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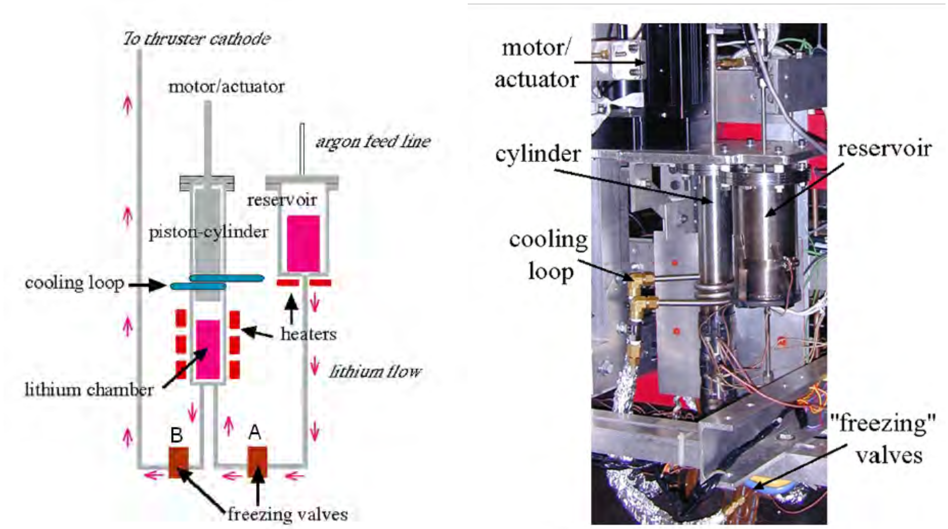
Summer EPPDyL Report

JxB Pump Feed System Development

In the summer of 2015 I worked as an intern under Professor Edgar Choueiri at Princeton’s Electric Propulsion and Plasma Dynamics Lab (EPPDyL). During my internship, I worked alongside graduate student William Coogan conducting research on the lab’s Lithium Lorentz Force Accelerator (LiLFA). The Lithium Lorentz Force Accelerator (LiLFA) is a type of applied-field magnetoplasmadynamic thruster (AF MPDT) that uses lithium specifically for the propellant. It works by using an electrical current and a magnetic field to create a J x B force to propel the plasma out of the thruster. The benefit of MPD thrusters over existing ion or Hall thrusters is that they achieve exhaust velocities as high as those of Hall thrusters, but generate an order of magnitude more thrust. This allows you to use fuel more efficiently and achieve higher travel velocities without having to carry more propellant than the Ion or Hall thruster would require. The usage of AF MPD thrusters is currently limited however, because optimal performance requires more power than is currently available in space (up to 200kW). This quantity of energy is expected to be available in the near future and so building and testing AF MPD thrusters now will allow us to prepare for when that time comes.

The focus of my summer internship was to continue the work of the previous intern Jeremy Mehl, who was working on building and optimizing the propellant delivery system for the lab's Lithium Lorentz Force Accelerator. The fuel delivery system I was implementing used a JxB pump to drive the propellant into the thruster at a controllable rate (pump details and specifications can be found in reference[1]). My task was to integrate the pump into the actual thruster in the system that was built for the old piston-cylinder system of fuel delivery (FIG 1) and to build a system that would measure the flow rate and write new code to control it, the pump, and the piston. A diagram of the old system using the piston is shown below.

Figure 1: Previous LiLFA Propellant feed system



The new system would replace the piston with the JxB pump thus allowing the reservoir channel to lead directly to the cathode. This would simplify the design and remove many of the problems that the old system presented. A feed system using the JxB pump relies on fewer moving parts which decreases the chance for setbacks from jams and leaks.

My first task was to recreate the experiment that the previous intern had devised, and to make sure the pump worked in that configuration. The thruster will use liquid lithium propellant during thruster trials because it is electrically conductive, however we used Gallium as the propellant when testing the pump because lithium is reactive with the water in the air. To test the pump, I connected a reservoir that was filled with gallium to the pump and attached a second pipe from the pump outlet that lead to a beaker where the gallium would be deposited. We used an Acopian Y05LX7000 DC power supply to run current through the red and black leads on either side of the pump. The set up is shown below in FIG 2:

FIGURE 2: The JxB Pump set up, pumping gallium into a beaker.

