Experimental Testing of a High Current Lanthanum Hexaboride Hollow Cathode

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In a collaboration between Pulsar Fusion LTD and the University of Southampton's Astronautics Group, we have worked on the design, manufacture and testing of a high current hollow cathode. The cathode is designed for operation with Pulsar Fusion's 8 - 15 kW Hall thruster, as well as nominally with their smaller approximately 1kW Hall thruster. Hall effect thrusters and gridded ion thrusters both require an external source of electrons for operation, this source of electrons has been historically provided by an external cathode. Here a commercial prototype high current external heated hollow cathode has been tested in both diode and triode configurations. This testing intends to investigate the present capabilities of the design. These preliminary tests of this prototype cathode will attempt to operate the cathode up to 100 amp of discharge current; the design is capable of supplying in-excess of 150 amps at an insert temperature of 1700 ^{o}C. The cathode will be operated using krypton as the propellant and have the transient current output recorded with a high frequency oscilloscope.

Nomenclature

A = Cross-sectional area, m^2
D = Material specific Richardson-Dushman constant, A cm^{-2} K^{-2}
e = Elementary charge
J = Current density, Acm^{-2}
k = Boltzmann constant
L = Length, m
T = Temperature, K

ρ = Electrical resistivity, Ωm
ϕ_0 = Work function, eV
Ω = Electrical resistance, Ω

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I. Introduction

Electron sources are a pivotal technology for enabling many forms of electric propulsion. Namely, Hall effect thrusters and gridded ion thrusters which utilise electron sources for both ionisation and neutralisation of the thrust producing ions. Cathodes are a type of electron source used in electric propulsion where a thermionic material is used, normally heated, to emit electrons at a desired rate. Historically the simplest of these were coiled tungsten or tantalum filament wires, which would be resistively heated to a temperature where electrons are emitted [1]. Typically, around 2300 K to achieve current densities of the order of 1 A/cm^2 [2]. However, the lifetime of these systems was very short due to the material evaporating and limited in their use due to the low extractable current. Moreover, the heating power to achieve these temperatures often massively exceeds the extracted power making these systems inefficient and unattractive for in space use [2].

Several of the short comings of these initial electron sources were resolved with the advancement of hollow cathode technology and the discovery of other thermionic emission materials with more desirable work functions. These insert materials, such as cerium hexaboride (CeB_6), barium oxide (BaO-W) and lanthanum hexaboride (LaB_6) to list some examples, also require heating but have the ability to reliably provide larger currents than was traditionally achievable with filament cathodes [2, 3].

Hollow cathodes are a very mature technology with flight heritage almost as long as electric propulsion in space, as well as extensive use in laboratories for electron guns. Whereas the majority of these have been in single to tens of amp range, only recent developments in the last few decades at NASA and some others have ventured into hundreds to several hundreds of amp cathodes [4–7].

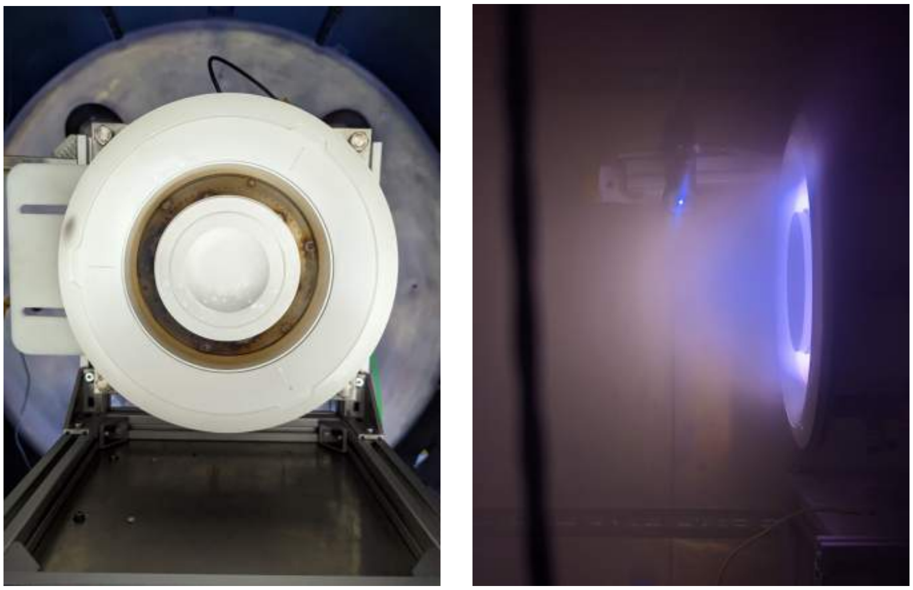
Lanthanum Hexaboride was first developed in the 1950's by Lafferty alongside other boride compounds [8]. With this development largely enabling higher power electric propulsion systems to be designed and operated with some of the earliest Hall effect thruster utilising a LaB_6 cathode [9]. The was to understand the current extraction capabilities of cathode materials is via the work function, a value that relates the temperature of the material and the extracted current [1, 2]. LaB_6 whilst having a relatively high work function, than some other insert materials, is very robust to poising and erosion. This is most unlike the dispenser type of cathode which utilise a reservoir of a chemical mixture that once at the surface of the emitter undergoes a chemical reaction that results in a very low work function. However, these low work function dispenser cathodes are highly susceptible to poisoning from moisture and impurities in the working gas; as these interfere with the chemical reaction, resulting in an increased work function. As it is purely the internal crystal structure of LaB_6 that is responsible for the emission of electrons it is highly resilient to poisoning, even being able to operate with background O_2 levels of approximately 1.3e-4 mbar [10].

