

Hollow Cathode Operation with Different Gases

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Abstract

Hollow cathodes are key components in several electric propulsion devices, including gridded ion engines (GIEs), Hall Effect Thrusters (HETs) and HEMPTs. Because of recent interest in the use of electric thrusters, in particular HETs and GIEs, for orbit raising and the availability and cost of the standard and preferred propellant of xenon, there has been renewed interest in the use of alternative propellants, including krypton and iodine. Clearly understanding the operation and testing of hollow cathodes with these propellants is needed. In this paper, the results of the testing of an LaB6 insert, hollow cathode in diode mode with a range of gases, including hydrogen, krypton, xenon and gas mixtures of H₂/Xe and Xe/Kr are presented. The emphasis is on comparative performance over a wide range of currents and flow rates along with establishing spot to plume mode transition.

1. Introduction

Although low work function insert cathodes have been run on different gases, including inert gases, hydrogen and some gas mixtures, there have not been many systematic investigations of the same cathode with different propellants [1]. For MPD and arcjet thrusters [2,3], hydrogen is of interest and although insert hollow cathodes are not normally used the possibility of using them could have some advantages in terms of lower erosion. Indeed, a recent paper [4], has examined the use of multi-channel hollow cathodes in permanent magnet, steady state MPD thrusters using a range of propellants, including hydrogen and argon. Additionally, hollow cathodes have been previously investigated in hydrogen ion sources for neutral beam injectors for heating fusion plasmas [5,6]. Typical flow rates with xenon were between 7 and 20 sccm and between 50 and 250 sccm for hydrogen with a 1mm cathode orifice. The vacuum facility was 0.6m in diameter and 1.5m long, pumped by two Edwards, maglev turbomolecular pumps (4500l/s, N2) giving a base pressure of around 10^{-8} mbar with no flow and between 5×10^{-5} and 8×10^{-3} mbar, depending on gas and flow rate (higher for hydrogen). The initial cathode orifice was 1mm diameter but this increased to about 2mm after operation of several tens of hours; although two cathode anode separations were tried, most of the test were at a separation of 3mm. The emphasis was on comparative performance over a range of currents and flow rates with single gases but the effects of a magnetic field and gas mixtures were also investigated.

2. Experimental Arrangement

A photograph showing the diode arrangement mounted on a platform which allowed the anode cathode distance to be varied is shown in Figure 2.1.

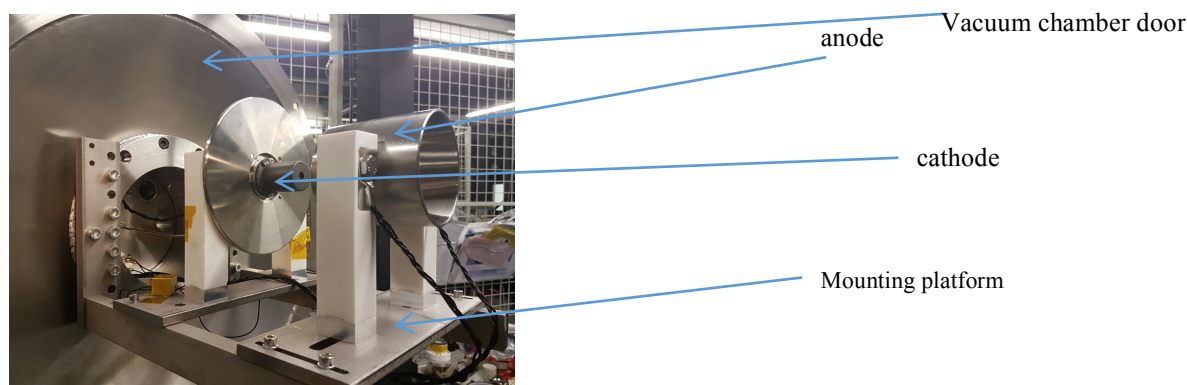


Figure 2.1 Diode set-up in vacuum chamber.

The hollow cathode was obtained from Mars Space Ltd and is based on an LaB6 insert with an enclosed graphite keeper and a graphite heater.

The first prototype of this cathode design was developed in conjunction with JAXA and IHI for use on a Hall Effect Thruster (HET) and has subsequently been modified for use as a cathode neutraliser in an RF gridded ion

engine(GIE)(commercial contract with a major European Aerospace Company) and for use as the main discharge cathode in a RC GIE under an ESA funded grant.

The insert is enclosed by a graphite tube (with a tight fit) which is inserted into a tantalum tube; this carbon sleeve prevents reactions of the LaB6 with the tantalum tube at high temperatures. The main cathode body tube(tantalum) is surrounded by the heater and a multifoil heat shield to decrease radiative heat losses and improve thermal efficiency. The anode used a TP316L seamless, ASTM A312 stainless steel 3.5" N.B. (I/D) schedule 10S pipe. From the ASTM standard the nominal dimensions before polishing were :101.6 mm outer diameter,3.05 mm wall thickness,100 mm long.

2.2 Mounting system and electrical connections for the diode configuration

The cathode was grounded and supported by mounted with a back flange to the door of the vacuum chamber. The anode was mounted on a support rail system (as shown in figure 2.1) which was also attached to the vacuum chamber door. Electrical isolation was provided by mounting the anode through 2 support columns made of macor. Slots in the rail system allowed the separation between anode and cathode to be varied.

The cathode body was connected to the vacuum chamber wall (earth)with 4 wires (4 of 16 AWG, 65.6 A current capability) and the anode with 2 connections of 3 (16 AWG, 98.4 A) wires to a vacuum feedthrough which was then connected to the anode power supply. A similar arrangement was used for the keeper (2 of 16 AWG, 32.8 A) which was insulated from the cathode by an insulating disc, hereafter referred to as the keeper insulator.

