Cathode Position and Orientation Effects on Cathode Coupling in a 6-kW Hall Thruster

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Abstract: **Cathode coupling effects in a Hall thruster are presented in an experimental study comparing operation with an external LaB$_6$ hollow cathode at varied positions and orientations to nominal operation with a nearly identical center-mount internal cathode. The study is performed on a 6-kW laboratory model Hall thruster, a joint development effort of the Air Force Research Laboratory, the Jet Propulsion Laboratory and the University of Michigan. Testing is performed at the nominal design point of 300 volts and 20 mg/s. The plasma potential is measured via Langmuir probe in the far field plume and used with the cathode floating voltage to determine the cathode coupling voltage. Efficiency is calculated using thrust measurements from a null-type inverted pendulum thrust stand. Use of the internal cathode gives peak anode efficiency at least 3% greater than all external cases. Among the external operating cases the farthest separation distances are found to yield the best performance, including an improved cathode coupling voltage over the internal cathode baseline.**

Nomenclature

η_V	=	amplitude of oscillation
Θ	=	angle between thruster centerline and cathode
V_b	=	cylinder diameter
V_c	=	coupling voltage
V_d	=	discharge voltage
V_{cg}	=	cathode floating potential or cathode to ground voltage
V_{pg}	=	plasma potential or plasma to ground voltage

I.   Introduction

A Hall thruster or Hall-effect thruster (HET) is a class of electric space propulsion device using electric and magnetic fields to accelerate ions and produce thrust. In a typical HET the cathode supplies electrons to an annular discharge chamber, where crossed electric and magnetic fields induce an azimuthal drift known as the Hall current. The anode rests at the rear of the discharge chamber where it doubles as the distributor for the propellant: xenon or, less commonly, krypton. Inelastic collisions between Hall current electrons and neutral propellant atoms

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create ions which, too massive to be caught in the magnetic field, accelerate through the electric field reaching speeds of tens of kilometers per second.

An active area of HET research is into the mechanism of anomalous electron transport across strong magnetic fields to the anode. This is manifest in the many schools of thought on optimal cathode placement and orientation for peak HET performance or efficiency. Walker and Gallimore[1] found that a cathode-thruster separation of up to a meter had no effect on thrust, although the cathode floating potential deteriorated. Sommerville[2] reported nearly the opposite, that both thrust and cathode floating potential improved with increased radial separation. Tilley et al.[3] reported the ideal external cathode location for maximum thrust to be as close to the outer magnetic poles as possible, oriented axially. Hofer[5], Jameson[6,7], and others have found the internal cathode to be preferred, with overall efficiency gains on the order of 2-3% over the best external cases.

While most recent results have identified the internally mounted cathode as the optimal solution, a detailed physical explanation of thruster sensitivity to cathode placement is lacking. Through an efficiency analysis similar to the method outlined by Hofer[8], Jameson identified one large cause of the more efficient internal cathode operation in a twin model to the 6-kW thruster used in this paper to be an increased voltage utilization efficiency η_v, measured as the ratio of the beam voltage V_b to the discharge voltage V_d (Eqn. 1).

