

The Effect of Anode Position on Operation of a 25-A class Hollow Cathode

IEPC-2019-299

*Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019*

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The effect of the distance between a hollow cathode and a cylindrical anode on cathode operation is investigated for two anode geometries. Simulations were performed that demonstrate that the anode diameter and distance from the cathode exit affect the neutral density downstream of the cathode. For a 64-mm diameter cylindrical anode, downstream neutral density is an order of magnitude higher than that for a 254-mm diameter anode and two orders of magnitude higher than the simulation results for in-thruster operation. To experimentally characterize the effect of these differences on cathode operation, axially-segmented molybdenum anodes were then constructed to these dimensions. For each anode design, cathode performance was characterized for varying anode/cathode distance using metrics such as discharge voltage and oscillation magnitudes, and the radial ion voltage spectra were characterized using a retarding potential analyzer. It was found that as local neutral pressure decreased, discharge voltage and high-voltage ion content in the plume increased. For the 254-mm diameter anode, a tail in excess of 200 V was measured on the ion voltage distribution function for nominal cathode flow rates. The implications of these results for component-level hollow cathode development tests are discussed.

Nomenclature

A_c	=	collector area
e	=	elementary charge
$f(\epsilon)$	=	ion energy distribution function
$f(V)$	=	ion voltage distribution function
I	=	current
m_i	=	ion mass
n_i	=	ion density

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q_j = charge of species j
 V = voltage

I. Introduction

NASA continues to evolve a human exploration approach for beyond low-Earth orbit and to do so, where practical, in a manner involving international, academic, and industrial partners [1]. Towards that end, NASA publicly presented a reference exploration concept at the Human Exploration and Operations Mission Directorate (HEOMD) Committee of the NASA Advisory Council meeting on March 28, 2017 [2]. This approach is based on an evolutionary human exploration architecture, expanding into the solar system with cislunar flight-testing and validation of exploration capabilities followed crewed missions.

The center of this approach is NASA Gateway that is envisioned to provide a maneuverable outpost in Luna orbit to extend human presence in deep space and expand on NASA exploration goals. The Gateway represents the initial step in NASA's architecture for human cislunar operations, lunar surface access and missions to Mars. NASA recently announced plans to send astronauts to the Lunar surface by 2024 as part of the newly formed Artemis program. A key enabling aspect of the Artemis program is the Gateway that provides access to the Moon surface. The first element of the Gateway is the Power and Propulsion Element (PPE), in which NASA recently announced a commercial partnership to develop and demonstration a high-powered Solar Electric Propulsion (SEP) spacecraft with Maxar Technologies, formerly SSL [3]. The PPE will reach and maintain Lunar orbit by incorporating two high-powered SEP systems developed by NASA, in partnership with Aerojet Rocketdyne, and Maxar [4]. The PPE is baselined to include two 13-kW Advanced Electric Propulsion System (AEPS) and four 6-kW Hall thrusters, currently under development by Maxar, for a total beginning of life propulsion power of over 60 kW.

High-power solar electric propulsion is one of the key technologies that has been prioritized because of its significant exploration benefits, specifically, for missions beyond low Earth orbit. Spacecraft size and mass are dominated by onboard chemical propulsion systems and propellants that may constitute more than 50 percent of spacecraft mass. This impact can be substantially reduced through the utilization of SEP, due to its higher specific impulse and lower propellant load required to meet the equivalent mission delta-V. Studies performed for NASA's HEOMD and Science Mission Directorate (SMD) have demonstrated that a 40-kW-class SEP provides the necessary capabilities that would enable near term and future architectures, and science missions [5].

Accordingly, since 2012, NASA has been developing a 13-kW-class Hall thruster electric propulsion string that can serve as the building block for a 40-kW-class SEP capability. The 13-kW Hall thruster electric propulsion string development, led by the NASA Glenn Research Center (GRC) and the Jet Propulsion Laboratory (JPL), began with maturation of the high-power Hall thruster and Power Processing Unit (PPU). The technology development work has transitioned to Aerojet Rocketdyne via a competitive procurement selection for the AEPS contract in May, 2016. The AEPS Electric Propulsion (EP) string consists of the Hall Current Thruster (HCT), PPU (including digital control and interface functionality), Xenon Flow Controller (XFC), and associated intra-string harnesses. Management of the AEPS contract is being led by NASA GRC with funding from the Space Technology Mission Directorate. NASA continues to support the AEPS string development leveraging in-house expertise, plasma modeling capability, and world-class test facilities. NASA also executes risk reduction activities to support the AEPS string development and mission application.

II. Background

Anode configuration has been known to affect hollow cathode operation for many years. As far back as 1978 Siegfried and Wilbur demonstrated that increasing the distance between the anode and cathode can cause a cathode operating in quiescent "spot" mode to transition to the oscillatory "plume" mode [6]. This result was confirmed during more recent research in which Potrivitu found that for a given discharge current and flow rate, the cathode would operate in spot mode when the planar anode was close to the cathode (20-40 mm away) and would transition to plume mode for distances > 45 mm [7]. Studies performed by JPL showed that changing from a cylindrical to a conical anode resulted in cathode discharge voltages much closer to those attained by the cathode while operating within a gridded ion thruster [8].

The changes in cathode operation that JPL observed was attributed to the change in downstream neutral pressure, as the conical geometry provided a lower pressure that more closely matched that inside the actual thruster. More recently, simulation work performed by Mikellides at JPL demonstrated the role of local downstream neutral pressure in hollow cathode operation [9]. The simulations were initially conducted with a constant facility background pressure and were unable to accurately capture the increase in keeper voltage oscillations observed in the laboratory as cathode flow rate was decreased. However, when the simulations were repeated with a variable facility background pressure

that decreased with decreasing flow rate, the increased keeper voltage oscillations were replicated. Mikellides identified that during an oscillation cycle, the neutrals in front of the keeper orifice were fully depleted and reached the arbitrary background pressure limit set in the simulation. This neutral depletion and its related ionization phenomena appeared to be the cause of the transition to plume mode. Thus, though the work is ongoing, the early results suggest that the neutral pressure in the vicinity of the cathode has significant impact on mode transitions.

Mikellides has shown that properly capturing the background pressure in simulation work is crucial to accurately matching experimental results, but what has not yet been explored is the effect of background pressure on cathode operation. Recently, NASA GRC performed a series of experiments to study these effects in more detail, with specific focus on the role of neutral pressure due to anode geometry in the operation of a hollow cathode. We began by performing neutral flow simulations to quantify the effect that anode diameter and position has on the neutral pressure environment downstream of a hollow cathode operating in a cathode test facility and how those neutral pressure results compare to what the cathode experiences within an operating Hall thruster. Based on the results of those simulations, we constructed two axially-segmented anodes [8], one with a diameter of 64 mm and another with a diameter of 254 mm. We then performed a characterization of a 25-A class barium oxide hollow cathode with each anode. We varied the axial distance between the anode and the cathode and studied how cathode parameters such as the discharge voltage varied. We also used a retarding potential analyzer (RPA) to measure the radial ion voltage distribution function. To better isolate the neutral density effects, we also performed a characterization with each anode wherein we only biased two axial segments at each anode position. As we moved the anode farther from the cathode, we changed which segments were biased such that the distance from the cathode to the collecting surface remained constant.

Our paper is structured as follows. First, we present the experimental apparatus and data reduction techniques in Section III. Next, we present the results of our neutral flow simulations, which provide further motivation for this experiment, in Section IV. We present our experimental results in Section V, which include those from the 64-mm diameter anode in Section V-A, from the 254-mm diameter anode in Section V-B, and from the two-segment study in Section V-C. Finally, we present a discussion of the data, including implications on component-level cathode testing, in Section VI and provide conclusions in Section VII.

III. Experimental Apparatus and Data Reduction

In addition to the segmented anodes, we used an ionization gauge with a sense tube, a retarding potential analyzer (RPA), and a dedicated power rack and data acquisition system for this experiment. We detail each of these below, including the data reduction techniques for the RPA results. Figure 1 shows a schematic of the internal setup for this experiment.

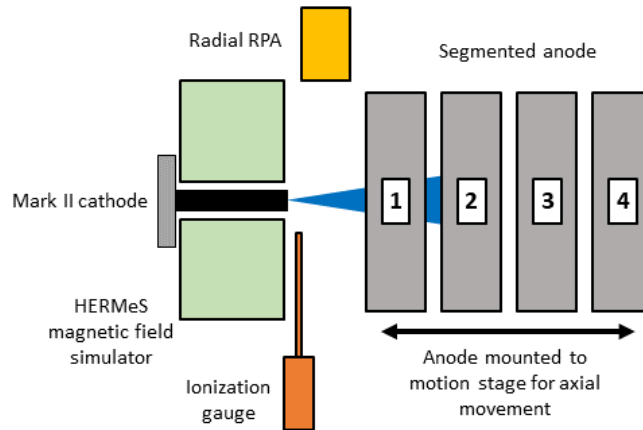


Figure 1. Schematic of the internal setup for this experiment, including the segmented anode, RPA, and local neutral pressure ionization gauge apparatus.

A. Segmented Anodes

We constructed a set of two axially-segmented cylindrical anodes for this experiment, one 64 mm in diameter and the other 254 mm in diameter (Figure 2). We refer herein to these two anodes as the Small Anode and the Large Anode, respectively. These anodes each consisted of four 50 mm-long cylinders constructed from molybdenum sheet. The segments were arranged with 2 mm axial spacing. The segmented anode was operated from a single discharge

supply using a dedicated breakout box. This breakout box received the output of the discharge supply and split it to the four anode segments in parallel. The voltage and current of each segment was measured within the breakout box using voltage sense lines and current shunts, respectively. Each segment was individually able to be electrically isolated or connected to the power supply, such that the anode could be operated with any combination of one, two, three, or four segments collecting current. Non-collecting segments were allowed to electrically float. Throughout this paper we refer to the segments in sequence, starting with the segment closest to the cathode as Segment 1 and increasing in numerical order as shown in Figure 1.

We mounted the anode assembly under test to an axial motion stage such that the anode/cathode distance could be varied. For the results presented below, we positioned each anode in four positions, which we refer to in increasing order of anode/cathode gap as Position 1, Position 2, etc. The positions were selected such that they were each one anode segment width apart, as illustrated in Figure 3. The anode/cathode distance is characterized by the distance between the downstream keeper face of the cathode and the upstream entrance to Segment 1 of the anode.



