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Lithium Lorentz Force Accelerator: Lithium Feed System Redesign

Summer 2014 PPST Internship Report

During the summer of 2014, I worked as a research assistant in the Electric Propulsion and Plasma Dynamics Laboratory (EPPDyL) at Princeton University under the direction of Professor Edgar Choueiri. During my time in the lab, I worked on various projects, but I spent the majority of my summer working with two first-year graduate students, Will Coogan and Michael Hepler, to design an improved lithium feed system for the Lithium Lorentz Force Accelerator (LiLFA). This report will be concerned with the details of that design process.

Developing an accurate and reliable lithium feed system is important because propellant flow rate is a significant factor affecting thruster performance. If the rate of liquid lithium reaching the vaporizer cathode cannot be accurately measured, then it is not possible to precisely predict the thrust produced. Lithium is also highly reactive, so leaks can be potentially dangerous and can damage components. The reactive nature of lithium places severe material limitations on any parts that interface directly with lithium.

The current feed system was developed at EPPDyL and is a mechanically actuated system that uses a positive displacement pump. Solid lithium is loaded into the stainless steel reservoir and heated to its melting temperature of 180.5°C. Positive argon pressure is used to transport the lithium from the reservoir to the cylinder. Once the lithium is in the cylinder, a piston driven by a servomotor and a linear actuator pushes the lithium out of the cylinder and through stainless steel pipes to the thruster cathode. In order to prevent lithium from traveling back to the reservoir, freeze valves made of copper blocks with pipes carrying cold water freeze the lithium in the pipes. Similarly, to prevent additional lithium from leaking around the piston, the cooling loop around the cylinder freezes any lithium that reaches above a certain level.

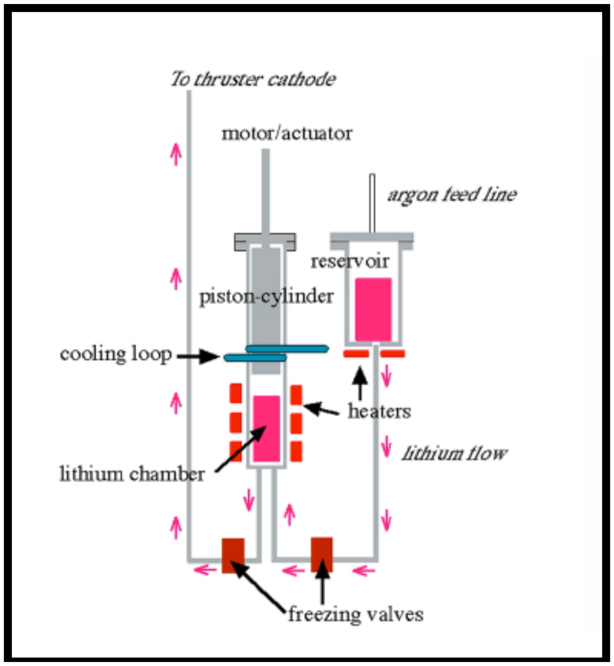

Figure 1: Diagram of current lithium feed system

The advantage of the current lithium feed system is that it is simple to determine the flow rate because it is only a function of the piston speed, the inner diameter of the cylinder, and the density of lithium. All three of these quantities can be known to a high degree of accuracy. The disadvantages of the current system are that it is complex and prone to leaks around the piston. The cooling loop succeeds in limiting the size of these leaks, but it also causes the piston to shear through frozen lithium around the inside of the cylinder. This causes the servomotor to exert a large amount of torque that can potentially damage important components.

The objective of the redesigned lithium feed system is to measure and control lithium flow rates of 8-25 mg/s to the thruster cathode. The reservoir must be detachable and it must be possible to load 130 grams of solid lithium into the reservoir within the Lithium Handling Facility, a 0.5 m^3 stainless steel glove box. Lithium will react with the moisture in the air, so it is necessary to seal the lithium inside the reservoir and keep it airtight until it can be installed into the feed system and placed under argon pressure. The solid lithium must then be heated to a melting temperature of 180.5 °C before it can be transported to the cathode. The goals of the redesign were to control mass flow rates with a resolution of ≤ 0.5 mg/s and measure mass flow rates with accuracy of ± 0.25 mg/s.

We decided that an electromagnetic (EM) pump would suit our needs because liquid lithium is electrically conductive. There are various configurations for EM pumps, but they all function according to the same principle. If a magnetic field is applied perpendicular to an electric current passing though a conductive liquid, then a force will be applied to the liquid that is perpendicular to both the magnetic field and the current. There are two main types of EM pumps: induction pumps, where a current is induced in the liquid, and conduction pumps, where a current is directly applied to the liquid.

