Coupling of Electrical and Pressure Facility Effects in Hall Effect Thruster Testing

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Changes in the acceleration region dynamics and cathode coupling of a magnetically-shielded Hall thruster are characterized under different pressure, electrical, and cathode configurations. Due to the growing popularity of Hall thrusters, and lacking a validated physics-based predictive model of their operation, there is strong motivation to devise methods to mitigate or account for facility effects during thruster validation and characterization tests. To this end, the combined effects of typical mitigation and extrapolation techniques are examined in light of their effects on the the acceleration region, cathode coupling, and plasma potential of the plume of a state-of-the-art Hall thruster. A large downstream beam dump was electrically isolated from the facility and electrically biased both above and below ground by up to 30 V. Simultaneously, the pressure in the facility was altered by adjusting the number of active cryopumps. It was found, using laser induced fluorescence, that the effect of pressure induced acceleration region migration was unaffected by the electrically based beam dump. Additionally, a far-field Langmuir probe indicated the while the electrical bias of the beam dump caused the cathode to ground and plasma potentials to float with respect to ground, it did not effect the cathode coupling voltage to a significant degree. Finally, when used as a Langmuir probe, the collected current of the beam dump was significantly effected by background pressure reducing the ion saturation current by nearly 25%. These results indicate that while a stable far-field potential does not appear to alter thruster operation, it reveals that background pressure is a strong driver of how the thruster and plume couple to the facility at large.

I. Introduction

Hall thrusters are one of the most successful and mature forms of electric propulsion flown today, but there is an open question about the fidelity of the test environments that are currently employed to qualify these systems. This is due to a few subtle but significant differences between the ground testing environment and the one experienced on-orbit. These differences, so-called facility effects, have been shown to alter the thruster's performance and operation. These effects can be organized into two primary categories: back-pressure effects and electrical effects.

Back-pressure effects stem from the fact that even the most state of the art ground testing facilities operate with background pressures many orders of magnitude higher than orbital pressures. This residual background neutral gas has been shown to affect several major aspects of the thruster's operation and performance, including but not limited to the thrust, cathode coupling potential, and divergence angle [1–10]. The electrical facility effects originate from the conducting and grounded wall of the vacuum facility which can alter the potential structure of the plume and provide alternate current paths that do not exist on orbit[11, 12].

Since these facility effects greatly complicate qualification efforts, there has been a strong push to develop methods of altering the facility conditions to be more flight-like. Previously, these strategies have included parametrically

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varying the background pressure while tracking the changes in thruster operation to find critical pressures which are deemed sufficiently space-like for extrapolations[13]. Others have used electrically biased surfaces in an attempt to electrically isolate the thruster discharge from the walls of the facility[14]. While separately these methods show some repeatable trends across thrusters and facilities, it is possible that electrical facility effects are convolved with background pressure effects. Since both effects must simultaneously be mitigated to more directly relate ground operation to orbital performance, it is critical to map the relative dependence of each effect on different aspects of thruster operation.

The goal of this work is to examine the coupling between these two seemingly disparate facility effects. It is organized in the following way. We begin by describing the experimental apparatus and hall thruster. In the next section we share the results of our three experiments. Following that, we analyze these results and discuss them in terms of future hall thruster validation experiments. Finally we draw some conclusions.

II. Experiment

In this study we examine the effects of both variations in background pressure and an electrically biased chamber boundary condition on the acceleration region location of a state of the art Hall effect thruster. The device under test was the H9, a magnetically-shielded hall thruster jointly developed by the Jet Propulsion Laboratory, the University of Michigan, and the Air Force Research Laboratory. The thruster was operated at the nominal operating condition of 300V-15A while cathode-tied and electrically isolated from the facility. The thruster was outfitted with both an internal in external cathode of identical design.

The experiment was performed in the Large Vacuum Test Facility at the University of Michigan, a 6 m diameter by 9 m long cryogenically pumped vacuum chamber. The pressure in the facility was varied by changing the number and configuration of active cryopumps. We operated at two different pressures – as measured by a calibrated stabil-ion gauge positioned approximately 1 m from the thruster in the thruster exit-plane – 20 $\mu Torr$ and 5 $\mu Torr$. Positioned at the downstream end of the chamber was a large 4 m x 4 m beam-dump which was electrically isolated from the chamber. The beam-dump was composed of graphite panels which were angled with respect to the thruster plume and were electrically biased with respect to facility ground to control the electrical coupling of the thruster plume. This circuit as well as the relative locations of the other diagnostics used in this experiment can be seen in fig.1.

