Ian Trase September 21, 2012

Summer EPPDyL Internship Report

Over this past summer, I worked at the Electric Propulsion and Plasma Dynamics Lab at Princeton University, run by my research advisor Edgar Choueiri. I worked with Justin Little, a graduate student, to help design and build a plasma source for the Plasma Detachment Experiment (PDX). In my capacity as intern I worked on various projects. I began by using the Labview programming language to automate the various calibration and measurement apparatus in the high vacuum tank in which the experiment is to be housed. The second half of the internship was concerned with constructing and testing various parts of the experiment, including water and gas flow systems, an antennae to heat the plasma, the matching network for the antennae, and various enclosures for each system. I also helped to prepare the orange tank for vacuum conditions.

The thrust stand that I automated is located inside the large orange tank in the EPPDyL. It is composed of a stand mounted on a swinging arm attached to a LVDT. The LVDT converts the linear displacement of the arm into an electrical voltage signal, which is then fed into a control box located outside the tank. The swinging arm also has a force transducer attached to it for calibration purposes. The equation that describes the motion of the stand and arm as a function of time is a normal damped sine wave:

$$x(t) = \Delta x \sin(\omega' t)\, e^{-\gamma t}$$

where x is the displacement of the arm, ω' is the frequency of oscillation, and γ is the damping coefficient. The constants $\Delta x, \omega',$ and γ can be found by taking the signal generated from the LVDT and fitting it to a curve. These constants can be used to determine the thrust of the device through the formula: $\Delta u = \frac{I_{thrust}}{m_{eff}}$, where $\Delta u = \left.\frac{dx}{dt}\right|_{t=0} = \Delta x\omega'$ and m_{eff} is the effective mass of the stand.

The effective stand mass is found by attaching a force transducer to the swinging arm and thus equating a known amount of force from a hitting arm to a known voltage signal from the LVDT. This signal will look like a spike, and from it can be extracted both the initial velocity of the hit through differentiation and the total impulse through integration. The slope of the line for velocity and impulse will give the effective mass of the system (which of course changes whenever a plasma source is added to the thrust stand). Since the force transducer and the stand are located at different points on the swinging arm, all that remains to be done is to multiply the mass by the ratio of the radial distances of the stand and the transducer.

Both the LVDT signal and the force transducer signal are fed to a Tektronix oscilloscope. Before this summer, the data for all of the calibration and impulse measurements was being manually extracted from the oscilloscope. I hooked the oscilloscope up to a computer and wrote a program in Labview that would control the scope and automate its ability to take data, greatly decreasing the time required for calibration and significantly increasing the accuracy of the results. Labview will automatically take multiple sets of data, create a graph of the results, and determines the slope, as well as performing error analysis. It also integrates and differentiates the LVDT signal, making using a separate Matlab program unnecessary. For actual thrust testing, the program can automatically fit a curve to the damped sine wave that the LVDT outputs when a plasma source is fired.

After creating the programs for the experiment, I moved on to constructing various parts of the apparatus, starting with the antenna used to heat the plasma. The antenna was constructed from a single piece of copper tubing tightly wound in a spiral with the ends sticking out parallel to the axis of rotation. Copper tubing was the chosen material as it is a good conductor and also very ductile. Tubing was chosen in order to let cooling water flow through the antenna. Different sizes of copper tubing were tested for their electrical, thermal, and flow rate properties. Eventually a 3/16" diameter sizing was selected. I carried out a detailed fluid mechanics analysis on the chosen diameter to determine the average flow rate through the antenna, and then a thermal analysis to determine its maximum temperature. These analyses, shown in Appendices 1 and 2, were necessary to make sure that in the event that the antenna was entirely unmatched, a kilowatt's worth of waste heat would still not be enough to melt any components near the antenna. The analyses showed that the antenna was indeed safe and would operate well within accepted heat levels. The plasma itself was set up in a glass tube bordered by two Teflon caps. One cap was fixed, but the other was moveable. It was behind the moveable cap that the antenna was placed, so that the antenna could be moved up and down the glass tube, providing another variable with which to test.

The antenna was tested to determine its impedance, which is critical to finding the precise type of matching network required. In order to find the impedance as a function of frequency, the antenna was hooked up to a function generator and its resistance and phase were measured from 10Mhz to 30Mhz. For the experiment, there were two options for frequency, 13.5Mhz and 27Mhz, and this analysis also helped to determine which of these frequencies would be more appropriate for the matching network and the ability to deliver power. In the end the 13.5Mhz range was chosen, as it would be easier to match and stayed on the inductive side of the resonance curve. The resonance point was somewhere around 22Mhz. The data from the impedance tests is shown in Appendix 3.

