Low-Power Operation and Plasma Characterization of a Qualification Model SPT-140 Hall Thruster for NASA Science Missions

Charles E. Garner[1], Benjamin A. Jorns[2], Steven van Derventer,[3] and Richard R. Hofer[4]
Jet Propulsion laboratory, California Institute of Technology, Pasadena, CA 91109

Ryan Rickard[5], Raymond Liang[6] and Jorge Delgado[7]
SSL, 3825 Fabian Way, Palo Alto, CA 94303-4604

Hall thruster systems based on commercial product lines can potentially lead to lower-cost electric propulsion (EP) systems for deep space science missions. A 4.5-kW SPT-140 Hall thruster presently under qualification testing by SSL leverages the substantial heritage of the SPT-100 being flown on Russian and US commercial satellites. The Jet Propulsion Laboratory is exploring the use of commercial EP systems, including the SPT-140, for deep-space science missions, and initiated a program to evaluate the SPT-140 in the areas of low-power operation and thruster operating life. A qualification model SPT-140 designated QM002 was evaluated for operation and plasma properties along channel centerline, from 4.5 kW to 0.8 kW. Additional testing was performed on a development model SPT-140 designated DM4 to evaluate operation with a Moog proportional flow control valve (PFCV). The PFCV was commanded by an SSL engineering model PPU-140 Power Processing Unit (PPU). Performance measurements on QM002 at 0.8 kW discharge power were 50 mN of thrust at a total specific impulse of 1250 s, a total thruster efficiency of 0.38, and discharge current oscillations of under 3% of the mean current. Steady-state operation at 0.8 kW was demonstrated during a 27 h firing. The SPT-140 DM4 was operated in closed-loop control of the discharge current with the PFCV and PPU over discharge power levels of 0.8-4.5 kW. QM002 and DM4 test data indicate that the SPT-140 design is a viable candidate for NASA missions requiring power throttling down to low thruster input power.

I. Introduction

Since their introduction to the West in 1991, Hall thrusters have played an increasingly important role in electric propulsion research and applications. Their unique combination of performance, reliability, and simplicity have led to their wide use on commercial satellites for north/south and east/west station-keeping. Over 240 xenon Hall thrusters have been successfully flown since their first use on-board the Soviet satellite Meteor launched in 1971 [1] . Most of these Hall thrusters have been based on the Stationary Plasma Thruster (SPT) designed and manufactured at Experimental Design Bureau (EDB) Fakel, and include the SPT-70 and SPT-100 designs. In the West, communication satellite manufacturer SSL, based in Palo Alto, CA, has flown the SPT-100 on-board 17 commercial satellites and has accumulated over 40,000 hours of operating time and over 35,000 on-orbit firings. In

[1] Engineer, Propulsion and Fluid Flight Systems Group, MS-264-839.
[2] Engineer, Electric Propulsion Group, MS-125-126, member AIAA.
[3] Student, Academic Part Time Staff, Electric Propulsion Group, MS-125-126.
[4] Senior Engineer, Electric Propulsion Group, MS-125-126, Associate Fellow AIAA.
[5] Engineer, Power Electronics Group, MS-G17
[6] Senior Engineer, Research and Development, MS-G86, Senior Member AIAA.
[7] Electric Propulsion Architect, MS-G86.

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2011 the U.S. Air Force's Advanced Extremely High Frequency (AEHF) satellite was successfully placed into a geosynchronous orbit from a highly elliptical orbit around Earth using the spacecraft's Hall thruster station-keeping propulsion system [2] after the propulsion system originally intended for the orbit maneuver failed. Since then two additional satellites with Aerojet Rocketdyne XR-5 Hall thrusters on-board were successfully launched and operated. In 2003 the SMART-1 spacecraft was launched using a Snecma PPS-1350 Hall thruster for primary propulsion [3] for a lunar rendezvous, becoming the first mission to use electric propulsion in lunar orbit.

In addition to its use for station keeping of Earth-orbiting spacecraft, mission studies have shown Solar Electric Propulsion (SEP) to provide substantial reductions in overall system mass and cost for deep space missions and is enabling for the most hard-to-reach, scientifically compelling missions such as future rendezvous and sample return missions to asteroids and comets, a proposed Mars Sample Return Mission, and the proposed Asteroid Redirect Mission. For example, NASA's Dawn mission, which is part of the Discovery program, was enabled using an ion propulsion system for primary in-space propulsion that greatly reduced overall mission cost. Dawn's mission will end at a solar distance of approximately three astronomical units (AU) from the sun, and will be completed using just 402 kg of xenon to deliver approximately 11 km/s of delta-V to the spacecraft [4].

In order to provide a wide range of SEP options to the mission planning community proposing electric propulsion for competed missions, the Jet Propulsion Laboratory (JPL) has been investigating the applicability of commercial Hall thrusters to deep space missions. Key questions this study has sought to address pertain to identifying the stable throttling range of commercial thrusters over a power range required for deep space missions which spans operating points well below the nominal operating power of these thrusters. Further, thruster life for deep space missions, which typically require more than 10,000 h of operation for science missions, must be evaluated. Fundamentally different operating conditions for the thrusters, such as low-power steady-state continuous operation, and deep space environmental factors also must be considered. The study program contains both experimental and modeling efforts to address these key issues. The modeling work largely evaluates the lifetime question by simulating erosion of the cathode, discharge chamber walls, and pole piece surfaces. These modeling efforts must be advised by measured performance and plasma properties.

Fakel/SSL's SPT-140, introduced in the 1990s, leverages the successful flight operations and design heritage of the SPT-100. Operating at up to 4.5 kW, the SPT-140 is designed for greater total impulse in order to provide more extensive orbit-raising capability as compared to the 1.35 kW SPT-100 [5]. Older versions of this thruster were evaluated in 1997 [6,7] and 2000 [8]. A newer version of the SPT-140 is undergoing flight qualification and testing at EDB Fakel and SSL. Both a life test thruster and a systems test thruster have been built for qualification activities. The latter has completed plume characterization and performance testing at NASA Glenn Research Center and the Aerospace Corporation [5] at 3 kW and 4.5 kW power levels. JPL evaluated a development model SPT-140 with performance characteristics very similar to the qualification model SPT-140, across a power range of 0.15 to 4.5 kW [9]. However, the SPT-140 has not been evaluated for sustained operation at the lower power throttling range typical of deep space science missions.

As part of the commercial Hall thruster investigations, JPL evaluated the applicability of the SPT-140 Hall thruster for NASA deep-space missions in the specific areas of steady-state low-power operation and thruster operating life. The evaluation included measurements of thrust, discharge current oscillations, thruster temperatures, plasma plume characteristics, long-term thruster operational stability down to 0.8 kW, and operation using a proportional flow control valve and power processing unit in closed-loop control of the discharge current. These measurements were obtained on a qualification model SPT-140 thruster and a development model thruster, both on loan from SSL. The information obtained from these tests will be included in a plasma model to assess operating life for an SPT-140 that is power-throttled down to 0.8 kW, with the goal of implementing lower-cost Hall thruster options for high delta-V deep space missions. This paper summarizes JPL's evaluation of SSL's SPT-140 qualification model thruster and flow control testing on an SPT-140 development model thruster for NASA deep space missions.

II. Test Setup and Methods

A. SPT-140 QM002 and SPT-140 DM4 Thrusters

Performance, operational stability at low power, and plasma property measurements were made on a Qualification Model SPT-140 designated QM002, and flow control measurements were made on a Demonstration Model thruster designated as SPT-140 DM4.