Three experiments were performed during this study to explore the coupling between the two types of facility effects. The first experiment was an I-V sweep of the beam dump to characterize the coupling of the plume to the beam dump and facility. Composed many individual carbon carbon panels each connected in parallel, the beam dump was first biased up to +30V above ground in 5V increments, then the power supply polarity was switched and the beam dump was biased to -30V below ground in 5V increments. At each voltage point the current sourced/sunk by the beam dump was measured with a calibrated multi-meter and the V_{C2G} and background pressure was recorded. This was repeated for both the internal and external cathode configurations, and at both background pressures. Bias voltages at which all configurations and pressures were in either electron or ion saturation (+/- 20V) were chosen to be used as common bias points for the other two experiments.

The second experiment was a far-field Langmuir probe to measure the response of plasma potential under each electrical, pressure, and cathode combination. The Langmuir probe was positioned 2.1m downstream on thruster centerline. Each trace was collected from -40V to 40V in 1V increments. Each trace was used to calculate the plasma potential, and thereby, the cathode coupling voltages to measure any dependencies on facility conditions.

The final experiment was a time averaged laser induced fluorescence (LIF) velocimitry map of the acceleration region. The axial measurement grid, shown in fig.2, was performed at the 3 o'clock thruster position for each facility configuration. The thruster was positioned for each grid point via a set of motion stages to a precision of 0.1 mm. A tunable diode laser was fiber-coupled and injected into the thruster channel and used to excite the $5d^4_{7/2} \rightarrow 6p^3_{5/2}$ meta-stable Xenon ion transition. The fluorescence light was collected with a second fiber coupled optic positioned 20cm from the interrogation point at the 4 o'clock position. Ion velocity distributions were built from this signal for each of the 13 points of the grid.

III. Results

In this section we present the results and observations made during our three tests. Beginning with the beam dump I-V traces and it's effects on thruster operation, followed by the downstream Langmuir probe sweeps, and finally some