$$\eta_V = \frac{V_b}{V_d} = 1 - \frac{V_c}{V_d} \qquad (1)$$

The discharge voltage is a fixed potential drop between anode and cathode enforced by the discharge power supply (see below). However, both electrodes are allowed to float relative to ground and the cathode floating potential or cathode-ground voltage V_{cg} often varies from several to a few tens of volts negative. The ion beam can only be accelerated through the beam voltage V_b, so the difference between the plasma potential V_{pg} and negative cathode floating potential V_{cg} is a loss term that we define as the cathode coupling voltage V_c. Note that even a "perfectly efficient" thruster would have a nonzero cathode coupling voltage; remember that electrons must have enough energy upon arrival in the discharge chamber to ionize the propellant, 12.1 V for xenon.
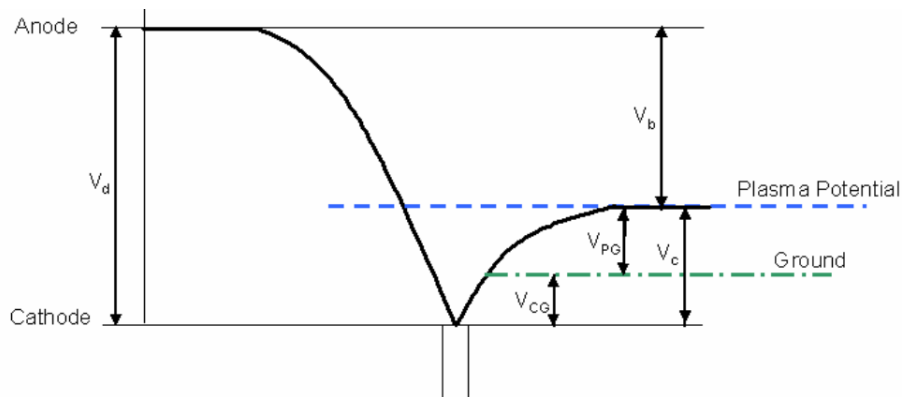

Figure 1: Hall Thruster Conceptual Voltage Profile[6]

In this study we have focused on measuring the cathode coupling voltage, discharge current and thrust as a function of external cathode position and orientation, using the internal cathode operation as a control value for comparison. The thruster is capable of running on either an internal or external cathode, and by installing independent propellant and power lines and a system of motion stages we are able to operate the external cathode at various axial, radial or theta positions or switch to the internal cathode without breaking vacuum. To the author's knowledge, this study is unique in its combination of range and three degrees of freedom of the external cathode, and the use of an internal center-mount cathode as a control.

II.   Experimental Details

A. Setup

This experiment operated a 6-kW laboratory model Hall thruster (henceforth "the thruster", see Figure 2) with a mobile external cathode and monitored the cathode floating potential, plume plasma potential and the discharge current to compare to the nominal operating point with an identical internal center-mounted cathode. The external cathode position was varied in the radial direction from 0.24 m to 1.5 m off thruster centerline, or roughly one to ten thruster diameters off center. Closer radial approach was impossible due to interference with the thrust stand (Figure 4). The axial position varied from 1 cm forward of the thruster exit plane, level with the nominal placement of the internal cathode, to 11 cm forward. Again, nearer axial approach was impossible due to interference with the thrust stand (Figure 5). A rotational stage allowed the cathode to turn from 0° (axial) to 90° (radial) at each radial and axial location. The test matrix (Figure 6) consisted of 14 radial and 5 axial positions with 7 orientations at each location spaced evenly from 0-90°.
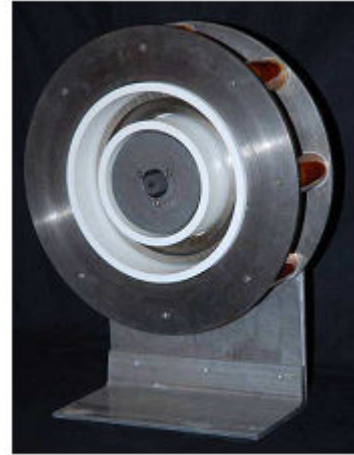

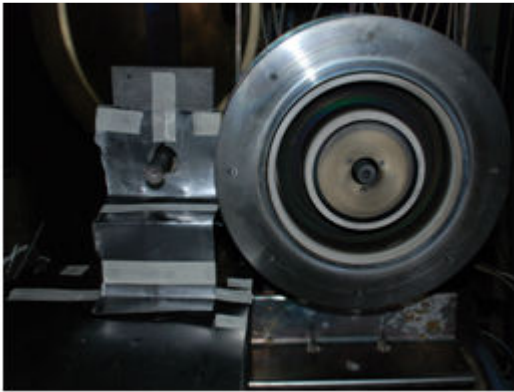**Figure 2: The 6-kW laboratory model Hall thruster**

