Effects of Internally Mounted Cathodes on Hall Thruster Plume Properties

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***Abstract*—The effects of cathode position on the operation and plume properties of an 8-kW Hall thruster are discussed. Thruster operation was investigated at operating conditions ranging from 200 to 500 V of discharge voltage, 10–40 A of discharge current, and 2–8 kW of discharge power, with a cathode positioned either in the traditional externally mounted configuration outside the outer magnetic pole piece or in an internally mounted configuration central to the inner magnetic core. With the external cathode, substantial emission in the visible spectrum that follows magnetic field lines surrounds the exterior pole pieces of the thruster. With the internal cathode, the emission is largely absent while the cathode plume is compressed and elongated in the axial direction by the strong axial magnetic field on the thruster centerline. Discharge current oscillation and ion species fraction measurements were found to be similar for the cathode locations, whereas the operation with the internal cathode was found to favor an improved coupling of the cathode plume with the thruster discharge. Ion current density measurements show that with respect to externally mounted designs, internally mounted cathodes reduce plume divergence and increase the symmetry of the near-field plume. The impacts of internally mounted cathodes on thruster physics and spacecraft integration activities are assessed.**

***Index Terms*—Hall thrusters, hollow cathodes, plasma propulsion.**

I. Introduction

The use of electric propulsion (EP) on board spacecraft has steadily increased since the 1980s due to the rapid increase of in-space power, the rise of the global telecommunications industry, and the realization of commercial and government investment in EP technology dating to the early 1960s. While the majority of these spacecraft have used resistojets and arcjets, ion and Hall thrusters are now being widely adopted by nearly every major commercial satellite manufacturer due to the much higher efficiency and specific impulse that can be attained. Commercial satellites in the United States (U.S.) began using Hall and ion thrusters in 1997, and recently, more than 32 commercial geosynchronous Earth-orbiting communication satellites of U.S. origin have flown [1].

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 at thrust efficiencies between 50%–60%, 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 [2], [3].

Shown schematically in Fig. 1, the Hall thruster is constructed from four major components, which are the 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, which are 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 the neutralization of the ion exhaust.

Cathodes used with Hall thrusters have traditionally been mounted external to the magnetic circuit of the thruster. An illustration of an externally mounted cathode is shown on the left side of Fig. 1. Flight-model thrusters (e.g., SPT-100, PPS-1350, BHT-200, and BPT-4000) have, to date, made use of externally mounted cathodes. As the thruster power increases beyond a few kilowatts, the concomitant increase in the thruster size allows for the possibility of mounting the cathode on thruster centerline, internal to the inner magnetic core. An internally mounted cathode is shown on the right side of Fig. 1.

The concept of an internally mounted cathode has, for decades, been occasionally discussed in the Russian literature but was probably never seriously studied due to the low power thruster designs that were being developed then for flight applications (i.e., less than 1.5 kW). The first reported use in the U.S. of an internally mounted cathode was by Manzella *et al.*, in 2002, on a 50-kW Hall thruster [4]. In 2004, Szabo *et al.* [5] reported the use of an internally mounted cathode on the 8-kW Busek BHT-8000 Hall thruster that is the subject of this paper. Additional high-power Hall thruster designs with internal cathode mounting have been reported in [6]–[10]. Beal *et al.* [11] studied the effects of cathode positioning in clusters of Hall thrusters. In this paper, we study how external and internal mounting schemes affect the operating characteristics and plume divergence of the 8-kW thruster described in [5]. Our results complement several other investigations that have studied how to affect plume divergence. For example, the plume divergence has been shown to be affected

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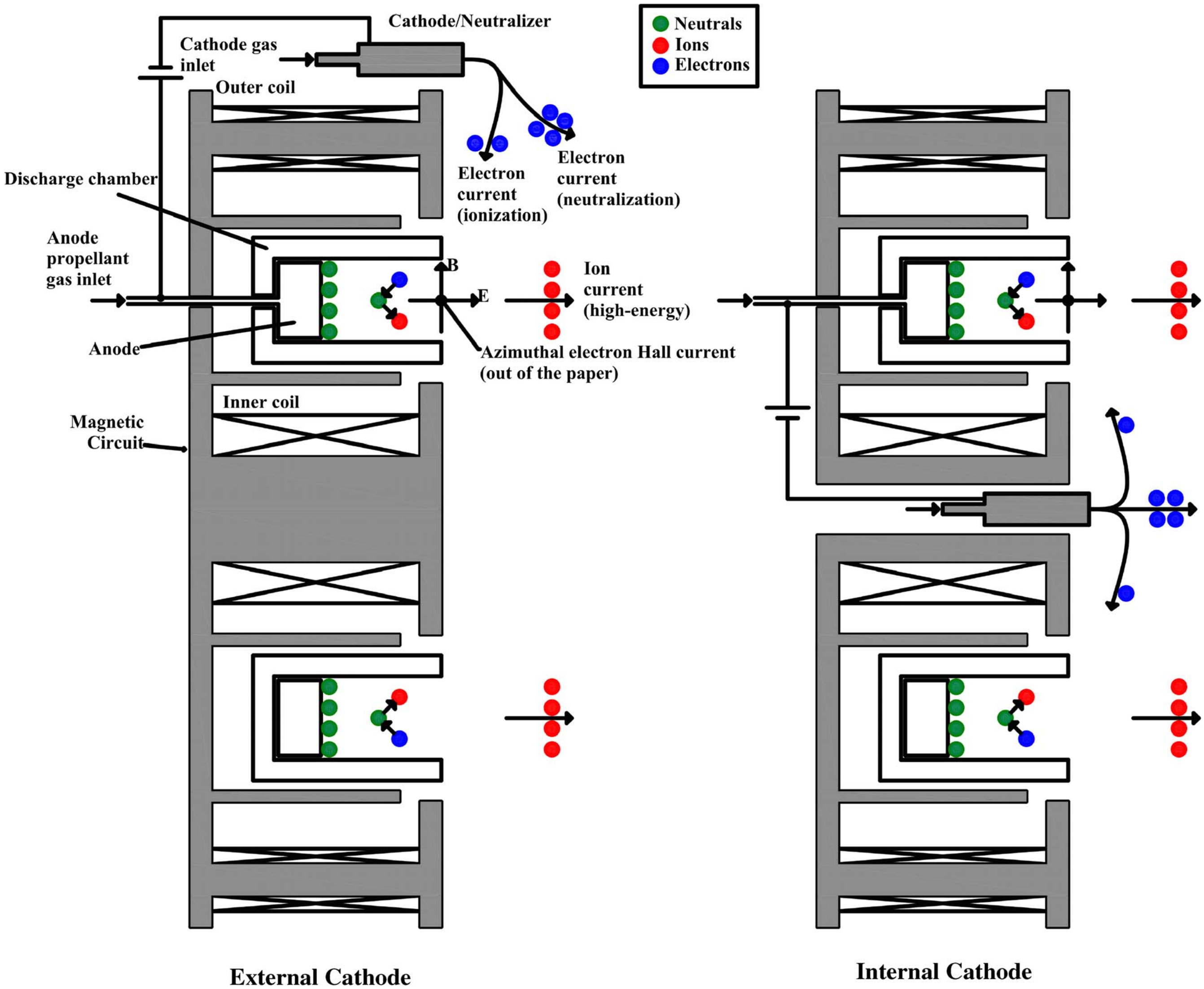