Moreover, in the application to high current hollow cathode, dispenser cathodes can suffer from the rate of consumption or evaporation of the dispenser chemical mix required for the low work function becoming greater than the porous flow at high temperatures. This limits the operation emission temperatures and the maximum extractable current of the dispenser type of cathode. However, LaB_6 does not require a chemical process and as a result can be operated at significantly higher temperatures and emission densities. As a result, making them well suited for the application of high current hollow cathodes [1].

A. Motivation

Hall effect thrusters are currently the most utilised form of spacecraft propulsion flown in space today, with no signs of this changing in the near future [11, 12]. With the continued and significant expansion of the space market, satellites have grown in number and size, increasing the maximum power available to sub-systems [12, 13]. With the increased power expected to be available to satellite platforms in the near future, propulsion systems capable of meeting these possibilities need to be developed.

Here the **Pulsar Fusion LTD** has collaborated with **University of Southampton**'s astronautics group to test a series of newly developed Hall thrusters and a high current cathode, the focus of this paper. The high current capable heated hollow cathode has been developed by Pulsar Fusion intended to support the high power HET designed to fill this development gap. The large accompanying Hall thruster, designated the **BN500**, can be seen in Fig. 1.



(a) The BN500 Hall thruster mounted in the large vacuum chamber. **(b) The BN500 Hall thruster during krypton testing in the large vacuum chamber.**

Fig. 1 The Large Hall effect thruster: BN500, designed in tandem with cathode for joint operation. The testing of the large HET has so far been conducted with a "Model 5000 Hollow cathode electron source" from Iontech and can be seen in Fig. 1b.

II. Cathode theory

The cathode being tested here utilises Lanthanum Hexaboride as the insert material responsible for the electron production. LaB_6 is rapidly becoming commonplace in industry and a research standard for hollow cathodes, however for low current laboratory application BaO-W cathodes are still very attractive [1]. There are several methods of understanding the thermionic emission of the insert material have been developed. The most common method is with the use of the Richardson-Dushman equation which once modified for material specific constants can be described as [2],

$$J = DT^2 e^{-e\phi_0/kT} \tag{1}$$

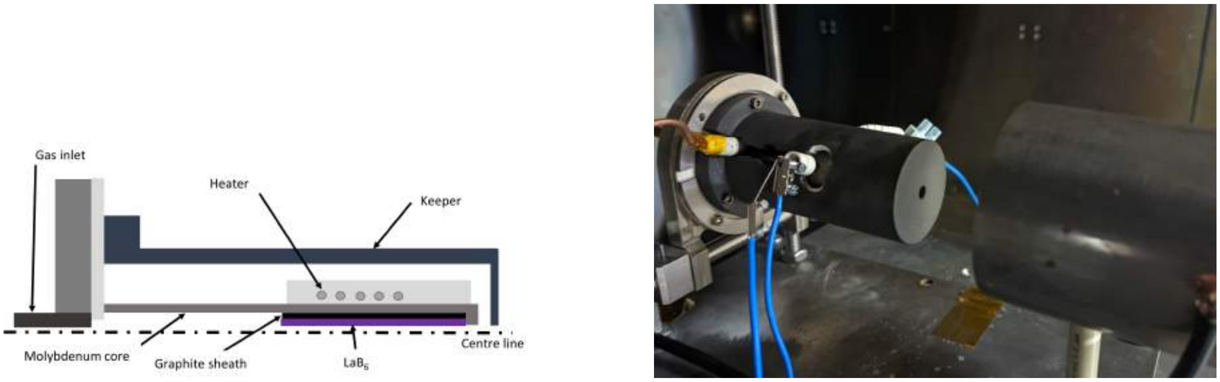
where J is the emission density, D is the material specific Richardson-Dushman constant, T is the insert temperature in kelvin, ϕ_0 is the classical work function of the material, e is the elementary charge, and k is the Boltzmann constant. Traditionally J and D are given in unit of Acm^{-2} and $Acm^{-2}K^{-2}$ respectively. This equation allows, for a known material, to form a relation between the temperature of the insert and the emission density. For LaB_6, D is taken as 110 $A/cm^{-2}K^{-2}$ and ϕ_0 is taken as 2.87 eV [2, 14].