Figure 3: Front view, external cathode mount and thruster. The cathode's closest radial approach is about 1.5 thruster diameters off centerline.
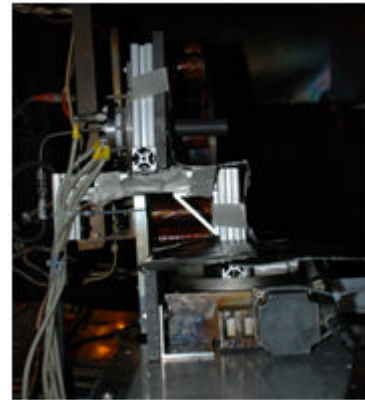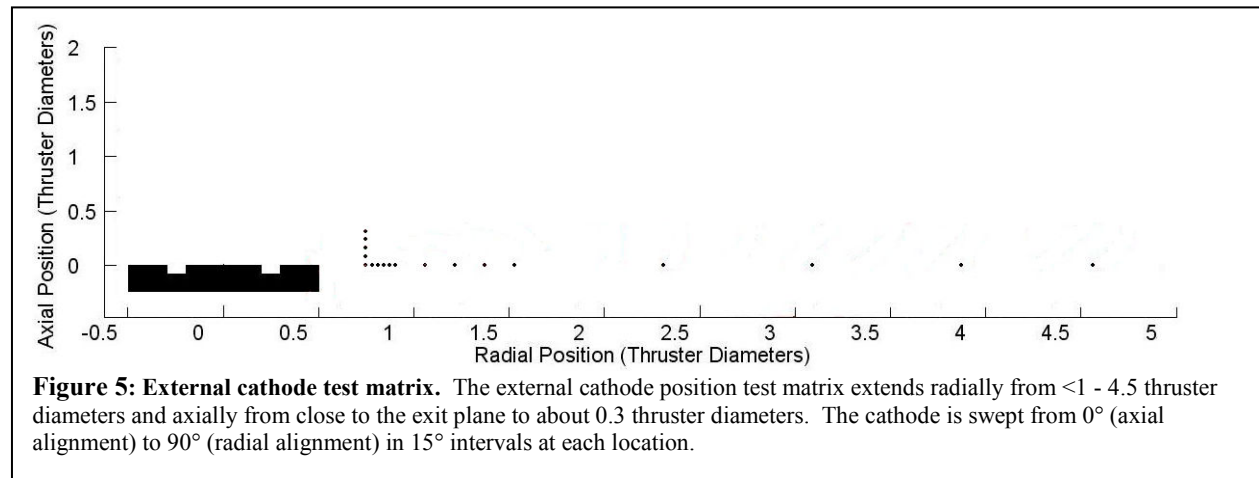

Figure 4: Side view, external cathode mounting assembly. The cathode orifice is roughly 1 cm forward of the exit plane at its closest approach.

Figure 5: External cathode test matrix. The external cathode position test matrix extends radially from <1 - 4.5 thruster diameters and axially from close to the exit plane to about 0.3 thruster diameters. The cathode is swept from 0° (axial alignment) to 90° (radial alignment) in 15° intervals at each location.
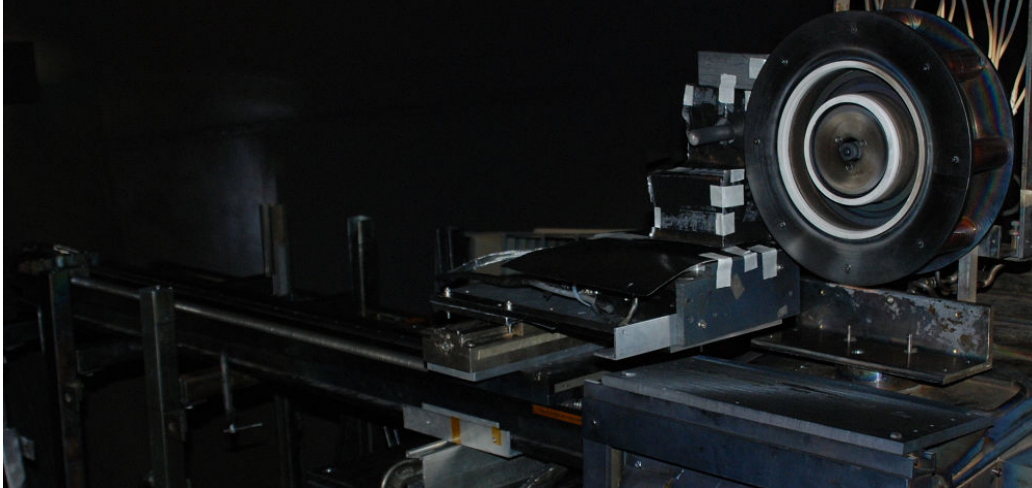
Figure 6: External cathode axial, radial and theta motion system. The external cathode is mounted on a 1.5 m radial table with a 30 cm axial table and a rotational stage. The rotational stage is hidden from view beneath graphite and Grafoil shielding.

