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Effects of an Internally-Mounted Cathode on Hall Thruster Plume Properties

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The effects of cathode position on the plume properties of an 8 kW BHT-8000 Busek Hall thruster are discussed. Experiments were conducted at the Jet Propulsion Laboratory (JPL) in a vacuum chamber suitable for the development and qualification of high-power Hall thrusters. Multi-mode Hall thruster operation was demonstrated at operating conditions ranging from 200-500 V discharge voltage, 10-40 A discharge current, and 2-8 kW discharge power. Reductions in plume divergence and increased near-field plume symmetries were found to result from the use of an internally-mounted cathode instead of the traditional externally-mounted configuration. High-current hollow cathodes developed at JPL utilizing lanthanum hexaboride (LaB_6) emitters were also demonstrated. Discharge currents up to 100 A were achieved with the cathode operating alone and up to 40 A during operation with the Hall thruster. LaB_6 cathodes were investigated because of their potential to reduce overall system cost and risk due to less stringent xenon purity and handling requirements.

I. Introduction

HALL thrusters are plasma propulsion devices that have found application on-board spacecraft for stationkeeping, orbit transfers, orbit raising, and interplanetary missions. A unique combination of thrust efficiency, thrust density, and specific impulse makes Hall thrusters qualified to fill such a varied array of missions. Commercially developed Hall thrusters typically operate between 50–60% efficiency, thrust densities of 1 mN/cm^2, and specific impulses of 1200–2000 s. Efforts to expand the specific impulse range have shown that the technology can readily be expanded in the near-term to specific impulses of 1000-3000 s with minor design modifications.[1,2]

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Commercial Hall thrusters are available in the United States through foreign and domestic sources. International Space Technologies Incorporated (ISTI) licenses Russian-developed Hall thrusters that are currently flying on Space Systems/Loral communication satellites.[3] Busek and Aerojet offer American-developed Hall thruster technology. Busek will likely be the first to demonstrate American Hall thruster technology when the 200 W BHT-200 flies on board the TacSat-2 spacecraft in 2006.[4,5] Aerojet is qualifying the 4.5 kW BPT-4000 for geosynchronous Earth orbit (GEO) applications, with a planned launch date of 2008.[6]

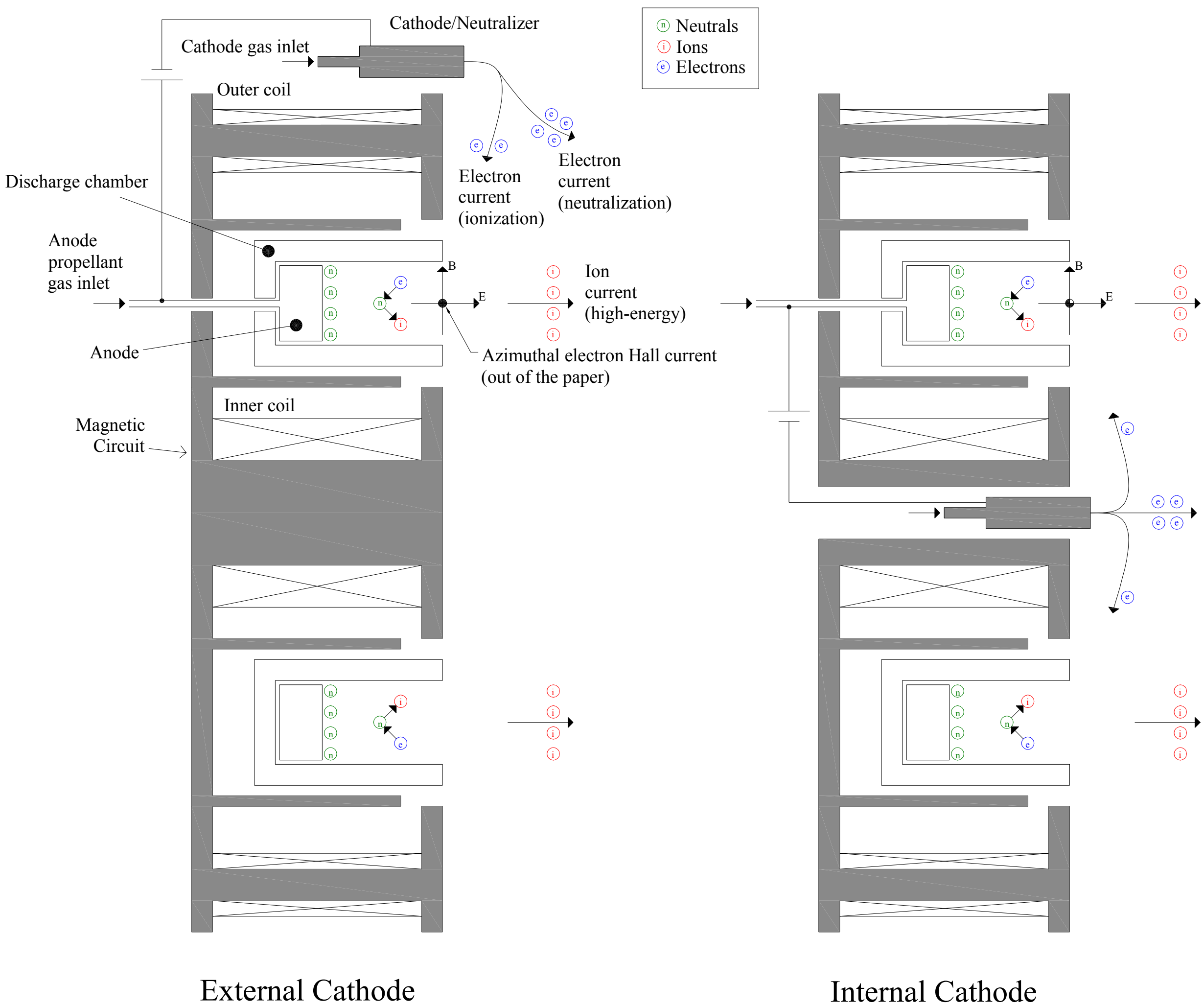

Figure 1. Cross-sectional schematic of typical Hall thrusters with external or internal cathode mounting (not to scale).

Shown schematically in Figure 1, the Hall thruster is constructed from four major components: magnetic circuit, discharge chamber, anode, and cathode. The magnetic circuit supplies the magnetic field that confines the plasma in the discharge chamber and acts as the support structure for the other thruster components. The ceramic walls of the discharge chamber, typically made from boron nitride (BN), house an anode through which a neutral propellant gas is injected. The anode acts both as the positive electrode for the applied voltage and the gas distributor for the propellant gas, which is typically xenon. The cathode supplies electrons to the discharge for ionization and to the plume for neutralization of the ion exhaust. Cathodes are usually mounted external to the thruster body, but can also be mounted internally on thruster centerline if the inner core is hollow (see Figure 1). Such an approach is used with the Busek BHT-8000 Hall thruster used in these experiments. The BHT-8000, developed under an Air Force Small Business Innovation Research (SBIR) Phase II program, is shown in Figure 2 (the cathode is not visible in the photograph).[7,8,9]

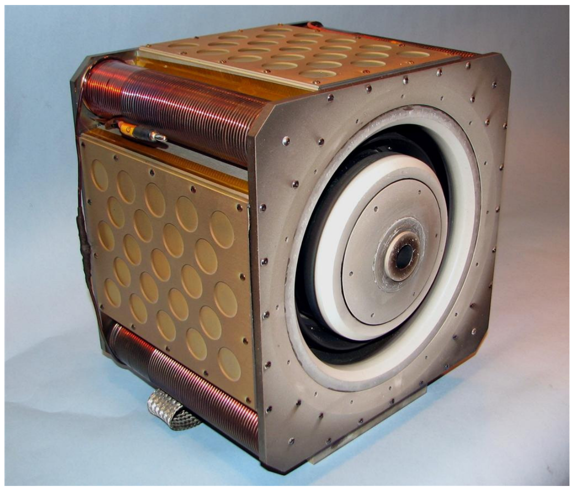

Figure 2. Photograph of the laboratory-model 8 kW Busek BHT-8000 Hall thruster.

Conventional hollow cathodes used in ion and Hall thrusters utilize a porous tungsten insert that is impregnated with an emissive mix of barium, calcium oxides and alumina.[10] This is called a barium oxide (BaO) dispenser cathode because the tungsten matrix acts as a reservoir for barium that is "dispensed" from the pores to activate the emitter surface. One of the major drawbacks of using BaO dispenser cathodes in electric propulsion applications is the extremely high feed gas purity required, which has resulted in requirements for a special "propulsion-grade" xenon with 99.9995% purity as well as special cleaning and handling of the feed system.

Lanthanum hexaboride (LaB_6) is an alternative cathode material being developed at the Jet Propulsion Laboratory (JPL) for use in hollow cathodes for ion and Hall thruster applications. LaB_6 is a crystalline material made by press sintering powder into rods or plates and then 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 will emit over 10 A/cm^2 at a temperature of 1650 °C. Since the bulk material is emitting, there is no chemistry involved in establishing the low work function surface that is sensitive to gas-system impurities, and the cathode life is determined primarily by the surface evaporation rate of the LaB_6 material at the operating temperature. The higher operating temperature of LaB_6 compared to BaO dispenser cathodes and the need to support and make electrical contact with materials that inhibit boron diffusion at the operating temperature require some consideration, but are not difficult problems to overcome. LaB_6 cathodes are arguably the most widely used electron emitter worldwide in industrial applications such as scanning electron microscopes, ion sources, plasma processing devices, arc melters, etc.

