Development of a 50,000-s, Lithium-fueled, Gridded Ion Thruster

IEPC-2017-042

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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The ion propulsion system on NASA's Dawn mission provided over 11 km/s delta-V to the spacecraft. There is potential interest in missions that have delta-V's an order of magnitude greater than this, i.e., 100 km/s to 200 km/s. To perform such missions would require a thruster that can produce a specific impulse roughly an order of magnitude greater than the 3100 s of the Dawn ion propulsion system. A 50-kW gridded ion thruster is being developed for operation with lithium propellant to produce a specific impulse of 50,000 s. The resulting thruster design requires a net accelerating voltage of 9 kV and a beam current of 5.5 A. Discharge chamber modeling is used to design a 35-cm diameter ring-cusp discharge chamber with six magnet rings. The discharge chamber is masked down to produce an active grid area that is ~25 cm diameter. Modeling suggests that the unique ionization characteristics of lithium may enable discharge chamber operation at a propellant efficiency of 99%. Operation at such a high propellant efficiency could significantly reduce the production of charge-exchange ions and thereby significantly reduce erosion of the accelerator grid.

I.Introduction

The highly successful Dawn mission to the giant asteroid (4) Vesta and the dwarf planet (1) Ceres was enabled by its ion propulsion system that provided more than 11 km/s delta-V to the spacecraft [1]. This is by far the largest delta-V provided by any onboard propulsion system, ever. However, there is a class of possible future missions with characteristic velocities an order of magnitude greater than this, in the range of 100 km/s to 200 km/s. Such missions include traveling out to 550 AU from the sun—the distance at which solar gravity lensing could be used to image exoplanets [2]—in less than 15 years; a Pluto orbiter mission with a flight time of less than 4 years; or even human missions to the Jovian system. For such extremely high delta-V missions, the rocket equation requires a corresponding increase in specific impulse. Consequently, we have initiated the development of an ion thruster that can provide a specific impulse of 50,000 s, roughly an order of magnitude greater than that of the NEXT ion thruster [3].

To achieve such a high specific impulse lithium is used as the propellant in a gridded ion thruster. Lithium's low atomic mass enables a very high specific impulse at reasonable net accelerating voltages. For example, with lithium a voltage of about 9 kV will produce a specific impulse of about 50,000 s. To achieve the same specific impulse with xenon would require a voltage of roughly 170 kV. In addition, lithium may be stored as a solid, is easily ionized, and is very difficult to doubly ionize. Lithium's ionization properties should enable thruster operation at nearly 100% discharge chamber propellant efficiency, minimizing neutral gas leakage from the thruster. This minimizes production of the charge-exchange plasma that is responsible for accelerator grid erosion and current collection on the spacecraft's photovoltaic arrays.

A 50,000-s Isp ion thruster is a key element of a propulsion system architecture that is currently being investigated under a NASA Innovative Advanced Concepts (NIAC) study. This propulsion system architecture may provide the ability to perform missions with characteristic velocities of 100-200 km/s providing rapid transportation throughout the solar system and even into the near interstellar medium. The key features of any system for rapid space

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transportation is the ability to process a lot of power with little dry mass, combined with the ability to provide a very high total spacecraft velocity change without a lot of propellant. These two requirements translate into the need for a very low specific mass (kg/kW) and a very high specific impulse. The NIAC study is designed to investigate the feasibility of a conceptual propulsion system architecture that may enable spacecraft specific masses as low as 0.25 kg/kW and specific impulses of 50,000 s or more. For comparison, the specific mass of the Dawn spacecraft is about 300 kg/kW at a specific impulse of 3100 s. The ultra-low specific mass in this conceptual system assumes that the power source and most of the power conversion hardware are removed from the spacecraft and are replaced with a lightweight, photovoltaic array in a direct-drive configuration. The photovoltaic array would output electric power at 9 kV, the voltage needed to directly-drive a lithium-fueled, gridded ion thruster system at a specific impulse of 50,000 s. In this conceptual architecture, power is supplied by a very large, very high power laser that beams power across the solar system to the spacecraft and is collected by the photovoltaic array with cells tuned to the laser frequency. The laser is based on concepts such as those being developed by Lubin for interstellar mission concepts[4]. The resulting Laser Electric Propulsion (LEP) system architecture would have the following three key features:

1. A very high-power laser array that beams power across the solar system increasing the power density of photons to the spacecraft's photovoltaic array by approximately two orders of magnitude relative to solar power at all solar ranges.
2. A light-weight, photovoltaic array with 70% efficient cells tuned to the laser frequency producing output power at 9 kV.
3. A multi-megawatt, direct-drive, lithium-fueled ion propulsion system with a specific impulse of 50,000 s.