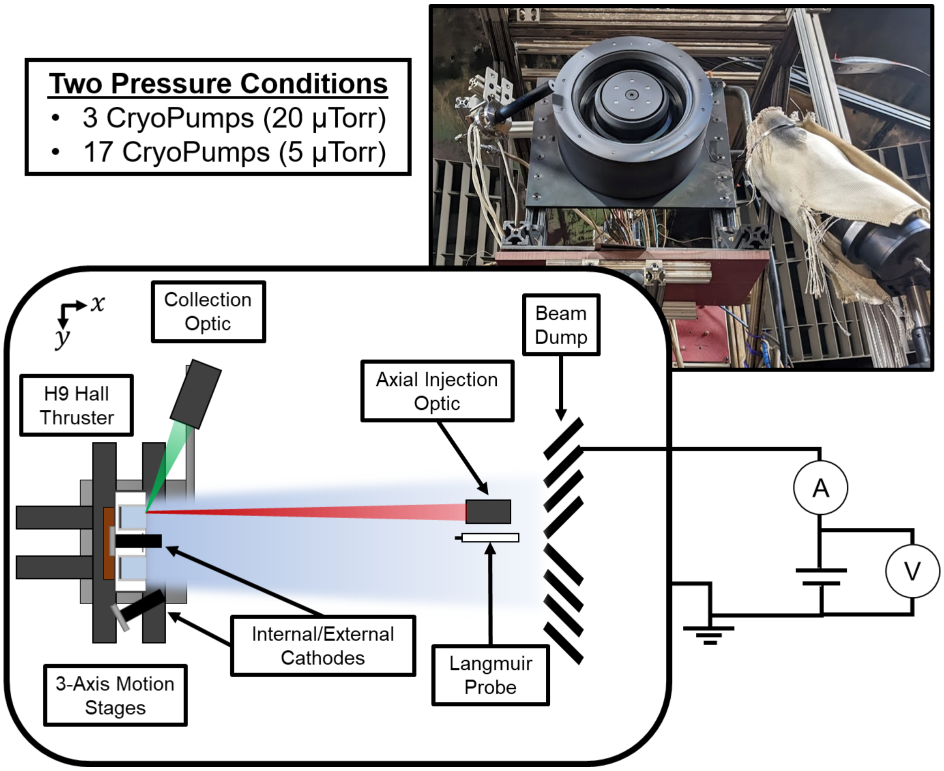


Fig. 1 Diagram (Bottom-Left) and Picture (Top-Right) of the experimental set-up, showing the notional layout of the various diagnostics and structures within the facility.

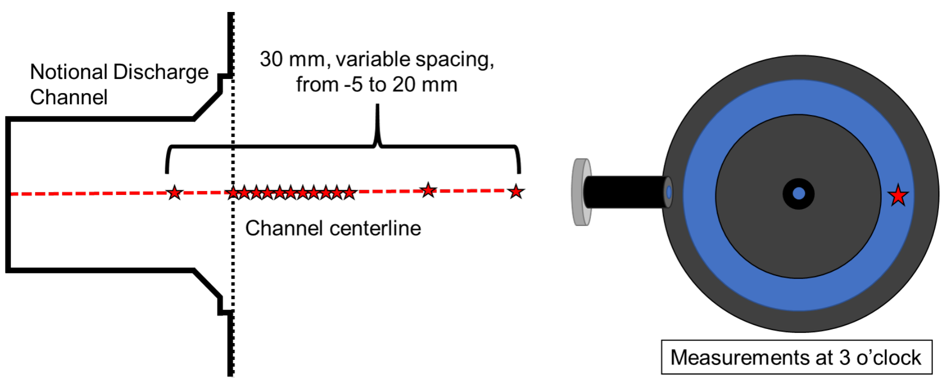


Fig. 2 Cross-section Diagram (Left) and End-on Picture (Right) of the axial LIF grid to characterize the acceleration region.

representative IVDFs of the acceleration region measured using the LIF system.

A. Beam Dump as Langmuir Probe

The first experiment that we performed was a I-V sweep of the beam dump, measuring the collected current as a function of bias voltage for each of the 4 cathode and background pressure combinations. The sweeps are plotted in fig.3.The collected current never approaches the discharge current of 15A. The low pressure traces in both configurations always sink or source more current than the high pressure traces. They also appear to be more symmetric, asymptoting at nearly the same current in both ion and electron saturation. The high pressure cases in both configurations are asymmetric and reach ion saturation at lower voltages. Voltages at or above +/- 30V cause repeated intermittent shorts to occur between beam dump and structures within the chamber. These shorts caused visible sparks in the chamber, simultaneously the power supply holding the beam dump bias switches to current control and the spikes in the cathode to ground measurements are observed. We hypothesize the reasons for these behaviors in the discussion section.

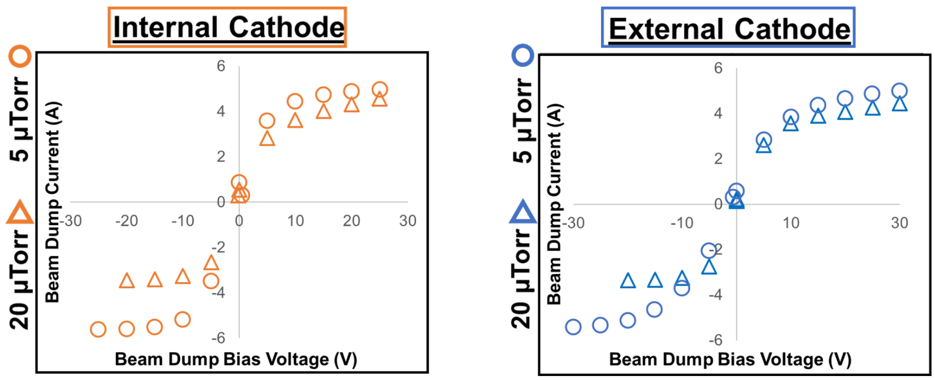


Fig. 3 I-V sweeps of the beam dump bias voltage and current for the internal cathode configuration (Left) and the external cathode (Right) for both $5\mu Torr$ and $20\mu Torr$ background pressures.

