Flexible LaB_6 Hollow Cathode for Lab Tests

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Gridded Ion Engines and Hall Effect Thrusters require hollow cathodes to emit electrons that ionize the propellant forming the plasma and to neutralize the positively charged ion beam. A hollow cathode for laboratory use has been developed utilizing an advanced heater technology and lanthanum hexaboride (LaB6) inserts for increased reliability, robustness and ease of use. The experimental campaign shows the flexible performances: discharge current in the range 5A – 45 A with an operating voltage in the range 15 V – 21 V with a heater power of 50 W needed for the switch-on.

Nomenclature

HC	=	Hollow Cathode
LaB_6	=	Lanthanum hexaboride

I. Introduction

HOLLOW cathodes (HCs) are essential elements in the field of electric propulsion: gridded ion engines and Hall effect thrusters require HCs to emit electrons to ionize the propellant (hence forming the plasma) and to neutralize the positively charged ion beam. In addition, hollow cathodes have been studied during the last decade to be used as standalone thruster (Hollow Cathode Thrusters, HCTs) on board all-electric spacecraft for station keeping and safety manoeuvres [1-7]. HCs consist of a hollow cylinder made of a refractory metal (the cathode body), enclosed at the downstream end with a tip with an axial orifice. An electron emitter is positioned against the orifice plate, inside the cathode body. In the region of the emitter, on the cathode body outer surface, a heating element is placed to raise the insert to the emissive temperature, as sketched in Figure 1.

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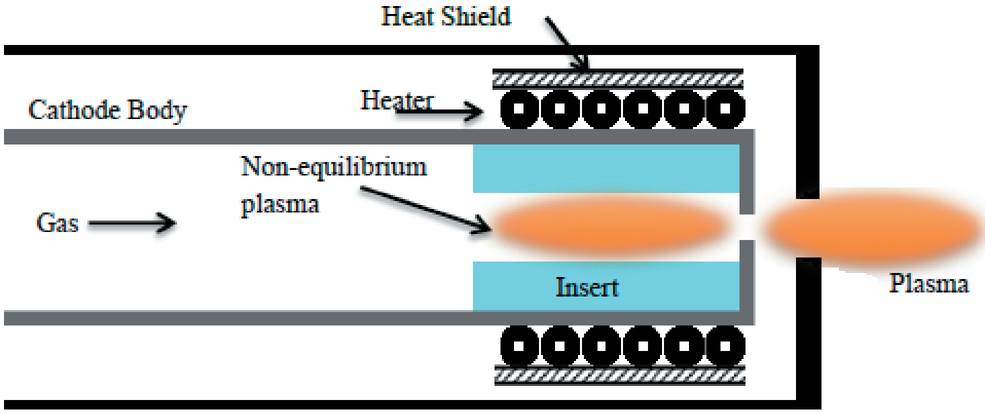


Figure 1. General configuration of a HC

The insert, when heated, thermionically emits electrons that will ionize the flowing gas forming a plasma: the choice of the emitter material and its geometry hence are key criteria for the design of a hollow cathode. The most common emitters used in hollow cathodes for electric propulsion are either impregnated with mixtures containing low work function compounds [8, 9] or are made of LaB_6 [10, 11].

Impregnated inserts commonly employ a porous tungsten matrix impregnated with a mix of Barium Oxide (BaO), Calcium Oxide (CaO) and Aluminates (Al_2O_3) in the proportion 4:1:1 [12]. At temperatures higher than 1000 °C chemical reactions produce free barium at the emitter surface, lowering the emitter work function from that of bare tungsten (4.55 eV [13]) down to 2 – 2.3 eV [12]. Since electron emission is the result of chemical reactions, this type of emitters is subject to poisoning. In particular, water vapour and impurities in the gas can react with the emitter matrix at the working temperature significantly altering the emitter behavior by increasing the work function or preventing the emission [14]. Long outgassing procedures have to be carried out and expensive equipment (extremely pure gas and contaminants traps) have to be implemented when using this type of emitters.