B. Operation

Before acquiring data, the thruster was warmed up for approximately 60 minutes to bake off contaminants in the ceramic discharge chamber walls and to allow the discharge current to equilibrate. The keeper was left on drawing 0.5 A for the first 45 minutes of operation, maintaining a cathode floating potential of -11.4 V at the farthest radial position. At this point the keeper was turned off for the remainder of the test, and the floating potential dropped to -12.1 V.

After this initial warmup period, testing proceeded quickly. Full passage through the 18 radial/axial locations, each with 7 orientations, took about 3 hours total, for an average of between 60 and 90 seconds per point when the cathode movement time is accounted for. Ten Langmuir probe sweeps over ±70V at 10 Hz were taken at each location to obtain the plasma potential. The thrust, cathode floating potential and discharge current were simultaneously sampled at 125 kHz for approximately a tenth of a second and the resulting signals averaged. The Langmuir probe sweeps and other measurements were after the thrust stand inclination had been manually adjusted and the floating potential appeared to have settled into a steady value at each point.

Background pressure in the chamber ranged from 1.1 to 2.6 x 10^{-5} Torr during testing, indicating some potential for facility effects. Thermocouples placed on the cathode supporting structure during the test registered an increase of some 40° C, from 68°C at the far radial locations to nearly 110°C in the near field. No attempt was made to compensate or actively cool the cathode.

C. Equipment

1. Vacuum Chamber

All experiments were performed in the Large Vacuum Test Facility (LVTF) at the University of Michigan. The LVTF is a cylindrical stainless steel-clad vacuum chamber, 6 meters in diameter and 9 meters in length, with seven cryopumps and a maximum pumping capacity of 240,000 L/sec on xenon. The thruster was mounted coaxially with the chamber on a thrust stand described below.

2. Cathodes

The internal and external cathodes are JPL-designed LaB6 hollow cathodes of identical dimensions, sized for nominal operation at the thruster design point.

3. Thrust stand

The thrust stand is a null-displacement inverted pendulum model based on the NASA GRC design[10]. Thrust stand inclination is manually adjusted at each test position. The thrust stand is calibrated by a linear least-squares fit to the response to a series of known applied weights, with an accuracy determined by the residuals of the fit to within 5 mN. Due to the close approach of the external cathode mounting assembly to the outer magnet poles, careful efforts were made to minimize magnetic tearing by using only aluminum or non-magnetic stainless steel

parts on the cathode supporting structure. Tests indicated no discernible magnetic tearing even at the points of closest cathode approach.

4. Mass Flow System

Mass flow control is performed by several commercial units from MKS. The anode uses a 500 sccm controller, while the internal and external cathodes use 50 and 20 sccm controllers, respectively. In-house mass flow calibrations for the anode and both cathodes use a constant-volume calibration method [reference] with slight corrections for xenon compressibility. The external cathode was calibrated immediately before this round of testing; however, the anode and internal cathode were last calibrated some months before testing and the anode flow setting used as 20 mg/s in this test was later found to correspond to 20.8 mg/s. This is most apparent in the measured discharge current and thrust.

5. Langmuir Probe

Plasma potential measurements were taken with a cylindrical Langmuir probe 5.77 mm long and 0.38 mm in diameter. The probe was placed approximately on the thruster centerline, 2 m downstream of the exit plane. A sawtooth voltage signal was driven through the probe at 10 Hz by a waveform generator directing a bipolar power supply, and the resulting current signal was sampled at 5 kHz over the course of ten traces. The plasma potential reported is the intercept of linear regression lines fit to the electron temperature and electron saturation segments of the Langmuir probe trace.

