Lithium Hollow Cathode for a Very High Isp Interstellar Precursor Ion Thruster

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Dan M. Goebel¹, Giulia Becatti² and Ryan Conversano³
Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109 USA

and

Kenneth Marsh⁴ and Chand Joshi⁵
University of California, Los Angeles, Los Angeles, CA 90024

Abstract: An ion thruster that produces a specific impulse of the order of 50,000 s is in development for a propulsion system that enables very high delta-V (up to 200 km/s) deep space missions. Such a thruster could potentially be used in interstellar precursor missions and may enable rapid transportation throughout the solar system. The ion thruster must run on lithium in order to produce such a high Isp at reasonable acceleration voltages. The demonstration model thruster in development is a sub-scale, 50,000-s, lithium-fueled gridded ion thruster that will be tested at up to 50 kW input power. However, there is no long-life hollow cathode for this thruster that will work in lithium. This paper describes the design and testing of a lithium hollow cathode that uses a LaB₆ thermionic electron emitter and supporting materials specifically selected to be compatible with liquid and vapor-phase lithium. The cathode is designed to provide 50 to 75 A of discharge current continuously. The design is a derivative of the high current LaB₆ hollow cathodes under development at JPL for the past 10 years combined with a lithium reservoir and delivery system. Tests of the cathode in a small vacuum system at UCLA capable of handling lithium have demonstrated operation at discharge currents up to 25 A to date. Inspections have shown no adverse materials interactions with the LaB₆ emitter or refractor metals used in the construction. The operation and challenges of hollow cathodes using lithium are described.

Introduction

A 50,000 s specific impulse (Isp) ion thruster is in development¹ at JPL for a propulsion system that enables high delta-V (up to 200 km/s) deep space missions. This type of thruster can potentially be used in interstellar precursor missions² capable of delivering a New Horizons-sized spacecraft in a flight time of about 12 years to over 500 AU; a location where solar gravity lensing illustrated in Figure 1 can be used to image exoplanets³. The propulsion system and the beam-power system to run it has been described elsewhere⁴, and may also enable rapid transportation throughout the solar system. In order to achieve such high values of Isp without inordinately high voltages, the ion thruster must run on lithium as the propellant. Using acceleration voltages between 5 and 10 kV,
which have been previously demonstrated in high power ion thrusters, the thruster can accelerate the light lithium ions to very high exhaust velocities and thereby achieve high Isp. The demonstration model thruster in development is a sub-scale, 50,000-s, lithium-fueled gridded ion thruster that will be tested at up to 50 kW input power. However, there is no long-life hollow cathode for this thruster that will work in lithium.

Existing EP missions (DS1, Dawn, Psyche), and all of the recently proposed science missions to NASA, use xenon for propellant due to its inert nature, ease of ionization, and good storability (≈1 gm/cc). All ion and Hall thruster development programs that have used alternative propellants over the past 30 years have used a separate xenon feed system to operate the hollow cathode.

There are significant advantages to using other propellants for some missions. Ion and Hall thrusters have been demonstrated operating in other propellants such as iodine, bismuth and magnesium. Such liquid and solid metal propellants provide higher storage density (>5 gm/cc) that is desirable for cubesats and other missions. While lithium does not provide this level of storage density, it does enable very high Isp operation at reasonable acceleration voltages.

This paper describes the design and testing of a lithium hollow cathode that uses a thermionic electron emitter and supporting materials specifically selected to be compatible with liquid and vapor-phase lithium. The cathode is designed to provide 50 to 75 A of discharge current continuously. The cathode is a derivative of the high current hollow cathodes under development at JPL for the past 10 years. The thermionic electron emitter is lanthanum hexaboride (LaB$_6$), which we have found is compatible with lithium and other alternative propellants. The other parts of the cathode have to also be compatible with lithium, which is a significant challenge at the temperatures of over 1000 °C found throughout the cathode construction because lithium is very reactive with nearly all carbon and oxygen containing materials. The prototype version of this cathode uses only molybdenum, tungsten, tantalum and boron nitride in its construction. The lithium reservoir design is based on lithium oven technology where the solid lithium is loaded into the reservoir and is melted into a molybdenum mesh lining the walls where it is vaporized at temperatures above 500 °C. The cathode has successfully operated in a special lithium test facility at UCLA at up to 50 A of discharge current in argon and 25 A of discharge current in lithium to date.