Figure 2. Photographs of the two molybdenum, axially-segmented anodes used in this experiment: the 64-mm diameter Small Anode (left) and the 254-mm diameter Large Anode (right).

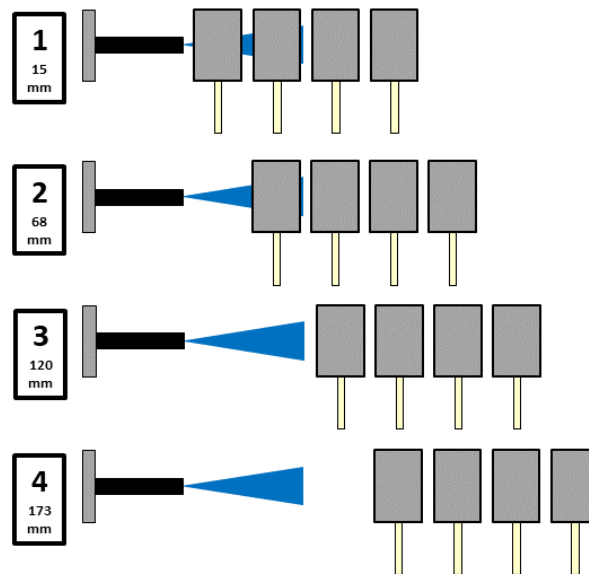


Figure 3. Illustration of the four anode positions tested in this experiment, including the anode/cathode distance for each (not to scale).

B. GRC Mark II Cathode

For this experiment we used the second-generation cathode developed for the HERMeS Hall thruster called the Mark II [10], shown in Figure 4. The Mark II cathode is a 25-A class cathode with a barium oxide emitter. The cathode features brazed joints [11] and draws heritage from a number of previous GRC cathode development efforts, including the International Space Station Plasma Contactor [12,13], the NSTAR and NEXT ion thruster neutralizer and discharge cathode assemblies [14,15], and previous high-current cathode technology projects [16–18]. The key dimensions of the cathode, including the cathode tube, orifice, and keeper dimensions, all match the laboratory model cathodes used in the Technology Demonstration Unit (TDU) -1 and TDU-3 thrusters at NASA GRC [19–22,22–24] and for component-level testing [25]. The key dimensions are also similar to the HERMeS cathode developed and tested extensively by JPL [26–31], although the JPL cathode utilizes a lanthanum hexaboride emitter. For all operation reported here, the Mark II was operated at the nominal HERMeS discharge current of 20.8 A and was allowed to electrically float relative to facility ground.



Figure 4. The Mark II cathode, a 25-A class barium oxide hollow cathode developed for the HERMeS Hall Thruster.

C. Magnetic Field Simulator

We constructed a magnetic field simulator that produced similar cathode centerline magnetic field profile and magnitude as the HERMeS Hall thruster. The simulator provided comparable centerline peak magnetic field strengths and centerline profiles as the full HERMeS circuit. For reference, herein when we refer to a magnetic field strength, it is the peak cathode centerline value. For this testing, we operated at two representative magnetic field conditions, which we refer to as 0 G and 325 G.

D. Local Pressure Measurement

To characterize the neutral pressure in the near-downstream region of the cathode, we implemented an ionization vacuum pressure gauge with a sense tube positioned near the cathode keeper orifice. The sense tube consisted of a 6.4-mm diameter stainless steel tube which was allowed to electrically float using a ceramic isolator between the tube and the ionization gauge. This configuration minimized plasma interaction with the tube. This gauge was calibrated on nitrogen and corrected for xenon using typical industry practices [32]. We did not attempt to correct to a “true” pressure like what was performed by Huang [33]. This gauge was used to characterize the relative pressure change between operating conditions and anode positions, but was not used to directly compare to or anchor our neutral flow simulations, so a correction was not needed. Thermal effects were not accounted for in the ionization gauge results, but these effects are expected to be second-order. Uncertainty on the pressure measurement was estimated as $\pm 20\%$ of the reading.

E. Vacuum Facility and Test Apparatus

This experiment occurred in Vacuum Facility 1 (VF-1) at NASA GRC. This facility was recently refurbished and outfitted for hollow cathode testing [10]. VF-1 is a 1.5-m diameter, 4.5-m long cylindrical vacuum facility, with a 0.9-m diameter cryogenic pump that provides base pressures on the order of 1×10^{-7} Torr and operating pressures on the

order of 18 $\mu\text{Torr-Xe}$ (as measured by an ionization gauge mounted on the facility wall approximately 60 cm behind the cathode exit plane) at the nominal Mark II flow rate of 14.7 sccm of xenon.

In addition to the dedicated segmented-anode breakout box discussed above, we used a second breakout box that contained the keeper, heater, cathode return, and electromagnet power and sense lines. We recorded telemetry, which included the voltage and current telemetry from both breakout boxes as well as facility and local pressure, using a commercial multiplexed data acquisition system. Uncertainty on the voltages measured by the DAQ was estimated as ± 0.01 V. Electric propulsion-grade (99.9995%) xenon was provided to the cathode using a 50-sccm commercial mass flow controller and electropolished stainless steel tubing. We collected high-speed voltage and current information from the cathode using two digital oscilloscopes. High-speed differential voltage probes provided peak-to-peak measurements of the voltage oscillations on each of the four anode segments. The estimated uncertainty of these peak-to-peak measurements was ± 0.2 V.

F. Retarding Potential Analyzer

We used a four-grid retarding potential analyzer (RPA) [34] to characterize the ion voltage per charge radially from the cathode exit. This RPA is the Air Force Research Laboratory design used by Huang in previous GRC thruster testing [35,36]. The first grid of the RPA was allowed to float; the second was biased to -30 V to repel electrons from entering the RPA; the third grid was swept from 0 V to 250 V to selectively repel ions; the fourth grid was biased to -30 V to suppress secondary electrons emitted by ions striking the collector. The second and fourth grids were tied together and biased using a 30 V, 1 A laboratory power supply; the bias grid was swept using a commercial high-voltage sourcemeter; and the collector current was measured using a commercial picoammeter. A typical RPA sweep took approximately 30 seconds.

The RPA was operated with respect to facility ground for ease of implementation. However, in much of the cathode literature RPAs are operated with respect to cathode potential [37,38]. To match the literature, we corrected the reference potential of our results to the cathode-to-ground voltage for each test condition. Thus, a reported peak location of 20 V, for example, indicates 20 V above the cathode potential. After this correction, a numerical derivative of the voltage-current trace was calculated. The negative of this derivative is equal to [34,35]:

$$-\frac{dI}{dV} = \frac{q_j^2 e^2 n_i A_c}{m_i} f(V), \quad (1)$$

where q_j is the charge of species j , e is the elementary charge, n_i is the ion density, A_c is the collector area, m_i is the ion mass, and $f(V)$ is the ion voltage distribution function. For Hall thruster plume analysis, a single species is typically assumed and $-dI/dV$ is taken to be proportional to the ion energy distribution function $f(\epsilon)$. However, without charge state measurements, we cannot make that assumption with our data. Recent measurements by Polk on the JPL HERMeS cathode demonstrate a measureable population of doubly-charged ions in the radial direction [31]. With a lack of information on charge state and ion density we can only treat $-dI/dV$ from our results as proportional to the ion voltage distribution function $f(V)$ [39]. Nonetheless this analysis provides important insights into the plume ion population.

In Hall thruster plume measurements, the emphasis in RPA analysis is typically on the most probable voltage or average voltage. Typical thruster plume traces feature a quasi-Maxwellian population with a most probable voltage near the thruster discharge voltage [35]. However, as numerous works in the literature demonstrate [38,40–42], cathode ion voltage distributions not only are often not Maxwellian but even have multiple populations of ions. In our results, we found a peak in $f(V)$ at approximately the discharge voltage, in some cases a second peak at approximately double the discharge voltage, and a high-voltage tail that extended from 10 V to 200 V above the peak locations. Thus, our analysis focuses on what we call Peak 1, Peak 2, and the 95% Population Extent, which refer respectively to the locations of the first, lower-voltage ion peak; the second, higher-voltage ion peak (if present); and the voltage at which 95% of the area under the curve is captured. The 95% curve area metric was chosen arbitrarily as a means to characterize the extent of the tail that was robust against noise for all operating conditions. Uncertainty in these three values is estimated as ± 0.5 V. These features are annotated on an example $f(V)$ trace in Figure 5.

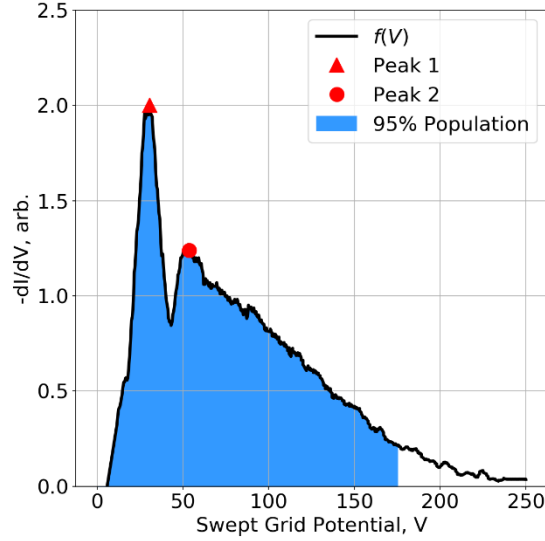


Figure 5. Example $f(V)$ trace illustrating the two peak locations and the 95% population extent.

IV. Motivation: Neutral Flow Simulations

Prior to constructing hardware we performed neutral-flow simulations to quantify the effect of anode geometry on the neutral environment in the vicinity of the cathode. These simulations emulate operation in VF-1, using its background pressure and pumping speed, and were all performed at 14.7 sccm, the nominal flow rate for this cathode. This is a 2D axisymmetric version of a direct simulation Monte-Carlo code previously used for various neutral gas flow studies [43,44]. For the gas inflow, we assumed diffuse flow with temperatures of approximately 1500 K for cathode flow and 300 K for facility background gas. We assumed a cathode flow rate of 15 sccm and a propellant utilization of 5%, resulting in a cathode neutral flow of approximately 14 sccm, and used a background pressure of approximately 2×10^{-5} Torr to emulate the test environment in VF-1 [9].

