

The Effect of a Hall Thruster-like Magnetic Field on Operation of a 25-A class Hollow Cathode

IEPC-2019-300

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

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Abstract: The effect of applying a Hall thruster-like magnetic field to a 25-A class hollow cathode is experimentally characterized. Cathode parameters such as discharge voltage, discharge and keeper oscillation magnitudes, and ion voltage spectra were measured as the magnetic field applied by a Hall thruster simulator was varied. The simulator approximated the centerline topology of NASA's Hall Effect Rocket with Magnetic Shielding (HERMeS) Hall thruster and produced peak centerline magnetic field strengths up to 325 G. For the nominal xenon flow rate of 14.7 sccm, increasing the peak centerline magnetic field from 0 G to 325 G increased the discharge voltage from 20 V to 40 V and the cathode orifice plate temperature increased from 934 °C to 981 °C. In addition, the extent of the ion voltage distribution function tail increased from 50 V to 175 V. Despite these changes, oscillations of the discharge voltage, discharge current, and keeper voltage all remained quiescent at values below 1 V, 5 A, and 1.5 V respectively. The implications of these results on existing cathode operational mode definitions, component-level cathode testing, and operation in a Hall thruster are discussed.

Nomenclature

A_c = collector area
 e = elementary charge

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$f(\epsilon)$	=	ion energy distribution function
$f(V)$	=	ion voltage distribution function
I	=	current
m_i	=	ion mass
n_i	=	ion density
q_i	=	charge of species i
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 STMD. 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

Much of the early development of hollow cathodes for electric propulsion applications was performed without an applied magnetic field. This is largely due to the fact that in the United States these cathodes were being used in gridded ion thrusters with magnetic fields below 100 G in peak centerline strength. Numerous studies investigated the behavior of phenomena such as cathode oscillations [6–14], temperature [15–18], and high-energy ion production [19–23], all with either no applied axial magnetic field or one less than 100 G in strength.

One of the most longstanding and prominent products of this body of work is the framework for cathode operational modes. Mode transitions in orificed hollow cathodes are some of the best-studied phenomenon in the lab, and a majority of electric propulsion cathodes demonstrate the behavior in some fashion. As detailed by Mikellides [24], hollow cathode behavior is generally split into two broad operational modes: spot mode and plume mode. Spot mode is correlated with a small quiescent ball or spot of plasma directly downstream of the cathode keeper and few

high-energy ions to contribute to sputter erosion of cathode or thruster components. Plume mode is correlated with a large, luminescent cathode plume, large discharge current oscillations, notable wave phenomena in the plasma [25], and significant populations of high-energy ions. Thus, generally, spot mode is the preferred mode of cathode operation both when operating alone (e.g., in plasma contactor configurations) and in thrusters (e.g., in Hall and gridded ion thrusters). These two modes of operation have been known since the late 1960s when Rawlin and Pawlik documented the mode transition phenomenon with a mercury hollow cathode [6] and have been studied in great detail across the literature [7,8,23,26].

Typically, the transition from spot mode to plume mode is associated with either increasing the cathode current or decreasing the cathode flow rate. Mandell and Katz developed a simple zero-dimensional model of the orifice plasma in a hollow cathode, which they used to investigate the transition from spot to plume mode [9]. Their results suggested that the keeper sheath plays a pivotal role in the onset of plume mode, wherein at low enough discharge currents, sheath-enhanced collection is required, which drives plume mode. More recently, significant work has been done studying the role that ion acoustic turbulence (IAT) has in mode transitions. Work by Jorns [12] experimentally identified IAT in the plume of a 100-A hollow cathode operated without a magnetic field, and ongoing work by Georgin and Jorns is exploring the relationship between the appearance of IAT and the onset of plume mode [25,27,28].

Though the framework of spot and plume modes and the transition between them was generally born from experiments performed without an applied magnetic field, the concept is still often applied to cathodes operating with a strong axial magnetic field. This type of operating condition has become increasingly prominent with the emergence of high-power Hall thrusters with centrally-mounted cathodes [29–36]. Unlike the externally-mounted configuration, centrally-mounting the hollow cathode exposes it to a strong axial magnetic field, typically between 3 and 10 times larger than the axial field experienced by a discharge cathode in a gridded ion thruster.

Previous experiments have studied the effects of gridded ion thruster-like axial magnetic fields [37,38]. These studies have demonstrated that cathode operation is affected by the magnetic field. However, little work has been done to characterize this difference in operation for stronger Hall thruster-like fields, and to explore whether it is set apart from the typical no-field hollow cathode framework. Numerous questions remain, including the magnitude of the difference between no-field operation and operation in a Hall thruster-like field, how key parameters such as ion energy spectra and oscillation magnitude differ between the cases, whether changes onset gradually between no magnetic field and full magnetic field or instead onset abruptly at some critical field strength, and whether this difference in operation corresponds to a different mode or is simply an extension of the spot/plume mode framework.

Recently, we conducted an experiment at NASA GRC to study the effects of a Hall thruster-like magnetic field on the operation of a 25-A class barium oxide hollow cathode. This test was intended to provide a preliminary assessment of how the strength of a Hall thruster-like magnetic field affects the plasma structure, oscillation behavior, and ion voltage spectra. The paper is structured as follows. In Section III, we discuss the experimental apparatus, including the cathode, anode, vacuum facility, and diagnostics, as well as data reduction techniques. In Section IV we discuss the results, which include varying the peak centerline magnetic field strength from 0 G to 325 G at constant field topology in Section IV-A and sweeping the mass flow rate at two magnetic field strengths in Section IV-B. We then discuss these results, including whether magnetization of electrons is a possible mechanism for the observed changes in plasma structure, and the potential implications of these results for both component-level cathode testing and for operation within a Hall thruster, in Section V. Finally, we conclude the paper in Section VI.

III. Experimental Apparatus and Data Reduction

Here we detail our experimental apparatus and data reduction techniques. We show a schematic of our experimental setup in Figure 1. It included a 25 A barium oxide hollow cathode, a thruster magnetic field simulator, an axially-segmented molybdenum anode, and a radially-positioned retarding potential analyzer. The apparatus is similar to that in our companion paper [39].

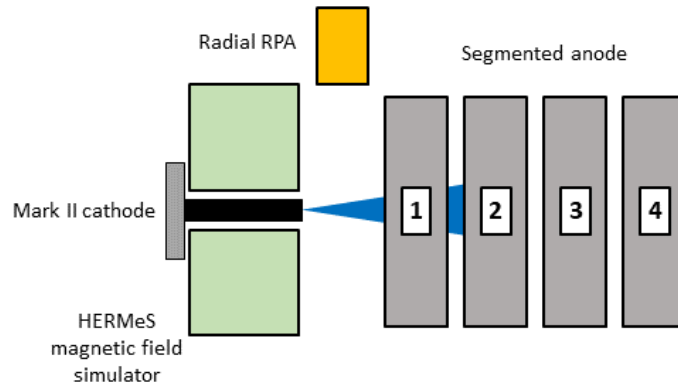


Figure 1. A schematic of the experimental apparatus (not to scale). As shown, the anode segments are numbered from 1-4 in order of increasing distance from the cathode exit.

A. GRC Mark II Cathode

For this experiment we used the second-generation cathode developed for the Hall Effect Rocket with Magnetic Shielding (HERMeS) Hall thruster called the Mark II [40], which we show in the photograph in Figure 2. The Mark II cathode is a 25-A class cathode with a barium oxide emitter. The cathode features brazed joints [35] and draws heritage from a number of previous GRC cathode development efforts, including the International Space Station Plasma Contactor [15,41], the NSTAR and NEXT ion thruster neutralizer and discharge cathode assemblies [42,43], and previous high-current cathode technology projects [44–46]. The key dimensions of the cathode, including the cathode tube, orifice, and keeper dimensions, all match the laboratory model cathode used for the Technology Demonstration Unit (TDU) -1 and TDU-3 thruster testing at NASA GRC [47–50,50–52] and in component-level testing [53]. The key dimensions are also similar to the HERMeS cathode developed and tested extensively by JPL [13,54–58], although the JPL cathode utilizes a lanthanum hexaboride emitter. For all operation described here the Mark II was operated at its nominal 20.8 A discharge current and was allowed to electrically float relative to facility ground.



Figure 2. The Mark II cathode, a 25-A class barium oxide hollow cathode developed for the HERMeS Hall Thruster.

B. Segmented Anode

We used a 254-mm diameter molybdenum anode that was axially split into four segments. The segments were 50 mm long and separated by 2 mm. This segmented anode was operated from a single discharge laboratory power supply capable of providing up to 60 V and 55 A. We constructed a specialized breakout box which took the discharge supply output and divided it to each of the four anode segments in parallel. Each of these anode segments could be connected to the power supply or allowed to electrically float, though for the experiments performed here all segments were always tied to the positive terminal of the power supply. Within the breakout box, the current and voltage of each anode segment was separately measured, allowing for a quantification of how the cathode was coupling to each segment of the anode.

The anode was positioned 68 mm from the cathode keeper exit plane. Throughout this paper, we will refer to the segment closest to the cathode as “Segment 1”, with Segments 2, 3, and 4 being sequentially downstream from the cathode. A photograph of the segmented anode is shown in Figure 3.