2.3 Power Supplies

2.3.1 Electrical circuit

The initial electrical system is shown in figure 2.3.1 below where there are 3 power supplies: one for the heater(ELEKTRO AUTOMATIK EA-PS-2084-10B (max 84V, max 10A)), one for the keeper(ELEKTRO AUTOMATIK EA-PS 9750-12(max 750V, max 12A)) and one for the anode(ELEKTRO AUTOMATIK EA-PS 9200-70(max 200V, max 70A)).

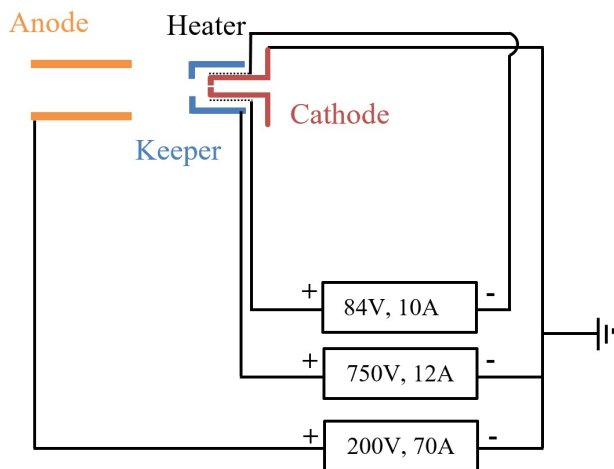


Figure 2.3.1

After initial testing with hydrogen in which it was not possible to ignite the cathode the electrical set-up was modified to include a higher voltage keeper supply(HVKS) which could provide voltages up to 10kV; to protect the keeper supply(KS), diodes were used but these were found to be unreliable and by increasing the flow rates ignition was possible with the 750V keeper supply.

2.4 Vacuum Facility and mass flow control

The vacuum chamber has an inner diameter of approximately 0.6m and is about 1.5m long. It is pumped by two Edwards maglev turbomolecular pumps each of which has a pumping speed of 4500l/s for nitrogen. The backing pump is an Edwards EM240 oil based mechanical pump and the pressure in the chamber is measured by 2 gauges, one a cold cathode penning from Edwards which is combined with a Pirani Gauge for higher pressures ($> \sim 10^{-3}$ mbar) and a Kurt J Lesker hot ionisation gauge(calibrated). Base pressures with no flow were typically around 1×10^{-8} mbar and with flow between a few times 10^{-3} and 5×10^{-5} mbar, depending on the gas and flow rate (typically pressures with H_2 were higher than with Xe)

The flow rate was controlled with Bronkhorst mass flow controllers which were factory calibrated; initial commissioning of the cathode was performed using Xe to check that it was working properly, in which case the mass flow controller used was one that had been calibrated for use with Xe gas in the 0-20sccm range.

Again initial testing was performed with a controller calibrated for flow rates from 0-50sccm of hydrogen but after failure to ignite, the flow controller was returned to Bronkhorst where it was recalibrated for 0-750sccm and another Xe one re-calibrated for 0-100sccm, giving the possibility by combining them of a flow rate of 850sccm of H₂.

Since one of the goals of this work was to use the cathode in a 'bucket' type ion source, some preliminary testing on what the effects of a magnetic field might be on the cathode operation. To accomplish this, 2 high strength Neodymium Boron bar magnets were positioned at the back of the hollow cathode assembly as shown in Figures 2.4.1 2.4.2.

Magnet orientation viewed from rear of the hollow cathode

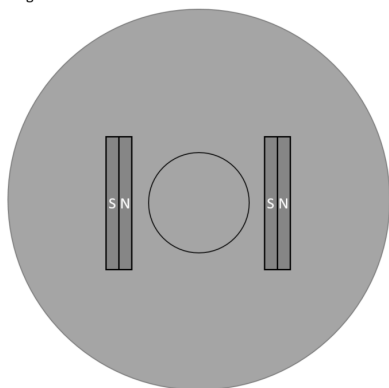


Figure 2.4.1 Schematic of magnet location

Magnets

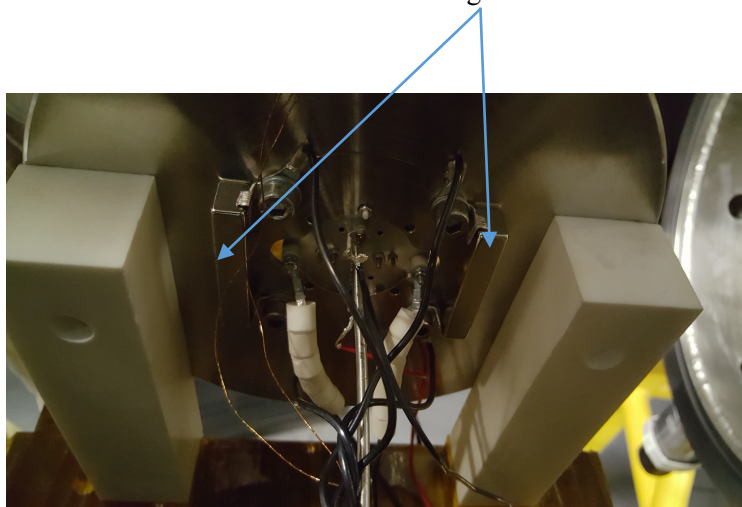


Figure 2.4.2 Magnets at back of the hollow cathode

3. Results

3.1 Initial Results

Preliminary results for operation with hydrogen are shown in Figure 2 for the highest flow rate tested, 250 sccm; in these tests the heater was kept on to ensure stability of the discharge but with the other flow rates used, 100 to 180, stable discharges could be achieved without the heater. As can be seen from the figure typical keeper currents and voltages were of the order of 1.2-2.5A and 32-36V, respectively whilst anode voltages were between 30 and 67V over the range of currents from 6 to 15A. Starting potentials were about 500V at 100 sccm but at 180 sccm 80V was sufficient to ignite the plasma, which is the same as for xenon.

