

Preliminary Characterization of a LaB_6 Hollow Cathode for Low-Power Hall Effect Thrusters

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An experimental investigation of the operating characteristics of a heaterless LaB_6 hollow cathode was performed to examine low-current and low flow rate operation. The cathode has been continuously operated at Xe mass flow rates between 0.08 mg/s and 1 mg/s and discharge currents ranging from 0.5 to 3 A in diode mode for two different orifice diameters. The minimum power consumption was of about 25 W while the minimum mass flow rate required for spot-mode emission was approximately 0.08 mg/s Xe. The experimental data gathered during the test campaign were used to refine the theoretical model developed by Alta for the performance assessment of rare-earth thermionic hollow cathodes.

Nomenclature

AR	= Aspect ratio
D	= Diameter, m
f	= Frequency, s^{-1}
L	= Length, m
R	= Radius, m
<i>Subscripts</i>	
o	= Orifice region
e	= Emitter region
k	= Keeper

I. Introduction

WHILE state-of-the-art (SoA) electric propulsion (EP) systems provide remarkable mass and cost advantages with respect to chemical thrusters for both station-keeping and attitude control missions, a need remains for performance improvement in sub-kilowatt propulsion systems for small satellites.¹ In this context, the cathode plays a fundamental role in the overall performance of low power (< 500 W) ion and Hall thrusters. As a matter of fact, Patterson¹ reported that a typical impregnated cathode/neutralizer for a 100 W-class ion thruster could degrade the thrust efficiency by approximately 20% and reduce the specific impulse by as much as 2000 s. In addition, since typical missions for ion and Hall thrusters require thousands of hours of operation, cathodes lifetime becomes a crucial issue especially for attitude-control operations where

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intensive on-off cycles are required. As already stated by Warner,³ the hollow cathodes commonly employed for US space propulsion applications require nitrogen purging to ensure that the impregnated insert is not contaminated by water vapour or oxygen. In addition, before a hollow cathode discharge can be initiated, a slow temperature increase up to thermionic-emission temperatures ($\simeq 1400 - 1900$ K) is needed to drive off all the residual contaminants. This lengthy procedure, called conditioning, is usually accomplished by using an external heating element and can drain non-negligible fractions of the available on-board power, typically 50-100 W. The operation of rare-earth emitters, e.g. lanthanum hexaboride LaB_6 and cerium hexaboride CeB_6 , as considered in the present work, is definitely less sensitive to impurities and air exposure since it does not rely upon chemical build-up of low-work function layers near the emitting surface.⁴ In addition, rare-earth emitters does not require specific activation procedures since the electron emission comes from the bulk material and no porous matrices are needed.

All in all, it is possible to conclude that conventional impregnated hollow cathodes suffer from two major failure modes: emitter poisoning and heater failure. As a consequence, the development of a heaterless LaB_6 cathode allows to address these two critical issues at once. Although LaB_6 cathodes have a long in-space heritage in Russia, few researchers have been following Russian studies in other countries. In the United States, Goebel reported the first time use of LaB_6 in a hollow cathode in 1978⁶ and presented the first high-current LaB_6 cathode as a plasma source in 1985.⁷ In the following years, almost all the published work on rare-earth cathodes for space applications focussed on high-current devices. Recently, Courtney developed and tested a LaB_6 hollow cathode for low current (< 2 A) applications⁸ while Warner investigated the feasibility of both LaB_6 and CeB_6 as low current (< 10 A) hollow cathode emitters.³ By following these few researches, the results of the preliminary characterization of a heaterless LaB_6 cathode for low-power applications are here presented and discussed. The present work is, to the authors best knowledge, the first attempt to experimentally investigate the feasibility of a rare-earth cathode operating in the 0.5-3 A current range without employing an external heating for the discharge initiation and sustainment. The hollow cathode here presented is intended as main electron source for the low-power Hall effect thrusters (HT-100 and HT-400) currently under advanced development at Alta.⁵

