Alternative Propellants for Gridded Ion Engines: Hollow cathode operation using Kr and Xe/Kr mixture

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Xenon is the preferred propellant for electric propulsion thrusters, providing high thruster efficiency and long life. However, xenon is very expensive and has limited availability, which could impose serious constraints on the use of electric propulsion in some future missions. Therefore, there has been a renewed interest in the use of alternative propellants in electric propulsion. A critical component affected by the transition to alternative propellants is the hollow cathode, which is used in several devices (such as Gridded Ion Engines, Hall Effect Thrusters, etc.). This report presents the initial characterization of an LaB_6 cathode operating in diode mode using krypton and a 1:4 Xe/Kr mixture instead of xenon. The emphasis is on the comparative performance over a wide range of currents and flow rates along with establishing spot to plume mode transition. The results of this comparison indicate that operations with the three gases were similar but, in general, higher mass flow rates were necessary to maintain the cathode in spot mode with krypton and the mixture.

I. Nomenclature

Ia = anode current [A]
Ik = keeper current [A]
Va = anode potential [V]
Vk = keeper potential [V]

II. Introduction

The development of the GIESEPP project [1], the first European Plug and Play Gridded Ion Engine Standardised Electric Propulsion Platform, targets reducing the cost of GIE systems and increasing their production capacities. In an attempt to achieve these objectives, an investigation into the functionality and performance of the GIESEPP systems with propellants other than xenon is highly beneficial.

Xenon is the most common propellant used for space electric propulsion applications, particularly in GIEs and Hall Effect Thrusters (HETs), due to its peculiar physical and chemical properties, such as low first ionization energy, high atomic mass, and chemical inertness. However, this gas has some disadvantages, such as limited availability (and, consequently, high cost) and low density (compared to liquid and solid propellants). In particular, the former one is predicted to become more and more relevant in the future due to the increasing demand not only in the space propulsion sector, but also in many other industries (e.g., electronics, automotive, medicine, lighting, etc.). Therefore, the search for viable alternative propellants has gained momentum in the last decade because of the revival of EP technologies targeting a growing diversity of vehicles, missions, and manoeuvres.

An initial assessment [2] was carried out through a comprehensive review of the published data on the usage of alternative propellants, such as other noble gases, iodine, and other more exotic propellants (i.e.,

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Buckminsterfullerene and Adamantane). Thereafter, a qualitative analysis was performed which looked at the impact of this range of candidates on the different GIE's systems (e.g., storage, FCU and PPU, cathode operation, plume/spacecraft interaction, toxicity, and lifetime). This was followed by a more in-depth and quantitative analysis which calculated the effects on performance. Based on these preliminary results, the best alternative within the GIESEPP project's scope would appear to be krypton if all of the selected impacts are taken into consideration; in fact, iodine has the best performance, but it was eliminated because of system compatibility issues, in addition to spacecraft contamination and toxicity. A further option is to use a Xe/Kr mixture in the storage ratio of 1:4 Xe/Kr since this is the production mixture obtained as by-product of the separation of air into oxygen and nitrogen using conventional methods [3].

From this initial assessment, it appeared that a critical component affected by the use of lighter gases is the hollow cathode, which is a key element in several EP devices (e.g. GIEs, HETs, etc.). A clear understanding of the operations and testing of these devices with alternative propellants is fundamental, and very few systematic investigations are available in literature [4-5]. A consistent outcome of these studies is the requirement for higher propellant mass flow in order to operate the cathode in spot mode.

The objective of this paper is to quantify the impact of using these alternative propellants when operating a LaB6 cathode in diode mode. The emphasis will be on the comparative performance over a wide range of currents and flow rates along with establishing spot to plume mode transition.

The paper is organized as follow: in Section III, the experimental setup is described, in Section IV, the experimental results are presented and discussed, and, finally, general conclusion and possible perspectives are summarized in Section V.