In electron saturation the current asymptotes at 5A in both internal and external cathode configurations, with only slight variation at different background pressure conditions. In ion saturation the asymptotic current is strongly pressure dependent. At the $20\mu Torr$ condition the current asymptotes at 3.5A in both internal and external cathode configurations. At the $5\mu Torr$ condition the current asymptotes at nearly 6A in both cathode configurations. The biases of +/- 20V were chosen to be in both ion and electron saturation at each pressure and cathode configuration while still being below the on-set voltage of the intermittent shorting issue.

B. Far-Field Langmuir Probe Results

The second experiments we performed were a series of far-field Langmuir probe sweeps at each of the chosen bias and pressure points. Figure 4 shows the 8 Langmuir probe traces measured during this test. The influence of cathode configuration, background pressure, and bias potential is clear by the different slopes and inflection points of each of the traces.

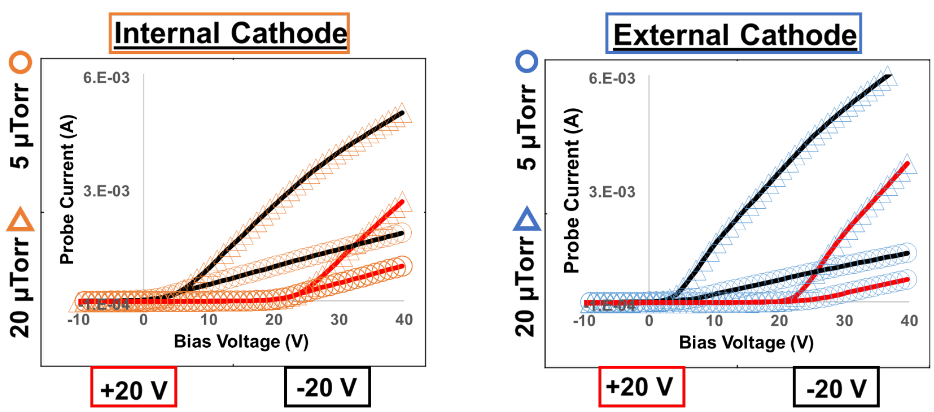


Fig. 4 Langmuir probe traces taken under different bias voltages (Red+/Black-), different pressures ($5\mu Torr$ Circle, $20\mu Torr$ Triangle), and cathode configurations (Internal Left/Orange, External Right/Blue)

C. Laser Induced Fluorescence

The third and final measurement we performed was a LIF interrogation of the acceleration zone. Figure 5 shows an example of IVDFs taken at the furthest downstream position in the grid in both cathode configurations. Each IVDF was measured with a 500 m/s velocity resolution. The most notable feature of the comparison is the significantly higher noise floor on the external cathode IVDF when compared to the internal cathode IVDF. Even though both IVDFs were measured at the same axial position and facility configuration, the larger secondary plasma halo that forms around the body likely causes extra non-fluorescence light to be collected. It is a feature of all traces taken with the external cathode, especially those taken at the higher background pressures.

