

Preliminary Characterization of Ion Energy Spectra Acquired from High Current Hollow Cathodes

IEPC-2013-437

*Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013*

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Abstract: The production of energetic ions in high current hollow cathode discharges is a potential life limitation for high power thrusters. Several mechanisms have been proposed to explain the origin of these species as well as mitigation methods such as external gas injection but no comprehensive theory currently exists. This paper presents preliminary results in an effort to identify the performance regime over which the energetic ions appear for two types of high current cathodes--a BaO cathode, and a LaB₆ cathode.

Nomenclature

RPA	= Retarding Potential Analyzer
M_i	= Ion Mass
A_c	= effective RPA collection area
e	= electron charge
n_i	= total ion beam density
I_c	= RPA collector current
V_d	= RPA discriminator grid voltage
V_{local}	= Plasma potential outside the RPA
λ_d	= Debye length inside the RPA
$f(E)$	= Ion energy distribution

I. Introduction

The emergence of lightweight solar power approaches such as thin film and concentrator arrays has allowed the possibility of space missions featuring several hundred kilowatts of electric power¹. Among the thruster systems envisioned for these missions are mature electric propulsion systems such as hall thrusters and gridded ion thrusters. Although these thrusters can be scaled up to high power in a relatively straightforward manner, there does not yet exist an ion or Hall engine capable of processing 20-100 kW of power with reasonable lifetime (>10,000 hrs). This level of operation would require cathodes operating at high current levels, possibly exceeding 100 A. At high operating currents, it has been observed that energetic ion streams form within the cathode plasma. These ions can

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lead to severe erosion of the hollow cathode assembly through accumulated sputtering damage. For example, the severe erosion of the NSTAR discharge cathode assembly during the extended life test has been attributed to the presence of energetic ions originating at the cathode².

The documentation of energetic ions in hollow cathode discharges dates back to the 70's in which severe baffle erosion in mercury ion thrusters was observed. Studies led by Manteneiks³, Rawlin⁴, and Brophy/Garner⁵ all observed severe baffle erosion that was suggestive of energetic ion bombardment. In 1992, Friedly and Wilbur⁶ measured the presence of energetic ions originating at the discharge hollow cathode. In the time since, several other studies have found evidence of energetic ions in cathode plumes⁷⁻¹⁰. Theories attempting to describe the production mechanisms of these ions range from the existence of a steady state potential hill^{6,8}, to magnetohydrodynamic effects⁹ to hydrodynamic drag driven primarily by electron-ion collisions¹⁰. Recently, it has been postulated that energetic ions are generated by large amplitude potential oscillations—associated presumably with the ion acoustic instability¹¹. To date, there has not been a complete explanation offered for the production of the energetic ions. It is therefore a priority to understand the conditions of their occurrence and implement solutions to mitigate the formation of these ions. Presented in this paper are initial results of an effort aimed at characterizing conditions for energetic ion formation in two types of cathodes: 1) a 50 A barium oxide cathode and 2) a 60 A lanthanum hexaboride cathode. The ion energy spectra are characterized using both a retarding potential analyzer and an emissive probe for plasma potential measurements in the plasma plume.

II. Experimental Approach

A. Measuring Ion Energy Spectra: The Retarding Potential Analyzer

The energy spectrum of ions emerging from a cathode plasma can be measured using a gridded retarding potential analyzer (RPA)¹². In this work, the RPA is composed of four electrostatically biased mesh grids and a collector plate, as seen in Fig. 1. During operation, the RPA grids function as follows. The front grid, G4, is grounded to shield the RPA from the ambient plasma. The next grid, G3, often called the electron repeller, is biased negatively to prevent plasma electrons from entering the RPA. Ions, in contrast, are transmitted through to the remaining grids. The ion discriminating grid, G2, is biased at positive voltage, V_d , to allow passage of ions with energy greater than eV_d to pass through to the collector. Finally, the innermost grid, G1, is biased at negative voltage to prevent the escape of secondary electrons created by ion bombardment within the RPA. These backward travelling secondary electrons otherwise would be falsely counted as ion current incident on the collector.