Fig. 1. Cross-sectional schematic of Hall thrusters using (left) external or (right) internal cathode mounting (not to scale).

by magnetic field shape, intensity, and the use of segmented electrodes [2], [12]–[15].

In this paper, we discuss experiments conducted at the Jet Propulsion Laboratory (JPL) with an 8-kW Hall thruster using internal and external cathode mounting configurations. Several diagnostics were employed, including discharge current, ExB, and Faraday probes. Discharge current oscillation and ion species fraction measurements were found to be similar for the cathode locations, whereas operation with the internal cathode was found to favor the improved coupling of the cathode plume with the thruster discharge. Of primary importance, we find that with respect to external cathode designs, internal cathode configurations result in decreased plume divergence and improved plume symmetry.

II. Experimental Apparatus

A. Busek BHT-8000 Hall Thruster

The thruster used in these experiments was a laboratory model, which is the Busek BHT-8000 Version 2 Hall thruster [5]. Fig. 2 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 multimode 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 [16].

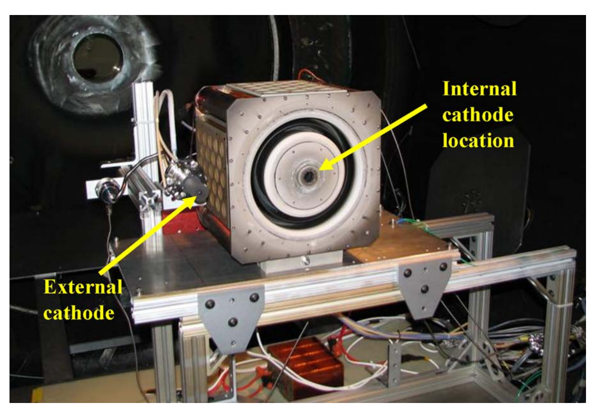

Fig. 2. BHT-8000 installed in the ETF at the JPL.

B. Hollow Cathodes

Two types of hollow cathodes were used in the experiments, namely, an internally mounted barium oxide (BaO) dispenser cathode and an externally mounted lanthanum hexaboride (LaB_6) cathode. The BaO cathode was mounted on thruster centerline, which is slightly recessed upstream of a hollow section of the inner magnetic pole. The LaB_6 cathode was mounted external to the thruster outer front pole, as shown in Fig. 2. The major axis of both cathodes was aligned parallel with the thrust axis of the BHT-8000. Although no attempts were made to optimize the thruster operation through variations in the position of the external cathode, the position used was typical of Hall thrusters with optimized cathode locations [17]. For each operating condition, the xenon mass flow rate through the cathode was maintained at 10% of the anode mass flow rate such that the cathode mass flow rate was the same regardless of the cathode location.

Barium-oxide (BaO)-impregnated dispenser cathodes have been used in the U.S. aerospace industry in ion and Hall thrusters, plasma contactors, and plasma neutralizers since the 1960s. In contrast, over 238 Russian Hall thrusters have successfully flown on over 48 spacecraft since 1971 using lanthanum hexaboride (LaB_6) hollow cathodes [18]. LaB_6 cathodes are being investigated at the JPL due to their long life, high current capabilities, and less stringent xenon purity and handling requirements compared with the BaO cathodes. Goebel *et al.* [19] provide an extensive review of LaB_6 cathode development.

The original LaB_6 cathode developed at the JPL for thruster applications [19] had a 1.3-cm outer diameter cathode tube and demonstrated 100 A of discharge current at xenon flow rates of 0.88 mg/s. To provide lower insert temperatures and a 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 that it is scaled in radius to the large diameter. Until these experiments, the 2-cm LaB_6 cathode had not been tested with a Hall thruster. Investigations of material choice, heater design, and cathode construction are ongoing at the JPL.

C. Vacuum Facility

Experiments were performed in the Endurance Test Facility (ETF) at the JPL. The 3-m-diameter by 10-m-long vacuum chamber was previously used for the 30-kh 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 [20], [21]. The facility is cryogenically pumped and typically achieves a base pressure between 10^{-8} and 10^{-7} torr. Fig. 3 shows the backpressure versus xenon flow rate during the thruster operation at 8 kW, as measured by a xenon calibrated ionization gauge located below the thruster. Over xenon flow rates of 17–34 mg/s, the operating pressure in the ETF ranged from 1×10^{-5} to 2×10^{-5} torr.

