

# Characterization of a 600 A Barium Oxide-Based Hollow Cathode

**Roberto Martelli**

`roberto.martelli@colostate.edu`

Colorado State University

**Seth Thompson**

Colorado State University

**Casey C. Farnell**

Plasma Controls, LLC

**Tait Freestone**

Colorado State University

**John D. Williams**

Colorado State University

---

## Research Article

**Keywords:** Cathodes, High-Power, Barium-Oxide Cathode, Krypton

**Posted Date:** October 14th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10891188/v1>

**License:** © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

**Additional Declarations:** No competing interests reported.

---

# Characterization of a 600 A Barium Oxide-Based Hollow Cathode

Roberto Martelli<sup>1\*</sup>, Seth Thompson<sup>1,2</sup>, Casey C. Farnell<sup>1, 2</sup>,  
Tait Freestone<sup>1</sup>, John D. Williams<sup>1, 2</sup>

<sup>1\*</sup>Department of Mechanical Engineering, Colorado State University,  
1320 Campus Delivery, Fort Collins, 80523, CO, USA.

<sup>2</sup>Plasma Controls, LLC, 1320 Campus Delivery, Fort Collins, 80523,  
CO, USA.

\*Corresponding author(s). E-mail(s): [roberto.martelli@colostate.edu](mailto:roberto.martelli@colostate.edu);  
Contributing authors: [seth.thompson@colostate.edu](mailto:seth.thompson@colostate.edu);  
[Casey.Farnell@colostate.edu](mailto:Casey.Farnell@colostate.edu); [tait.freestone@colostate.edu](mailto:tait.freestone@colostate.edu);  
[john.d.williams@colostate.edu](mailto:john.d.williams@colostate.edu);

## Abstract

As power levels rise in Hall thruster (HT)-based electric propulsion devices, so do the current requirements on their cathodes. Such cathodes also have lifetime requirements in the many kilohour range at these high currents to allow sustained thrust maneuvers. Traditional hollow cathodes typically use inserts as the electron emitter that are made from monolithic LaB<sub>6</sub> or porous tungsten that is impregnated with a BaO containing ceramic material, specifically barium calcium aluminate. A hollow cathode capable of supplying 500A over such lifetimes has been developed and tested using a LaB<sub>6</sub> insert, but one using a BaO insert at these currents has not. This paper presents the design and characterization of a cathode operating at sustained discharge currents up to 600A using a tungsten and barium-calcium-alumina-scandate (BCA-S) cermet insert. The insert, formed in a one-step furnace firing process from tungsten, BaCO<sub>3</sub>, CaCO<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, and Sc<sub>2</sub>O<sub>3</sub> powders offers simple fabrication and lower production costs, in addition to lower operating temperatures due to the lower work function of BaO-based emitters. Shaping the insert to include an orifice plate pre-firing further simplifies the overall cathode assembly fabrication process. Operation data are presented on Krypton as a propellant at a range of currents and flow rates with discussion of stable versus unstable operating modes, and a preliminary estimate of the insert's operational lifetime as a function of discharge current.

**Keywords:** Hollow Cathodes, High-Power, Barium-Oxide Cathode, Krypton

## 1 Introduction

Cathodes are an integral component of electric propulsion devices; from gridded-ion thrusters (GITs) to Hall thrusters (HTs) to magnetoplasmadynamic thrusters (MPDs), as a source of electrons is critical to their operation. GITs and HTs in particular have used hollow cathodes to provide electrons for propellant ionization and plume neutralization for decades. One feature of cathode performance and lifetime is its electron-emitting insert material, which is engineered to maintain a low work function and high emission current density throughout the life of the thruster - up to the range of many tens of kilohours for sustained-thrust maneuvers. When thruster requirements have called for high electron currents ( $>50\text{A}$ ), as they have been doing with increasing frequency, the insert material of choice has been Lanthanum Hexaboride ( $\text{LaB}_6$ ) due to its high emission current density and low evaporation rate when compared to the alternative used at lower currents - barium-calcium-aluminate (BCA) dispensers [1, 2]. Where  $\text{LaB}_6$  inserts are a monolithic insert material, BCA dispenser-style inserts are instead a composite, with a porous tungsten matrix infiltrated with the BCA material. The barium within the BCA ceramic is released via thermal decomposition at elevated temperatures as a vapor, which adheres to oxygen on the tungsten surface and resulting in a work function around  $2\text{eV}$ , or as low as  $1.6\text{eV}$  if scandate is included in the ceramic [3]. This is in contrast to the  $2.6\text{--}2.9\text{eV}$  work function range for  $\text{LaB}_6$ , which means an increase in operation temperatures of about  $500^\circ\text{C}$ , from  $\sim 1100^\circ\text{C}$  to  $\sim 1600^\circ\text{C}$  at  $10\text{A}/\text{cm}^2$  emission currents. This operating temperature, in the absence of contaminants in the propellant, is the primary determining factor in the cathode lifetime, as the bulk  $\text{LaB}_6$ , or Ba within the ceramic impregnant, evaporates and is lost. In the case of BCA dispenser cathodes, the evaporation rate of Ba can exceed its diffusion rate through the tungsten pores, leading to a reduction in internal Ba vapor pressures and loss of surface coverage of the tungsten [2]. Loss of this coverage means an increase in the insert work function and subsequent severe worsening of insert performance. For this reason, BCA dispenser cathodes are primarily used in applications where their emission current densities - and thus operation temperatures - remain low. The degradation of a BCA insert has been shown in a study with BCA hollow cathodes at extreme current densities in an MPD within 10 hours of operation [4], however, the current densities tested were in the hundreds of amps per  $\text{cm}^2$ , which is substantially beyond current requirements for HTs or GITs.

Reference 5 shows a variation of the BCA cathode, where the insert is formed in a single-step process, as opposed to first forming porous tungsten, then infiltrating it with ceramic. Such inserts operate above  $20\text{A}/\text{cm}^2$  without noted degradation in performance, in contrast to ones of similar composition. A commercial cathode using this material and designed for emission current densities above  $20\text{A}/\text{cm}^2$  is shown in ref. [6]. This performance, alongside the ease of manufacture of the inserts, makes the

material a promising candidate for high-current cathode inserts and would represent an alternative to  $\text{LaB}_6$ , where the lower operation temperatures would reduce the design challenges associated with heating the insert at startup and controlling the heat generated by the cathode during operation [1]. This paper also identifies new challenges with high-current BCA inserts and suggests steps necessary in future testing to address them.