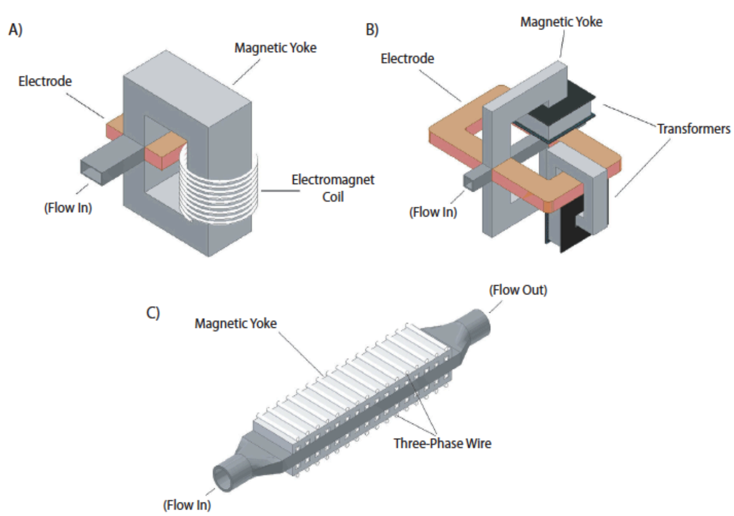

Figure 2: Examples of types of EM pumps A.) A direct current conduction pump B.) An alternating current conduction pump C.) A flat linear induction pump

Much of the research into EM pumps has been for the purpose of designing cooling systems for nuclear reactors, because molten sodium is often used as a coolant. Research has also been performed at the NASA Marshall Space Flight Center for the purpose of developing an EM pump and flow sensor for a lithium-fed thruster. The researchers, Kurt Polzin and Thomas Markusic, concluded that a direct current conduction pump presented the best design option because it is simple and compact. I also considered an induction pump based upon rotating magnets because researchers at PPPL had recently constructed one to transport liquid lithium to an experiment, but eventually came to the conclusion that a DC conduction pump would be cheaper, easier to construct, and more suited to our flow rate regime.

By integrating over the volume of the pump and assuming that the current, magnetic field, and fluid flow are all uniform throughout the channel, it is possible to calculate the pressure generated by a DC conduction pump.

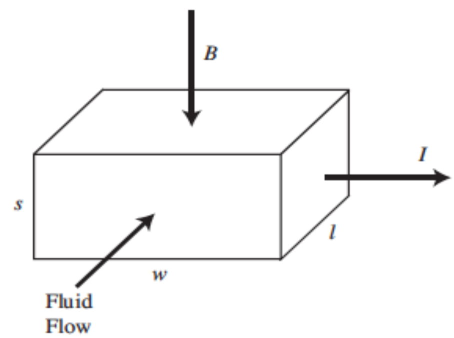

Figure 3: Idealized schematic of a DC conduction pump

$$\left|\vec{F}\right| = \int \vec{j} \times \vec{B} d^3x \tag{1}$$

$$F = \frac{I}{ls} Blsw = IBw \tag{2}$$

$$P = \frac{F}{sw} = I\frac{B}{s} \tag{3}$$

The pressure, P, is equal to the current, I, multiplied by the magnetic field strength, B, divided by the height of the channel, s. A flow sensor works by the inverse principle. When an electrically conductive liquid moves perpendicular to an applied magnetic field, an electric field is produced.

$$\vec{E} = -\vec{u} \times \vec{B} \tag{4}$$

$$V = uBw \tag{5}$$

$$V = \frac{B\dot{m}}{s\rho} = \frac{B}{s}\dot{\upsilon} \tag{6}$$

The voltage produced, V, is directly proportional to the volumetric flow rate, $\dot{\upsilon}$, multiplied by the magnetic field strength, B, divided by the height of the channel, s. These equations are independent of the conducting properties of the fluid. Both the pump and the flow sensor are defined by a constant B/s value. The greater the B/s value, the greater the pressure produced by the pump and the greater the voltage induced by the flow sensor. In both devices, the magnetic field is provided by two permanent magnets. Polzin and Markusic concluded that the maximum achievable B/s value was on the order of 10 T/cm. For the pressures needed from the pump, this implied that we would need to provide current on the order of 10 amps to the pump, which is reasonable. For our flow rates, however, the maximum achievable B/s value implied that we would need to read voltages on the order of microvolts. We concluded that this was not feasible because there is no equipment in the lab capable of detecting voltages that small and because the large voltages produced by the thruster would generate noise that would drown out the signal. We decided to use a DC conduction pump to control the flow rate, but decided that the flow sensor would be unable to measure such small flow rates. Instead we chose to measure flow rates during the experiment by tracking the level of the lithium with the servomotor and linear actuator used in the current feed system.