It is generally accepted in the Hall thruster community that pressures of less than 2.0×10^{-5} torr are sufficient to reliably obtain performance measurements without needing to correct for neutral gas ingestion [2], [22], [23]. Backpressures approaching 10^{-4} torr are generally the upper limit before facility effects begin to drastically influence the thruster stability. Thus, the JPL ETF, which sustained a pressure of 2×10^{-5} torr at 34 mg/s (8 kW) and which has also successfully tested 20-kW ion thrusters, has the demonstrated capability to be a reliable test bed for high-power Hall thruster development and qualification.

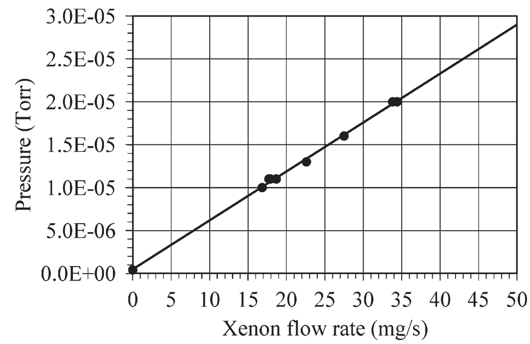

Fig. 3. Chamber pressure in the ETF versus xenon mass flow rate during thruster operation at 8 kW.

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, which provided a maximum output consisting of 500 V and 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. Research-grade 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 $\pm 1\%$ of the set point.

E. Discharge Current Probe

A 20-MHz current monitor and an 8-b 1-GHz oscilloscope were used to measure the discharge current oscillations during steady-state thruster operation with an accuracy of $\pm 3\%$. The current probe was mounted inside the vacuum chamber on the anode side of the power input between the thruster and capacitor described earlier. Oscillations were quantified by calculating the oscillation amplitude of the discharge current defined by

$$\Delta \equiv \frac{1}{\langle I_d \rangle} \sqrt{\frac{\int_0^{\tau} [I_d(t) - \langle I_d \rangle]^2 \, dt}{\tau}} \tag{1}$$

where $I_d(t)$ is the time-dependent discharge current, $\langle I_d \rangle$ is the time-averaged discharge current, and τ is the sampling period.

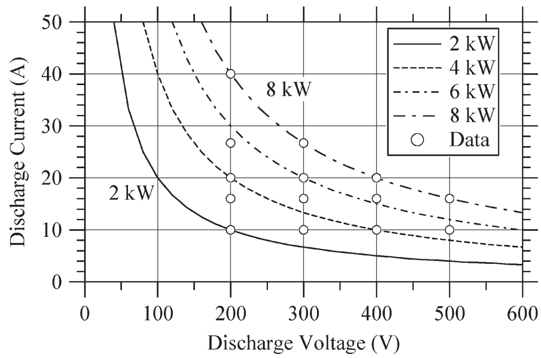

Fig. 4. Discharge current and voltage operating conditions investigated in the BHT-8000 experiments. Lines of constant power are included for reference.

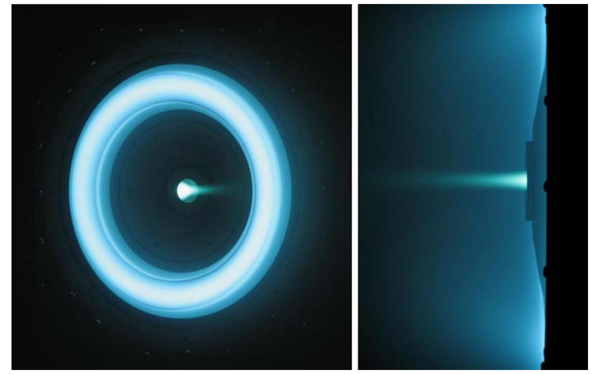

Fig. 5. Photographs of the BHT-8000 operating at 300 V and 26.7 A (8 kW) with the internal cathode.

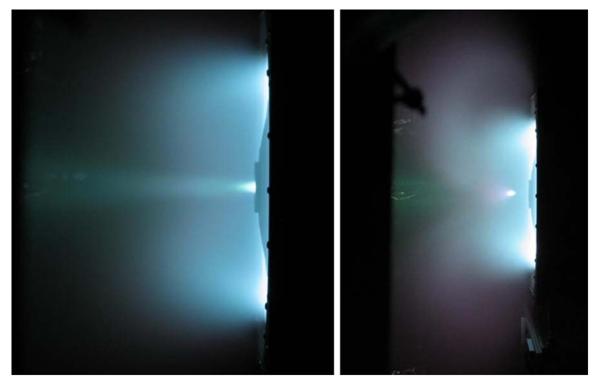

Fig. 6. Photographs of the BHT-8000 operating at 500 V and 16 A (8 kW) with the (left) internal and (right) external cathodes. With the external cathode, a "halo" that follows the magnetic field lines surrounds the thruster. The halo is not present during internal cathode operation.

F. ExB Probe

An ExB probe, or Wien filter, is a bandpass ion filter that selects ions according to their velocities through the application of crossed electric and magnetic fields [24]–[26]. Considering that 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. The analysis of the ion current from the probe characteristic can then be used to compute the ion species fractions.

The ExB probe used in these experiments was previously used during the NSTAR extended-life test at the JPL [20]. The probe was positioned 5 m downstream of the thruster exit plane on thruster centerline. A correction was made for the loss of multiply charged xenon ions due to charge-exchange collisions with the neutral background gas [27]. 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 Probe

Surveys of the ion current density in the thruster plume were taken using a Faraday probe. The probe was used to conduct radial surveys from thruster centerline at axial distances ranging from 7 to 35 cm from the thruster exit plane. The 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. The 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 the facility ground to repel electrons.

III. RESULTS

Multimode high-power operation of the Hall thruster was investigated at thruster operating conditions ranging from 200- to 500-V discharge voltage, 10- to 40-A discharge current, and 2- to 8-kW discharge power. Fig. 4 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 the loss of stability, the ability of the thruster to return to the same discharge conditions after restarts, and the stability of the discharge current over long periods of time (drifts were typically no more than 0.1–0.2 A over timescales of 30–60 min). The total thruster operating time was 21 h. A continuous operation of more than 4 h was demonstrated during three different runs. During each of these runs, the thruster continuously spent more than 2 h at 8 kW.