QM002 is a qualification model thruster built at EDB Fakel and undergoing flight qualification and systems testing at SSL [5]. SPT-140 DM4 is a development model thruster tested recently at JPL [9]. The QM002 design includes a single circumferential outer coil in series with a single inner coil, and a single lanthanum hexaboride

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hollow cathode mounted near the discharge chamber. However, the DM4 thruster as tested included two cathodes mounted externally to the discharge chamber at a location specified by SSL. Photographs of both thrusters installed on support plates are shown in Figure 1.

QM002 was mounted to a thrust stand with the cathode oriented at the 9:00 location when viewed downstream of the thruster (Figure 1a). The thruster included a cable harness with flying leads for supplying electrical power to the thruster. Temperature sensors were installed at three locations on the thruster to monitor thruster temperatures during testing: one sensor on the periphery of the thruster's radiation plate designated the thruster body, one sensor on the rear of the thruster body near the center designated the thruster backcap, and one sensor on the cathode bracket.

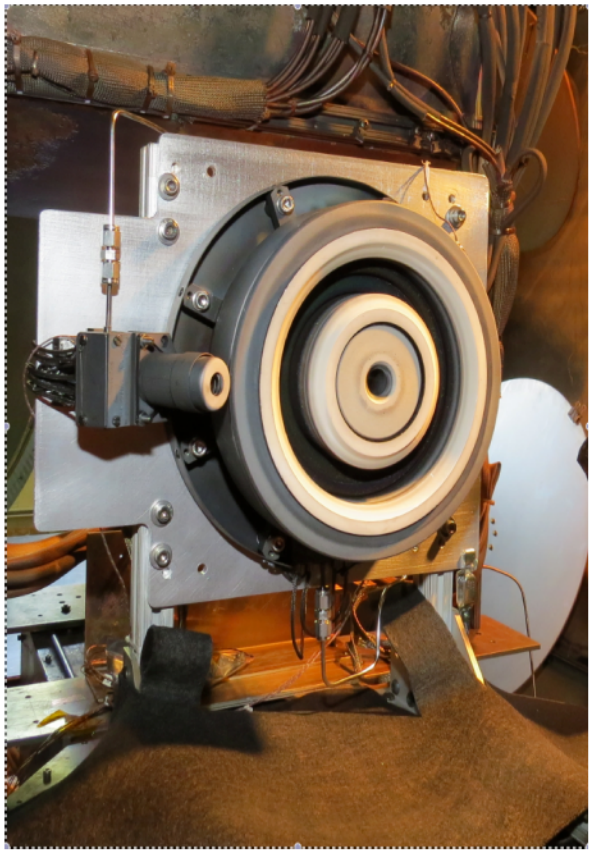

Figure 1a. SPT-140 QM002 installed on a support plate mounted to a thrust stand.

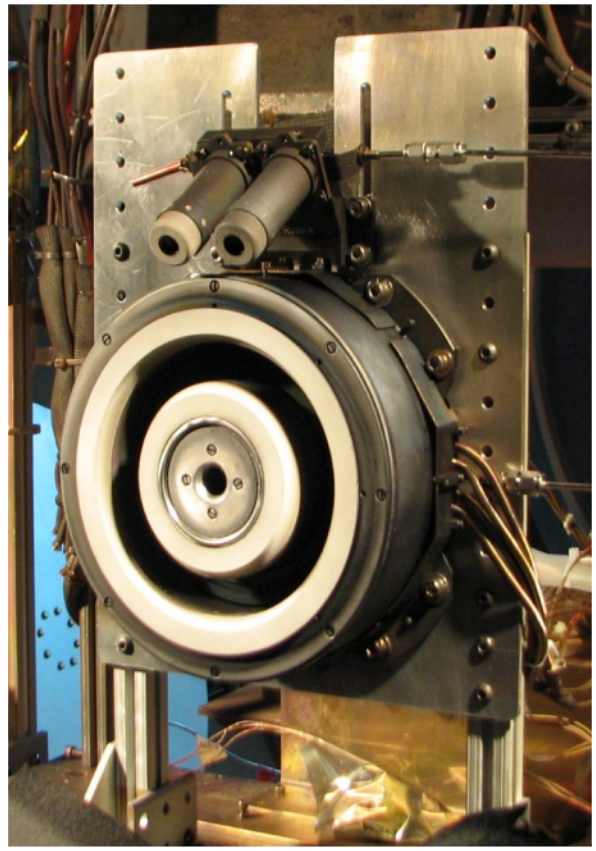

Figure 1b. SPT-140 DM4 installed on a support plate mounted to a thrust stand.

The SPT-140 DM4 used for flow control testing was mounted to a thrust stand with the cathodes oriented at the 12:00 location when viewed downstream of the thruster (Figure 1b). Both thrusters displayed wear on the ceramic rings in the discharge chambers that was consistent with operation for several hundred hours. The thrusters included cable harnesses with flying leads for supplying electrical power.

B. Test Facility and Instrumentation

SPT-140 performance and plume measurement data were obtained with the thrusters operating in JPL's 3 m diameter by 10 m stainless steel vacuum chamber (Owens vacuum chamber). This vacuum chamber includes three each 1.2 m diameter cryopumps and nine each xenon cryopumps. No-load base pressures were typically 2 x 10^{-7} torr

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or less. The operating pressure was measured with an ionization gauge mounted at the exit plane of the thruster and approximately three thruster diameters radially from thruster centerline. The inlet to the ionization gauge was shielded with a grounded mesh and also included a 90 degree elbow. The entire gauge assembly was calibrated on xenon. The gauge inlet was oriented such that a vector normal to the inlet was pointed in the azimuthal direction such that the thrust axis was tangent to the inlet. The maximum pressure measured during testing with the thruster operating at 4.5 kW was 1.08 x 10^{-5} torr. The interior of the vacuum chamber was lined with graphite beam targets to reduce the amount of material back-sputtered from vacuum chamber surfaces to the thruster due to thruster plume impingement.

Power for QM002 was provided by laboratory power supplies for the discharge, magnet coils, heaters, cathode ignitor and cathode keeper. An 80 μF capacitor was placed in parallel with the discharge supply output as the electrical filter. Power for DM4 was provided by SSL's PPU-140 power processor which was modified to operate a Moog 051E339 proportional flow control valve (PFCV). Oscillations in the discharge current of both thrusters were measured using current probes placed on the positive and negative sides of the discharge supplies, between the supply and the 80 μF capacitor, with the probe signals feeding into an oscilloscope. Oscilloscope traces were captured by triggering off a user-set amplitude in the oscillations in the current and stored on the oscilloscope for later analysis.

A laboratory flow system with stainless-steel propellant lines and commercial flow controllers for anode and cathode flow control was used for testing QM002. The flow controllers used in this laboratory flow system have demonstrated excellent flow calibration stability over years of use, and were calibrated just prior to testing DM4 and then QM002. During thruster operations the flow rates were controlled to within an accuracy of ± 1% of the desired set points. The flow system included 7 μm filters installed in the cathode and anode propellant lines immediately upstream of QM002. The same flow system was used for testing the DM4, but the Moog PFCV was used for flow control instead of the commercial flow controllers. Xenon to the thrusters was research grade with a purity specification of 99.9995%.

Thrust measurements were made with an inverted pendulum thrust stand that includes water cooling, active damping of the thruster movement, and inclination control. Calibrations were performed *in situ* by deploying a series of known weights spanning the range of 39 to 302 mN, ten times each. When inclination and thermal drift were accounted for during post-processing, the thrust stand response was repeatable and linear to the applied force. Thrust measurements were made after reaching stable operation at each power level of interest for a minimum of twenty minutes. Thermal drifts of the thrust stand zero are typically the single largest uncertainty in the thrust measurement. To minimize the effects of thrust stand zero drift, thrust stand zero data points were measured within two minutes of thruster shutdown. For all thrust stand zero measurements pneumatic valves located within three meters of the thruster were closed to reduce thrust measurement errors resulting from xenon escaping the thruster with the thruster off. Analysis of thrust stand data indicated a thrust uncertainty of ±1%. Thrust measurements were not corrected for flow ingestion or pressure differences across the throttling range.