As expected, operation with xenon was easier and stable discharges were observed using a wide range of flow rates from 7.5sccm to 20 sccm at currents ranging from 4 to 40A. Remarkably low anode voltages of about 12.5 V with very stable discharges were found at 20sccm and 40A with no keeper discharge; this voltage is close to the first ionisation potential of Xe which is 12.1299V. At these operating conditions the discharge was hardly visible and in spot mode. Transition to plume mode could be triggered as usual by lowering flow rates at a given current but also by small changes in the keeper current of less than 0.5A and could be predicted just by the appearance of a bright, fluctuating plasma plume. Figure 3 shows some V-I curves for 3 flow rates with the multiple voltages at a given anode current being caused by these small changes in keeper currents inducing spot to plume transitions. Indeed on occasions a bistable mode was found which would oscillate between plume and spot before stabilising at one or the other.

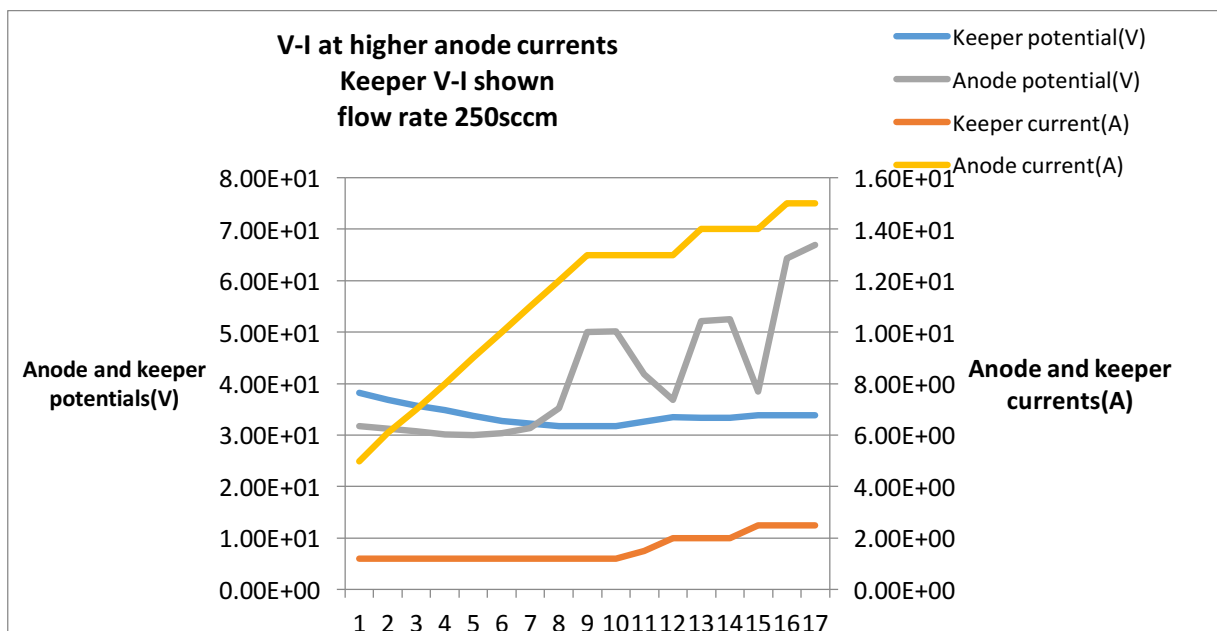


Figure 2 Hydrogen keeper and anode discharge voltages and currents

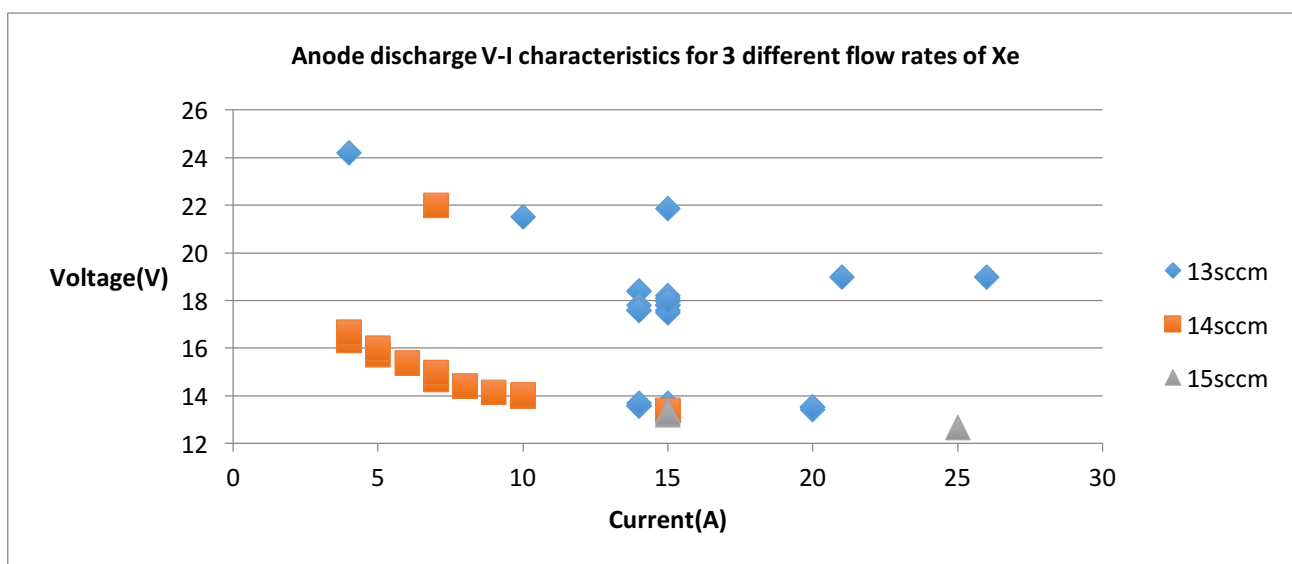


Figure 3.1 V-I characteristics for xenon