Fig. 5 shows the photographs of the thruster operating at 300 V and 26.7 A (8 kW) with the internal cathode. Fig. 6 are photographs comparing the visual appearance of the near-field plasma structure during operation at 500 V and 16 A (8 kW) with either the internal or external cathode. As previously observed by Szabo *et al.* [5], the visual appearance of the internal cathode plume was markedly different than that of the external cathode. With the internal cathode operating, the cathode plume was compressed and elongated in the axial direction by the axial magnetic field emanating from the inner magnetic circuit of the thruster. The plasma exhaust was collimated and appeared to be axially well directed (these observations were also supported by the current density measurements discussed later). There was also a notable absence of emission in the visible spectrum surrounding the exterior pole pieces of the thruster. This plasma "halo," which is typical of external cathode configurations, is shown in the right photograph in Fig. 6. Note how the halo in

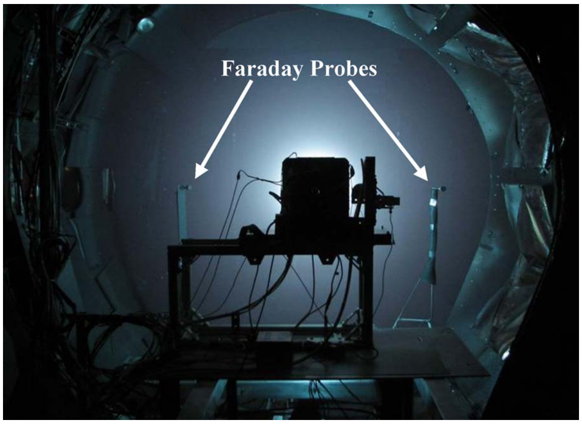

Fig. 7. Photograph taken from the rear of the BHT-8000 during operation at 200 V and 40 A (8 kW) with the internal cathode. Faraday probes used to measure the ion current density can be seen on opposite sides of the thruster.

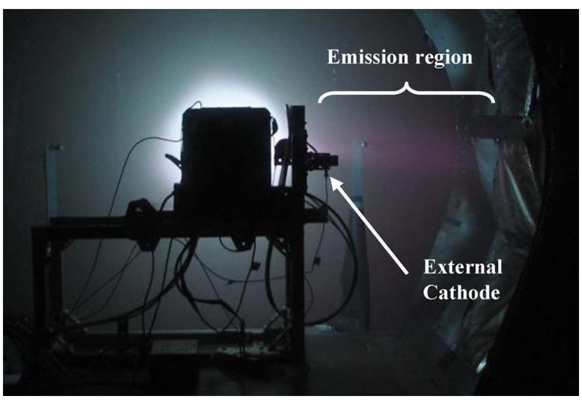

Fig. 8. Photograph taken from the rear of the BHT-8000 during operation at 300 V and 26.7 A (8 kW) with the external cathode operating. Note the red tinted emission to the right of the thruster in the photograph. This region is not present during internal cathode operation (see Fig. 7).

Fig. 6 has a reddish tint and appears to follow magnetic field lines. The red tint is indicative of emission from xenon neutrals, which is most likely from collisions with cathode electrons that are trapped on the magnetic field lines.

Fig. 7 is a photograph taken from the rear of the thruster at an operating condition with 200 V and 40 A (8 kW) with the internal cathode, whereas Fig. 8 is a similar view under a 300-V and 26.7-A (8 kW) operation with the external cathode. Note the red emission to the right of the external cathode in Fig. 8. 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 Fig. 6).

In these experiments, cathodes with different emitters were used in different mounting locations. To assess the possible effects of these variables on the thruster operation, the measurements of cathode floating potential, discharge current oscillations, ion species fractions, and current density were taken.

Fig. 9 shows the cathode floating potential with respect to the vacuum chamber electrical ground as a function of the discharge current during the thruster operation at 8 kW. The internally mounted BaO cathode potential was roughly constant between the 16- and 40-A discharge current, ranging from -10 to -13 V. The externally mounted LaB_6 cathode potential

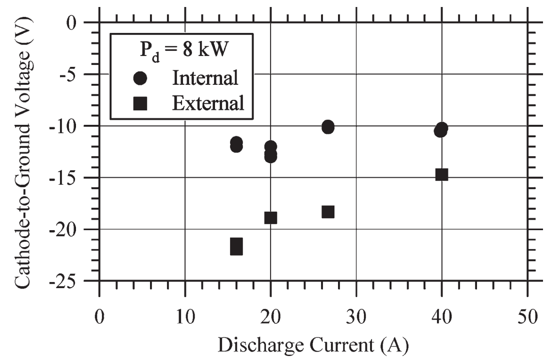

Fig. 9. Cathode to ground coupling voltage versus discharge current for the internally and externally mounted cathodes during thruster operation at 8 kW.

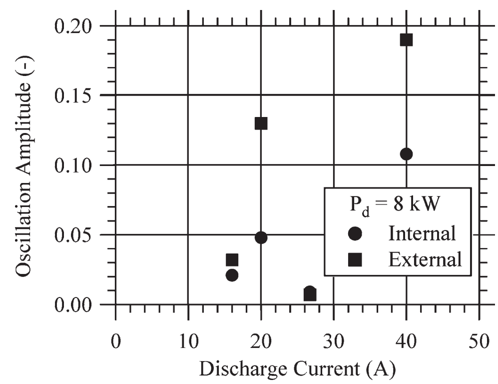

Fig. 10. Amplitude of discharge current oscillations versus discharge current during operation with the internal and external cathodes at a constant discharge power of 8 kW.

ranged from -22 to -15 V as the discharge current increased from 16 to 40 A. These coupling voltages are typical of the -10 to -20 V usually achieved in Hall thrusters with optimized cathodes [2]. Of whether the differences in the coupling voltages at the same operating condition were primarily determined by the emitter material or the cathode location is discussed in the next section.