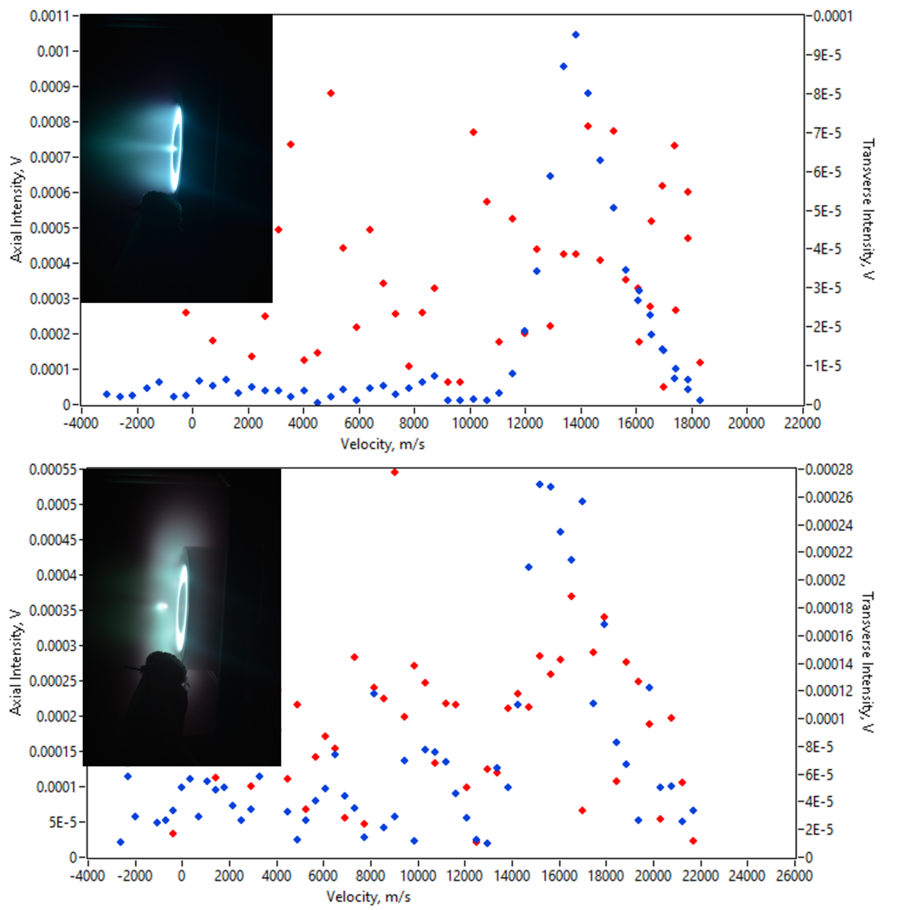


Fig. 5 A comparison of the most downstream IVDF in the Internal cathode configuration (Top) and External cathode configuration (Bottom). As evident in the pictures, the increased secondary plasma causes a significant increase in the noise floor.

IV. Analysis & Discussion

In this section we analyze the results of our three experiments, and discuss those analysis in terms of future Hall thruster validation experiments. First, we examine the beam dump I-V traces and discuss the possible reasons for the saturation currents and changes caused by increased facility pressure. We then analyze the far-field Langmuir probe traces, calculating the electron temperature and plasma potential, and discuss the effect of the bias voltage on the changes in cathode coupling voltage. Finally, we extract the most probable velocity from each IVDF and plot them as a function of axial position, we compare them and discuss the similarities under different facility conditions.

A. Low Observed Beam Current

One of the more striking features of the beam dump I-V traces, shown in Fig.3, is the clear ion and electron saturation regions. In the low background pressure configuration, given by the orange and blue circles, the shape is reminiscent of a symmetric double probe trace for both internal and external cathodes. The saturation currents are nearly the same in magnitude in both electron and ion saturation. If it were a symmetric double probe, this indicates that the electron saturation current is limited by the ion current flux to the probe. We hypothesize that the same is likely true in this case, that the circuit set up by the chamber and beam dump limits the electron current that can be drawn from the plume by the ion current which can reach the chamber walls and floor. This hypothesis is borne out by the differences in electron saturation at different background pressures. The lower current observed at higher pressures can be explained by the changing divergence angle, which is smaller at higher pressures and leads to reduced ion flux to the walls.

The other feature of note is the large disparity in ion saturation current seen at different background pressures. The ion current collected by the beam dump was reduced by nearly 25% at the $20\mu Torr$ condition when compared to the $5\mu Torr$ condition. This disparity it cannot plausibly be explained by a double probe-like effect, as electrons should not be so limited in their flux to the walls as the ions. Further in neither pressure condition does the collected ion current approach the expected beam current. We hypothesize that there could be a few explanations for this, but it will require further study to more than speculate. The first, and most plausible, explanation is that many of the ions are charge exchanging before they reach the beam dump. This is consistent with the reduction in current at observed at higher pressures which would have significantly more charge exchange interactions. The second possible explanation is that at the higher pressures the anode flow rates are reduced due to neutral ingestion and could conceivably lead to lower measured beam currents. This, however, is not consistent with the magnitude of the change in collected current. The final possible explanation is that the beam is being obstructed by structures within the chamber, such as those supporting the optics and probes. While this could possible explain why the current is reduced, it cannot explain the changes in current. Regardless of the reasons, this effect indicates that the background pressure can indeed alter how the thruster couples to the facility.