III. Experimental setup

A. The hollow cathode

The experimental campaign was carried out at the University of Southampton TDHVL facilities. The hollow cathode (model name MSL_HC40) was previously obtained from Mars Space Ltd and it is optimized for a discharge current of 40 A at 20 sccm of xenon, but its flexible design allows to be operated at different operational points in terms of discharge current (from 40 A to 5 A) and mass flow rates in order to minimize the discharge power. A schematic diagram and an actual picture of the device are shown in Figure 1. The cathode uses a LaB_6 insert instead of the conventional tungsten-impregnated emitter because it has little to no susceptibility to oxygen poisoning which is a great advantage when several configurations need to be tested removing the requirement of long outgassing procedures and allowing the use of lower-purity gases. LaB_6 inserts are also cheaper, but they cannot be in direct contact with many refractory metals because of chemical reactions at high temperature (i.e. boron diffusion) that can cause embrittlement in the metals and, in addition, LaB_6 work function is higher resulting in a higher working temperature for the same emitted current density.

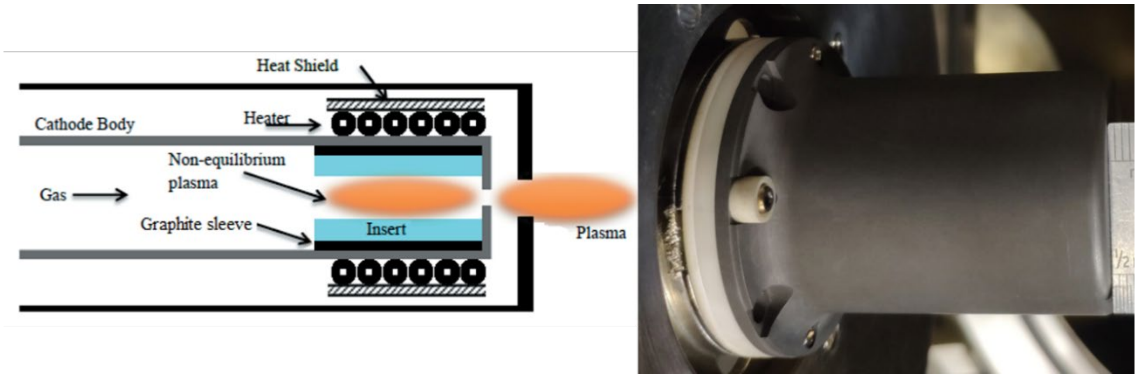

Figure 1 General schematics of a hollow cathode (left) and picture of MSL_HC40

The hollow cathode consists of a stainless-steel mounting flange which is attached to the chamber mounting system using bolts which are electrically isolated with ceramic bushes. A 1/8-inch pipe is electron beam welded to the rear of the mounting flange and this pipe is connected to a ceramic isolator upstream, which is then connected to the main propellant line of the chamber. The cathode body (i.e. the tube containing the insert) is made of tantalum and is bolted to the mounting flange. The LaB_6 emitter is pushed to the end of the cathode body, and a thin graphite sleeve is used to mechanically separate the emitter itself from the tantalum tube to avoid the above-mentioned boron diffusion issues, while maintaining the electrical connection. A graphite orifice disc is positioned between the end of the cathode body and the emitter, and its dimensions are 1 mm thickness and 1 mm nominal orifice diameter. The advantage of using this disc is that can be substituted with similar discs having smaller or bigger diameter so that different configurations can be tested. The cathode body is surrounded by the heater and a multi-layered tantalum thermal shield is wrapped around it to decrease radiative thermal losses and improve thermal efficiency. A graphite casing is then used to support the thermal shield in place. The keeper electrode which encloses the entire assembly is made of graphite for its low sputter yield and it is bolted to the stainless-steel base of the cathode with an insulating ceramic disc and with ceramic alumina washers to prevent short-circuiting of the electrodes. Ceramic discs with different thickness are present and stacking and/or removing them allow to change the distance between the cathode tube and the keeper for further flexibility during testing.

B. Vacuum Facility and Mounting System

The hollow cathode was tested in diode mode utilizing Vacuum Chamber 1 (TDHVL-VC1). This is an ultra-high throughput bi-turbo cylindrical chamber, constructed from 404 stainless steel, and it is 1.2 m long and 0.6 m in diameter. The chamber has a 10 cm port on one end and a hinged door for quick access on the other end. The door has ISO mounting point on the inside for experimental apparatus mounting, several ports for electrical/gas feedthroughs through the door, and more ports around the cylindrical surface. The pumping system consists of:

- an Edwards E2M40 oil-based mechanical pump, used as a backing pump to reach a pressure of $5x10^{-2}$ mbar;
- two ultra-high throughput Edwards STP-iXA4506C turbomolecular maglev pumps giving a combined pumping speed of 8600 L/s of N_2 and reaching a base pressure below $1x10^{-8}$ mbar (unbaked).