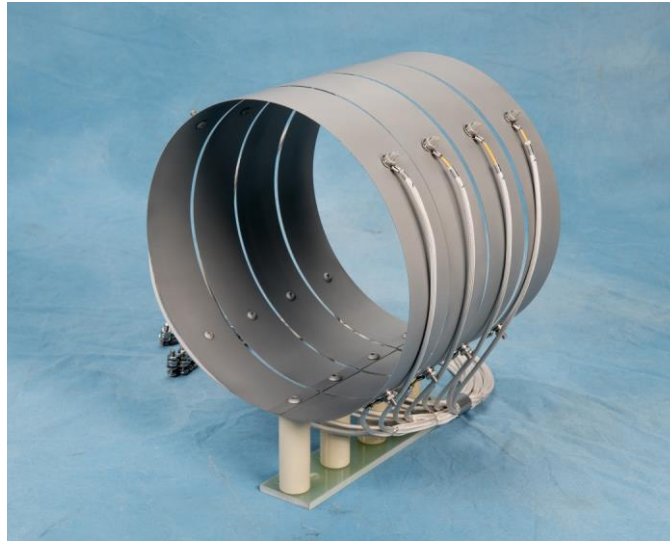


Figure 3. The 254-mm diameter, axially-segmented molybdenum anode used in this experiment.

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.

D. 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 [40]. 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 μ Torr-Xe at the nominal Mark II flow rate of 14.7 sccm of xenon as measured by an ionization gauge mounted on the facility wall approximately 60 cm behind the cathode exit plane.

In addition to the dedicated segmented-anode breakout box discussed above, we used a second breakout box that handled the keeper, heater, cathode return, and electromagnet power and sense lines. We recorded these cathode telemetry, which included the telemetry from both breakout boxes, facility pressure, and cathode orifice plate thermocouple temperature, using a commercially-available multiplexed data acquisition system. Uncertainty on the currents and voltages measured by the DAQ are approximately ± 0.02 A and ± 0.01 V, respectively. Cathode orifice plate temperature was measured using a type-R thermocouple spot-welded to the edge of the orifice plate. Uncertainty of the thermocouple measurement is estimated as ± 2.5 °C. Electric propulsion-grade (99.9995%) xenon was provided to the cathode using a commercial 50-sccm 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 the cathode keeper as well as each of the four anode segments, and a high-speed split-core current probe provided peak-to-peak

measurements of the cathode return current. The estimated uncertainty of the peak-to-peak voltage and current measurements is ± 0.2 V and ± 1.0 A, respectively.

E. Retarding Potential Analyzer

We used a four-grid retarding potential analyzer (RPA) [59] to characterize the ion voltage spectra radially from the cathode exit. This RPA is the Air Force Research Laboratory design used by Huang in previous GRC thruster testing [60,61]. 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 grids were biased with respect to facility ground for ease of implementation. However, in much of the cathode literature RPAs are operated with respect to the cathode potential [22,38]. 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 [59,60]:

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

where q_i is the charge of species i , 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 [58]. 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 $f(V)$ [62]. Nonetheless, these results are still useful for assessment of the voltage of the ions in the plume, even if care must be taken not to over-state the results of our analysis.

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 [60]. However, as numerous works in the literature demonstrate [20,21,38,63], 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 4.

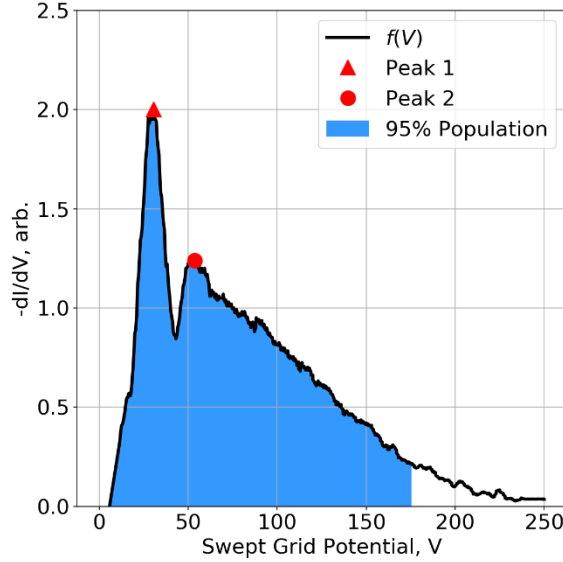


Figure 4. Example $f(V)$ trace illustrating the two peak locations and the 95% population extent.

IV. Results

The experiment consisted of two portions. In the first, we held the cathode flow rate constant at four values and increased the magnetic field strength from 0 G to 325 G in increments of 8 G up to 163 G, then increments of 40 G thereafter. At each magnetic field strength, we measured the steady-state cathode telemetry (e.g., discharge voltage, cathode-to-ground voltage, current collected by each anode segment, etc.), high-speed oscillation information via the oscilloscopes, and the ion voltage spectrum using the RPA. In the second portion of the experiment, we held the magnetic field constant at two settings, 0 G and 325 G, and varied the cathode flow rate.

A. Magnetic Field Strength Sweeps

At cathode flow rates of 11.5, 14.7, 18.5, and 25.0 sccm, we swept the magnetic field strength from 0 G to 325 G as noted above. We discuss below results from each of the parameters we studied, first for the nominal 14.7 sccm case and then for all flow rates tested to study the effect of flow rate on observed trends.

1. Photographs

The cathode plasma visually changed noticeably between 0 G and 325 G. Figure 5 presents photographs from the 14.7 sccm set of conditions illustrating this change. All photographs were taken through a vacuum facility viewport with a quartz window. We used no filtering or post-processing to alter the cathode plasma appearance, and all photographs but the 0 G photo in Figure 5 were taken with the same camera settings.

These photographs clearly show the change in the cathode plume structure with the application of magnetic field. With no magnetic field, the plasma is diffuse and mostly purple, which is typically associated with neutral xenon excitation and low ionization fraction [64]. With the magnetic field strength at 81 G, the plasma has become axially collimated, and there is a distinct jet forming along the center axis of the plume. This behavior is qualitatively similar to results found in an experiment using an axial magnetic field with a hollow cathode of a different configuration [65]. At a field strength of 163 G, the plasma is much bluer, with the only purple visible in the edges of the beam. This blue color is typically associated with ionized xenon and is indicative of a higher ionization fraction [64]. However, the shape of the plasma is similar to that at 81 G. The visual change between 163 G and 325 G is much subtler, with the plasma becoming brighter but not changing in color or physical shape. Note that the photograph for 0 G was taken with a longer exposure time than the others to assist in highlighting the plasma structure; the remaining three were taken with the exact same camera settings to aid in comparison. The 0 G case required the longer exposure time because the plasma was significantly dimmer than that with the magnetic field applied.

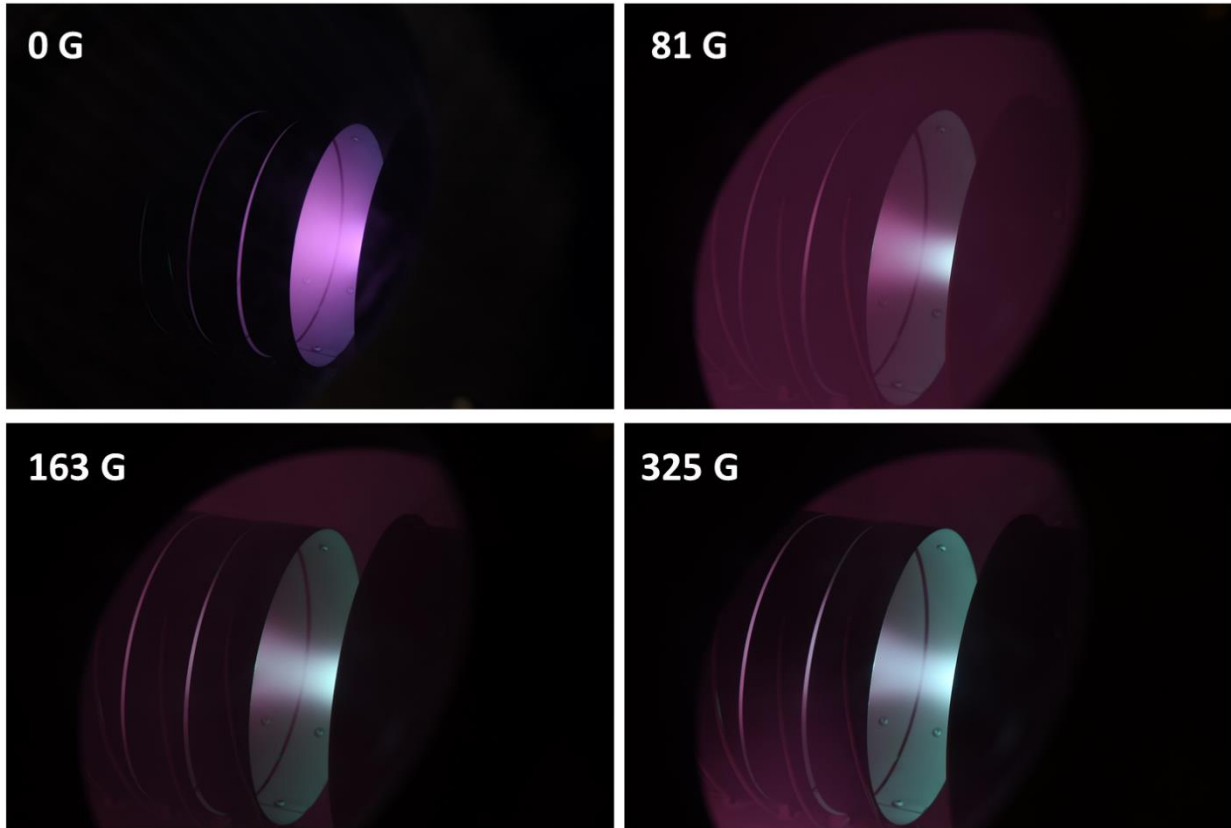


Figure 5. Photographs of the cathode plume at 14.7 sccm and increasing magnetic field strength. Note that the photograph for 0 G has a longer exposure time than the remaining photographs, which were all taken with the same camera settings.