III. Heated cathode design

A. Insert

Pulsar fusion's heated hollow high current cathode designated the **G100**, utilises a large LaB_6 emitter surface with an internal diameter of 6 mm and a length of 50 mm. Resulting in a total emitter area of 9.42 cm^2, whilst it is unreasonable to expect the entire surface to be emitting due to thermal gradients causing uneven heating and plasma effects [15]. However, this area can be used to suggest a maximum theoretical extractable current, by using Eq. 1 and an assumed temperature of 1700 ^oC, results in a current of 188.2 A. Moreover, at an assumed temperature of 1500 ^oC the expected emittance would be approximately 22 A.

The insert is held in place by a pusher and a spring whilst enclosed in a thin graphite sleeve. The whole assembly is housed within the refractory metal Molybdenum (Mo) cathode tube.



(a) High current hollow cathode cross section (not to scale).

(b) The G100 cathode prior to testing; mounted in the large vacuum chamber at the University of Southampton.

Fig. 2 The G100 Hollow cathode developed by Pulsar Fusion LTD.

B. Cathode tube

The design also features a molybdenum cathode tube with a graphite sheath for the LaB_6 insert to prevent boron diffusion embrittling the cathode tube and effecting the LaB_6 quality [1]. The orifice of the cathode tube is held in-place by the pressure applied from the insert that results from the pusher spring at the base. The orifice plate has a diameter of 6 mm, the same as the LaB_6 insert making this design orifice-less as there is no constriction of the plasma around the insert. This decision will reduce the gas and plasma pressure in the insert region and will certainly have an impact on the heating mechanisms of the LaB_6 insert [2].

C. Keeper

The keeper electrode is manufactured from a solid graphite piece providing a low splutter yield making it ideal for the large discharge currents [1, 16]. The low splutter yield will ensure that the keeper orifice geometry changes at a minimal rate over the lifetime of the cathode. Moreover, cathode lifetime becomes an issue of concern for high current cathodes as there is significant ion bombardment that can erode away cathode components in high current discharges[10].

Moreover, the use of graphite also avoids issues with material incompatibilities due to the low reactivity of the material even at extreme temperatures. The keeper orifice diameter is also 6 mm, making the aspect ratio between the insert, cathode tube orifice, and the keeper 1:1:1.

D. Heater

The heater of the cathode is required to get the insert to emission temperatures and historically is the largest point of failure within hollow cathode designs. Here a co-axial tantalum (Ta) magnesium oxide (MgO) heater is used. These heaters are common in cathode design due to the compact nature and the benefits brought from having the terminals of the heater existing on the same end [1].

Within this design the heater is coiled around a boron nitride (BN) spool that mounts to the outside of the cathode tube; there is also an outer sheath of boron nitride that aims to reduce radiative losses of the heater to the keeper during operation. This design currently forgoes the use of additional refractory metal radiation shielding which are common in other designs [1]. This was done due to the heater cable for these tests being routed through the side of the keeper and such would interfere with these shields. However, a heat shield was in original intended for use within this design.

Several initial heater tests were undertaken prior to any attempt to ignite the cathode. This was done with the intent to understand the thermal paths of the cathode when the heater was operated. These tests were done with and without the BN sheath which was seen to greatly improve the effectiveness of the heater. One of these tests can be seen in Fig. 3, where thermocouple reading of various parts of the cathode were taken and the heater connection can be clearly seen. This connection was later modified, by shortening, to reduce the amount of the heater that was external to further reduce radiative losses related to the connection.

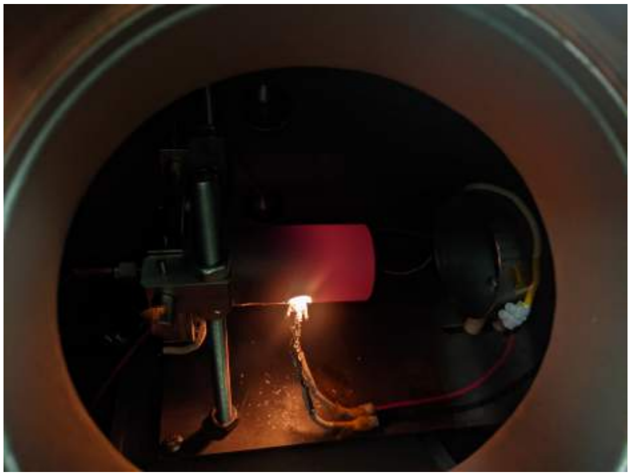


Fig. 3 The G100 in the micro propulsion chamber at The University of Southampton undergoing a preliminary heater test. Heater cable connection routed through the keeper can clear be seen due to the viable emittance.

IV. Experimental set-up and data collection method

A. Approach

The Cathode was tested experimentally with and without an external cylinder type anode in triode and diode configuration respectfully. These tests were undertaken within both the micro-propulsion and the main vacuum chambers at the University of Southampton. Transient current of the insert was recorded with a high frequency oscilloscope, along with several thermocouple measurements of external non-electrical components of the cathode. This data will be used to better understand optimal operation of this high current cathode for a range of neutraliser applications.