Fig. 10 shows the amplitude of the discharge current oscillations versus the discharge current during operation with the internal and external cathodes at a constant discharge power of 8 kW. The oscillation amplitude ranged from 1% to 19%, depending on the operating condition, which are typical values for the Hall thrusters [2]. There was some indication that the external cathode was increasing the oscillation amplitude at certain operating conditions; however, no consistent trend emerged.

Table I shows the ion species fractions on thruster centerline at 8 kW and 300–500 V during operation with the internal and external cathodes. The Xe^{+} ion species fraction ranged from 94% to 95%, and the Xe^{2+} fraction was 5%–6%. These are typical results for Hall thrusters operating at discharge voltages of 300–500 V [28]. Within the margin of error, the measurements were identical for the cathode positions and operating conditions. Additional measurements, particularly at angles off thruster centerline, are needed to better quantify the possible effects of cathode position on the ion species fractions.

TABLE I
ION SPECIES FRACTIONS ON THRUSTER CENTERLINE AT 8 kW AND 300–500 V DURING OPERATION WITH THE INTERNAL AND EXTERNAL CATHODES

Cathode	V_d (V)	Species Fraction		
		Xe^{+}	Xe^{2+}	Xe^{3+}
Internal	300	95%	5%	<0.5%
	400	94%	6%	<0.5%
	500	94%	6%	<0.5%
External	300	95%	5%	<0.5%
	400	95%	5%	<0.5%
	500	95%	5%	<0.5%

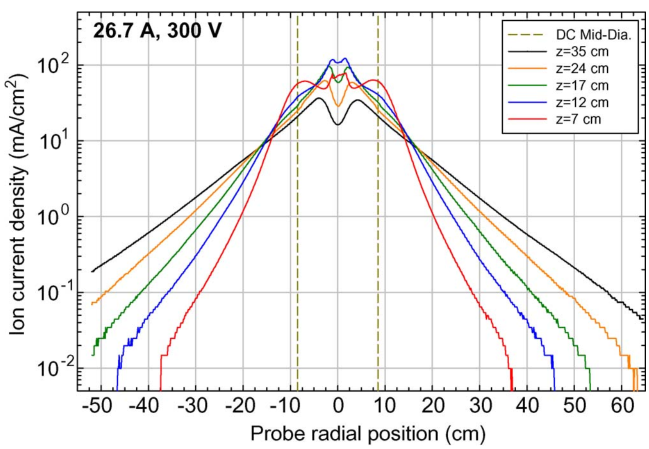

Fig. 11. Current density versus probe position (internal cathode, 26.7 A and 300 V).

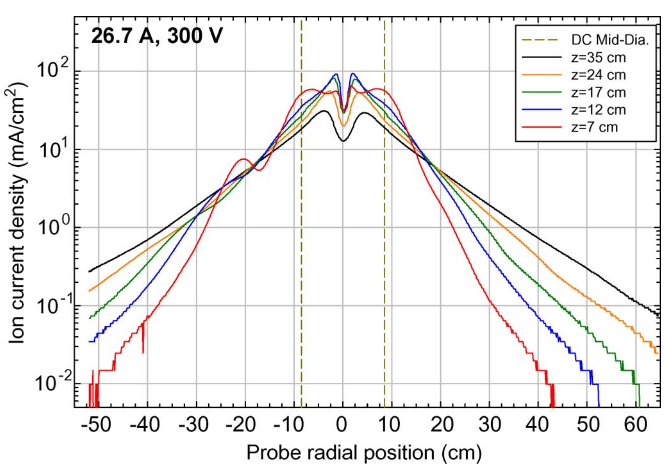

Fig. 12. Current density versus probe position (external cathode, 26.7 A and 300 V).

Ion current density data were collected with the Faraday probe 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. 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 thruster exit plane. The probe face was always aligned perpendicular to the axis defined by thruster centerline.

Figs. 11 and 12 are representative results from the entire data set showing ion current density over the sampling domain for operation at 300 V and 26.7 A with the internal and external cathodes, respectively. The cathode plume is evident with either location at 7 cm from the thruster. Regardless of cathode position, the thruster produces a low divergence ion beam, as evidenced by the double peak structure of the ion current density profiles at distances of 35 cm.

IV. DISCUSSION

Measurements comparing the internal and external cathodes have shown some important similarities and differences in the thruster properties. The visual observations of the plume have shown the persistence of a large halo of emission surrounding the thruster under an external cathode operation that was not present in the internal cathode. This confirms the earlier results on the BHT-8000 by Szabo *et al.* [5], where visual observations were reported, indicating that the operation with the internal cathode resulted in a more collimated and symmetric plume than with the external cathode.

Discharge current oscillation and ion species fraction measurements were found to be similar for the cathode locations, which indicates that the effects of the cathodes were largely confined to the near-field plume. However, over all the operating conditions, the internal cathode was found to improve the cathode coupling potential with respect to the external cathode operation. The differences in the coupling voltages at the same operating condition could be the result of either the emitter material or the cathode location. It can be expected that some small fraction of the coupling voltage difference would be due to the emitter considering that at constant current and geometry, a LaB_6 emitter should require larger coupling voltages than a BaO emitter because the emitter must be maintained at a higher temperature [19]. However, Jameson *et al.* [9], [10] have reported experiments with a 6-kW Hall thruster that considered how identical internally and externally mounted LaB_6 cathodes affect the cathode operation, thruster performance, and plume characteristics. Over a discharge voltage range of 150–500 V and a constant power of 6 kW, it was found that the internally mounted cathode configuration resulted in improved cathode coupling, superior performance, and reduced plume divergence. The differences in the coupling voltage due to the cathode locations reported in [9] and [10] were between 6 and 11 V. These are almost identical to the differences shown in Fig. 9, which shows a difference of 5–10 V. Taken together, the results presented in this paper and those of [9] and [10] demonstrate that the cathode location is the driving mechanism in the improved coupling voltages. Regardless of the emitter used, mounting the cathode on the thruster centerline favors the improved coupling of the cathode plume with the thruster discharge.