This paper describes the design of a 50-kW, lithium-fueled gridded ion thruster for operation at a specific impulse of 50,000 s, including plans for its fabrication and test. Successful development of this thruster would be a key part in the development of a capability to perform missions with characteristic velocities greater than 100 km/s.

II.Lithium Ion Thruster

The design and development of a lithium-fueled, gridded ion thruster presents a unique set of opportunities and challenges. The opportunities result from the unique ionization characteristics of lithium and the challenges arise from the need to identify materials that are compatible with lithium at elevated temperatures. The preliminary design of a 50-kW, 50,000-s, lithium ion thruster that deals with these opportunities and challenges is described below.

A. Ion Optics Design for 50,000-s Isp Operation

The design of any new gridded ion thruster begins with the ion accelerator system since this component processes most of the power input to the thruster. As mentioned above, for a specific impulse of 50,000 s a net accelerating voltage of about 9,000 V is required. To achieve the desired thruster input power of 50 kW, a beam current of roughly 5.5 A is necessary. Preliminary scaling is accomplished by assuming a maximum electric field between the grids in a two-grid system of 2500 V/mm, a net-to-total voltage ratio of 0.90, a uniform plasma upstream of the ion optics, and limiting the perveance to 53% of the theoretical maximum value. This scaling results in a required active grid size of about 25 cm diameter with a total of 360 grid apertures and a current of 15 mA per aperture. The resulting thruster would produce a thrust of 195 mN at 50,000 s at an input power of 50.4 kW with an overall thruster efficiency of 0.95 (not including the neutralizer).

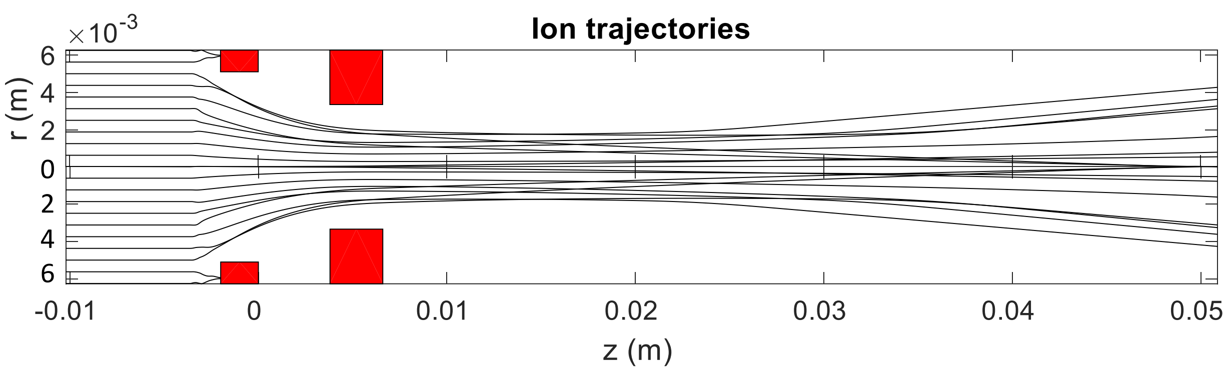

Figure 1. Ion optics design for operation at 50,000 s with lithium. Screen grid voltage = 9 kV, Accelerator grid voltage = -1000 V, 15 mA/aperture.