The power system, flow system, and facility telemetry were controlled and monitored with a Labview-based data acquisition and control system. The data system recorded thruster currents, voltages, and flow rates as well as facility data at a user-specified rate, with data storage rates at approximately 10-second intervals. The software used to record data was also used to control the thruster power supplies and flow rates. The thruster discharge supply was operated at approximately 300 V in voltage control mode.

Pre-test electrical checks were performed on the thrusters before and after installation onto the JPL thrust stand, and post-test electrical checks were performed once all testing was completed. Electrical checks included resistance measurements and high voltage isolation tests per SSL's standard electrical check procedure. Both thrusters were tested with the thruster body connected to facility ground.

The QM002 start procedure was as follows: after a short cathode pre-heat with xenon flow, thruster operation was initiated with application of low voltage to the cathode keeper from the laboratory cathode keeper supply. Within 30 seconds of cathode ignition, the laboratory discharge supply was turned on to start the thruster discharge. During thruster ignitions, xenon flow rates and coil current were consistent with a start at 3 kW discharge power. The cathode keeper and cathode heater supplies were turned off within a few seconds of ignition of the thruster discharge, with the cathode operating in a self-heating mode. A thruster bake out for a minimum of two hours was performed at 3 kW if the thruster was previously exposed to atmosphere. Thruster shutdowns were performed by first switching the discharge supply off, followed by the magnetic coil current supply and xenon flows.

Power throttling was performed by adjusting the cathode flow rate, anode flow rate, and the magnetic coil current, with the discharge voltage at a fixed value of approximately 300 V. Data for identifying optimal operating conditions below 3 kW power levels were determined by sweeping across multiple values of flow rates and magnet

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coil currents at power levels of interest. Optimal operating conditions for performance measurements were then selected based on a combination of thruster operating characteristics including magnetic coil current, cathode common-to-ground voltage and the magnitude of oscillations in the discharge current.

C. Diagnostics for internal plasma measurements

A single Langmuir probe was mounted on a high-speed translation stage as the primary plasma diagnostic for the experimental investigation. This setup and the associated data acquisition and analysis techniques (described in detail in Ref. [10]) enabled highly repeatable, spatially resolved measurements of the electron temperature along the thruster channel centerline. The positional error associated with this high-speed system was ~1 mm, and the resolution was 1.5-2 mm. Each spatial profile extended from the anode to z = 1.75 L where L is the length of the discharge chamber.

D. Test setup for xenon flow control test

While laboratory experiments at JPL [9] have served to demonstrate the wide throttling range of the SPT-140, the current xenon flow system (XFS) being qualified by SSL is only capable of throttling down to 2 kW. This is because the system utilizes a thermothrottle with a lower bound on the flow control. This limitation can be eliminated by replacing the thermothrottle with a proportional flow control valve (PFCV). A PFCV is capable of restricting flow to arbitrarily low values, and it is a low risk substitution given the demonstrated flight heritage of this type of component (c.f. Ref. [11]). Moreover, it is only necessary to modify a single tray of SPT-140's power processing unit (PPU-140) in order to interface with a PFCV instead of the standard thermothrottle. The small scale of these modifications suggested the feasibility of the modified flow system could be explored through a low-cost test. To this end, SSL prepared a modified PPU tray, and JPL constructed a PFCV-based flow system in the Owens chamber vacuum facility. The combined PPU and XFS were then tested at JPL with the SPT-140 DM4. Setup for this test including equipment are outlined below.

Figure 2 includes a schematic diagram of the PFCV-based xenon propellant flow control system used for this test. In this configuration, a K-bottle of xenon at 5516 kPa pressure is stepped down through a regulator to 276 kPa. The line then passes through a 300 sccm flow meter and series of valves before entering the vacuum chamber. Inside the chamber the line is connected to a modified version of the Standard Architecture Xenon Flow System (SAXFS) [12]. This flow manifold, shown in Fig. 3, was intended for an ion propulsion system, but was adapted to serve as an XFS controller for the SPT-140 test. In this modified configuration, the supply line passed through a PFCV and then was split between two legs---one for the cathode and the other for the anode. The operating principle of the PFCV is that a small solenoid valve inside the component opens in proportion to the current applied to it. Increasing current therefore corresponds to more flow. The Moog PFCV 051X339 used for this test is comparable to a model that was flown on the SEP United States Air Force TACSAT-2 mission [10], with a maximum output pressure of 276 kPa. It also has an inline filter with 25 micron size that maintain gas purity.

Each leg of the SAXFS downstream of the PFCV featured a differently sized Lee Company viscojet, which served to restrict flow and dictate the flow split between the cathode and anode. A single pressure transducer was placed upstream of the viscojets before the line split, and two independent transducers were placed downstream of each leg. This configuration permited real time monitoring of the pressure drop across each viscojet. Flow rate and flow split through each leg were determined from calibration curves and the pressure drop data. Figure 4 includes the cathode to anode flow fraction measured for the test as a function of operating power. At all power levels the flow split exceeded the nominal value of 7.7% (at 3 kW thruster power) to avoid the possibility of starving the cathode. Flow fraction decreased with total flow rate (lower power). This may reflect the fact that the viscojets were becoming unchoked for this low flow regime. By margining the flow split to be high, a flow fraction above 8.4% was maintained, which was sufficient for stable thruster operation at the lowest power setting of 800 W.

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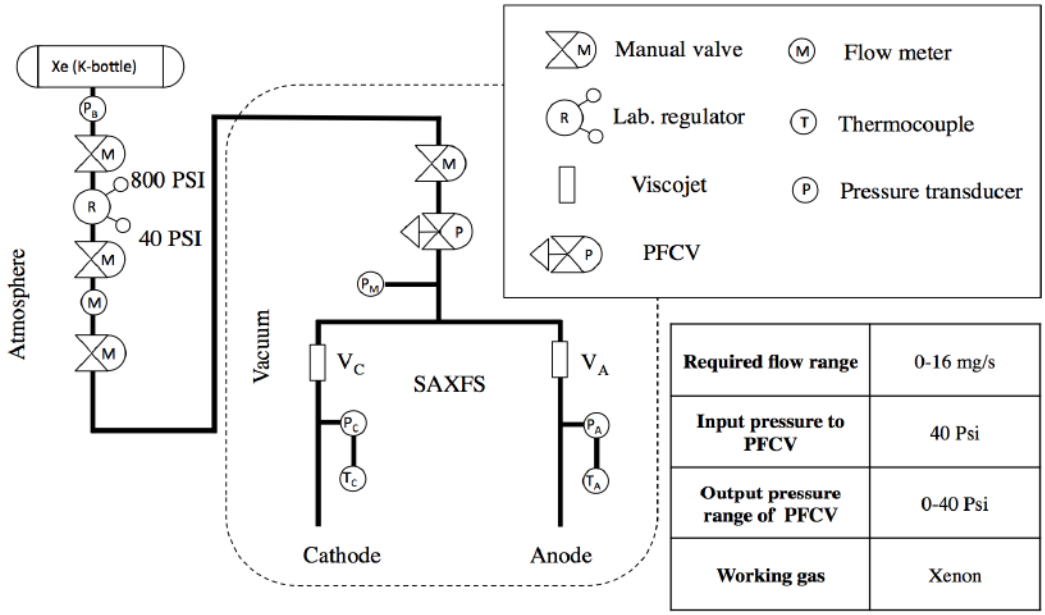

Required flow range	0-16 mg/s
Input pressure to PFCV	40 Psi
Output pressure range of PFCV	0-40 Psi
Working gas	Xenon

Figure 2. Schematic for xenon flow system in the JPL Owens chamber employed for the SPT-140 DM4 test.