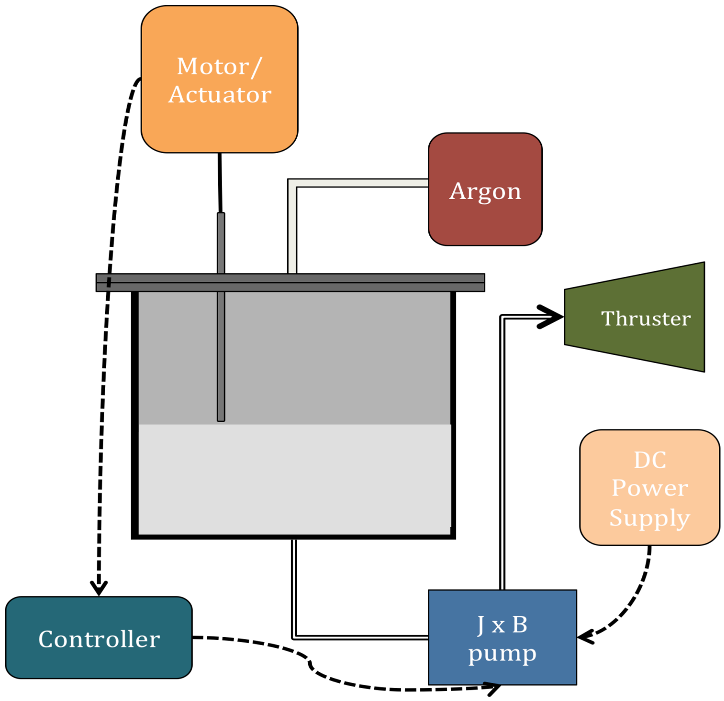

Figure 4: Proposed feed system redesign

In designing the conduction pump, I looked at two different prototypes created by researchers at NASA. The first one was designed specifically for the purpose of transporting lithium to a lithium-fed thruster. The second prototype was designed to transport NaK coolant to a nuclear reactor on the lunar surface. NaK has similar reactivity to lithium, so the pump design faces the same material limitations.