B. Vacuum chamber facilities

1. Micro-propulsion chamber

The micro-propulsion chamber facility at the University of Southampton has a base background pressure of 3.3e-5 mbar and expected operational background pressure of 5.9e-4 mbar at flows of approximately 15 sccm of xenon. This chamber is primarily used for testing of non-gaseous propulsion systems such as vacuum arc thrusters, electrospray thrusters, etc. and makes use of a single diffusion pump to maintain its vacuum. This chamber was used for some preliminary testing of the heater and some attempts of ignition. The background pressure of the chamber was measured over a range of input propellant flow rate to understand the limits of the flow that could be tested in this limited set-up. The result of one of these tests can be seen in Fig. 4.

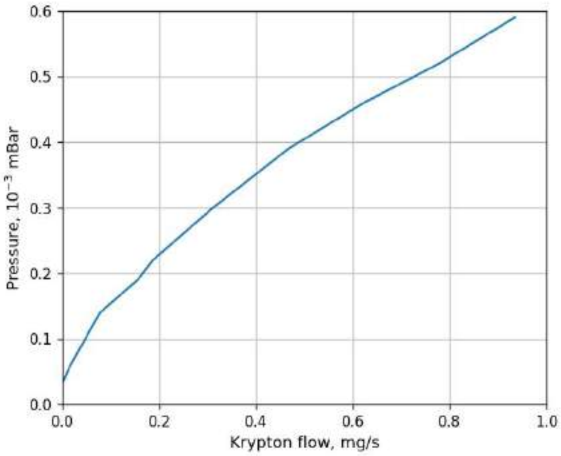


Fig. 4 The pumping capacity testing of the out-gassing chamber with addition of krypton propellant.

Here it can be seen that at flow rates greater than 0.8 mgs^{-1} the pressure will exceed 6e-4 mbar, which is greater than the background pressure at which contaminants could begin to poison the cathode [10]. For this reason, only zero or very low flow testing would be undertaken within this chamber.

2. Large vacuum chamber

The large vacuum chamber facilities at the University of Southampton, as seen in Fig. 5, features a 2.0 m diameter and 4.5 m length internal chamber. Equipped with a single Oerlikon Leybold LV140C roughing pump, two Coolpower 140T cryo compressors and two Coolpack 6000H 20K cold heads, and two MAG W 2200 iP magnetically levitated turbopumps. With a maximum achievable vacuum of <9.0e-8 mbar and can be operated at pressures of <5.0e-5 mbar with 28 sccm of xenon injected.

Fig. 5 The large vacuum chamber at the University of Southampton.

The experimental set-up used for both the triode and diode testing can be seen in Fig. 6. The set-up was unchanged for both triode and diode attempts, with the diode tests being run without powering the anode. Data collected was primarily the current draw measurements of the insert material from the ground. This was done using a high frequency oscilloscope, the Teledyne WaveSurfer3024 using a 150 A rated CP150 current probe. The oscilloscope was used to measure the current draw as well as the high frequency behaviour.

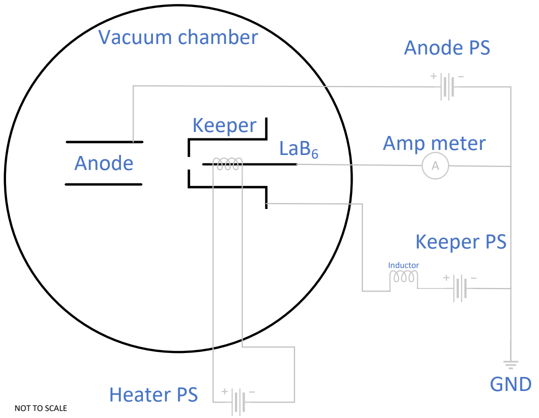


Fig. 6 Electrical and data collection set-up for ignition testing within the large vacuum chamber at the University of Southampton.

V. Preliminary heater testing

The first tests conducted with the cathode were done within the micro-propulsion vacuum chamber and aimed to assess required heater powers for ignition. This was conducted by placing thermocouples on the cathode, the placement was changed between tests to focus on specific locations. As previously discussed, the first of these tests were conducted without the BN heater sheath. These tests suffered from large heat losses from internal thermal radiation of the heater to the keeper.

Fig. 7 Thermocouple data for preliminary heater tests of the G100 without the internal BN heat shield. Minor noise can be seen on the thermocouple readings, this occurred when slight arcing occurred within the chamber and effected the thermocouple reading.

As can be seen in Fig. 7, the power draw of the heater to achieve relatively low temperatures is huge. Peak power draw of 362.7 W to achieve temperatures significantly below that of any measurable electron emission. This heater power is significantly more than has been required for previous similarly sized LaB_6 cathodes, for example the 300 A hollow cathode developed for use with the X3 Hall thruster has a heater power draw of 350 W to achieve its high current discharge [1, 17].