Note that even small errors in the regression fits can lead to large errors, on the order of a volt or more, in the estimate of Vpg. We estimate ±1.5V uncertainty in the reported plasma potential measurements from the Langmuir probe. For the sake of consistency the same algorithm was used to generate Vpg for each point, with no manual corrections for apparent outliers.

6. Other Probes

The cathode floating potential and main discharge current signals were recorded on a high-speed data acquisition system sampling at 125 kHz over a tenth of a second. The average of these values is reported. The cathode floating potential was fed through a 50:1 voltage divider, while the discharge current was monitored by a F.W. Bell NT-50 magneto-resistive current sensor.

III. Experimental Results

The thruster design operating condition is 300V at 20 mg/s on xenon using the center-mount internal cathode at a 7% cathode flow fraction. As mentioned previously, this affords us the use of the internal cathode operating condition as a high-performance control case. Relevant operating parameters during this case are given below:

Floating Potential	-11.8 V
Plasma Potential*	12.8 V
Discharge Current	19.94 A

Table 1: Thruster Design Point Internal Cathode Operating Parameters

*plasma potential taken at 20.8 mg/s

A. Floating Potential

The magnitude of the cathode coupling voltage during external cathode operation $|V_{cg}|_{ext}$ decreased in the far radial direction (Figure 7), falling beneath $|V_{cg}|_{int}$ beyond about six thruster diameters (TD). By contrast, as the cathode approached the thruster outer diameter $|V_{cg}|_{ext}$ spiked above 14V. We also observe, similar to Sommerville,[11] a trough in V_{cg} in the mid-radial range, between 1-3 TD, most prominently near 2.5 TD. Variation in cathode θ-orientation generally had only small effects on V_{cg} when compared to the more prominent radial trends, but the θ dependence was most pronounced in this trough.

Despite an axial positioning range less than a tenth of the radial range, we observed comparable effects on V_{cg} in the axial tests. Again, increased distance from the thruster improved Vcg (lowered |Vcg|). Orientation had a stronger effect for these near-field positions, as evidenced both in a larger range of coupling voltages at a given axial position than previously observed at any one radial position, and also in what appeared to be a "preferred" orientation near 45° for most of the range.

B. Plasma Potential

The plasma potential V_{pg} was substantially higher during all external cathode operation than for the nominal internal case, in many cases jumping over 50%. While the plasma potential appears substantially noisier than the floating potential, a similar broad trend appears: an improved (lowered) Vpg with increased radial or axial cathode separation. No clear orientation effects are noticeable.

The outlier point at zero axial/radial position and 90° orientation illustrates some of this sensitive behavior discussed previously, as a manual inspection of the computer-generated regression fits shows that this value is likely too low by at least 1 V. It is difficult to tell how much of the variation in Vpg is due to regression analysis error versus real physics. A more robust algorithm for plasma potential determination or else a framework for manual adjustment of outliers will need to be developed in the future.

Nevertheless, the shallow trend of decreased Vpg with increased cathode separation appears to hold within the errors of the probe measurement. At the very least, this precludes an *increased* Vpg with increased cathode separation, an important point we shall make note of in the discussion.

C. Discharge Current

Far-field radial separation caused the discharge current to increase by up to a quarter-amp across all orientations, or about one percent of the full discharge current. In general, cathode orientation was not a factor until the cathode came within about 1.25 thruster diameters. Within this range, a trend emerges where I_d increases with theta, reaching a maximum at θ=90°when the cathode is pointed directly at the thruster. The effect is most pronounced at the point of closest radial approach, with a 0.15 A difference between θ=0° and θ=90°.

This trend continues in the axial cases. While the axial position variation has negligible effect on I_d, there is a 0.20-0.25 A increase from θ=0° to θ=90°.