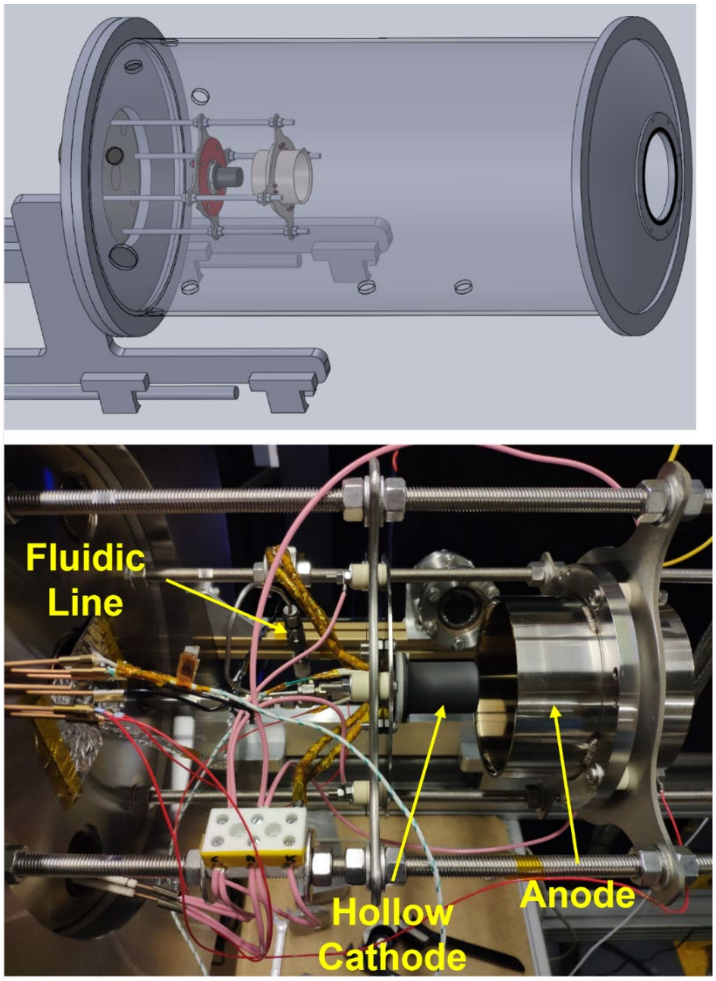

Figure 2 Diode setup in vacuum chamber (CAD and picture)

The pressure inside the chamber is measured by two gauges:

- an Applied Vacuum calibrated Edwards APG-M Active Pirani Gauge, with an Edwards active gauge controller, for low vacuum pressure,
- a calibrated Kurt J. Lesker KJLC 354 Series Ion Gauge, with pre-configured correction factors for the gases used, for high vacuum pressure.

The cathode-anode setup is connected to the sliding door flange using four metal threaded studs as illustrated in Figure 2.

C. Electrical and Fluidic Ground Support Equipment

When the cathode is operated in diode mode, electrical connections to the cathode body, to the heater and to the anode are required. An overview of the Electrical Ground Support Equipment (EGSE) utilized for testing is shown in Figure 3 and it consist of a dedicated rack comprising of:

- an EA PSI-5200-10 (output 200 V, 10 A) for the heater,
- an EA PS-9750-12 (output 750 V, 12 A) for the keeper,
- an EA PS-9200-70 (output 200 V, 70 A) for the anode,
- two sense DMMs to measure anode and keeper's voltages with higher accuracy,

Furthermore, a Temperature Reference Point (TRP) is measured with Type-K thermocouples, which is located at the cathode base.