## 2 Test Setup

### 2.1 Facility and Testing Apparatus

The 600A cathode was tested in the Cygnus Vacuum Test Facility at Colorado State University, a 1.2m diameter by 4.6m long vacuum chamber pumped to vacuum by both a cryopump and turbopump mounted to flanges on the chamber floor, as shown in figure 1. This pumping scheme achieves pressures of  $1\mu\text{Torr}$  ( $133\text{ }\mu\text{Pa}$ ) with no gas flow. The maximum pressure observed was  $3\text{mTorr}$  ( $0.4\text{Pa}$ ) at a maximum flow of 1000 standard cubic centimeters per minute (sccm) of Krypton through the cathode. Propellant gases of Argon and Krypton are supplied by compressed gas bottles, fed through a pressure regulator to a MFC. The mass flow controller maintains the flow to within 1% of the target flow rate. Power is supplied to the cathode components and magnetic coils from a rack of power supplies through isolated electrical feedthroughs. The electrical setup is detailed further later in this section. The anode is made from copper tubing coiled with an internal diameter of 12 inches (30.5cm). Water is flowed through the anode coil during operation to prevent damage to the copper from excessive heating and to minimize thermal impacts to the test facility.

A retarding potential analyzer (RPA) was mounted to the chamber floor, located axially between the keeper orifice plate and the upstream face of the anode and radially at 0.5 meters from the cathode centerline. The RPA has four biased grids to selectively reject ions of increasing energy from a grounded collector plate, which records the ion current. Recording the change in current as the ion rejection voltage is increased provides a distribution function for the ion energies within the plasma. The RPA used throughout testing is described in ref. [7]. At the far end of the chamber, an optical pyrometer is directed through a window in the vacuum chamber to the cathode orifice plate. The optical pyrometer uses a 'disappearing' filament which is resistively heated to match the emission of the measured surface, then the filament temperature profile versus heating current data are used to determine the surface temperature.

To replicate the cathode operation within a thruster, a magnetic field simulator as described in [8] is used to generate a strong axial magnetic field (200 Gauss) at the downstream end of the cathode, shown in figure 2 as the 'High Field Region'. The simulator consists of a large copper wire-based solenoid winding integrated into in a 1018 steel housing, designed in magnetic modeling software to match a typical hall thruster field profile. Although a considerably smaller simulator could have been made using specialized magnetic materials such as pure iron or Hiperco, the present material was found to have acceptable performance with a significant reduction in cost. The magnetic coil body is isolated from the chamber ground. Also shown in figure 2 is the cathode gas feed tube, which uses a ceramic isolator along the flow path

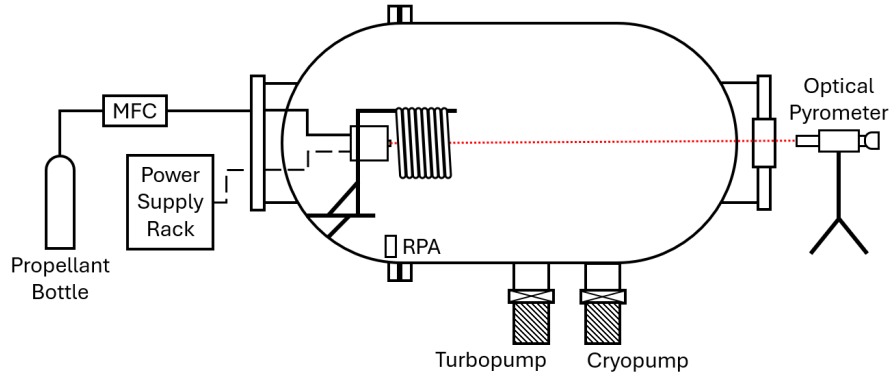


**Fig. 1** Cygnus Testing Facility Diagram

to prevent coupling to ground. A total of 3 thermocouples are placed at the upstream end, midpoint, and downstream end of the magnetic coils. These thermocouples are used to ensure the magnetic coils are not raised to temperatures above 400°C, where the isolation used between coil wraps could degrade and lead to electrical shorts.

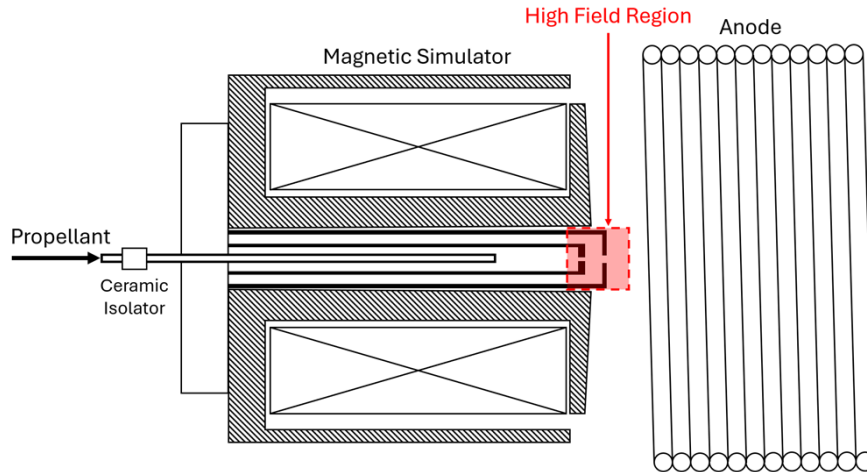


**Fig. 2** Cathode, Magnetic Simulator, and Anode Setup

## 2.2 Cathode Construction

The cathode assembly, presented in figure 3, is formed of three primary components - the keeper, cathode, and heater, each of which is electrically isolated from the other two by 6mm alumina silicate plates. The keeper and its backplate are made of a single piece of machined graphite, with the orifice plate affixed using a high-temperature

graphite adhesive. The keeper's outer diameter (OD) is 3.8cm, with 3.8mm thick walls; the orifice plate is the same thickness, with a 1.9cm orifice. Originally, a 1.3cm orifice had been used, but this led to excessive heating of the keeper; all data presented herein were collected with the larger keeper orifice. The cathode consists of a kovar backplate, a tantalum support tube, and the insert. The 2.5cm OD, 0.5mm thick tantalum tube is laser welded to the backplate to provide mounting and electrical connection points. The insert is formed from tungsten powder;  $\text{BaCO}_3$ ,  $\text{CaCO}_3$ , and  $\text{Al}_2\text{O}_3$  powders in a 5:3:2 ratio; and  $\text{Sc}_2\text{O}_3$  powder. The formation process is described in [5], and allows for the formation of the insert in the geometry shown in figure 3, where the cathode orifice is made as part of the insert. The insert walls, including the orifice plate, are 5.5mm thick, the whole insert is 6.4cm long, and the orifice diameter is 7.6mm. This provides for a total possible emission area of  $27\text{cm}^2$ , and a minimum current density at 600A of  $22.4\text{A}/\text{cm}^2$ , although the anticipated density is anticipated to be significantly higher due to the attachment length not spanning the full insert.