Note that discharge current data from this experiment is not directly comparable to other published data[6,7] for this thruster, as the thruster was operated at a slightly higher flowrate than nominal (20.8 mg/s instead of 20) due to an outdated anode mass flow calibration. However, the external cathode was calibrated immediately before the test, and is accurate to within ±1%.
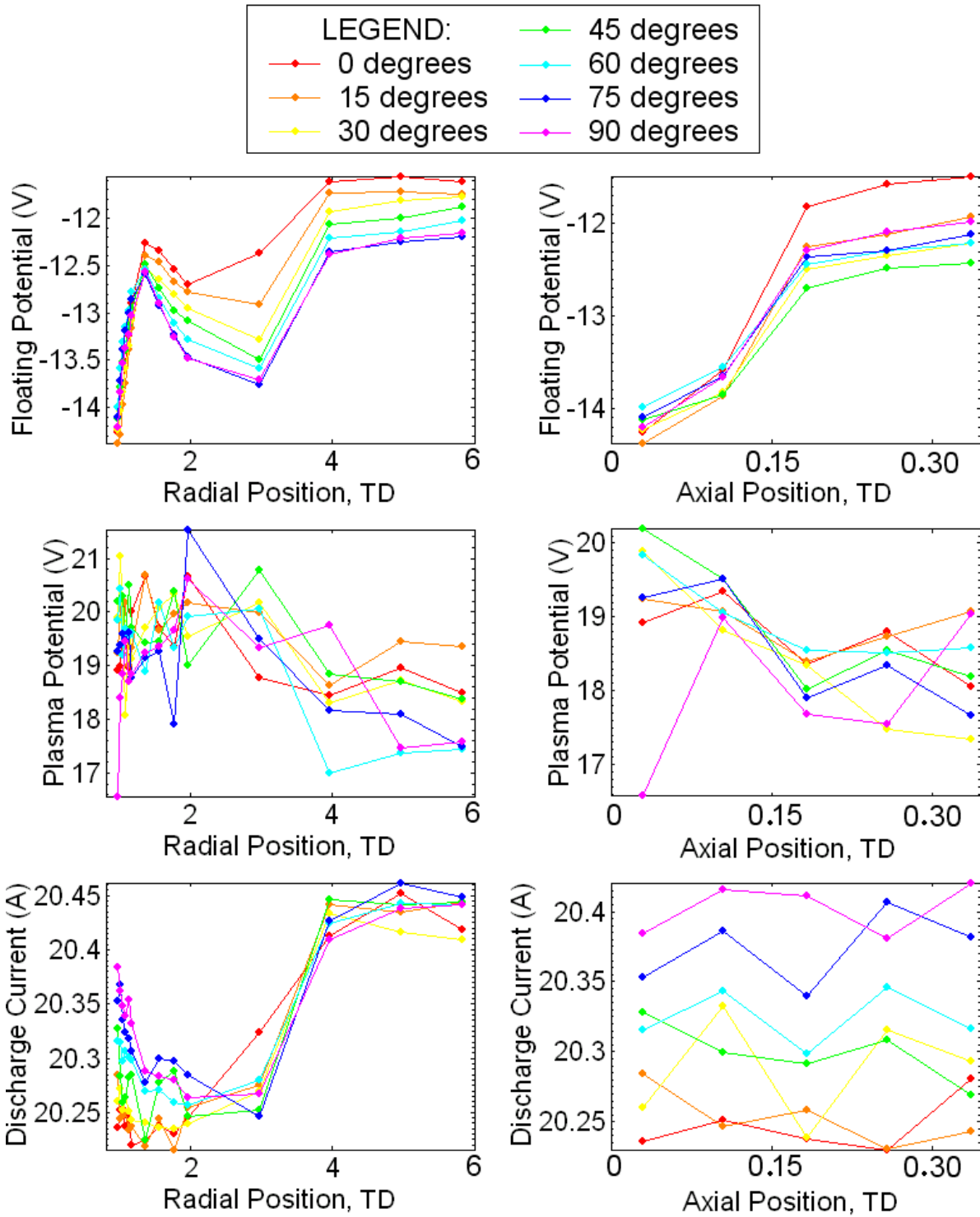
Figure 7: Experimental Results

IV.   Discussion

The unexpected result of this test has been to show that, within the confines of the test matrix shown in Figure 5, the best performance was achieved at the farthest separation of the cathode from the thruster discharge channel, nearly 5 thruster diameters radially separated from the thruster centerline. This is in contrast to the results obtained by Walker in the same facility with the P5 Hall thruster, a predecessor to the current thruster. Walker's results with the P5 were at a lower power (3 kW), flowrate (10 mg/s) and base pressure (5.3 x 10^{-5} Torr Xe), and so are not a perfect comparison, but the results are nevertheless surprising.