I. Cathode and Reservoir Description

The biggest challenge in adapting conventional hollow cathode technology to lithium is the problem with materials compatibility. It is necessary select the materials that support and heat the thermionic cathode only with refractory metals and ceramics that don’t react with this propellant. A list of some candidate alternative propellants and their properties is listed in Table 1. Lithium is seen to have a very low ionization potential and reasonable melting temperature (180 °C). Cathode body materials that have been identified to be compatible with lithium are molybdenum, tungsten, tantalum, rhenium and TZM. Molybdenum was used exclusively for the cathode tube and flanges, and tungsten was used for the cathode orifice plate and keeper. Likewise, the lithium reservoir and vaporizer is made entirely of molybdenum. Fortunately, the materials that are compatible with lithium are also compatible with most of the other propellants listed in Table 1, so this cathode design is extendable to other alternative propellants.

Finding thermionic electron emitters that are compatible with lithium is also a challenge. The literature suggests that lanthanum hexaboride (LaB$_6$) does not react with lithium, so this electron emitter was selected for this cathode. Lanthanum hexaboride was first developed as an electron emitter by Lafferty in the 1950’s and its characteristics extensively described in our previous publications. Lanthanum hexaboride is a crystalline material made by press-sintering LaB$_6$ powder into rods or plates and then electron-discharge machining the material to the desired shape. Polycrystalline LaB$_6$ cathodes have a work function of about 2.67 eV depending on the surface stoichiometry, and

Figure 1. Proposed interstellar precursor mission to 500 AU to use the sun as a Gravitational Lens for imaging Exoplanets.
will emit over 10 A/cm² at a temperature of 1650 °C. Since the bulk material is emitting, there is no chemistry involved in establishing the low work function surface and LaB₆ cathodes are insensitive to impurities and air exposures that would normally destroy other cathodes. This feature appears to be also true for lithium. Inspection of the LaB₆ insert used in this cathode in lithium show no compatibility issues to date.

However, none of the refractory materials listed above that can be used with lithium can directly touch LaB₆ when it is hot due to diffusion of boron into the material. Normally graphite or carbon is used for this function, but carbon is not compatible with lithium and cannot be used. Based on the literature, it was reported that rhenium was compatible with LaB₆. Initial experiments of the cathode in argon using a rhenium foil proved this to be completely false. After an operation time of only ten’s of hours, the thin rhenium foil placed between the LaB₆ insert and the moly tube as a diffusion barrier completely disappeared, and the LaB₆ insert had crumbled into powder at the hottest end near the cathode orifice. Another material sometimes used in contact with LaB₆ is tantalum carbide, where the carbide surface on a tantalum foil acts as the diffusion inhibitor. The rhenium foil was replaced with a tantalum foil with a thin layer of carbon on the interfacing surface. The cathode was heated and the carbon reacted to form the thin surface layer of Ta-carbide in contact with the LaB₆. Examination of the foil and LaB₆ surfaces after operation in argon showed slight material transfer to the LaB₆ surface (a thin grey/silver coating), but the LaB₆ insert was intact and the cathode ran well. More work is needed to establish the life of this interface material, but it proved sufficient to date for operation for hundreds of hours to date without issue.

The cathode configuration follows previously developed LaB₆ cathodes. The moly tube, tantalum sheathed heater and LaB₆ insert are shown in Figure 2, where the 1.3-cm outside-dia. by 2.5-cm-long insert, the TaC foils and a BN pusher tube that slides inside the moly tube and pushes the insert against the tungsten orifice plate are seen. After the first test in argon, the BN pusher tube was replaced with a molybdenum pusher tube that was less fragile and easier to install and remove to inspect the insert.