Lanthanum hexaboride was first developed as an electron emitter by Lafferty in the 1950s.[11] The thermionic emission of lanthanum-boron compounds as a function of surface stoichiometry was extensively studied by several authors.[12,13,14,15] The emission current density of LaB_6 is plotted in Figure 3 as a function of emitter temperature with several other common cathode materials. In spite of a large variation in the work function and coefficient to the Richardson-Dushman equation reported in the literature, the actual emission current density of LaB_6 predicted by the different references is within about 25%, as shown in the figure. LaB_6 operates at several hundred degrees higher temperature than a BaO dispenser cathode for the same emission current density. Lanthanum hexaboride offers long lifetimes compared to other cathodes because the evaporation rate is significantly lower than for refractory metals and even lower than BaO dispenser cathodes at the same current density.[16]

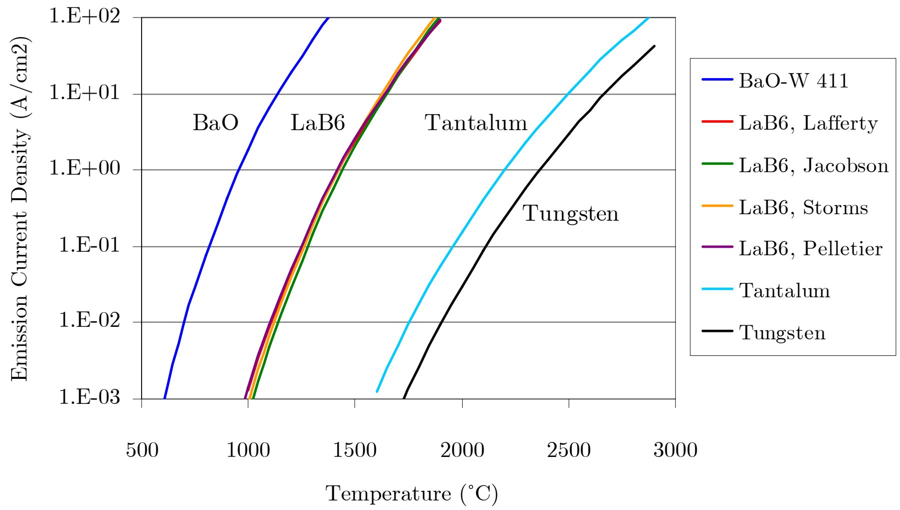

Figure 3. Emission current density versus temperature.

The first use of LaB_6 in a hollow cathode was reported by Goebel, et al. in 1978,[17] and a high current LaB_6 cathode developed for plasma sources was described by Goebel, et al. in 1985.[18] Russian Hall thrusters, such as the SPT-100 flown domestically by SS/L, use LaB_6 cathodes.[19] The development at JPL of high-current LaB_6 hollow cathodes for high-power ion and Hall thruster applications was reported in 2005.[20] In this paper, we present results from a larger LaB_6 hollow cathode that reliably produced discharge currents from 10 to 50 A, and was tested for short periods at currents up to 100 A.

Several authors have investigated and discussed the poisoning of BaO dispenser cathodes[21,22,23] and LaB_6 cathodes.[20,24] The most potent poisons for both cathodes are oxygen and water, with other gases such as CO_2 and air causing poisoning at higher partial pressures. As mentioned previously, LaB_6 is insensitive to impurities that tend to limit the performance and life of BaO dispenser cathodes. This is illustrated in Figure 4, where the fraction of the possible thermionic emission for a BaO dispenser cathode and LaB_6 is plotted as a function of the partial pressures of oxygen and water for two different emitter temperatures. The curves for water and air poisoning of LaB_6 are off the graph to the right at much higher partial pressures. We see that a partial pressure of oxygen below 10^{-6} Torr in the background or feed gas exposed to a dispenser cathode at temperatures of up to 1100 °C will cause significant degradation in the electron emission. In a similar manner, water vapor at partial pressures below 10^{-5} Torr will poison BaO dispenser cathodes at temperatures below 1110 °C. In comparison, LaB_6 at 1570 °C, where the electron emission current density is nearly the same as for the dispenser cathode at 1100 °C, can withstand oxygen partial pressures up to 10^{-4} Torr without degradation in the electron emission. This means that LaB_6 can tolerate two orders of magnitude higher impurity levels in the feed gas compared to dispenser cathodes. For the case of xenon Hall thrusters, LaB_6 cathodes can tolerate the crudest grade of xenon available (99.99% purity) without affecting the LaB_6 electron emission or life. The robustness of the LaB_6 material makes handling and processing electric propulsion devices that use these cathodes significantly easier than thrusters that use BaO dispenser cathodes. The end result of the reduced purity and handling requirements are decreased cost and risk for development and flight programs.

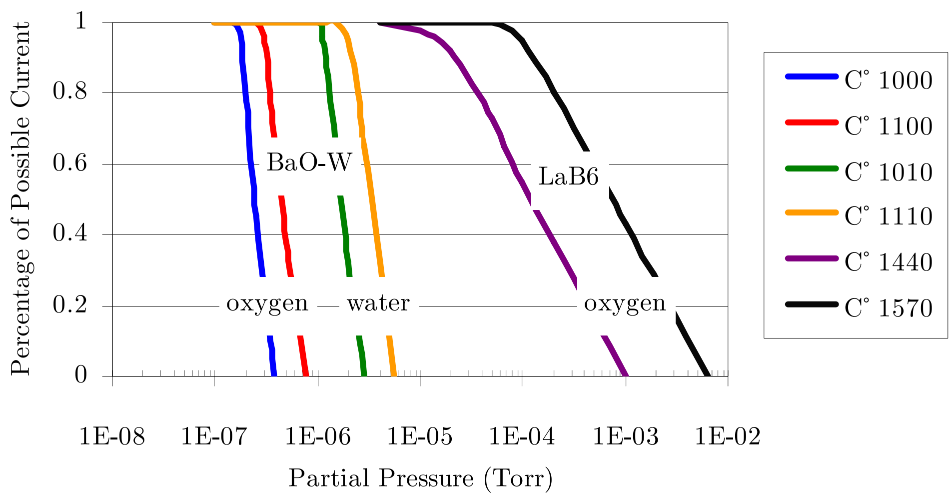

Figure 4. Percentage of possible thermionic emission versus partial pressure of oxygen and water showing the poisoning of dispenser cathodes relative to LaB_6.

In this paper, we discuss experiments conducted with an 8 kW Busek Hall thruster using internal and external cathode mounting configurations. All internal cathode experiments were conducted with a BaO cathode, while the external cathode experiments were with a LaB_6 cathode. Several diagnostics were employed, including a discharge current probe, ExB probe, and Faraday probes. The LaB_6 cathode was successfully demonstrated at discharge currents up to 100 A when operated alone and up to 40 A when operated with the thruster. Additionally, we find that internally-mounted cathode configurations result in decreased plume divergence and improved plume symmetry.

II. Experimental Apparatus

A. Busek BHT-8000 Hall Thruster

Shown in Figure 2, the thruster used in these experiments was a laboratory-model, Busek BHT-8000 Version 2 Hall thruster.[7,8,9] Figure 5 shows the thruster installed in the vacuum chamber. The nominal discharge power of the thruster is 8 kW. Busek has operated the thruster at over 12 kW. The multi-mode, high-power BHT-8000 features a patented discharge chamber geometry that employs a combination of conductive, magnetic, and insulating materials and a unique propellant injection method.[9] A BaO dispenser cathode was internally mounted on thruster centerline inside a hollow section of the inner magnetic circuit. The thruster was also operated using an externally-mounted LaB_6 cathode (see next section).

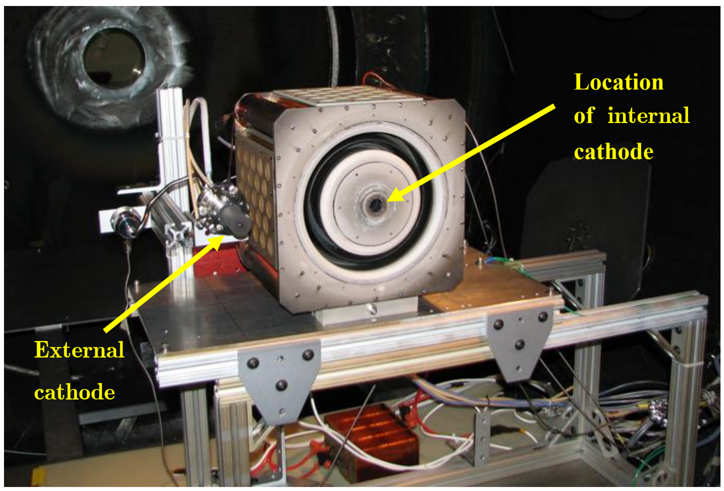

Figure 5. The BHT-8000 installed in the Endurance Test Facility at JPL.