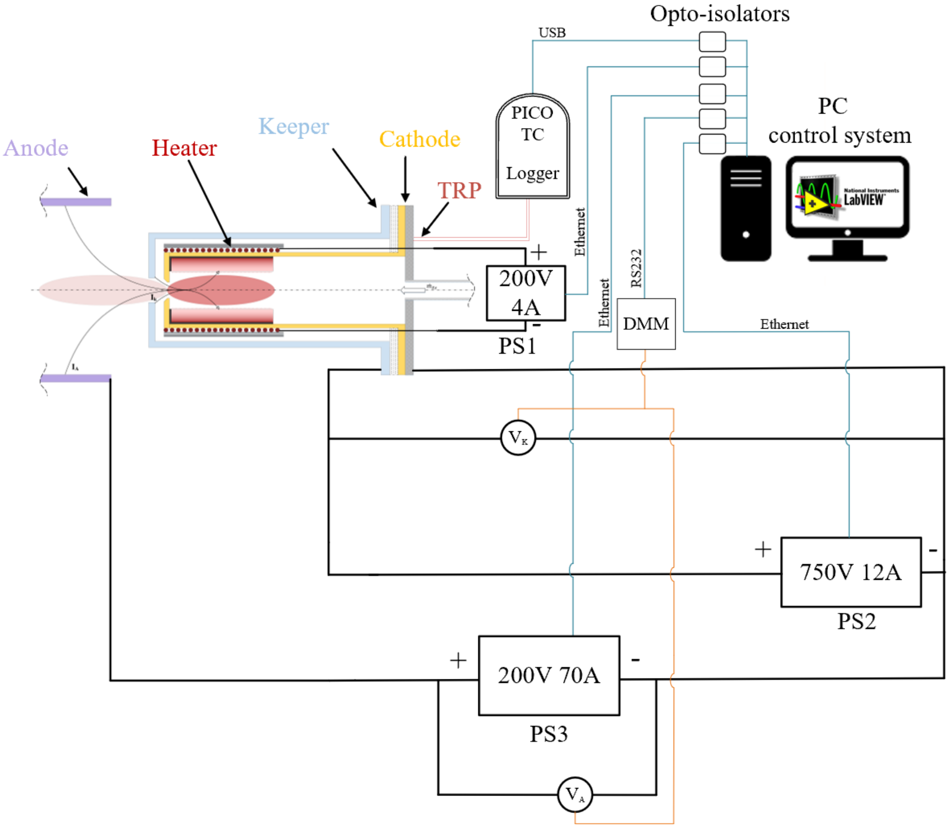

Figure 3 Electrical schematic of the diode-mode setup

The Fluidic Ground Support Equipment (FGSE) supplies the hollow cathode with the required gas at the desired flow rate, and it is shown in Figure 4. Two pressure regulators (one for each bottle) maintain a constant upstream pressure of 1.5 bar during the test. The flow rate to the cathode is controlled with two Bronkhorst mass flow controllers (MFCs) which are factory calibrated with an accuracy of ±0.5% read value plus ±0.1% full scale value: the Xe-MFC has a range of 0-20sccm, and the Kr-MFC has a range of 0-100sccm. Downstream of the MFC, ¼” stainless steel piping with VCR seals is utilized to minimize risk of an air leak contamination. A series of on/off manual valves are in place to enable isolation of various parts of the FGSE. For the testing conducted in the study xenon and krypton of 99.999% minimum purity (N5.0) are utilized.

All the instrumentation (i.e. power supplies, MFCs, and pressure gauges) is connected to a PC, and is controlled and logged using a LabView program at a sampling rate of 1 Hz. In addition, all the interfaces between the control system and the test apparatus are isolated using inline USB/RS232 optocouplers.