An axisymmetric two-dimensional ion optics code, CEX2D[5], was used to develop and evaluate a preliminary design of the ion optics. Ion trajectories from that code, given in Fig. 1, indicate operation well away from the perveance limit resulting in well-focused beamlets. For this geometry, beam voltage, and current per aperture, an accelerator voltage of at least -880 V is needed to prevent electron backstreaming. The ion trajectories in Fig. 1 were calculated assuming an accelerator grid voltage of -1000 V.

Erosion of the accelerator grid by charge-exchange ions is well known to be one of the major life-limiting mechanisms for gridded ion thrusters [6]. Resonant charge-exchange collision cross sections for lithium (from Sakabe and Izawa [7]) as a function of ion speed are compared to those for xenon in Fig. 2. This comparison indicates that the charge-exchange cross section for lithium at 50,000 s is not much greater than it is for xenon at 3000 s. Note, however, that at the same specific impulse, the charge-exchange cross section for lithium would be much greater than that for xenon. This is just one of many reasons why you wouldn't want to design a lithium-fueled gridded ion thruster for operation at specific impulses of a few thousand seconds.

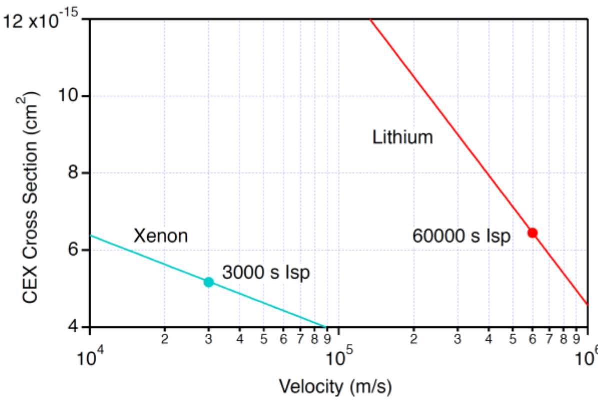

Figure 2. Charge-exchange (CEX) cross sections for lithium and xenon. At specific impulses in the range 50,000 s to 60,000 s the CEX cross sections for lithium are just slightly higher than that of xenon at 3,000 s.

Erosion of the accelerator grid from charge-exchange ions can be minimized by operating the discharge chamber at very high propellant utilization efficiencies. This may be possible due to the unique characteristics of lithium as discussed in the next section.

B. Discharge Chamber Design and Performance Modeling

A ring-cusp discharge chamber for operation with lithium was designed using the model developed by Goebel, et al [8]. To use this model the appropriate ionization and excitation cross section data for lithium are required. These cross sections are given in Figs. 3 and 4 where the corresponding cross sections for xenon are given for comparison [9-11]. It is noteworthy that the first ionization potential for lithium is 5.39 eV, or less than half that for xenon (12.13 eV). Significantly, the second ionization potential for lithium is 75.64 eV, roughly 3.5 times that for xenon (21.21 eV). These data suggest that lithium should be much easier to ionize than xenon and virtually impossible to doubly ionize. It also suggests that it should be possible to operate a lithium discharge with a very low voltage, in the range 15 V to 20 V.

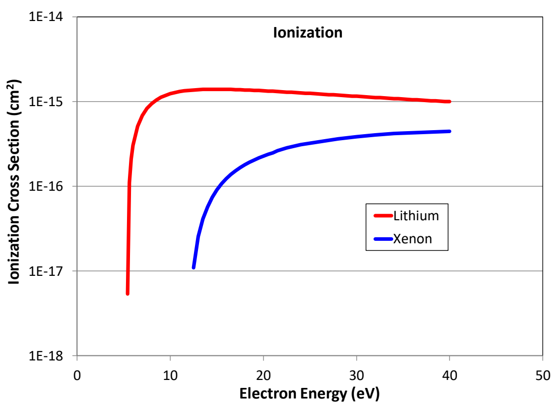

Figure 3. Lithium ionization cross section compared to xenon.