II. Experimental Apparatus

A. Hollow Cathode Design

The Alta LaB_6 hollow cathode has the same basic components as many hollow cathode designs, namely a thermionic electron emitter placed inside a structural cathode tube, a heat shield and an enclosing electrode - called keeper - used to help cathode ignition and to protect the orifice plate from ion bombardment. The cathode was designed as an engineering model allowing for orifice changes and time-saving component replacements. A schematic of the cathode under investigation is shown in Figure 1. The design featured

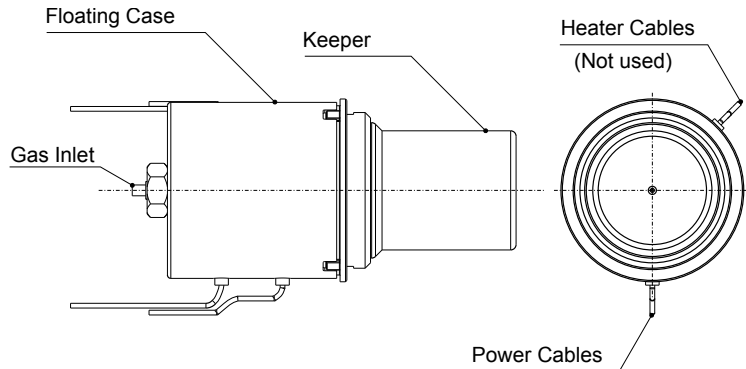


Figure 1. Schematic of the Alta LaB_6 low-current hollow cathode.

a polycrystalline LaB_6 cylindrical insert in a tantalum hollow cathode structure with a molybdenum-alloy keeper. The LaB_6 insert is protected from direct contact with the refractory metal tube by a thin, graphite sleeve in a cup-arrangement around the ends of the insert. The insert and the boron-diffusion barrier are

held in place by a tungsten-alloy spring placed inside the main tube. The insert has an outer diameter of 6.5 mm, an inner diameter of 3 mm and a length of 6 mm providing 0.56 cm^2 of emission area exposed to the plasma. Two LaB_6 emitters in series are typically used to guarantee proper plasma-wall interactions at low mass flow rates (low-pressure operations).

The 0.4 mm thick tantalum orifice plate features chamfered ends and a sub-millimetric hole obtained through electrical-discharge machining. The cathode tube is manufactured with steps to hold the orifice plate and clamp the tube into the mounting flange eliminating the need of costly e-beam welding. Due to the relatively high work-function of the LaB_6 emitter ($\sim 2.7 \text{ eV}$, see Lafferty⁹), heat losses by conduction and radiation are critical for the cathode operation. Careful thermal analyses have been performed in order for the cathode to handle remarkable temperature gradients ($\sim 20 \text{ K/mm}$) without incurring in excessive thermal stresses or unacceptable thermal deformations of the structure. The molybdenum-alloy keeper has an orifice of approximately 0.6 mm and the keeper-to-cathode gap is about 2 mm along the longitudinal axis.

B. Testing Facility

All the tests described in the present paper were carried out at Alta in the IV4 vacuum chamber. The Alta IV4 facility consists of two different bodies made of AISI 316L stainless steel with low magnetic relative permeability ($\mu_r < 1.06$): the main vessel (Auxiliary Chamber - AC) 2 m dia., 3.2 m length and the service chamber (Small Chamber - SC), 1 m dia. 1 m length. The two bodies are connected through a 1 m dia. gate valve. The small chamber was used to accommodate the cathode setup, its electrical and gas-feeding systems while the AC allowed for a free expansion of the plasma plume and it is directly connected to the main pumping system. At the far end of the AC, on the opposite side with respect to the cathode, a bi-conical, water cooled, Grafoil-lined target is installed in order to dump the beam energy down. The chamber pumping system is capable of maintaining a back pressure in the range of 10^{-5} Pa by using a primary stage located in the AC and a secondary stage located in the SC. The combined pumping speed of the system is approximately 130,000 l/s for xenon. The pressure level within the chamber is continuously monitored by three Leybold-Inficom IT90 Pirani/Bayard-Alpert sensors and recorded via LabVIEW.