Lanthanum hexaboride inserts are usually made by press sintering LaB_6 powder into a raw shape that is then machined to the final design. In this type of inserts there are no chemical reactions involved, since the bulk material is emitting. This is the main advantages of LaB_6 inserts: little to no susceptibility to oxygen poisoning, hence much lower gas-fed impurity level requirement when compared to impregnated cathodes, and no outgassing procedures required after exposure to air [15]. This is a great advantage during lab tests because of the less stringent facility requirements and shorter cathode ignition procedures that will be particularly beneficial when several openings of the vacuum chamber have to be performed. Moreover the cost and manufacturing time relative to a LaB_6 insert are significantly lower than those relative to conventional porous tungsten impregnated dispensers. On the other hand, LaB_6 inserts cannot be in direct contact with many refractory metals because of chemical reactions at high temperatures (boron diffusion) that will cause embrittlement in the metals. Another drawbacks is the higher work function, about 2.67 eV [16], resulting in a higher working temperature in comparison with impregnated inserts for the same emitted current density.

II. Design

Mars Space is currently developing its own range of hollow cathodes for laboratory use based on LaB_6. This range of hollow cathodes employs an advanced heater technology for increased reliability and robustness, and a modular design for ease of use and to minimize the cost. The first Mars Space Hollow cathode (MSL_HC40) is optimized for a discharge current of 40 A at 20 sccm but it is designed to deliver flexible performance in terms of discharge current (from 40 to 5A) and mass flow rate minimizing the discharge power.

For what concerns the insert, LaB_6 has been preferred over the conventional impregnated tungsten emitter mainly for the advantage of eliminating the long outgassing procedure and using lower-purity gas. As already discussed, this is a key element in ground tests where several configurations have to be tested hence several openings of the vacuum chamber have to be performed. The key criterion for a correct design of the emitter is that its area needs to be sufficiently large to guarantee the emission of the desired current; the cathode to orifice insert ratio is 1.5.

The cathode body, i.e. the tube containing the insert, is made of tantalum and its length to thickness ratio is sufficiently high to minimize the heat conducted from the heater to the cathode base. Moreover tantalum has a melting point of about 3000 °C and lower sputter yield when compared to molybdenum and tungsten [17, 18]. A lower sputter yield generally results in lower orifice erosion, which is one of the lifetime limiting mechanisms.

For what concerns the heater, its design is different from that typically used in impregnated cathodes consisting of a tungsten wire coiled on a ceramic mandrel. This assembly typically has a limit temperature of about 1300 °C because of the ceramic melting point. Moreover thermal cycling can cause embrittlement of the wire. This is particularly important since it can result in potential failures during vibration testing when this is performed after the cathode has been subject to thermal cycling (as it is the case if the HC has been operated to confirm its performances). The new heater assembly is capable of reaching higher temperatures with no chemical reactions or embrittlement of the heating element letting the LaB_6 inserts achieve the higher emissive temperature they require.

The keeper electrode is made in graphite for its low sputter yield and bolted to the base of the cathode with an insulating ceramic to prevent short-circuiting of the electrodes. The hollow cathode is shown in its complete assembly in Figure 2.