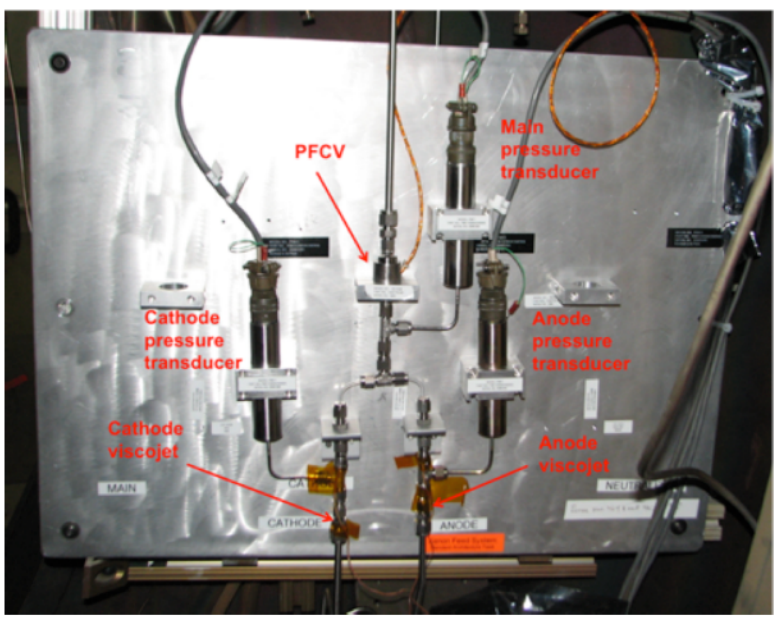

Figure 3. Modified Standard Architecture Xenon Flow System (SAXFS) installed in Owens chamber.

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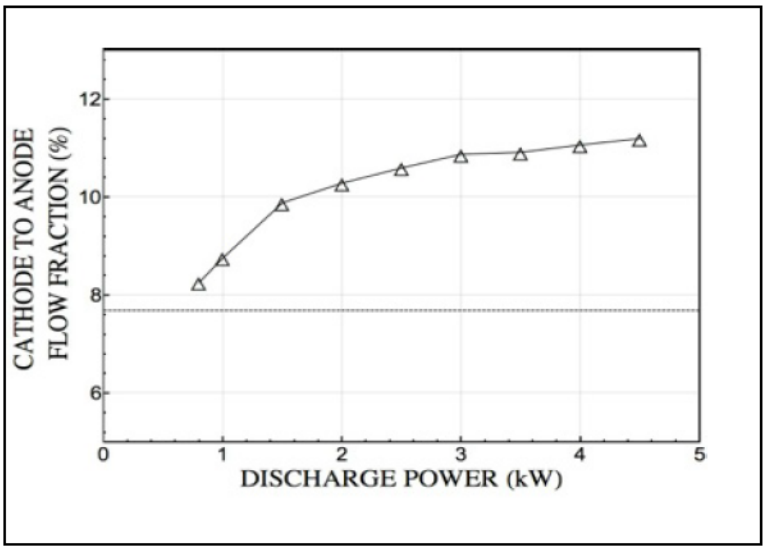

Figure 4. Percentage cathode to anode flow fraction as a function of discharge power. The dotted line is the 7.7% typically used when the SPT-140 is operated at 3.0 and 4.5 kW.

1. Modified PPU-140

The modified SSL PPU-140 and its associated components for this test are shown in Figure 5. The Thruster Auxiliary Support Unit (TASU) is an electrostatic discharge protection and filter unit that is placed between the PPU-140 and the electrical connections to the thruster. The PPU-140 module (close up shown in the right side of Figure 5) has several trays that command thruster functions. The standard PPU-140's flow control tray is designed to interface with a thermothrottle, which produces higher flow when the applied current is reduced. For this test, however, SSL modified the flow control tray in the PPU-140 to interface with a PFCV-driven xenon flow system. In practice, the PPU measures the thruster discharge current and compares it to the discharge current set point. If the current is below the set point, the PPU-140's modified tray sends more current to the PFCV, permitting more flow and therefore current. For too low flow, the opposite effect happens. The degree to which the valve opening is adjusted is proportional to the difference between the set point and the measured current. The magnitude of the correction can be tailored by adjusting the gain of the control loop. Similarly, adjusting the phase of the controller feedback changes the timescale on which this correction is applied. A variable component including a potentiometer and interchangeable capacitors permited real time tuning of this phase and gain.

Even though the PFCV flow was dictated by current, the output of the control loop in the PPU-140 was based on applying a set voltage from 0 to 10.2 V. This configuration was sufficient for this test since the PFCV solenoid was assumed to have an approximately constant resistance. Before starting the experimental campaign, a small ballast resistor was added in series with the PPU-140 control loop output and the PFCV solenoid. This resistor was adjusted until the current to the PFCV generated by the PPU-140's maximum voltage of 10.2 V yielded a maximum flow rate of 20 mg/s. This adjustment was made to ensure that the PPU-commanded flow rate would never permit a discharge current in excess of the PPU-140's safety limits.

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Figure 5. *Left*: PPU-140 and associated components. The blue cover is an ESD mat. *Right*: Close up view of the PPU-140 trays including a device that permits tunable gain and phase.

III. Experimental Results-SPT-140 QM002

The QM002 evaluation included performance mapping, an operating stability test at low power, and plasma measurements.

A. Performance Mapping

Table 1 lists the ten different power levels evaluated on QM002 after optimization testing. All data were taken with a discharge voltage of approximately 300 V, over a discharge power range of 0.8-4.5 kW. Images of QM002 operating at 3 kW and 0.8 kW are shown in Figure 6. The cathode flow fraction was fixed at SSL's standard value of 7.7% except at power levels of 0.8-1.25 kW, where the cathode flow fraction was set to approximately 20% to minimize cathode common-to-ground voltage.

Table 1. Range of discharge power, cathode flow fractions and tank pressures investigated on QM002.

Discharge Power (kW)	Discharge Current (A)	Cathode Flow Fraction	Tank Pressure (Torr)
4.50	15	7.7	1.08E-05
3.01	10.02	7.7	8.00E-06
2.50	8.34	7.7	7.00E-06
2.25	7.51	7.7	6.51E-06
2.00	6.66	7.7	5.91E-06
1.76	5.85	7.7	5.16E-06
1.50	5	7.7	4.78E-06
1.25	4.16	20.0	4.13E-06
1.00	3.33	19.9	3.69E-06
0.80	2.67	20.0	2.97E-06

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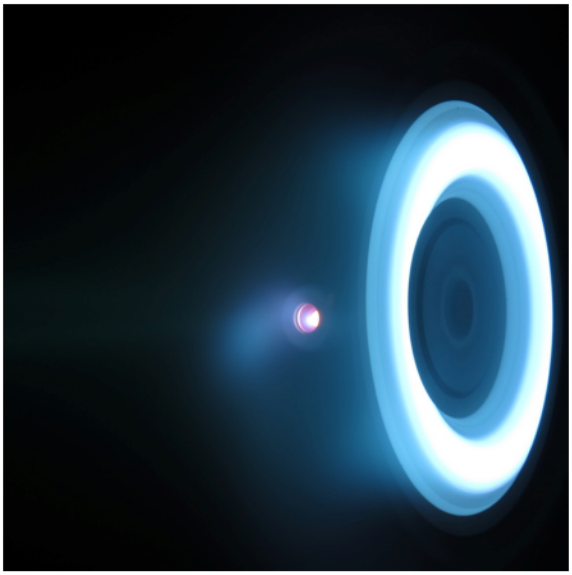

Figure 6a. SPT-140 QM002 operating at 3 kW.

