5-100 A LaB6 Hollow Cathodes for High-Power Hall Thrusters

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Abstract: The demand of high-power electric propulsion system for the next generation of Earth observation satellites or interplanetary missions is growing towards the space agencies and industries. In this scenario SITAEL is actively developing Hall thrusters in the power range between 5 and 20 kW, and the dedicated hollow cathodes, with discharge current varying in the 5-100 A range. One critical aspect in the Hall thrusters' development programs at SITAEL includes the life demonstration at up to 2000 hours of operation with krypton. In preparation of this long test, we demonstrated the feasibility of the cathode to operate with both xenon and krypton at the operating points required by the thrusters. The latest cathodes upgrades regard the improvement of the heater design and the plume plasma parameters measurements with triple Langmuir probes with the cathodes operating in xenon and krypton as main propellant.

Nomenclature

n	=	plasma density
T_e	=	electron temperature
V_{GP}	=	plasma potential with respect to ground
CRP	=	cathode reference potential
TC	=	thermocouple

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I.Introduction

HIGH-CURRENT lanthanum hexaboride (LaB_6) hollow cathodes have been under development at SITAEL for many years to be coupled with the next generation of high-power Hall thrusters, suitable for space exploration and transportation missions as well as Earth observation satellites, requiring a lifetime in the order of 10^4 hours[1-5].

LaB_6 is characterized by a work function of 2.67 eV[6], and, consequently, the operating temperature of the LaB_6 emitter to provide a current density in the order of 10^5 A/m^2 is about 1,600 °C[7]. Despite the high operating temperature of the boride compound, LaB_6 was selected for its low evaporation rate and low sensitivity to contaminants and air exposure. Moreover, LaB_6 cathodes have been used with many different propellants, as all the noble gases, reactive gas like hydrogen, condensable propellant like lithium and a variety of additional material. Additionally, a LaB_6 cathode guarantees higher current density and longer lifetime capabilities with respect to conventional impregnated cathodes.

An important aspect currently under evaluation at SITAEL regards the identification of propellants alternative to xenon for long-duration tests. Krypton has raised lot of interest as a propellant[8,9], since a transition from xenon-fed optimized propulsion systems to krypton-fed systems is quite straight-forward. With its lower atomic mass krypton would allow high specific impulse operations without the need of discharge voltage above 800 V. However, some concern has arisen given its low storage density, and the lower propulsive efficiency.

LaB_6 hollow cathodes proved to operate with krypton at the current level required by the thrusters; however, very few studies on the characterization of the plasma parameters of the cathode operating with krypton have been performed.

This paper presents the stand-alone characterization of two cathodes in terms of electrical characteristics with xenon and krypton as propellant. Plasma plume measurements were performed along the cathode axis with triple Langmuir probes, designed according to the expected plasma parameters in the cathode plume and mounted on a moving system[1]. The data have been analyzed with the thin sheath theory, refined by implementing the parametrization of the Laframboise solution for cylindrical Langmuir probes, and integrated with a Bayesian data analysis approach to compute the error trends.

The two cathodes investigated, namely HC20 and HC60, were designed to be coupled with SITAEL's HT5k and HT20k (5 kW- and 20kW-class) Hall thrusters. HC60 is capable of providing discharge current between 20 and 100 A, whereas HC20 was designed to sustain 5 to 30 A. After the characterization in stand-alone configuration, the cathodes were coupled with the thrusters.

The experimental results highlight the capability of HC60 to operate between 25 and 100 A of discharge current with both xenon and krypton as propellant. The plasma parameters analyzed along the cathode plume at a distance up to 40 mm from the keeper exit plate present similar trends comparing the two different propellants, with slightly higher electron temperature and plasma potential with krypton. HC20 was tested at the present time only with xenon between 10-30 A, and the plume plasma parameters proved to be comparable with similar data available in the literature.

II.Cathode description

A. Cathode Design

The mid-to-high current cathodes have been developed as the general architecture shown in Figure 1. The thermionic emission material, LaB_6, is shaped as a hollow cylinder and contained inside a tube, made of refractory metal and terminated in an orifice. The emitter is surrounded by a graphite cup, to avoid dangerous boron diffusion in the refractory metal, and is held in position against the orifice plate with a spacer and a spring. The propellant is injected inside the tube at a given mass flow rate, and a proper selection of the orifice diameter establishes the pressure conditions inside the cathode to facilitate the ionization. The cathode is enclosed in an additional electrode named keeper. The keeper serves to promote the ignition discharge and to protect the cathode elements from plasma bombardment. A dedicated heater is usually included in the cathode design to facilitate the ignition by pre-heating the insert surface up to thermionic emission. As soon as the discharge is initiated, the heater can be turned off and the cathode operates in self-heating mode. Utilizing the heater, the ignition voltage is reduced at values below 50V and the ignition procedure was proved to be reliable.