The testing was subsequently moved to the large vacuum chamber for some additional heater tests whilst preparing the cathode for ignition testing. These later tests forgo the use of thermocouples and rather opted to infer the heater temperature from measured resistance of the heater during operation. Whilst lowering the confidence in the temperature of the LaB_6, this provided a simplified experiential set-up and avoids issues involving current to the unshielded type-K thermocouples. This operation used the equation,

$$\Omega = \rho(T)\frac{A}{L} \tag{2}$$

Where, Ω, is the resistance, ρ is the resistivity, T is heater temperature, A is the cross-sectional area, and L is the length. As the heater type being used is co-axial, there was no straight forward way to measure A and L. As a result, the resistance of the heater would be measured at room temperature and the value of A/L would be calibrated for. Before heating the resistance of the heater at room temperature was a consistent 0.5 Ω.

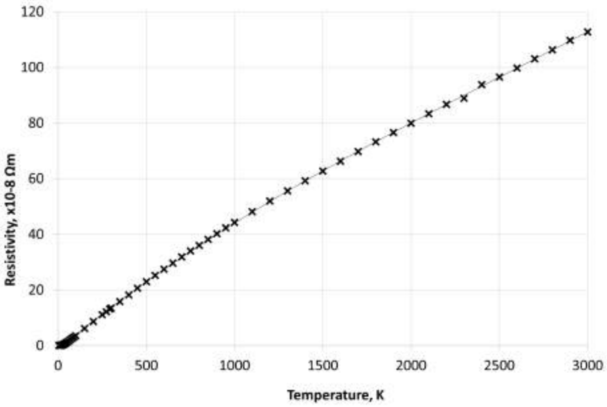


Fig. 8 Resistivity behaviour of Tantalum used for estimating the heater temperature from the measured resistance [18].

With Eq. 2 and Fig. 8, the measured resistance and the known value of A/L at room temperature was used to estimate the heater temperature without the use of invasive thermocouples. However, there is a lower confidence in the temperature of the LaB_6 as the temperature measurement is that of the heater and significant thermal losses are expected between the heater and the insert [18]. With this information further heater testing was conducted within the large vacuum chamber.

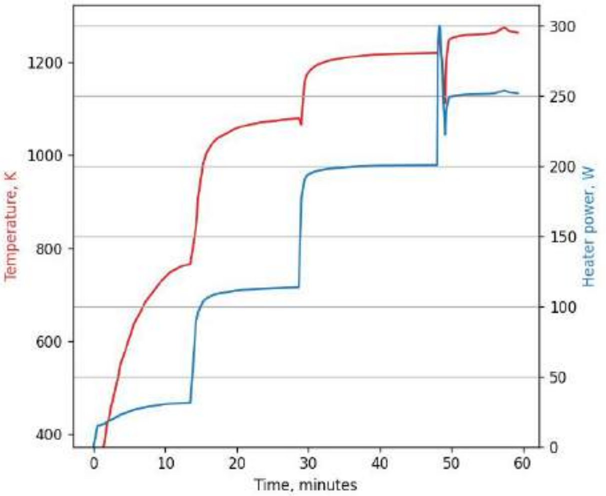


Fig. 9 Interpolated heater temperature against heater power for a heater test run with BN thermal sheath surrounding the heater element.

Later heater testing conducted with the BN thermal sheath showed an improvement in the thermal characteristics. This can be seen in Fig. 9 where significantly increased heater temperatures are recorded for approximately 100 W less heater power than the tests without the sheath as seen in Fig. 7. However, these temperature values are inferred from the electrical resistance from the heater and no longer being directly measured and as such without precise calibration there is relatively low confidence in the temperature reading.

In Fig. 9, A sharp drop in temperature can be seen around the 48-minute mark, this coincided with an increase in the heater current. It is thought that the heaters internal MgO isolator had formed voids or cavities which can be common in these heater types due to the thermal cycling [19]. Once the current reaches a threshold these cavities can become shorting points, dropping the heater power and result in a drop of measured resistance [10].

The issue of the heater power being limited and the thermal paths being relatively uninsulated presented itself as a hurdle moving forward for testing. This is due to the highest temperature the LaB_6 could be heated to prior to ignition was entirely limited to the heater which was limited to an approximate max temperature of 1200 K. Using Eq. 1 again, this temperature would only produce an approximate 1.3 mA.

As a result of the heater tests, it was seen that the insert was unlikely to reach temperatures where significant current emission would initiate easily. As a result, it was concluded that for ignition a large keeper voltage would be required and high internal gas pressures. This would hopefully allow an arc discharge to form that would assist in further heating the LaB_6 insert to the required emission temperatures. The heater tests had allowed the identification of likely ignition requirements, such that a high flow rate gas board and high voltage power supply (PS) was used for the keeper.

VI. Cathode ignition testing

All ignition tests were conducted within the large vacuum chamber using the set-up as described in Fig. 6. The testing was conducted in two phases. The first, low current triode testing where an external anode was used, these tests aimed to understand the ignition behaviour of the cathode. The second testing utilised a higher flow rate controller without an anode to try to achieve higher current extraction.