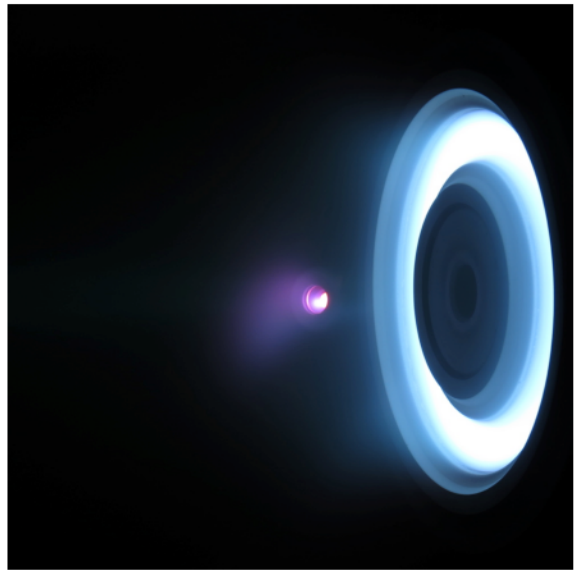

Figure 6b. SPT-140 QM002 operating at 0.8 kW.

QM002 performance as a function of discharge power is shown in Figures 7-10, which include data from measurements made on the SPT-140 DM4 thruster evaluated at JPL in 2009 [6]. Thrust data plotted in Figure 7 are scaled from test data to exact values for power (0.80 kW, 1.00 kW, etc.).

QM002 was easily operable at all power levels checked. Thrust, total specific impulse, and thruster efficiency were similar to performance measurements obtained for DM4 at the same discharge power (Figures 7-10). Thrust was essentially linear with power. There was a significant change in specific impulse and thruster efficiency at 1.25 kW discharge power, due partially to increasing the cathode flow rate to 20% of the anode flow rate at power levels below 1.5 kW. Cathode common voltage measured on QM002 was generally more negative than was measured on DM4 in 2009. At 0.8 kW discharge power cathode common voltage measured for QM002 was -26.8 V with respect to facility ground with the cathode flow rate at 20% of the anode flow rate. Peak-to-peak oscillations in discharge current measured on the positive side of the discharge supply averaged about 22% of the discharge current (Figure 11), and at both 4.5 kW and 0.8 kW discharge power, the peak-to-peak discharge current was approximately 23% of the discharge current. Measured RMS discharge current oscillations shown in Figures 11-12 were less than 5% of the discharge current and compare favorably to RMS values of the discharge current reported for DM4 in [6].

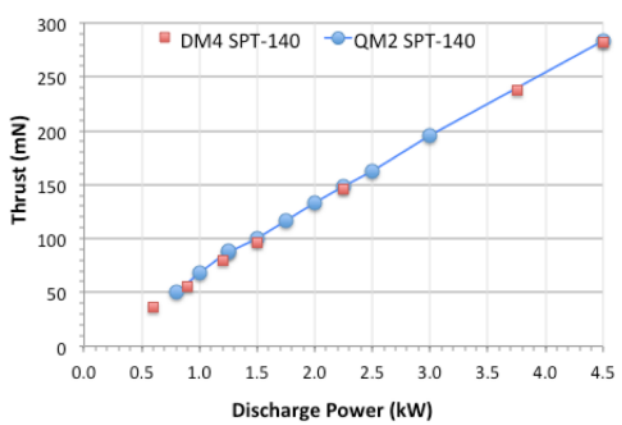

Figure 7. SPT-140 Thrust vs. Discharge Power

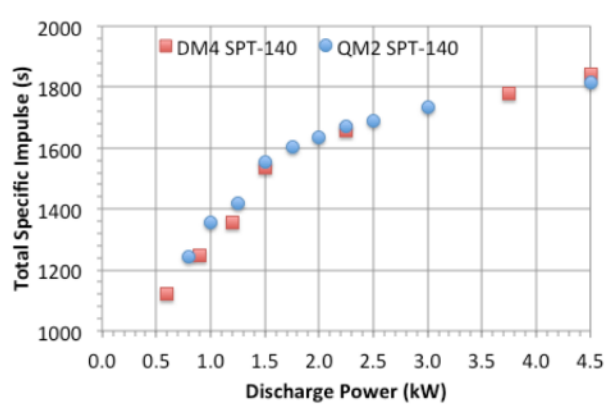

Figure 8. SPT-140 Specific Impulse vs. Discharge Power

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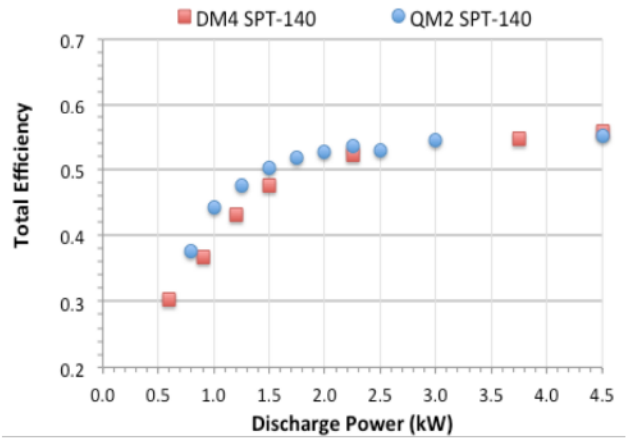

Figure 9. Thruster Efficiency vs. Discharge Power

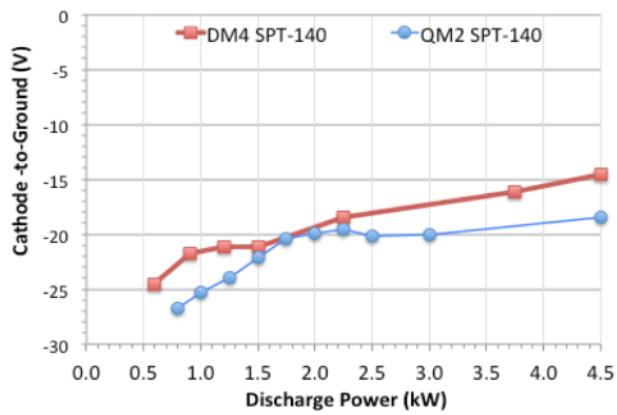

Figure 10. Cathode Common Voltage vs. Discharge Power

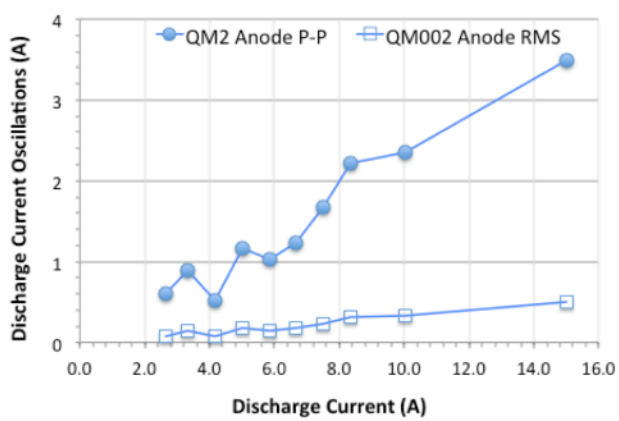

Figure 11. Peak-to-Peak (P-P) and Root Mean Squaree (RMS) oscillations in the discharge current for QM002.