These photographs illustrate that the largest visual change in the plasma occurs between 0 G and 81 G. To study that change in more detail, Figure 6 presents photographs from 0 G to 65 G. Unlike in Figure 5, the photographs here were all taken with the same camera settings, so all are directly comparable. As can be seen, field strengths as low as 8 G facilitate a change in the plasma, and at 33 G the plasma has increased significantly in brightness and blueness and is confined along centerline. The brightness continues to increase with magnetic field strength to 65 G, at which point the plasma structure appears to mostly be established. Looking back to Figure 5, it can be seen that the difference between 65 G and 81 G is only slight. As the field strength continues up to 325 G, the only apparent difference captured in the photographs is an increase in the brightness of the plume.

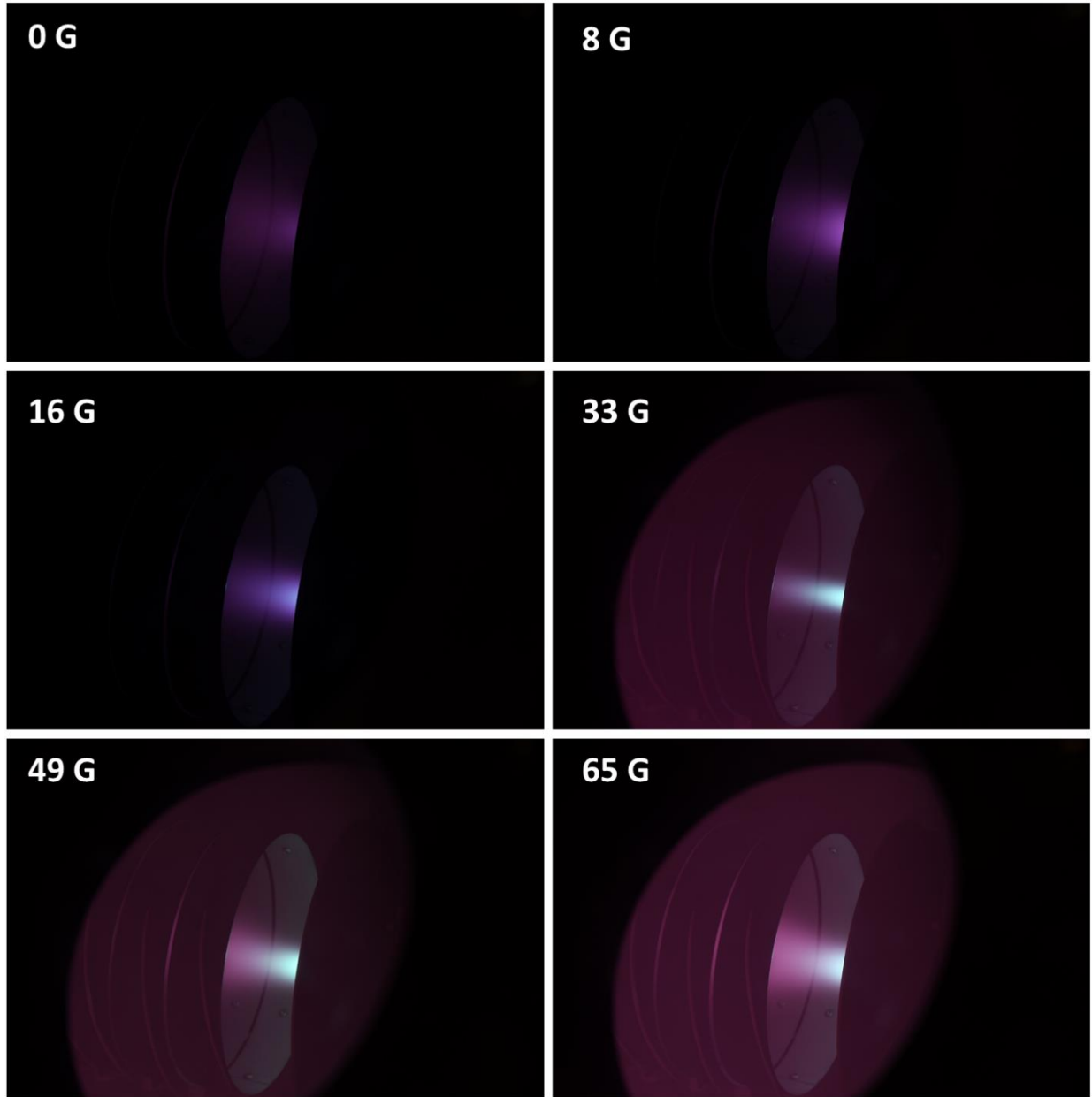


Figure 6. Photographs of the cathode plume at 14.7 sccm and increasing magnetic field strength. These photographs focus on the change in structure at low field strengths.

These photographs reveal the visual changes in the plume as the magnetic field strength is increased, including the change from diffuse to collimated plasma and the increase in blueness and overall brightness. They also indicate that the changes predominantly happen between 0 G and 65 G, and that the changes from there to 325 G are less substantial. However, although these photographs are qualitatively useful, they alone cannot be used to infer anything about possible changes in the plasmadynamics of the cathode plume. Other metrics, such as the segmented anode current, provide more quantitative information about changes occurring in the plasma as the field strength is increased.

2. *Segmented Anode Collected Current*

The segmented anode provides an opportunity to quantify the change in physical plasma shape. By studying how the current collected by each segment changes with changing magnetic field strength, we can see whether and to what degree the plasma is being moved relative to the anode. Figure 7 shows the change in discharge current collected by

each anode segment versus magnetic field strength for the 14.7 sccm case. On the left are the full range of magnetic field strengths tested, and on the right are field strengths from 0 G to 81 G.

As magnetic field is increased we find that the current collected by Segment 4 (farthest from the cathode) increases, while that of Segments 1-3 decreases. Note that the total discharge current of 20.8 A was maintained for all operating conditions. The largest changes in current distribution occur between 0 G and approximately 81 G, above which the current collected by each anode is changing by less than 10% from condition to condition. Indeed, by focusing in on the lower range of field strengths on the right, we see that the most substantial changes in collected current happen between 0 G and 33 G.

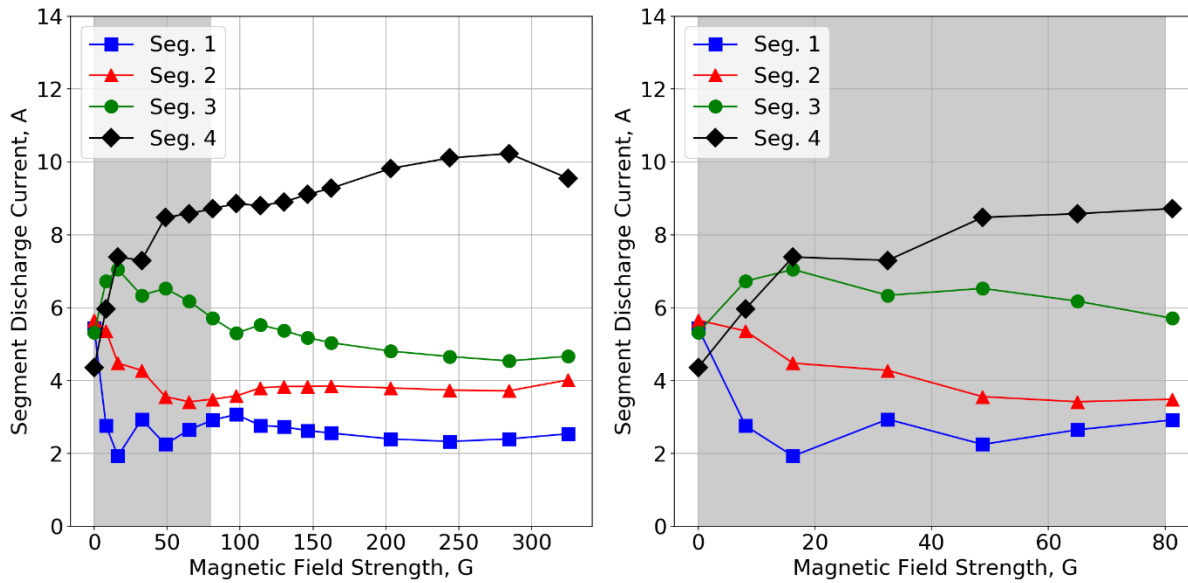


Figure 7. Discharge current collected by each anode segment versus magnetic field strength. The plot on the left shows the entire range of magnetic field strengths, and the plot on the right shows the lower end of the sweep range (shaded in gray on the left-hand plot). Measurement uncertainty is smaller than the marker size.