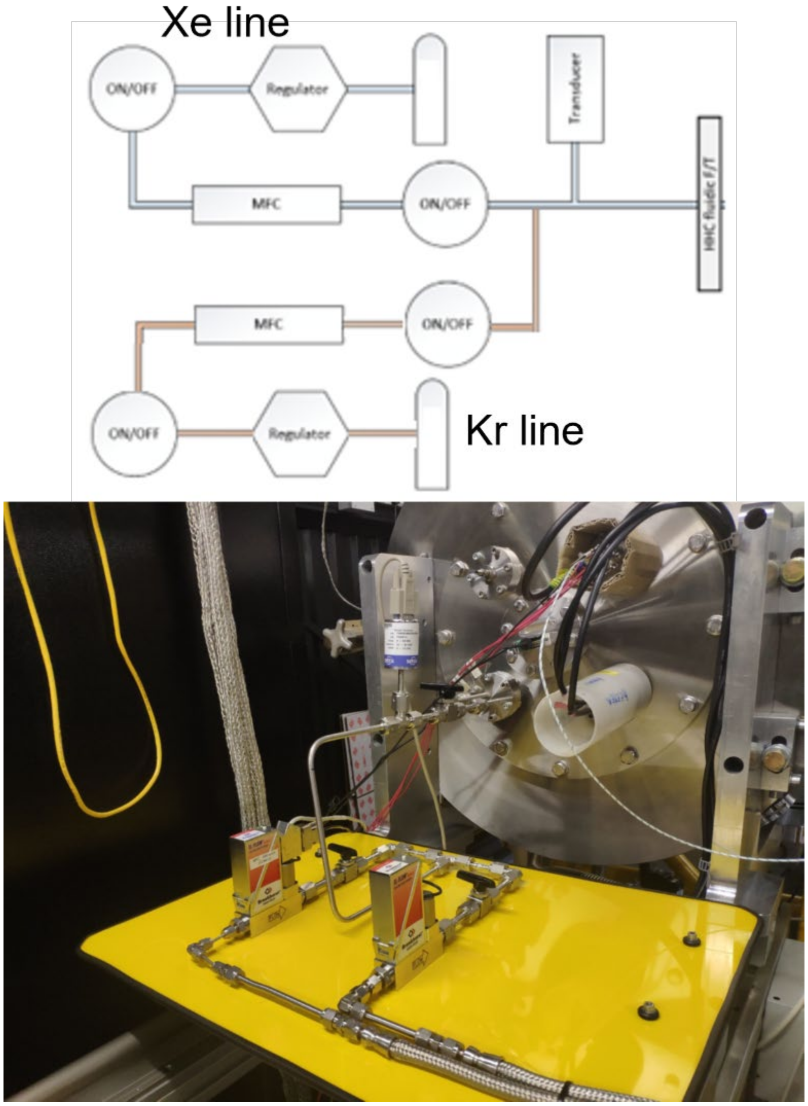

Figure 4 Fluidic setup for the testing

IV. Experimental Results and Discussion

The hollow cathode was operated in both spot and plume mode allowing the measurement of the operating parameters at different operating conditions with xenon, krypton, and a 1:4 Xe/Kr mixture. Spot and plume mode are the two modes of operation of hollow cathodes for electric thrusters (Figure 5):

- Spot mode is characterized by a small and convergent plume, and it is desirable due to more stable plasma, low amplitude oscillations, and reduced erosion of the orifice.
- Plume mode is associated with a bright divergent plume, and it is characterized by relatively large oscillations of discharge voltage and current.

The transition between spot and plume mode can usually be triggered by lowering the flow rate at a given current but also by changing the keeper current, and it can be visually detected and associated with ample oscillations of the cathode potential.

The preliminary results for operations of the HC40 cathode with xenon, krypton and a 1:4 Xe/Kr mixture are presented in the following paragraphs with a particular focus on the transition from spot to plume mode and the operating conditions (i.e. mass flow rate, anode voltage and current, keeper voltage and current) were measured at the last stable point before the transition for the different gases.