B. Cathode Coupling and Plasma Potential Effects

The Langmuir probe sweeps were analyzed according to the recommended practices detailed in [15]. From each of them we calculated the electron temperature (T_e) and plasma potential (V_{plasma}). These values are displayed in Table 1, and Fig.6 along with the cathode to ground voltage (V_{C2G}) and cathode coupling voltage (V_{cc}) for each facility configuration. We observed that the bias of the beam dump causes the plasma potential and cathode to ground voltage to float up in concert with the beam potential in the positive direction. This indicated that the entire discharge floats with up with the beam dump bias. When the beam dump is biased in the negative direction the potentials in the plume remain largely unaffected by the bias instead remaining the same as in the grounded configuration. This could indicate that coupling to the facility, which would be increased by the negative potential, has already saturated when in the unbiased configuration. The most telling result of this experiment, however, is that the cathode coupling voltage is largely invariant with bias voltage. While it is still effected by the increasing background pressure, it varies by less the 10% due to bias potential changes.

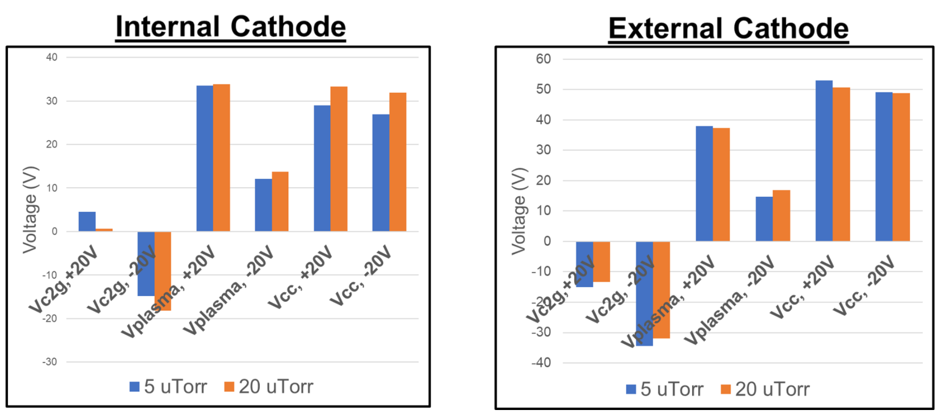


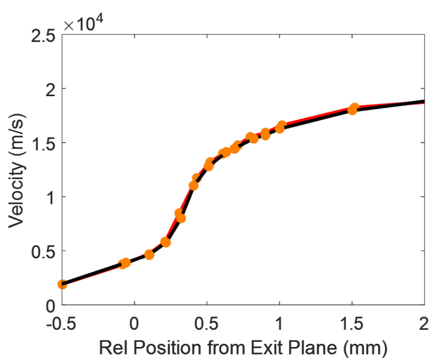
Fig. 6 Bar plot showing the relative potentials for the Internal Cathode (Left) and External Cathode (Right). Cathode to ground voltage (V_{C2G}) was measured from a calibrated voltage divider, V_{plasma} was calculated from the Langmuir probe traces, and V_{cc} was calculated by subtracting the cathode to ground voltage from the plasma potential.

Table 1 Plasma parameters calculated from the far-field Langmuir probe traces for each facility configuration.

Cathode Config.	Background Pressure ($\mu Torr$)	Beam-Dump Bias Potential (V)	T_e(eV)	V_{C2G}	V_{plasma}	V_{cc}
Int	5	20	3.6	4.5	33.5	29
Int	5	-20	3.2	-14.8	12.1	26.9
Int	20	20	3.5	0.6	33.9	33.3
Int	20	-20	3.3	-18.2	13.7	31.9
Ext	5	20	3.8	-15.1	37.9	53
Ext	5	-20	3.3	-34.4	14.7	49.1
Ext	20	20	3.4	-13.3	37.4	50.7
Ext	20	-20	3.2	-32	16.9	48.9