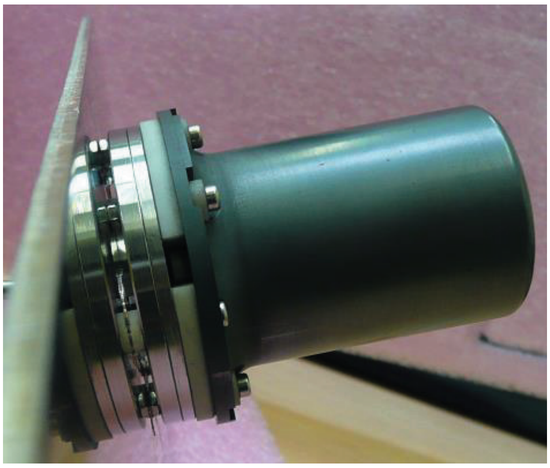


Figure 2. MSL_HC40

III. Test Setup

The cathode was tested at Mars Space electric propulsion laboratory. The hollow cathode was mounted in MSLC-2, an L-shaped vacuum chamber 150 cm long and an internal diameter of 60 cm, shown in Figure 3. The pumping system is composed of a low and a high vacuum system. The low vacuum pumping system consists of an Edwards 35 m^3/h scroll pump, used to bring the chamber pressure down to $5x10^{-2}$ mbar. This pump is also used as backing pump for the High Vacuum Pumping System, which includes a 4,500 l/s turbomolecular pump which can deliver a base pressure of about $7 \cdot 10^{-7}$ mbar and an operating pressure of about $1 \cdot 10^{-4}$ mbar with 20 sccm of xenon.

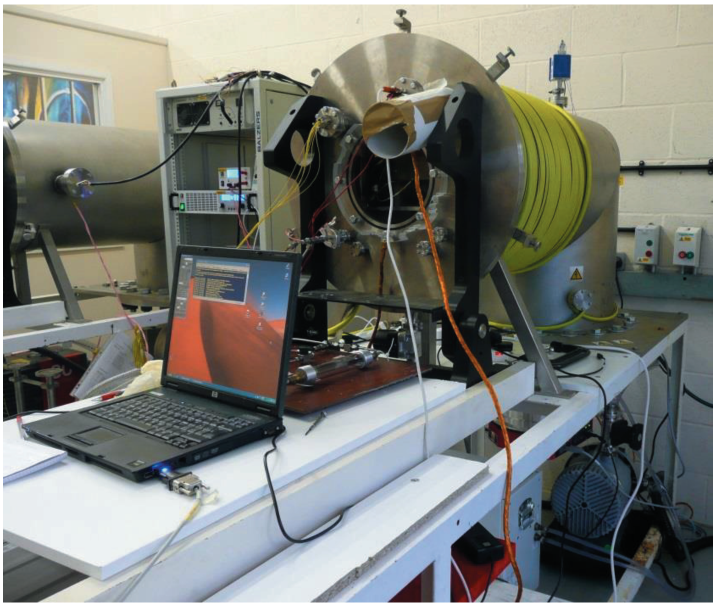


Figure 3. Vacuum chamber MSLC-2 in MSL propulsion laboratory

The fluidic line used to feed the cathode is shown in Figure 4-b. From the cylinder the xenon propellant passes through a gas filter to remove particulate contaminants and then through the mass flow controller that regulates the mass flow rate supplied to the cathode. A series of On/Off valves are in place to ensure that each part of the fluidic line can be evacuated independently, allowing for the change of the xenon cylinder without having to vent the chamber.

To operate the HC electrical connections to the cathode body, the heater and the anode are needed. The number of cables that needs to be passed through the chamber depends on the grounding scheme. In this configuration the cathode is connected to the vacuum chamber that is grounded whereas the heater power supply outputs are floating, as shown in Figure 5-a and Figure 5-b, which are the electric set-up for respectively the first six ignitions and the rest of the test as it will be discussed later on. The cathode was tested in diode mode with the anode plate placed 100 mm away from the enclosed keeper exit plane, as shown in Figure 4-a.