These data support the visual indications that the photographs provided, namely that the largest physical change in the plasma shape occurs at the outset of magnetic field application, and that above about 81 G the changes in shape are much less significant. Additionally, the relative current values support the qualitative structure change seen in the photographs, wherein the plasma was collimated on centerline. This collimation likely served to reduce the divergence of the cathode plume, which caused the intersection between the plume and the anode to move downstream—that is, toward Segment 4. All segments start out at approximately equal amounts of current. From 0 G to 16 G, the collected currents of Segments 1 and 2 decrease, while that of Segments 3 and 4 increase. The two segments with the largest change are Segment 1 (decrease from 5.5 A to 2.0 A) and Segment 4 (increase from 4.5 A to 7.5 A). For field strengths greater than 81 G we find that Segments 1 and 2 maintain nearly constant current collection while Segment 3 decreases approximately 1 A and Segment 4 increases approximately the same. These results indicate that the visual change between 0 G and 81 G captured in the photographs corresponds to the largest change in current collection along the anode, and that the lack of visual changes at field strengths above 81 G corresponds to similar invariance in current collection among anode segments.

3. Discharge Voltage

Figure 8 shows time-averaged or DC discharge voltage as a function of magnetic field strength. Unlike the change in discharge current distribution, discharge voltage shows a nearly monotonic increase with increasing magnetic field, moving from approximately 20 V at 0 G to over 35 V at 325 G. This is an indication that the change in current distribution and axial plasma structure is not the only change occurring with increasing magnetic field strength, and that other aspects of the plasma continue to change for magnetic field strengths between 81 G and 325 G.

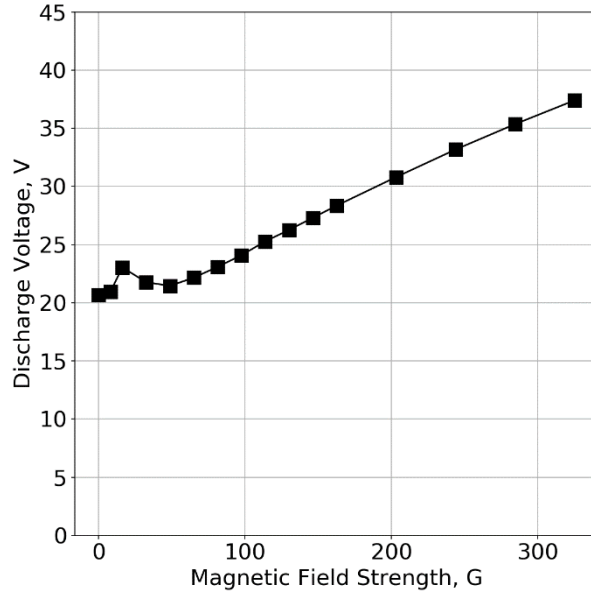


Figure 8. Discharge voltage versus normalized magnetic field strength for the 14.7 sccm case. Measurement uncertainty is smaller than the marker size.

4. Oscillatory Behavior

Next, the oscillatory behavior of the cathode is characterized in Figure 9 by the peak to peak values of the discharge current, discharge voltage, and keeper voltage. Generally in the cathode literature, larger oscillation levels are associated with the generation of high-energy ions and thus with detrimental phenomena such as keeper erosion [22,26,66]. Therefore, it is typically preferred to operate cathodes in quiescent, low-oscillation conditions. Specifically, the keeper peak to peak floating voltage is often used as an indicator of the cathode mode for cathodes without a magnetic field; a typical metric used in the literature is keeper voltage oscillations in excess of 5 V peak to peak being indicative of the cathode entering the plume mode [24]. Here we present the keeper oscillations along with those of the discharge current and anode voltage to provide a full picture of the oscillatory behavior of the cathode.

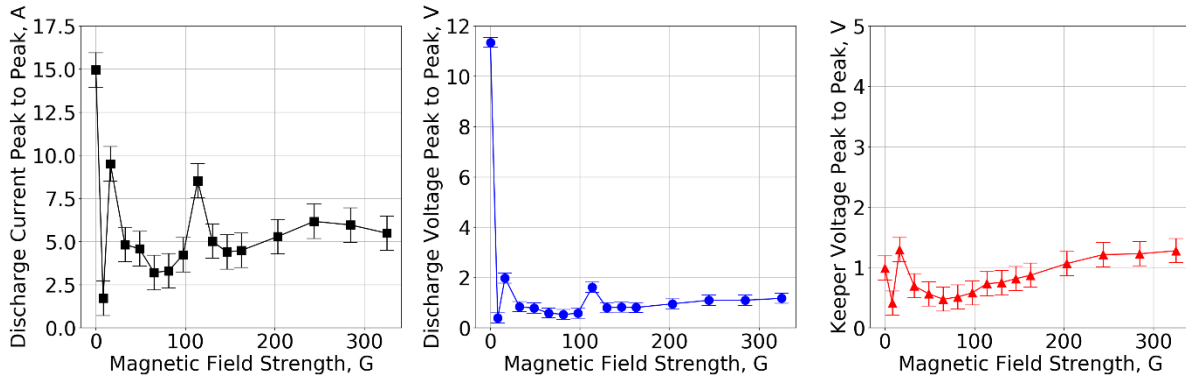


Figure 9. The peak-to-peak oscillation levels of the discharge current, anode voltage, and keeper voltage (left to right respectively) as a function of magnetic field strength.

The three oscillation parameters exhibit generally similar behavior. On the left of Figure 9 is discharge current peak to peak versus magnetic field strength. At 0 G these oscillations are relatively large, over 50% of the DC value of 20.8 A. The oscillations decrease to less than 2 A at 8 G, then increase to nearly 10 A at 16 G, before settling into a band between 4 and 6 A for field strengths between 130 G and 325 G. The discharge voltage shows a similar trend, with oscillations of over 11 V at 0 G giving way to oscillations of less than 2 V for the remaining conditions. Generally the shape matches that of the discharge current oscillations, with higher values at 16 G and 98 G compared to the

surrounding magnetic field strengths. For all magnetic field strengths greater than zero, the discharge voltage oscillations amounted to less than 10% of the DC value. Keeper voltage oscillations, on the right-hand side of Figure 9, show a slightly different trend. Unlike the other oscillations, keeper voltage oscillations are small at 0 G, and the notable increase in oscillations at 98 G does not appear. Additionally noteworthy, none of these values is above 1.5 V, well below the standard threshold for plume mode of 5 V. Overall, all three oscillation magnitudes indicate that as magnetic field is increased the cathode operates in a stable and quiescent mode. In fact, both discharge current and anode voltage oscillations were substantially reduced for all values of non-zero magnetic field compared to the zero-field case.

5. Cathode Orifice Plate Temperature

It is well established that barium evaporation increases with increasing emitter temperature [67,68]. Because of this, cathode emitter temperature is often used as a reliable relative indication of cathode lifetime. As noted above, we measured cathode orifice plate temperature using a type-R thermocouple spot-welded to the edge of the orifice plate as a proxy for emitter temperature. Although the absolute temperature values will differ from the emitter surface temperature, we expect that the trends will be similar [16].

Figure 10 presents orifice plate temperature versus magnetic field strength. The temperature shows a nearly linear increase with magnetic field strength, increasing from 934 °C at 0 G to 981 °C at 325 G, an increase of 47 °C. Over the course of testing, we found that the temperature at a given magnetic field setting was repeatable. For instance, after ramping the field from 0 G to 325 G over the course of 90 minutes, we changed directly from 325 G to 0 G and found that the temperature returned to within 0.2 °C of the original 0 G temperature reading.

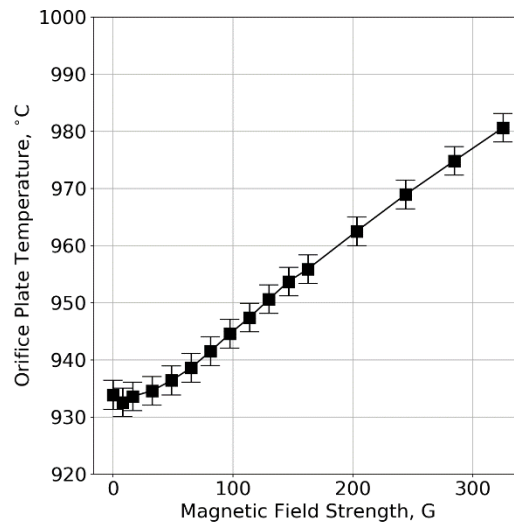


Figure 10. Cathode orifice plate temperature versus magnetic field strength for the 14.7 sccm flow rate case.

6. Radial Ion Voltage Spectra

Figure 11 presents example ion voltage distribution functions ($f(V)$ s) for various cases. There was a notable difference in these traces as magnetic field strength increased. On the left of the figure are $f(V)$ s for the 0, 81, 163, and 325 G cases. The 0 G case shows a single Maxwellian distribution, with a most probable voltage of about 22 V (very close to the discharge voltage of 20 V) and no detectable ion population above approximately 60 V. At 81 G the distribution has developed a distinct second peak. The first peak, though larger, remains near the discharge voltage. The second population has a peak at 38 V and a much broader tail, with a detectable ion population out to 100 V. As magnetic field continues to increase, the near-discharge voltage peak remains, but the tail content of the second peak continues to increase.