The discriminator grid, G2, can be swept through a range of positive voltage to produce a current-voltage trace. The total ion current incident on the collector, I_c is related to the discriminator voltage by¹³,

$$I_c(V_d) = \frac{e^2 n_i A_c}{M_i} \int_{eV_d}^{\infty} f(E) dE \quad (1)$$

In Eq. (1), e is the electronic charge, n_i , the total ion beam density, A_c , the effective RPA collection area, and M_i , the ion mass. This relation can be differentiated to yield the ion energy distribution incident on the RPA,

$$f(eV_d) \propto - \frac{dI_c}{dV_d} \quad (2)$$

The RPA used in this work was fabricated at Electrodynamics Applications Inc. The collector plate and grids are housed in a grounded shell to prevent leakage of the plasma into the RPA interior. During operation, the collector was biased at -20 V, the secondary electron grid, at -10 V, and the electron repelling grid at -30 V. The discriminator was swept in the range 0-200 V. All grids were set relative to chamber ground, which differed from the cathode floating potential by no more than 1 V DC during operation. Normal operation of the RPA requires that the Debye length, λ_d inside the RPA be much larger than the grid spacing. This assures that the electrostatic fields from the grids can influence the incoming ion beam. In this work, the RPA was relatively close to the plasma source (~25 cm), so it was imperative to maximize the attenuation of the plasma source through the first two grids.

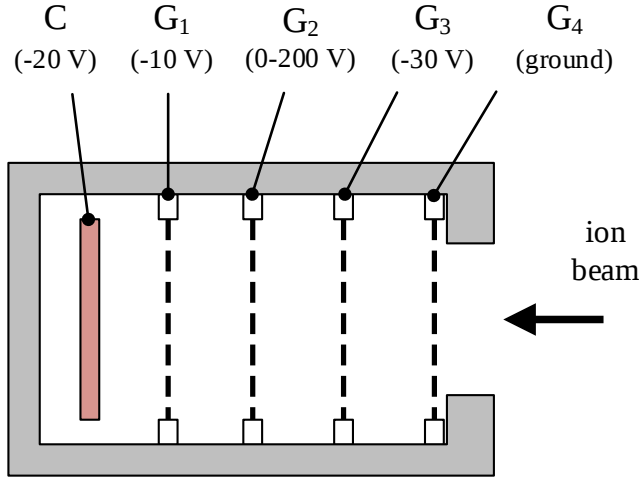


Figure 1. Retarding Potential Analyzer. The four grid RPA fabricated at EDA. The front grid, G_4 is grounded while the second grid, G_3 , repels plasma electrons away from the collector. The discriminator, G_2 , is swept over the range 0-200 V, repelling ions with energy below eV_d . The final grid, G_4 , is used to prevent secondary electrons created by ion bombardment from escaping the RPA.



Figure 2. Emissive Probes. (Top) the alumina emissive probe body shown with tungsten filament. (Bottom) The emissive probe in floating point operation.

B. Plasma Potential

Energetic ion production may be influenced by the variation of plasma potential near the cathode. Measurement of this plasma potential provides insight into the source of the ion acceleration process. Furthermore, knowledge of the plasma potential outside of the RPA is necessary to appropriately interpret the ion energy spectra measured by the RPA. As ions leave the source plasma and enter the RPA, they gain extra energy equal to eV_{local} , where V_{local} is the local plasma potential outside the RPA. This energy gain is due only to the presence of the RPA in the downstream plasma and does not accurately reflect energy gained by ions created in the cathode plasma. The energy distribution must therefore be shifted down by a value equal to the local plasma potential,

$$f(eV_d - eV_{local}) \propto -\frac{dI_c}{dV_d} \quad (3)$$

In this work, the local plasma potential was measured using emissive probes, which were operated using the floating point method, an established electrostatic probe technique for measuring plasma potential, particularly in Hall thruster channels¹⁴. The probe tip, shown in Fig. 2, consists of a tungsten filament heated at 1.3 A current. As the filament current is increased, the probe emits an increasing flux of electrons into the plasma until it saturates, at which point the floating potential provides an indication of the local plasma potential.

The emissive probe filaments were attached to two copper wires fed through a double bore alumina tube. Two different probe sizes were used: (1) a 3 mm diameter alumina tube with 1.5 mm loop radius and (2) a 1.3 mm alumina tube with 0.7 mm loop radius. Both probe sizes were used with 0.06 mm diameter tungsten wire. The first type was used for a stationary emissive probe placed 3.2 cm from the entrance of the RPA. This probe was used to correct the ion energy spectra as described above. The second, smaller, probe size was used to perform a 1-D axial plasma potential profile of the downstream cathode plasma. The details of this experiment are provided in section C.

C. Cathode Facilities and Diagnostic Setup

Ion energy spectra were obtained for two different hollow cathodes: (1) a Busek 60 A barium oxide (BaO) cathode and (2) a 60 A lanthanum hexaboride (LaB_6) graphite cathode. The Busek cathode was operated for this project in the range of 5-40 A. The LaB_6 cathode is based on a design by Goebel, Watkins, and Jameson¹⁵. A conical copper sheet, shown in Fig. 3, was fabricated to act as the anode in the cathode circuit. The discharge circuit is formed between the cathode and the conical anode, both isolated from ground. Copper tube was silver soldered to

the anode body to provide water cooling during operation. The axial length of the anode along centerline was 35 cm, with 9.5 cm and 44 cm diameter openings on either side of the cone.