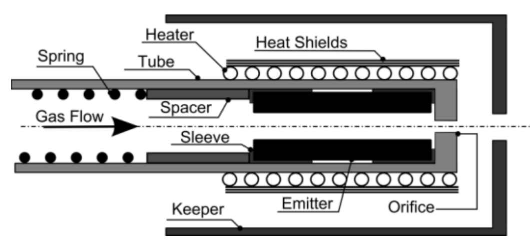


Figure 1. Hollow cathode general architecture.

Two heater configurations have been developed for these cathodes. The first heater-type is a home-made assembly, featuring a refractory metal wire (such as tungsten or tungsten-rhenium alloy) wrapped on a ceramic base and surrounded by an additional insulating cap. The second heater-type employs high temperature mineral insulated cables directly wrapped around the cathode tube. Both the mid-to-high current cathodes have been tested with the two heaters configuration (see Section IV A). The heater assembly is enclosed by a thermal shield, needed to reduce the thermal losses during both the pre-heating phase and the steady-state operation.

The main functional dimensions of the cathodes derive from a theoretical model developed at SITAEL[10] to describe the operation of orificed hollow cathodes. The model results were analyzed to select the emitter inner and outer diameters, the emitter length, and the orifice diameter and length. The plasma model is then coupled with a dedicated lumped-parameter thermal model, and the combined systems of equations are solved by means of an iterative procedure to compute the plasma parameters, temperature profile, and total discharge power.

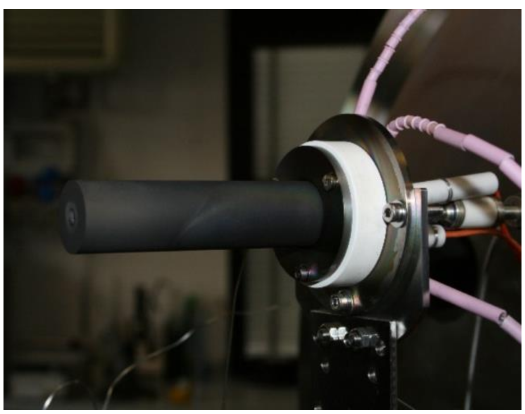
B. HC20 Cathode

HC20 is a 20 A nominal discharge current LaB_6 hollow cathode, capable to operate in the 5-30 A discharge current range at 0.5-2 mg/s of xenon mass flow rate. The cathode was designed to be coupled with SITAEL's HT5k Hall effect thruster, and it has been previously characterized both in stand-alone configuration[5] and in operation with the thruster[11].

Two versions of this cathode have been developed, named HC20, Figure 2a, and HC20h, Figure 2b. The main differences between these two versions are the dimension of the emitter and the inclusion of a heater. In fact, HC20 was conceived to operate in heaterless configuration, while HC20h assembly includes a heater. The ignition procedure of HC20 thus requires the initialization of the propellant flow rate, usually higher (up to three times) with respect to a cathode provided with a heater, and then the application of a high voltage (800–1,000 V) between keeper and cathode to initiate the gas breakdown. After the gas breakdown is achieved, the cathode requires about 5 minutes to reach thermal steady-state and operate in the thermionic emission regime. The cathode mass without cables is about 350 g. HC20h has a more compact configuration, with a smaller LaB_6 emitter and a smaller orifice diameter. The cathode mass (without cables) is about 160 g. The expected lifetime of both cathodes is higher than 10^4 hours. Additional information on the HC20 and HC20h cathodes can be found in (12).

The cathode development program included the investigation of different orifice diameters[13] with particular attention on the effect on the average plume plasma parameters and plasma dynamics[14].

a)



b)

Figure 2. a) HC20 and b) HC20h appearance

C. HC60 Cathode

HC60 is under development to be coupled with the HT20k high-power Hall thruster. The cathode nominal discharge current is 60A, and it has been previously characterized in stand-alone configuration[5] and coupled with the thruster[15].

The HC60 was designed similarly to the other cathodes developed in SITAEL, with a LaB_6 emitter located in a refractory metal tube, and it includes a heater to facilitate the discharge. The cathode mass without cables is 450 g and the expected lifetime exceeds 10^4 hours. Figure 3 shows the HC60 cathode during a stand-alone campaign.

The cathode design has been improved with the inclusion of minerally insulated tantalum heaters and the optimization of the cathode orifice diameter. The cathode has been proved to operate in stand-alone configuration at up to 100A of discharge current with both xenon and krypton at discharge voltage below 25V. The cathode mass flow varies between 1.5-3 mg/s in xenon and krypton.