We first performed simulations on the Small Anode geometry (64-mm diameter) in two positions relative to the cathode. This anode geometry is very similar to one used for many previous tests on the HERMeS cathodes both at GRC [25] and JPL [27,45], including the experiments used by Mikellides for his simulations [9]. Figure 6 presents these results for the anode in two positions: 13 mm (top) and 76 mm (bottom) from the keeper exit. Immediately apparent is that the neutral density inside the anode is significantly above the ambient facility pressure for both positions, remaining approximately 1.5 orders of magnitude above the facility neutral density for the length of the anode. The anode position makes a large difference as well: with the anode in the 13 mm position, the region where the neutral density is above $1 \times 10^{19} \text{ m}^{-3}$ along centerline extends approximately 10 times further than in the 76 mm case. For reference, using the assumptions detailed above, the neutral density in this region corresponds to a pressure of approximately 1×10^{-3} Torr.

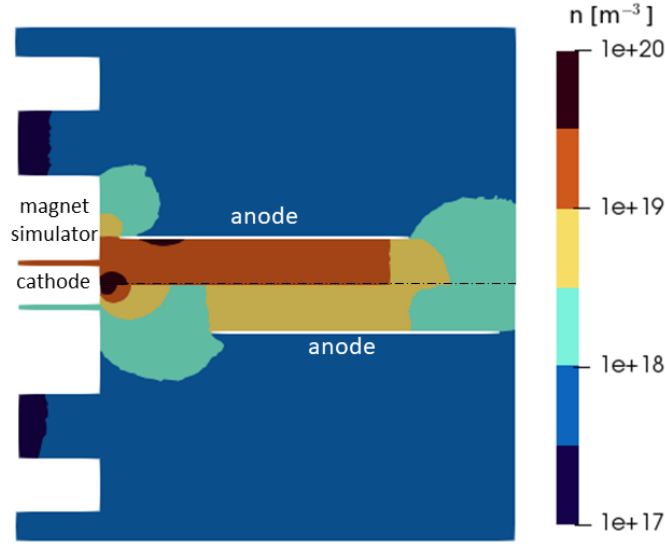


Figure 6. Neutral flow simulation results for a 64-mm diameter anode located 13 mm (top) and 76 mm (bottom) from the keeper exit plane. The results are for a cathode flow of 14.7 sccm and simulate the pumping environment of VF-1. Figure is notional and not to scale.

Next we modeled the Large Anode (254-mm diameter) geometry, which mimics a geometry used during previous GRC high-current cathode development testing [17,18]. We performed simulations for the same two anode/cathode distances, the results of which are in Figure 7. For easy comparison we present these results scaled to the same coloring as those in Figure 6. The Large Anode allows the neutral density to decrease on cathode centerline much more quickly than the Small Anode, falling below $1 \times 10^{19} \text{ m}^{-3}$ by about 15 mm downstream in both cases. For comparison, with the Small anode in the 13-mm position this density was not reached until approximately 250 mm downstream of the cathode exit. The near-cathode region looks very similar between the two positions for the Large Anode. The density falls below $5 \times 10^{18} \text{ m}^{-3}$ approximately 10 mm closer to the cathode with the anode in the 76 mm position as compared to the 13 mm position. The remaining distribution along centerline is approximately uniform for both anode positions.

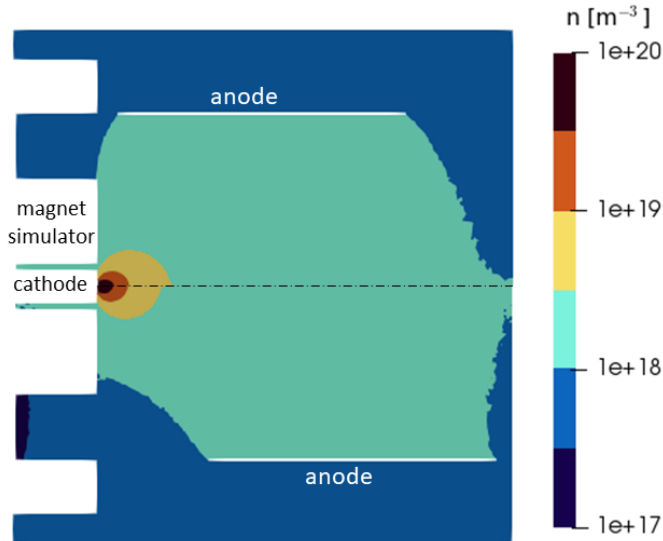


Figure 7. Neutral flow simulation results for a 254-mm diameter anode located 13 mm (top) and 76 mm (bottom) from the keeper exit plane. The results are for a cathode flow of 14.7 sccm and simulate the pumping environment of VF-1. Figure is notional and not to scale.

These results show that for a given test facility, the neutral pressure downstream of the cathode will be affected by the anode position, and that the smaller-diameter anode increases the sensitivity to axial anode/cathode distance. However, these simulations do not make any indication of what geometry is preferable. This will be dictated by the pressure environment the cathode experiences while operating inside the thruster. For this cathode, the most relevant environment for comparison is to HERMeS operating in VF-5 at NASA GRC [19–22,36,46,47].

Using this same simulation tool, we modeled the neutral environment in the vicinity of the cathode for HERMeS operating in VF-5. For this we assumed a 95% propellant utilization of the thruster flow rate of 225 sccm, resulting in approximately 11 sccm of neutral flow from the thruster. The ambient background pressure for the VF-5 case was 5×10^{-6} Torr to match what is typically achieved during HERMeS testing [47]. We acknowledge that these diffuse neutral flow simulations only approximate the true neutral density profiles, as various effects from the presence of the plasma (e.g. ionization, charge exchange collisions, etc.) are ignored. However, they are still illustrative of general trends and of relative comparisons with respect to the neutral gas environment for various cathode test environments.

Figure 8 compares these in-thruster results to each of the anode geometry simulations. The densities attained within the Small Anode are significantly higher along the entire centerline of the simulation. Whereas in the VF-5 simulation the density decreases below $1 \times 10^{18} \text{ m}^{-3}$ 60 mm or so downstream from the cathode, the Small Anode maintains a density above that value out to the downstream boundary of our simulation domain, approximately 350 mm downstream of the cathode exit. With the Small Anode in the 76 mm position, the density follows the in-thruster contours much more closely until the entrance to the anode, at which point the density increases by half an order of magnitude. Even the Large Anode does not allow the density in front of the cathode to fall to VF-5 levels: although the region above $1 \times 10^{19} \text{ m}^{-3}$ immediately downstream of the cathode exit matches much more closely than either Small Anode case, the distance at which the density falls below $1 \times 10^{18} \text{ m}^{-3}$ still extends beyond the simulation domain along cathode centerline for both Large Anode cases.

These results demonstrate that the Small Anode geometry elevates the neutral density along cathode centerline approximately 1.5 orders of magnitude above what the cathode experiences while operating in the HERMeS thruster in VF-5. The Large Anode provides a neutral pressure environment more similar to that of the thruster in VF-5, especially in the near-field cathode region (60 mm downstream or so), though the far-field neutral pressure remains half an order of magnitude higher than the in-thruster results. Though these differences appear large, the simulations do not identify what effect—if any—the change in neutral pressure has on cathode operation. To study this question in more detail, we operated the Mark II cathode with segmented anodes constructed with the same dimensions used in the simulations. We discuss these tests below.

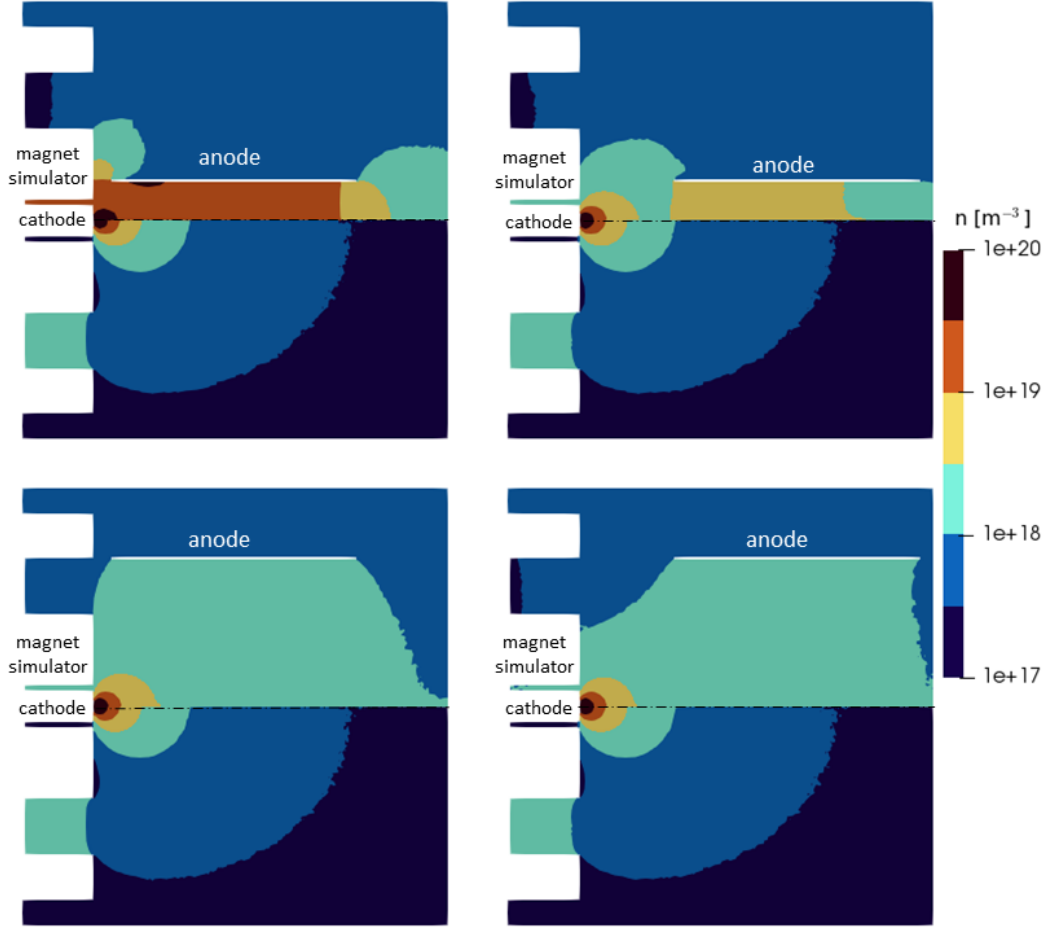


Figure 8. Neutral flow simulation results for the anode geometries presented above (top in each figure) compared to the neutral flow simulation results for the HERMeS thruster operating at nominal conditions in VF-5. Figure is notional and not to scale.