The cathode was placed outside of the anode, approximately 3-5 cm from the small opening of the conical geometry, similar to the setup used by Goebel¹⁶. The two cathodes were run in the vacuum facility at Electrodynamics Applications, which was pumped by Cryo pump and had a base pressure of 10^{-6} Torr. xenon flow rates were in the range 5-10 sccm, leading to an operating pressure in the range $4.4\text{-}9.9\cdot 10^{-5}$ Torr. The orientation of the cathode, anode, and diagnostics is shown in Fig. 3. The RPA and emissive probes were aligned along the centerline of the cathode orifice. The 1-D stage provided the capability of measuring both ion energy distributions and plasma potential as a function of axial position. During all RPA testing, a stationary emissive probe was placed directly outside the RPA to correct the measured ion energy spectra, as discussed in section A.

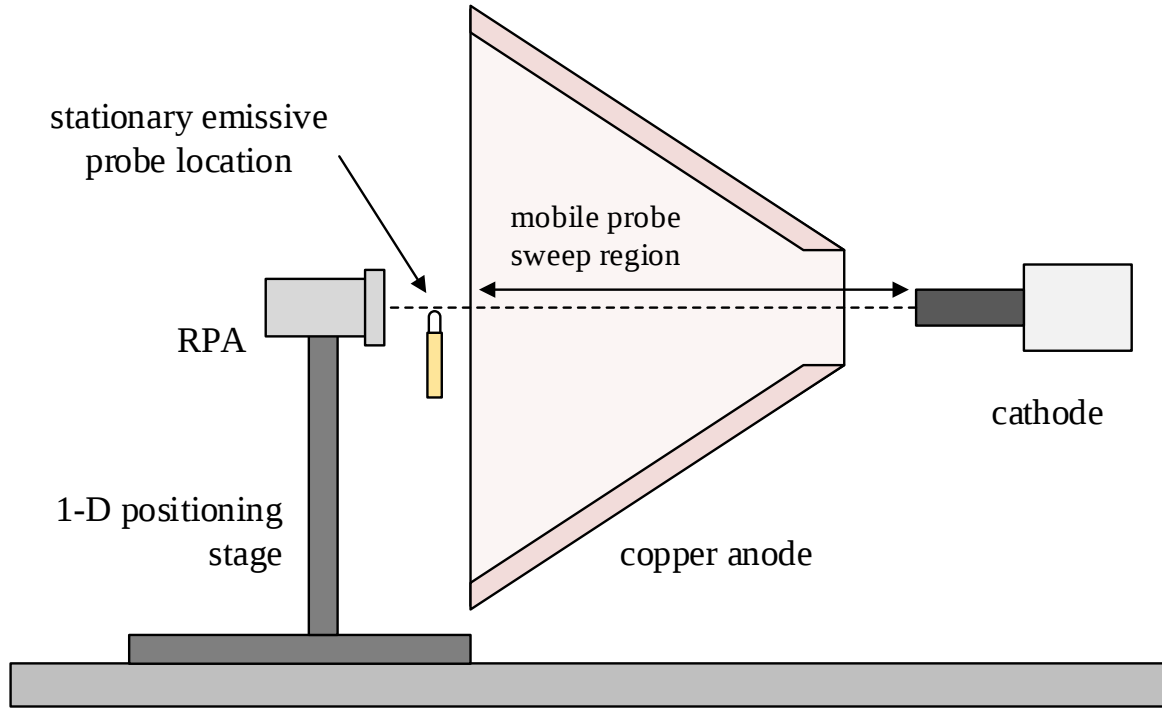


Figure 3. Diagnostic Setup. The RPA and emissive probes are aligned on centerline with the cathode. The 1D stage was used to position either the RPA or the emissive probe relative to the cathode orifice. A stationary emissive probe was also placed directly outside the RPA in order to correct the ion energy spectra. Dimensions are not drawn to scale.

III. Results

A. Cathode Operating Conditions

The discharge voltage and current of each cathode is shown below in Fig. 4, each over a range of xenon flows. The BaO cathode was capable of operating at low voltage (under 30 V) up to 40 A. The LaB₆, in contrast, was capable of operating up to 80 A, 30 V at 10 sccm. In general, the discharge voltage was observed to increase when the cathode current became sufficiently small or large. The range of stable, low voltage operation could be extended out to higher current by increasing the flow rate. It was also observed that an increase in both the cathode current and flow rate led to the emergence of plasma downstream of the cathode in the vicinity of the RPA.