C. Effect of Beam Dump Bias on the Acceleration Region

We extracted the most probable velocity from each of the IVDFs by fitting a double-Gaussian to each them, extracting then plotting the peak velocity as a function of downstream distance. These are plotted in figures 7-10 to compare the effect of each of the different facility variation. Fig.7 shows the comparison between the high and low bias conditions for the internal cathode for both pressure conditions. The velocity curves appear to lay directly on top of each other indicating that there is no significant effect of the bias potential in either pressure condition for the internal cathode. Fig.8 shows the comparison between the high and low bias conditions for the external cathode. Similar to the internal cathode configuration, the velocity curves appear to only vary slightly with bias potential. This also indicates that the cathode configuration does not impact the response to a downstream potential, and gives further evidence that such potentials do not influence thruster operation. Fig.9 shows the effect on background pressure on the acceleration region of the H9 in the internal cathode configuration under both bias voltage conditions. The velocity curves each appear shifted by approximately 1mm towards the exit plane with increasing background pressure. This is consistent we previous measurements of the H9[5] and has not obviously been altered by the beam dump potential. Fig.9 shows the effect on background pressure on the acceleration region of the H9 in the internal cathode configuration under both bias voltage conditions. The velocity curves each appear shifted by approximately 1mm towards the exit plane with increasing background pressure. This is consistent we previous measurements of the H9[5] and has not obviously been altered by the beam dump potential. Fig.10 shows the effect on background pressure on the acceleration region of the H9 in the external cathode configuration under both bias voltage conditions. The velocity curves both appear shifted by approximately 2mm towards the exit plane with increasing background pressure. This is also consistent with previous measurements of the H9 in this configuration and has not obviously been altered by the beam dump potential.



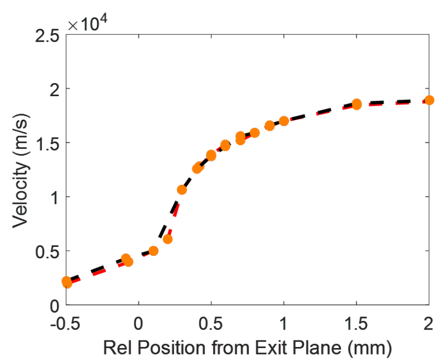


Fig. 7 Comparison of the most probable velocities for the internal cathode (Orange Points). The left plot compares the +20V (Red Line) and -20V (Black Line) beam dump bias conditions at a background pressure of $5\mu Torr$ (Solid Line). The right plot compares the +20V (Red Line) and -20V (Black Line) beam dump bias conditions at a background pressure of $20\mu Torr$ (Dashed Line)

In general, there appears to be no significant impact on the acceleration region dynamics due to a bias potential of

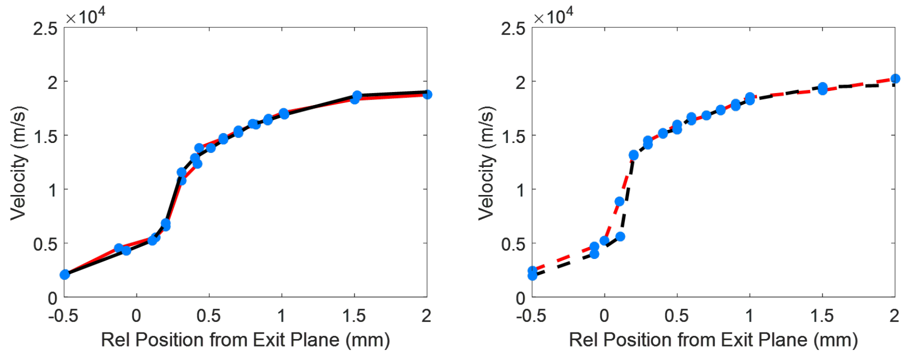


Fig. 8 Comparison of the most probable velocities for the external cathode (Blue Points). The left plot compares the +20V (Red Line) and -20V (Black Line) beam dump bias conditions at a background pressure of $5\mu Torr$ (Solid Line). The right plot compares the +20V (Red Line) and -20V (Black Line) beam dump bias conditions at a background pressure of $20\mu Torr$ (Dashed Line)

