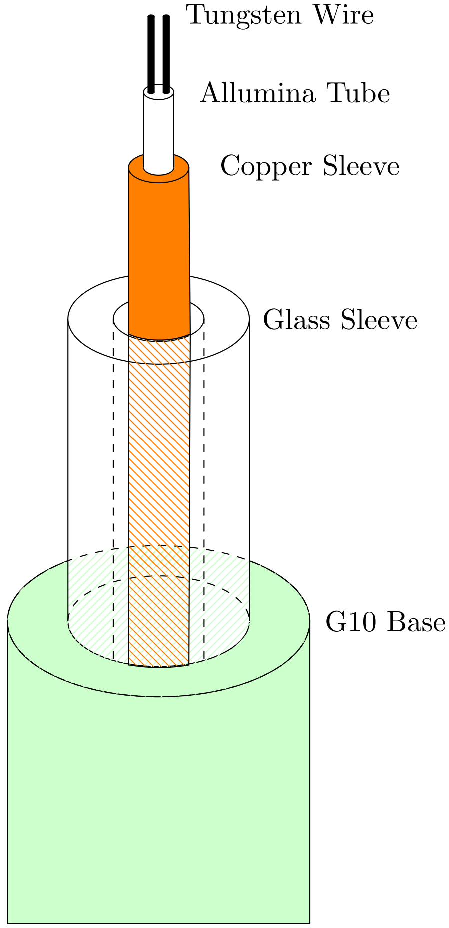


Figure 6: Cutaway display of the components of the Langmuir Probes

3.2.2. Wiring

The electric currents collected with the electrodes are transferred to outside of the vacuum. The probe must connect to some wires without the shielding contacting the plasma. These wires must also be fed through to atmosphere without any air leaking from within the vacuum.

A shielded multiple pair Belden cable is fed through the rods. On one end, two inner wires and shielding wrap around the tungsten wires and copper tube respectively. The entire thing is encased in zirconia and entrenched in small grooves within the arms (see Appendix B.3). The wires have enough room to flex slightly as the arm is in motion. The other end is connected to feed-throughs shown in Appendix B.4. The feed-throughs are made of acrylic and secured with Loctite sealant. The wires are then connected to BNC or banana cables, which can easily connect to a circuit.

3.2.3. Circuit

The circuit required to create an I-V Trace is quite simple. In order for a current to flow between the two electrodes, a voltage must be applied between them. This voltage was applied using a variable DC power supply and measured using a voltmeter. An ammeter was used to measure the currents, and the two values were recorded for later analysis. This circuit is shown in Figure 7.

4. Results and Analysis

4.1. Measurements

Using the mount discussed in Section 3.1 and the circuit discussed in Section 3.2, a series of measurements were recorded. The maximum voltage of the power supply was 35 volts. The measurements were incremented by 1 V while the current was recorded. Also swapping the positive and negative leads on the power supply, negative voltages were able to be recorded. Thus the total range for voltage measurements was from -35 to 35 V. Traditionally the voltage is swept across a desired range, but due to the limitations in hardware the voltage was incremented instead.

Data was taken from three separate plasmas. One was a low power (50 W) unmagnetized plasma. Another was a low power magnetized plasma. The third was a high power (300 W) magnetized plasma. Unfortunately the data collected within this plasma was corrupt due to the shielding becoming exposed. A MATLAB script was created that would take the data gathered from each plasma and break them into the three regions discussed in Section

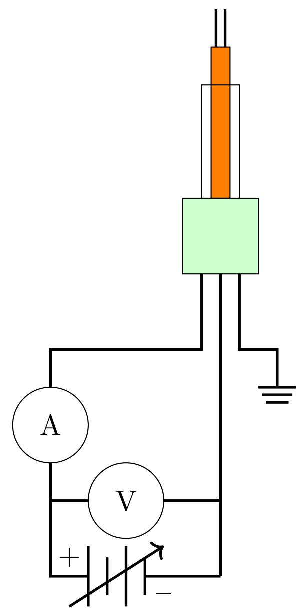
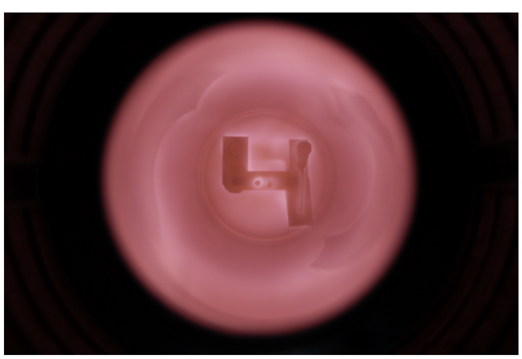