C. Propellant and Power Systems

The schematic of the electrical circuit used during the test is shown in Figure 2. A current-limited Huttiger PFG-5000 (1000V-6A) DC power supply controlled the cathode-to-keeper voltage and current. The cathode was operated in diode mode and no external anode was used during the present test campaign. The gas feeding system consisted of two independent lines, each equipped with dedicated mass flow controllers (Bronkhorst F-201C-FAC-22-V and Bronkhorst F-201C-FAC-88-V for cathode and anode lines, respectively), connecting the xenon tank to the test item. All tests were performed using grade 4.5 xenon. The electrical

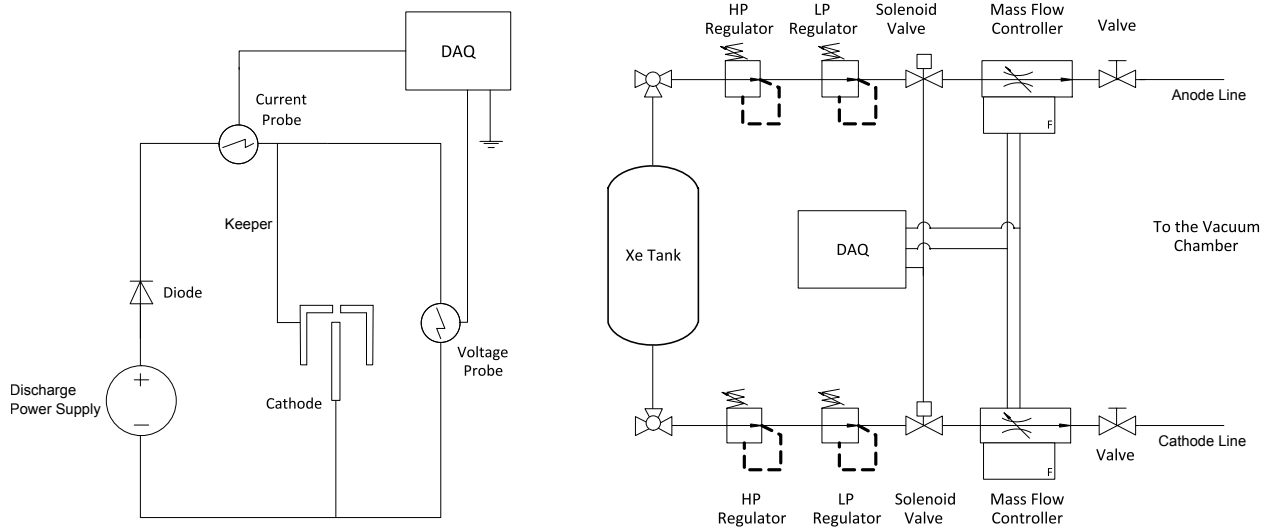


Figure 2. Schematic of the electrical and propellant feed systems.

parameters were measured by using current (LEM LA25-NP) and voltage probes (LEM LV25-P). All the sensing probes were calibrated before the test and connected to the DAQ system controlled via LabVIEW software. The error associated with the DC voltage measurements is $\pm 2\%$ while a relative error of $\pm 1\%$ is evaluated for the current measurements.

III. Test Results and Discussion

In order to assess the effect of the geometry on the performance of the cathode, two different orifice plates were tested. The orifice diameter and length were chosen by combining manufacturing considerations with numerical results from the model by Albertoni et al.¹⁰ The investigated length-to-diameter aspect ratios were 1.2 and 0.9, respectively. A preliminary heating-up phase of about 10 minutes at 3 A and constant mass flow rate was performed before each characterization test in order to recover full emission capabilities after extended air exposure. After the shutdown, Xe was flowed for about 5 min at 1 mg/s to force the cooling of the cathode and to prevent oxygen contamination of the emitter at high temperatures.