B. JPL LaB_6 Hollow Cathode

A LaB_6 cathode can be configured in a similar geometry as conventional dispenser hollow cathodes, but requires controlled interface materials to the LaB_6 insert, and may require more heater power to achieve the higher emission temperatures. Investigations of material choice, heater design, and cathode construction are on-going at JPL. The original LaB_6 cathode developed at JPL for thruster applications[20] had a 1.3 cm outer diameter cathode tube, and demonstrated 100 A of discharge current at xenon flow rates of 9 sccm. To provide lower insert temperatures and longer cathode life, a 2 cm outer diameter LaB_6 cathode was designed and fabricated. The geometry of this cathode was nearly identical to the 1.3 cm cathode except scaled in radius to the large diameter. Figure 6 shows a photograph of the 2 cm LaB_6 cathode with the keeper electrode removed so that the heater and heat shielding are shown. Until these experiments, the 2 cm LaB_6 cathode had not been tested with a Hall thruster. The LaB_6 cathode, which was only used for a short portion of the entire testing window, was mounted external to the thruster outer front pole as shown in Figure 5. The major axis of the cathode was aligned parallel with the thrust axis of the BHT-8000. No attempts were made to optimize thruster operation through variations in the cathode position.

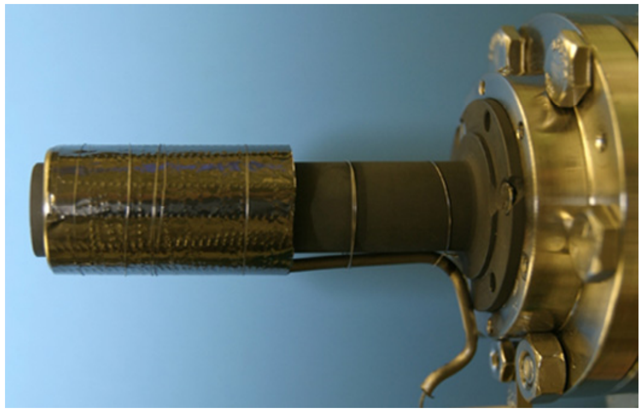

Figure 6. Photograph of the LaB_6 hollow cathode with keeper electrode removed.

C. Vacuum Facility

The thruster experiments were performed in the Endurance Test Facility (ETF) at JPL. The 3 m diameter by 10 m long vacuum chamber was previously used for the 30,000 h life test of the 2.3 kW NSTAR ion thruster and has also been used to test the NEXIS ion thruster at power levels exceeding 20 kW.[25,26] The facility is cryogenically pumped and typically achieves a base pressure between 10^{-8} to 10^{-7} Torr. Figure 7 shows the backpressure versus xenon flow rate during thruster operation at 8 kW as measured by a xenon calibrated ionization gauge located below the thruster. Over the range of flow rates shown, the average pumping speed was 190,000 L/s and at the highest flow rate of 34 mg/s the pressure was 2.0 x 10^{-5} Torr.

It is generally accepted in the Hall thruster community that pressures of less than 2.0 x 10^{-5} Torr are sufficient to reliably obtain performance measurements without needing to correct for neutral gas ingestion.[1,27,28] Backpressures approaching 10^{-4} Torr are generally the upper limit before facility effects begin to drastically influence thruster stability. Thus, the JPL ETF, which sustained a pressure of 2.0 x 10^{-5} Torr at 34 mg/s (8 kW) and has also successfully tested 20 kW ion thrusters, has demonstrated the capability to be a reliable test bed for future high-power Hall thruster development and qualification.

D. Power Electronics and Propellant Delivery System

Power and propellant were delivered to the BHT-8000 with commercially available power supplies and flow controllers. The plasma discharge was sustained by a matching pair of power supplies wired in parallel that provided a maximum output of 500 V, 40 A. The discharge filter consisted of a 40 μF capacitor in parallel with the discharge power supply outputs. Additional power supplies were used to power the magnet coils and the cathode heater and keeper. The cathode heater and keeper were used only during the thruster ignition sequence. Xenon (99.9995% pure) was supplied through stainless steel feed lines with 50 and 500 sccm mass flow controllers. The controllers were calibrated before the experiment and were digitally controlled with an accuracy of ±1% of the set point.

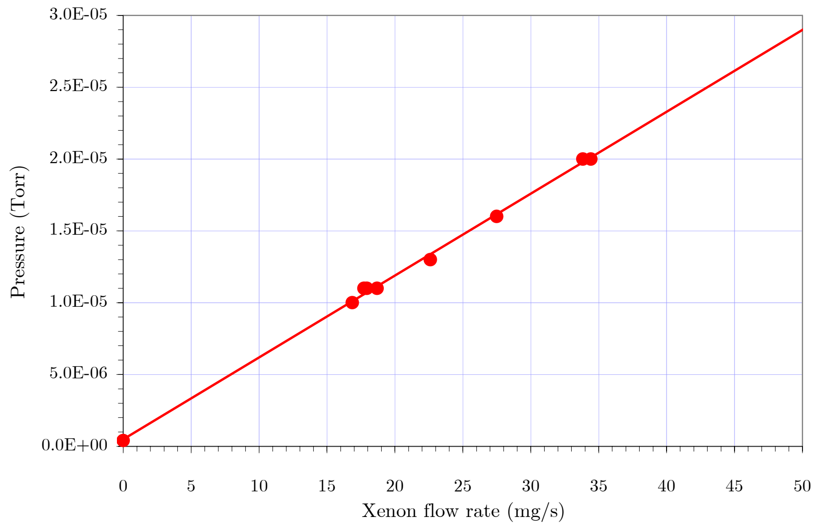

Figure 7. Chamber pressure in the ETF versus xenon mass flow rate during thruster operation at 8 kW.

E. Discharge Current Probe

A 20 MHz current monitor and an 8-bit, 1 GHz oscilloscope were used to measure discharge current oscillations during steady-state thruster operation with an accuracy of ±3%. The current probe was mounted inside the vacuum chamber on the anode side of the power input between the thruster and capacitor described above. Oscillations were quantified by calculating the standard deviation of the discharge current over the sampling period.

F. ExB Probe (Wien Filter)

An ExB probe, or Wien filter, is a band-pass ion filter that selects ions according to their velocities through the application of crossed electric and magnetic fields.[29,30] Because the velocity of multiply-charged ions in Hall thrusters is proportional to the square root of their charge-state, an ExB probe can be used to discriminate between ion species. Analysis of the ion current peaks from the probe characteristic can then be used to compute the ion species fractions.

The ExB probe used in these experiments was used previously during the NSTAR extended life test at JPL.[25] The probe was positioned five meters downstream of the thruster exit plane on thruster centerline. A correction was made for the loss of singly-charged xenon ions due to charge-exchange collisions with the neutral background gas. The absolute measurement uncertainty of the species fractions was estimated to be ±0.04, ±0.02, and ±0.01 for Xe^{+}, Xe^{2+}, and Xe^{3+}, respectively.

G. Faraday Probes

Surveys of the ion current density in the thruster plume were taken using a pair of Faraday probes. The far-field probe sampled the plume at distances on the order of several thruster diameters, while the near-field probe was used to conduct radial surveys from thruster centerline at axial distances ranging from 7-35 cm (0.4-2.1 mid-channel diameters) from the thruster exit plane. The near-field probe sampled in the plane of the external cathode, which allowed the influence of the internal and external cathodes on the thruster plume to be studied. Only data from the near-field probe are reported here. Shown sampling the plume in Figure 8, the near-field probe consisted of a 5.1 cm diameter collection electrode enclosed within an 8.6 cm diameter guard ring. The guard ring and collector were separated by a 0.1 cm gap, were fabricated from graphite, and were biased –30 V below facility ground to repel electrons.

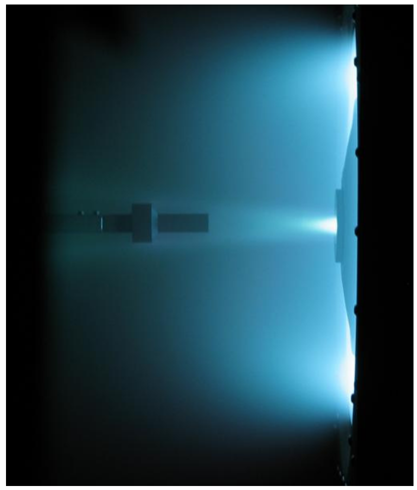

Figure 8. Photograph of the near-field Faraday probe passing through the plume of the internal cathode. The thruster operating condition is 300 V, 16 A (4.8 kW).

III. Experimental Results

A. LaB_6 Cathode Performance

Before testing the LaB_6 hollow cathode with the thruster, the cathode was tested in a 1 m diameter, 2 m long vacuum chamber that obtained a 1500 L/s xenon pumping speed with cryogenic pumping. The cathode was coupled to a cylindrical water-cooled copper anode and a 100 A discharge power supply. The discharge voltage versus current behavior of the 1.3 cm cathode[20] is shown in Figure 9 for several xenon flow rates. The cathode achieved 100 A discharge current for xenon flow rates of 9 sccm or higher. The maximum current available from the LaB_6 cathode was actually limited only by the discharge power supply.