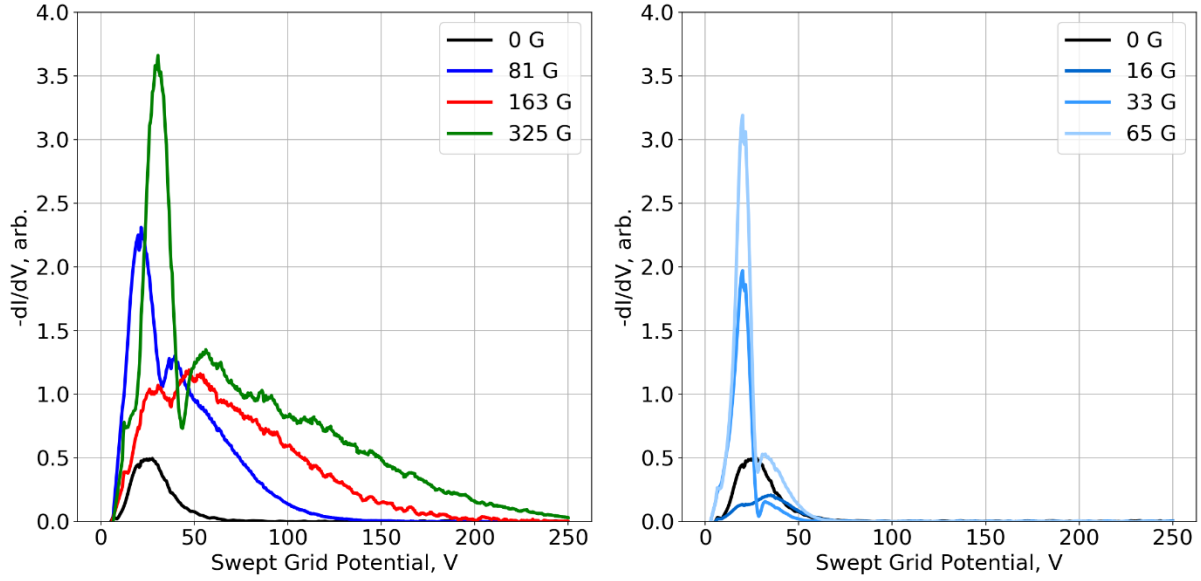


Figure 11. Ion voltage distribution functions for various magnetic field strengths for 14.7 sccm. On the left, traces for 0, 81, 163, and 325 G, and on the right, traces for 0, 16, 33, and 65 G.

The right-hand plot of Figure 11 features the low-end of the magnetic field strength sweep. Here, $f(V)$ initially shifts to higher voltage and flattens but remains approximately Maxwellian for the 16 G case. At 33 G, the $f(V)$ has assumed the two-population shape seen throughout the remainder of the magnetic field sweep. The higher-voltage population then continues to grow with increasing magnetic field strength.

To quantify these changes, we identified the location of both peaks as well as the 95% population extent in the tail as described above. The results for the 14.7 sccm case are in Figure 12. There are a number of noteworthy features in this plot. First, Peak 1 (the lower-voltage peak) tracks within 2 V of the discharge voltage for field strengths in excess of 33 G. Second, Peak 2 (the higher-voltage peak) appears at 33 G, and although it is at higher voltages than Peak 1, it also tracks with discharge voltage. The high-voltage tail, as characterized by the 95% population extent, shows a much faster increase with increasing magnetic field strength than either peak location. Indeed, at 325 G we find that the discharge voltage and Peak 1 are at about 37 V and Peak 2 is at about 64 V, yet the tail of the high-voltage population extends beyond 175 V.

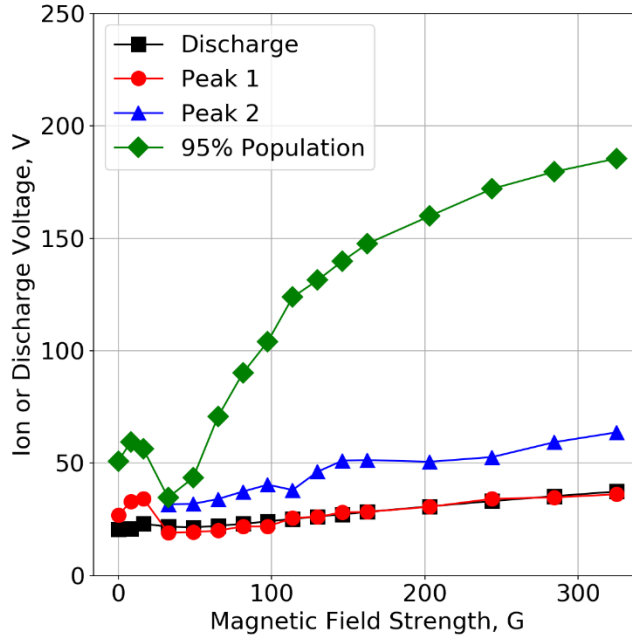


Figure 12. Various features of the ion voltage distribution function as a function of magnetic field strength for the 14.7 sccm case. Measurement uncertainty is smaller than the marker size.

7. Effect of Flow Rate

In addition to the 14.7 sccm case, which was highlighted above because it is the nominal flow rate for the Mark II cathode, we performed the same magnetic field strength sweep at three other flow rates—25 sccm, 18.5 sccm, and 11.5 sccm—to see what effect cathode flow rate had on the trends presented above.

Visually, there was little change in the plasma plume shape, but a distinct change in its coloring. As an example, Figure 13 shows photographs of the cathode operating at 325 G at each of the four flow rates. For clarity, all four of the photographs were taken with the same exposure settings. The most noticeable difference in the photographs is the increasing presence of purple background plasma. As discussed above, this purple color is typically associated with the presence of xenon neutral atoms [64], and thus the observed differences are likely due to the increased facility pressure, which varied linearly with flowrate and thus approximately doubled between 11.5 sccm and 25.0 sccm. The overall shape of the plasma appears to be approximately constant for all flow rates.

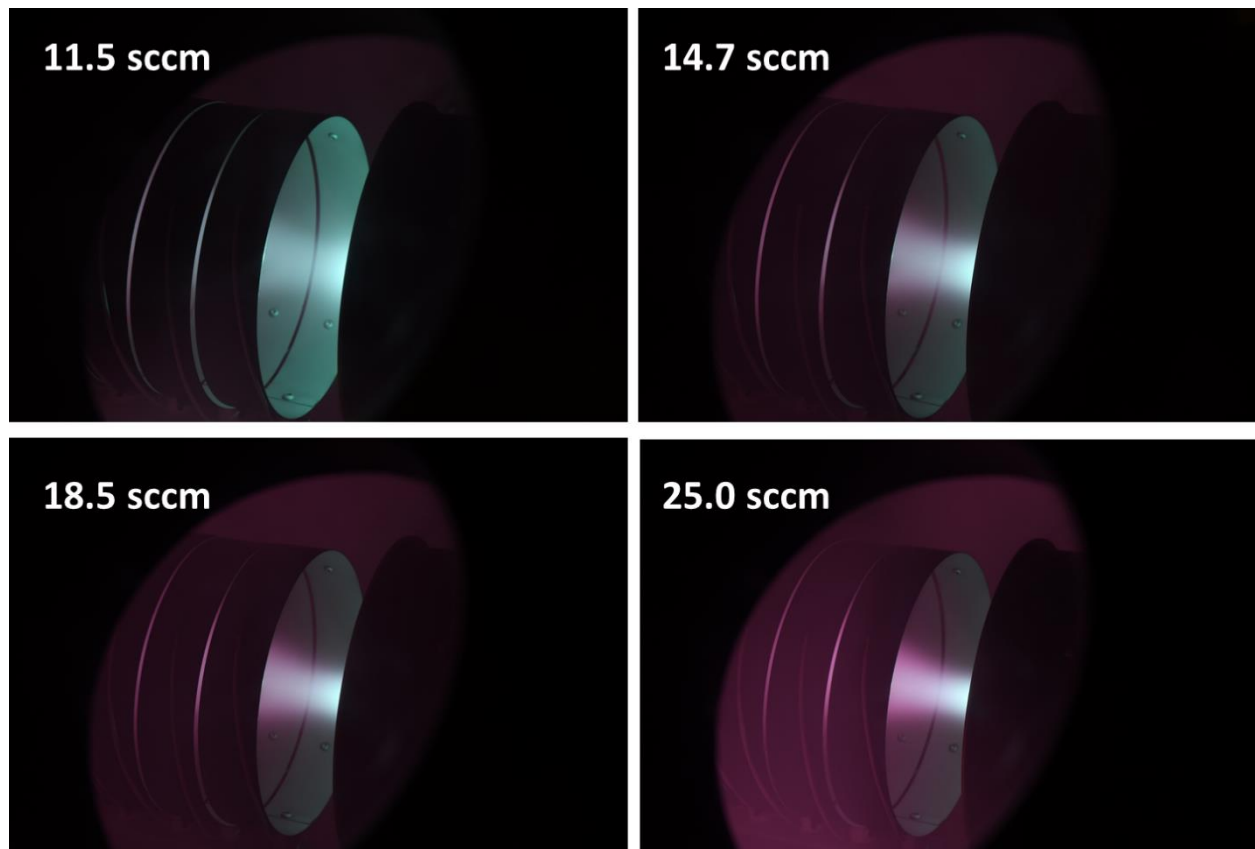


Figure 13. Photographs of the cathode operating at 325 G and four different flow rates. All photographs were taken with the same camera exposure settings.