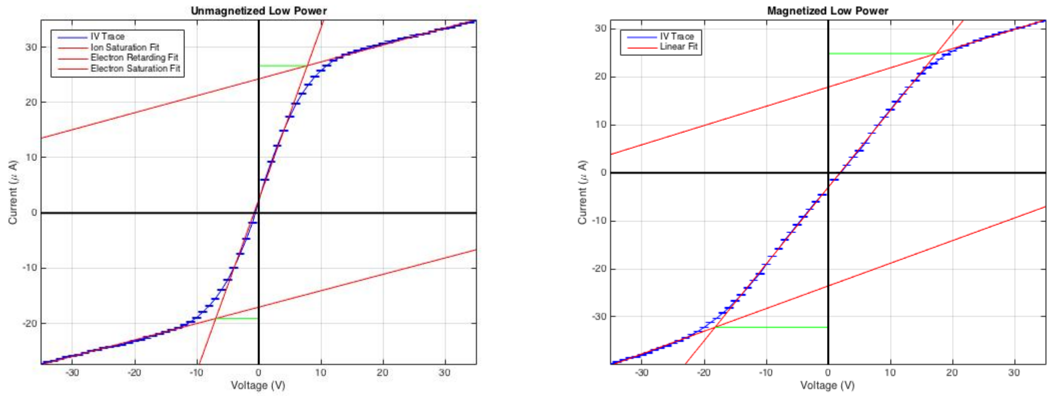
Figure 7: Circuit used to measure the I-V trace



(a) Front view in plasma

(b) 3D view in plasma

Figure 8: Photos of probe and mount within the plasma



(a) Unmagnetized Low Power

(b) Magnetized Low Power

Figure 9: I-V Traces for various plasmas with fit lines

Plasma	Variable	Value
UMLP	T	$4\ eV$
UMLP	n_e	$2.53 * 10^{22}/m^3$
MLP	T	$9\ eV$
MLP	n_e	$4.33 * 10^{22}/m^3$

Table 1: Calculated Values for plasma quantities

2.2. The I-V traces for each of these measurements are shown in Figure 9. Linear fit lines were created for each region and the values from Figure 1 were calculated. Then using these values, as well as Equations 5 and 12, the plasma temperature and density were calculated. These values are tabulated in Table 1. As expected, the magnetized plasma had greater temperature and density than the unmagnetized plasma. The magnetic field allows more electrons to dissociate themselves from the ions, which causes the higher temperatures and densities.

4.2. Future

The probe mount will continue to be used in the EPPDyL. With the RF antenna, standing waves will be injected into the plasma. This will create oscillations in the potential of the plasma. At the nodes of these waves the potential will remain constant. The probe mount will attempt locate these nodes. This allows one to measure the wavelength, but doesn't account for fractional wavelengths. To account for this, the probes can move, while any increase or decrease in potential is measured. This will determine exactly the wavelength of the plasma wave. The same measurements will be taken using the LIF method, which will measure the plasma dispersion relation. A cost-benefit analysis will be performed between these two methods to determine if the additional cost of the LIF system provides any significant benefits in accuracy.

References

[1] FF Chen. Langmuir probe diagnostics. *... -Course on Plasma Diagnostics, IEEE-ICOPS Meeting, ...*, page 42, 2003.

[2] Francis F. Chen. *Introduction to Plasma Physics*. Plenum Publishing Corporation, New York, 1974.

[3] I. H. Hutchinson. *Principles of Plasma Diagnostics*. Cambridge University Press, New York, second edi edition, 2002.

[4] Benjamin Jorns and Edgar Choueiri. Experimental Characterization of Plasma Heating with Beating Electrostatic Waves. *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, (November):1–14, 2012.

[5] D. K. Owens. Lecture IV: Langmuir Probes. A Technical Report. Technical report, Princeton Plasma Physics Laboratory, Princeton, 2000.

A. RF Plasma Source

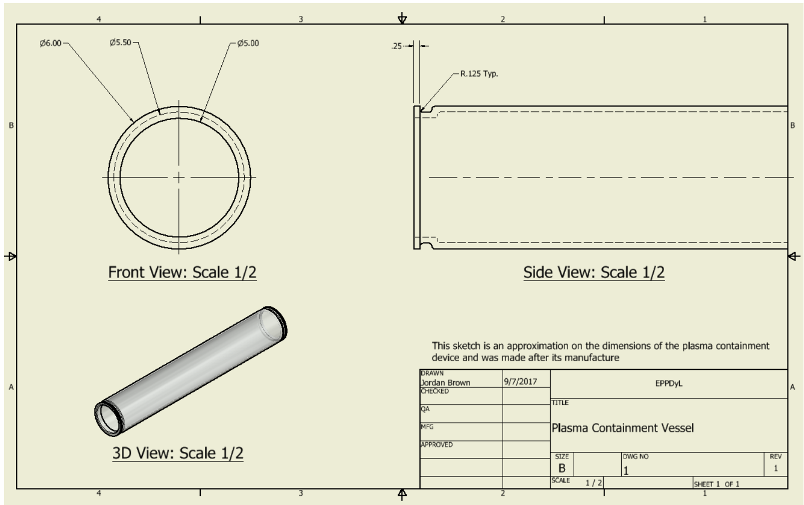


Figure 10: Quartz vessel in which the plasma was created and maintained

B. Design Process

The parts described below were machined with a standard lathe, and mill. Parts are made out of G10, a carbon fiberglass composite.