The performance of the 2 cm LaB_6 hollow cathode in the discharge test fixture is shown in Figure 10. The discharge behavior was similar to the 1.3 cm cathode, and again the cathode demonstrated the 100 A discharge current goal. Operation at 10 sccm and above reduced the discharge voltage significantly. During operation with the Hall thruster, still lower coupling voltages were obtained than in the discharge test facility due to the higher flow rates (see Figure 16).

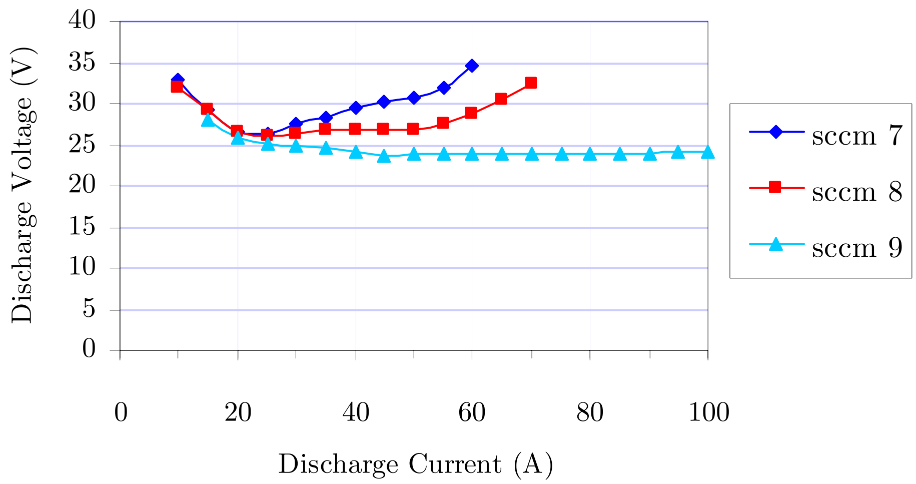

Figure 9. Discharge current and voltage for the 1.3 cm cathode from Ref. 20.

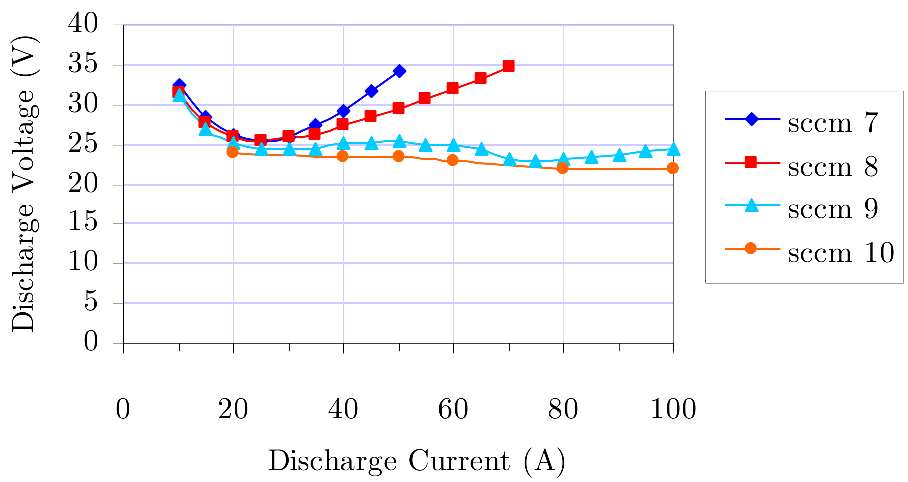

Figure 10. Discharge current and voltage for the 2 cm cathode.

B. Thruster Experiments

Multi-mode, high-power Hall thruster operation was demonstrated at thruster operating conditions ranging from 200-500 V discharge voltage, 10-40 A discharge current, and 2-8 kW discharge power. Figure 11 shows the discharge current and voltage combinations that were investigated with the BHT-8000. Over the entire operating range, the thruster demonstrated excellent stability and thermal margin. This was evidenced by the ease of starting the thruster from cold and hot starts, the ability of the thruster to change operating conditions without loss of stability, the ability of the thruster to return to the same discharge conditions after re-starts, and the stability of the discharge current over long period of times (drifts were typically no more than 0.1-0.2 A over time scales of 30-60 min). The total thruster operating time was 21 hours. Continuous operation of more than 4 hours was demonstrated during three different runs. During each of these runs, the thruster spent more than 2 hours continuously at 8 kW.

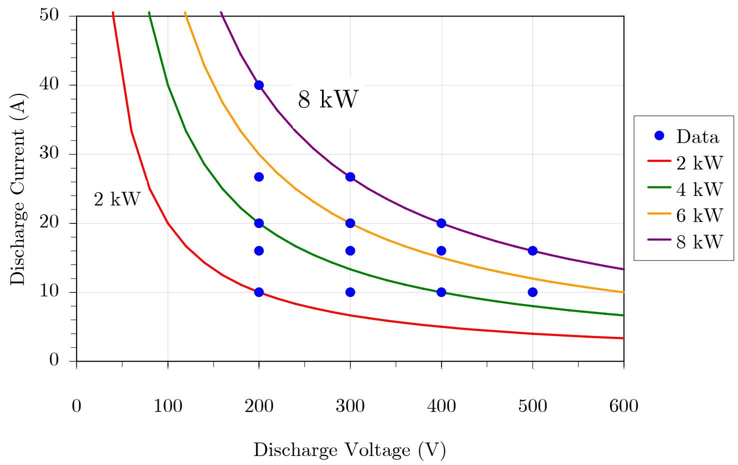

Figure 11. Discharge current and voltage operating conditions demonstrated in the BHT-8000 experiments. Lines of constant power are included for reference.

Figure 12 shows photographs of the thruster operating at 300 V, 26.7 A (8 kW) with the internal cathode. Figure 13 are photographs comparing the visual appearance of the near-field plasma structure during operation at 500 V, 16 A (8 kW) with either the internal or external cathode. As previously observed by Szabo, et al.[8], the visual appearance of the internal cathode plume was markedly different than with the external cathode. Since the external cathode plume was typical of other Hall thrusters with external cathodes, it was unlikely that the differences were the result of using cathodes with different emitter materials. With the internal cathode operating, the cathode plume appeared to be compressed and elongated in the axial direction by the magnetic field emanating from the inner circuit of the thruster. The plasma exhaust was collimated and appeared to be well-directed axially (these observations were also supported by current density measurements discussed below). There was also a notable absence of plasma emission surrounding the exterior pole pieces of the thruster. This plasma “halo,” which is typical of external cathode configurations, is seen in the right photograph in Figure 13. Note how the halo in Figure 13 has a reddish tint and appears to be following magnetic field lines. The red tint is indicative of emission from xenon neutrals, most likely from collisions with cathode electrons that are trapped on magnetic field lines.

Figure 14 is a photograph taken from the rear of the thruster at an operating condition of 200 V, 40 A (8 kW) with the internal cathode, while Figure 15 is a similar view under 300 V, 26.7 A (8 kW) operation with the external cathode. Note the red emission to the right of the external cathode in Figure 15. This was an indication that the effects of the external cathode were extending beyond the physical location of the cathode and the vicinity of the exit plane (as shown in Figure 13).

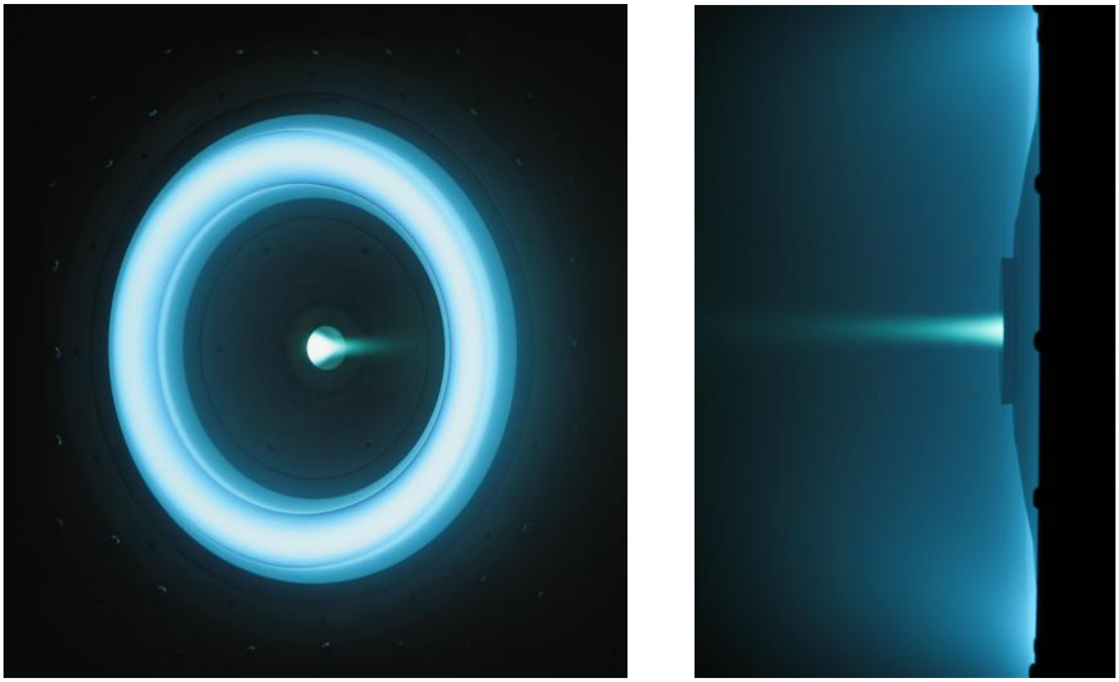

Figure 12. Photographs of the BHT-8000 operating at 300 V, 26.7 A (8 kW) with the internal cathode.