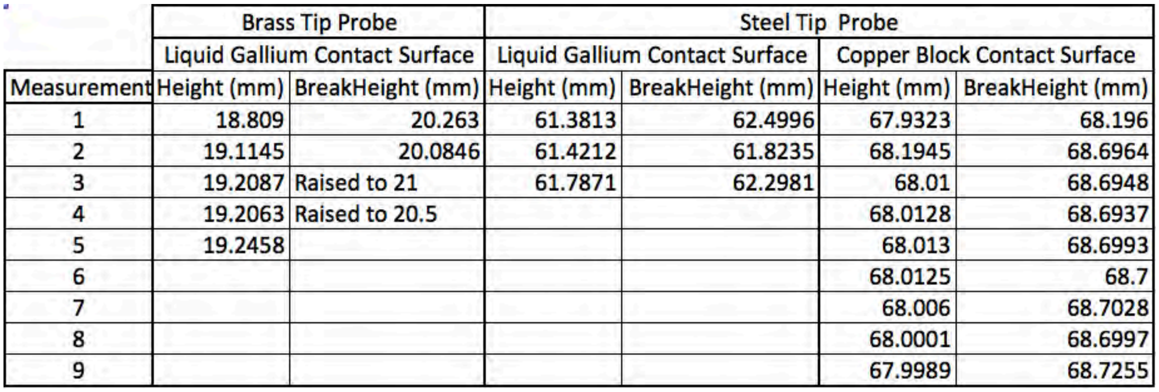
In this configuration, the exit tube is at the same level of elevation as the pump exit, thus the pressure difference between the gallium in the reservoir, and the gallium in the exit tube on the opposite side of the pump would drive the flow regardless of whether or not any current was flowing through the leads. This ultimately would not be an optimal design because it would make the flow rate difficult to control since there could still be propellant moving through the pump when there is no current flowing. We chose not to elevate the exit tube in this case however, because despite having current well above what should have been needed to produce flow, we were unable to drive a high or expected flow rates when the exit tube was elevated. This result suggested that the heating conduction in the pipes was poor and the gallium may have been solidifying and partially blocking the path on the inside of the exit tube. It may also suggest that there is an issue or misalignment within the pump causing the force produced by the pump to be minimal and only gravity was driving the flow. We decided that the latter was unlikely because even though we were unable to see high flow rates, when the current was removed, the flow rate slowed considerably. We also did not consider the low flow rates a particularly troubling obstacle because the actual experiment only requires a propellant flow rate of 8-20 mg/s.

After assembling the pump set up and verifying that it was functional, I needed a way to measure the flow rate through the pump. To do this, we decided to use a plumb bob attached to the old piston that could move up and down and stop when it made contact with the surface of the propellant in the reservoir. This was optimal because we were still able to utilize the piston from the old set up and the speed of the piston was easily controllable using LabView code that had previously been written for past experimentation. We used a brass plumb bob initially to test and se if our design would work and ultimately transitioned to a steel tip plum bob because neither gallium nor lithium will wet to the steel at high temperatures. This was a very important requirement because the change in reservoir height will be on the order of microns per second, thus even a small amount of wetting would give an imprecise flow rate measurement. To detect when the tip of the plum bob had made contact with the surface of the gallium in the reservoir we connected the reservoir and the plumb bob to two ends of a power source, thus when contact was made the circuit would be complete and we would detect current flow through the circuit using an ammeter. We then would send a signal to the piston motor to stop until the circuit was broken and no current was detected anymore, indicating that the level of gallium in the reservoir had receded far enough to lose contact with the probe. The set up for the contact circuit is shown in FIG 3.

Figures 3 (a-b): 3a shows the power source and connection pins for the contact circuit placed in an insulating fiberglass block. 3b shows the probe hanging from the piston next to the gallium reservoir.

We were able to test the contact made by the probe to determine the accuracy of the piston movements and if the circuit would be completed by the contact. We experimented with a brass probe on liquid gallium and a steel probe on both liquid gallium and a solid copper block for a control since the height of the block would not change. We discovered that there is a 0.68-millimeter recoil when changing piston directions. This could be a result of small spaces between the gears that move the piston. The data from the calibration testing is shown below in TABLE 1:

TABLE 1: Surface Contact Calibration with brass and steel probe to determine wetting and recoil.



	Brass Tip Probe		Steel Tip Probe			
	Liquid Gallium Contact Surface		Liquid Gallium Contact Surface		Copper Block Contact Surface	
Measurement	Height (mm)	BreakHeight (mm)	Height (mm)	BreakHeight (mm)	Height (mm)	BreakHeight (mm)
1	18.809	20.263	61.3813	62.4996	67.9323	68.196
2	19.1145	20.0846	61.4212	61.8235	68.1945	68.6964
3	19.2087	Raised to 21	61.7871	62.2981	68.01	68.6948
4	19.2063	Raised to 20.5			68.0128	68.6937
5	19.2458				68.013	68.6993
6					68.0125	68.7
7					68.006	68.7028
8					68.0001	68.6997
9					67.9989	68.7255