To start up the cathode, a heater is needed to bring the insert to thermionic emission temperatures, which are in the  $1000^\circ\text{C}$  range for the insert used. Cathodes have typically used a resistive heating coil around the insert, which takes considerable time to heat the cathode, and can be damaged at high-temperature cathode operating points. Alternatives to this approach have been used, including a design where the propellant feed tube radiates to the insert [9]. The cathode presented in this paper uses a different method - a secondary electron emitter integrated in the feed tube emitting an electron current to the primary insert, thereby heating it. This secondary insert is a 6.3mm diameter cylinder with machined flats to allow gas flow, and is capable of supplying up to 15A of electron current to the primary insert. This secondary cathode is ignited through biasing at 400V negative of the primary insert to initiate a Paschen discharge, which triggers a plasma discharge arc that rapidly heats the heater insert to thermionic emission temperatures. Throughout the testing presented in this paper, the heating current was 1A, which was sufficient to consistently start the primary insert within 2 minutes. This startup time may also be attributed to the cathode downstream orifice face being a thermionic emitter, which allows easier plasma generation between the cathode and keeper during startup. In a typical barium oxide hollow cathode, a similar process is achieved by gradual barium coverage of the cathode orifice plate face, which contributes to its longer startup time [10].

### 2.3 Electrical Setup

A simplified electrical diagram of the cathode, anode, keeper, and heater is shown in figure 4. This shows the keeper and anode biased positive of the cathode, and the heater biased negative of it. The anode power supply used is a set of five 160V, 120A programmable DC power supplies operating in parallel to supply the full 600A of discharge current. The power supplies each have an upper limit of 5kW in power output, leading to an overall maximum power of 25kW, or 41.5V at 600A. Not shown in the diagram is the discharge filter used, which originally consisted of an inductor and capacitor network as described in [8]. The inductor was removed due to overheating at 400A and above, leaving just the 1mF capacitor network. Programmable DC power

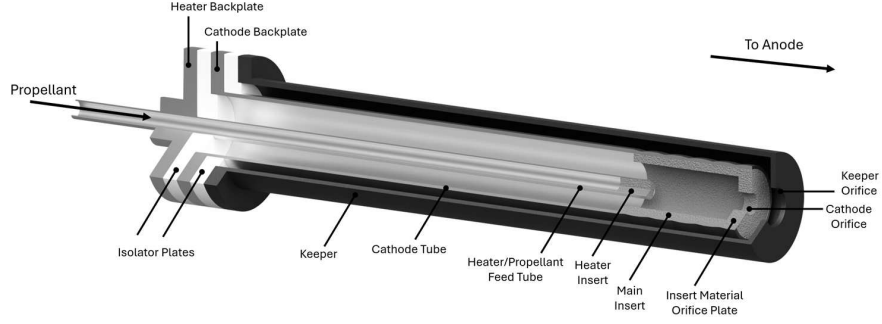


**Fig. 3** Render of the Cathode Assembly

supplies are also used for the keeper (1000V, 20A) and heater (600V, 2.5A). Neither of these includes a filter as the discharge does, but both use the bypass and blocking diode power supply protection shown in [8]. Both the heater and keeper contain an in-line switch to prevent interference in voltage measurements from their respective supplies. The heater switch additionally prevents high current emission from the relatively small heater insert, which would damage the insert and heater power supply. Voltage measurements of each component are taken by sense leads separate from the power supply circuits, as shown in figure. For all leads but the heater, these use shielded coaxial cables to prevent electromagnetic interference in high-speed measurements. An additional sense lead is also connected to the magnetic simulator body to serve as an analog for a thruster body. The cathode-keeper voltage, anode current, and cathode-anode voltage are measured at high speed by an 8-bit, 8 GHz sample rate oscilloscope; the current measurement is obtained from a 650A current transducer clamp.

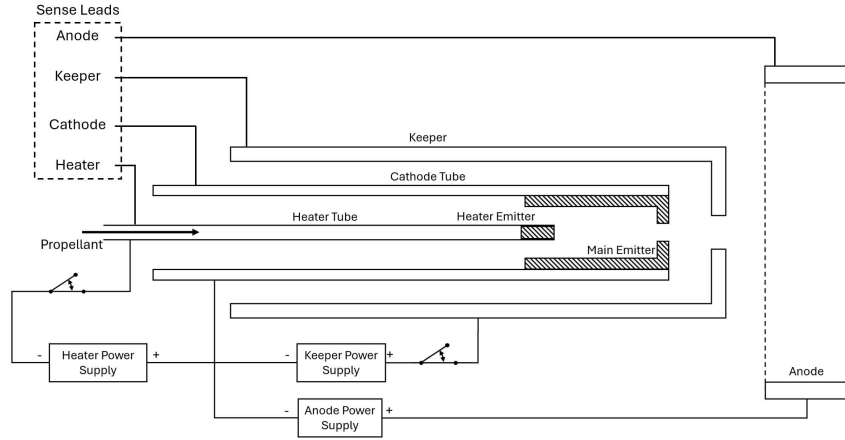


**Fig. 4** Cathode Testing Configuration Electrical Diagram

### 3 Results

The cathode was successfully operated at currents ranging from 50A to 600A on both argon and krypton as propellants, and at a variety of propellant flow rates on each gas. Most data was obtained using krypton due to the lower anode voltages (by  $\sim 10$  volts) and more stable cathode operation compared to argon, resulting in less strain on the power supplies and greater consistency in measurements. Operation of the cathode was characterized along two axes - the first being total discharge current, with flow fixed at a ratio representative of typical operation within a thruster, and the second being flow rate with current fixed at 600A, as the cathode was designed for.