Once the antenna design was finalized, the next task was to get the water flowing through the tank and into the antenna. This involved educating myself on various pipe fixtures and fittings in order to provide tight seals and maximal flow rate throughout the machine. With the fittings in place and connected to the antenna, more tests were run to determine if the earlier flow rate analysis was accurate and that a minimal required level of flow was maintained, which it was. The water tubing was also hooked up to existing equipment which allowed the rate to be measured, and if need be manually limited. A similar process was used for the argon gas used as the plasma source, and it too was affixed to the existing equipment.

With the impedance for the antenna measured, it was determined that a matching network consisting of two capacitors, one in series and one in parallel, would be most effective in cheaply matching the impedances of the source (50 Ohms, 0 Phase), and the antenna at 13.56Mhz. The antenna was hooked up to a makeshift network with the desired configuration and attached to a function generator and oscilloscope. The capacitors were made of two interlocking sets of metal semicircles, one of which could be rotated. When the set of semicircles was rotated, it could move from a position where all of the semicircles were lined up to one where they were on opposite sides of the system- i.e. one could use a knob to adjust the capacitance of the system. After testing the system to try and get the voltage and current in phase with the desired resistance, it was determined that the capacitance of the test system did not go low enough, which helped to inform us of which capacitors to eventually purchase. New capacitors had to be purchased in order to handle the very large amount of voltage and current used in the real system.

The last couple weeks of the summer were spent building various enclosures and helping to get the orange tank to vacuum-ready status. This involved removing all of the plastic windows and manually cleaning the O-rings used to keep the vacuum seal. These were washed with isopropanol and inspected for any imperfections, then re-greased and refitted into the chamber. When faulty O-rings were found, they were disposed of and new ones were crafted to replace them.

Several enclosures needed to be built for the system, including a box for the matching network and a stand for the antenna. It was determined that the antenna was to be placed on a separate stand behind the thrust stand so that the various wires and tubes attached to it would not pull on the thrust stand and introduce error into the measurements. This stand was built with interlocking extruded metal pipes that did not require welding or cutting beforehand. The matching network was housed in a fiberglass container, and so I hand cut fiberglass and threaded holes for that. I also cut and drilled various other small fiberglass and plastic parts, fiberglass being chosen for its high melting temperature.

Unfortunately, the internship was over before the plasma source had been fully put together, and so no actually data or research in the tank could be done before I left. Nevertheless, the experience was very rewarding and taught me a great deal in regards to the various mechanical and electrical engineering requirements of putting together a complex scientific experiment.

Appendix 1: Water flow calculations

Use the energy equation for pipe flow:

$$\frac{p_1}{\rho} + gz_1 + \frac{V_1^2}{2} = \frac{p_2}{\rho} + gz_2 + \frac{V_2^2}{2} + gh_l$$

Assumptions:

$$p_2 = p_{atm}, \qquad z_1 \approx z_2, \qquad V_1 = V_2, \qquad p_{w,g} = 45\text{psi}$$

$$\frac{p_{w,g}}{\rho} = gh_l$$

$$h_l = \left(f\frac{L}{D} + K\right)\frac{V^2}{2g}, \qquad K \approx 60f$$

$$\frac{p_{w,g}}{\rho} = \left(f\left(\frac{L}{D} + 60\right)\right)\frac{V^2}{2}$$

$$V^2 = \frac{2 * p_{w,g}}{\rho f\left(\frac{L}{D_i} + 60\right)} = \frac{620.5}{f\left(\frac{L}{D_i} + 60\right)}\frac{\mathrm{m}^2}{\mathrm{s}^2}$$

Calculation for L:

$$L = \frac{\pi(d_o - d_i)(d_o + d_i)}{4D_o}, \qquad d_o = 6\text{in}, \qquad d_i = 1\text{in}$$

$$L = \frac{27.489}{D_o}\ \text{in}$$

$$\boxed{V^2 = \frac{620.5}{f\left(\frac{27.489\text{in}^2}{D_o D_i} + 60\right)}\frac{\mathrm{m}^2}{\mathrm{s}^2}}$$

Colebrook equation:

$$\frac{1}{\sqrt{f}} = -2 * \log_{10}\left(\frac{\epsilon}{3.7 * D_i} + \frac{2.51\mu}{\rho V D_i\sqrt{f}}\right), \epsilon_c = 5 * 10^{-6}\text{ft}$$

$$\frac{1}{\sqrt{f}} = -2 * \log_{10}\left(\frac{1.622 * 10^{-5}\ \text{in}}{D_i} + \frac{8.795 * 10^{-5}\,\frac{\mathrm{m} * \text{in}}{\mathrm{s}}}{V D_i\sqrt{f}}\right)$$