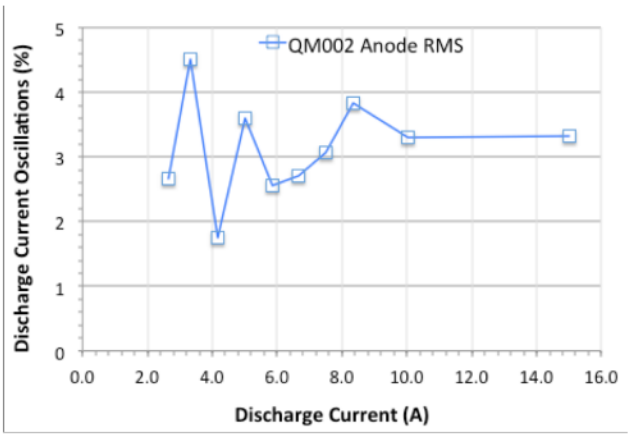

Figure 12. RMS oscillations of the discharge current for QM002 relative to the mean discharge current.

B. Low-Power Stability Test

A test was performed to assess the operational stability of QM002 at low power. A discharge power of 0.8 kW was selected for the test based on trajectory analysis that identified the lower range of thruster input power with margin needed for a variety of NASA deep space missions. A time period of approximately 24 hours was selected based on programmatic limitations. The test was performed after the thruster had already been baked out at 3 kW and operated in the vacuum chamber for approximately 30 hours of testing over a range of thruster discharge power levels up to 4.5 kW, and after nominal thruster operating characteristics at 0.8 kW had already been established. The stability test was performed under computer control which continuously monitored thruster/facility data and software set point limits established for the magnetic coil current, tank pressure, flow rates, discharge current and voltage, cathode common-to-ground voltage, cathode bracket temperature, and anode backcap temperature. A separate hardware interlock was set using the ion gauge to disconnect the discharge supply power relay connecting the supply to electrical service in the event the tank pressure set point was exceeded. Thruster and facility data were monitored by the data acquisition system and stored at 10 second intervals.

After thruster ignition at approximately 3 kW, thruster power was reduced to 0.8 kW and some limited testing was performed with varying coil currents and cathode flow rates to verify that flow rates and magnetic coil current values identified in the optimization testing were repeatable and valid for the test. Once optimization verification was completed, magnetic coil current and cathode flow was reset to optimal values and the stability test was started.

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Tank pressure throughout the stability test was approximately 3.4 x 10^{-6} torr. After approximately 7.5 hours of stable operation at 0.8 kW the test was placed under computer control and operated for approximately an additional 19 hours, for a total of 26.9 hours of continuous operations at 0.8 kW under optimal conditions.

Data from the stability test are shown in Figures 13-16. QM002 was very operable at 0.8 kW, the lowest power level evaluated. Discharge voltage and current for the stability test are shown in Figure 13. The data indicate the discharge current did not change throughout the test, with the discharge supply operating in constant voltage mode and the flow rates fixed at constant values under computer control (i.e., the discharge current was not closed-loop controlled). Thruster temperatures, shown in Figure 14, required about ten hours of operation to reach steady-state values of approximately 92 degrees C for the thruster backcap, 74 degrees C for the thruster radiation shield structure, and 55 degrees C for the cathode bracket. Cathode common to ground voltage, shown in Figure 15, was -27.1 V at the start of the test and steadily decreased in magnitude for 22 hours until reaching a steady-state value of -25.5 V for the remaining approximately 4.9 hours of the test. Cathode common voltage changes may be related to temperature changes in the cathode assembly, or to conditioning of the cathode emitter for this particular operating condition, although as previously noted the thruster had already been operated for 30 hours at various power levels. Peak-to-peak oscillations measured in the discharge current on the positive side of the discharge supply were 0.44 A or 16.5% of the discharge current at the start of operations and 0.56 A and 21% of the discharge current at the end of the test. RMS values of oscillations measured in the discharge current on the positive side of the discharge supply were 0.058 A or 2.2% of the discharge current at the start of operations and 0.072 A and 2.7% of the discharge current at the end of the test. The magnitude of oscillations in the discharge current were still changing when the test was stopped, but the measured values were still within a range typically judged to be low for Hall thrusters.

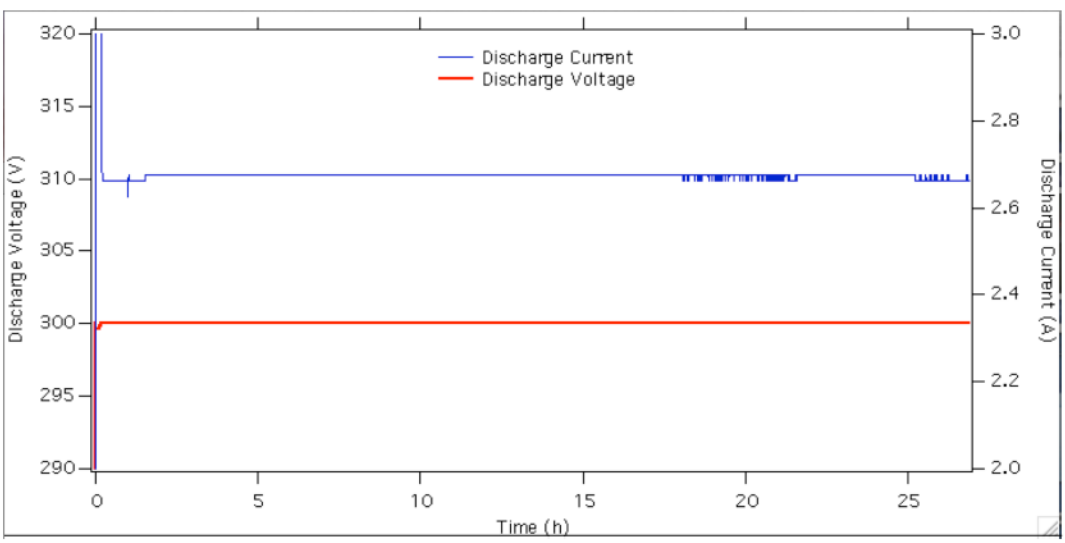

Figure 13. Discharge current and voltage during the stability test of QM002 at 0.8 kW.

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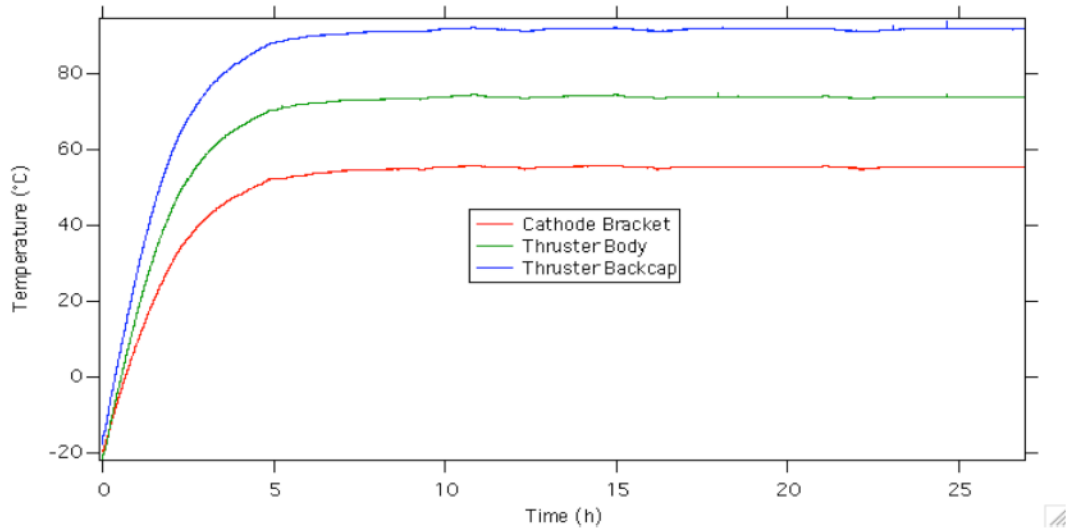

Figure 14. Thruster temperatures during the stability test of QM002 at 0.8 kW.