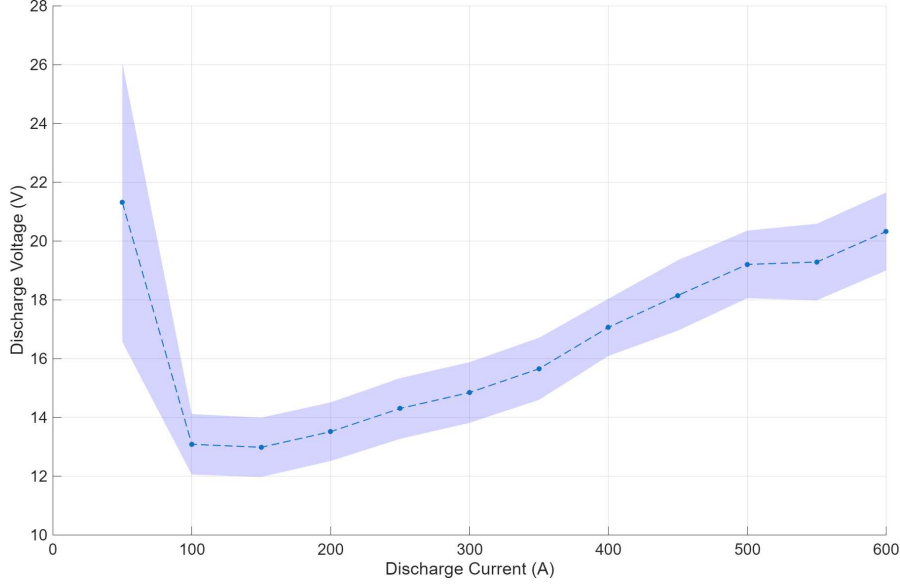


**Fig. 5** Current Sweeps at a Fixed Flow-Rate-to-Current Ratio

Figure 5 shows the discharge voltage plotted against discharge current, where the flow was varied to match what it would be in a thruster using a 7% flow split to the cathode. This corresponds to a 1:1 ratio between the current in amps and the flow rate in sccm - i.e. the flow at 200A was 200 sccm of krypton. The shaded region of the plot shows the peak-to-peak oscillation range of the discharge voltage, providing insight into the stability at each operating point. The plot shows a generally linear trend of discharge voltage with the discharge current and peak-to-peak voltage within 15% of the average. The exception to this trend is the extreme low current case of 50A, where the average rises to 21V and the peak-to-peak is 45% of the average, indicating an unstable operating point.

The flow rate sweep at 600A shown in figure 6 reveals the expected trend of increasing discharge voltage and instability as the flow rate is reduced. The voltage is relatively constant and stable at 20.5V with a 10% peak-to-peak oscillation magnitude between 600 and 1000 sccm, but begins to gradually become unstable below 600

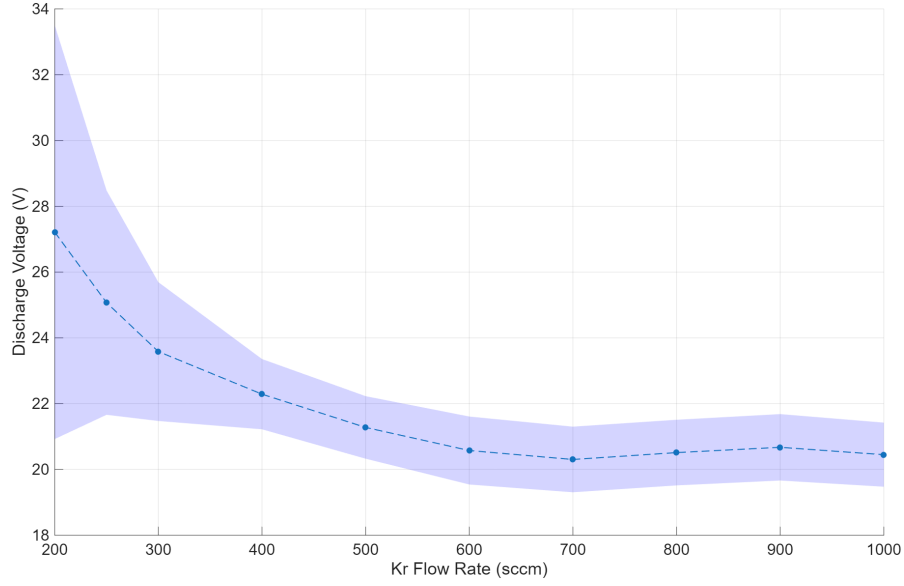


**Fig. 6** Krypton Flow Rate Sweep at 600A Discharge Current

sccm. At 200 sccm, the lowest flow rate tested, the voltage rose to an average of 27V with 45% (12V) peak-to-peak oscillations.

Due to the need for optical temperature measurements without interference from the brightness of the plasma, the cathode was also operated at times in a pulsed mode, where the discharge would periodically be turned on and off at a given duty cycle. Re-ignition of the cathode in this mode was achieved solely using the anode voltage, and the full current was able to be re-established within a second of ignition. These tests were conducted down to a duty cycle of 20% (2 seconds on, 8 seconds off), and continued to be successful over the  $\sim 2000$  cycles tested. The cathode was also tested with varying axial magnetic field strengths measured just downstream of the cathode orifice that ranged from 0-400 Gauss. Reducing the field tended to reduce discharge voltages, but increase their oscillation amplitude. Increasing the field, on the other hand, increased both the average discharge voltage and the magnitude of oscillation. A minimum of discharge oscillation magnitude was found at the 200 gauss field magnitude, which was used for all results presented in this paper.

## 4 Discussion

### 4.1 Overall Performance

Discharge voltages for this cathode were similar in magnitude and trend to the 500A LaB<sub>6</sub> presented in [1], as was the onset of increasing discharge oscillations with decreasing flow rates. In both cases, however, the flow rates for this cathode were around 5 times higher - in part due to the use of krypton instead of xenon, a lack of downstream gas injection, and a larger anode diameter. The rise in discharge voltage at

50A observed in figure 5 was also present in [1], albeit less pronounced and without the corresponding rise in oscillation amplitude. This indicates that the performance issues at this operating point were more due to the 50 sccm flow rate used per the scaling ratio, leading to a neutral density too low to sustain a quiescent discharge; this is explored further in the following section.

The ignition and relight capabilities of this cathode were considerably better than what was expected due to the lack of a typical heater coil and large thermal mass of the insert. We judge this was due to a combination of the internal secondary insert used for heating and the use of insert material to form the orifice plate, resulting in barium-rich surfaces within the orifice and on the keeper-facing side of the cathode.