For $D_{outer} = \frac{3}{16}\text{in}, \ D_{inner} = \frac{1}{8}\text{in}$

$$V^2 = \frac{0.503}{f}\frac{\mathrm{m}^2}{\mathrm{s}^2}$$

$$\frac{1}{\sqrt{f}} = -2 * \log_{10}(1.298 * 10^{-4} + 1.399 * 10^{-3})$$

$$\frac{1}{\sqrt{f}} = 5.631$$

$$\boxed{V = 3.994\frac{\mathrm{m}}{\mathrm{s}}}$$

Rise of 7.573°C

$$\underline{\text{For } D_o = \tfrac{1}{4}\text{ in},\ \ D_i = \tfrac{3}{16}\text{ in}}$$

$$V^2 = \frac{0.9599}{f}\frac{\text{m}^2}{\text{s}^2}$$

$$\frac{1}{\sqrt{f}} = -2 * \log_{10}\left(8.651 * 10^{-5} + \frac{4.691 * 10^{-4}\,\frac{\text{m}}{\text{s}}}{V\sqrt{f}}\right)$$

$$\frac{1}{\sqrt{f}} = -2 * \log_{10}(8.651 * 10^{-5} + 4.788 * 10^{-4})$$

$$\frac{1}{\sqrt{f}} = 6.495, \qquad f = 0.0237$$

$$\boxed{V = 6.36\,\frac{\text{m}}{\text{s}}}$$

Appendix 2: Thermal analysis for copper antenna

$$P = 1\text{kW}, \qquad P = P_{water} + P_{radiation}$$

$$P_{water} = c_{P,water} * \left(T_{w,f} - T_{w,i}\right) * \dot{m}, \qquad P_{radiation} = \varepsilon\sigma A T_{coil}^4$$

$$P_{water} = hA\left(T_{coil} - \frac{\left(T_{w,f} + T_{w,i}\right)}{2}\right), \qquad h = 14\,\frac{\text{W}}{\text{m}^2\text{K}}, \qquad \dot{m} = 113.3\,\frac{\text{g}}{\text{s}}$$

Unknowns: $T_{w,f}, T_{coil}$

Equations:

$$hA\left(T_{coil} - \frac{\left(T_{w,f} + T_{w,i}\right)}{2}\right) = c_{P,water} * \left(T_{w,f} - T_{w,i}\right) * \dot{m}$$

$$P = c_{P,water} * \left(T_{w,f} - T_{w,i}\right) * \dot{m} + \varepsilon\sigma A T_{coil}^4$$

$$A = 0.0147\text{ m}^2, \qquad c_{P,water} = 4.18\,\frac{\text{J}}{\text{g} * \text{K}}, \qquad \sigma = 5.67 * 10^{-8}\,\frac{\text{W}}{\text{m}^2\text{K}^4}, \qquad T_{w,i} = 296°\text{C},$$

$$P = 1\text{kW}$$

$$h\left(T_{coil} - \frac{(T_{w,f} + 296)}{2}\right) = 284.354(T_{w,f} - 296) * \dot{m}$$

$$1000 = 4.18(T_{w,f} - 296)\dot{m} + 8.335 * 10^{-10}(0.934 - 0.0002T_{coil})T_{coil}^4$$