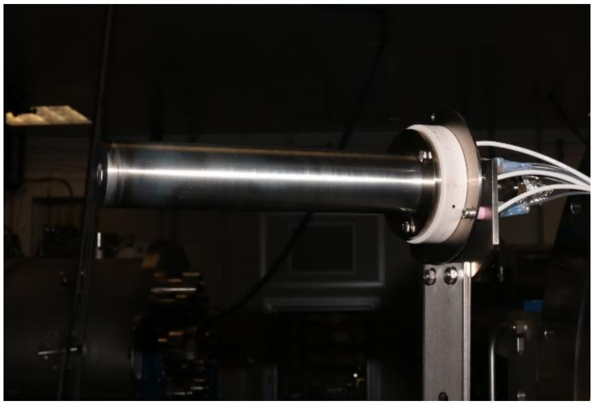


Figure 3. HC60 appearance

III. Experimental setup and data analysis

A. Test campaign

The novel mineral insulated cathodes' heaters test was performed in two parts. The first part aimed at assessing the heater electrical characteristic and temperature in a "stand-alone" configuration without the cathode assembly. This part of the test was performed in SITAEL's IV7 facility, shown in Figure 4a. During this part of the test the heater voltage is recorded at fixed current, and the heater temperature is measured in two points, in the rear and in the front part of the item, with type D thermocouples. The second part of the heater characterization is done in SITAEL's IV9 vacuum chamber, with the heater integrated in the cathode assembly. The purpose of this test is the characterization of the heating time and the temperature reached at the selected thermocouple points.

a) b)

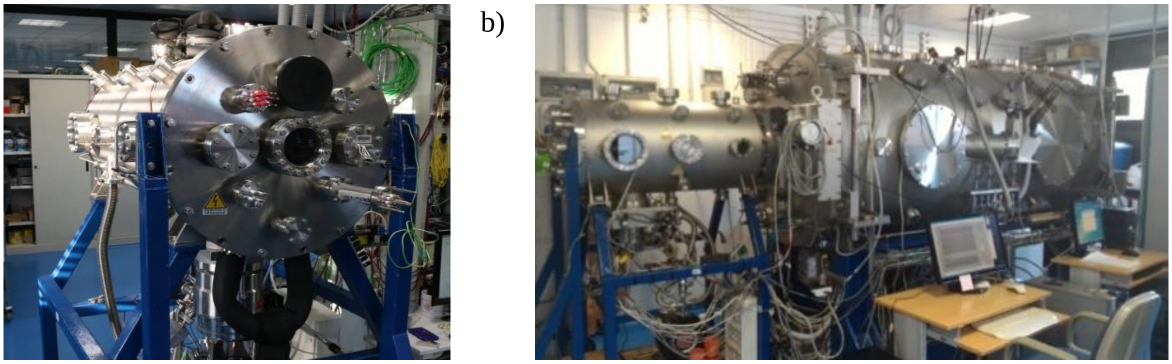


Figure 4. a) IV7 vacuum facility, and b) IV9 vacuum facility

The cathodes were tested in SITAEL's IV9 vacuum facility, shown in Figure 4b, which can reach an ultimate pressure lower than 5×10^{-6} Pa. The experimental setup includes the cathode under test and a cylindrical stainless-steel anode, both mounted over a mounting flange and insulated through proper ceramic stand-offs. The anode has an inner diameter of 150 mm, a length of 200 mm and is placed at a distance of 30 mm from the keeper exit plane. The experimental setup in shown in Figure 5a.

The electrical equipment is similar to the one described in (13). All the cathode electrical parameters were recorded via LabView DAQ. Additionally, the keeper voltage, anode voltage and cathode to ground potential were measured with digital multimeters.

The cathode plume plasma characteristics and dynamics were measured along the cathode axis with a triple probe mounted on a scanning arm, as described in (1). The movement system, depicted in the schematic in Figure 5b, was designed to ensure a quasi-linear trajectory of the probe tip in the near plume region along the cathode axis. The maximum off-center deviation is detailed in (16). Following the approach described in (1), the arm rapidly inserts and extracts the probe from the cathode plume, with a maximum residence time in the dense plasma region of less than 0.2 s.

The perturbation induced by the probe to the plasma has been carefully considered by measuring the cathode-to-ground potential during the probe scan. No significant changes of the CRP were observed until the probe tip reached the proximity of the keeper, where a change of ∼10% of the CRP was measured.

a)

b)

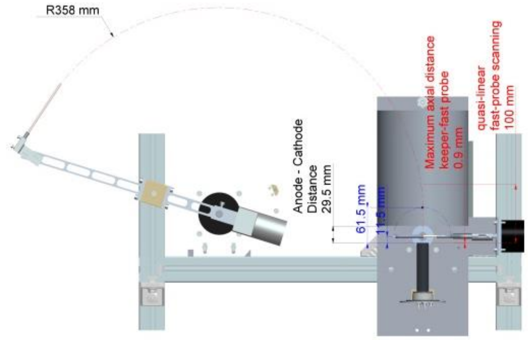


Figure 5. a) Experimental setup, b) fast probe schematic

Triple Langmuir probes have been employed as main diagnostic technique for the plasma parameters and plasma dynamics analysis. With respect to single and double probes, triple probes offer the possibility to perform direct measurements without any voltage sweep[17], and they guarantee the continuous acquisition of the parameters. These features allow them to be applied to understand the dynamics of the plasma if the temporal response of the measurement circuit is sufficiently fast to track the plasma time scales of interest[18]. The triple probe was configured in "voltage mode", see Figure 3, with one electrode left floating and two electrodes biased at a fixed voltage. The potential of the floating electrode as well as the current passing through the biased electrodes was then measured with a high-resolution oscilloscope.