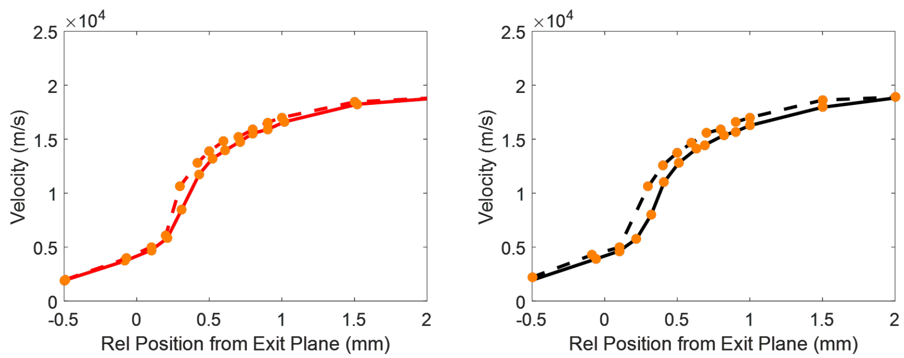


Fig. 9 Comparison of the most probable velocities for the internal cathode (Orange Points). The left plot compares the $5\mu Torr$ (Solid Line) background pressure condition and the $20\mu Torr$ (Dashed Line) background pressure condition at a beam dump bias voltage of +20V (Red Line). The right plot compares the $5\mu Torr$ (Solid Line) background pressure condition and the $20\mu Torr$ (Dashed Line) background pressure condition at a beam dump bias voltage of -20V (Black Line).

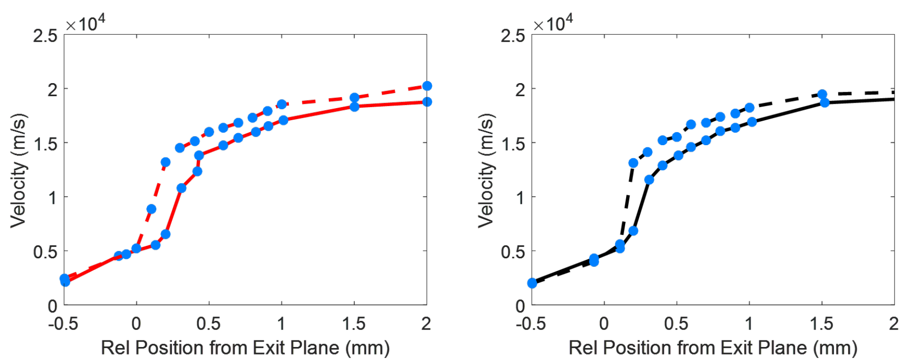


Fig. 10 Comparison of the most probable velocities for the external cathode (Blue Points).The left plot compares the $5\mu Torr$ (Solid Line) background pressure condition and the $20\mu Torr$ (Dashed Line) background pressure condition at a beam dump bias voltage of +20V (Red Line). The right plot compares the $5\mu Torr$ (Solid Line) background pressure condition and the $20\mu Torr$ (Dashed Line) background pressure condition at a beam dump bias voltage of -20V (Black Line).

the beam dump. Any differences in the velocity plots can be attributed to the uncertainty in the velocity measurements. This is an expected result as any stable (not varying) downstream bias should be screened out from the perspective of the discharge. Said another way the fact that the discharge floats up with the beam dump bias potential indicates that there is nearly no current flowing through the plume to the beam dump. If, however, the bias potential were changing, this equilibrium would be disrupted and the momentary difference in potential would allow currents to flow through the plume (from the cathode to the beam dump).

V. Conclusions

In conclusion, the dynamics of the acceleration region does not appear to be strongly effected by the beam dump bias in any cathode configuration or background pressure condition. This, combined with the fact that while the plasma potential and cathode to ground potential float with the beam dump voltage, the cathode coupling voltage is invariant with respect to bias voltages and is strong evidence that the beam dump bias voltage does not directly influence thruster operation, and can be safely be used in future thruster characterization studies. Finally, the significant drop in ion saturation current with increased background pressure, the missing ion saturation current at lower pressures, and the double probe like effect evident in the beam dump I-V traces indicates that the background pressure does indeed influence the way the thruster plume couples to the facility.

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