The current distribution between anode segments was similarly invariant. As an example, Table 1 shows the current distribution among the four anode segments for each of the four flow rates for 325 G operation. The current to each segment changed by less than 1 A for Segments 1, 2, and 3, and less than 1.5 A for Segment 4 across all four flow rates. Generally, the current collected by Segment 1 and 2 increased with decreasing flow rate, whereas that for Segment 4 decreased with decreasing flow rate. The trends at different field strengths were similar.

Table 1. Collected current of each segment at 325 G for each mass flow rate tested.

Flow Rate, sccm	I_{seg1}, A	I_{seg2}, A	I_{seg3}, A	I_{seg4}, A
25.0	2.28	3.87	4.89	9.69
18.5	2.16	3.76	4.67	10.21
14.7	2.54	4.02	4.67	9.55
11.5	2.63	4.55	4.75	8.91

Unlike the collected current distribution among the segments, discharge voltage showed a trend with mass flow rate, as illustrated in Figure 14. Although the overall trend with increasing magnetic field strength is similar and the discharge voltage values were very similar for each flow rate at 0G, the values increasingly diverge with increasing strength, starting around 100 G. At 325 G, discharge voltage ranged from 27 V at 25 sccm to 57 V at 11.5 sccm.

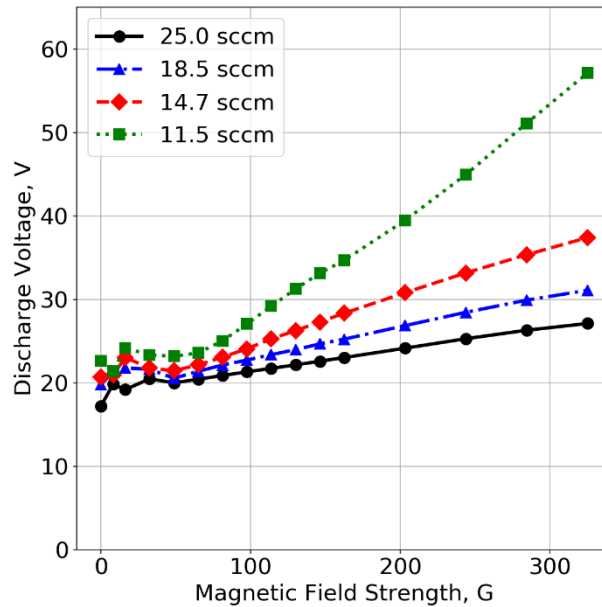


Figure 14. Discharge voltage versus magnetic field strength for each of the four flow rates tested. Measurement uncertainty is smaller than the marker size.

Orifice plate temperature also showed a flow rate effect. As Figure 15 shows, the difference with flow rate predominantly occurred at low magnetic field strengths, with temperature differences between flow rates of 25 °C at 0 G but only 8 °C at 325 G. For all flow rates tested, increasing the magnetic field from 0 G to 325 G resulted in a change in cathode orifice plate temperature of at least 25 °C.

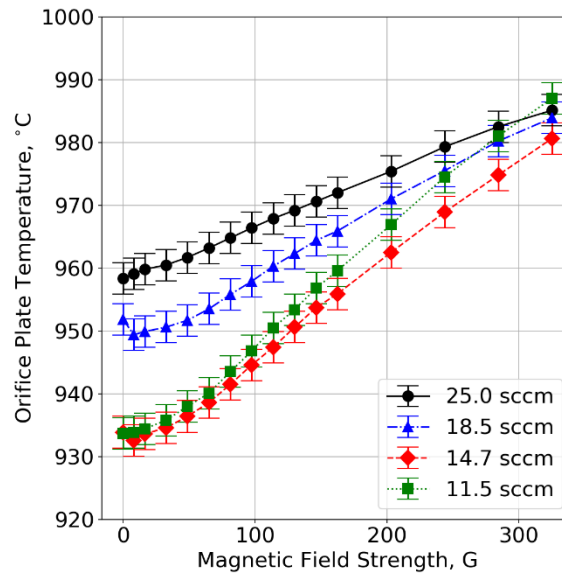


Figure 15. Orifice plate temperature versus magnetic field strength for all four flow rates tested.

Unsurprisingly, the ion voltage spectra showed trends with flow rate as well, as illustrated in Figure 16 with the 95% population extent. For all flow rates, the tail increases with increasing magnetic field strength faster than the discharge voltage increase. The extent of the tail also increases with decreasing flow rate, and at 11.5 sccm, the tail extends nearly to the 250 V limit of the RPA.

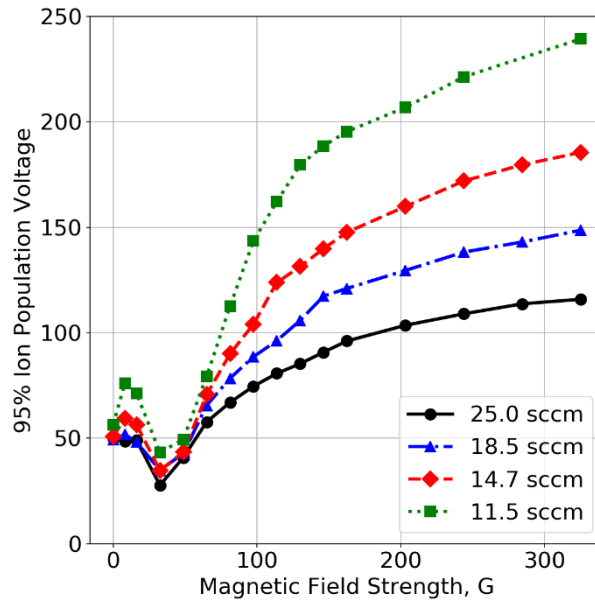


Figure 16. High-voltage ion population tail decay location vs. magnetic field strength for all four flow rate conditions tested.

B. Difference in Behavior with Changing Flow Rate

Finally, we performed a flow rate sweep at 0 G and 325 G. This sweep, which extended from 25.0 sccm to the lowest flow rate the discharge power supply could support (6.4 sccm in the 0 G case and 11.5 sccm in the 325 G case), mimics a typical approach taken in mode transition studies where the spot-to-plume transition is studied at fixed discharge current. As discussed above, it is often seen that as the flow rate is decreased, a critical flow rate is reached at which point the oscillation levels, as well as the luminosity of the cathode plume, increase significantly.

As shown in Figure 17, both magnetic field conditions show a trend of increasing discharge voltage with decreasing flow rate. For all flow rates, the discharge voltage for 325 G is between 1.5 and 2.3 times that for the 0 G case. This matches the trend seen in the field strength sweeps above, wherein increasing the field strength increased the discharge voltage.

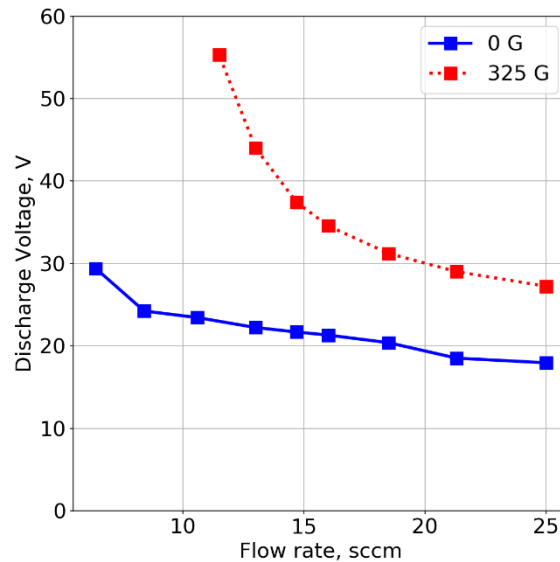


Figure 17. Discharge voltage versus flow rate for the 0 G and 325 G cases. Measurement uncertainty is smaller than the marker size.

Oscillation magnitudes and trends also differed between the two conditions. Figure 18 shows that for 0 G all three oscillation levels increase significantly for the 6.4 sccm case, which indicates the cathode has entered the traditionally-defined plume mode. Unfortunately, as noted above, due to the much larger discharge voltage magnitude in the 325 G case, the cathode was unable to operate below 11.5 sccm at 325 G. For all flow rates tested at 325 G, the discharge was quiescent, with discharge current peak to peak values less than 50% of the mean and discharge and keeper voltage oscillations less than 2.5 V for all cases. The 0 G case had similarly low voltage oscillations at similar flow rates, but the discharge current oscillations were between two and three times larger than those in the 325 G case for flow rates from 13.0 to 18.5 sccm.