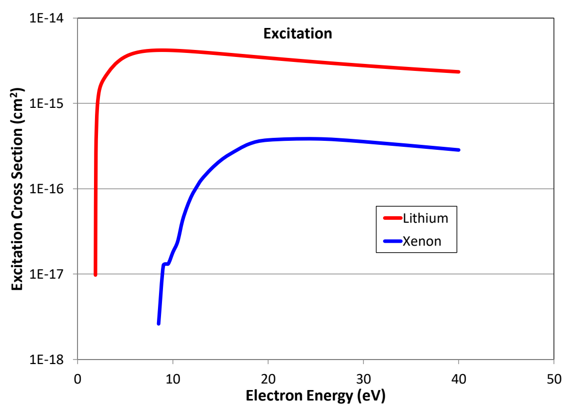

Figure 4. Lithium excitation cross section compared to xenon.

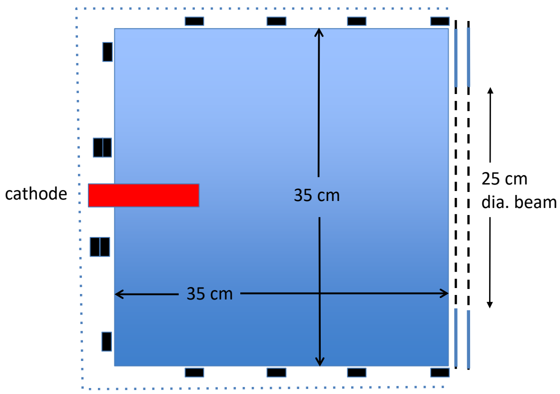

Figure 5. Conceptual configuration of a ring-cusp discharge chamber for a 50,000-s, 50-kW, lithium ion thruster.

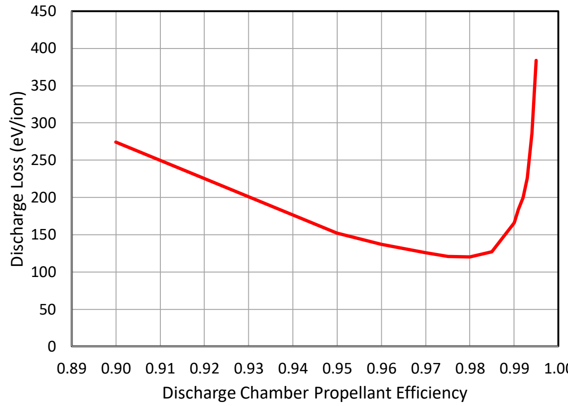

Figure 6. Calculated discharge chamber performance. The ionization properties of lithium may enable discharge chamber operation at propellant efficiencies of ~99%.

The resulting discharge chamber conceptual configuration is given in Fig. 5. This configuration has six rings of magnets and a discharge chamber diameter of 35 cm. The length of the discharge chamber is approximately equal to its diameter and the active grid area is masked down to 25 cm diameter. These features are designed to maximize the uniformity of the plasma density across the active grid area. The calculated discharge chamber performance is given in Fig. 6. This curve indicates a minimum discharge loss of about 120 eV/ion, at a discharge voltage of 17 V and a propellant efficiency of 98%. The unique ionization properties of lithium are believe to be responsible for the unusually shaped discharge chamber performance curve where the discharge loss increases significantly for values of the discharge chamber propellant efficiency less than the optimum at 98%. At lower propellant efficiencies, excitation losses play an increasingly important role, resulting in greater discharge losses. The curve in Fig. 6 also suggests that it may be possible to operate the discharge chamber with a propellant efficiency of 99% where the model indicates that the discharge loss will still be only about 160 eV/ion. At this discharge chamber propellant efficiency the neutral lithium atom density at the grids is expected to be of order $1\text{x}10^{17}$ m^{-3}, or about an order of magnitude lower than is typical for xenon ion thrusters.

C. Accelerator Grid Erosion

If the unique characteristics of a lithium plasma discharge can be exploited to enable operation at a propellant efficiency of 99%, then the resulting order-of-magnitude lower neutral atom density could result in an order of magnitude lower ion current to the accelerator grid. Erosion of the accelerator grid, however, depends not only on the flux of charge-exchange ions to the surface, but also on the grid material and the corresponding sputtering characteristics of lithium ions incident on that material.