V. Results

We present our results in three parts. First, we study the trends with anode position for the Small Anode, then the Large Anode. For both of these studies, all four anode segments were collecting current at each position. Finally, we discuss the results of a study in which only two of the anode segments were biased in each position, with the segments selected at each position such that the collecting surface was the same distance from the cathode exit regardless of the anode position. This was intended to isolate the effect of the change in background pressure from the effect of changing the location of the anode collecting surface.

One notable finding illustrated by the results below is that the minimum attainable flow rate for the cathode increased with increasing anode/cathode distance, where the Small Anode was more sensitive than the Large Anode. For instance, the minimum stable flow rate for the Small Anode at 0 G was 4.6 sccm in Position 1, 8.6 sccm in Position 2, 10.6 sccm in Position 3, and 21.3 sccm in Position 4. The Large Anode was able to operate in all four positions at 0 G at flow rates as low as 6.4 sccm.

A. Small Anode Results

1. Local Pressure

Figure 9 shows the local pressure measured using the ionization gauge and sense tube. On the left are results for the 0 G condition, and on the right are those for the 325 G condition. For the 0 G condition, the pressure decreases by approximately a factor of three from Position 1 to Position 2, but the change from Position 2 to Position 4 is much smaller, such that the local pressure for these three positions is the same within the measurement uncertainty. For the

325 G case the change is not as dramatic from Position 1 to Position 2, but is still nearly a factor of 2 decrease. Once again the neutral pressure of Positions 2, 3, and 4 are within the measurement uncertainty.

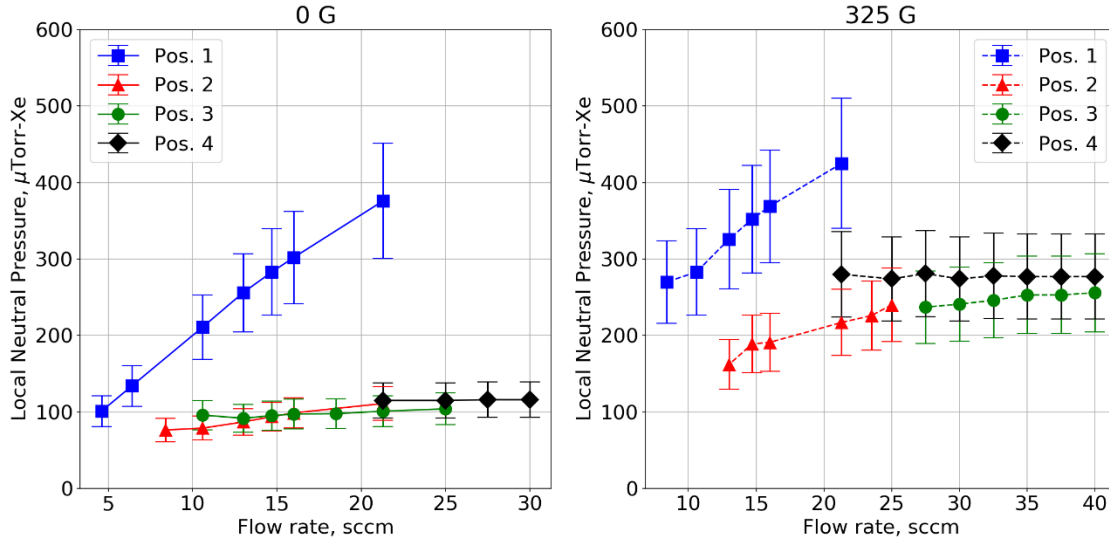


Figure 9. Local pressure versus flow rate for the Small Anode for the 0 G condition (left) and the 325 G condition (right).

2. Discharge Voltage

Figure 10 shows the behavior of the discharge voltage for 0 G and 325 G. In both cases discharge voltage increases with both decreasing flow rate and increasing anode/cathode distance. It is also notable that the discharge voltage for the 325 G case is always larger than the comparable 0 G condition. Whereas the discharge voltage never exceeds 30 V in the 0 G case, it exceeds 50 V for a number of conditions in the 325 G case. A more detailed investigation of the role that the magnetic field has in cathode operation is presented in our companion paper [48].

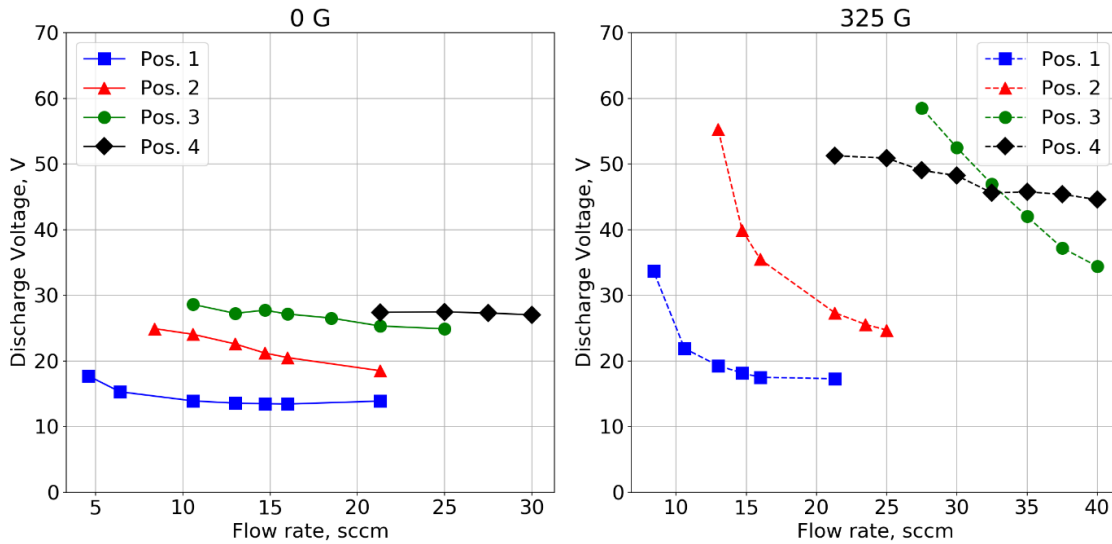


Figure 10. Discharge voltage versus flow rate for the 0 G case (left) and the 325 G case (right) for the Small Anode. Measurement uncertainty is smaller than the marker size.

3. Discharge Voltage Oscillations

Discharge voltage oscillations are characterized by the peak-to-peak voltage as measured using the high-speed voltage probes and the oscilloscope described above. Here these peak to peak values are normalized by the DC discharge voltage values, providing the oscillations as a percentage of full scale. As Figure 11 shows, these oscillations generally increase in magnitude with increasing anode/cathode distance. Unlike the DC discharge voltage values, the

magnitude of oscillations between the 0 G and 325 G cases are very similar. For both, Position 1 provides the lowest oscillation magnitudes (less than 10% the DC value), and Position 4 provides the highest (approximately 30% the DC value). However, the trend with flow rate is reversed: for 0 G oscillation magnitude increases with decreasing flow rate whereas for 325 G oscillation magnitude decreases with decreasing flow rate.

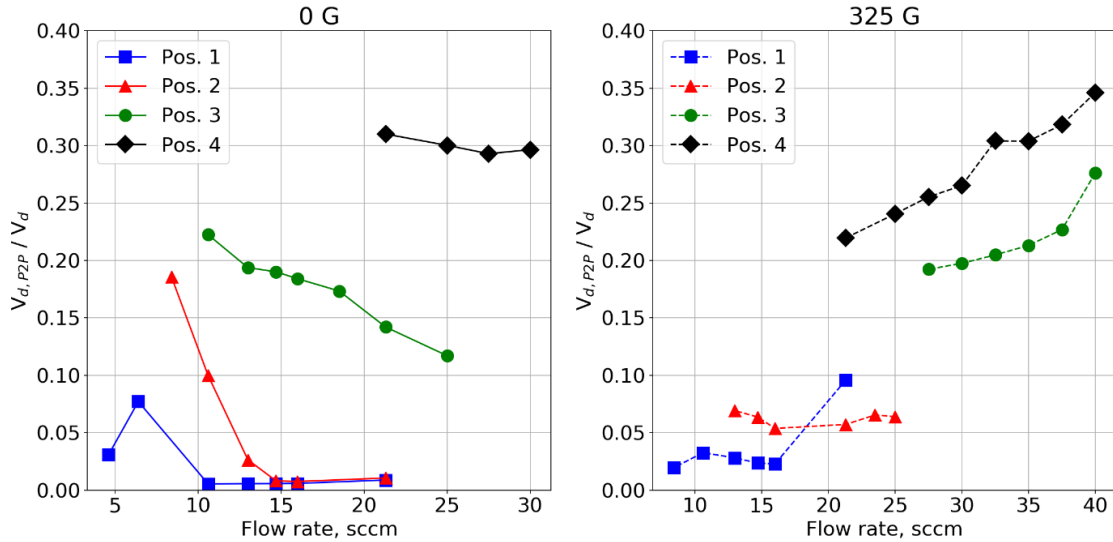


Figure 11. The discharge voltage peak to peak oscillation magnitude (normalized by the steady-state discharge voltage value) for the Small Anode for both the 0 G (left) and 325 G (right) cases. Measurement uncertainty is on the order of the marker size.

4. Ion Voltage Spectra

Figure 12 presents the location of the peak of $f(V)$ with respect to flow rate for both magnetic field strengths. The trends generally match those of discharge voltage. The 0 G case shows a slight increase in the peak location with decreasing flow rate and with increasing anode/cathode distance, with magnitudes less than 30 V for all but a single condition. The 325 G case shows a stronger increase with decreasing flow rate, similar to that of discharge voltage, and a more notable difference between Position 1 and Positions 2, 3, and 4. For example, the peak location is nearly a factor of two higher at Positions 2 and 3 than at Position 1 at 21.3 sccm. Additionally, the overall magnitudes of the peak location are much higher for the 325 G case than the 0 G case, with peaks in excess of 60 V for some cases.