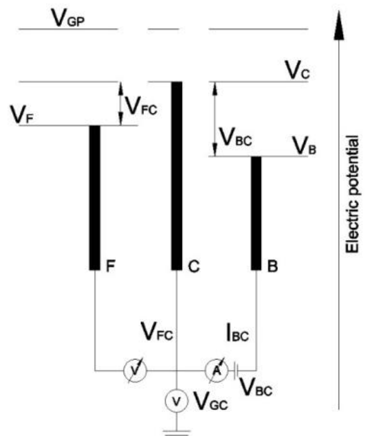


Figure 6 Triple probe schematic

B. Bayesian approach for data analysis

The methodology developed by Saravia et al.[16] was applied for calculating the plasma properties from triple probe measurements. It is based on the Bayesian approach to data analysis, and as such, the knowledge one has of a certain property is associated to a probability distribution which is updated by means of the Bayes rule in the presence of new information, i.e., the experimental measurements. One feature of this approach is that it allows to consistently combine datasets to perform the best inference possible of the plasma parameters given the available information, while also keeping track of the inference uncertainties[19,20]. In this case, the properties to be estimated are the plasma density n, electron temperature T_e and plasma potential V_{GP} with respect to ground. It is worth remarking that the particle collection model considered is based on a parametrization of the Laframboise solution of the plasma sheath[21,22], which considered the sheath thickness variation with potential, thus yielding a more reliable inference of the plasma density with respect to a thin sheath analysis. The results are presented in the form of histograms as a function of the probe position, as seen in Figure 4, superimposed to a plot with error bars, which depict the most likely value and the associated uncertainty for a given location.

The performed measurements consisted of a series of repeated fast probe measurements using a bias voltage of 36 V between B and C electrodes. Measurements with different electrode arrangements were used to reduce the impact of plasma non-homogeneities on the properties sensed by the different electrodes.

IV.Experimental results

A. Heaters characterization

The preliminary test on the mineral insulated heater for HC20h has been effectuated in IV7, with the heater mounted on a specifically made tube. The temperature during the test was recorded in 3 locations with type D thermocouples: tube tip, heater middle position and heater rear position. The heater achieved the following results during the preliminary characterization:

- Stable operation up to 68 W;
- Maximum temperature measured at the tube tip location of 953°C.

Figure 7a shows the heater power and the measured temperature during the preliminary phase.

During the second phase of the MIC heater characterization, the cathode was reassembled with the MIC heater and the thermal shield. Figure 7b shows the results of the second MIC characterization compared with the in-house developed heater. The MIC heater demonstrated stable operation at about 83W, at the same power level as the in-house heater. Unfortunately, a failure in the TC prevented the measurement of the temperature during the characterization with the MIC heater.

After the characterization of the heater, the cathode was ignited with 2 mg/s of applied mass flow rate and ignition voltage as low as 70V. The same ignition procedure is applied with the in-house heater.

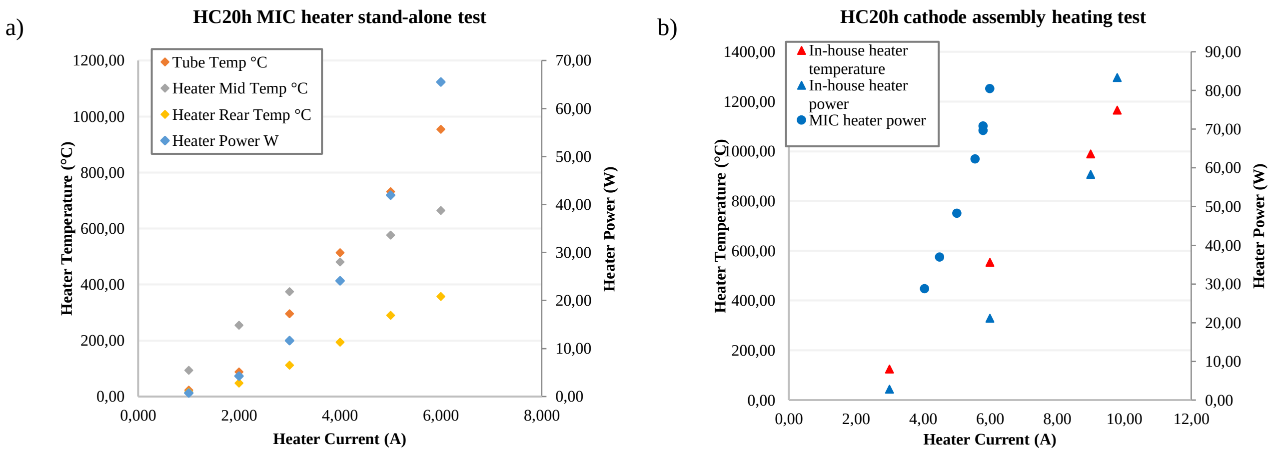


Figure 7 a) HC20h MIC heater stand-alone characterization, b) HC20h MIC and in-house heater test with cathode assembly

The HC60 with the mineral insulated heater was first tested assembled on the structural components of the HC60 cathode. The heater was mounted on the tube and assembled with the thermal shield, see Figure 8. During the first validation test the heater achieved the following results:

- Stable operation up to 156 W;
- Maximum temperature measured at the heater middle location of 1124°C.