A. Low current triode tests

Low current testing of the cathode was conducted with krypton propellant. First the heater was turned on and the current raised incrementally until the voltage drop was seen, implying that the heater was at the effective operational limit. This limit is assumed to be due to internal shorting within the co-axial heater. The heater was held at this temperature, on the order of 1200 K to 1450 K, for approximately 10 minutes to allow ensure LaB_6 had time to reach a uniform temperature. Whilst waiting for the LaB_6 to get to a steady temperature a small amount of gas was supplied to the cathode, on the order of 3-5 sccm of krypton, this was done to ensure that LaB_6 had an impurity free environment whilst at high temperatures.

Once sufficient time had elapsed to assume the insert was at equilibrium, the flow was increased for these tests to the flow controller maximum of 28 sccm. The keeper and anode were then powered. For these tests the respective power supplies used for the anode and keeper can be seen in Tab. 1.

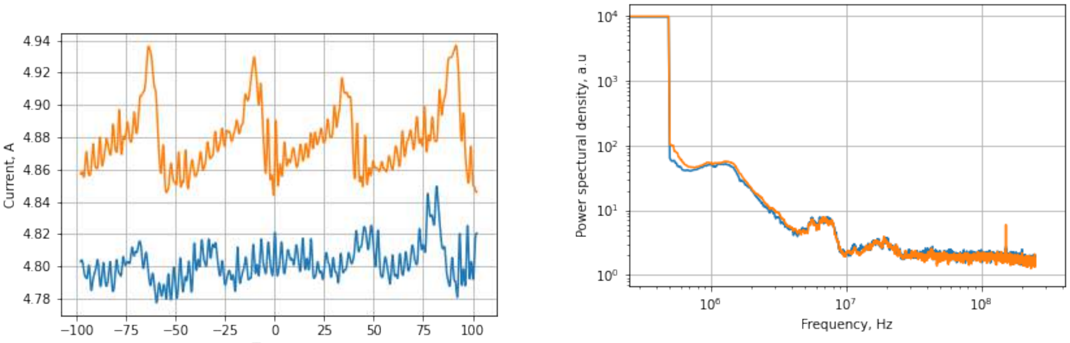
	Voltage, V	Current, A	Name
Keeper power supply	603.4	2.6	Sorensen, XG 600-2.3
Anode power supply	300.3	5.6	Sorensen, XG 300-5.6

Tab. 1 The power supplies and the voltage current values used for testing in triode low flow configuration.

Using a needle valve, the flow controller was bypassed and the flow to the cathode was greatly increased in the attempt to ignite the cathode. This was successful in igniting the cathode but shortly after a plasma was established significant sparking was observed, and the plume would not settle into a stable steady state.

Whilst the cathode was ignited the keeper voltage was a consistent 71.1 V, this is very high for a LaB_6 cathode, where something on the order of 20 - 30 V is more standard [1]. This is likely due to the low-level current emission of the insert with the larger keeper voltage being responsible for the plasma discharge.

During the period of time the cathode was powered several high frequency traces of the current draw by the insert were taken. A plot of these can be seen in Fig. 10a and the fast Fourier transfer of the same runs can be seen in Fig. 10b.



(a) LaB$_6$ current draw for triode testing.

(b) Fast Fourier transfer of the LaB$_6$ current draw for triode testing.

Fig. 10 Data obtained from the cathode current frequency response within low current triode transient discharge.

In Fig. 10, the high frequency oscillation of the emitted current can be seen, showing the emitted current for these tests being approximately 4.8 - 4.9 A, relatively low for the surface area of the LaB$_6$ insert. Using Eq. 1, assuming the entire LaB$_6$ is emitting, this suggests an insert temperature of approximately 1650 K. This value is significantly greater than the estimated heater temperature for these tests.

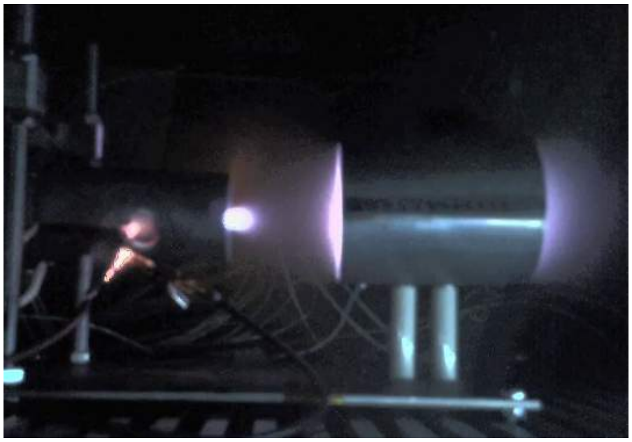


Fig. 11 Captured image of the cathode operating transiently in triode configuration

The majority of this current is thought to be the result of a small portion of the insert being heated by the high-density plasma and or arcs that were formed in the burst gas ignition. This would cause a small portion of the insert to reach much higher temperatures and begin to emit current. This suggestion is somewhat anecdotally supported in the transient nature as once the flow rate returned to the 28 sccm the plasma environment was insufficient to maintain the insert temperatures and the plasma would extinguish.