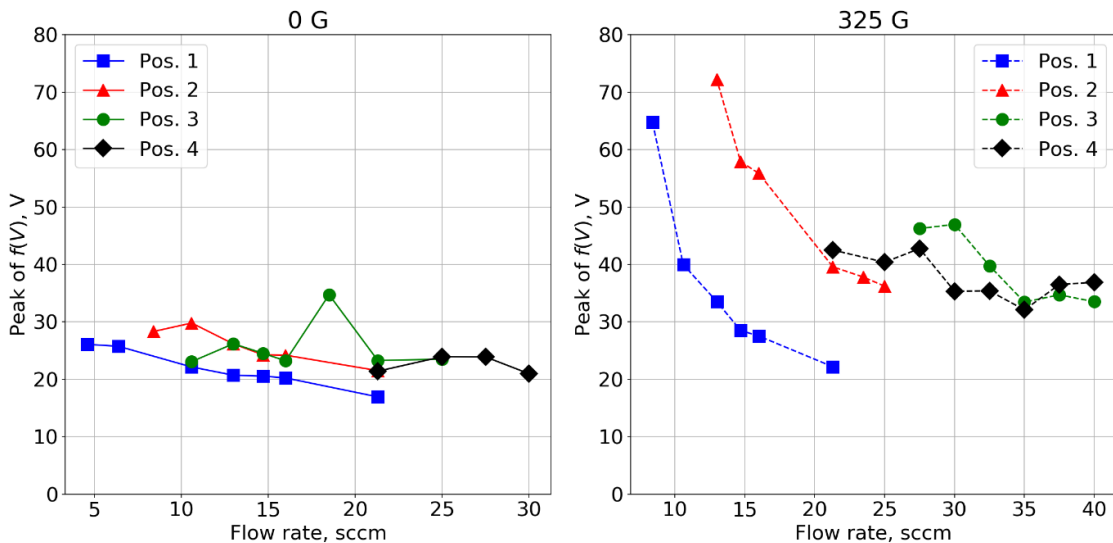


Figure 12. The location of the $f(V)$ peak for the Small Anode for the 0 G case (left) and the 325 G case (right). Measurement uncertainty is smaller than the marker size.

In addition to the location of the peak, the extent of the high-voltage tail changed as well. Figure 13 shows the 95% population extent. The trends here are qualitatively similar to the peak location. For the 0 G case, the tail extent increases with decreasing flow rate and for increasing anode/cathode distance. Generally, the tail extends to approximately twice the peak location, with voltages up to 60 V. The 325 G case also follows the trends of the peak location, with the extent of the tail increasing with decreasing flow rate and with increasing anode/cathode distance. Here, the tail generally extends to closer to three times the voltage of the peak, which results in a tail extending beyond 175 V in some cases. However, it is worth noting that for 325 G, the highest-voltage tail corresponds to the lowest oscillation magnitude as shown in Figure 11. This is opposite the trend typically found in spot and plume mode (where lower flow rate results in both higher ion energies and higher oscillation magnitudes), a result we explore in more detail in our companion paper [48]. Much like the peak location, the ion voltage tails in Positions 2, 3, and 4 are much more similar than for Position 1. For a given flow rate, this results in significantly higher-voltage tail on $f(V)$ for Positions 2, 3, and 4. For instance, at 21.3 sccm the tail extends to 40 V in Position 1 and 125 V in Positions 2 and 3.

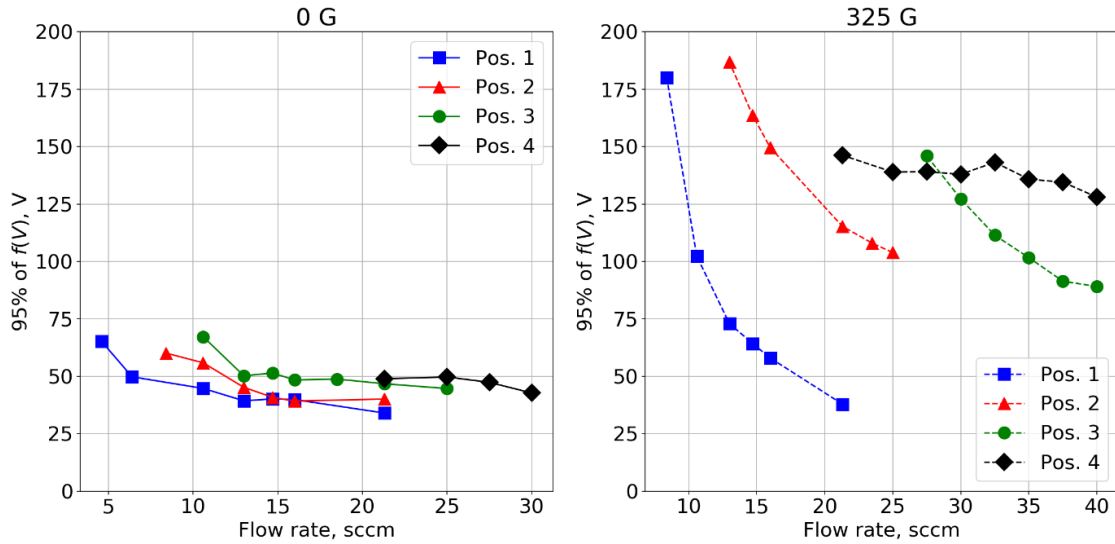


Figure 13. Extent of the high-voltage ion tail for the Small Anode for 0 G (left) and 325 G (right). Measurement uncertainty is smaller than the marker size.

B. Large Anode Results

1. Local Pressure

Figure 14 presents the local neutral pressure for the Large Anode for both magnetic field strengths. Unlike for the Small Anode, the pressure at a given flow rate is within the measurement uncertainty at all four positions. The maximum pressure difference between positions at a given flow rate range from 1% to 16% for both 0 G and 325 G. These differences are much smaller than the 50% difference between Position 1 and Positions 2, 3, and 4 for the Small Anode.

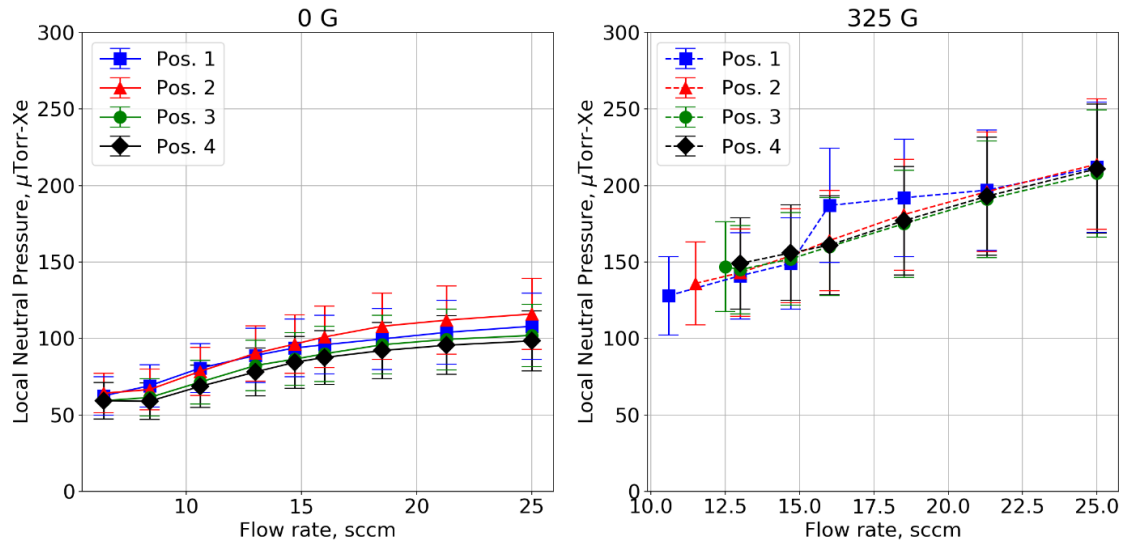


Figure 14. Local pressure for the Large Anode for the 0 G case (left) and the 325 G case (right).

2. Discharge Voltage

Figure 15 shows the trends of discharge voltage with flow rate. Much like the neutral pressure results, there is much less difference in these data than for those from the Small Anode as a function of position. For the 0 G case, the maximum difference in discharge voltage for a given flow rate is less than 5 V. The difference is larger for the 325 G case and increases with decreasing flow rate, for a maximum difference of 17 V. Nonetheless, both cases are considerably more consistent between positions than the Small Anode was. The overall trends—namely an increase in discharge voltage with decreasing flow rate for both 0 G and 325 G, and a larger discharge voltage magnitude at 325 G than at 0 G—match the Small Anode results.

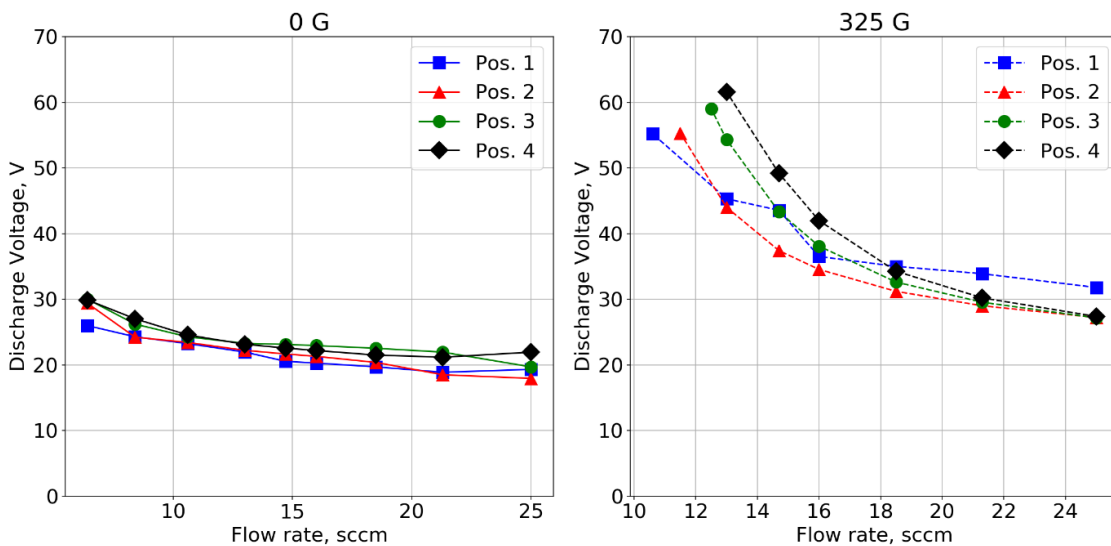


Figure 15. Discharge voltage versus flow rate for the Large Anode for both the 0 G and the 325 G cases. Measurement uncertainty is smaller than the marker size.