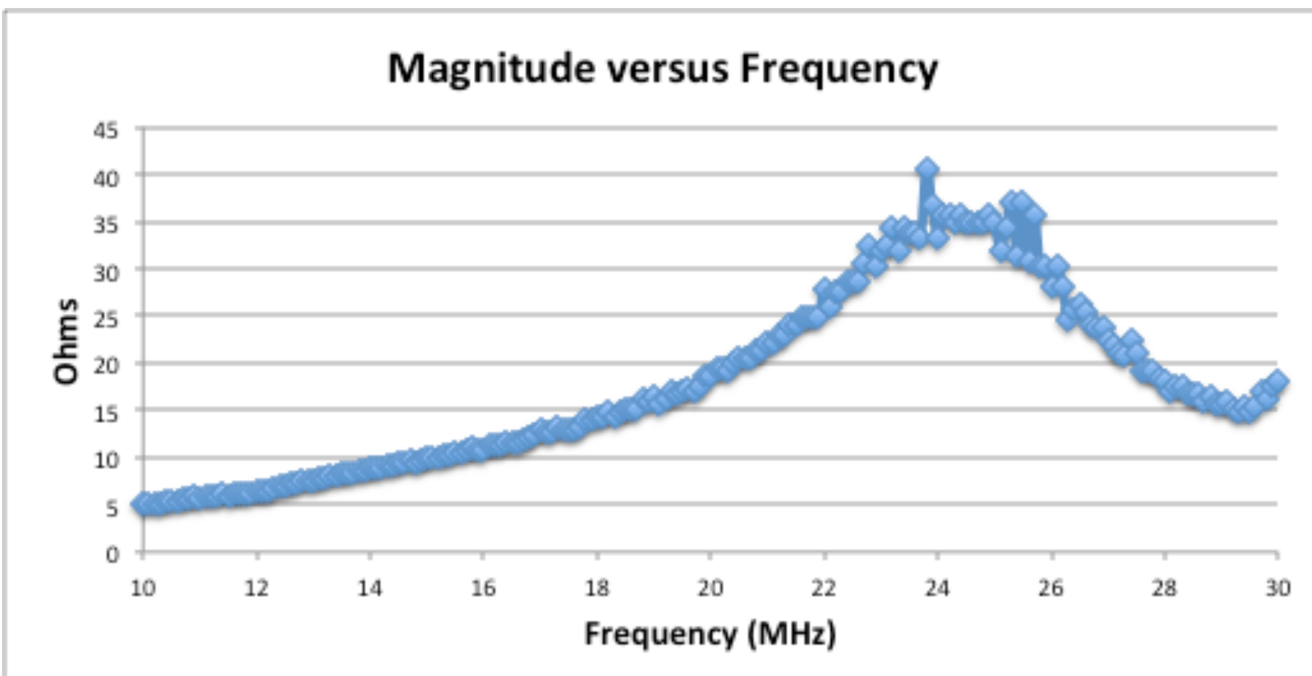
$$\varepsilon = 0.934 - 0.0002T_{coil}, \qquad h = 14\frac{\text{W}}{\text{m}^2\text{K}}?, \qquad \dot{m} = 113.3\frac{\text{g}}{\text{s}}$$

$$T_{coil} = 1066.64\text{K}, \qquad T_{w,f} = 297.202\text{K}$$

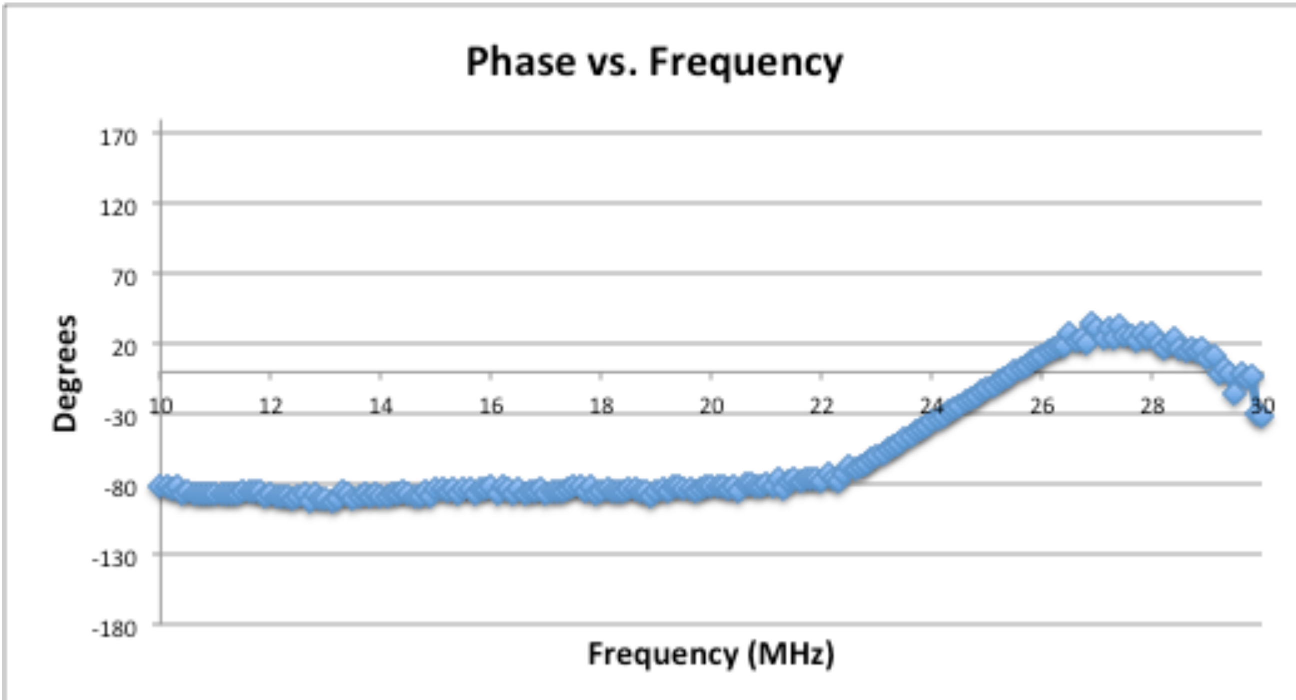
$$P_{rad,coil} = 0.5 * 6.501 * 10^{-10}T_{coil}^4, \qquad P_{rad,Teflon} = 2.069 * 10^{-10}T_{Teflon}^4$$