## 4.2 Stable and Unstable Operation Modes

Cathodes tend to operate in two distinct operation modes - a high discharge voltage, unstable 'plume' mode, and a lower discharge voltage, stable 'spot' mode. Figure 7 shows the cathode operating in both a spot and plume mode. The plume mode is characterized by a diffuse plasma extending past the cathode, while the spot mode has a more concentrated plasma near the cathode orifice; these features are shown in figure 7. As noted in the results section, the unstable mode displayed higher discharge voltage oscillation amplitudes and was associated with lower flow rates and higher currents, which is expected for operation in the plume mode [3, 12].

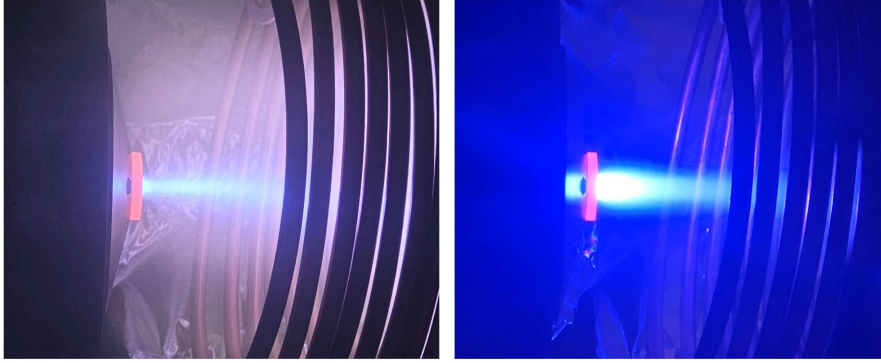


**Fig. 7** Cathode Operating in Plume (left) and Spot (right) Modes

Instabilities in the cathode operation are associated with an increase in high-energy ions within the plasma, which are damaging to the keeper [13] and cathode [14], and can limit the cathode lifetime. Figure 8 shows the ion energy distribution functions (IEDFs) for the plasma measured at a radial location of 50cm. The three traces are all taken at 500A of discharge with decreasing flow rates of Argon. At the maximum flow rate, 1000 sccm, a single sharp peak exists at 12eV, with a small tail of energetic ions, but effectively none above 35eV. At the lower flow rates, the location of the peak remains the same, but the magnitude and extent of the high energy ion tail increases significantly. The high and low flow operating points corresponded with the plasma appearing in a spot and plume mode respectively, similar to the images in figure 7,

indicating that operating in the plume mode results in the production of high-energy ions that will likely cause degradation to the cathode lifetime. A similar set of traces was attempted on krypton as the propellant, but the RPA used was not able to reject electrons sufficiently to form clear and accurate distribution functions. Subsequent inspection of the RPA revealed that high-energy ions in the krypton test resulted in damage to the RPA grids, which prevented the acquisition of further IEDFs.

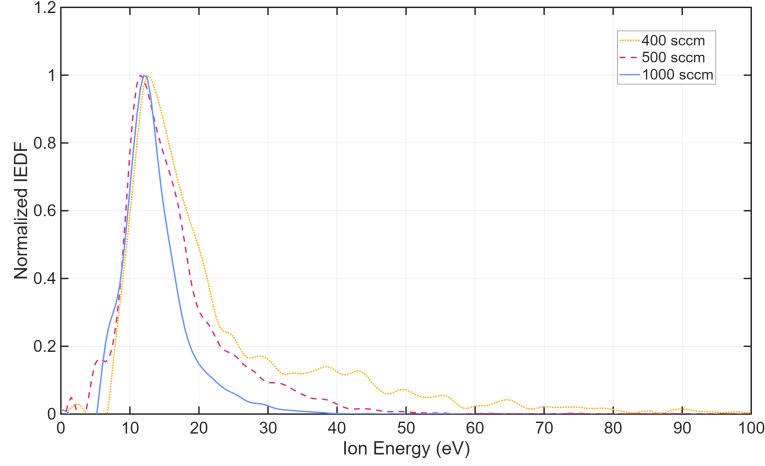


**Fig. 8** RPA Traces taken at Various Flow Rates of Argon and 500A of Discharge Current

For high-current hollow cathodes, there are three primary instability modes - ionization instabilities, magnetohydrodynamic (MHD) modes, and ion acoustic turbulence (IAT) [1]. During the current and flow rate sweeps presented in figures 5 and 6, the oscilloscope was used to capture high-speed data of the keeper voltage at each of the operating points. Using this data, the power spectral density of the cathode oscillations was estimated at each point via Welch's method. The results of this for each of the sweeps are presented in figures 9 and 10, providing insight on the types of discharge instability present.

Figure 9 corresponds to the data in figure 5 and shows the increasing energy in the cathode oscillations as the current and flow rate are reduced. The difference between operation at 100A/100sccm and 400A/400sccm is minimal, with some broad band increases in energy in the 100-200 kHz range. Similar to figure 5, there is a drastic increase in the magnitude of oscillations at the 50A/50sccm operating point, which is most prominent in the 50-200 kHz range. This frequency profile indicates the instability is not caused by IAT, which occurs in the megahertz range [13]. Since the instability is onset only at low currents, it is also unlikely due to MHD modes, which are associated with higher currents [15], though ruling this out definitively would require dispersion relations and/or high-speed camera data. This results in ionization instabilities being the most likely cause, which aligns with the low neutral density caused by the reduced flow rate and large cathode orifice.