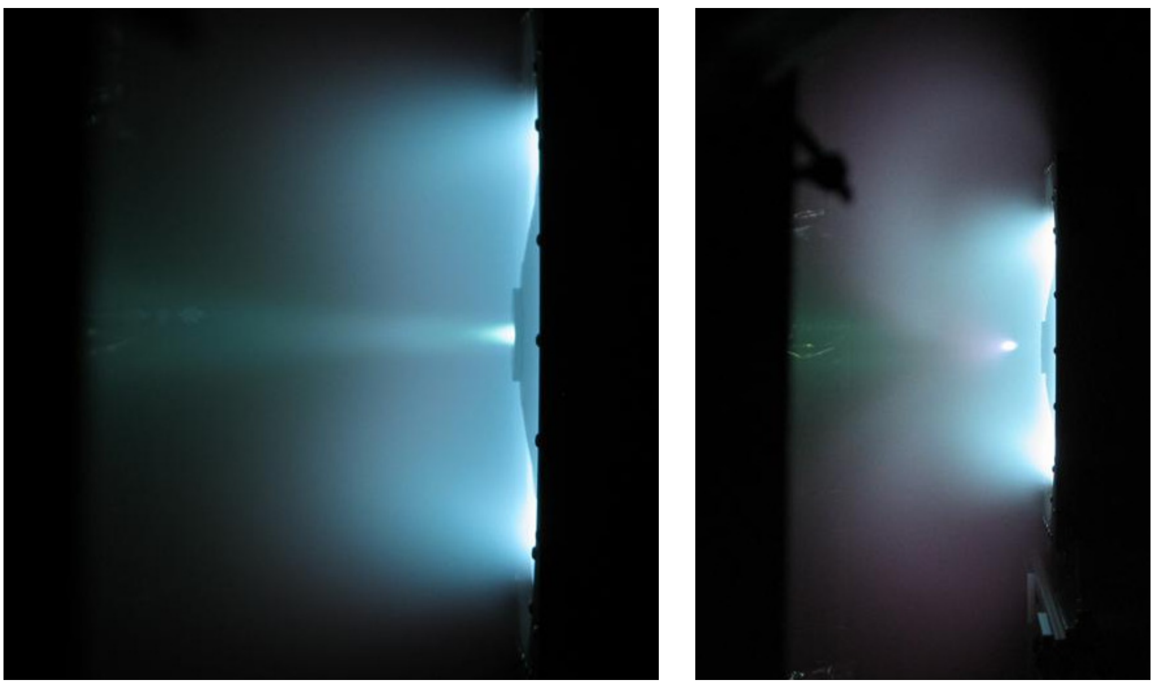

Figure 13 Photographs of the BHT-8000 operating at 500 V, 16 A (8 kW) with the internal cathode (left photo) and the external cathode (right). With the external cathode, a "halo" that follows the magnetic field lines surrounds the thruster. The halo is not present during internal cathode operation.

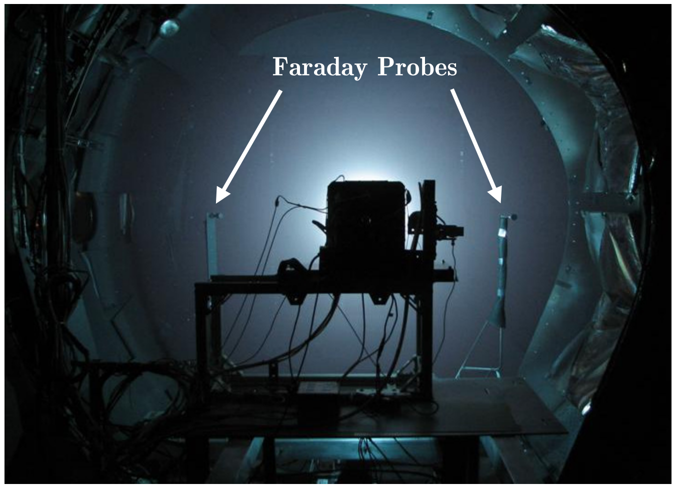

Figure 14. Photograph taken from the rear of the BHT-8000 during operation at 200 V, 40 A (8 kW) with the internal cathode. The near-field and far-field Faraday probes can be seen on opposite sides of the thruster.

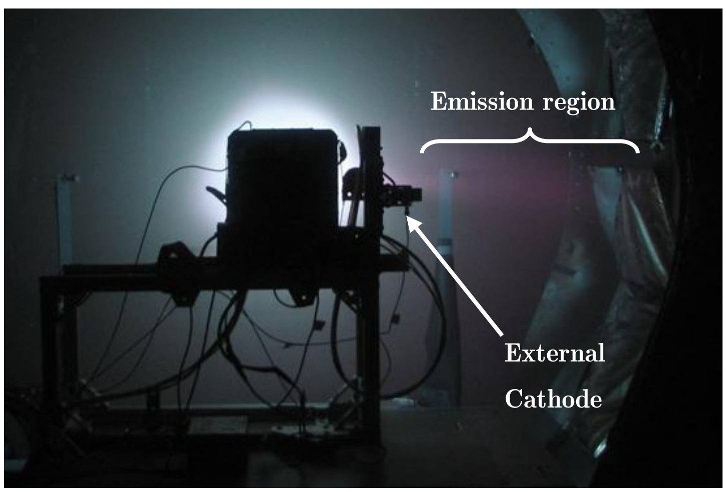

Figure 15. Photograph taken from the rear of the BHT-8000 during operation at 300 V, 26.7 A (8 kW) with the external cathode operating. Note the red tinted plasma emission to the right of the thruster in the photograph. This region is not present during internal cathode operation (see Figure 14).

Differences in thruster operation due to the cathode materials and locations were quantified with measurements of the cathode floating potential, ion species fractions, and current density. Figure 16 plots the cathode floating potential with respect to the vacuum chamber electrical ground as a function of the discharge current during thruster operation at 8 kW. The BaO cathode potential was roughly constant between 16-40 A discharge current, ranging from -10 to -13 V. These coupling voltages are typical for Hall thrusters with optimized cathodes.[1] The LaB_6 cathode potential ranged from -22 to -15 V as the discharge current increased from 16 to 40 A. This trend was likely due to the cathode operating at currents less than its nominal design point (i.e., 50 A), rather than its positioning. (Poor coupling voltages related to positioning are usually independent of discharge current.)

Figure 17 shows the standard deviation of the discharge current oscillations (expressed as a percentage of the discharge current) versus discharge current during operation with the internal and external cathodes at a constant discharge power of 8 kW. The standard deviation ranged from 1-19% depending on the operating condition, which are typical values for Hall thrusters.[1] There was some indication that the LaB_6 cathode was increasing the level of oscillations at certain operating conditions, but no consistent trend emerged.

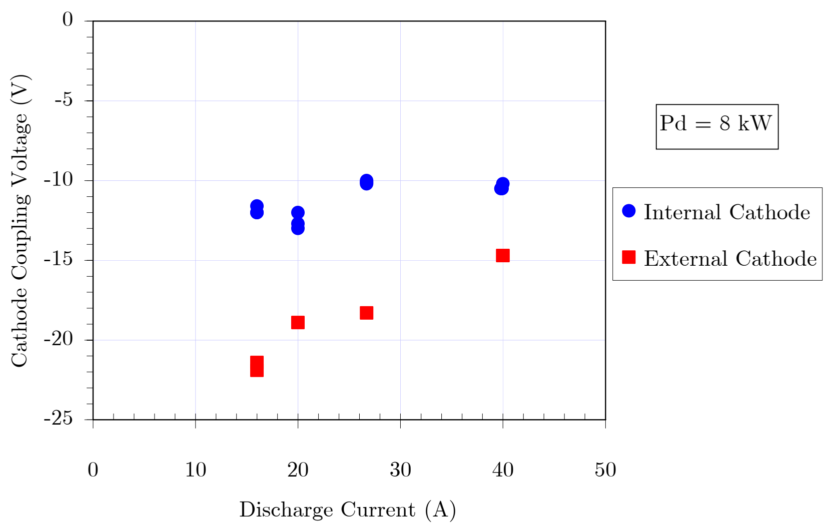

Figure 16. Cathode to ground coupling voltage versus discharge current for the internally mounted BaO cathode and the externally mounted LaB_6 cathode at 8 kW.