The ionisation energies of hydrogen(molecules) and xenon(atoms) are not that different, 13.6 for hydrogen(atomic) and 12.2 for xenon; but to dissociate the H₂ molecule into 2 H atoms requires an approximately 4.7eV. Aside for the extra energy needed to create hydrogen ions(protons) another difference that might explain the failure to ignite at flow rates up to a maximum of 50sccm is that at these flow rates of hydrogen the pressure inside the hollow cathode is significantly lower due to the much lower hydrogen density (atomic number).

3.2 Hydrogen

Stable operation or indeed operation at all, at least in the sense of a current controlled discharge between the anode and cathode was in general difficult to achieve and impossible at flow rates below about 170 sccm. Below that flow rate, high voltage low current (voltage control) discharges were sometimes observed and on occasions, the whole chamber was filled with a plasma with the chamber walls acting as part of the cathode. Figure 3.2.1 shows a summary of the anode voltage current characteristics with and without the presence of a magnetic field.

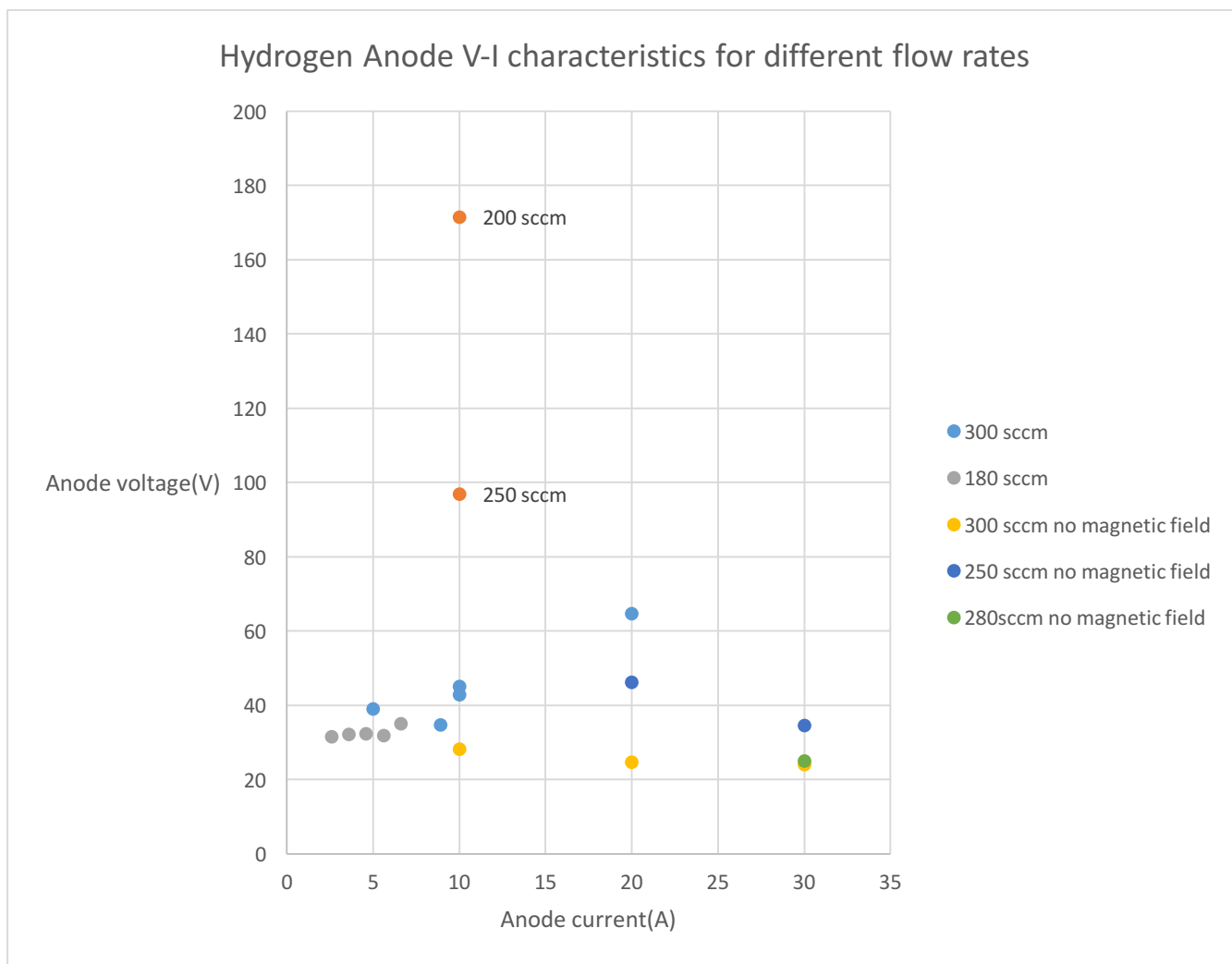


Figure 3.2.1 Hydrogen anode V-I curves with and without a magnetic field for various mass flow rates.