3. Discharge Voltage Oscillations

The discharge voltage oscillations were similar in magnitude between the two anodes, as shown in Figure 16. However, unlike the Small Anode, trends with increasing anode/cathode distance are not as clear. For the 0 G case, the oscillation magnitude in the middle flow rates (from about 8.6 sccm to about 20 sccm) is generally less than 12% for all cases, with magnitudes falling to less than 5% for Positions 3 and 4. However, at Positions 3 and 4 the traces

take on a “U” shape wherein the oscillation magnitudes at the highest and lowest flow rates increase to above 20%. For the 325 G case, the oscillations decrease significantly from Position 1 to Positions 2-4, with the oscillations for the latter remaining below 7% for all flow rates and often similar to within the measurement uncertainty. For Position 1, the oscillation magnitude increases with increasing flow rate, similar to what was seen for the Small Anode. All oscillation magnitudes in the 325 G case remain below 20%.

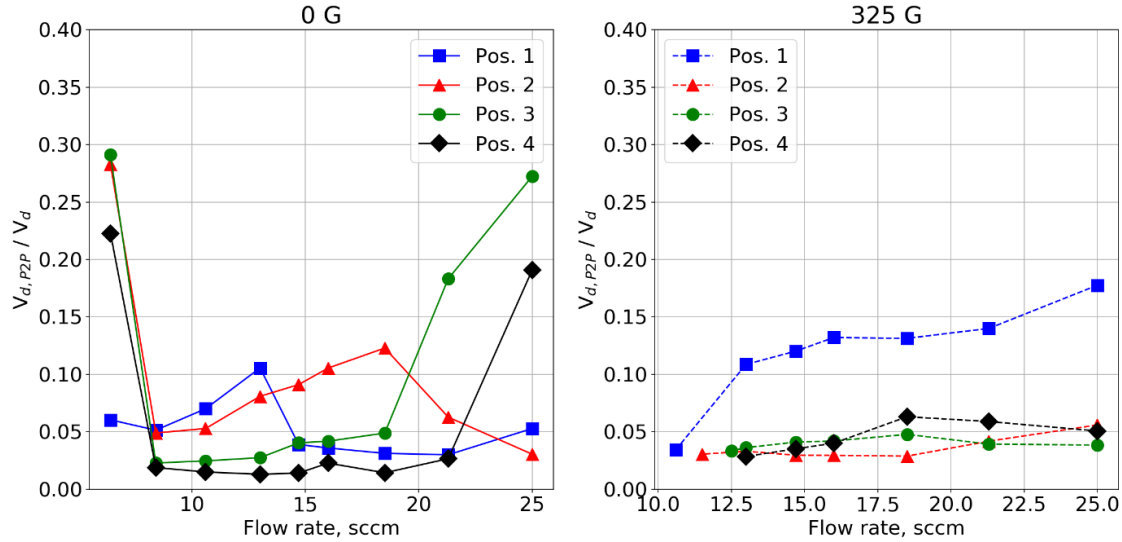


Figure 16. Discharge voltage oscillations, normalized by the DC discharge voltage, for the Large Anode at both 0 G (left) and 325 G (right). Measurement uncertainty is on the order of the marker size.

4. Ion Voltage Spectra

For the Large Anode, the 0 G ion voltage spectra were qualitatively similar to those for the Small Anode. However, some of the 325 G spectra were different in that they featured the second peak (Peak 2) at voltages between 1.5—2.5 times the discharge voltage. For some anode positions, these two peaks appeared to blend together. Whether the $f(V)$ s featured one peak or two they always had a tail that extended to voltages approximately 4-5 times that of Peak 1.

As shown in Figure 17, the behavior of the location of Peak 1 is similar for both magnetic field conditions to that of the Small Anode. For both cases, the peak voltage increases with decreasing flow rate. The change with flow rate is significantly less for the 0 G case than for the 325 G case. For the 0 G case, the ion voltage peak remains below 40 V for all but the lowest flow rate in Position 1, and below 30 V for all but a single condition for Positions 2, 3, and 4. Conversely, the 325 G peaks are at much higher voltages, with locations ranging from 30 V to 55 V for Positions 1 and 2 and from 30 V to 90 V for Positions 3 and 4. The sensitivity to flow rate increases with increased anode/cathode distance.

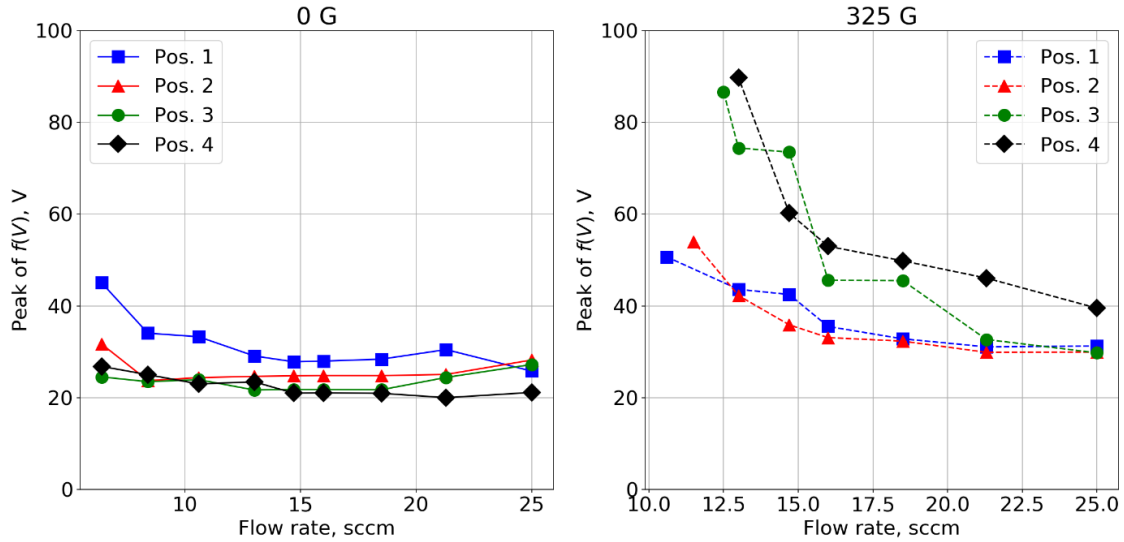


Figure 17. Voltage of Peak 1 (lower voltage) of $f(V)$ for the Large Anode, for both the 0 G case (left) and the 325 G case (right). Measurement uncertainty is smaller than the marker size.

Again like the Small Anode, there is a significant increase in the extent of the high-voltage ion tail for the 325 G case as compared to the 0 G case, which Figure 18 illustrates. For both magnetic field strengths the extent of the tail generally tracks with the peak location and thus increasing with decreasing flow rate. In the 0 G case, the extent of the tail remains below 125 V for all conditions. In the 325 G case, however, all conditions feature a tail in excess of 100 V, with the population extending to between 175 V and 225 V at the nominal 14.7 sccm flow rate.

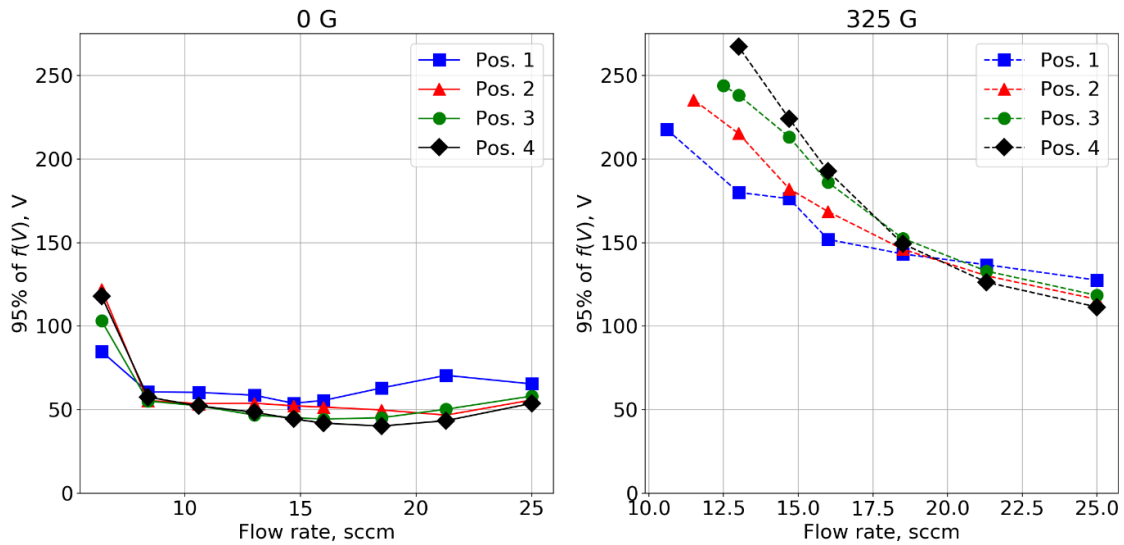


Figure 18. Extent of the high-voltage ion tail for the Large Anode for both the 0 G case (left) and the 325 G case (right). Measurement uncertainty is smaller than the marker size.

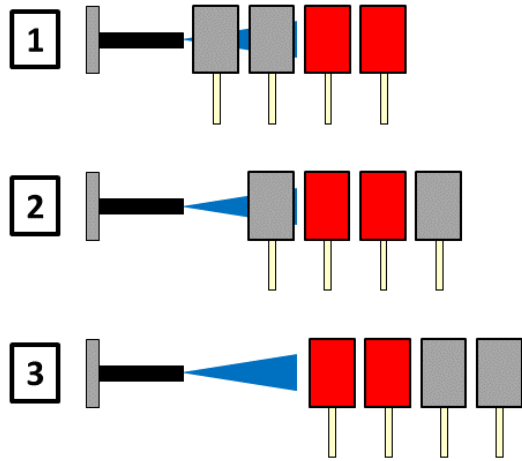


Figure 19. Graphic illustrating two-segment operation, wherein only two segments (noted in red) are biased at each position.

C. Two-Segment Operation to Isolate Neutral Pressure Effect

Although the experiments above—with the full anode biased—are informative and illustrative of the impact that anode position has on cathode operation, it is difficult to infer what may be driving the changes observed. As an attempt to isolate the change in neutral pressure due to the anode position, we performed an additional sweep with each anode assembly for the 325 G case in which we only operated two segments of the anode at a given position. This is illustrated in a graphic in Figure 19. By biasing segments 3 and 4 in Position 1; segments 2 and 3 in Position 2; and segments 1 and 2 in Position 3, the anode collecting surface remains the same distance from the cathode for all conditions. Though the floating segments may still affect cathode operation in some capacity, especially when between the cathode and the biased segments, the Debye length in this region is small enough to shield most of these effects from the bulk of the discharge. Thus, the role of neutral pressure has not been perfectly isolated here, but these sweeps offer further insight into the processes driving the phenomena we observed.