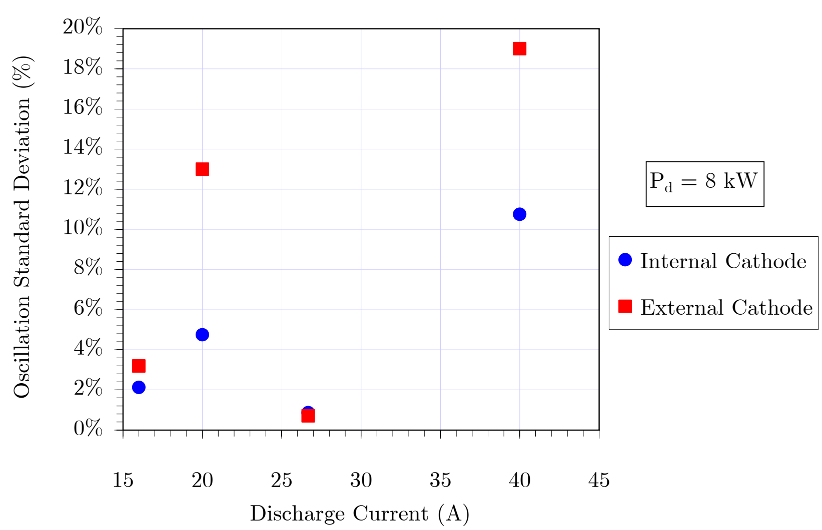

Figure 17. Standard deviation of the discharge current oscillations versus discharge current during operation with the internal and external cathodes at a constant discharge power of 8 kW.

Table 1 shows the ion species fractions on thruster centerline at 8 kW, 500 V during operation with the internal and external cathodes. The Xe^{+} ion species fraction ranged from 0.92-0.94 and the Xe^{2+} fraction was 0.05-0.07, which are typical for Hall thrusters operating at discharge voltages of 500 V.[1] Within the margin of error, the measurements were identical for the two cathode positions, which likely indicates that the electron temperature from either cathode were approximately equivalent. Additional measurements, especially at angles off thruster centerline, are needed to better quantify the possible effects of cathode position on the ion species fractions.

Table 1. Ion species fractions on thruster centerline at 8 kW, 500 V during operation with the internal and external cathodes.

	Xe^{+}	Xe^{2+}	Xe^{3+}
Internal Cathode	0.92	0.07	0.01
External Cathode	0.94	0.05	0.01

Table 2 summarizes the ion current density data collected with the near-field Faraday probe. Data were collected at either constant current (16 A) or constant power (8 kW) over discharge voltages of 200-500 V and with the cathode mounted internally or externally. Internal mounting used the BaO cathode, while external mounting used the LaB_6 cathode. For each data set, the probe sampled the plume in radial sweeps (i.e., the sampling plane was perpendicular to the axis defined by thruster centerline) at axial locations 7-35 cm downstream of the exit plane. The probe face was always aligned perpendicular to the axis defined by thruster centerline. No corrections were made to the data for cosine losses at high-angles. Figure 18 through Figure 21 shows ion current density during operation with the internal cathode at a constant discharge current of 16 A and discharge voltages of 200-500 V. Figure 22 through Figure 24 and Figure 21 shows ion current density during internal cathode operation at a constant discharge power of 8 kW and discharge voltages of 200-500 V. Figure 25 - Figure 28 shows ion current density during external cathode operation at a constant discharge power of 8 kW and discharge voltages of 200-500 V.

Table 2. Data sets collected during Faraday probe measurements.

Operating Conditions	Cathode Position, Type	Corresponding Figures
16 A, 200-500 V	Internal, BaO	Figure 18 - Figure 21
8 kW, 200-500 V	Internal, BaO	Figure 22 - Figure 24, Figure 21
8 kW, 200-500 V	External, LaB_6	Figure 25 - Figure 28

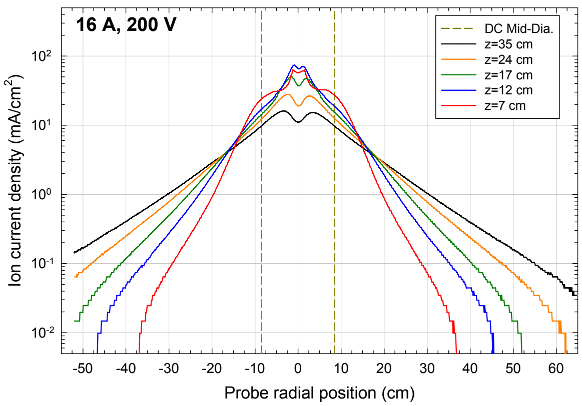

Figure 18. Current density vs probe position. (Internal cathode; 16 A, 200 V)

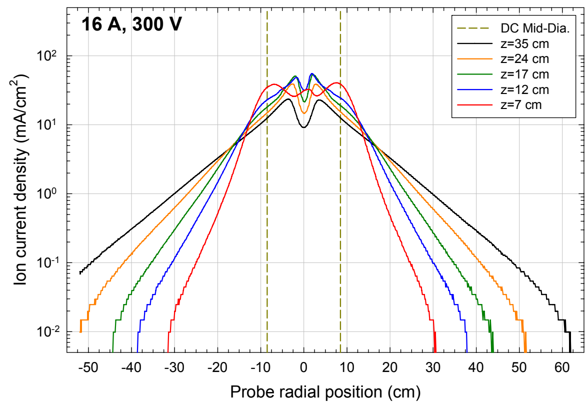

Figure 19. Current density vs probe position. (Internal cathode; 16 A, 300 V)

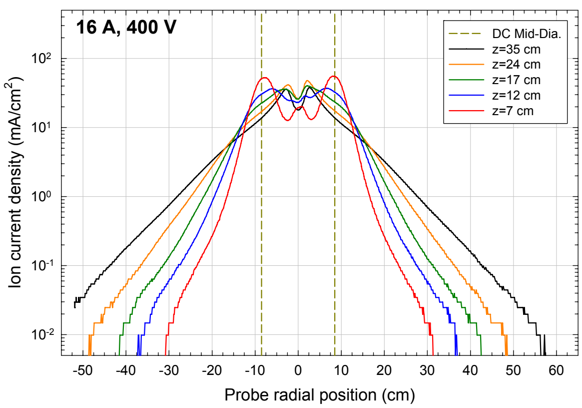

Figure 20. Current density vs probe position. (Internal cathode; 16 A, 400 V)

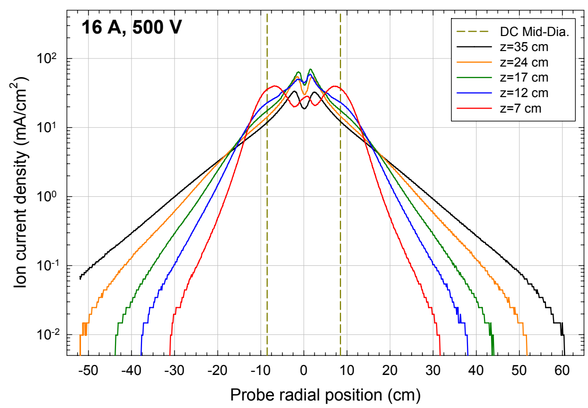

Figure 21. Current density vs probe position. (Internal cathode; 16 A, 500 V)

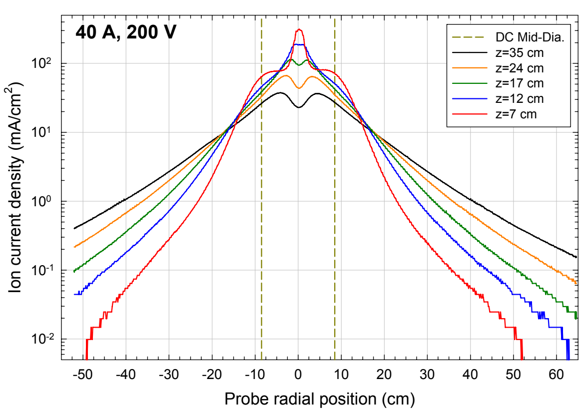

Figure 22. Current density vs probe position. (Internal cathode; 40 A, 200 V)

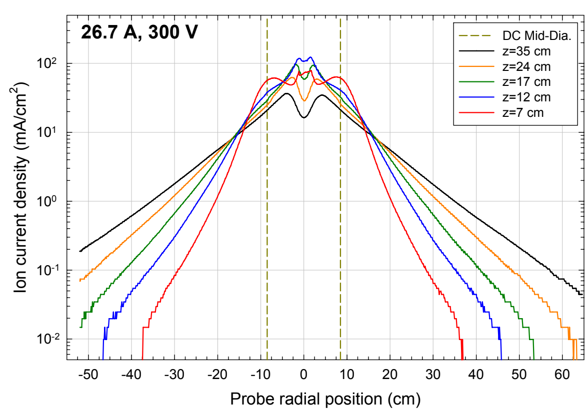

Figure 23. Current density vs probe position. (Internal cathode; 26.7 A, 300 V)