The heater required to start the hollow cathode can also be an issue in lithium. For these tests we used a tantalum sheathed heater with powdered alumina insulation, shown in Fig. 2, that is capable of heating the cathode to over 1500 °C to start. At the mounting end of the cathode where the alumina is exposed, the heater is much cooler and so a ceramic paste was used to seal the heater end. This proved to work very well and no materials compatibility issues with lithium were observed with this heater. However, we have previously developed a heater based on a boron nitride insulator with a tantalum or rhenium filament that is compatible with lithium and other alternative

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass (AMU)</th>
<th>Ionization potential</th>
<th>Isp Relative to Xe</th>
<th>Melting Temperature C</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium</td>
<td>6.9</td>
<td>5.4</td>
<td>4.3</td>
<td>180.5</td>
<td>0.53</td>
</tr>
<tr>
<td>Krypton</td>
<td>83.8</td>
<td>14.0</td>
<td>1.3</td>
<td>-</td>
<td>&lt;0.9</td>
</tr>
<tr>
<td>Tin</td>
<td>118.7</td>
<td>7.3</td>
<td>1.05</td>
<td>232.9</td>
<td>7.3</td>
</tr>
<tr>
<td>Iodine</td>
<td>126.9</td>
<td>10.4</td>
<td>1.02</td>
<td>113.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Xenon</td>
<td>131.3</td>
<td>12.1</td>
<td>1.00</td>
<td>-</td>
<td>≈1</td>
</tr>
<tr>
<td>Cesium</td>
<td>132.9</td>
<td>3.9</td>
<td>0.99</td>
<td>28.4</td>
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<tr>
<td>Mercury</td>
<td>200.6</td>
<td>10.4</td>
<td>0.81</td>
<td>-38.8</td>
<td>13.7</td>
</tr>
<tr>
<td>Lead</td>
<td>207.2</td>
<td>7.4</td>
<td>0.80</td>
<td>327.5</td>
<td>11.3</td>
</tr>
<tr>
<td>Bizmuth</td>
<td>209.0</td>
<td>7.3</td>
<td>0.79</td>
<td>271.4</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Table 1. Alternative propellants of interest and their properties.

Figure 2. Cathode tube, heater, LaB₆ insert and TaC foil interface.
propellants and materials. The backup boron nitride heater configuration will be used in the next generation cathode tests.

To avoid the complications of installing an enclosed molybdenum keeper in these initial tests, the keeper consisted of a simple tungsten loop positioned downstream of the cathode orifice. The cathode downstream end with the heater and keeper installed is shown in Figure 3. Note that the tantalum heat shield normally wrapped around the heater is not shown in this photo, but was installed prior to operation of the cathode.

The reservoir is based on lithium-ovens designed for plasma generators developed at UCLA for advanced particle accelerator structures. It consists of a 2.5-cm dia., 20-cm long molybdenum tube with two to three layers of moly mesh wound onto the inner surface. The mesh serves to capture the molten lithium in the reservoir when heated to temperatures of over 300 °C, and to wick the liquid lithium to the hottest regions where evaporation occurs. The reservoir is surrounded by a heating element capable of up to 500 W of power, and includes a gas feed line connected to a high temperature valve to enable starting of the cathode and testing in argon. Operation at only 280 W of input power produced the desired 750°C reservoir temperatures anticipated for operation of the cathode in lithium. The reservoir holds enough lithium for hundreds of hours of operation, sufficient for initial testing of the cathode and the thruster. The reservoir tube is e-beam welded to a molybdenum flange and connected to the cathode tube by clamping together with the moly tube at the end of the cathode tube. The entire cathode/reservoir assembly is shown in Fig. 4 with the stainless steel heat shield installed on the reservoir heater and the tantalum foil heat shield installed on the cathode.

II. Testing Results

The lithium hollow cathode was run first at JPL in argon to check that the cathode and heaters worked properly. After fully outgassing the heaters and cathode assembly, the cathode discharge was run up to 75 A at 25 V, and the reservoir system was heated to 800°C. The cathode was then installed in the turbo-pumped test facility at UCLA, shown in Fig. 5, and operated in argon to validate that the design still worked properly. The cathode ran easily at the maximum current of their power supply of 50 A at 25 V with about 15 sccm of argon flowing. The reservoir heater was also run at 800 W successfully.

In the argon testing, the chamber was originally oriented vertically, as seen in Fig. 5, and the anode was a flat molybdenum plate. To run in lithium, we decided to install a cooled baffle plate over the turbopump port to keep lithium out of the pumps, and to install a water cooled anode to trap as much lithium as possible during running to facilitate cleanup during openings of the vacuum.
system. This required that the chamber be turned on its side, as shown in Fig. 6. The anode assembly, shown in Fig. 7, was installed from the right side in in Fig. 6, and isolated from the chamber ground and held at 20°C by a recirculating water cooling system.