The most obvious differences between the characteristics with and without the presence of a magnetic field are that the voltage increases with increasing current with a magnetic field and vice versa. It can also be seen that the voltages for the same current are higher with a magnetic field present for the same mass flow rate and that with decreasing mass flow rate the voltages increase with and without a magnetic field. The effect of the predominantly radial magnetic field can be seen visually in Figures 3.2.2, which show photographs of operation under different conditions. In Figure b) the 'bending' of the current(plume) towards the bottom of the anode can be seen along with clear heating of the anode along this surface.

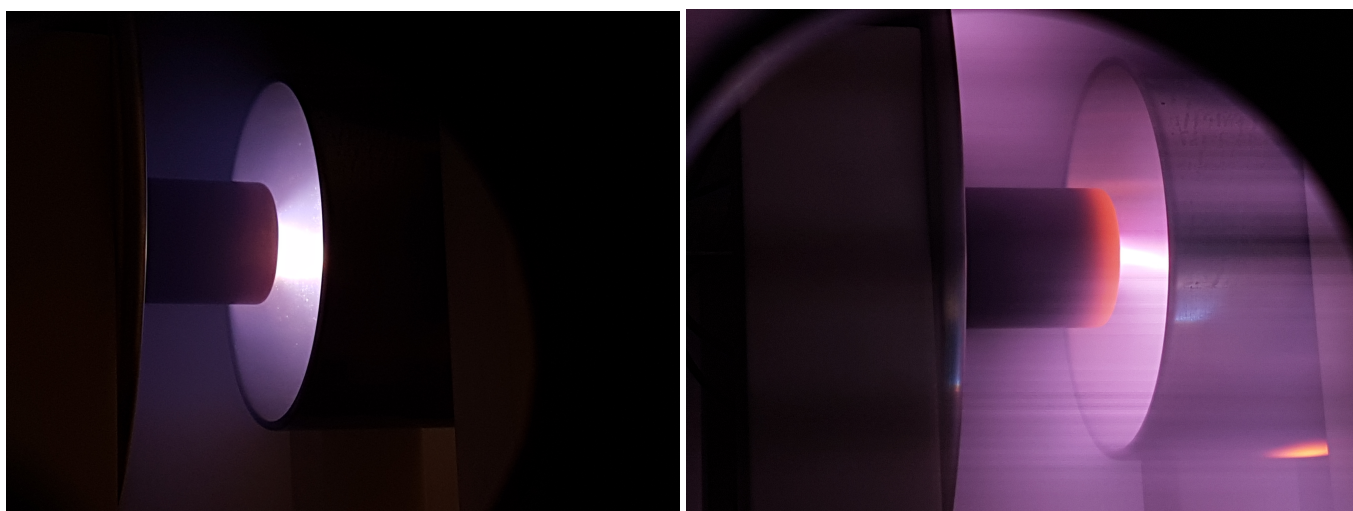


Figure 3.2.2 (a) Hydrogen with no applied magnetic field (b) with an applied magnetic field

3.3 Xenon

As mentioned before, operation with xenon was as expected much easier than with hydrogen, with reliable starting at applied keeper potentials of 80V and stable spot mode discharges from about 5 to 40A. Rather than the normal technique of determining if the cathode was running in plume mode by measuring keeper potential noise levels, the absolute value of the anode potential was found to be a rather good indicator and when in spot mode the discharge was almost invisible with almost no emitted light. The latter can be clearly seen in the photographs shown in Figures 3.3.1a) and b) which show spot and plume modes, respectively.

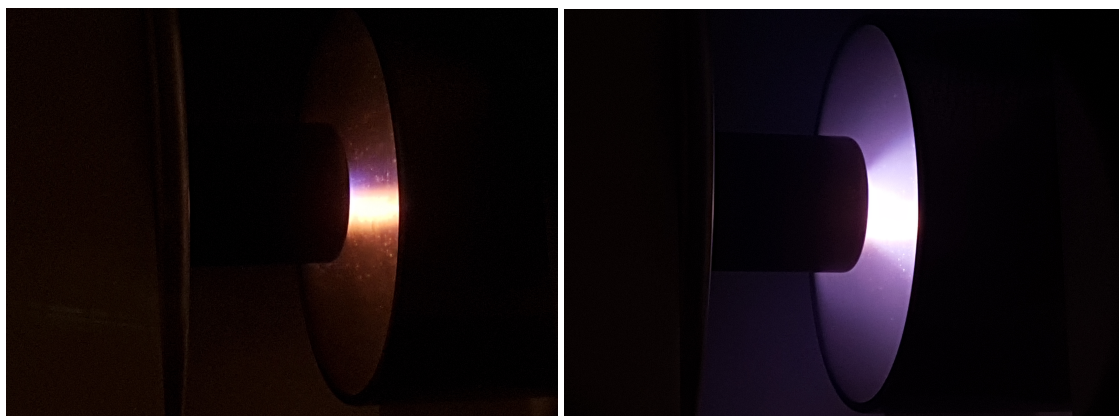


Figure 3.3.1(a) Xe spot mode

(b) Xe plume mode

Figure 3.3.2 summarises the voltage current characteristics for a range of currents and mass flow rates.

At 10 sccm, the anode voltages are relatively high indicative of plume mode and there is little change in the voltage with current whilst at 15sccm and 15A the voltage falls to around 13.7V indicative of spot mode; a lower flow rate of 7 sccm, the anode voltage increases to about 25.5V. For these tests the keeper currents were between 3 and 4A with voltages between 18.4 and 22.3V.