The effects of cathode position on the plume are considered in more detail in Figs. 13–16 that compare the ion current density distributions for the internally and externally mounted cathodes for a constant discharge power of 8 kW and discharge voltages of 200–500 V. In each figure, the internal and external cathode operations are compared for axial sampling planes of 7 and 35 cm. For the external cathode data, the asymmetries of the current density distributions at negative radial positions are due to the presence of the cathode. With the internal cathode

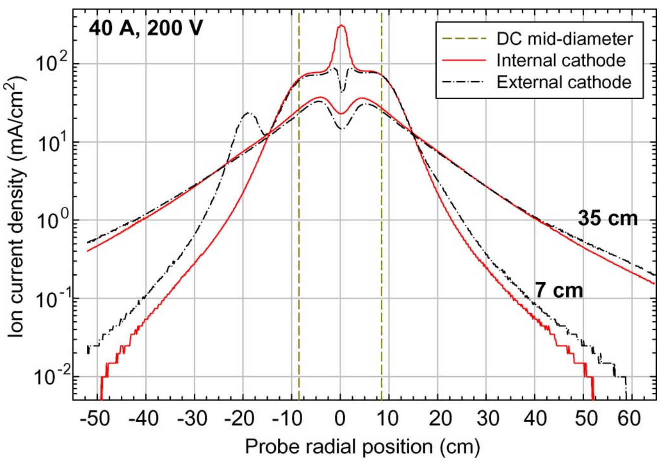

Fig. 13. Current density comparison for the internal and external cathodes (40 A and 200 V).

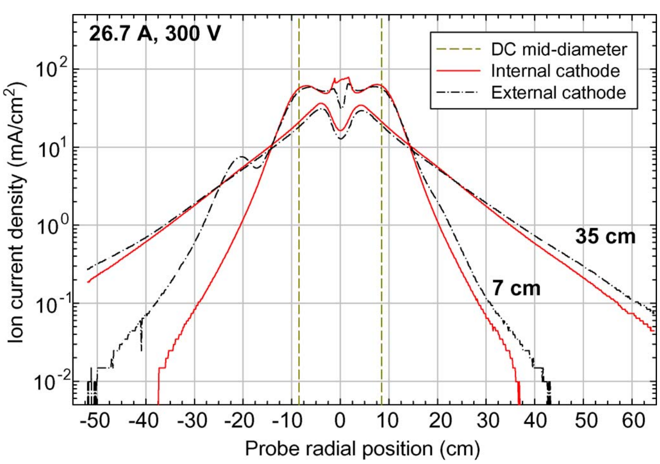

Fig. 14. Current density comparison for the internal and external cathodes (26.7 A and 300 V).

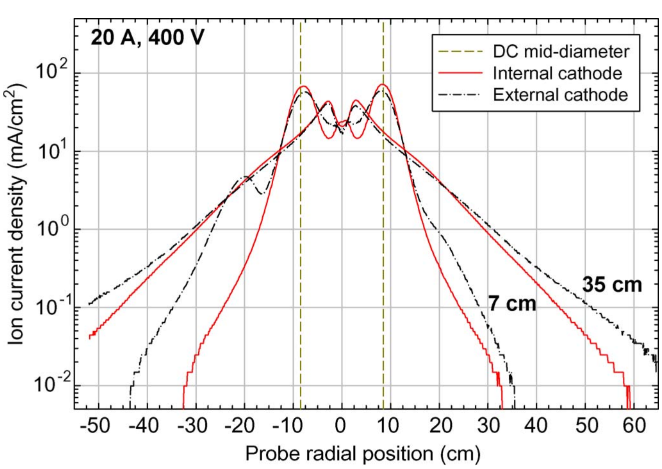

Fig. 15. Current density comparison for the internal and external cathodes (20 A and 400 V).

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 and the position of the pair of local maxima near the centerline. These local maxima are

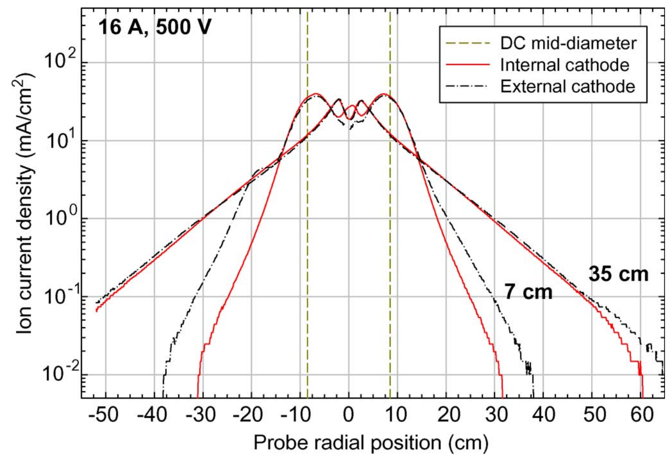

Fig. 16. Current density comparison for the internal and external cathodes (16 A and 500 V).

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 a lower plume divergence than the external cathode case. Considering that the same results were found for the experiments in [9] and [10] discussed earlier, we conclude that a Hall thruster with an internally mounted cathode should exhibit a lower plume divergence than an externally mounted configuration, regardless of the emitter material used.

These qualitative observations are quantified in Fig. 17, which shows the radial position from the outer wall of the discharge chamber that contains 90% of the total integrated flux at each axial location. The calculation was performed for the side of the thruster opposite the location of the external cathode. Linear fits are applied, and the corresponding divergence angles are computed. The divergence angles ranged from 37° to 54° and 45° to 55° for the internal and external cathodes, respectively. 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, whereas the divergence with the external cathode continuously decreased with the discharge voltage.