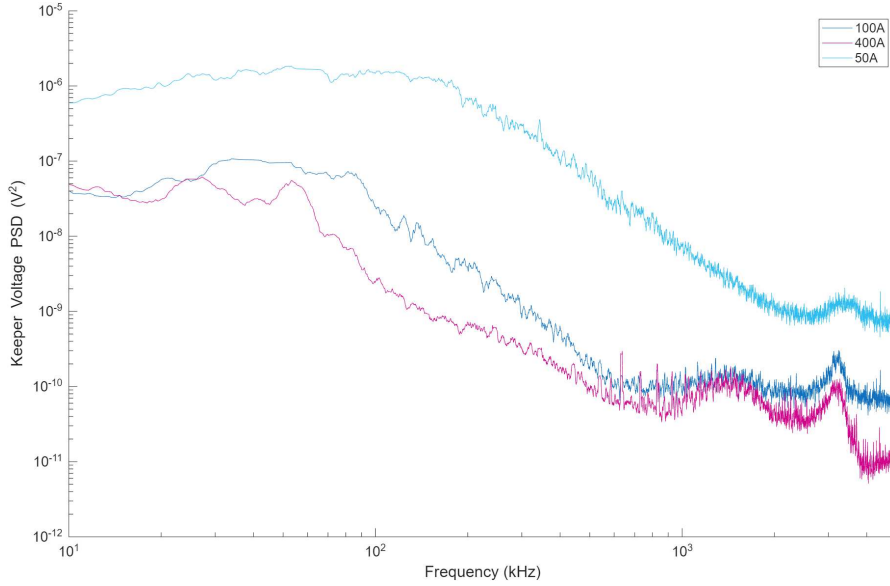


**Fig. 9** Welch PSDs of Keeper Voltage for a Fixed Flow-Rate-to-Current Ratio

The current sweep in figure 10 shows a more gradual transition between the quieter spot-like mode at high flow rates to the noisy plume-like mode at low rates. This is typical for high-current cathodes, which do not have as distinct of a transition between the two modes as lower current cathodes do [1]. The PSDs show two rising frequency peaks as the flow rate is reduced - one at 80kHz and the other at 5MHz alongside a general increase in noise across the spectrum. The 5MHz signal - likely to be IAT due to its high frequency, starts to become significant at 200sccm and lower. The lower frequency 80kHz peak could be either ionization instabilities or MHD modes, with more investigation required to determine which. Throughout all PSDs in figure 9, there is a peak at 3MHz that remains at roughly equal magnitude regardless of flow rate, indicating an instability mode which is not mitigated by simply increasing the propellant flow rate. This same peak was observed in figure 9 and appears to be consistent across all operating conditions with krypton. Frequency spectra obtained on argon did not show this same peak, indicating the peak is not equipment-dependent.

### 4.3 Lifetime Estimation

The cathode has been operated at currents of 300A or higher for a total of 30 hours during this testing campaign with no sign of degradation in performance. Flight cathodes, however, require lifetimes in the range of thousands of hours. The cathode was unable to be operated at high (>400A) currents continuously for more than around 3 hours due to overheating of the magnetic coils and high-current vacuum feedthroughs, and overloading of the cryopump. A preliminary estimate of the cathode lifetime, based on the loss rate of barium from the insert material, is presented.

Reference [14] presents a barium depletion lifetime model for hollow cathodes based on the time required for the barium to be depleted to a depth of 100 microns below the

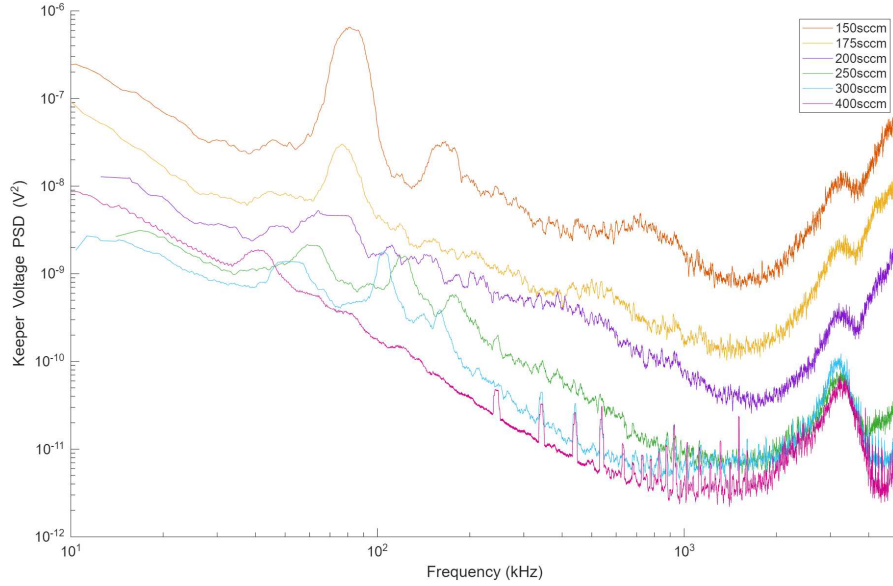


**Fig. 10** Welch PSDs of Keeper Voltage for a Varied Flow Rates at 600A of Discharge Current

insert surface ( $\tau_{100\mu m}$ ). This model is shown in equation 1, where  $y$  is the depletion depth in microns. The cathode insert has not been destructively analyzed to determine the depletion depth over the 30 hour cumulative run time. Instead, we have devised a method for estimating  $\tau_{100\mu m}$  based on the vapor pressures of Ba and BaO within the insert volume and their loss rate through the cathode orifice.

$$\tau_y = \tau_{100\mu m} \left( \frac{y}{100} \right)^2 \quad (1)$$

Figure 11 shows a ternary phase diagram of Barium-Calcium-Aluminate at 1250°C, adapted from [16] for higher resolution, and to remove phases in the non-relevant high- $\text{Al}_2\text{O}_3$  region. Note also that tie lines have been removed in some regions that are crucial to other BCA compositions such as 4:1:1, but are not for 5:3:2. Shown on the ternary plot are two compositions of BCA - 5:3:2 and 2:3:2, with the former being the initial composition and the latter representing an end-of-life composition as barium is lost from the cathode; the loss rate of  $\text{Al}_2\text{O}_3$  and  $\text{CaO}$  are negligible in comparison. The equilibrium vapor pressure for both Ba and BaO established by the cermet is determined using the methods established in [18]. Throughout the projected lifetime of the cathode, the composition exists in two distinct 3-phase regions, the first containing a mixture of  $\text{Ba}_4\text{Al}_2\text{O}_7$  (B4A),  $\text{Ba}_3\text{Al}_2\text{O}_6$  (B3A), and pure  $\text{CaO}$ , then the second containing B3A,  $\text{BaAl}_2\text{O}_4$  (BA) and  $\text{CaO}$ . Both the B4A and B3A phases are solid solutions at their respective maximum solubility limits of  $\text{CaO}$  - 23% and 18%, respectively. As described in [18], the solution stabilizes the phases, and thus reduces the BaO vapor pressure associated with their thermal decomposition.