1. Local Neutral Pressure

Figure 20 presents the local neutral pressure as a function of flow rate for both anode geometries. These results are very similar to those from the full anode tests above. The Small Anode exhibits a large decrease in pressure when moving from Position 1 to Position 2 and 3, whereas the pressure for the Large Anode at all three positions is nearly identical and within the measurement uncertainty. Not only do the trends match, but the magnitudes of the pressures also match those presented in Figure 9 and Figure 14. This is to be expected, as the electrical configuration of the anode should have minimal effect on the neutral gas behavior.

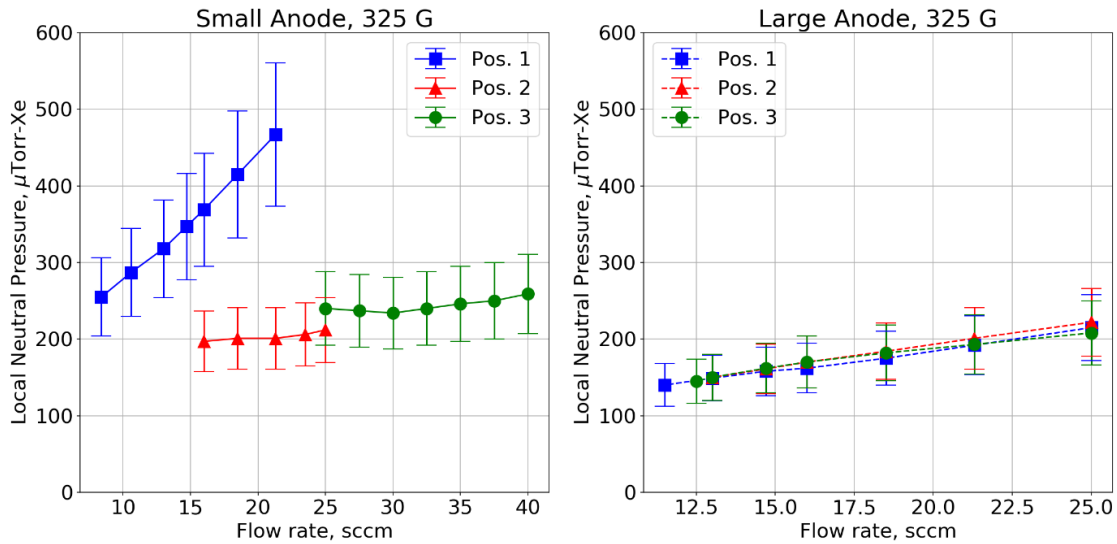


Figure 20. Local neutral pressure as a function of flow rate for the Small Anode (left) and Large Anode (right) for two-segment operation at 325 G.

2. Discharge Voltage

As shown in Figure 21, the discharge voltage behavior is also qualitatively similar to that in Sections VA and VB. For both anodes, discharge voltage increases with decreasing flow rate for all positions. For the Small Anode, discharge voltage increases by approximately 15 V for a given flow rate from Position 1 to Position 2, and an additional 15 V from Position 2 to Position 3. The variation in magnitude for the Large Anode is much smaller, with a variation

of less than 10 V across all positions for a given flow rate. Unlike for the Small Anode, Position 3 provides the lowest discharge voltage for most flow rates tested for the Large Anode.

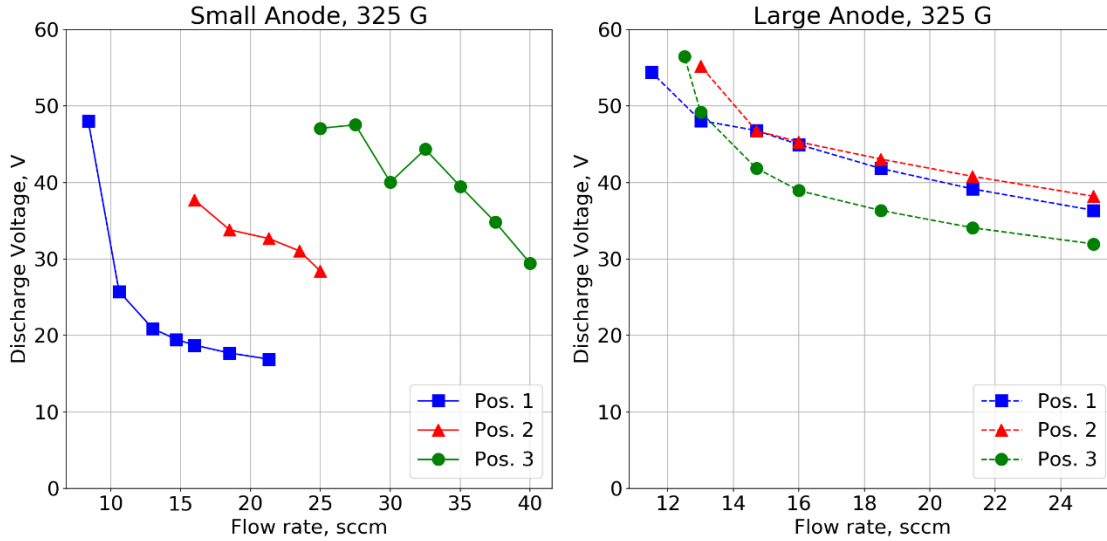


Figure 21. Discharge voltage versus flow rate for the Small Anode (left) and Large Anode (right) for two-segment operation at 325 G. Measurement uncertainty is smaller than the marker size.

3. Discharge Voltage Oscillations

Figure 22 presents the normalized discharge voltage oscillations. For the Small Anode, the magnitude of the oscillations increases with decreasing flow rate and is always less than 15% for Positions 1 and 2. Position 3 shows a marked increase in oscillation magnitude, much like it did for full anode operation as in Figure 11. Note that the trend with flow rate for the Small Anode is the opposite of that seen in full-anode operation, but that the magnitudes and trends with changing positions are approximately the same. The Large Anode always exhibited oscillations less than 25% the mean value that decreased with decreasing flow rate.

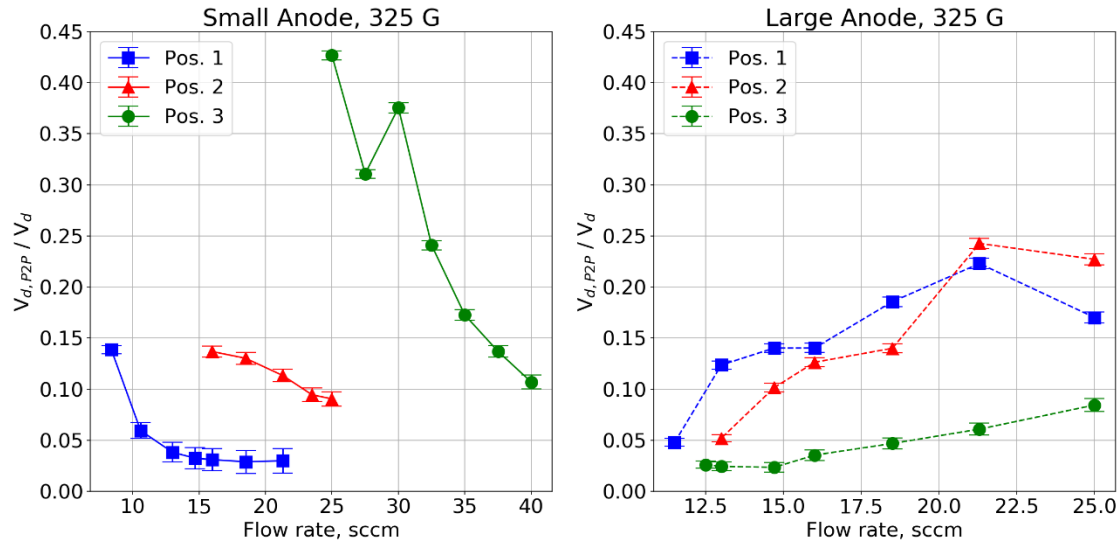


Figure 22. Normalized discharge voltage oscillations for the Small Anode (left) and Large Anode (right) for two-segment operation at 325 G. Measurement uncertainty is on the order of the marker size.

4. Ion Voltage Spectra

Qualitatively the ion voltage spectra for two-segment operation were similar to those for full-anode operation: the Small Anode typically exhibited only Peak 1, whereas the Large Anode exhibited both Peak 1 and Peak 2 and a higher-

voltage ion tail. Figure 23 shows the location of Peak 1 for the Small Anode (left) and the Large Anode (right). For the Small Anode, Position 1 exhibits a lower peak location by about 10 V than Positions 2 or 3. Like for full-anode operation, the peak location generally increases in voltage with decreasing flow rate, trending with the discharge voltage. For the Large Anode, we see similar behavior with decreasing flow rate. The peak varies by 5-10 V between positions. Note that Peak 1 in Position 3 was 10-20 V higher for full-anode operation than that measured here.

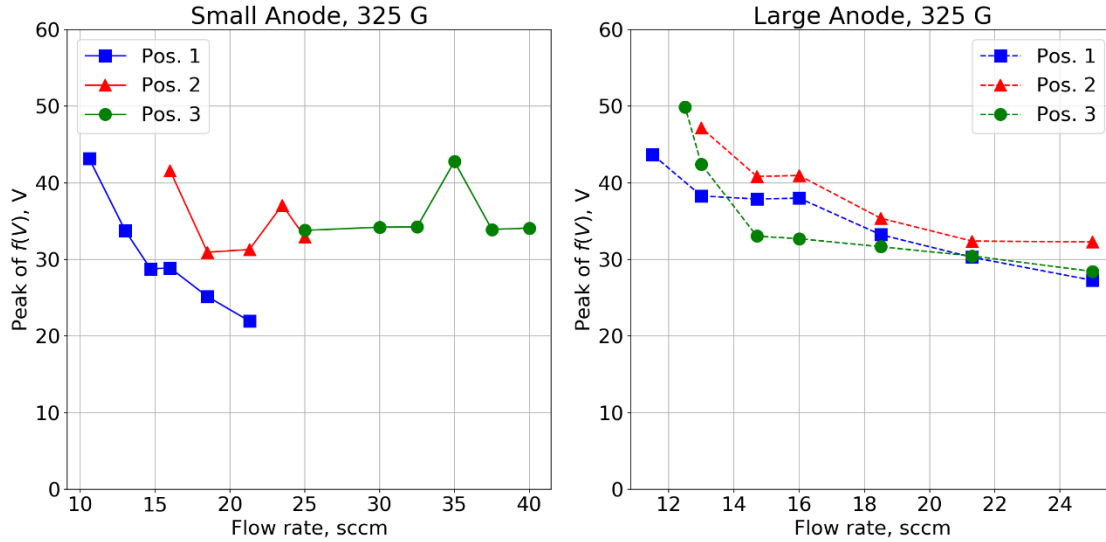


Figure 23. Ion voltage peak location versus flow rate for the Small Anode (left) and Large Anode (right) for two-segment operation at 325 G. Measurement uncertainty is smaller than the marker size.