A. Cathode Performance

The voltage-flow rate characteristics for the two cathode configurations at different discharge current are presented in Figure 3. The portion of the curves where the voltage is only weakly dependent upon the flow rate is known as spot mode. Spot mode is characterized by having negligible AC components in the voltage signal. By contrast, plume mode is usually detected by increases in the discharge voltage oscillations (e.g. higher than 5 V peak-to-peak as suggested by Brophy¹¹) or in the magnitude of the coupling voltage. By inspection of the data, the spot-to-plume mode transition appears to take place at lower mass flow rate for increased aspect ratios and at lower mass flow rates for increased discharge currents. This can be explained considering that the increased current density within the orifice facilitates both ion production and ambipolar ion emission. It is worth noticing that no substantial voltage variations between the two configurations can be observed in the operating range investigated. The effect of the keeper current on the discharge voltage is

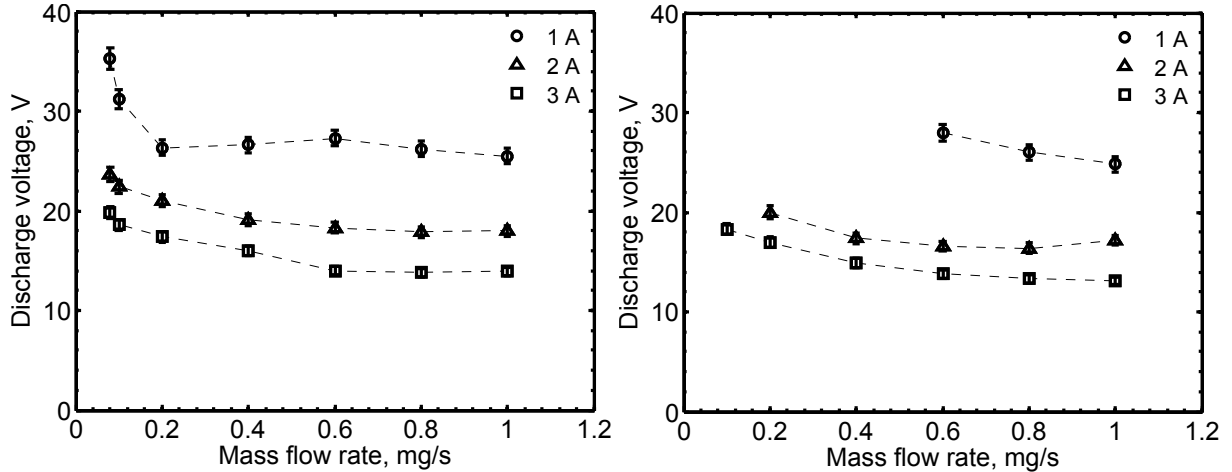


Figure 3. Cathode-to-keeper voltage as a function of the mass flow rate. left: AR=1.2 - right: AR=0.9.

shown in Figure 4. As expected, the discharge voltage slightly decreases for increasing keeper currents. The negative slope in the V-I dependance reveals a reduction in the diode impedance, $Z_d \sim 1/I_d$. This trend can be attributed mainly to a reduction in the plasma-emitter sheath potential. As a matter of fact, an increase in discharge current requires a higher emitter temperature, which is determined only by the ion energy flux toward the emitter surface. From a first-order perspective, the plasma-wall interaction phenomena can be described by the current and power balance equations at the emitting surface. By combining these two equations, the resulting expression writes

$$j_i \left(V_c + \varepsilon_i + \frac{2k_B T_e}{q} \right) = j \left(\varphi^* + \frac{2k_B T_e}{q} \right) + j_{em} \left(\frac{3}{2} \frac{k_B T_w}{q} - \frac{2k_B T_e}{q} \right) + \varepsilon_w \sigma T_w^4 + \kappa \frac{T_w - T_b}{L_c}, \quad (1)$$

where j_i is the ion current density collected at the cathode surface, j_{em} is the thermionic current density, j is the total current density, V_c is the sheath voltage, ε_i is the Xe first ionization energy, φ^* is the emitter effective work function and T_w is the emitter temperature assumed to be in thermal equilibrium with the heavy species, namely $T_n = T_i = T_w$. Equation (1) states that an increase in emitter temperature can be achieved either due to an increase in the energy of the ions striking the wall, i.e. increasing V_c , or by an increase in electron temperature and plasma density, i.e. increasing j_i , without changes in the sheath potential. However, an increase in the potential difference leads to a higher ion energy flux delivered to the emitter wall and thus to an increased thermionic emission and electron energy. Since the ionization results from the discrete energy deposition of the emitted electrons colliding with the neutrals, the increased electron energy leads to a higher plasma density. As a consequence, in order to maintain the required ion energy density toward the emitter, the sheath potential must decrease. All in all, the global effect of an increased discharge current is a reduction in the plasma-emitter sheath voltage after a transient time in the order of the characteristic time for plasma ionization, namely $\tau_i \sim 10^{-6}$ s.