Molybdenum, commonly used for the ion optics of xenon-fueled gridded ion thrusters, exhibits good compatibility with lithium. There appears, however, to be very limited actual sputter yield data for lithium ions on molybdenum available in the literature. Reference [11] gives the measured sputter yield for 400 eV lithium ions on molybdenum as approximately 0.11. Matsunami, et al. [12] provide a model for calculating sputter yields. The Matsunami model for lithium on molybdenum and xenon on molybdenum, along with the single data point from Martynenko [13], are given in Fig. 7. These calculations suggest that even with the more negative accelerator grid (-1000 V) required for

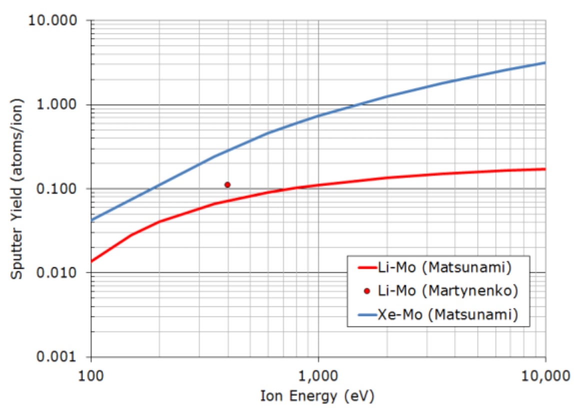

Figure 7. Sputter yields. Lithium ions incident on molybdenum are likely to produce sputter yields that are several times lower than xenon on molybdenum at the same energy.

thruster operation at 50,000-s Isp, the sputter-yield of lithium on molybdenum will be comparable to that of xenon on molybdenum for thruster operation at 3000 to 4000 s where acceleration grid voltages are typically in the -200 V to -300 V range.

D. Materials Compatibility with Lithium

Thruster materials must be chemically compatible with liquid lithium and lithium vapor, limiting the available choices for both conductive materials and insulators. In general the metals which are most resistant to attack by lithium at temperatures close to 1000 C are those of groups IVB, VB, VIB, and VIIB of the periodic table [14]. Specifically, molybdenum and tungsten have exhibited good compatibility with lithium. Insulator compatibility is more challenging. Most oxide-based insulator materials are incompatible with lithium. Fortunately, boron nitride (BN) appears to provide good compatibility with lithium vapor and will be used for all insulating surfaces that could come into contact with lithium.

E. Lithium Feed System

A flight lithium feed system would employ electromagnetic pumps and flow sensors with no moving parts [15]. For initial laboratory testing, however, we are developing a simpler feed system based on those successfully used for high power, lithium-fed MPD thrusters [16]. This system, shown schematically in Fig. 8, relies on delivering liquid lithium at a controlled flow rate from a stainless steel, bellows-sealed piston and cylinder to a vaporizer. The cylinder is loaded with lithium prior to testing from a reservoir which contains sufficient propellant for a single test. The reservoir is filled with solid lithium in an inert gas environment in a glovebox and then installed in the feed system inside the vacuum chamber. The reservoir is designed to be continuously purged with argon during pumpdown to prevent oxidation of the indium propellant.

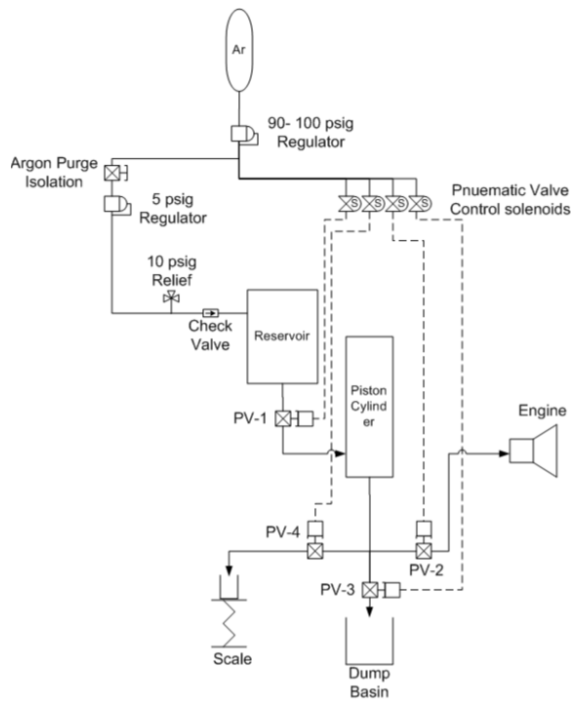

Figure 8. Laboratory lithium feed system schematic.