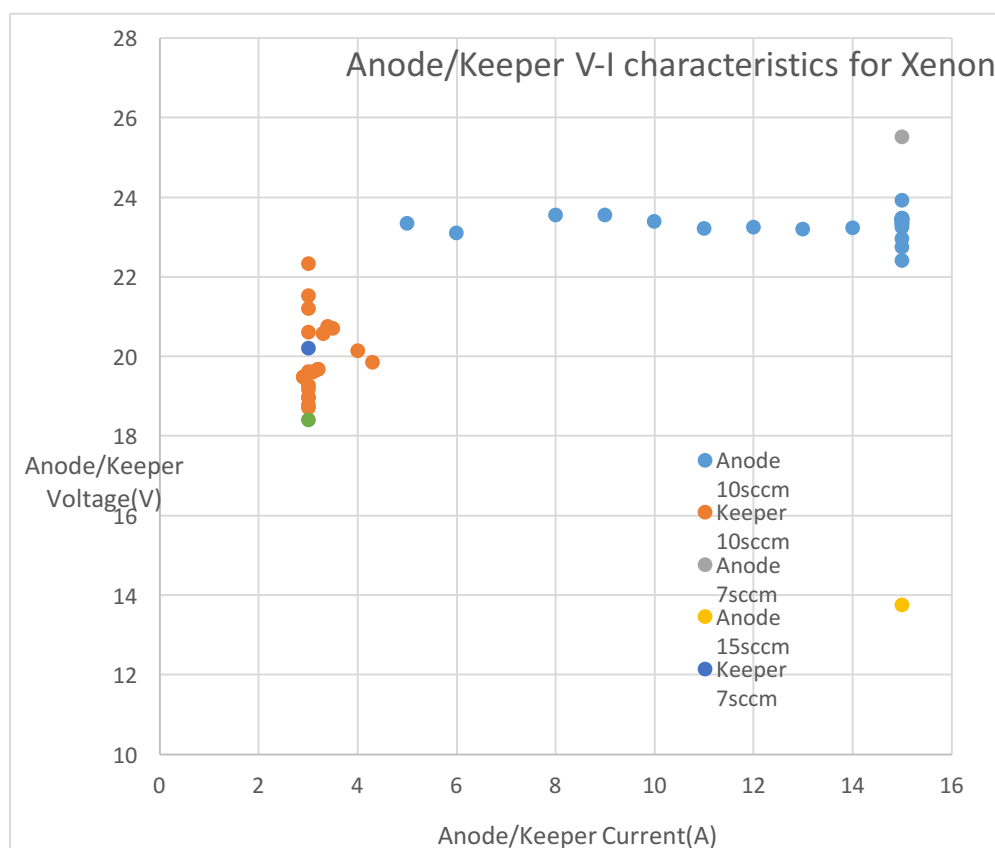


Figure 3.3.2 Xenon V-I characteristics for 5 to 15A anode currents.

3.4 Krypton

Operation with krypton was similar to that with xenon but in general higher mass flow rates were required for spot mode and anode potentials were higher than with xenon at the same current. A photograph of the cathode running with krypton is shown in Figure 3.4.1. The voltage current characteristics for krypton compared to xenon with the keeper off over the current range of 10 to 40A is shown in Figure 3.4.2.

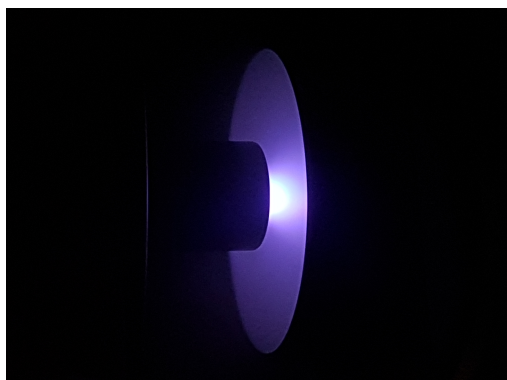


Figure 3.4.1

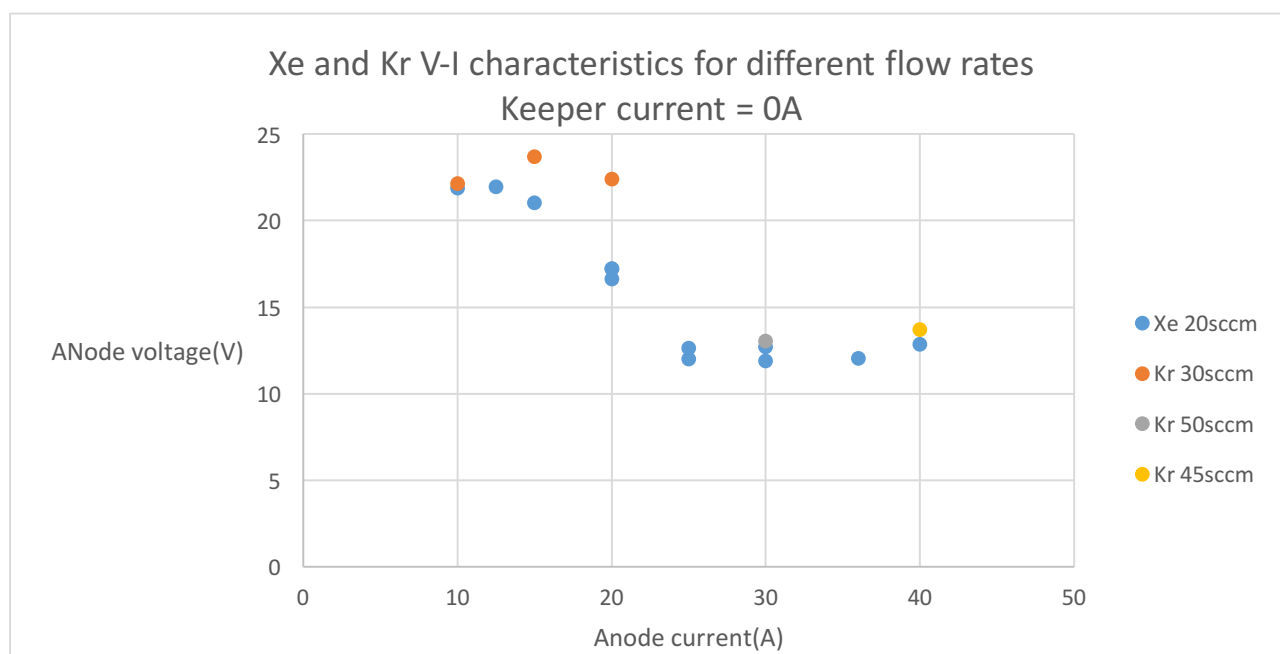


Figure 3.4.2 Xe and Kr discharge V-I characteristics between 10 and 40A.