During the characterization of the heater, a current ramp was applied and the results in terms of temperature and power are shown in Figure 9a.

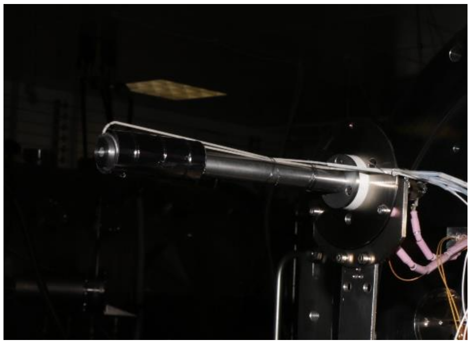


Figure 8. HC60 MIC heater on stand-alone experimental setup.

After the preliminary heater MIC characterization in IV7, the HC60 was completely assembled and mounted in IV9 for testing. This part of the test aimed at performing the same heater current sweep as the preliminary test, to evaluate the electrical characteristic of the heater when assembled on the entire cathode assembly. The heater achieved the following results:

- Stable operation up to 240W of input power;
- Maximum temperature at the heater middle location of 1340°C.

Figure 12b shows the temperature variation measured by the TC mounted on the MIC heater inside the cathode and the heater power. In order to compare the behavior of the newly adopted MIC heater with the previous in-house heater version, Figure 12b presents the in-house heating power and temperature measured inside the heater. As seen in the figure, with the HC60 the application of a mineral insulated heater is a clear advantage in terms of reduced thermal losses, and thus lower heating power consumption.

After the characterization of the electrical behavior of the heater by applying the selected ramp, a first ignition attempt was performed. The cathode was turned ON with a mass flow rate in xenon of 2 mg/s and an applied keeper voltage of 24V. Such very low ignition voltage is an indication of the excellent heating phase and a uniform emitter temperature due to the heating phase.

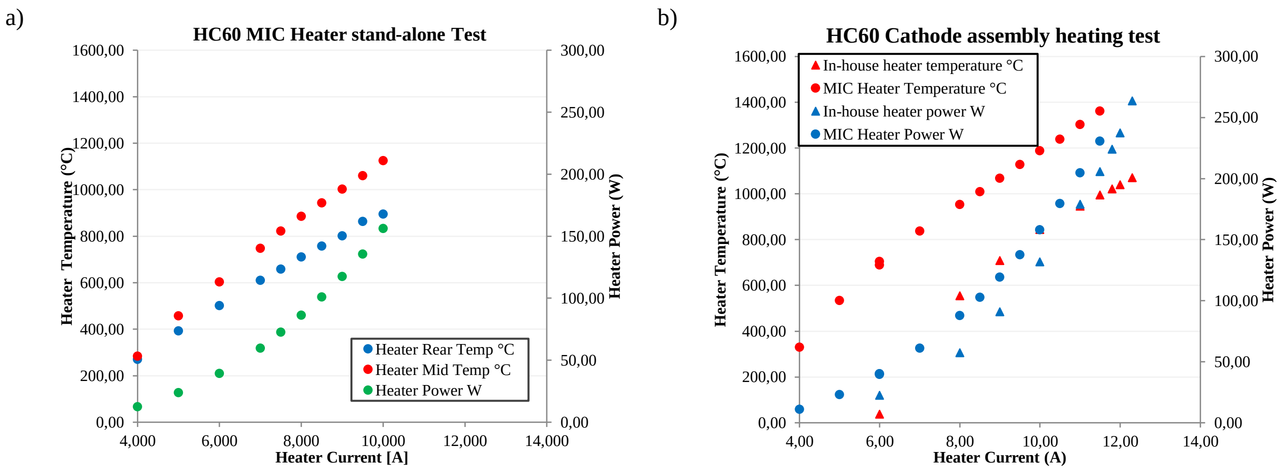


Figure 9. a) HC60 MIC heater stand-alone characterization, b) HC60 MIC and in-house heater test with cathode assembly.

B. HC20 cathode performance and plume parameters

The previous experimental campaign with the mid-size LaB_6 hollow cathode aimed at characterizing the discharge behavior at different mass flow rate and cathode orifice dimension[14]. The HC20 cathode electrical parameters as published in Ref. 14 are presented in Figure 10. The curves report the discharge voltage, keeper voltage and cathode-reference potential (CRP, namely the potential difference between cathode and ground) vs. the discharge current for the various conditions tested.