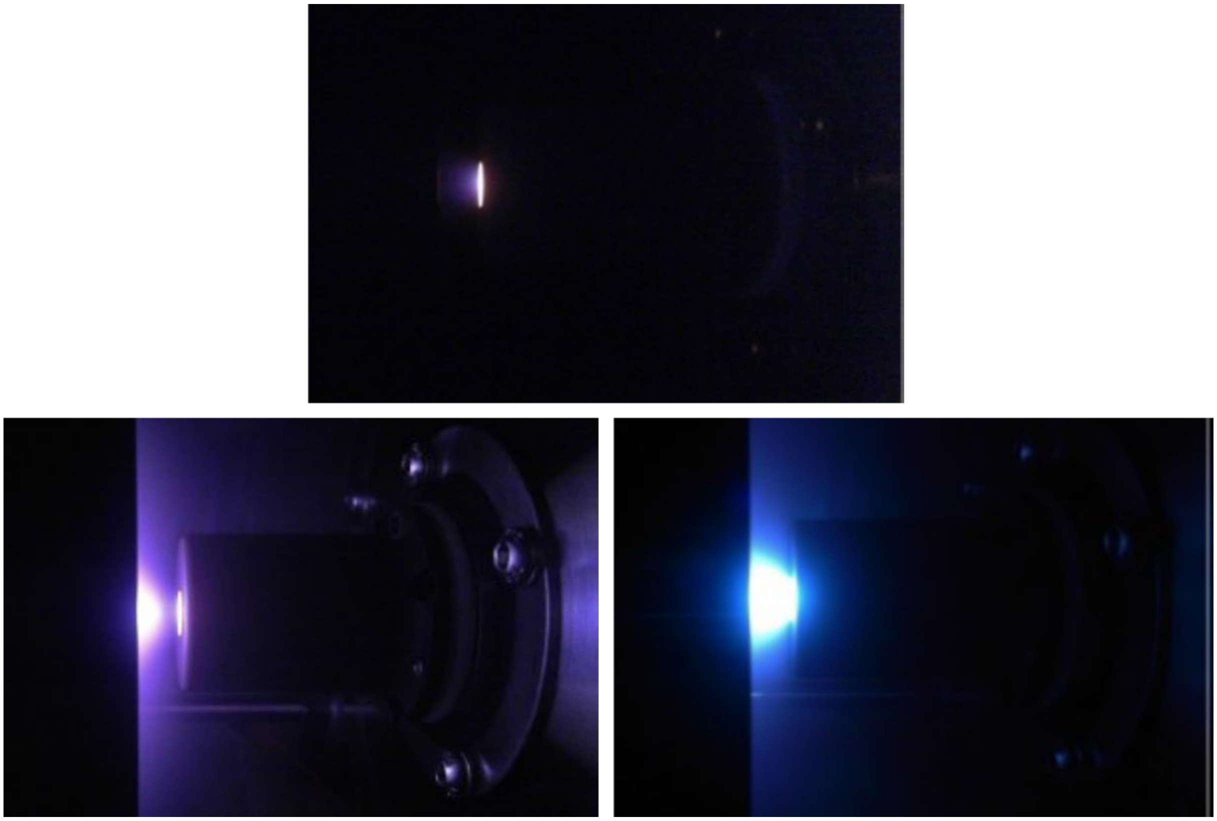

Figure 5 Example of operation in spot mode (top, Xe) and plume mode (bottom, Xe right & Kr left)

D. Transition flow rates

The minimum flow rates needed for spot mode for each gas at different operating conditions are shown in Table 1 (the complete results are available in Table 2 in the Appendix).

Operations with krypton and the mixture show that, in general, higher mass flow rates were necessary to maintain the cathode in spot mode compared to xenon. Overall, two general trends can be identified:

- Xe vs Kr: Kr flow rate is around 3 times higher than Xe flow rate, (slightly lower at lower anode currents, and slightly higher at higher anode currents)
- Kr vs mixture: at lower anode currents, the total mixture flow rate exceeds the Kr flow rate, and the opposite happens at higher anode currents

Table 1 Mass flow rates for different anode and keeper currents before transition from spot to plume

Anode Current [A]	3A	5A	10A	15A	20A	25A
GAS	Keeper current Ik = 0 A (Floating keeper)					
Xe	-	-	20 sccm	15 sccm	13 sccm	11 sccm
Kr	-	-	55 sccm	42 sccm	35 sccm	30 sccm
1:4 Xe:Kr	-	17/68 sccm	11/44 sccm	9/36 sccm	-	6/24 sccm
Anode Current [A]	3A	5A	10A	15A	20A	25A
GAS	Keeper current Ik = 2 A					
Xe	-	-	15 sccm	12 sccm	10 sccm	9 sccm
Kr	57 sccm	52 sccm	42 sccm	36 sccm	30 sccm	27 sccm
1:4 Xe:Kr	-	11/44 sccm	9/36 sccm	7/28 sccm	6/24 sccm	5/20 sccm
Anode Current [A]	3A	5A	10A	15A	20A	25A
GAS	Keeper current Ik = 4 A					
Xe	-	14 sccm	12 sccm	10 sccm	9 sccm	7 sccm
Kr	37 sccm	36 sccm	33 sccm	30 sccm	27 sccm	24 sccm
1:4 Xe:Kr	9/36 sccm	8/32 sccm	7/28 sccm	6/24 sccm	5/20 sccm	4/16 sccm