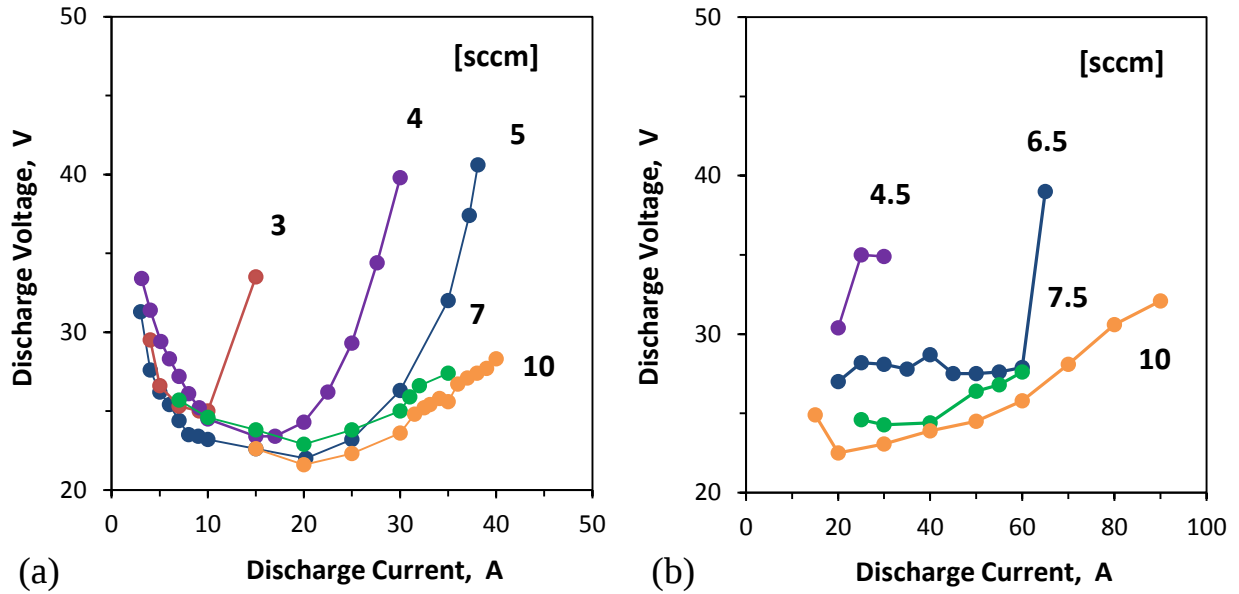


Figure 4. Cathode Characterization. Current and voltage traces for (a) The BaO cathode and (b) The LaB₆ cathode. Flow rates are shown in sccm beside each curve.