B.1. Extending Arm

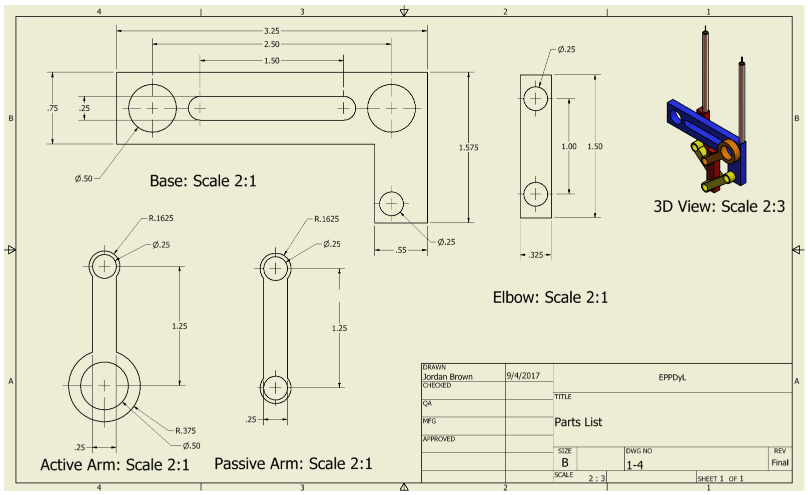


Figure 11: Extending Arm design is unable to move two probes

B.2. T-Slider

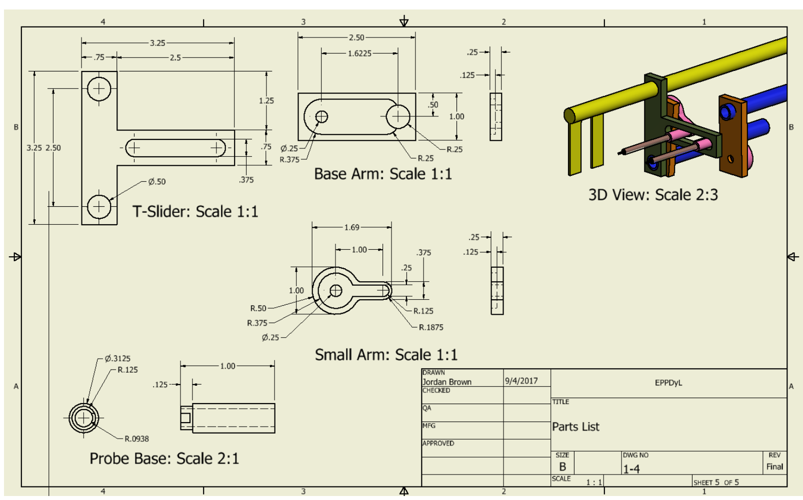
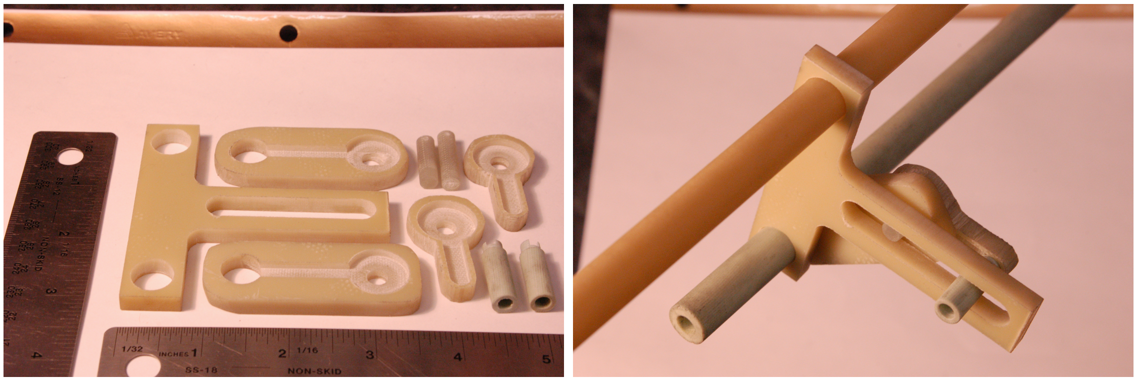