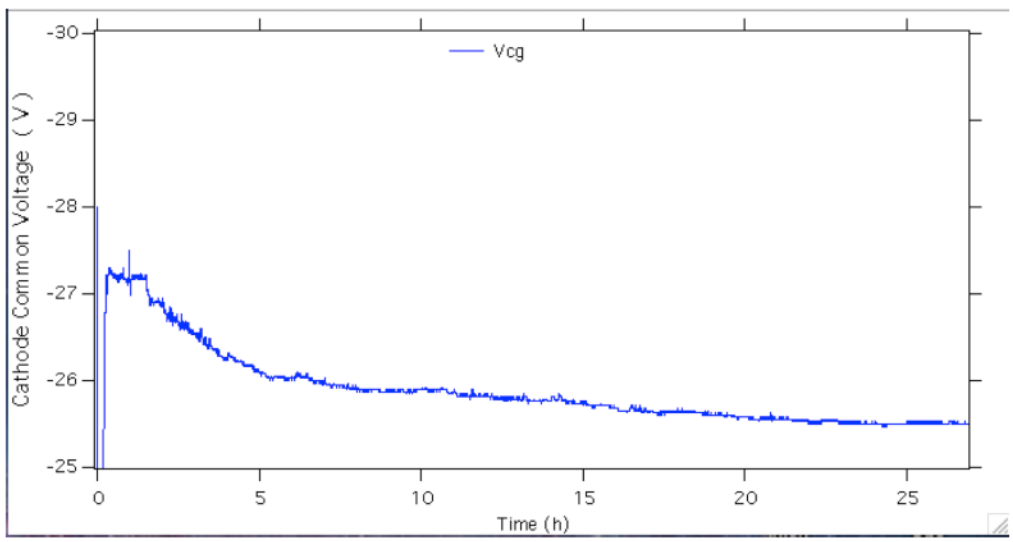

Figure 15. Cathode common voltage during the stability test of QM002 at 0.8 kW.

C. Centerline Electron Temperature Measurements for QM002

Data for the spatial dependence of the electron temperature over the investigated throttling range are shown in Figure 16. As can be seen from this plot, the electron temperature peaked upstream of the exit plane in all cases reported. The location where this peak occurred was invariant as the thruster power decreased from 4.5 kW to 1.5 kW, and the magnitude of this peak increased with decreasing power. In the transition from 1.5 kW to 1.25 kW, however, two significant changes occurred: the magnitude of the peak electron temperature decreased precipitously and the location of this peak shifted upstream. Both of these trends are illustrated in Fig. 17.

While the reason why this fundamental shift in the energy and location of the plasma occurs is not readily apparent, it appears changes to the electron plasma characteristics are mirrored by changes in thruster performance. As Figures 8-9 show, both the specific impulse and efficiency of the SPT-140 QM002 exhibited a marked change in slope as the thruster power decreased below 1.5 kW. Taken in the context of the plasma measurements, this drop in performance may be explained by the fact that the upstream shift of the plasma leads to enhanced plasma flux to the walls. Such a loss process chould adversely impact the performance.

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This enhanced contact with the walls also may play a limiting role in thruster life at low power. Since the electron temperature peak closely tracks the location of the peak electric field, the results illustrated in Figures 16-17 suggest that the ions are accelerated well upstream of the exit plane and suggests the possibility that high energy ions will have a direct path to the thruster walls—thereby leading to erosion. The effects of such a process were not examined in this study, though they may be elucidated through future modeling efforts now underway at JPL.

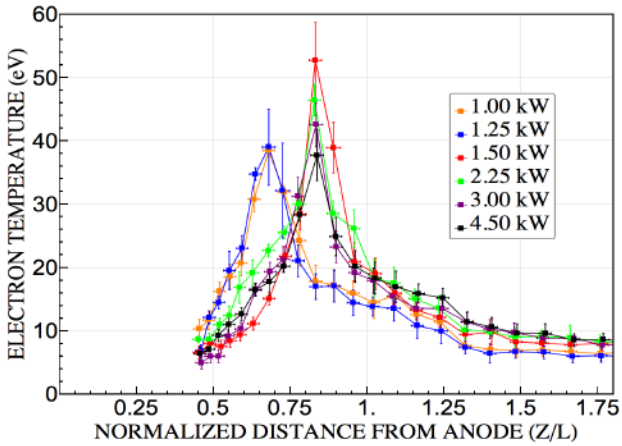

Figure 16: Electron temperature of the SPT-140 along channel centerline for several discharge powers.

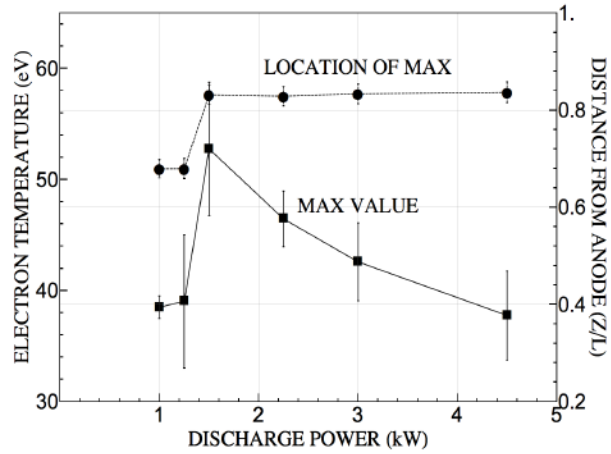

Figure 17. The spatial location and value of the maximum electron temperature on centerline as a function of discharge power.

IV. SPT-140 DM4 Xenon Flow Control Results

A. Objectives

In keeping with the objective of demonstrating the ability of the modified PPU-140 to function with a PFCV-based xenon flow system, three primary goals were identified for this test:

1. Demonstrate cathode ignition and thruster start up with the PFCV-based XFS driven by the modified PPU-140.
2. Demonstrate the power throttling capability of the XFS and modified PPU-140.
    a. Ramp up and down from 0.8 to 4.5 kW at 0.5 kW intervals and show stable thruster output at 10 minute increments
    b. Ramp up and down from 0.8 to 4.5 kW at 0.5 kW intervals and show stable thruster output at ~1.5 minute increments
3. Demonstrate thruster shut off with the XFS controlled by modified SPT-140.

B. Startup

Test data for the start up sequence of the SPT-140 DM4 with the PFCV-based XFS are shown in Figure 18. At the beginning of the sequence, the PPU enabled the cathode heater and commanded the output voltage of the PFCV to a holding value sufficiently low that the valve remained closed. At the 173 s mark, the PPU control loop---with a set point of 10 A---and igniter were activated. The control loop immediately sensed that there was no discharge current and correspondingly applied its maximum voltage to the PFCV to permit gas flow. This yielded a flow rate of 20 mg/s where there was sufficient gas for the igniter to spark the discharge. With the discharge lit, the controller began varying the flow rate to converge on the set point discharge current of 10 A. As can be seen from the right hand side of Figure 18, the system ultimately converged to the desired operating power of 3 kW and therefore demonstrated a stable startup.