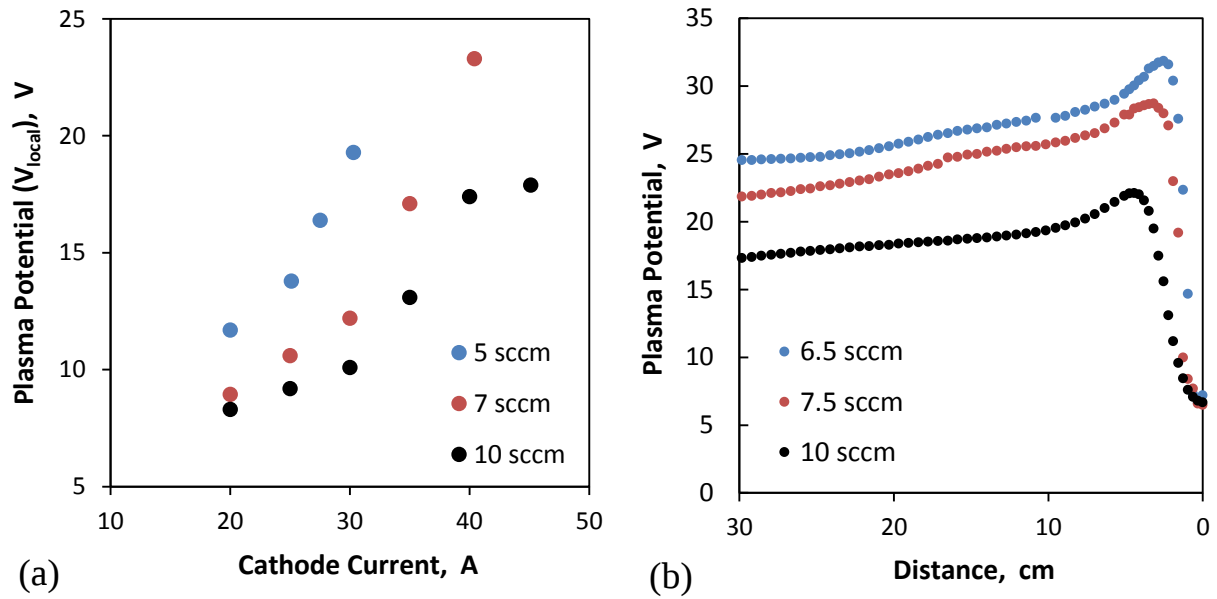


Figure 5. Plasma Potential (a) Plasma potential from an emissive probe located directly outside the RPA. (b) 1-D axial profiles of the emissive probe, swept from the cathode orifice ($x = 0$ cm) out to the RPA location ($x = 30$ cm).

Measurements of the local RPA plasma potential, V_{local} , are consistent with this observation. Three examples of V_{local} measured for the BaO cathode are shown in Fig. 5(a). As the cathode current and flow rate increase, the plasma potential increases. As discussed in section I, the value of V_{local} determines the effective sheath voltage through which energetic ions are accelerated as they exit the plasma and pass through the grounded grid of the RPA. The generation of plasma near the RPA also influences the quality of the RPA trace. A larger plasma density results in greater plasma leakage into the RPA and an eventual breakdown in the electrostatic assumptions of RPA operation. This ultimately limits the useful regime of RPA. The emergence of plasma near the RPA was also observed to be correlated with the observation of high amplitude oscillations of the cathode floating potential. These may be related to the excitation of ion acoustic waves responsible for the production of energetic ions¹¹. A similar transition is observed in the LaB₆ cathode.

To better understand the relationship between the RPA plasma and cathode plasma, a 1-D axial profile of plasma potential was performed on the translation stage outside the LaB₆ cathode. The stage was used to move the emissive probe, operating in floating point mode, from the edge of the anode cone, (-30.5 cm) all the way to the cathode orifice (0 cm). In order to minimize the physical shadow and interference from the probe body, the small alumina probe size (1.3 mm) was used. Figure 5(b) shows plasma potential profiles from the LaB₆ cathode operated at 30 A for three different flow rates: 6.5, 7.5, and 10 sccm. As observed in Fig. 5(a), the potential near the RPA decreases with increasing flow. The potential in the interior of the anode body stays relatively constant until up to a location 10 cm away from the orifice, at which point a small potential hill (~5 V) forms. On the other side of this hill is the cathode fall voltage, which ranges from 15 V at 10 sccm up to 25 V at 5 sccm. The characteristic length scale of the fall voltage is 5 cm, which increases with flow rate. Of particular interest in this figure is the region near the maximum potential. This region corresponds to a reversal in the sign of the electric field, indicating the presence of a double layer. A similar double layer structure of comparable magnitude has been observed downstream of the cathode orifice in ion thruster discharge plasma¹⁸. The small change in potential from the tip of the hill to the far field ambient plasma is a possible source of acceleration for ions produced in this region, though on average this drop corresponds to 5-7 V.

B. BaO Ion Energy Spectra

Figure 6 shows RPA traces obtained at two flow rates, 7 sccm and 10 sccm for the BaO cathode. The raw data was fitted using an 8th order polynomial. This was determined to be the maximum number of degrees of freedom capable of capturing the general shape of the curve while minimizing the presence of artificial features in the ion energy distribution. The primary effect of this distortion was to introduce artificial features of the energy distribution, particularly at the endpoints.

A common observation among all traces is a broad shape encompassing a wide range of apparent ion energies. As the cathode current is increased, the ion population extends further out to higher voltages (or equivalent ion energies). In the case of 7 sccm and 35 A cathode current, the RPA's collector current does not reach baseline until 150 V, indicating ions with energy up to 150 eV may be entering the RPA. At higher flow rate, a similar pattern is observed but with lower signal strength. One observation at high cathode current is a failure of the collector current to reach zero amps, indicating the leakage of plasma into the RPA. This is supported by the measurement of high plasma potentials in the vicinity of the RPA and visual confirmation of plasma glow around the RPA. In particular, for the case of 7 sccm and 40 A current, the RPA signal became too noisy to detect the expected ion signature. This may be due to plasma leakage into the RPA or high amplitude oscillations of the RPA signal, which would crowd out the steady state signal.