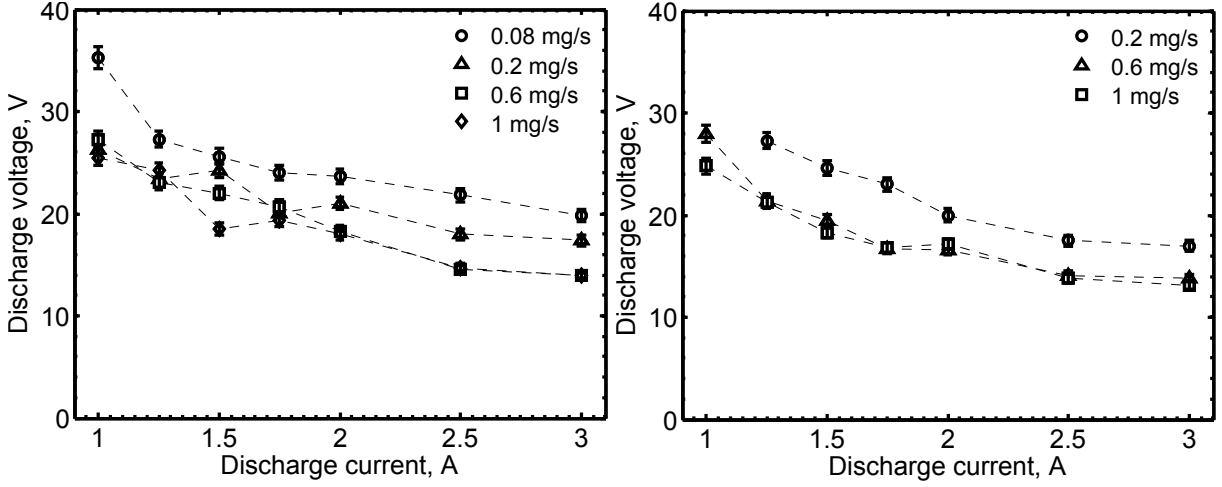


Figure 4. Cathode-to-keeper voltage as a function of the discharge current. left: AR=1.2 - right: AR=0.9.

Figure 5 and Figure 6 show the cathode power consumption as a function of both mass flow rate and discharge current, respectively. The power consumption is found to vary approximately in the 25-60 W range with a minimum at 1 mg/s and 1 A, independently of the aspect ratio. In order to better understand the experimental results, it is possible to roughly estimate the potential drop across the orifice. As a matter of fact, considering an electron temperature of about 1 eV and an ionization fraction higher than 1%, the plasma resistivity is $\eta \simeq 5 \times 10^{-2} \Omega\text{cm}$ while the channel resistance is given by $R = 4\eta/\pi \cdot AR/D_o$. Thus, the potential drop along the orifice is $V_{or} < 8$ V and change in aspect ratio accounts for only a $\Delta V_{or} \simeq 3$ V, namely 5 – 10% of the total discharge voltage.

For a Hall effect thruster operating in the 100-300 W power range, the present cathode requires a non-negligible fraction - between 8% and 25% - of the available power and operation without the keeper is expected to mitigate the power loss. However, considering the typical discharge currents of a low-power HET, the self-heating due to ion bombardment may be insufficient to sustain extended cathode operations or may result detrimental to thruster performance (increased coupling voltage). As a consequence, careful thermal management and design optimization are definitely needed to extend spot-mode operations of the present cathode.