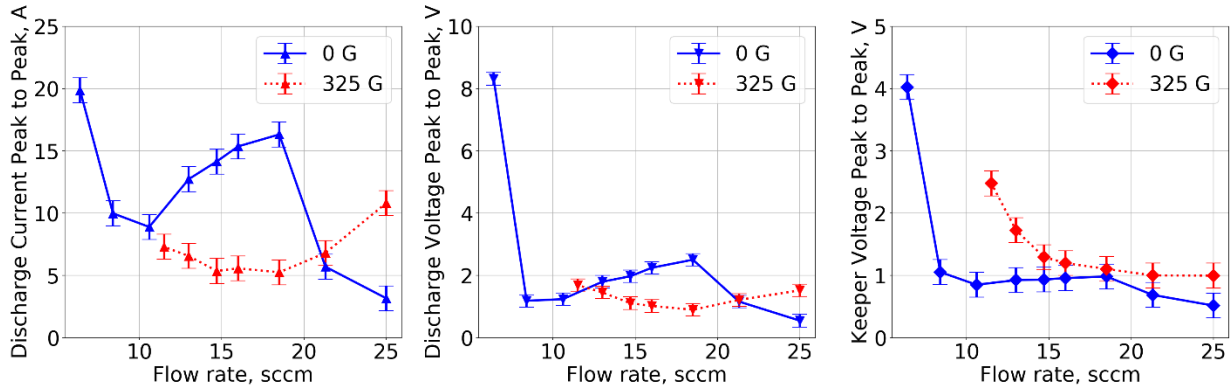


Figure 18. Discharge current (left), discharge voltage (center), and keeper voltage (right) oscillation peak-to-peak magnitudes versus flow rate for the 0 G and 325 G cases.

Cathode orifice plate temperature changed with flow rate for both cases, but as shown in Figure 19, the trends were opposite and the magnitude of the change was different. The 0 G case showed a trend of increasing orifice plate temperature with increasing flow rate, a trend similar to that reported by Polk [16]. The 325 G case showed the opposite trend. As we demonstrated above, the orifice plate is consistently 30 to 70 °C hotter in the 325 G case than in the 0 G case.

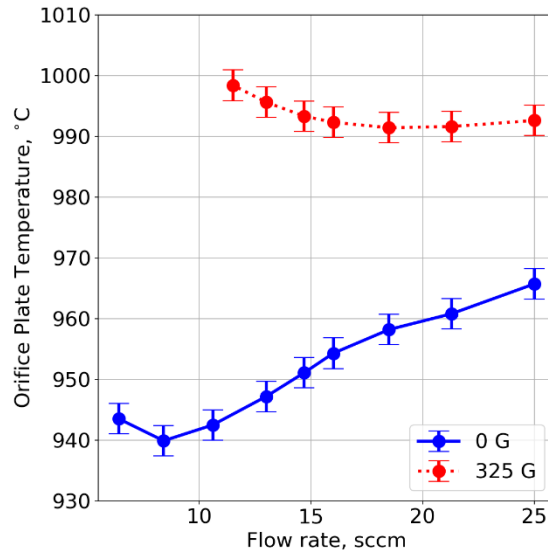


Figure 19. Cathode orifice plate temperature versus flow rate for the 0 G and 325 G cases.

Finally, Figure 20 shows the differences in the key ion voltage spectra characteristics. On the left side of the figure are the results for 0 G. For all but the lowest flow rate, there is no second peak present (and at the lowest flow rate, the trace was noisy enough that the appearance of Peak 2 may be an artifact of the analysis). The extent of 95% of the

population is nearly constant at 50 V except for the lowest flow rate of 6.4 sccm, for which the tail extended significantly farther, to about 125 V. This is in contrast to the right side of the figure, which shows the results for 325 G. There, Peak 1 behavior is identical to that for 0 G in that it tracked within 2 V for all flow rates tested. Peak 2 showed very similar trends to the results above in that it followed with discharge voltage but at a value around twice as high. However, the extent of 95% of the population shows remarkably different behavior from the 0 G case. Even at the smallest value measured, at 25.0 sccm, the tail extends to 116 V, nearly as far as the 6.4 sccm plume-mode results of the 0 G case. As flow rate is decreased, the extent of the tail increases, reaching 235 V for the 11.5 sccm operating point. Note that as shown in Figure 18, these results correspond to keeper voltage peak to peak oscillations of 2.5 V.

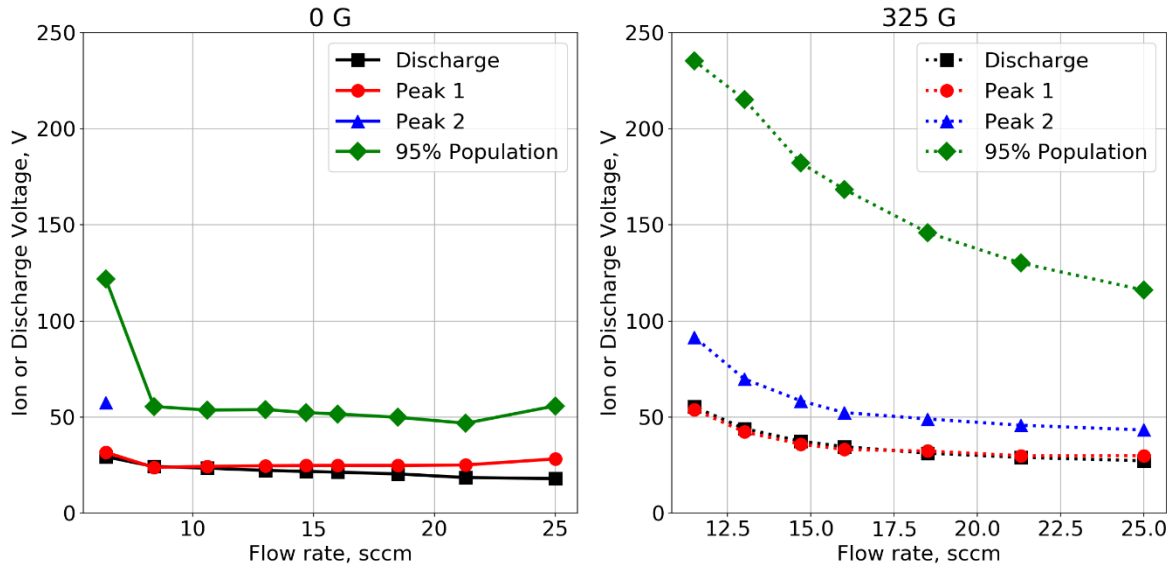


Figure 20. Ion voltage spectra behavior with changing flow rate for 0 G (left) and 325 G (right).

V. Discussion

These results illustrate that the application of a Hall thruster-like axial magnetic field profoundly changes the operation of a hollow cathode. These differences, which include changes in the visual appearance of the plume, the axial coupling to the anode, the ion voltage spectra, the orifice plate temperature, and the oscillation behavior, have implications for hollow cathode testing and development, as well as modeling and simulation efforts. It is not yet known whether the addition of the magnetic field here caused the cathode to operate more like it would in an actual thruster, and further investigation is required to assess this. Nonetheless, these results illustrate the effect that the strong magnetic field has on the operation of the cathode and emphasize its likely importance in hollow cathode development and characterization for Hall thrusters.

1. Effect of Magnetic Field on Plasma Behavior

The current collection between anode segments changed mostly at low magnetic field strengths, and that for strengths above 80 G the changes between conditions were less than 10%. These measurements were qualitatively supported by photographs of the cathode plume, which illustrated a substantial change in appearance over the same low field strengths and a comparative lack of change for the higher strengths. Yet other parameters, such as the discharge voltage and orifice plate temperature, increased more monotonically with increasing magnetic field strength. These results suggest that the magnetic field has a complex or multifaceted effect on the plasma, with some effects saturating at field strengths less than 100 G and others continuing until at least 325 G.

To illustrate the effect the application of the magnetic field has on the plasma, we first compare an estimate of the Larmor radius to a representative length scale in the experiment, which we choose to be the anode radius. The Larmor radius is:

$$r_{L,i,e} = \frac{m_{i,e} u_{th,i,e}}{eB}, \quad (2)$$

where subscripts i and e refer to ions and electrons, respectively, and m is the particle mass, u_{th} is the thermal velocity, e is the elementary charge, and B is the magnetic field strength. If we calculate the Larmor radius for plasma properties reported from a similar HERMeS cathode by Lopez-Ortega [57] (which we note are only approximations, as plasma property measurements were not collected here), we find that even at the lowest finite magnetic field strength tested of 8 G, the electron Larmor radius is many times smaller than the anode radius. However, at these low field strengths, the ion Larmor radius is still over two orders of magnitude larger than the anode radius. Both Larmor radii decrease linearly with increasing magnetic field strength as shown, and the ion Larmor radius approaches the order of the anode radius at 325 G. Thus, the physical effects of the magnetic field are experienced by the electrons at much lower field strengths than the ions.

Another measure of the effect of the magnetic field on the electrons is the Hall parameter. Goebel defines the condition of magnetization as the square of the Hall parameter being much larger than unity [68]:

$$\Omega_e^2 = \frac{\omega_c^2}{\nu^2} \gg 1, \quad (3)$$

where Ω_e is the electron Hall parameter, ω_c is the electron cyclotron frequency, and ν is the total collision frequency. Using the Coulomb collision frequency as defined by Goebel (as Coulomb collisions are dominant over collisions with neutrals for these operating conditions), the squared Hall parameter is order unity at field strengths as low as 8 G and increases with the square of magnetic field. This means that the condition of magnetization is met by 16 G, and at 325 G the squared Hall parameter has increased approximately three orders of magnitude from the 16 G value.