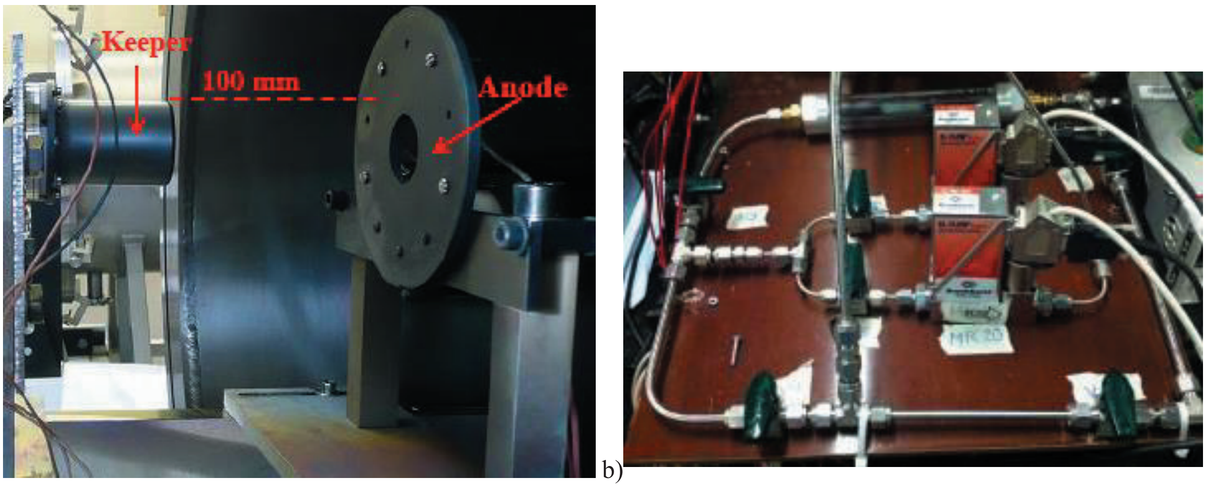
a) 

Figure 4. a)Test setup and b) fluidic Line

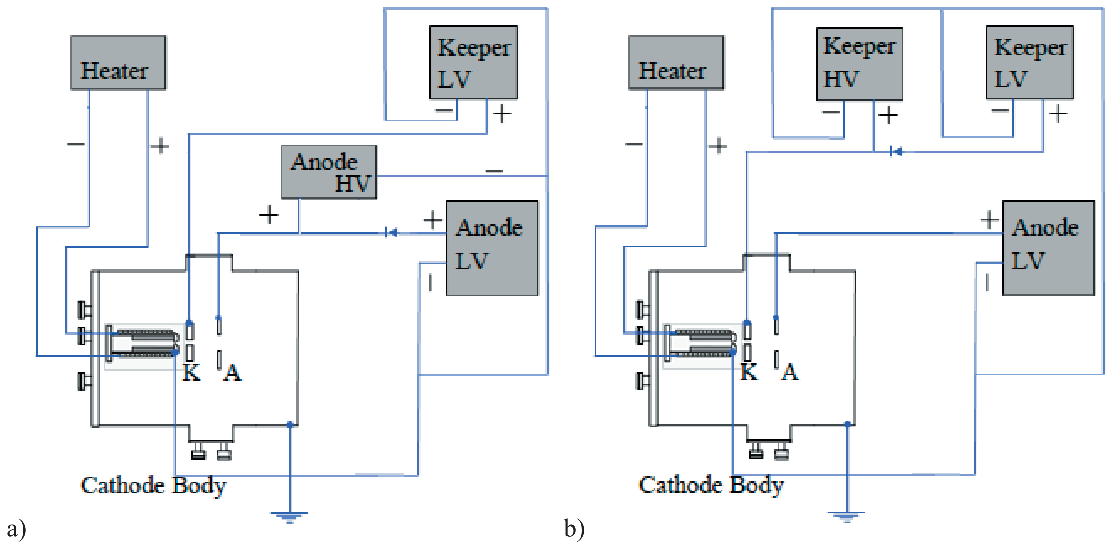


Figure 5. Electric setup a) for first six ignitions and b) for the following ignitions

IV. Performance

The hollow cathode underwent several tests. The objectives of the tests were:

1. to check that the HC was working once assembled;
2. to run the HC for 50 hours at the optimized set-point;
3. to determine the discharge power at the optimized set-point;
4. to determine the working range;
5. to carry out 25 ignition cycles and to identify a suitable ignition procedure.