The BHT-8000 data indicate that internally mounted cathodes can decrease the plume divergence. The effect could be due to the cathode plasma "filling" the space between the inner walls of the annular discharge chamber. This is explained by considering the electron momentum equation. The high-energy plume of a Hall thruster is well approximated as unmagnetized and collisionless such that the electron momentum equation may be reduced to

$$\vec{E} = -\frac{\nabla p}{n_e e} \tag{2}$$

which governs the evolution of the plume. In the radial direction, a plasma pressure gradient would induce an ambipolar electric field that can alter the trajectory of ions. With the externally mounted cathodes, the plasma density on the thruster centerline is significantly lower than the high-energy exhaust. This situation can induce electric fields that increase the radial

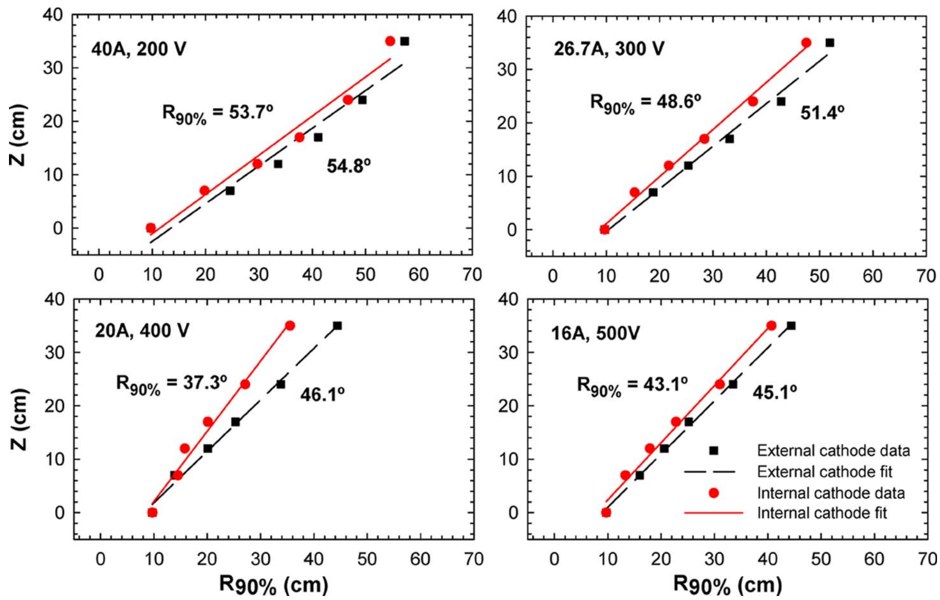

Fig. 17. Plume divergence angles for internal and external cathode operation at 8 kW and 200–500 V.

ion velocity, causing the beam to cross the thruster centerline at an axial position closer to the thruster than when these density gradients are not present (i.e., when an internal cathode fills the space with plasma). If an internal cathode reduces the radial electric fields in the near-field plume, the result should be a decrease in the plume divergence because the ion beam will cross the thruster centerline further downstream.

Equation (2) implies that increasing the plasma density on the centerline with the internally mounted cathode could decrease the radial plasma pressure gradients that induce an ambipolar electric field that tends to pull the ion beam toward the centerline. To test this hypothesis, we then ask the following: Assuming that the conditions at the exit plane of the discharge chamber are identical for both cathode locations, is the change in plume character due to the internal cathode sufficient to explain the difference in the divergence angle? To examine this, we use a first-order analysis considering the trajectory of a representative ion that is accelerated from the channel. The goal of this analysis is to find an approximation for a change in the plume electric field that will result in the observed change in plume divergence. The motion of the unmagnetized ions leaving the discharge chamber is described by

$$\frac{d\,\vec{\nu}}{dt} = \frac{q\,\vec{E}}{m}. \tag{3}$$

To approximate the average radial electric field that must act on the particle to explain the divergence, we assume that the axial component of the velocity is nearly unchanged $E_z \approx 0$ such that

$$\frac{\Delta\nu_r}{\Delta t} = \frac{qE_r}{m}. \tag{4}$$

We assume that the internal cathode plume affects the radial electric field upstream of the plume-crossing location which is approximately one thruster diameter D downstream. Therefore, the time during which the radial electric field is acting is $\Delta t = D/\nu_z$.

The required change in the angle of the ion velocity vector relative to the thruster axis $\Delta\theta$ is taken to be identical to the observed change in the plume divergence angle. We will estimate $\Delta\theta$ for a representative particle that starts at the channel exit with an initial velocity vector that intersects the plume crossing location; considering that the channel exit is located at $r = D/2$, the initial velocity ratio is $\nu_r/\nu_z = 0.5$ [29]. The axial ion energy is estimated to be the discharge voltage minus a 50-V loss voltage [30]. The relationship between $\Delta\theta$, the initial velocity, and the required change in radial velocity is

$$\Delta\theta = \tan^{-1}\left(\frac{\nu_r}{\nu_z}\right) - \tan^{-1}\left(\frac{\nu_r - \Delta\nu_r}{\nu_z}\right). \tag{5}$$

Therefore, the required change in radial velocity is simply

$$\Delta\nu_r = \nu_r - \nu_z \tan\left[\tan^{-1}\left(\frac{\nu_r}{\nu_z}\right) - \Delta\theta\right]. \tag{6}$$

Table II shows the required electric fields for operation at a constant power of 8 kW and discharge voltages of 200–500 V. The average radial electric field range needed to describe the change in plume divergence is within the range of values that are typically measured in near-field Hall thruster plumes [9], [11]. Thus, our hypothesis, which states that the plasma from the internal cathode acts to “fill” the interior regions of the plume and thereby decreases the pressure gradients that induce radial electric fields, should not be considered unreasonable. Furthermore, note that this mechanism is independent of the emitter type used in the hollow cathode, considering that all that is required is a sufficiently dense plasma from the cathode to decrease the density gradients that would otherwise persist along the thruster centerline. The larger field value required for a discharge voltage of 400 V may require additional influences such as discharge current oscillations. Discharge current

TABLE II
ESTIMATION OF RADIAL ELECTRIC FIELD REQUIRED IN THRUSTER PLUME TO ACCOUNT FOR DIFFERENCES IN PLUME DIVERGENCE ANGLE FOR EXTERNAL AND INTERNAL CATHODE POSITIONS