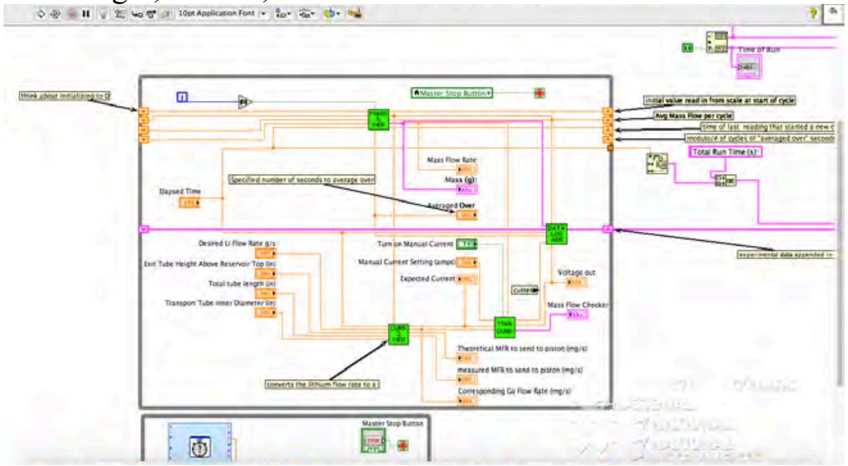
The last piece of the internship was writing code so that all the individual components of the feed system could work simultaneously in one user friendly program. The program would be able to be used with correct flow rates and current if lithium was used instead of gallium and be able to respond to the changes in mass flow rates and propellant surface level in the reservoir. I began by writing code to send out a voltage signal that would control the power from the Acopian power source. Because LabView can only send out 0-10 volts and the power supply can supply 70 amps, I wrote a program to correspond the voltage from LabView to the voltage the power supply read in to produce the high current levels. We determined the correct amount of current for a desired flow rate from the work the previous intern Jeremy Mehl had done in his thesis [2]. The conversion is shown below in FIG 4:

FIGURE 4: Calculation of current (I) necessary for a flow rate based off of reservoir height (h), friction loss coefficient (k), magnetic field in the pump (Bs), viscosity (μ**),** transport tube length (L), and tube diameter (D).

$$I = \frac{1}{B_s}\left[\frac{\left(\frac{4(1+k)\dot{m}}{\pi} + 32\mu L\right)^2 - (32\mu L)^2}{2\rho(1+k)D^4} + \rho g h\right]$$

We wanted the pump to deposit the propellant into a beaker that was placed on a measuring scale. The scale provides an initial mass flow rate measurement that corresponds to the speed piston-probe system should be set to, and allows for verification of the mass flow rate detected with the probe. For that set up, I wrote a program that read in the value displayed on the scale and to sent it to LabView so that we could view and manipulate the mass flow rate. The scale did not easily work with the Mac computer or with LabView, so I ended up downloading a driver for my computer and wrote a python code that could speak to the scale and display the value from the scale on the terminal in real time. Next I wrote a python code which converted a desired lithium mass flow rate to the corresponding mass flow rate and displayed the amount of current necessary to achieve that flow rate through the pump using the above conversion. I then made a LabView program that used the expected current and real time scale reading to control the mass flow rate. Lastly the program sent the data to a user specified file so that the experimental data could be logged. The last major piece of the program I wrote was code to detect when contact had been made by the probe, start and stop the piston accordingly, and report the mass flow rate detected by the piston-probe assembly the main code is shown in FIG 5.

FIGURE 5: The main LabView program that keeps track of mass, expected and actual mass flow rates, and current needed based on input parameters such as propellant, tube length, and reservoir height, contact,



During the Final week of the eight-week internship we attempted to test the entire feed system with the new programing and mass flow rate detection system. We found that were unable to use the code to drive the propellant through the pump at high flow rates, so in order to test the pump we connected it to a large power source and ran 100 amps through it. Instead of pushing the liquid gallium out of the exit tube as should have happened we noticed gallium began to leak from the seams of the metal casing of the JxB pump, which suggested that the fittings inside the pump were not the right size, or that the metal casing of the pump had warped. We were unable then to gather data during my time on the full feed propellant system because of the malfunctioning pump. However after I had left, William opened up the pump and found that the O-rings were about 0.01 inches shorter than the O-ring grooves. Thus they did not seal the tubes properly. Also, the magnets in the pump were not as long as the chamber they were fitted for, so they were sticking to the steel sides rather than sitting in the middle of the chamber. This could have reduced the B field by a factor of about 2, which would be why we needed much more current than we expected to use for a given flow rate. Lastly, Will found that one of the magnets was partially dissolved by gallium. To fix these issues, he made metal inserts to push the magnets to center and ordered new O-rings. When the pump is fixed, it will be possible to test the full system once again using the set up shown below.

FIGURE 6: This is the full set up of the mass propellant feed system in the vacuum tank. It can be controlled via LabView and can be set to adjust the current and piston speed autonomously to achieve the desired flow rate. The heating coils around the pump are to keep the propellant in liquid state.

Acknowledgements

Although I was unable to test the full set up of the new mass propellant feed system. I was still very rewarded by my time spent in the lab at EPPDyL this summer. I learned a lot about plasmas and their potential uses and space travel. I also gained practical experience in machining and in graduate level research and experimentation for which I am incredibly grateful. I would like to thank Professor Choueiri and Dr. Sam Cohen for this opportunity, and I would like to thank William Coogan and Bob Sorensen for their assistance, direction, and support during my time this summer.

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