Dependence on cathode orientation is strongest in the discharge current and cathode floating potential in the near radial and all axial locations. Magnetic field circuit simulations on the commercial software package MagNet indicate that this localization may be explained by the rapid magnetic field decay with distance from the thruster (Figure 8); in the radial direction little theta behavior appears beyond the first half of the test matrix, roughly 3 thruster diameters, where the local thruster magnetic field has dropped to less than 0.5 Gauss. In the axial direction, where the cathode only moved a short distance away, the field remains at several Gauss and the orientation continues to have a significant effect across the full axial range.
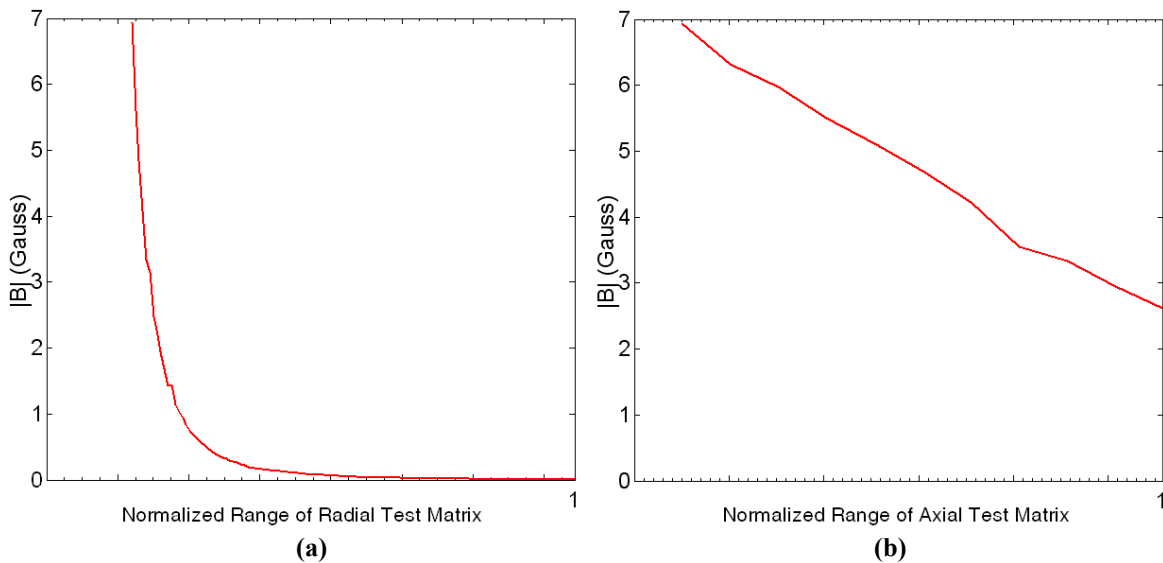

| | (a) | | (b) |

Figure 8: Magnetic field decay in the radial (a) and axial (b) directions. Graph (a) in the radial direction is for at the point of closest axial approach and graph (b) in the axial direction is for the point of closest radial approach. Both graphs follow the path of the external cathode from closest approach to farthest separation.

An early theory to explain the decrease in the magnitude of the cathode floating potential V$_{cg}$ at large radial separations was that in far field the neutralizing electrons of the cathode were coupling to the immediate tank structure instead of following the xenon ions out into the plume. However, this theory is contradicted by the decrease in the plasma potential V_{pg} in the plume while testing at those locations. If the neutralizing electrons were indeed simply coupling to the nearby grounded walls of the vacuum chamber, the depleted electron population in the plume should have led to a rise in the plasma potential at large radial separations. At the very least, as we observed in the previous section, this was not the case, and within the error bars the plasma potential actually appears to decrease with increasing radial separations.

An increase in discharge current and a corresponding increase in thrust were also observed as the cathode moved radially outward. This, along with the increasing anode efficiency in the radial direction, indicates that the increased discharge current was at least partially increased ion beam current, rather than simply an increased electron leakage current.