The first part of the test was to prove the cathode ignition. Two attempts were required to start the discharge for the first time after the assembling. The set-points of the power supplies and the mass flow rate during the ignition attempts are shown in Table 1. It should be noted that the HV power supply was connected to the anode during the first ignition, as shown in Figure 5-a. On the successful attempt, the heater voltage was set to 30 V and the current reached approximately 2.24 A after 15 minutes; the discharge stroke when a pulse of xenon gas of 200sccm was passed through the cathode to increase the pressure between the electrodes.

Table 1. Values for the first ignition

	Value
Keeper LV	80V, 5A
Anode LV	80V, 30A
Anode HV	1000V, 5mA
Mass flow rate	20 sccm
Mass flow rate strike	200 sccm

The second part of the test consisted in a 50-hour diode mode test, which was carried out without the HC showing any unexpected behavior. The value of the discharge voltage during the 50 hour test is shown in Figure 6. In the first 6h the voltage oscillated between 22.5 V and 20.7 V before rapidly decreasing to 16.9 V after 7h30 from the switch-on. For the following 7h30 the decrease in voltage is slower until it reaches the value of 15.2 V, which remained constant for the last 35h before the end of the test and in other following short tests carried out to confirm this value. The initial higher discharge voltage could have been due to the presence of some impurities on the emitter surface, caused by the manufacturing process and by the fact that the insert had not been cleaned for vacuum before its use. The value of the discharge voltage in steady operation is 15.2 V (not corrected for the cable voltage drop) at 40 A and 20 sccm, for a total power consumption of 626 W (inclusive of the power needed at the keeper). The results of this part of the test are summarized in Table 2.

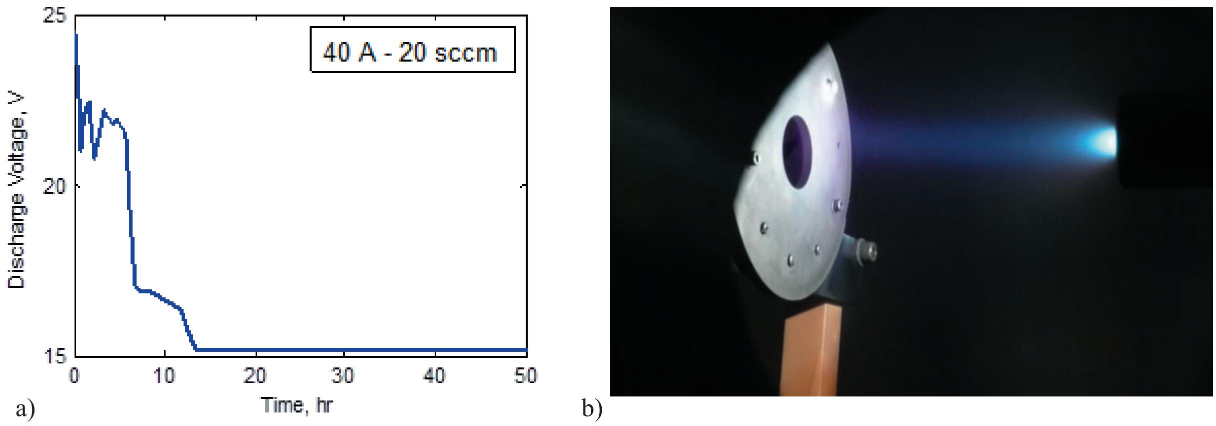


Figure 6. Discharge voltage during the 50 hrs test at 40 A and 20 sccm

Table 2. Optimized setpoint

	Value
Keeper Current	2 A
Keeper Voltage	9.2 V
Anode Current	40 A
Anode Voltage	15.2 A
Mass flow rate	20 sccm