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C. Power throttling

Power throttle testing was performed after a two-hour bake out period at a thruster power of 3 kW. Thruster discharge current and flow rate were controlled by adjusting the set points to the PPU-140. Thruster flow rates and discharge current were monitored during power changes. Control loop gain and phase of the PPU-140 flow control tray were iterated to establish a configuration that permitted stable and convergent transition between flow rates. An example of a thruster power transition is shown in Figure 19. While it is evident that the control loop was underdamped---exhibiting a decaying sinusoid with time---after a characteristic period of approximately 230 seconds, the discharge current did converge to a steady state value. This time could be optimized with further tailoring of the control loop, but for the purposes of this test, the steady state value achieved by the controller was sufficient to demonstrate the ability of the modified setup to power throttle the thruster.

For the slow ramp throttling test power level was incremented at 0.5 kW intervals from the bake out condition, 3 kW, up to 4.5 kW and then back down to 0.8 kW, the lower bound on operating power. In performing this power ramp, the discharge current and flow rate set points were commanded by the PPU, with the control loop driving the system to steady state. During power throttling the applied magnetic field was adjusted to minimize discharge current oscillations and cathode to ground voltage.

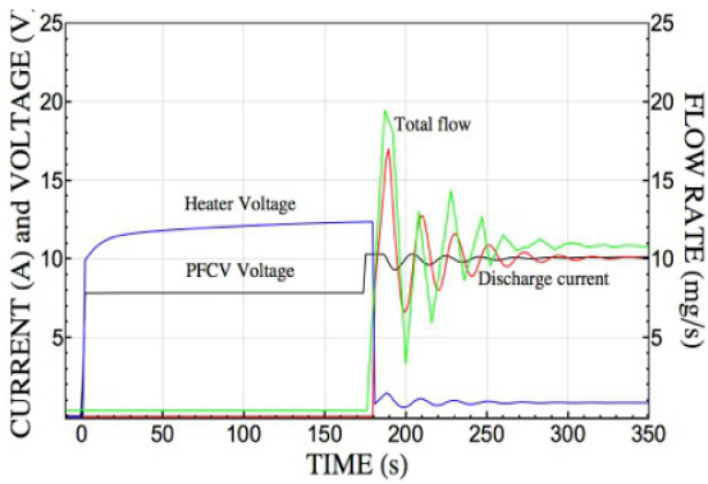

Figure 18: Start up sequence with the PFCV-based XFC. The resolution of the voltage and current data is 1 s. It is 10 s for the total flow.

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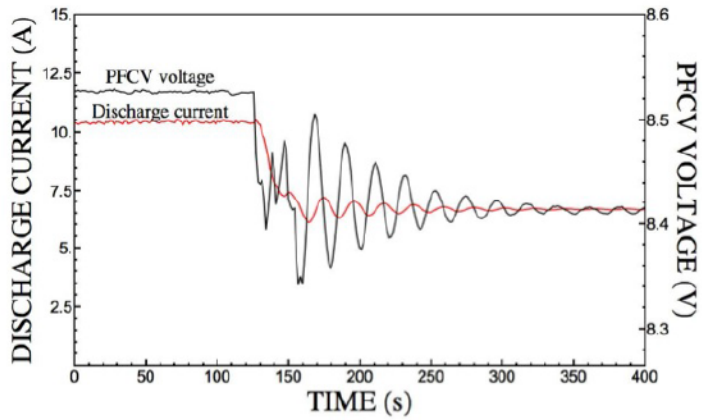

Figure 19: Transition from 3 kW to 2 kW operating condition as controlled by the modified PPU.

Results of the slow power ramp are depicted on the left of Fig. 20 as a function of time. It is important to note that after the thruster achieved 1 kW, the ramp increment was reduced to 100 W in order to approach the low power condition of 800 W more gradually. The reason for this was that the 2.6 A discharge current required for the 800 W power level was only slightly above a safety limit of the PPU-140. Slowly approaching 800 W ensured the control loop did not drop below this value. Once at 800 W, the controller maintained steady state operation.

Once the ability of the modified system to handle a slow power ramp was established, a fast ramp was implemented over the throttling range (right side of Fig. 17). Again, power was incremented by 500 W intervals but only when it was apparent that the controller was converging before again changing the power. This resulted in approximately 120 s between power changes and total time of ~12 minutes for each side of the power ramp. At the upper and lower power conditions, the control loop was allowed to completely converge before power changes, which demonstrated that even though the controller had not stabilized completely at the intermediate conditions, the modified flow system still could reach steady state after a fast ramp between the extremes of the power range. The ability of the PPU to throttle the SPT-140 with its PFCV-based XFS system was now fully demonstrated. Testing was completed by commanding the PPU to shut down the thruster. The system powered off and the PFCV valve was closed---thus confirming shut down capability of the modified system.

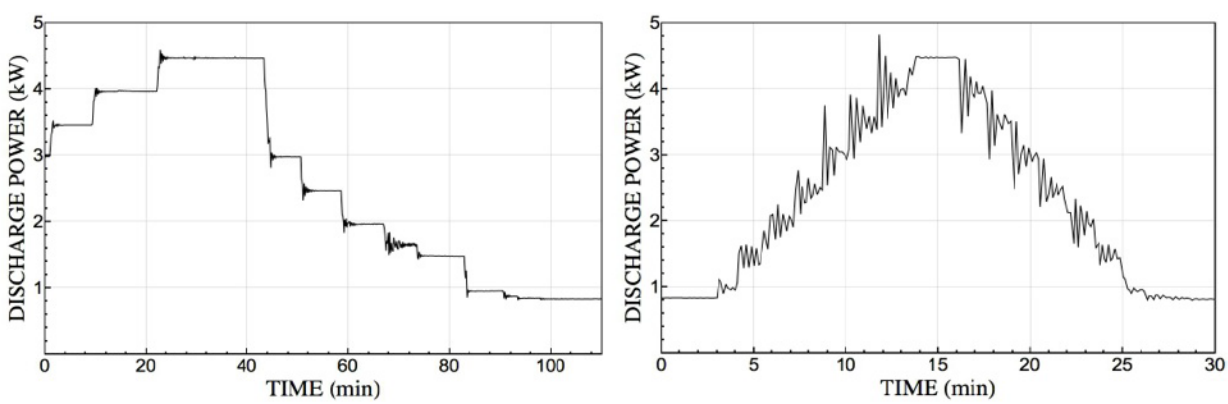

Figure 20: *Left:* Slow ramp for throttling thruster from maximum power condition, 4.5 kW, to lower value at 800 W. *Right:* Fast ramp throttling between maximum and minimum power conditions.

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V. Conclusions

A qualification model SPT-140 designated QM002 was evaluated for operation and plasma properties along channel centerline, from 4.5 kW to 0.8 kW, and tests were performed on a development model SPT-140 designated DM4 to evaluate operation on a proportional flow control valve. Performance measurements on QM002 at 0.8 kW discharge power were 50 mN of thrust at a specific impulse of 1250 s, a total thruster efficiency of 0.38, and discharge current oscillations of under 3% of the mean current. Cathode common to ground voltage increased in magnitude as thruster power decreased from a nominal 3 kW and reached approximately -25.5 V at 0.8 kW when the thruster was operated continuously for approximately 27 hours with a cathode flow fraction of 20% of the anode flow rate. The development model SPT-140 DM4 was fully operable over a 0.8-4.5 kW power range on the PFCV driven by a modified SPT-140 PPU. The SPT-140 PPU appears to require minimal additional modifications to operate and control an SPT-140 thruster operating with a PFCV. QM002 and DM4 test data indicate that the SPT-140 design is a viable candidate for NASA missions requiring power throttling down to low power.

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