We recall that the cathode coupling voltage is sometimes interpreted as a measure of the ease with which electrons travel from the cathode to the anode[6]. If this is the case, then the lowered cathode coupling voltage in the far radial positions suggests that, despite the increased distance of a meter or more, the electrons have a favorable

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path to the anode. This prompted an analysis of magnetic field streamlines, again generated from MagNet (Figure 9), over the range of cathode positions studied.
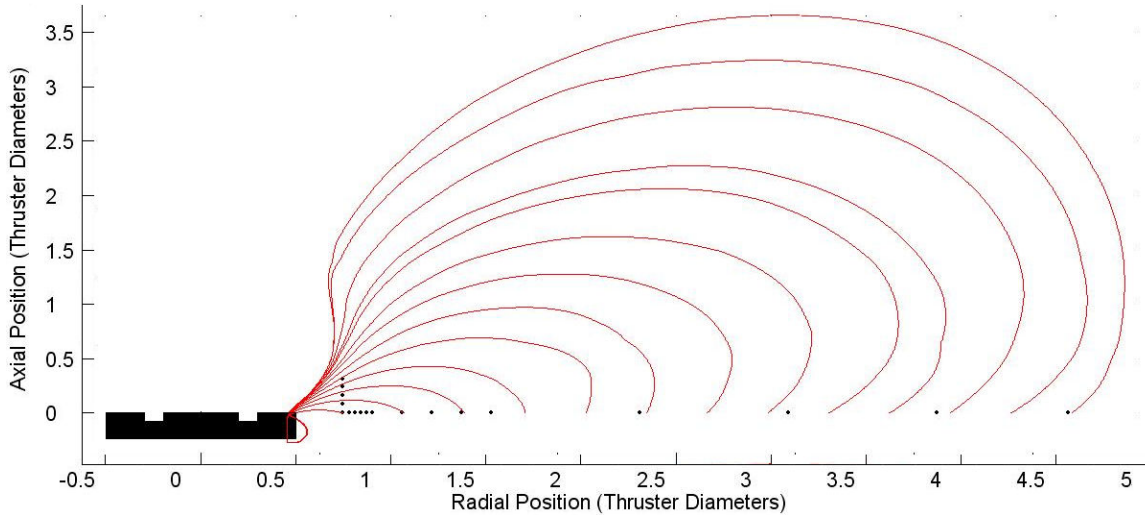

Figure 9: Magnetic field streamlines through test matrix. The streamlines are derived from a MagNet simulation.

The magnetic field lines, shown in red, pass through the outer magnetic pole of the thruster. The magnitude of the field is very weak in the far-radial locations, and without further plume data it is impossible to say whether or not the magnetic field is indeed providing a favored path for electrons into the discharge chamber from these extreme radial positions. However, the possibility that weak magnetic fields also have a significant influence in the far field is a topic worthy of further study.

V.   Future work

This study is intended as the first in a series of experiments seeking a greater understanding of the physical mechanisms behind cathode coupling in Hall thrusters. Future work will focus on adding a greater depth of plume diagnostics, extending into low voltage and high thrust-to-power operation, and introducing high-speed time resolved measurements of the cathode coupling voltage, discharge current and associated transient phenomena.

Shortcomings of this study to be addressed in future work are the lack of a robust algorithm for smoothing Langmuir probe traces and extracting the plasma potential, and the high background pressure during this test.

VI.   Summary and conclusions

Optimal performance for an external cathode in a laboratory-model 6-kW Hall thruster is demonstrated to occur at the farthest radial separation possible from the thruster within a test matrix of large radial extent. Overall efficiency for this optimal placement is still approximately 3% lower than for operation with an internal center-mount cathode.

In the near field, the effects of axial separation up to 11 cm in front of the thruster exit plane on performance were inconclusive. However, at these locations cathode orientation was shown to have a strong effect, leading to changes in the discharge current of nearly 1% and thrust changes of 15-25 mN. The influence of the magnetic field is identified as a likely source for this dependency on cathode orientation in the near field.

Acknowledgments

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