The fourth part of the test was aimed at determining the hollow cathode working range. It was decided to decrease the mass flow rate first, maintaining the discharge current at 40 A at the anode, and then to decrease the discharge current keeping the mass flow rate constant. As it can be seen in Figure 7-a, when the mass flow rate is decreased keeping a constant discharge current of 40 A, the discharge voltage increases. Voltages in the range 15.2V – 18V where obtained for mass flow rates in the range 20 sccm – 14 sccm. The discharge voltage increases also when the discharge current is decreased while maintaining a constant mass flow rate of 20 sccm, as shown in Figure 7-b. In this case the discharge voltage is in the range 20.5 V – 15.2 V for discharge currents in the range 3 A – 40 A. The values for the minimum set-point reached are summarized in Table 3. The trends of the discharge voltage were expected since these are the typical ones shown by hollow cathodes and hollow cathode thrusters [4, 6, 20].

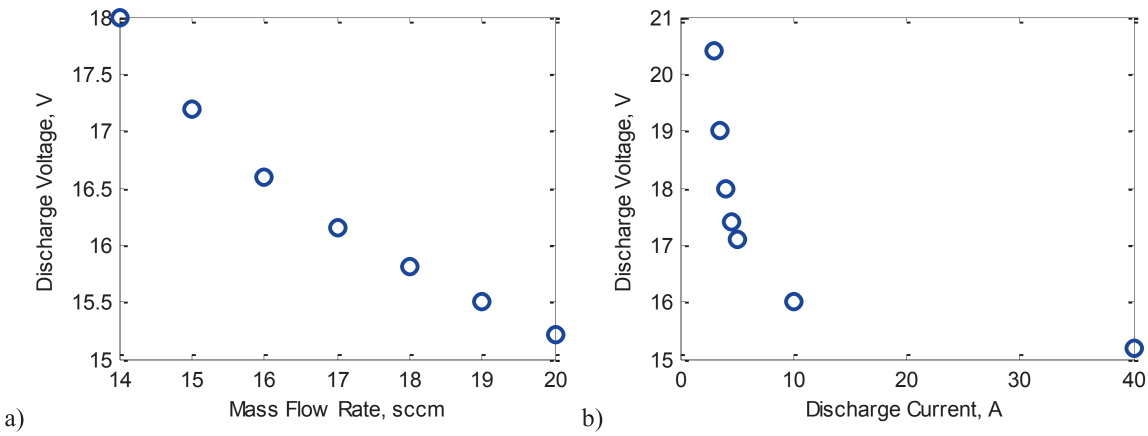


Figure 7. Discharge voltage at a constant value of a) 40 A and b) 20 sccm

Table 3. Minimum set-point

	Value
Keeper Current	1.5 A
Keeper Voltage	17.8 V
Anode Current	3 A
Anode Voltage	20.5 A
Mass flow rate	20 sccm

The last part of the test concerned the ignition procedure. The cathode underwent a total of 25 ignitions, starting from cold, with no particular problems encountered. The HV power supply was connected to the anode, as shown in Figure 5-a, for the first ignition and for the following five. From ignition #7 the HV power supply was connected to the keeper according to the electric set-up in Figure 5-b. The ignition procedure (from ignition #7 on) consisted of several steps:

1. switch the heater on at a fixed voltage of 35V and wait about 15 minutes until the heater current has reached a value in excess of 1.45A;
2. apply the low voltage to the keeper (80V at a constant current of 10A);
3. set the mass flow rate at 20 sccm;
4. switch on the HV keeper power supply already set at 350V (current at several mA) and command a gas pulse of 200 sccm to the mass flow controller;
5. at this point the discharge should start and the HV power supply and heater power supply can be switched off;
6. if for any reason the discharge does not happen, repeat steps 4 and 5 gently increasing the HV voltage.