B. High current diode tests

After the unsteady transient operation of the cathode, it was thought that stable operation might be achieved with the use of a higher voltage PS on the keeper to avoid the need for an unmeasured flow for ignition. The gas flow controllers were also swapped out for a higher flow board with the capability to provide flows in excess of 100 mg/s of xenon.

	Voltage, V	Current, A	Name
Keeper power supply	2000	0.8	MAGNA XR
Anode power supply	-	-	-

Tab. 2 The power supplies and the voltage current values used for testing in triode low flow configuration.

The ignition process of the cathode in diode mode, only keeper powered, is similar to that in the low current triode testing. The heater would be brought up to temperatures, as can be seen in Fig. 12 and held for several minute before testing would begin. The keeper voltage was set to approximately 500 V and incrementally increased with a large flow of krypton propellant supplied to the cathode until ignition was seen. After some initial testing the cathode keeper voltage was held at 2000 V for all subsequent ignitions with the flow rate required being approximately 320 - 480 sccm. Once plasma formation was seen the flow would be reduced to the flow controller's minimum of 128 sccm of krypton. This flow rate massively exceeds that of similar sized cathodes which tend to require approximately 20-30 sccm for >100 A discharges [1, 10].

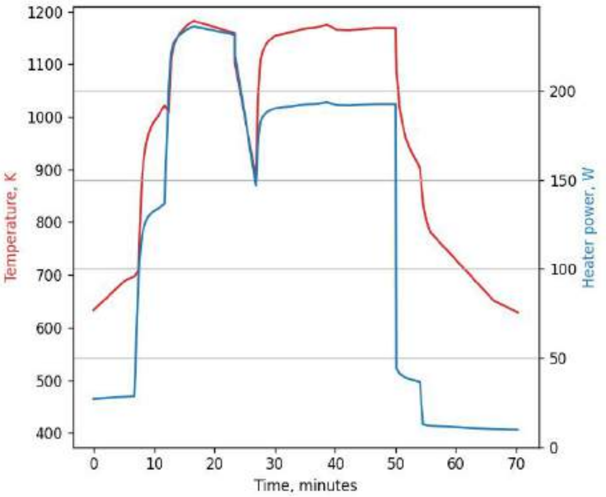
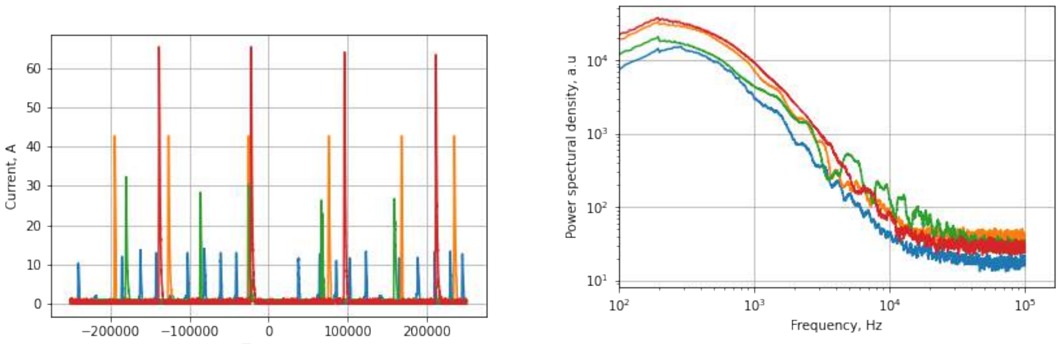


Fig. 12 Interpolated heater temperature against heater power for a diode test run

Unfortunately, steady operation was once again not observed, with the cathode regularly pulsing large discharges. Whilst this extracted current and plasma was pulsing, the keeper voltage and current were constant. This is likely due to the large inductor placed between the cathode keeper and the power supply smoothing the draw of the cathode. This inductor was first introduced to prevent the initial cathode ignition from tripping the power supplies current draw protection. During all high current testing the cathode keeper voltage was 300 - 400 V with a current draw of approximately 0.3 A. The transient discharge was also extinguished if the keeper was un-powered, suggesting that the LaB_6 was not readily emitting electrons.



(a) LaB$_6$ current draw for triode testing.

(b) Fast Fourier transfer of the LaB$_6$ current draw for triode testing.

Fig. 13 Data obtained from the cathode current frequency response within high current diode in pulsed unstable transient discharge.

The oscilloscope measurements of the inserts current draw can be seen in Fig. 13a with the peak current measured to be 64.5 A. The cathode was operating in this pulsed mode continuously at the flow rate provided. However, small sparks were seen being ejected from the cathode orifice and it was feared that this could be damaging parts of the cathode, so this testing was concluded after only several attempts.

Fig. 13b show the fast Fourier transfer of the current draw, with some peaks being viable, particularly in the green trace, within in the 5 - 50 kHz range. However, it is unclear if this is anything to do with the emission behaviour or rather just coupling between the extracted current, the inductor, and the keeper power supply.