For the estimation of  $\tau_{100\mu m}$ , the Ba and BaO are modeled as being lost through the cathode orifice, as a fraction of the propellant gas. The loss rate from this process is calculated as the molecular fraction of Ba and BaO gas in the insert volume relative

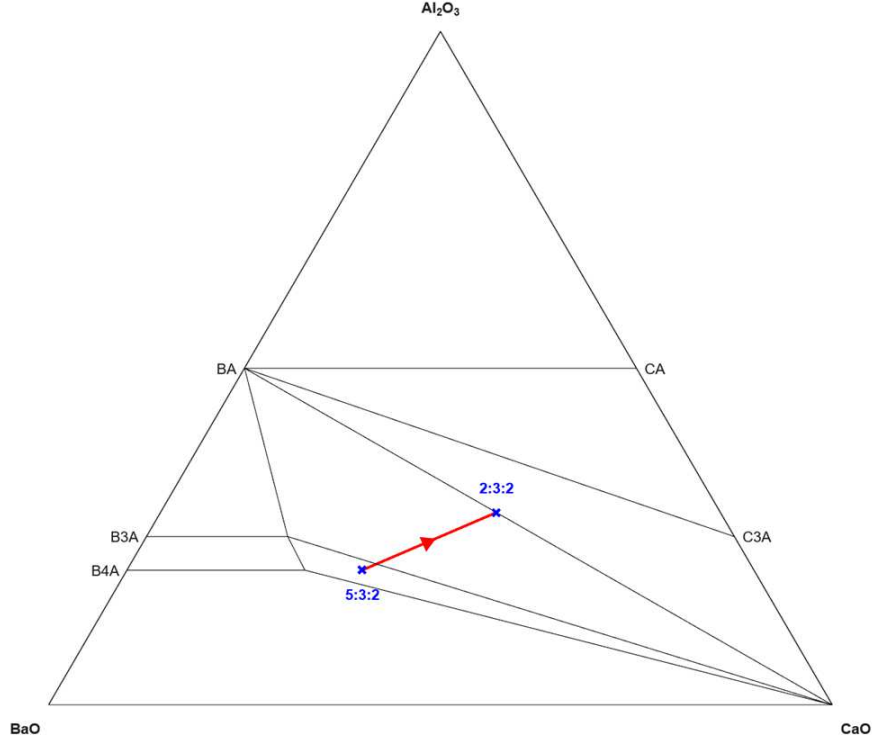


**Fig. 11** Predicted Change in 532 BCA Composition Over Operation Time

to the propellant gas, multiplied by the total molecular flow rate of propellant supplied to the cathode. The molecular fractions of Ba and BaO are set equal to the ratio of each species' vapor pressure relative to the overall in the insert volume set by the propellant. The method for calculating internal cathode pressure from reference [3] has been used, with a mass flow rate of 400 sccm. The total loss rate of barium from the cathode is then a sum of the loss rates of barium and barium oxide gases, as shown in equation 2.

$$\dot{N}_{Ba} = \frac{\dot{N}_{prop}}{P_{cath}} (P_{vap,Ba} + P_{vap,BaO}) \quad (2)$$

These loss rates were used to calculate two values for  $\tau_{100\mu m}$  at each operating temperature - labeled the 1<sup>st</sup> and 2<sup>nd</sup> transitions and presented in table 1. At the first transition, enough barium has left the material up to the given depletion depth that the B4A phase is no longer present at equilibrium, and at the second transition, enough barium has left that the B3A phase is no longer present. The B4A phase exerts the highest barium vapor pressure, and when it is lost, the vapor pressure drops to that exerted by the B3A phase – approximately half of the original. This is a significant alteration to the insert's functionality, as the lower barium vapor is expected to cause worsened surface coverage of the tungsten and an increased overall work function for

the insert. The 2<sup>nd</sup> transition, where the B3A phase is lost, is presented as an end-of-life scenario, as the barium vapor pressure exerted by the remaining BA phase beyond this point is around 500 times lower.

**Table 1** Estimated times until different barium depletion depths, in hours

| Transition                       | 1300°C            |              |                | 1400°C            |              |                |
|----------------------------------|-------------------|--------------|----------------|-------------------|--------------|----------------|
|                                  | $\tau_{100\mu m}$ | $\tau_{1mm}$ | $\tau_{5.5mm}$ | $\tau_{100\mu m}$ | $\tau_{1mm}$ | $\tau_{5.5mm}$ |
| 1 <sup>st</sup> (B4A phase lost) | 36                | 3,615        | 109,354        | 7.4               | 741          | 22,415         |
| 2 <sup>nd</sup> (B4A phase lost) | 687               | 68,700       | 2,078,175      | 120               | 12,007       | 363,212        |

Table 1 shows the times to deplete barium up to the 1st and 2nd transitions to depths of 1mm and 5.5mm ( $\tau_{1mm}$  and  $\tau_{5.5mm}$ ), calculated using equation 1. The 1mm case is presented as a reference for smaller cathodes, and the 5.5mm depth corresponds to the total thickness of the insert walls. The two temperatures provided were selected to encompass the range of temperatures measured while operating between 500-600A of discharge current (see figure 12). At 1400°C, the 1<sup>st</sup> transition for the full insert thickness occurs only at over 22,000 hours of operation, indicating that operation up to that point will be similar to testing data presented herein. Beyond this, the 2<sup>nd</sup> transition and end-of-life are expected at 363,000 hours of operation; these lifetimes are sufficient for a flight cathode, though more work is needed to prove the accuracy of the model used – particularly the  $\tau_{100\mu m}$  estimate.

Figure 12 shows the full range of temperatures measured across all cathode operating points; the krypton flow rates at each condition are the same as those presented in figure 5, while the argon flow rates are 25% higher, measured in sccm. The temperatures were fairly linear with discharge current for both argon and krypton, though operation on argon consistently showed temperatures 10-20°C lower below 350 A and 10-20°C higher between 400-500A, with the two temperatures converging at 1400°C and 600A. These temperatures are measured at the orifice plate, which is expected to be the hottest point of the cathode [14], and so this presents an upper bound to the temperature and worst-case scenario for the lifetime estimate. This lifetime estimate does not account for barium recycling within the insert volume, where barium gas is ionized, then returned to the insert by the strong radial electric field; this could significantly increase the lifetimes. It, however, also does not account for other end-of-life scenarios for the cathode, including keeper degradation via high-energy ion bombardment [13] or a the loss rate of barium outpacing its supply rate to the surface of the insert – either through the increased depletion depth or clogging of pores. Each of these mechanisms could cause end-of-life significantly before the time predicted in table 1.