E. V-I Characteristics

Figure 6 summarizes the voltage-current characteristics for the considered range of keeper currents (the mass flow rates for the different conditions are reported in Table 1). This figure shows that the operations with the three gases are:

- keeper voltages are very similar for each operating point over the various keeper (0, 2, and 4A) and anode (3, 5, 10, 15, 20, and 25 A) currents,
- anode voltages are generally comparable at lower anode current and for the various keeper setpoints, but they are slightly higher (2-4V) for xenon compared to krypton at higher anode currents, with the mixture results between the other two gases.

While these initial tests do not provide a definitive answer about the operating conditions of a hollow cathode running with different gases, they represent a valid benchmark for future experiments. In fact, further tests are planned and will be conducted using various cathode configurations (e.g. changing orifice size, distance between orifice and keeper, etc.) and with the support of a diagnostics tools (e.g. Langmuir probe, emissive probe, ExB probe) to verify these initial results and to measure the plasma parameters.

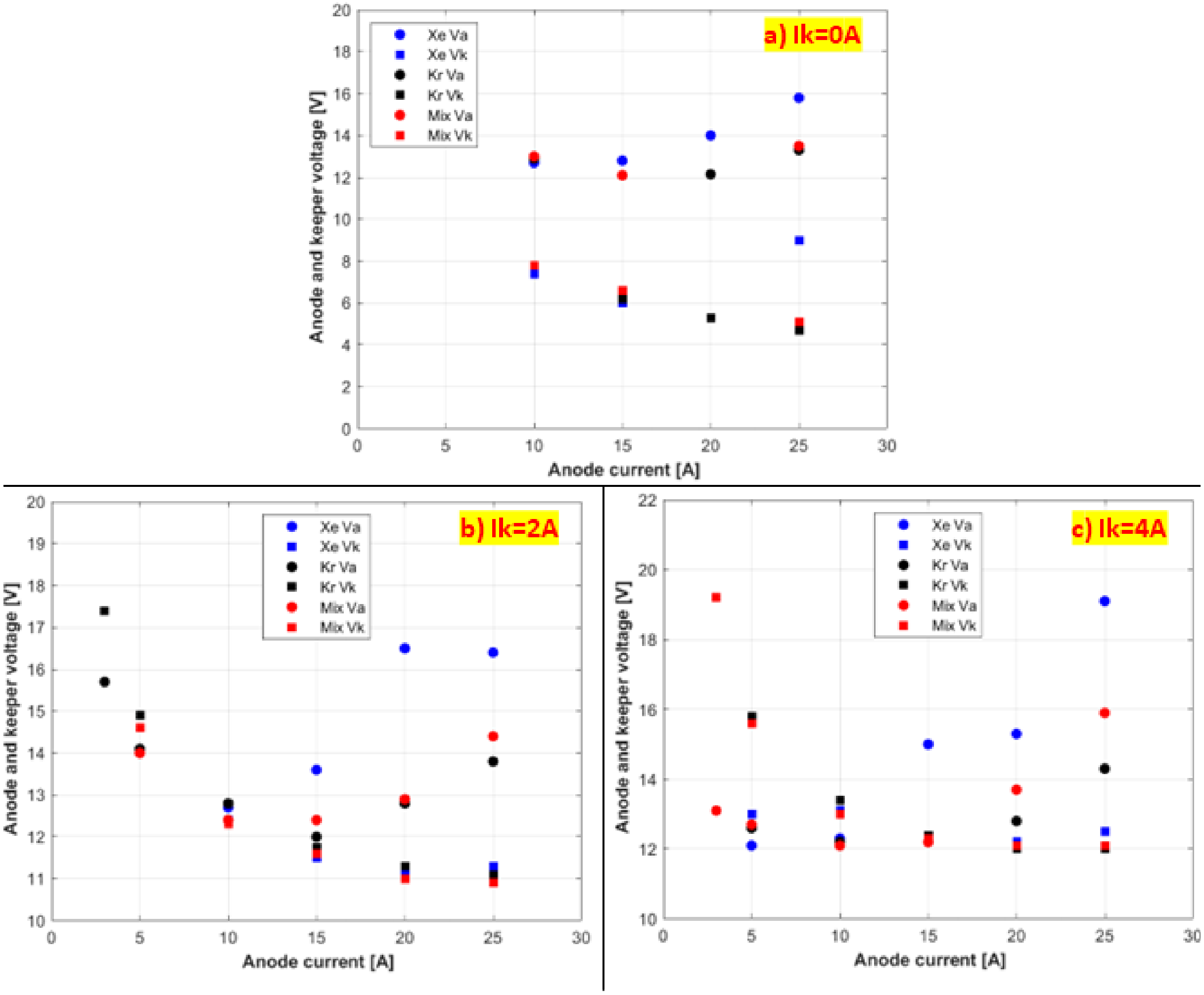

Figure 6 V-I characteristics for Xe, Kr, and 1:4 mixture, for floating (Ik=0 A) keeper (top), Ik=2 A (bottom left), Ik=4 A (bottom, right)

V. Conclusion

The characterization of a LaB_6 hollow cathode in diode mode with three different gases (i.e. xenon, krypton, a 1:4 Xe/Kr mixture) over a wide range of flow rates and currents has been presented with a particular attention to the transition between spot and plume mode. The operations with the gases are very similar with respect to the potentials, but, in general, higher flow rate are required to maintain the cathode in spot mode with krypton and the mixture. These early results represent a useful starting point for future experiments which will be carried out using different cathode configurations (e.g. orifice shape, size, and relative position, etc.) and with the addition of a diagnostics setup (including Langmuir and emissive probes, ExB probe).