At 10A, a flow rate of 30 sccm of krypton gives approximately the same anode potential of approximately 22V with a flow rate of 20 sccm of xenon, while at this same flow rate of krypton, the anode potentials are 3 and 5 V higher at currents of 15A and 20 A, respectively. At higher currents of 30 and 40A, Kr flow rates of 50 and 40 sccm, respectively are needed to get about the same anode potentials with Xe at 20 sccm.

3.5 Gas Mixtures

Testing was performed with gas mixtures of xenon and hydrogen and xenon with krypton over a range of currents and mixture ratios to see if the addition of a small quantity of xenon to hydrogen could a) reduce the starting potentials and b) allow more stable operation, preferably in spot mode with lower flow rates of hydrogen; for krypton the objectives were more aimed at investigating under which mixture ratios spot mode could be achieved. Figure 3.5.1 summarises the results for both xenon/hydrogen and xenon/krypton testing and shows a plot of the anode potential against the mixture ratio, defined as the ratio of the xenon volumetric flow rate to that of the other gas. This parameter was selected since it was found to be a good indicator of which mode the discharge was running in.

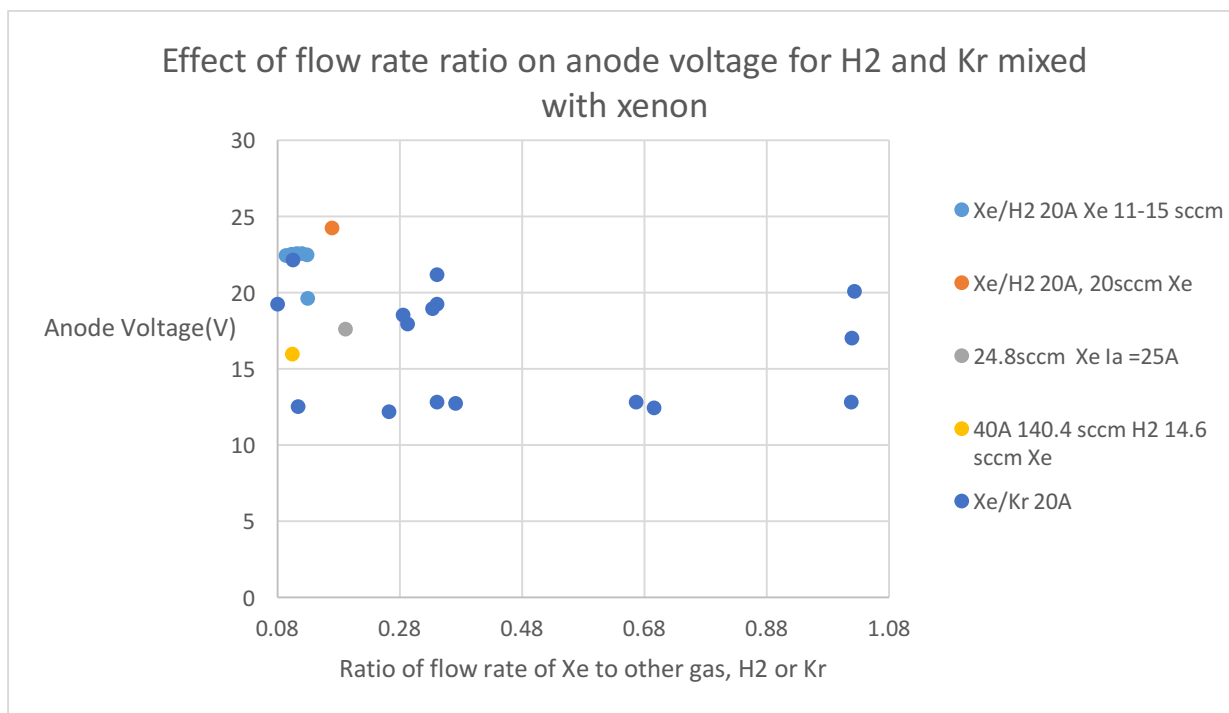


Figure 3.5.1 Anode potential versus gas mixture ratio

Testing with krypton hydrogen was also tried and resulted in similar results to the Xe/H₂ tests, but which are not shown here; in general, the results were not as good in the sense that higher flow rates of krypton were needed for a given hydrogen flow rate to achieve stable spot mode operation at a given current. As far as starting of hydrogen discharges, with about 15 sccm of xenon and a flow rate of 115sccm, starting could be achieved with 50V on the keeper.