This procedure was repeated for ignitions #7 to #25, allowing 2 hours for the HC to cool down between the end of an ignition and the beginning of the following one. The ignition of the discharge on the keeper was regularly obtained at every first attempt, a part from one time after exposure to air, when 3 attempts were needed.

V. Lifetime Estimation

The cathode has been designed to deliver 40 A of discharge current with a lifetime in excess of 25,000 hours. For a correct estimation of the insert lifetime, the theoretical HC plasma model developed in-house [7] has been used and coupled with a Comsol™ thermal model to take into account the thermal dissipation via the cathode mounting flange and radiation to the external environment. The lifetime of the insert, neglecting sputtering of the surface, is estimated from its temperature: Running the model the insert temperature of MSL_HC40 at 40 A and 20 sccm was estimated to be about 2100 K, as shown in Figure 8. Considering that the evaporation rate of the LaB_6 at 2100 K is about 4.07×10^{-7} g/cm^2/s [21], the lifetime of the insert has then been estimated to be about 30,000 hours.

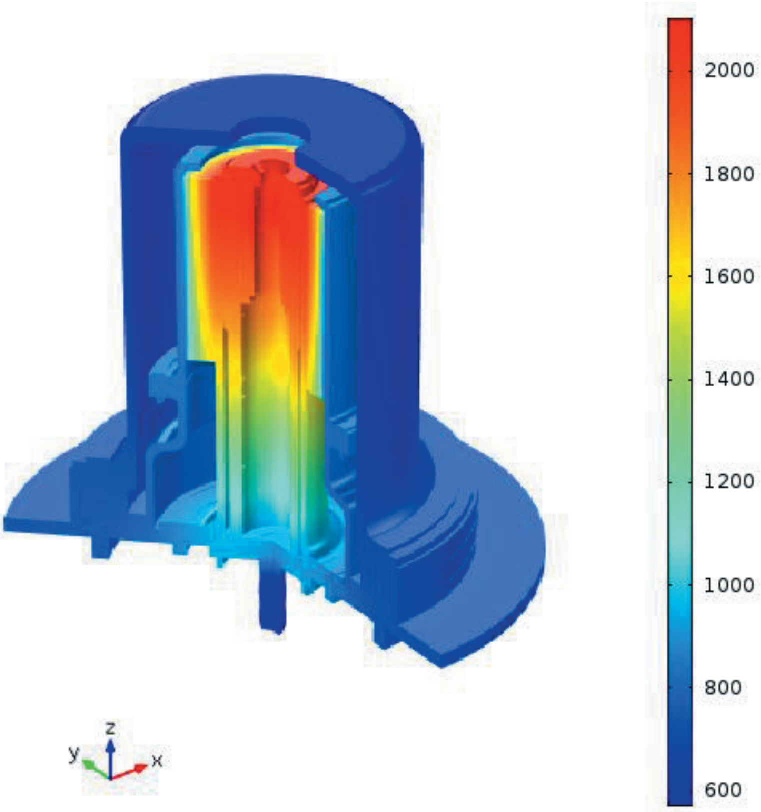


Figure 8. Temperature of the cathode at 40 A and 20 sccm, colorbar in K

VI. Conclusions and Future Work

The first hollow cathode of a future bigger family has been designed, manufactured, assembled and tested. The cathode employs a LaB_6 emitter and an advanced heater technology for increased reliability and robustness, and modular design for ease of use and to minimize the cost. The HC showed good performance (15.2V) at the optimized set-point (20sccm and 40A at the anode).

Future work will include a better assessment of the heater and ignition procedure. The main objective will be that of igniting the discharge without the need of a HV power supply and with no gas pulse. In order to achieve the goal, a higher heater power may be used hence a study on the working range of the heater will be carried out. The orifice diameter to insert diameter ratio and the distance between the electrodes will also be optimized to ensure the use of a lower ignition voltage.

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