Parameter	Units	Operating Condition			
		40 A, 200 V	**26.7 A, 300 V**	**20 A, 400 V**	**16 A, 500 V**
Discharge voltage, V_d	(V)	200	300	400	500
Accelerating voltage, V_{accel}	(V)	150	250	350	450
Divergence angle (external cathode)	(°)	54.8	51.4	46.1	45.1
Divergence angle (internal cathode)	(°)	53.7	48.6	37.3	43.1
Difference in divergence angle, $\Delta\theta$	(°)	1.1	2.8	8.8	2
Assumed initial angle of ion	(°)	26.6	26.6	26.6	26.6
$\lvert\mathbf{v}\rvert$	(m/s)	14793	19098	22597	25623
v_z	(m/s)	13231	17082	20211	22918
v_r	(m/s)	6616	8541	10106	11459
Δv_r	(m/s)	315	1019	3630	983
Δt	(s)	1.47E-05	1.14E-05	9.65E-06	8.51E-06
Required average radial electric field, E_r	**(V/m)**	**29**	**122**	**516**	**158**

oscillations of sufficient intensity to affect plume divergence have been observed in other thrusters [2]. This analysis does not account for the minor changes to the discharge exit conditions that may arise from the internal cathode conditions; therefore, it may be of interest to investigate these effects with a detailed multidimensional Hall thruster model that can account for this behavior.

Our results demonstrate how the use of internally mounted cathodes can positively impact the operating characteristics of Hall thrusters. How these benefits affect other aspects of Hall thrusters, as well as some of the potential drawbacks of internal cathodes, is discussed in the following.

Internal cathode arrangements provide several potential benefits to spacecraft integration activities and our understanding of thruster physics. The benefits are driven by the improved plume symmetry and lower plume divergence that internal cathodes provide. Asymmetries due to external cathode placement are known to cause the asymmetric erosion of the thruster discharge chamber. Reducing these asymmetries with an internal cathode could potentially increase thruster life and, more importantly, increase the accuracy of lifetime models that typically do not resolve this 3-D feature of erosion [31]. Axisymmetric numerical simulations of the plasma discharge, such as HPHall-2 [32], which must artificially introduce electrons for external cathode mounting, also benefit because the system can now be more precisely modeled. The beam symmetry also improves the fidelity of plume codes used to predict the sputtering of sensitive spacecraft components (e.g., solar arrays). In concert with the lower plume divergence, the improved beam symmetry also eases integration issues related to thruster placement on the spacecraft bus.

The potential drawbacks of internally mounted cathodes include issues related to thermal and mechanical integrations and cathode erosion. The internal mounting scheme can potentially lead to overheating of the thruster's inner magnetic circuit due to radiation from the hot cathode insert. However, as evidenced by several thrusters now employing internal cathodes, careful thermal engineering can resolve these concerns. Internal cathodes are also typically cantilevered from the back pole of the thruster's magnetic circuit. The cathode body is then suspended over a large moment arm, which can present challenges for meeting the vibration requirements during spacecraft launch. However, the careful mechanical engineering of the cathode mounting scheme can resolve these concerns. Finally, the placement of the cathode on thruster centerline may potentially increase the erosion of the cathode keeper. This central region of the thruster, which is largely unstudied in the Hall thruster literature despite nearly five decades of research, is characterized by an axially diverging magnetic field with an intensity on the order of the peak field strength in the discharge chamber (i.e., 100–300 G). Thus, the thruster centerline may act as an efficient trap for low-energy ions created near the exit plane of the thruster. Depending on the potential structure that is created due to the presence of the cathode, ions may be accelerated back to the cathode keeper, increasing the erosion rate. While this may be an issue, it is worth noting that inner core erosion is negligible in external cathode arrangements, and similar to the thermal and mechanical issues discussed earlier, careful attention to the materials used in the cathode design is expected to ameliorate any potential drawbacks of internally mounted cathodes. Investigations aimed at better understanding this region of the thruster plume and its effects on cathode coupling and erosion are ongoing [9], [10].

V. CONCLUSION

Experiments with a multimode high-power Hall thruster were performed, demonstrating the benefits of an internally mounted cathode over the traditional externally mounted configuration. The primary result of these experiments is that with respect to external cathode designs, internal cathodes reduce plume divergence and increase the plume symmetry in the near-field plume.

Visual observations during internal cathode operation revealed a plume that was markedly different than that in the operation with the external cathode. With the external cathode, substantial emission in the visible spectrum surrounds the thruster in a "halo." With the internal cathode, the halo is largely absent while the cathode plume is compressed and elongated in the axial direction by the strong axial magnetic field on thruster centerline.

Measurements comparing the internal and external cathodes have shown some important similarities and differences in thruster properties. Discharge current oscillation and ion species fraction measurements were found to be similar for the cathode locations, and the internal cathode operation was found to favor the improved coupling of the cathode plume with the thruster discharge. Over the range of operating conditions investigated, the internal cathode configuration always had a lower divergence angle and higher degree of symmetry than the external cathode configuration. The effect could be due to the cathode plasma "filling" the space between the discharge chamber inner walls. Increasing the plasma density on the centerline would decrease the plasma pressure gradients that tend to pull the ion beam toward the centerline. This hypothesis was supported by a first-order analysis of the radial electric fields induced by plasma density gradients, which would be needed to match the change in the measured plume divergence. Considering that it was found that the required electric fields were similar to electric fields already measured in the near-field of Hall thruster plumes, the proposed mechanism for the reduction in the plume divergence should not be considered unreasonable.

Internal cathode arrangements provide several potential benefits to spacecraft integration activities and our understanding of thruster physics. The potential drawbacks of internally mounted cathodes include issues related to thermal and mechanical integrations and cathode erosion. While it is currently thought that the benefits outweigh any potential drawbacks, investigations aimed at better understanding this region of the thruster plume and its effects on cathode coupling and erosion are ongoing.

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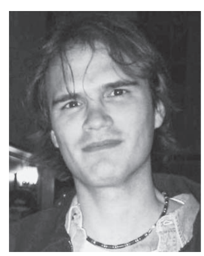

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