According to Eq. (2), the ion energy distribution is proportional to the negative derivative of the RPA trace. This can easily be calculated numerically using the polynomial fits in Fig. 6. Calculated distribution functions for the two flow rates of the BaO cathode are shown in Fig. 7. According to the axial plasma potential profile shown in Fig. 5, the cathode plasma extends out from the cathode all the way up to the RPA entrance. As described in section II, ions that exit the cathode plasma are accelerated by an additional potential as they cross the plasma sheath at the entrance of the RPA. This extra energy is not indicative of the true energy of the ions, but is instead due to the artificial attenuation created by the presence of the RPA. The calculated distribution function was thus corrected by shifting the distribution function to a lower energy by factor of, V_{local} , which was measured for each value of cathode current and flow rate.

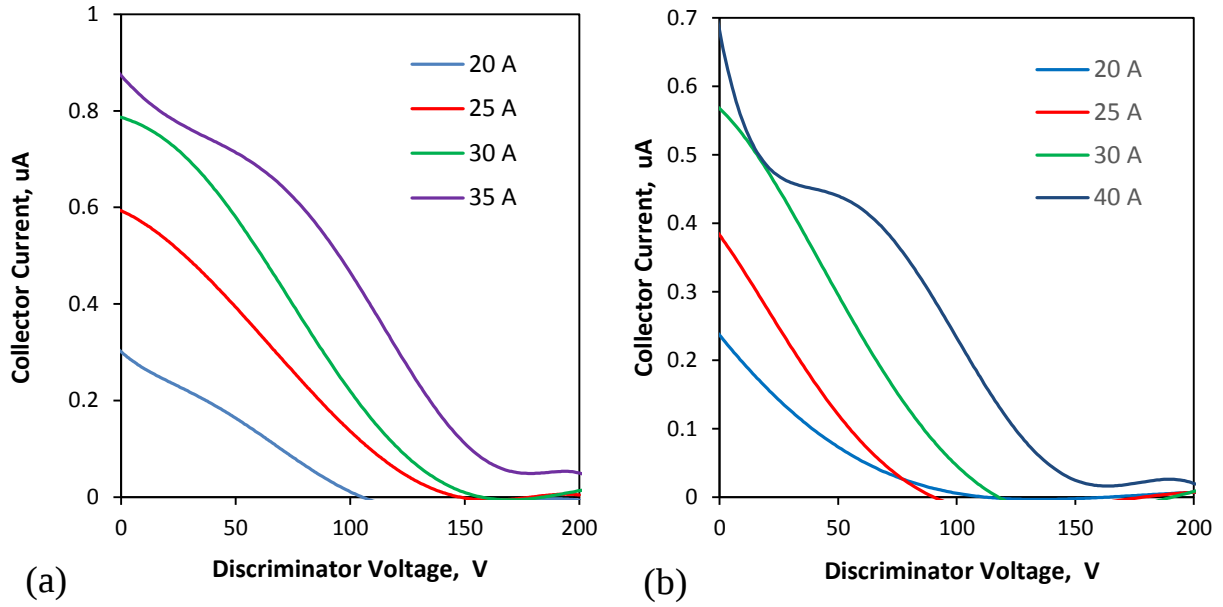


Figure 6. BaO RPA Traces. RPA traces taken at two flow rates (a) 7 sccm (b) 10 sccm . All traces are fitted with an 8th order polynomial.