The experimental campaign included measurements of the time-dependent voltage signals, which were processed to obtain power spectral densities in the frequency domain. The cathode geometry chosen for this analysis featured the AR 1.2 orifice, allowing to test a broader range of mass flow rates with respect to the AR 0.9 orifice. Three operating points were selected at the boundaries of the investigated operative envelope to assess the dependence of individual changes in both discharge current and mass flow rate. Illustrative results are reported in Figure 7, which refers to the cathode operated at 3 A and 1 mg/s. The signal shows a peak-to-peak voltage of about 4.5 V, whereas the estimate of the power spectral density displays no significant remarks. By decreasing the mass flow rate to 0.08 mg/s, the peak-to-peak voltage increased

to about 8 V at 3 A and about 11.2 V at 1 A. Despite the Brophy criterion¹¹ suggests that the cathode operated in plume mode, no signs of unstable behavior were detected by inspection of the power spectral density. As a matter of fact, the signals were found to be quiescent in all the test cases without the typical voltage oscillations in the 50-1000 kHz range as reported by Goebel.⁴ It is interesting to note that all the spectra display a $1/f^\alpha$ characteristic fall over a range of frequency above 10^{-1} kHz, with $1 < \alpha < 2$. The spectra deviate from this trend at lower frequencies, but these deviations are of less interest for the cathode behaviour than the high-frequency spectra. The superimposed fit line on the power spectrum corresponds to the function $1/f^{1.9}$, indicating a fractional Brownian motion.

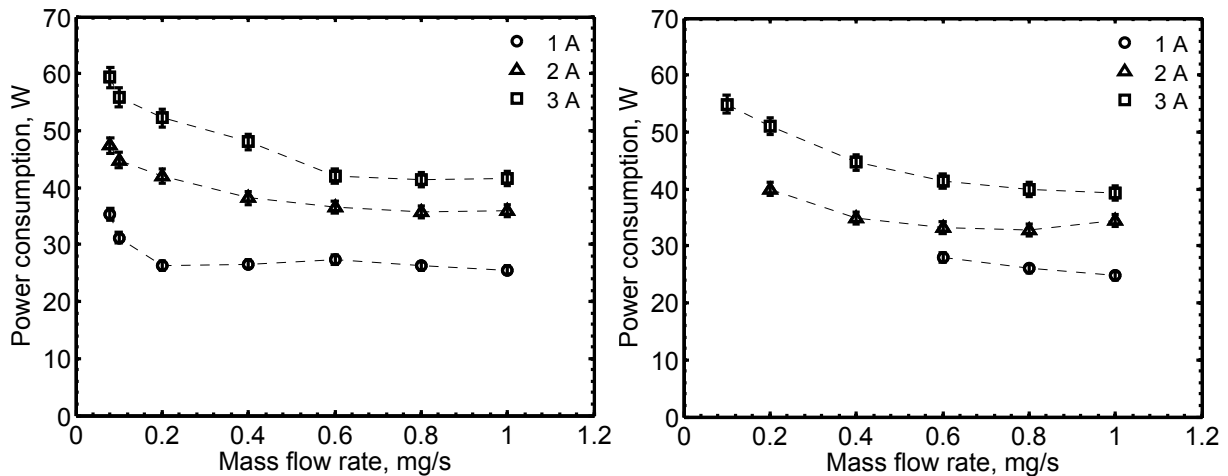


Figure 5. Power consumption as a function of the mass flow rate. left: AR=1.2 - right: AR=0.9.