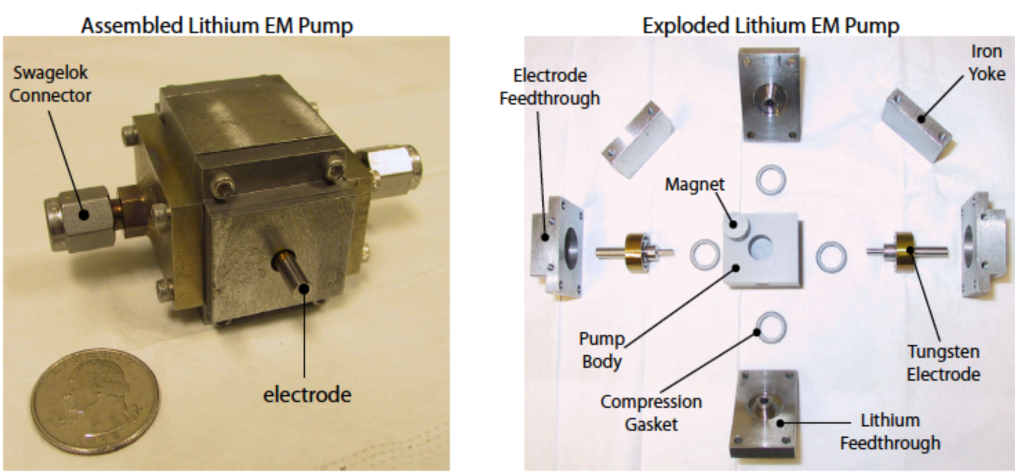

Figure 5: Lithium conduction pump prototype for a lithium-fed thruster

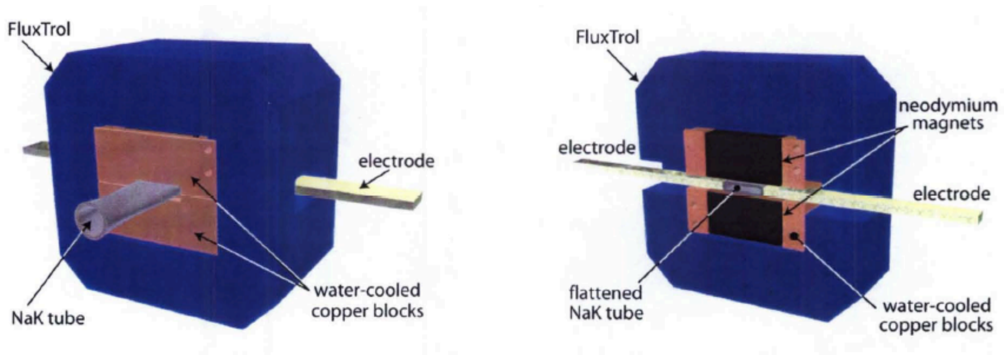

Figure 6: NaK conduction pump prototype for lunar nuclear reactor

Both pumps are compact and use permanent magnets to supply the magnetic field. The lithium pump uses samarium cobalt magnets, which have a Curie temperature higher than the melting temperature of lithium. The NaK pump uses neodymium magnets, which have greater magnetic strength, but also a lower Curie temperature and must be actively cooled in order to avoid demagnetization. In a DC conduction pump, current conducting through the walls of the channel, rather than the liquid, reduces the efficiency of the pump. In order to reduce conduction through the walls of the pump, the lithium pump has an aluminum nitride body. Aluminum nitride is a ceramic that has a very low electrical conductivity and is resistant to corrosion by lithium. The NaK pump uses a flattened stainless steel pipe to transport the fluid. I had intended to construct a pump that borrowed ideas from both of these designs, incorporating samarium cobalt magnets for their high Curie temperature, but not including an aluminum nitride body because it is prohibitively expensive. Ultimately, however, Kurt Polzin at NASA agreed to lend the lithium pump prototype to EPPDyL for use with the LiLFA, so such a design was unnecessary. If the pump needs to be sent back to NASA though, I believe that my design would be a cost-effective replacement.

In order to size the DC power supply needed for the pump, I had to calculate the pressure required from the pump given our desired flow rates.

$$Total\ pressure = \rho gh + \frac{1}{2}\rho v^2 + \frac{128\mu LQ}{\pi d^4} + k\frac{1}{2}\rho v^2 \quad (7)$$

The pressure needed to lift the lithium from the reservoir to the thruster, also known as the static lift, was orders of magnitude greater the pressure required to overcome friction losses along the length of the pipe. This meant that the pump would not be able to control the flow rate with a large amount of precision because small changes in pressure would result in large changes in flow rate. In order to increase the friction losses such that they were of the same order of magnitude as the static lift, I considered constructing a throttling gate valve similar to a design implemented by Kurt Polzin at NASA. Commercially available gate valves would not be suitable because lithium would destroy the rubber gaskets, so the device would need to be hermetically sealed with a metallic bellows. I concluded, however, that it would be easier and simpler to just add a length of very small stainless steel tubing to the fuel line, just before the thruster cathode.