The cathode was dismounted from the reservoir and about 5 gm of lithium was loaded into the reservoir under an argon purge. The cathode/reservoir system was reassembled and the assembly inserted from the left side of the chamber in Fig. 6 with the cathode exit positioned about 10 cm from the anode opening. A scanning Langmuir probe was also installed in the chamber to measure the plasma parameters in the discharge in between the cathode and anode assemblies. The chamber was pumped down into the $10^{-7}$ Torr range and the cathode discharge started in argon. First attempts to heat the reservoir and deliver lithium to the cathode failed to achieve significant lithium flow. This was attributed to the argon gas flow from the injection valve upstream of the reservoir through the reservoir, which tended to impede the lithium flow in a manner similar to the gas buffers used in lithium ovens.

For the second attempt to run in lithium, no argon was used and we heated the lithium reservoir to a temperature of 500°C where the vapor pressure is below $10^{-2}$ Torr and then turned on the cathode heater and applied the 300 V keeper voltage. The reservoir heater power was then increased until the reservoir reached about 700°C corresponding to a vapor pressure of about 0.5 Torr, where the keeper discharge ignited. The keeper was run at 2 A of current and operated between 6 and 12 V DC depending on the lithium reservoir temperature.

The discharge power supply was then turned on and the discharge transferred to the anode. The discharge was run at a maximum of 25 A at 12 V in lithium, shown in Figure 8. Lithium has a characteristic deep red color, and the discharge was very bright in spite of lithium condensing on the windows during operation. The discharge current in these tests was not very stable and drifted from low current (<1 A) to the maximum we tested (25 A) over seconds to minutes. This unstable operation was due to varying lithium flow through the cathode due to a problem with leakage between the reservoir and cathode flanges, and due to the formation of some insulating layers of lithium oxides on the cooled anode surface. The interface region between the reservoir and the hollow cathode tube is problematic due to differences in the tube sizes and the mounting flanges, and a redesign is planned to ensure that the lithium flow is not impeded in this region. Once the windows became relatively opaque from lithium condensation, the discharge was turned off and the reservoir allowed to cool.

The cathode and facility were disassembled and inspected. Figure 9 shows the cylindrical anode after operation, which is coated with lithium. However, the lithium was not collected just by the...
cooled anode and baffle plate as desired, but coated most of the chamber and windows. Some of this is due to the leakage observed at the interface between the reservoir and the cathode, but some was just lithium migration. The lithium surfaces in the facility easily oxidizes, and the base pressure in the chamber likely led to some oxidation on the anode before and during operation. Allowing the anode to run at elevated temperatures may be required to avoid the formation of insulating layers during operation and lithium deposition. Careful cleaning of lithium between operations of the cathode and good chamber base pressures are also likely required to achieve stable lithium plasma discharges.

The cathode was fully disassembled, cleaned of lithium, and inspected. The LaB$_6$ insert was removed from the cathode and found to be virtually unchanged from the as-new part. There was no evidence of chemical reactions or problems after operating in lithium with the LaB$_6$ insert, which is an excellent result. While the insert was exposed for only some ten’s of hours to lithium vapor while hot, it appears to be able to run in lithium without significant problems.

![Figure 9. Anode assembly shown after operation coated with lithium oxide.](image)

III. Conclusion

A lithium hollow cathode based on an LaB$_6$ thermionic electron emitter was constructed and successfully operated in lithium at discharge currents of up to 25 A. The lithium reservoir system design is based on lithium oven technology, and was able to provide sufficient lithium flow to the hollow cathode discharge. Problems with lithium flow stability, lithium leakage from the mid-region of the cathode, and lithium oxidation on the anode surface led to unstable discharge currents. Since the LaB$_6$ insert and the reservoir system survived these tests, upgrades to the interface region between the reservoir and cathode, modification of the anode temperature, and better vacuum practices are anticipated to solve these problems. These changes are in work and results will be reported in the near future at higher discharge currents and for longer operation times.

Acknowledgments

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References


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