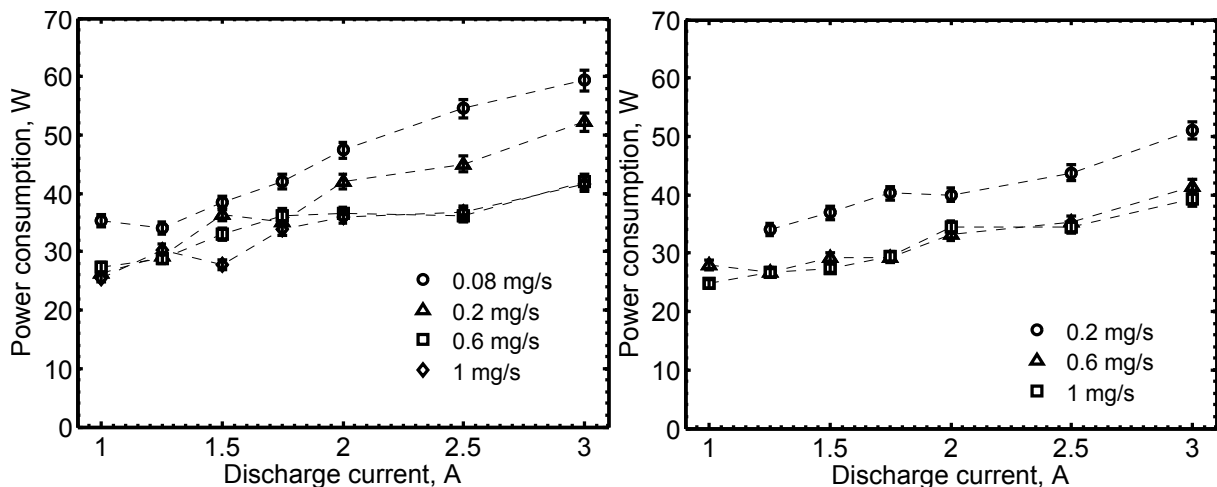


Figure 6. Power consumption as a function of the discharge current. left: AR=1.2 - right: AR=0.9.

B. Post-Test Visual Inspection

As discussed previously, the most common cathode life-limiting factors include cathode failure-to-start due to emitter contamination, heater failure and keeper-to-cathode common shorting. In addition, wear mechanisms such as orifice clogging, orifice erosion and keeper erosion due to direct beam ion impingement might deteriorate the cathode performance. In order to assess the effect of extended operations on the main components, post-test inspection of the cathode assembly was performed after approximately 50 hours of operation and more than 100 cold ignitions. Optical inspections of the insert, orifice plate, cathode tube, keeper assembly and insulators were performed. The post-test condition of the LaB₆ inserts was documented after

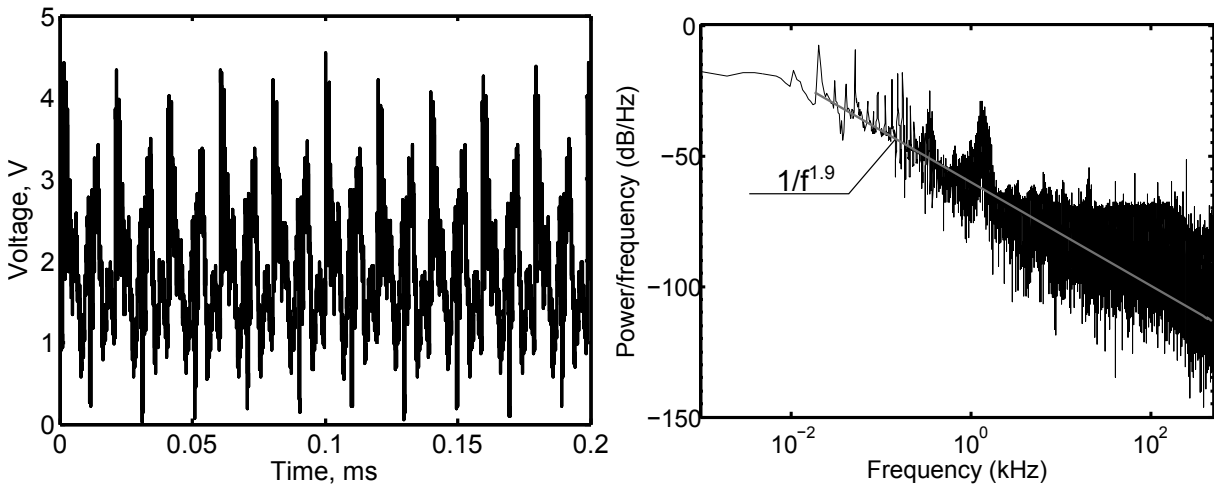


Figure 7. left: Keeper voltage vs time at 1 mg/s-3 A. right: power spectral density.