With the heater power for these tests being on the range of 150 - 250 W, this would put the cathode on comparable heater power draw as the Hermes cathode [1]. The Hermes cathode was capable of producing an approximately 100 A of discharge current for the same heater power, suggesting there are significant inefficiencies within the current G100 design as stable operation was not achieved and the peak pulsed current drawn was less than that of similar sized cathodes.

VII. Conclusion

Throughout all tests conducted, diode and triode, stable operation of the G100 hollow cathode was not achieved. However, with peak current emitted, in a pulsed manner, of 64.5 A; the sizing of the cathode is clearly capable of high current discharges. It is believed that the primary issue with the current design is the heaters inability to heat the LaB$_6$ insert to temperatures capable of producing a 10 A/cm^2 surface emission density. With the addition of internal heat shield reflectors, common in other cathode designs, and a change in the heater design this cathode or a successive design should be capable of providing a continuous reliable high current electron source.

Acknowledgements

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References

[1] Lev, D. R., Mikellides, I. G., Pedrini, D., Goebel, D. M., Jorns, B. A., and McDonald, M. S., "Recent progress in research and development of hollow cathodes for electric propulsion," *Reviews of Modern Plasma Physics*, Vol. 3, No. 1, 2019, pp. 1–89.

[2] Goebel, D. M., and Katz, I., *Fundamentals of electric propulsion: ion and Hall thrusters*, Vol. 1, John Wiley & Sons, 2008.

[3] Potrivitu, G.-C., Mazouffre, S., Grimaud, L., and Joussot, R., "Anode geometry influence on LaB6 cathode discharge characteristics," *Physics of Plasmas*, Vol. 26, No. 11, 2019, p. 113506.

[4] Goebel, D. M., and Chu, E., "High-current lanthanum hexaboride hollow cathode for high-power Hall thrusters," *Journal of Propulsion and Power*, Vol. 30, No. 1, 2014, pp. 35–40.

[5] Carpenter, C. B., and Patterson, M. J., "High-current hollow cathode development," *Paper No. IEPC-01-274. Proposed for presentation at the International Electric Propulsion Conference*, 2001.

[6] Kubota, K., Oshio, Y., Watanabe, H., Cho, S., Ohkawa, Y., and Funaki, I., "Numerical and experimental study on discharge characteristics of high-current hollow cathode," *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, 2016, p. 4628.

[7] Goebel, D. M., Becatto, G., Reilly, S., Tilley, K., and Hall, S., "High current lanthanum hexaboride hollow cathode for 20-200 kW Hall thrusters," 2017.

[8] Lafferty, J., "Boride cathodes," *Journal of Applied Physics*, Vol. 22, No. 3, 1951, pp. 299–309.

[9] Kim, V., Popov, G., Arkhipov, B., Murashko, V., Gorshkov, O., Koroteyev, A., Garkusha, V., Semenkin, A., and Tverdokhlebov, S., "Electric propulsion activity in Russia," *IEPC Paper*, Vol. 5, 2001, p. 2001.

[10] Becatti, G., and Goebel, D. M., "500-A LaB6 Hollow cathode for high power electric thrusters," *Vacuum*, 2022, p. 110895.

[11] McDowell, J. C., "The Low Earth Orbit Satellite Population and Impacts of the SpaceX Starlink Constellation," *The Astrophysical Journal Letters*, Vol. 892, No. 2, 2020, p. L36.

[12] Lev, D., Myers, R. M., Lemmer, K. M., Kolbeck, J., Koizumi, H., and Polzin, K., "The technological and commercial expansion of electric propulsion," *Acta Astronautica*, Vol. 159, 2019, pp. 213–227.

[13] del Amo, J. G., "European space agency (ESA) electric propulsion activities," *34th International Electric Propulsion Conference, Kobe*, 2015, pp. 4–10.

[14] Jacobson, D., and Storms, E., "Work function measurement of lanthanum-boron compounds," *IEEE Transactions on Plasma Science*, Vol. 6, No. 2, 1978, pp. 191–199.

[15] Guerrero Vela, P. P., Polk, J. E., Richter, M. H., and Lopez Ortega, A., "Dynamic thermal behavior of polycrystalline LaB6 hollow cathodes," *Journal of Applied Physics*, Vol. 130, No. 8, 2021, p. 083303.

[16] Frollani, D., Coletti, M., and Gabriel, S. B., "Flexible LaB6 hollow cathode for lab tests," *34th Int. Electric Propulsion Conf.*, 2015.

[17] Becatti, G., Goebel, D. M., Yoke, C. V., Ortega, A. L., and Mikellides, I. G., "High current hollow cathode for the X3 100-kW class nested Hall thruster," *36th International Electric Propulsion Conference*, 2019.

[18] Desai, P., Chu, T., James, H. M., and Ho, C., "Electrical resistivity of selected elements," *Journal of physical and chemical reference data*, Vol. 13, No. 4, 1984, pp. 1069–1096.

[19] Goebel, D. M., and Watkins, R. M., "Compact lanthanum hexaboride hollow cathode," *Review of Scientific Instruments*, Vol. 81, No. 8, 2010, p. 083504.