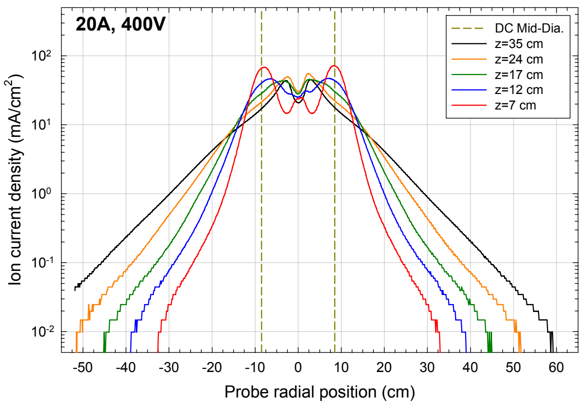

Figure 24. Current density vs probe position. (Internal cathode; 20 A, 400 V)

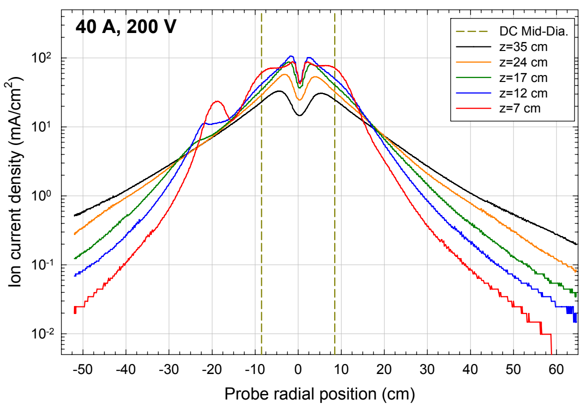

Figure 25. Current density vs probe position. (External cathode; 40 A, 200 V)

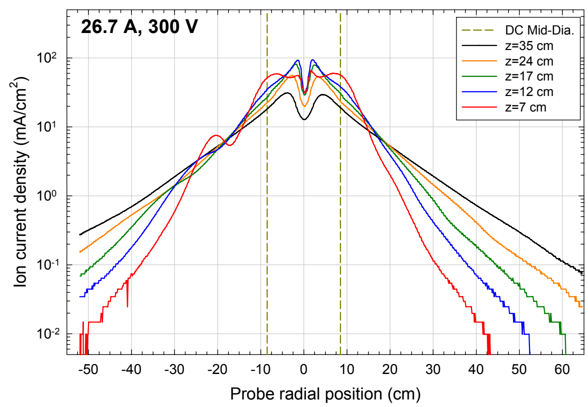

Figure 26. Current density vs probe position. (External cathode; 26.7 A, 300 V)

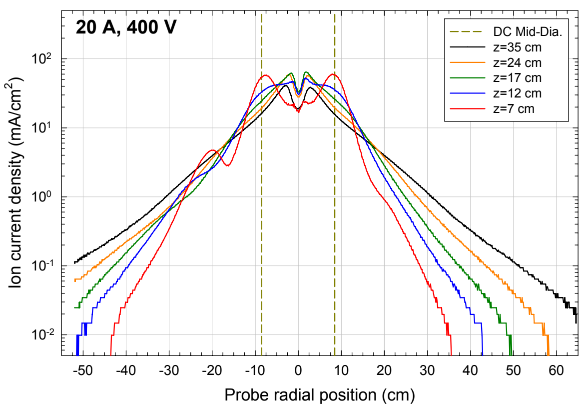

Figure 27. Current density vs probe position. (External cathode; 20 A, 400 V)

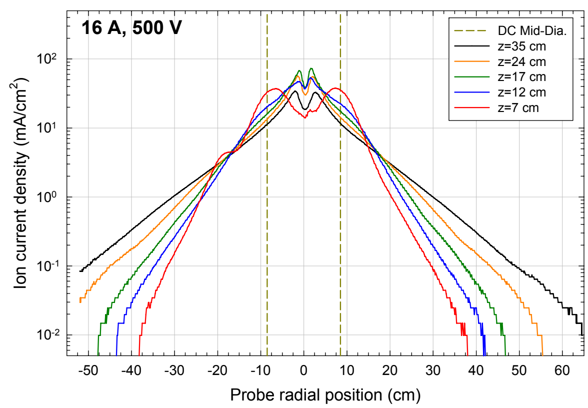

Figure 28. Current density vs probe position. (External cathode; 16 A, 500 V)

IV. Discussion

A. High-Current LaB_6 Cathodes

High-current, LaB_6 cathodes have been designed, fabricated, and tested by JPL over discharge currents of 10-100 A. Sustained, stable operation of the LaB_6 cathode with the Hall thruster was demonstrated at discharge currents of 10-40 A. The LaB_6 cathode was very simple to operate throughout testing, with no conditioning or activation procedures required.

A LaB_6 cathode has a lifetime limited only by the evaporation rate of the insert. As the insert evaporates the inner diameter increases and the surface area enlarges. This causes the required current density and temperature to decrease, which reduces the evaporation rate of the insert. The life of the LaB_6 cathode can be calculated taking into account this change in the emission area with time, and represents an upper limit on the projected life. Figure 29 shows the calculated life[31] for the 2 cm diameter LaB_6 cathode with two different wall thicknesses, and a 2 cm BaO diameter dispenser cathode for comparison. The LaB_6 cathode provide over 250 kHrs of life at 50 A, and over 80 kHrs of life at 100 A of discharge current. While both BaO and LaB_6 cathodes can provide lifetimes of several tens of kHrs, the LaB_6 cathode is anticipated to provide this life with much higher tolerance to feed gas impurities compared to the BaO dispenser cathode.

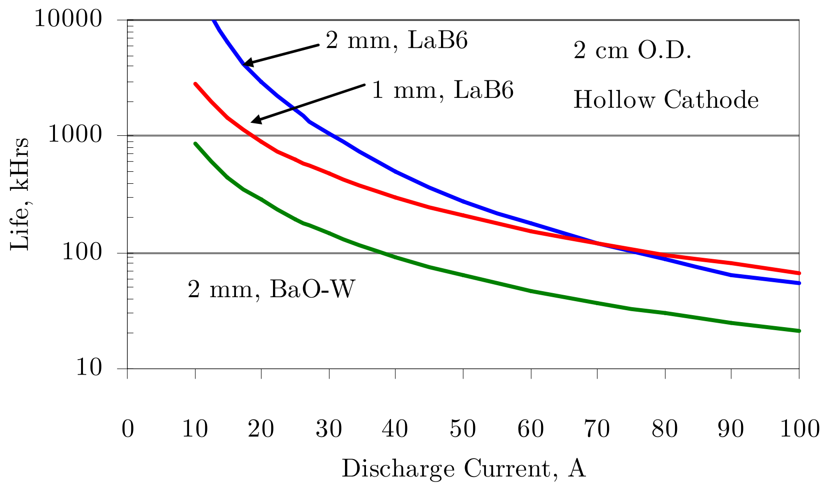

Figure 29. Cathode lifetime vs discharge current for BaO and LaB_6 cathodes.

B. Internal vs external cathode mounting

Consistent with Szabo, et al.[8], operation with the internally-mounted cathode resulted in a more collimated and symmetric plume than with an externally-mounted cathode. The current density distributions indicate the plume crossed centerline at greater than 17 cm (i.e., greater than one channel mid-diameter) with the internal cathode and less than 17 cm with the external cathode. This is in stark contrast with data taken on thrusters such as the SPT-100 or D-55, both of which use external cathodes, that have shown centerline crossings at less than one thruster diameter.[1,32,33] The BHT-8000 data therefore shows that internally-mounted cathodes can decrease plume divergence. The effect is likely due to the cathode plasma “filling” the space between the discharge chamber inner walls. This increases the plasma density and decreases the plasma pressure gradients that tend to pull the ion beam towards centerline.

Figure 30 through Figure 33 compare the ion current density distributions for the internal and external cathode configurations for a constant discharge power of 8 kW and discharge voltages of 200-500 V. In each figure, internal and external cathode operation are compared for axial sampling planes of 7 and 35 cm. For the external cathode data, the asymmetries on the left side of the current density distributions are due to the presence of the cathode. With the internal cathode operating, the plume displays a higher level of symmetry and is noticeably less divergent. The decreased plume divergence is evidenced by the rapid decrease of the current density from the peak of the distribution as well as the position of the pair of local maxima near centerline. These local maxima are due to the high-energy ion beam exhausting from either side of the discharge chamber. The net result is that the internal cathode configuration exhibits lower plume divergence than the external cathode case.