removal from the cathode tube. The post-test condition of the exterior can be seen in Figure 8-left. The external surface of both the emitters appears to be almost intact while the surface exposed to the plasma presents a thin and diffused layer of graphite. The graphite layer was found to be mostly located at the rear emitter where the temperature is expected to be lower than the tip temperature. Careful visual inspections revealed heavy graphite depositions at the external rim of the orifice plate as detailed in Figure 8-right. No substantial geometrical variations of both the emitters and the cathode orifice were detected. However, a longitudinal fracture was observed in the downstream graphite sleeve. No evident erosion patterns or defects were detected on the cathode tube, except for a net deposition on the interior. Minimal but measurable impedance degradations of the keeper-to-cathode insulator was experienced during the test. This effect is supposed to be tied with a partial deposition of either refractory metals from the cathode and keeper tubes or graphite from the spacers and sleeves on the downstream surface of the insulator. In summary, preliminary findings indicate that the downstream emitter maintained an emitting surface free from graphite layers and that thermal-shocks of the emitters at the cathode ignition seem not to be a critical issue so far. Design changes will be implemented to reduced ceramic degradation and black covering of the thermionic emitters.

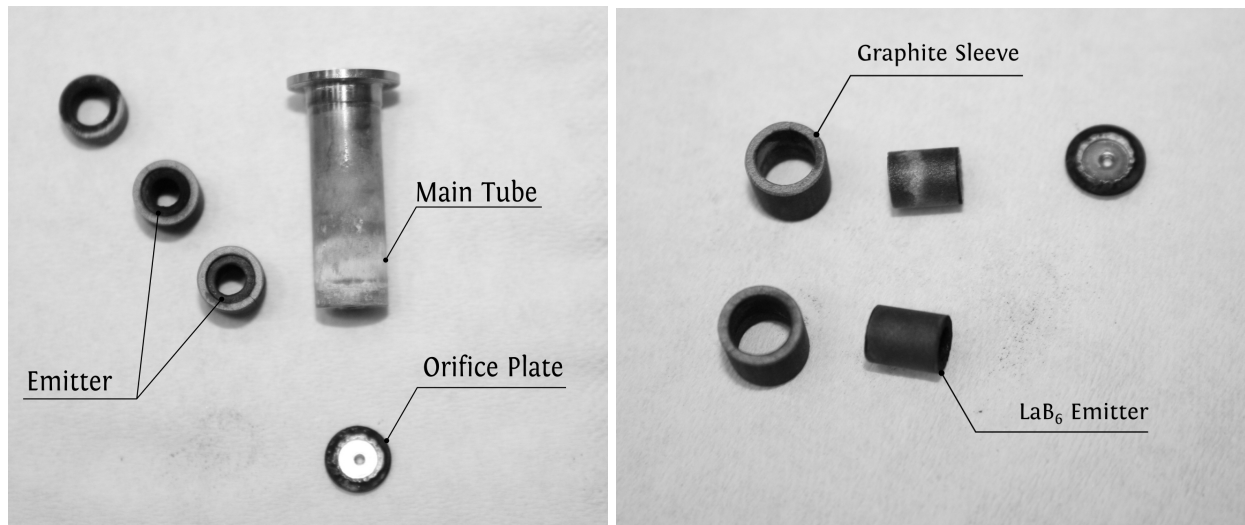


Figure 8. left: Cathode main tube and internal components. right: Orifice plate, LaB₆ emitters and dedicated diffusion-barriers.

IV. Conclusion

A LaB₆ hollow cathode was developed by Alta to investigate the typical low-current and low flow rate regime of 100-300 W HET. The cathode was tested with two different orifice plates to assess the effect of the aspect ratio on the overall performance. The discharge voltage was found to be relatively insensitive to the mass flow rate in the investigated range ensuring spot-mode operation. Performance characterizations also indicated that the aspect ratio variations have no significant effect on the total power consumption.

Improvements in the thermal and mechanical design of the cathode are in progress with the aim of reducing the power consumption as well as extending the spot-mode operation of the cathode. Further investigations will also include time-resolved plasma measurements in order to refine the theoretical model developed by Alta to predict the operation of rare-earth hollow cathodes.

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