The results at low magnetic field strength indicate that the electrons are magnetized—i.e., have many Larmor orbits prior to a scattering collision—at field strengths as low as 16 G. But the continued increase in the Hall parameter as the magnetic field strength increases has implications on the plasmadynamics of the plume, specifically through the perpendicular electron mobility, which Goebel defines as:

$$\mu_{\perp} = \frac{\mu}{1 + \Omega_e^2}, \quad (4)$$

where μ is the classical electron mobility. This expression indicates that as the square of the Hall parameter increases, the perpendicular electron mobility—that is, the mobility of electrons across magnetic field lines—will decrease. Thus, although the electrons are by definition magnetized at very low field strengths, the increase in magnetic field to 325 G will reduce the perpendicular electron mobility by over three orders of magnitude. For this anode design, none of the magnetic field lines intersecting the cathode orifice intersect the anode collection surface, which means that cross-field transport is required to collect electrons at the anode. The discharge voltage is, in a general sense, a measure of how difficult it is for the anode to extract electrons from the cathode, so the increase in discharge voltage with increasing magnetic field strength can be qualitatively explained by this relationship between magnetic field strength and electron mobility.

2. Implication on Cathode Mode Definitions

Our results suggest that with a strong Hall thruster-like axial magnetic field, the cathode may be operating in a mode outside of the existing definitions of spot and plume mode. The photographs of cathode operation in Figure 5 and Figure 6 show the formation of a jet-like plasma beam quite different from typical photographs of either spot or plume mode: it is bright and luminous like plume mode, but the directed jet of plasma differs from the large and diffuse plasma typically associated with that mode.

Perhaps more significantly, there does not appear to be a correlation between oscillation magnitude and high-voltage ion production. At the 14.7 sccm, 325 G condition, oscillation magnitudes of the keeper voltage, discharge voltage, and discharge current are either equal to or significantly less than the 0 G condition, yet the tail of $f(V)$ extends to voltages four times as high as at 0 G, with detectable ions in excess of 175 V for the 325 G case. These ions are being created while the cathode continues to operate in an apparently quiescent mode.

Further measurements are required to properly identify whether this “jet mode” operation truly represents a new cathode operating mode. It is possible that the high-voltage ions are being generated by the same mechanisms (namely ion acoustic turbulence or IAT [12,27]) as in the 0 G case but that the magnetic field only causes a change in the correlation of those ion generation mechanisms to oscillations in the keeper and discharge voltage, or a change in their

direction. Recent measurements at the University of Michigan confirmed the presence of IAT in the hollow cathode plume of the H9 magnetically shielded Hall thruster, which suggests that the mechanism is likely present in our test environment as well [69]. A much more detailed characterization is required to understand this cathode operation fully. However, these results certainly indicate that using keeper voltage oscillations is not a reliable means for identifying whether a cathode is generating high-voltage ions while operating in a Hall thruster-like magnetic field.

3. Potential implications on component-level cathode testing

There are two results that have an impact on cathode development testing, which is often performed at the component level (not in a thruster). The first result is the orifice plate temperature of the cathode. The cathode insert temperature—for which here we use orifice plate temperature as a proxy—is directly correlated with barium evaporation rates and thus cathode lifetime [68], with higher temperatures corresponding to higher evaporation rates and thus shorter lifetimes. Because of the exponential relationship, a relatively small change in cathode temperature can have a significant impact on cathode lifetime.

To illustrate this point, we deploy Goebel's model for barium evaporation, which was used previously by Lopez-Ortega to calculate the expected lifetime of an earlier version of the GRC HERMeS cathode [57]. The increase in cathode temperature of 47 °C between 0 G and 325 G at 14.7 sccm corresponds to a modeled decrease in expected cathode lifetime of a factor of three. The lifetime predicted by this model is still well in excess of the 23-khr expected service life of the HERMeS cathodes. However, this will not be true for every cathode and every thruster magnetic field environment. Thus, it is clear that any temperature measurements used to predict cathode lifetime, as well as any long-duration testing to empirically assess lifetime, must be matched to the operating temperature of the cathode in the thruster. Unfortunately, without orifice plate temperature measurements for cathode operation with HERMeS thrusters, it is unclear whether the addition of the magnetic field here makes the orifice plate temperature measurements agree better with in-thruster operation, a critical link to improving component-level cathode testing.

The increase in the high-voltage ion content with increasing magnetic field is important as well because of the role high-voltage ions are believed to have in sputtering erosion of cathode and thruster surfaces. Though it is true that cathode keeper erosion rates during long-duration testing of HERMeS have been well below the limit required to meet the service life goal [70], this may not be the case for all cathodes in all thruster configurations. Erosion measurements of the keeper electrode or other cathode surfaces may be artificially reduced in component-level testing if these high-voltage ions are not present.

4. Potential implications on operation in a Hall thruster

The life-limiting wear mechanism in magnetically-shielded Hall thrusters such as HERMeS is erosion of the front pole covers of the thruster by ion bombardment [70–72]. To date, the exact mechanism behind this erosion, and more specifically the reasons for the trends with thruster discharge voltage and background pressure, have not been fully identified. NASA GRC and JPL have conducted a years-long effort to study this phenomenon in more detail, including long-duration wear tests of the Technology Demonstration Unit (TDU)-1 and TDU-3 thrusters at GRC [49–51,61,70], short-duration wear and performance testing at JPL [58,73], laser-induced fluorescence measurements to study the ion populations near the front poles [74,75], and a detailed simulation effort using the JPL-developed numerical simulation code Hall2De [76,77]. Even with this effort, a clear theoretical understanding of the mechanisms behind pole erosion for all thruster operating conditions have eluded researchers. This understanding is critical to future high-power, magnetically-shielded Hall thruster development efforts.

Recently reported LIF results from a test performed at NASA GRC on the HERMeS TDU-1 thruster measured two populations of ions near the front pole of the thruster [75]. Huang proposed that one of these populations is borne from the thruster discharge and one from the cathode, though his measurements were not able to verify this. However, it is possible that this second population of ions measured in front of the thruster front pole is the same as the population of radial ions we measured here.

We emphasize here that it is not clear that these ions play any role in front pole erosion, and further tests must be conducted to answer that question. It is possible that this ion population, although high-voltage, is not large enough to have an appreciable impact on pole erosion. Our results do not provide any information on the ion density, only the voltage distribution of the population. Additionally, because our RPA was radially much farther from the cathode than the inner front pole, it is not clear that the ions we have measured are similar in character to the ions in that location. And finally, because our configuration did not perfectly mimic the magnetic field environment of the HERMeS thruster, it is possible that whatever mechanism is causing the appearance of these ions is not present during thruster operation. Thus, we cannot make any conclusive remarks on the role these ions may play in front pole erosion.

However, if these trends hold true when the cathode is operated within the Hall thruster, another noteworthy behavior is the increase in the voltage tail as flow rate is decreased. Decreasing the flow rate from 14.7 sccm to 11.5

sccm increased the extent of the high-voltage ion tail by at 55 V. For HERMeS operating at nominal conditions, this corresponds to a change in cathode flow fraction from approximately 7% to approximately 5.5%. This relatively small change in cathode flow fraction is within the range tested during TDU development testing [49]. During that test, Kamhawi found that across a range of cathode flow fractions of 5 to 9% and operation from 300 V to 600 V discharge voltage, the TDU-3 thruster produced nearly invariant anode efficiency and specific impulse for a given operating condition. However, we find here that a similar change in cathode flow rate had a significant impact on the cathode ion voltage spectra. Although lower cathode flow fractions are generally preferred from a system perspective to limit the xenon flow not being used for thrust generation, it is important to understand that these seemingly small changes in cathode flow may have significant impacts on the ion spectra from the cathode. If these ions are then found to play a significant role in pole erosion, a reduced cathode flow fraction could have serious impacts on front pole erosion rate and consequently thruster lifetime.

VI. Conclusion

We found that applying a Hall thruster-like magnetic field to a 25-A class hollow cathode significantly changed the way the cathode operated during component-level testing. These changes included visual changes in the plasma shape, which were verified by measuring the collected current for each segment of an axially-segmented anode; in the discharge current magnitude; in the oscillation behavior of the keeper voltage, discharge voltage, and discharge current; in the cathode orifice plate temperature; and in the ion voltage spectra.

The change in plasma shape, as characterized by the photographs and by the segmented anode current measurements, occurs predominantly at low magnetic field strengths. This change subsides for field strengths above approximately 80 G, where the current collection distribution between segments varies by less than 10% and photographs show only small changes in appearance. Other behaviors, such as the increase in discharge current, the increase in cathode orifice plate temperature, and the increase in high-voltage ion content, are more continuous with increasing field strength.

Overall, these results suggest that with the application of the magnetic field the cathode may be operating in a mode separate from both the spot and plume modes of the literature. This potential new “jet mode” is characterized by a high-voltage ion tail that extends to voltages four times the discharge voltage but with largely quiescent oscillation behavior in the discharge current, discharge voltage, and keeper voltage. This lack of correlation between high-voltage ion content and oscillation magnitudes differs from what is typically reported for spot/plume mode operation in cathodes without a strong applied magnetic field. These results also suggest that proper replication of the magnetic field environment experienced by a cathode is critical to achieving useful results in component-level cathode tests. The magnetic field had significant impact on the cathode operating temperature, which directly informs cathode lifetime predictions. Although further testing is needed both to better understand the mechanism(s) driving these changes with changing magnetic field strength and to better understand the way the cathode operates while inside a firing thruster, it is apparent that a Hall thruster-like magnetic field affects how a hollow cathode operates in a manner that should not be neglected.

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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