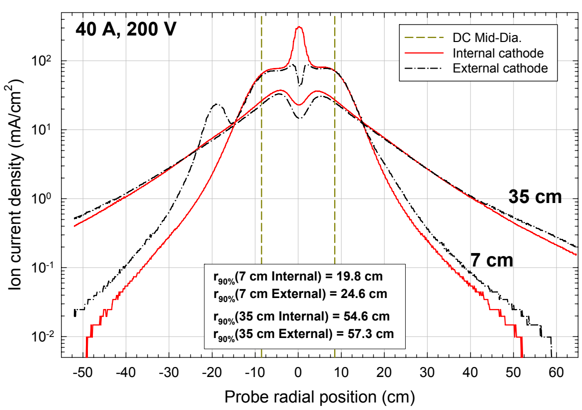

Figure 30. Current density comparison for the internal and external cathodes. (40 A, 200 V)

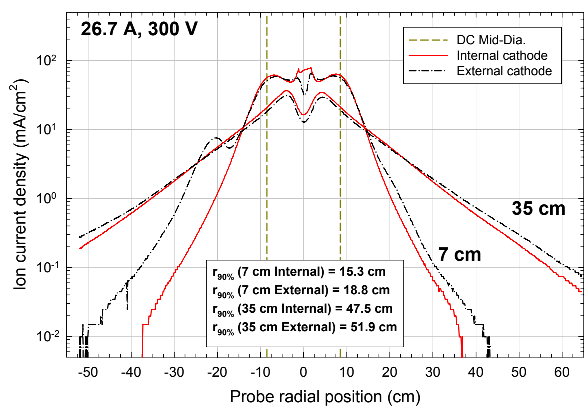

Figure 31. Current density comparison for the internal and external cathodes. (26.7 A, 300 V)

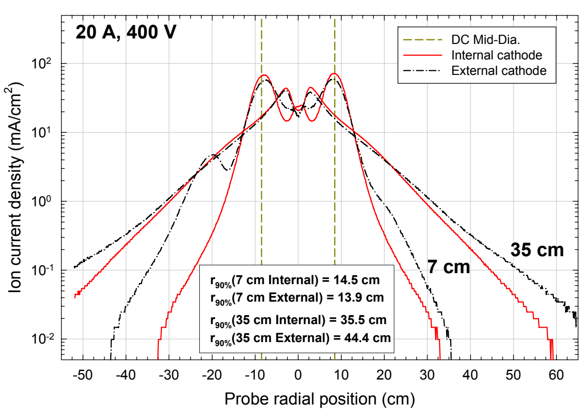

Figure 32. Current density comparison for the internal and external cathodes. (20 A, 400 V)

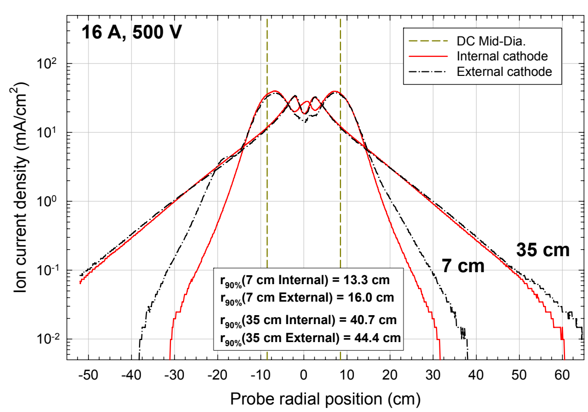

Figure 33. Current density comparison for the internal and external cathodes. (16 A, 500 V)

These qualitative observations are quantified in Figure 34, which plots the radial position from the outer wall of the discharge chamber that contains 90% of the total integrated flux at each axial location. Linear fits are applied and the corresponding divergence angles are computed. The divergence angles ranged from 37-54° for the internal cathode and 45-55° for the external cathode. As the current density distributions suggest, the internal cathode configuration always had a lower divergence angle than the external cathode configuration. Interestingly, the divergence with the internal cathode reached a minimum at 400 V, while the divergence with the external cathode continuously decreased with discharge voltage.

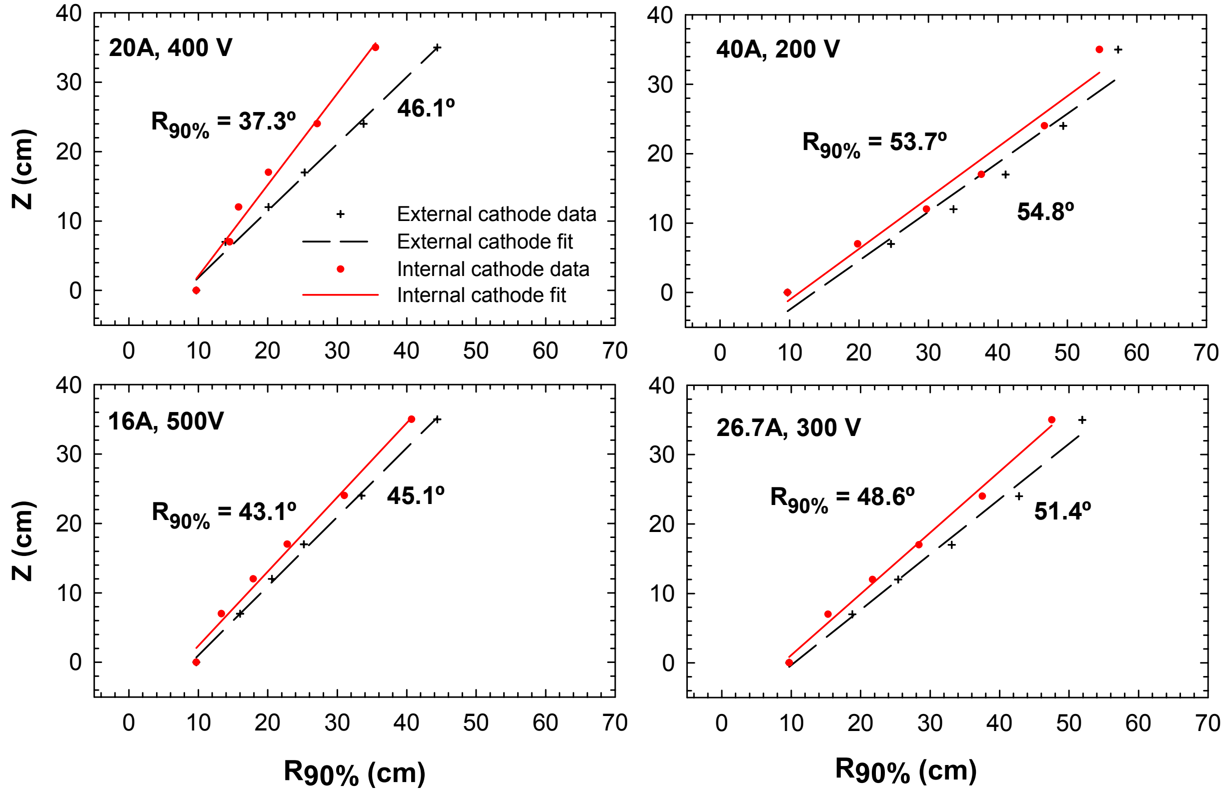

Figure 34. Plume divergence angles for internal and external cathode operation at 8 kW, 200-500 V.

Measurements comparing the internal and external cathodes have shown some important differences in the near-field plasma structure. Visual evidence showed the persistence of a large halo surrounding the thruster under external cathode operation that was not present with the internal cathode. Current density measurements have shown that external cathode operation exhibited higher plume divergence than internal cathode operation. Additionally, the current density measurements have also shown how an external cathode introduced asymmetries in the near-field plasma structure that were not present with the internal cathode. These types of asymmetries are known to cause asymmetric erosion of the thruster discharge chamber in the vicinity of the cathode. Thus, internal cathodes may reduce or eliminate azimuthal asymmetries in the erosion, which would increase thruster lifetime and, more importantly, increase the accuracy of thruster lifetime predictions derived from axisymmetric plasma simulations.[34]

Internal cathode arrangements also benefit spacecraft integration activities for at least two reasons. First, the symmetry improvements allow for more accurate estimates of the sputtering induced by the high-energy plasma exhaust interacting with spacecraft components (e.g., solar arrays). Secondly, the lower plume divergence eases the integration issues related to placement of the thrusters on the spacecraft bus.

Internal cathodes also offer some benefits for numerical simulations of the plasma discharge. Since Hall thruster plasma modeling with external cathodes has so far been limited to two spatial dimensions, modelers have always had to artificially introduce electrons in the simulations since the cathode location makes the problem three dimensional. The introduction of an internal cathode would allow the system to be more precisely modeled, which would presumably lead to results that more accurately reflect the physics of Hall thrusters. Fox has recently simulated a high-power Hall thruster with an internally-mounted cathode, with promising initial results.[35] In sum, internally mounted cathodes offer important benefits to understanding and predicting thruster physics, erosion, and spacecraft integration.

V. Conclusion

Experiments with the multi-mode Busek BHT-8000 Hall thruster have demonstrated the benefits of internal cathode mounting and the use of LaB_6 hollow cathodes. Vacuum facilities and thruster support equipment in-place at JPL have the demonstrated capabilities to serve as a reliable test-bed for future high-power Hall thruster development and qualification. Several plasma diagnostics have also been deployed that have provided new insight into the physics of Hall thruster operation. The use of an internal cathode instead of the traditional external cathode has been shown to result in reduced plume divergence and increased symmetry in the near-field plume. LaB_6 cathodes developed at JPL have also been demonstrated on a Hall thruster. LaB_6 technology offers several important benefits for electric propulsion systems, most notably the potential to reduce overall system cost and risk due to less stringent xenon purity and handling requirements.

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