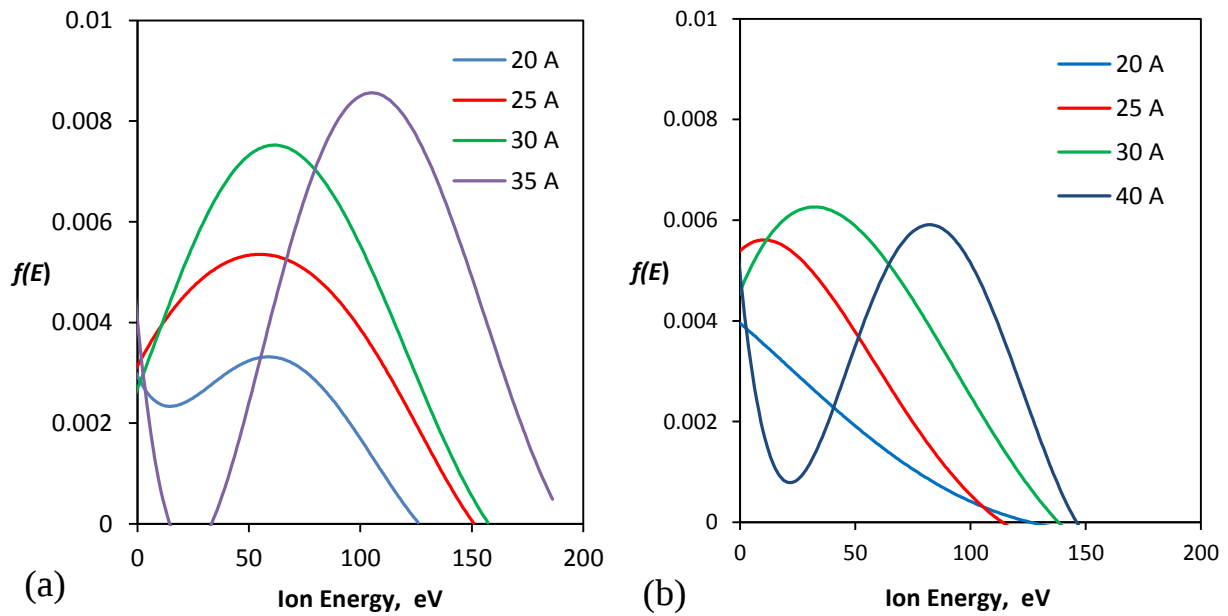


Figure 7. BaO Energy Distributions. Unnormalized ion energy distributions calculated for the BaO RPA traces at two flow rates: (a) 7 sccm and (b) 10 sccm. An increasing cathode current causes the distribution peak to spread to higher energies, reaching upwards of 110 eV in the case of 7 sccm.

Overall, the peak energy of the distribution tends to shift to higher energy as the cathode current is increased, reaching values of 100-110 eV at high values of cathode current. This transition appears to be sudden in the case of 7 sccm, but more gradual in the case of 10 sccm. Overall, the consistent observation of high energy peaks in these distributions indicates the presence of energetic ions in BaO cathode plasma. These values greatly exceed the discharge voltage (~ 30 V) and do not appear to be a product of the steady state plasma potential outside the cathode (see Fig. 5). In particular, the small potential hill observed outside the cathode (~ 5 V) is not nearly large enough to produce ions of this energy. These results suggest that energetic ions must be derived inside the cathode orifice or alternatively by time dependent plasma oscillations that are not captured by steady state measurements of the plasma potential. Such oscillations may be related to ion acoustic wave phenomena¹¹. This explanation is further supported by the observation of high amplitude oscillations of the cathode floating potential, which reaches nearly 20 V peak-to-peak under high current conditions.

C. LaB₆ Ion Energy Spectra

Ion RPA traces and energy spectra were also obtained for the LaB₆ cathode, operating over a range of 5-10 sccm and 15-80 A cathode current. RPA traces from two representative flow rates, 6.5 sccm and 10 sccm, are shown in Fig. 8. As observed in the case of the BaO cathode, ions with energies of nearly 100 eV are apparent from the collector current traces. In this case, this collector current does not extend as far (~ 100 V) compared to the case of BaO (150 eV) but energetic ions do still seem to be present. One primary difference between the two cases, is the dramatic increase in the RPA signal at 10 sccm, reaching nearly 8 μ A. Under these conditions, the peak to peak oscillations of the cathode are observed to reach up to 20-30 V.