Appendix

The complete results of the testing are shown in Table 1.

Table 2 Results of HC40 testing with different gases

Anode Current [A]		3A	5A	10A	15A	20A	25A
GAS	Keeper current Ik = 0 A (Floating keeper)						
Xe	flow rate [sccm]	-	-	20	15	13	11
	Anode Voltage [V]	-	-	12.7	12.8	14	15.8
	Keeper Voltage [V]	-	-	7.4	6	5.3	9
Kr	flow rate [sccm]	-	-	55	42	35	30
	Anode Voltage [V]	-	-	12.9	12.1	12.15	13.3
	Keeper Voltage [V]	-	-	7.8	6.2	5.3	4.7
1:4 Xe:Kr	flow rate [sccm]	-	17/68	11/44	9/36	-	6/24
	Anode Voltage [V]	-	15.7	13	12.1	-	13.5
	Keeper Voltage [V]	-	11.2	7.8	6.6	-	5.1
Anode Current [A]		3A	5A	10A	15A	20A	25A
GAS	Keeper current Ik = 2 A						
Xe	flow rate [sccm]	-	-	15	12	10	9
	Anode Voltage [V]	-	-	12.7	13.6	16.5	16.4
	Keeper Voltage [V]	-	-	12.4	11.5	11.2	11.3
Kr	flow rate [sccm]	57	52	42	36	30	27
	Anode Voltage [V]	15.7	14.1	12.8	12	12.8	13.8
	Keeper Voltage [V]	17.4	14.9	12.8	11.75	11.3	11.1
1:4 Xe:Kr	flow rate [sccm]	-	11/44	9/36	7/28	6/24	5/20
	Anode Voltage [V]	-	14	12.4	12.4	12.9	14.4
	Keeper Voltage [V]	-	14.6	12.3	11.6	11	10.9
Anode Current [A]		3A	5A	10A	15A	20A	25A
GAS	Keeper current Ik = 4 A						
Xe	flow rate [sccm]	-	14	12	10	9	7
	Anode Voltage [V]	-	12.1	12.3	15	15.3	19.1
	Keeper Voltage [V]	-	13	13.1	12.3	12.2	12.5
Kr	flow rate [sccm]	37	36	33	30	27	24
	Anode Voltage [V]	13.1	12.6	12.2	12.2	12.8	14.3
	Keeper Voltage [V]	30.5	15.8	13.4	12.4	12	12
1:4 Xe:Kr	flow rate [sccm]	9/36	8/32	7/28	6/24	5/20	4/16
	Anode Voltage [V]	13.1	12.7	12.1	12.2	13.7	15.9
	Keeper Voltage [V]	19.2	15.6	13	12.3	12.1	12.1

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