Temperature rise of 1.2°C

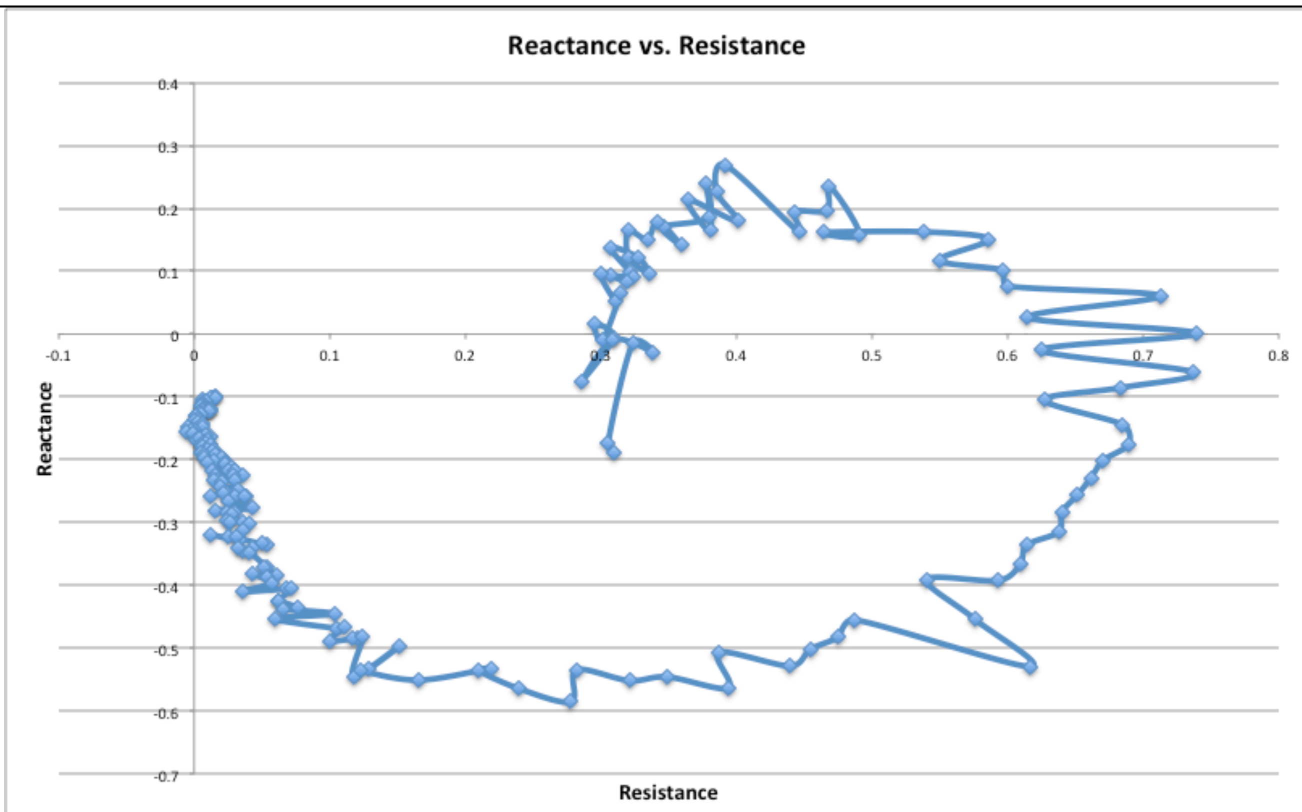
Appendix 3: Electrical antenna measurements



This is a graph of the resistance of the antenna versus the applied voltage frequency. One can see a clear spike at around 25MHz, where the antenna is at resonance. In order to be matched, the antenna must stay on the low end of the resonance spike, which ruled out using a higher frequency of 27MHz instead of 13.56MHz.



This graphs shows the phase of the impedance as a function of the frequency- note that it crosses from negative to positive at resonance.



This graph shows the reactance and resistance of the antenna.