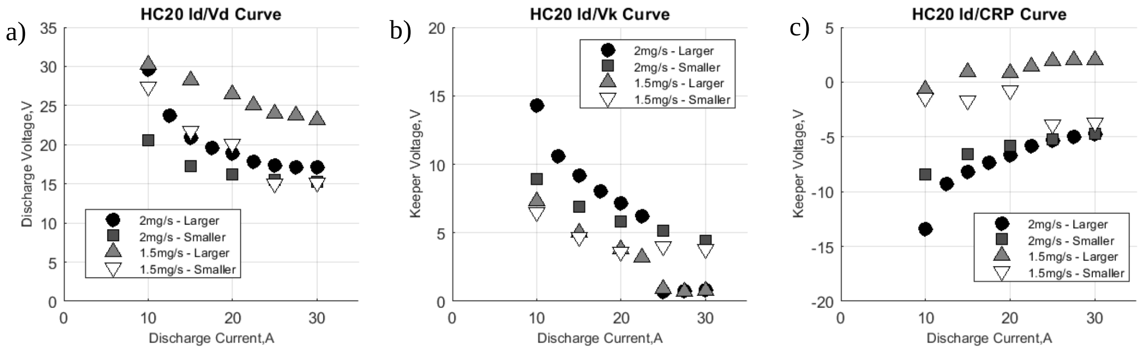


Figure 10. a) HC20 discharge current / discharge voltage curve, b) HC20 discharge current / keeper voltage curve, c) HC20 discharge current / CRP curve.

The previous investigation presented the plume plasma parameters along the cathode axis measured with a triple Langmuir probe mounted on the fast-scanning mechanism described in Section III.A. The plume plasma parameters at 30A of discharge current are presented in Figure 11.

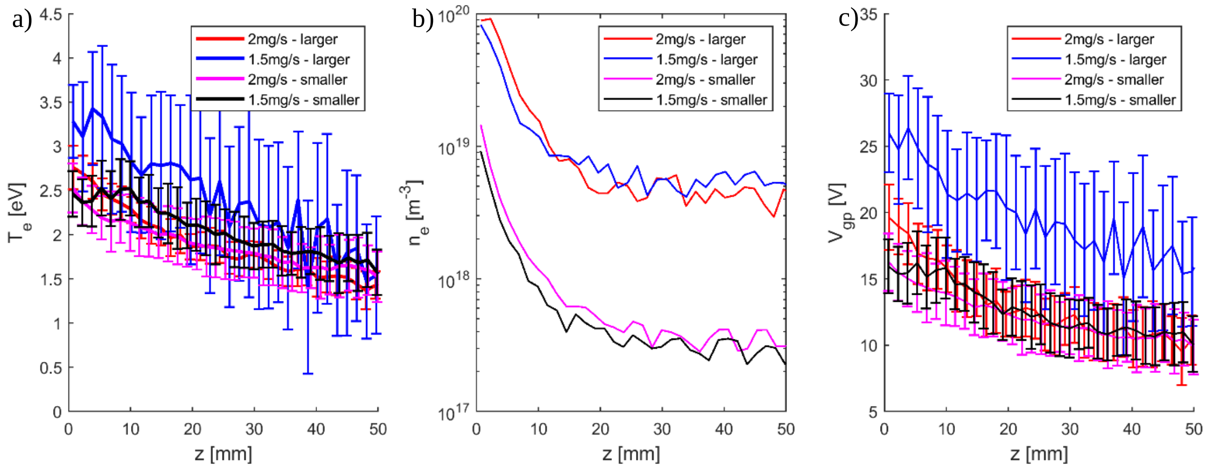


Figure 11. a) Electron temperature (eV), b) plasma density (m-3) and c) plasma potential (V) along the cathode axis

The plume plasma density (Figure 11b) decreases monotonically as the plasma expands in the plume region, with the peak at the keeper exit plane comprised between 10^{19} and 10^{20} m^{-3}. The electron temperature (Figure 11a) is found to be between 3.5 and 1.5 eV, showing a decreasing behavior moving away from the cathode axis. The plasma potential (Figure 11c) aligns to the electron temperature curves, with a decreasing trend as moving forward in the cathode plume. As seen in Figure 11 the condition with the larger diameter and lower mass flow rate shows the highest electron temperature value by about 1 eV at the keeper exit plane and the highest plasma potential by about 6V. As explained in Ref. 14, this behavior is ascribed to the arising of instabilities in the plume region most likely related to ionization instabilities.

C. HC60 cathode performance and plume parameters

With the upgraded design presented in Section II C, the HC60 cathode has been tested at discharge current up to 100A with xenon and krypton as feeding propellants. In xenon, the cathode was demonstrated at 1.5 and 2 mg/s, while in krypton the mass flow rate was varied between 1.62 and 5.75 mg/s. The discharge voltage, keeper voltage and cathode-to-ground potential are shown in Figure 12 with respect to discharge current.

The discharge voltage when krypton is applied is slightly higher with respect to xenon propellant. This fact is accentuated at the lowest krypton mass flow rate. However, the thruster unit does not require such low mass flow in krypton, and the difference is less than 1V at higher mass flow rate.