The extent of the high-voltage tail is shown in Figure 24. The Small Anode shows a difference in the extent of the high-voltage ion tail between Position 1 and Positions 2 and 3, with the latter typically extending 30 V or so higher than the former. The extent of the ion tail increases with decreasing flow rate. The highest-voltage tail for the Small Anode is in Position 1 at 10.6 sccm, at 113 V. Conversely, the smallest extent of the high-voltage ion tail for the large anode is 130 V for Position 3, 25 sccm. The extent of the tail also increases with decreasing flow rate for the Large Anode, approaching 225 V for the lowest flow rates. Just as for the discharge voltage, the extent of the tail was lowest for the Large Anode in Position 3 for most flow rates.

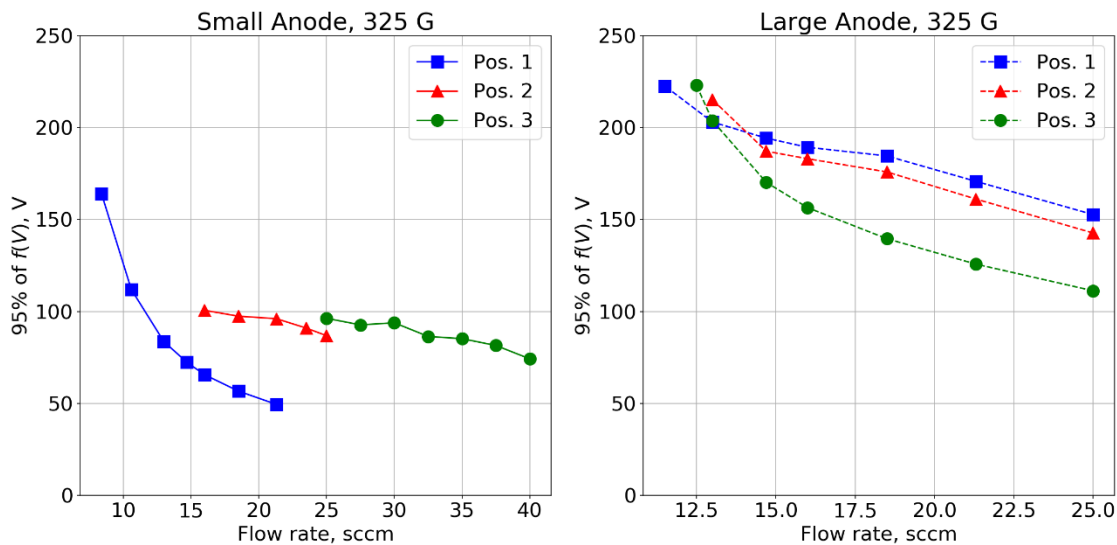


Figure 24. The extent of the high-voltage ion tail for the Small Anode (left) and Large Anode (right) for two-segment operation at 325 G. Measurement uncertainty is smaller than the marker size.

VI. Discussion

It is well established that increased neutral pressure in the near-plume of a hollow cathode damps out high-voltage ions. In the 1990s, experiments by Kameyama demonstrated that both elevating the ambient facility pressure and injecting cold gas immediately downstream of the orifice of a hollow cathode resulted in an increase in the ion population in the 25-35 eV range and a decrease in the high-voltage population at energies above 35 eV [49]. More recently, external injectors have been studied for use in Hall thrusters by both Brown [50] and by Chu [51]. Chu's experiments explored the concept of neutral injection in front of a 250-A class hollow cathode for applications on high-power Hall thruster systems and found that injecting cold gas downstream of the keeper exit at flow rates commensurate with the cathode flow rate reduced the most probable ion voltage and the extent of the high-voltage tail by upwards of 50 V, depending on operating condition.

A similar effect is likely at work here. As the neutral flow simulations suggest and the ionization gauge measurements confirm, increasing the anode/cathode distance decreases neutral pressure on cathode centerline. Additionally, the Small Anode both has a much higher neutral pressure and is much more sensitive to changes in position than the Large Anode. Indeed, we see these qualitative trends replicated in the ion voltage spectra results, wherein larger anode/cathode gaps produce higher ion energies for a given cathode flow rate and the Small Anode exhibits increased sensitivity to location, especially in moving from Position 1 to Position 2.

A simple way to confirm this would be to inject background gas at a given position until the local pressure measurement matches that of a closer position (e.g., with the anode in Position 2, flow background gas at a flow rate such that the local pressure measurement matches that in Position 1). Unfortunately, the local pressure is so far above the ambient background pressure—often an order of magnitude larger or more—that simply injecting auxiliary background gas through an axial upstream injector (behind the cathode) was insufficient to effectively elevate the local neutral pressure. This is a remarkable result: matching the facility background pressure between positions was not effective at matching the local neutral pressure in front of the cathode between the positions. The anode position is by far the dominant driver in local cathode neutral pressure.

This result implies that differences in cathode operation between test facilities are likely to be small for a given operating condition and anode geometry. This is further supported by the general agreement between our ion voltage spectra results from the Small Anode in Position 1 and the ion energy spectra measurements of Polk [31], which were measured in a very similar anode configuration. The results are similar even with an order-of-magnitude difference in background pressure between the two facilities. Yet differences in anode geometry within a given test facility can have significant impacts on cathode operation. This sensitivity suggests that improved understanding of cathode operation within a Hall thruster is required to then better tailor the anode geometry to produce similar operation in component-level testing.

A more holistic approach to anode design is likely preferable, one that takes into account not only the neutral pressure effects we studied here but other concerns such as electric field and anode/magnetic field intersection. As discussed in our companion paper [48], at 325 G the electrons are highly magnetized (i.e., they make many gyro-orbits prior to a scattering collision) and because of this, cross-field transport is reduced by 3 orders of magnitude compared to the 0 G case. For the magnetic field topology tested here, the magnetic field lines are predominantly axial near the cathode, meaning the electrons will be confined to a region near cathode centerline. Thus, a larger anode diameter will be farther from these magnetic field lines and require a higher voltage to extract the electrons [52], an effect reflected in our results. A more detailed study of this phenomenon and its effect on cathode operation is warranted. Other anode designs that better balance the requirements of neutral pressure and magnetic field topology—such as a mesh anode, which would provide a lower neutral pressure for a given diameter than a solid anode—should be considered as this investigation continues. A potential approach to experimentally optimizing anode design would be to match key operational parameters such as discharge voltage, oscillation magnitudes, and insert temperature to in-thruster operation. Though it is unlikely that component-level cathode operation will ever be made to match in-thruster operation completely, our results suggest that meaningful improvements can be made.

VII. Conclusion

We performed a series of tests to investigate the role that anode diameter and position—and specifically the neutral pressure caused by these parameters—have in hollow cathode operation. Numerical simulations of neutral flow from the cathode suggested that the small-diameter anode that has typically been used for HERMeS cathode development testing produces neutral pressures up to two orders of magnitude larger on centerline than what is experienced by the cathode while operating in the HERMeS Hall thruster in VF-5. Previous work has shown that increased neutral pressure in front of hollow cathodes decreases the high-voltage ion content and that anode position affects the cathode operational mode, but to date the phenomena have not been linked.

In our experiments we found that cathode operation is indeed sensitive to anode geometry and position. For a given anode diameter, we found differences in discharge voltage, oscillation magnitude, and ion voltage spectra with changing anode/cathode distance. For increasing distance—which both modeling and local neutral pressure measurements show corresponds to decreasing neutral pressure in front of the cathode—we found an increase in discharge voltage and in the extent of the high-voltage tail of the ion voltage distribution function. The Large Anode, which provided neutral pressures on centerline generally an order of magnitude lower than the Small Anode, typically exhibited larger discharge voltages and higher-voltage ions than the Small Anode.

To better isolate the electrical effects associated with changing the anode/cathode distance, we performed a test with each anode geometry in which we varied the anode position but selectively biased only certain segments of the anode, thus maintaining constant the distance between the cathode and the anode collecting surface while allowing the change in neutral pressure caused by the change in physical anode location. These results showed generally the same trends, with elevated discharge voltages and high-voltage ion tails with decreasing local pressure, suggesting that the trends—at least for a given anode diameter—were largely due to change in neutral pressure and not electrical effects.

It is not clear that either of the anode geometries tested are preferable. It seems that the Small Anode, especially very close to the cathode like in our Position 1, elevates the local neutral pressure to an unrepresentatively-high magnitude, and that reducing that local pressure to more representative values with the Large Anode significantly changes the discharge voltage and ion voltage spectra of the cathode plume. A clearer understanding of how the cathode operates in HERMeS, and what its neutral and electrical environment is, is required to further refine standalone cathode anode geometry to produce more representative results. A more detailed test campaign is ongoing and results will be reported in future publications. Still, our results here show that the anode geometry must be considered for any component-level testing if results are to be correlated with in-thruster operation of the cathode.

Acknowledgments

We gratefully acknowledge the support of the Space Technology Mission Directorate through the Solar Electric Propulsion Technology Demonstration Mission Project for funding the joint NASA GRC and JPL development of the HERMeS Hall thruster and PPU TDUs. We would also like to thank Jason Frieman, Wensheng Huang, and Jonathan Mackey of the GRC Electric Propulsion Systems Branch for their technical insight and Cody Drum, James Sadey, Luke Sorrelle, Tom Bollinger, Aaron Dozier, Matt Daugherty, Roland Gregg, Brandon Hale, Kevin McCormick, Mike Pastel, Jim Schneider, and Jim Szelagowski of the GRC Space Environments Test Branch for the design and construction of the test hardware and equipment, and operation of the vacuum facility.

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