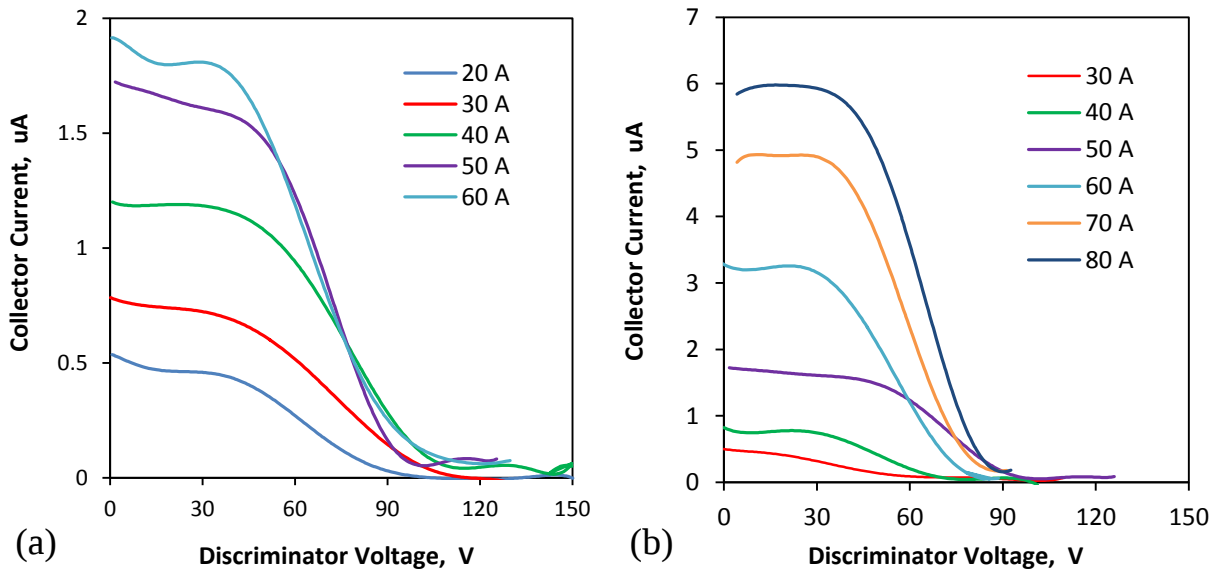


Figure 8. LaB₆ RPA Traces RPA traces taken at two flow rates (a) 6.5 sccm (b) 10 sccm for the LaB₆ cathode.

Representative cases of the calculated ion energy distributions, corrected for the local RPA plasma potential are shown in Fig. 9. One immediate observation is the lower variation in average ion energy, which does not increase with cathode current. On average, the energy corresponding to the peak of the distribution remains in the range 30-60 eV, even for values of cathode current as high as 80 A. For both 7 sccm and 10 sccm, the maximum value of peak ion energy occurs not at the maximum current but at an intermediate current: 40 A in the case of 6.5 sccm and 50 A in the case of 10 sccm.

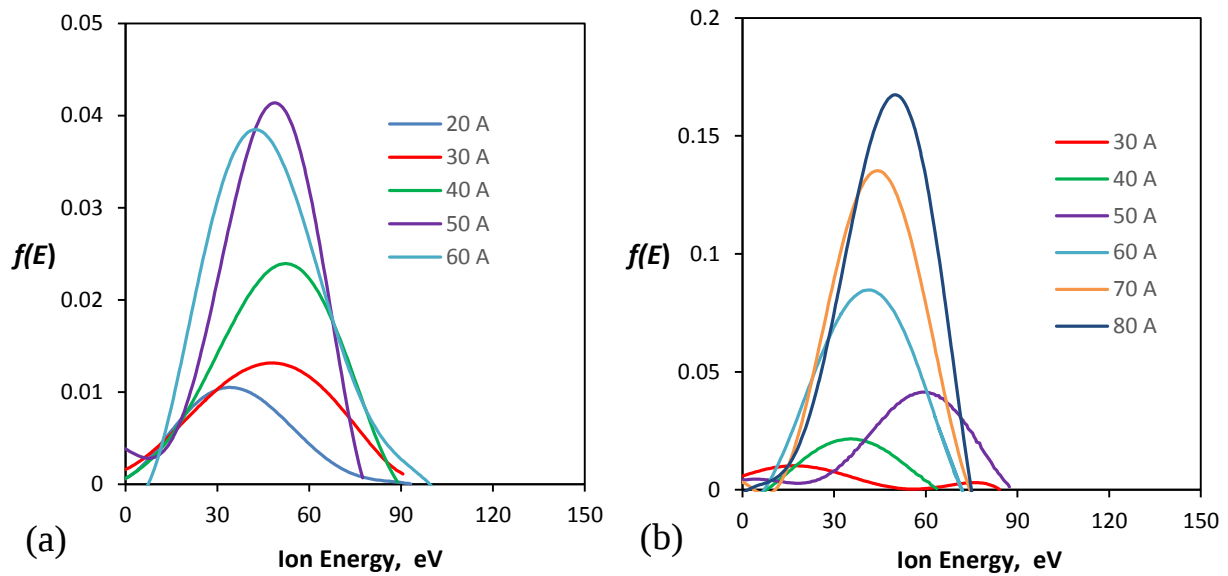


Figure 9. LaB6 Energy Spectra. Unnormalized Ion Energy Distributions calculated for the LaB6 data for two flow rates, (a) 6.5 sccm (b) 10 sccm. All cases are shifted down by the value of the local plasma potential outside the RPA.

IV. Conclusion

Ion energy spectra were obtained from two different types of high current hollow cathodes: 1) Barium Oxide and 2) LaB6. The goal of this effort was to map out the performance regime over which energetic ions appear. It was found that in the case of the BaO cathode, the energy distribution broadened and shifted toward high energies well in excess of the discharge voltage. High energy ions were also observed in the case of the LaB6 cathode, but at lower energy. Overall, plasma potential measurements indicate that the presence of the energetic ions could not be accounted for by the observed spatial variations in the plasma potential. Interestingly, a double layer was found to exist just downstream of the discharge cathode. However, the potential hill associated with this double layer structure was small compared to the spectrum of energetic ions observed.

Acknowledgments

This project was funded by a phase I SBIR, NASA contract NNX13CC13C.

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