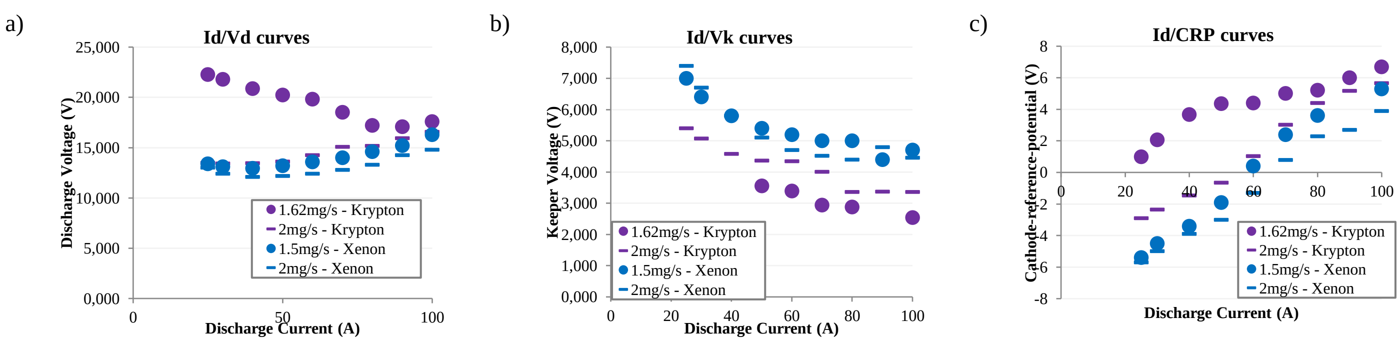


Figure 12. a) HC60 discharge current / discharge voltage curve, b) HC60 discharge current / keeper voltage curve, c) HC60 discharge current / CRP curve.

The cathode plume plasma parameters have been investigated with the fast-scanning triple Langmuir probe and the data have been analyzed with the Bayesian approach described in Section III.B.

The data analysis code results in general plots of the electron temperature, plasma density and plasma potential as shown in Figure 13, where the z axis refers to axial position starting from the keeper exit plane (at zero) and expanding in the cathode plume.

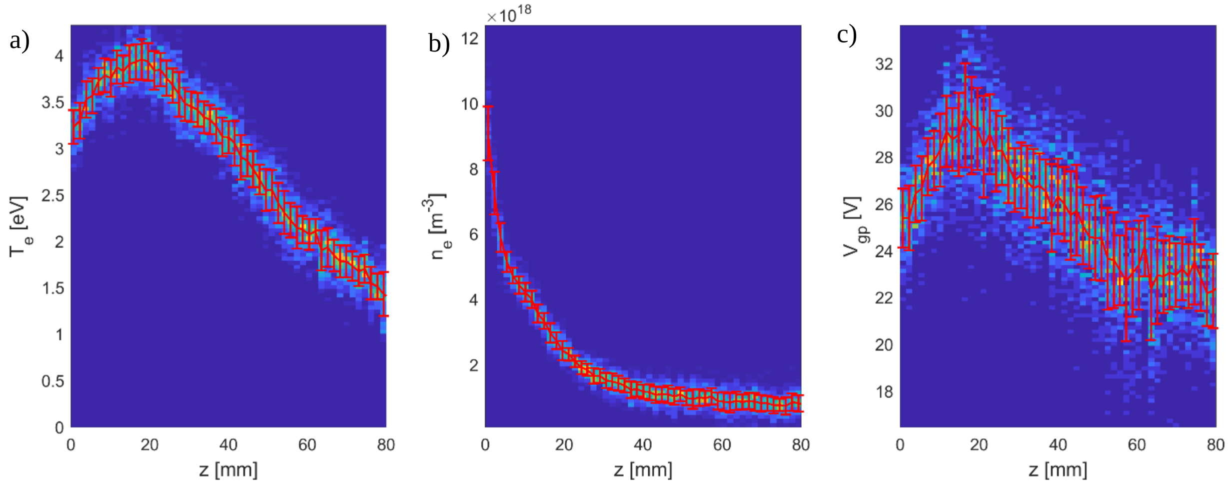
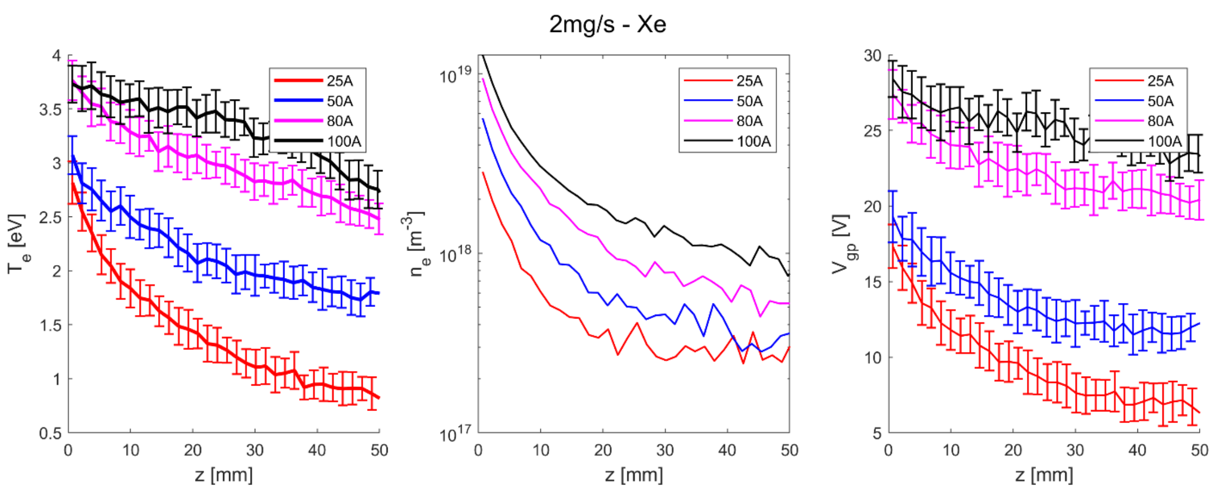