Once under high vacuum, the liquid feed system is heated to a temperature of about 200° C and a high temperature, pneumatically-actuated valve is opened, allowing liquid lithium from the reservoir to fill the cylinder. This valve is then closed, and a valve between the cylinder and the vaporizer is opened. A linear actuator drives the piston in the cylinder at a fixed velocity, delivering liquid lithium to the vaporizer at a controlled flow rate. The vaporizer consists of a cylindrical tantalum shell surrounding a tantalum cylinder with a spiral flow passage machined on its outer diameter and a swaged, coaxial heater, similar to those used in lanthanum hexaboride hollow cathodes [17], which is wrapped around the outer shell. The vaporizer is heated to about 1600°C, which transfers sufficient power to vaporize the liquid lithium as it flows through the spiral passage. The downstream end of the vaporizer will be attached to a gas manifold on the discharge chamber. Rather than tackle the challenge of making a propellant isolator that can operate at high temperature with lithium vapor at this point, we have chosen to float the entire feed system at the discharge chamber potential for laboratory testing. At the end of the test a third valve can be opened to drain any residual lithium from the feed system into a basin for disposal.

F. Vacuum Facility Preparation for Lithium Thruster Operation

In the mid 1990's JPL established a vacuum facility capable of testing condensable-metal propellants under the NASA's Advanced Concepts Program [18]. This test facility was designed to enable testing of multi-megawatt, steady-state, lithium-fueled, magnetoplasmadynamic (MPD) thrusters. The vacuum chamber, shown in Fig. 9, is 3 m diameter and 8 m long. It is equipped with a water-cooled liner capable of handling thermal loads up to 2 MW_{th}. The conically-shaped liner is 1.68 m in diameter at the upstream end, increasing to 2.44 m at the downstream end and is 5.16 m long. The liner provides 38 m^2 of surface area available to cropump the lithium exhaust resulting in an estimated pumping speed on lithium of 9,000,000 L/s. The vacuum chamber is also equipped with two 0.51-m diameter oil diffusion pumps to remove atmospheric gasses. For the lithium ion thruster described above, the maximum propellant flow rate is expected to be about 4×10^{-7} kg/s.

Beam power for the gridded ion thruster will be provided by an 80-kW power supply from Diversified Technologies, Inc. that can provide up to 10 A at 8000 V. This will enable thruster operation at a specific impulse of about 47,000 s and an input power of about 45 kW. Initial thruster testing is expected to begin in 2018 and will be performed using tungsten filament cathodes for both the main discharge cathode and the neutralizer. Subsequent testing will seek to replace these with LaB_6 cathodes designed to operate with lithium.

Figure 9. Vacuum chamber for testing electric thrusters with condensable-metal propellants, including lithium. The vacuum chamber is 3-m dia. by 8-m long. The water-cooled liner is 5.16-m long with a pumping surface area of 38 m^2 resulting in a lithium pumping speed of 9,000,000 L/s.

III. Conclusion

Development of an ion thruster with a specific impulse of 50,000 s would enable deep space missions with characteristic velocities in the range 100 km/s to 200 km/s. The use of lithium propellant enables specific impulses of tens of thousands of seconds at voltages less than roughly 10 kV. A 50-kW ion thruster has been designed for lithium propellant for operation at 50,000-s Isp. At 25-cm diameter, the active grid area of this thruster is comparable to the 5-kW XIPS ion thruster. Discharge chamber modeling suggests that it may be possible to operate the discharge chamber at a propellant efficiency of 99%. This would minimize charge-exchange erosion of the accelerator grid, possibly reducing it to a rate an order of magnitude less than state-of-the-art xenon-fueled ion thrusters.

Acknowledgments

The research described in this paper was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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