Figure 3.5.1 shows some trends in terms of the anode potential for a given anode current of 20A although they are not that clear; if one assumes that the lower anode potentials of around 12 to 12.8V are indicative of spot mode, then it seems that for Xe/Kr, spot mode is present over the full range of mixture ratios from about 0.1 to just over 1. However, there is over this whole range a sensitivity to the actual flow rate with even a small change in this mixture ratio resulting in a mode change to plume, with even the higher mixture ratio resulting in higher anode potentials, indicative of plume mode. An example of this is at the mixture ratios of 0.34 where for the same mixture ratios (within uncertainties), one gives an anode potential of 12.8V, 2 around 19 and one around 21V. The individual flow rates for the 12.8V point are Xe 10.49sccm, Kr 30.79sccm, for the 18.95V point Xe 9.99sccm, Kr 29.94sccm, for the 9.24V point Xe 8.99sccm, Kr 26.42sccm and for the 21.16V point Xe 7.49sccm, Kr 21.98sccm. So although the mixture ratios are almost the same, the flow rates of both gases are decreasing and hence the total flow rate.

For hydrogen xenon mixtures, the situation looks less clear since, for example, for the 2 points shown around a mixture ratio of 0.128, the individual flow rates are anode potential 22.47V, Xe 15.0, H₂ 116.54 sccms and 19.61V, Xe 14.9, H₂ 115.28 sccms; this seems to be contrary to the Xe/Kr results but needs further investigation including a systematic uncertainty analysis and repetition of these points. Nevertheless, the point shown as 20A, 20sccm seems to support these results since the flow rates are Xe 19.91sccm and H₂ 117.55sccm whilst the anode potential is 24.26V. For the 25A point shown, the flow rates are Xe 24.79sccm and H₂ 130.05sccm which is a higher flow rate of both gases and hence total yielding a lower voltage of 17.46V. At 40A, with a mixture ratio of about 10%, the anode potential drops to about 16V and the discharge would appear to be in spot mode.

Another way of looking at it is illustrated in Table 3.5.1 (20A anode discharge and 5A keeper currents) where the minimum flow rate needed for spot mode for each gas separately is shown. Assuming that if the same ratio of 15/44 (which is exactly the ratio used in the analysis above when describing Figure 3.5.1) would result in spot mode then by using 50% of the minimum for each gas should also give spot mode but does not, with 140% of the 7.5 and 22 sccms being required to maintain spot mode.

Table 3.5.1

anode voltage (v)	keeper voltage (v)	Xe (SCCM)	Kr (SCCM)	Comment
12.44	11.47	0	44	min spot
13.21	11.42	15	0	min spot
21.61	11.65	7.5	22	plume 50% ratio
19.29	11.22	9	26.4	plume 50% ratio, 120%
12.8	11.02	10.5	30.8	spot 50% ratio, 140%
12.39	11.07	3.75	33	

4. Conclusions

Testing has been performed on different gases, including hydrogen, krypton and xenon along with mixtures of H₂/Xe and Xe/Kr in a hollow cathode, in a diode configuration, with an LaB₆ insert over a wide range of flow rates, mixture ratios and currents. The results for hydrogen are probably the most comprehensive published to date and indicate stable spot mode operation at flow rates of around 300 sccm. Application of a strong magnetic field from 2 high strength bar magnets at the rear of the cathode assembly resulted in general in higher anode potentials and a clear asymmetry in the plasma plume which could be seen to bend towards the bottom of the cylindrical anode; the applied magnetic field also appeared to change the normal negative resistance characteristic to a positive one.

The V-I characteristics with xenon and krypton were consistent with other published data although comparison with krypton data is not readily available in the literature. With xenon spot mode was found to result in almost invisible plasma plumes and low voltages around the first ionisation potential (12.8V). By adding xenon to the hydrogen, starting could be achieved at lower flow rates and at keeper voltages around 50V. For the gas mixtures, the mode of operation was found to depend not only on the magnitude of the mixture ratio but also on the combined total flow rate, with higher total flows resulting in spot mode and whilst this trend seemed clear for Xe/Kr, the effect for Xe/H₂ was not so evident and needs further investigation.

References

- [1] I.F.M. Ahmed Rudwan and S.B. Gabriel, "Investigation of the Discharge Characteristics of the T6 Hollow Cathode Operating on Several Inert Gases and Kr/Xe Mixture", International Congress on Plasma Physics, Sydney, July 2002.
- [2] Gerd Krulle, Monika Auweter-Kurtz and Akihiro Sasoh, "Technology and Application Aspects of Applied Field Magnetoplasma-dynamic Propulsion", Journal of Propulsion and Power, Vol. 14, No. 5, September–October 1998
- [3] Adam Boxberger, Patrick Bambach, Georg Herdrich, Stefanos Fasoulas, Mario Merino, Eduardo Ahedo, "Experimental Investigation of Steady-State Applied-Field Magnetoplasma-dynamic Thrusters at Institute of Space Systems", AIAA 2012-4012, 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 30 July - 01 August 2012, Atlanta, Georgia
- [4] Tomoya Suzuki, Norihide Koyama, Yoshikazu Sugiyama, Hisao Sakoda and Hirokazu Tahara, "Performance Characteristics of Steady-State MPD Thrusters with Permanent Magnets and Multi Hollow Cathodes for Manned Mars Exploration", IEPC-2015-197 / ISTS-2015-b-197, Joint Conference of 30th International Symposium on Space Technology and Science 34th International Electric Propulsion Conference and 6th Nano-satellite Symposium, Hyogo-Kobe, Japan, July 4 – 10, 2015
- [5] J. S. Sovey and M. J. Mirtich, "A Hollow Cathode Hydrogen Ion Source" NASA Technical Memorandum NASA TM-73783, Seventh Symposium on Engineering Problems of Fusion Research sponsored by the Institute of Electrical and Electronics Engineers, Inc Knoxville, Tennessee, October 25-28, 1977
- [6] D. M. Goebel and A. T. Forrester, "Plasma studies on a hollow cathode, magnetic multipole ion source for neutral beam injection", Review of Scientific Instruments 53, 810 (1982); doi: 10.1063/1.1137051