Figure 13 Typical plasma parameters trend with triple probe (2 mg/s - 100 A - krypton)

In order to understand the effect of the different propellant applied in the cathode, Figure 14 shows the plume plasma parameters along the cathode axis for xenon (top figure) and krypton (bottom figure), when the cathode was operated between 25 and 100A at fixed mass flow rate, 2 mg/s.

The plasma density (Figure 14b in xenon, Figure 14e in krypton) is monotonically expanding along the axis, and it is slightly higher with krypton when compared at fixed discharge current.

The electron temperature (Figure 14a in xenon, Figure 14d in krypton)) and plasma potential (Figure 14c in xenon, Figure 14f in krypton)) are found to increase with discharge current, reaching 4eV at 100A with krypton. Interestingly, employing xenon as propellant, both the electron temperature and the plasma potential have a decreasing monotonic behavior. Instead, the use of krypton changes the plasma parameters trends. In fact, at the highest current level the electron temperature and the plasma potential show a peak at about 20mm distance from the keeper exit plane.



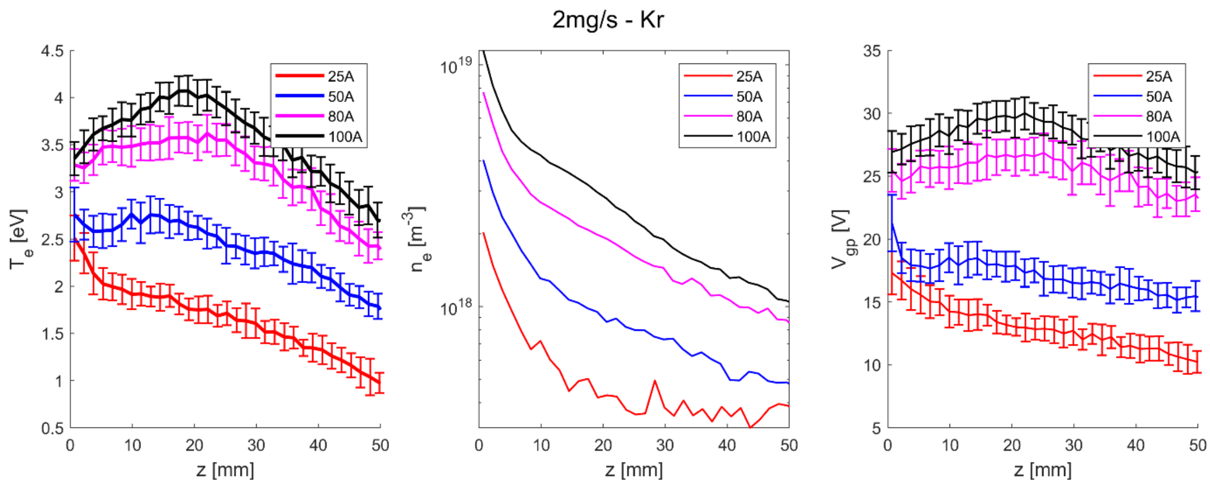


Figure 14 Plasma parameters with xenon at 2 mg/s (top), and with krypton at 2 mg/s (bottom).

Previous experimental campaigns done with high current cathodes in other groups have shown similar values of the plasma parameters when the cathodes were running in xenon. However, most of the results show a clear increase in the electron temperature and plasma potential with krypton when moving away from the keeper exit. The results shown here with xenon are instead similar to what has been found with HC20[14] (see Figure 11). In Ref. 14 this behavior has been ascribed to the adoption of a large diameter cylindrical anode, which forces the current to attach radially away from the cathode axis, and it has been demonstrated by computing the inertialess electron momentum (Ohm's law), in the absence of magnetic field[23]. Additional studies are on-going to understand the effect of krypton on the near-plume plasma parameters.

V. Conclusion

The high current hollow cathodes developed at SITAEL during the past years have been upgraded with novel heaters design and with an optimization of the geometrical dimensions.

The plasma plume of the hollow cathodes has been investigated by means of triple Langmuir probe scanning along the cathode axis. The plasma parameters have been computed by applying standard techniques refined with a Bayesian approach to evaluate the error related to the measurements. This technique has been applied for HC60 operating with both xenon and krypton as propellant. The results show that the electron temperature and plasma potential are slightly higher when krypton is applied. However, HC60 demonstrated to operate in the whole operating range up to 100A with both propellants with comparable results.

Future activities include the construction of the cathodes engineering model and life test with the thruster unit.

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