#### 4.4 Work Function Estimation

Based on the work in [19], the emission length of the insert can be estimated from the product of the orifice diameter and the insert pressure (calculated using the equation provided in [3]). From this, the insert’s active emission area can be calculated, and

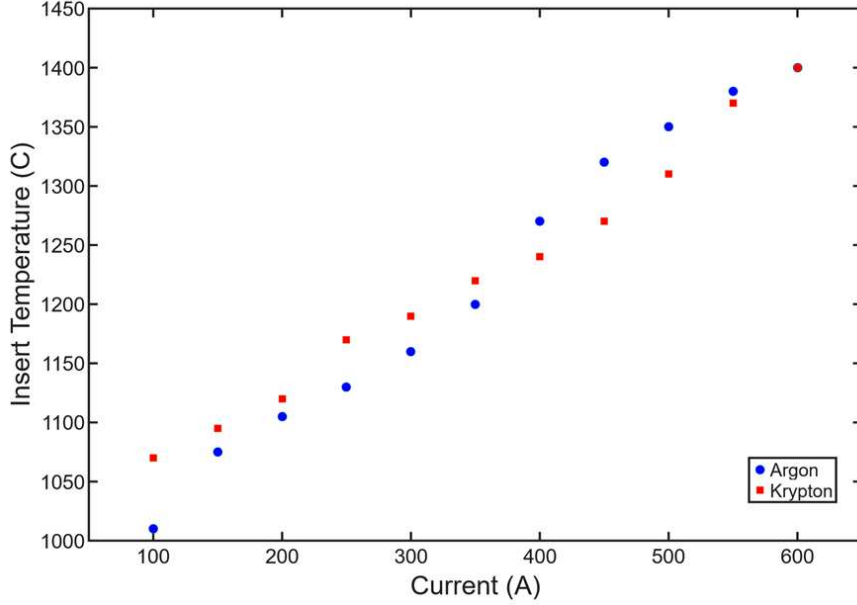


**Fig. 12** Optical Pyrometer Temperature Measurements of Cathode Orifice Plate

with the insert temperature shown in Figure 12, the Richardson-Dushman Equation can be used to estimate the insert's work function. Figure 13 shows this estimation for a 10% flow fraction operating condition over the full range of currents. For both propellants, the work function remains constant at 1.5eV below 300A, then begins to rise beyond that, to 1.7eV at the 600A operating condition. The presented values are the effective work function, which includes Schottky enhancement, and thus are reduced from the true material work function by the internal plasma's electric field at the emission surface. The trend potentially indicates the barium evaporation rate outpacing the supply rate through the pores of the material, as suggested by [2], however it is significantly less pronounced than expected. The observed rise may also be attributed to a change in emission area at these high currents, but measurements of the internal plasma properties are required to fully assess this possibility.

## 5 Conclusion

This paper presents a 600A barium oxide based hollow cathode, with operation data on krypton at various currents and flow rates. This characterization is conducted in a standalone cathode testing setup, with a magnetic coil simulating the field profile of a typical Hall Effect Thruster. At 600A of discharge and krypton flow rates above 500sccm, the discharge voltage remained between 20-21V, with oscillations of  $\pm 1V$ . Instabilities in the operation are identified in both the 5MHz range characteristic of IAT and 80kHz range, which could be ionization instabilities, MHD modes, or both pending further investigation. These cause increased erosion of the cathode insert material and keeper, but are mitigated through maintaining a flow rate above 200sccm

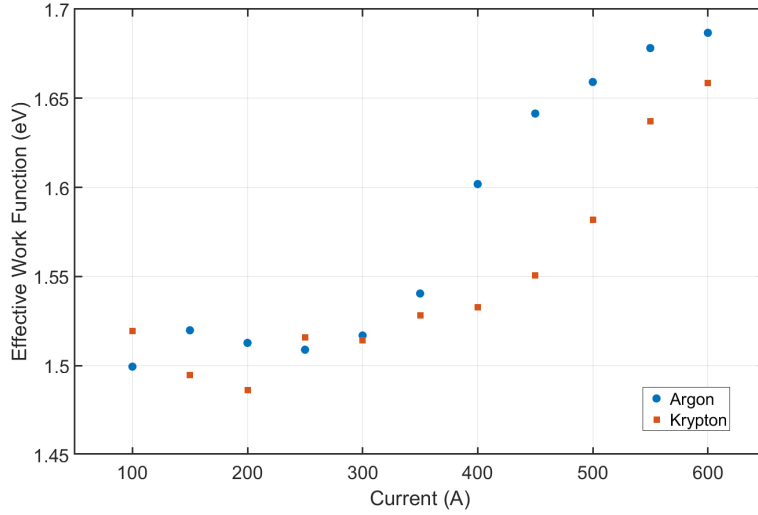


**Fig. 13** Optical Pyrometer Temperature Measurements of Cathode Orifice Plate

at 600A. An additional plasma oscillation at 3MHz was identified, which did not subside with increasing flow rate or reducing discharge current, but had a minimal impact on the overall oscillation magnitude. From operating temperatures, and the chemistry of the insert, a preliminary lifetime model has been developed, which indicates that under worst-case approximations assuming barium depletion-limited life, the cathode may have a lifetime up to 360,000 hours at 600A. For an more comprehensive life study of the cathode, the material would have to be analyzed for the depletion depth of the BCA and its composition change over operation time. This would need to coincide with an investigation into the mechanism for supplying barium internal to the insert material to its surface as the cathode operates and how it compares to the rate of barium loss. At present, planned future work includes using a rapid motion stage to obtain plasma property profile and insert temperature profile along the inside of the cathode, followed by destructive imaging of a cathode insert operated at an extreme current density to create an accelerated life test.

**Acknowledgements.** Martelli, R. would like to thank Alex Tutino, Tim Roberts, Rori Pumphrey, and Aaron Sawyer for their support in machining cathode and testing apparatus parts as well as preparing the vacuum testing facility for currents substantially beyond what has been previously achieved at CEPPE. This work was partially supported by NASA through the Joint Advanced Propulsion Institute (JANUS).

#### Declarations.

- **Funding.** This work was partially supported by NASA through the Joint Advanced Propulsion Institute (JANUS).
- **Conflict of interest.** The authors declare no conflict of interest.
- **Data availability.** All data used to generate the results presented in this paper are available upon request to the corresponding author.

- **Code availability.** Not applicable.
- **Author contribution.** R. Martelli wrote the main manuscript and prepared all figures. S. Thompson and J. D. Williams reviewed each draft and provided crucial edits. T. Freestone supported experimental setup and testing. C. C. Farnell provided crucial advice throughout the design process for the cathode and testing apparatus. All authors reviewed a draft of the manuscript.