Figure 12: T-slider design improving upon the Extending Arm Design



(a) T-Slider Parts (b) T-Slider Assembly

Figure 13: Photos of T-Slider Design

B.3. 4-Slider

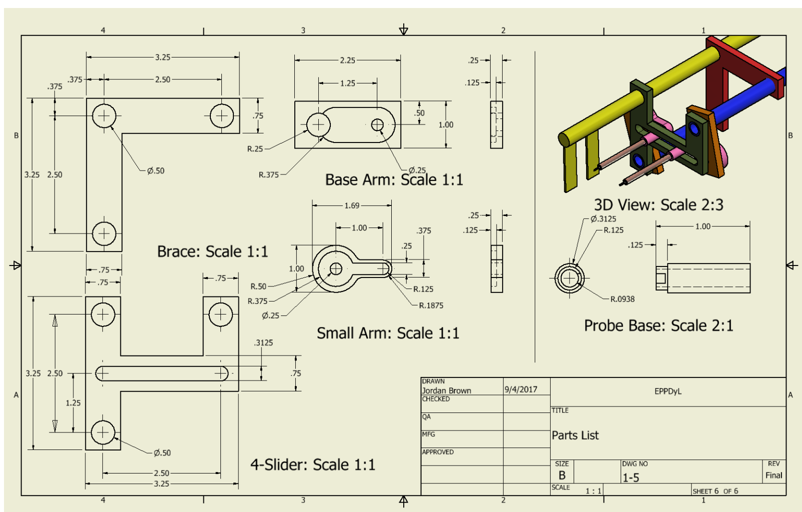
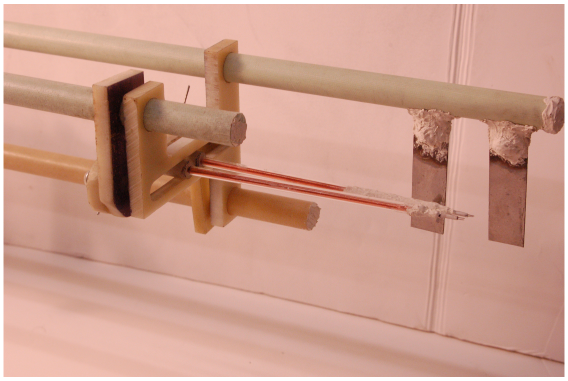
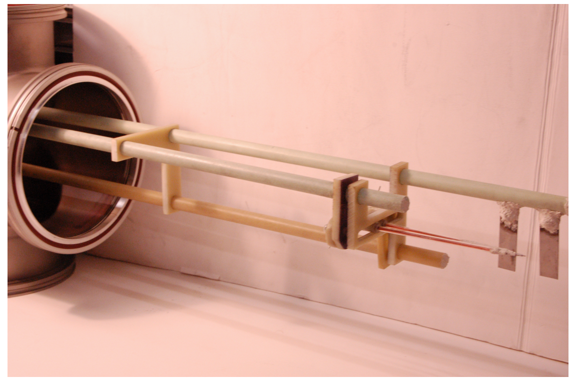


Figure 14: Final Design



(a) 4-Slider Assembly



(b) 4-Slider Assembly

Figure 15: Photos of 4-Slider Design

B.4. Feedthroughs

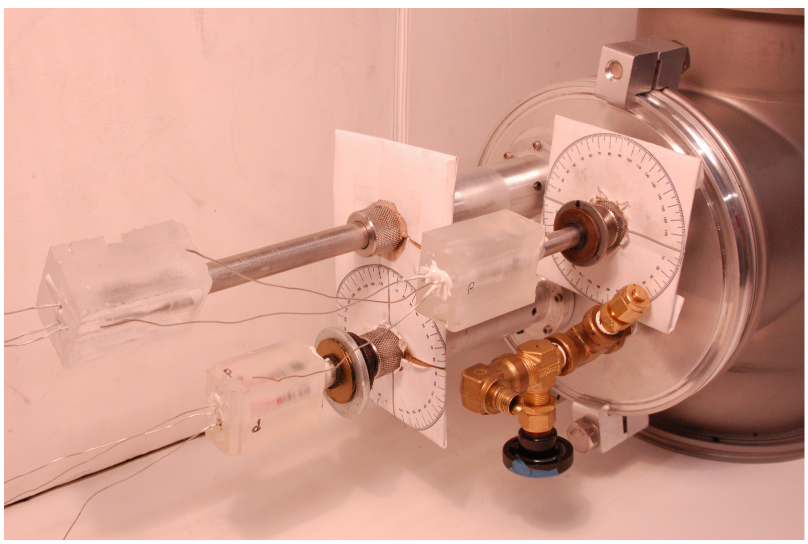


Figure 16: Feedthrough Photos