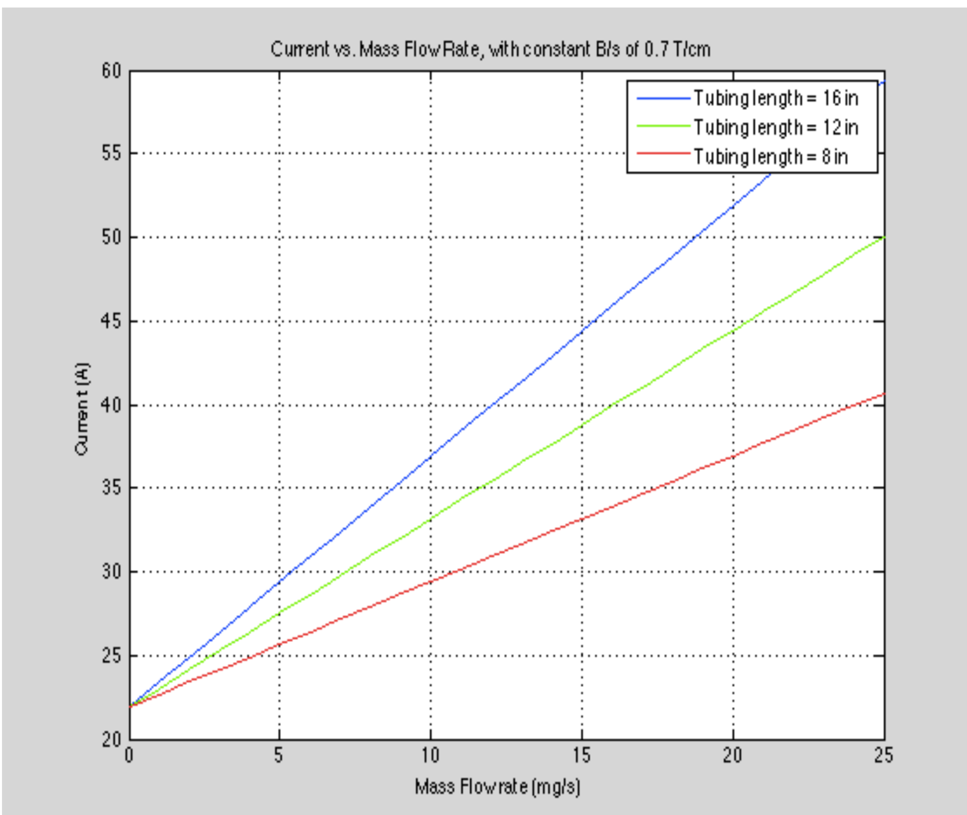

Figure 7: Current vs. Mass Flow Rate for various lengths of stainless steel tubing

The small inner diameter of the tubing increases the friction losses and allows for greater control of the flow rate. Increasing the length of the tubing increases the losses further and allows for a greater range of currents over which to achieve the desired flow rate of 8-25 mg/s. The band heaters normally used to heat the pipes and prevent lithium from freezing in the fuel line are too large for the smaller tubing, but the cathode heaters produce a large amount of heat. By placing the stainless steel tubing at the end of the fuel line, right before the cathode, the lithium should remain a liquid.

The DC current power supply for the conduction pump is probably the most expensive component required for the redesigned feed system. The power supply must have a large enough range of currents to provide flow rates from 8-25 mg/s and a resolution small enough to control flow rates within 0.5 mg/s. We did not purchase a power supply, but we did find a number of models that appeared to fit our needs.

The feed system must not only be able to control the flow rate, but it should also be able to directly measure the flow rate. It may be possible to calibrate the pump and determine which currents correspond to which flow rates, making in situ measurements unnecessary. Our goal, however, was to be able to measure the flow rate during operation of the feed system. After ruling out the EM flow sensor, we decided that we could measure the flow rate by repurposing the servomotor and linear actuator currently used to control the piston. Instead of forcing the lithium out of the cylinder, we could track the level of the lithium with a probe. The probe would be a pointed stainless steel rod connected to the linear actuator. The probe would be lowered until it came into contact with the lithium. Lithium is electrically conductive, so it would be possible to complete a circuit whenever the probe came into contact with the lithium. By using the probe as a switch, we can instruct the actuator to lower the probe until it comes into contact with the lithium and to then stop until the contact is broken. In this way, we can take a series of position measurements of the lithium level in the reservoir over time. We can then estimate the velocity by assuming that it is constant between measurements. In this way, we could measure the lithium flow rate during thruster operation.

The accuracy of this method depends on the interaction of stainless steel with liquid lithium and the resolution of the servomotor/actuator system. Lithium does not wet stainless steel at temperatures below 315°C, so the lithium should not cling to the probe and should allow for repeated measurements over a short period of time. Because stainless steel is a hydrophobic surface, it will deflect the lithium a small amount and make it difficult to get an absolute measurement of position. Yet it is only necessary to measure the relative change in height between measurements in order to approximate the velocity, so this should not present a problem. Regarding the resolution of the servomotor/actuator system, it has a very high gear ratio that translates 79 rotations of the servomotor into 1 mm of downward motion. The servomotor encodes its position with 16 bits. That means that the linear actuator should have a resolution of 1.97×10^{-7} mm. Given our mass flow rates, we can expect the lithium level in the reservoir to move at a rate of 0.003-0.009 mm/s, so the linear actuator could ostensibly take many position measurements per second. Such an incredibly small resolution may be possible in theory, but is almost certainly not achievable in practice. For this reasons, we intend to experimentally verify our technique to establish its feasibility. We intend to test the system with gallium, which is a conductive liquid that does not have the reactive properties of lithium and is easier to handle. We will empty gallium into a bucket on a digital scale and track the height of the gallium as it leaves the reservoir. By numerically differentiating the accumulation of mass, we can acquire an independent measurement of the mass flow rate and compare it to the flow rate determined by the servomotor/actuator measurement system.

Figure 8: Servomotor, gearbox, linear actuator

The next steps for the lithium feed system redesign will be to conduct the validation experiment with gallium to determine if the flow rate measurement technique is feasible. If the system is feasible, then a DC power supply should be purchased for the conduction pump. The entire system will then need to be calibrated to ensure that it provides accurate control and measurement of the lithium flow rate.

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