Optical Probe Measurements on the Internal Plasma of a T6 Type Hollow Cathode

S. J. Pottinger and S. B. Gabriel
Astronautics Research Group
University of Southampton SO17 1BJ
United Kingdom
sjp1@soton.ac.uk

Abstract

A preliminary investigation of the characteristics of a modified T6 hollow cathode has been undertaken. Initial optical emission spectra of the internal plasma of the hollow cathode have been recorded over a wavelength range of $200nm - 900nm$ using argon propellant. Data was collected over a range of mass flow rates from $1.0mg/s$ to $4.75mg/s$ for discharge currents in a range of $2Amp - 10Amp$.

1 Introduction

The hollow cathode is a source of primary electrons for electron bombardment thrusters and may also be used as a neutraliser. Hollow cathodes are now a space rated device [1], [2]. ESA's SMART-1 mission (small missions for advanced research in technology) is planned for launch later this year and will be another technology validation and science mission [3], [4]. In order for the cathode to reach the current levels of performance it has been extensively studied [5], [6]. However, the properties of the internal plasma of the hollow cathode have not been fully investigated. The high temperature environment within the cathode and the presence of high energy ions which may cause sputtering prohibits the use of conventional plasma diagnostic methods. The small scale of the plasma (diameter of approximately $2mm$ and length $20mm$) makes direct access to the plasma difficult and any perturbation of the plasma caused by diagnostic equipment must be considered. In order to avoid these problems previous studies have used externally placed probes. Radiation emitted from the plasma inside of the cathode was observed and plasma parameters determined [7], [8].

This paper will report on an alternative experimental set up which will allow diagnostic equipment direct access to the plasma with as little as possible physical intrusion into the internal plasma. A specially modified hollow cathode has been designed for this purpose. Diagnostic equipment has been developed which will function in the harsh environment of the cathodes' internal plasma without causing excessive plasma perturbations see section 2.3. Preliminary tests of cathode performance have been carried out. The ability of the optical probes to collect reliable data was investigated. The assessment of the capabilities of the experimental apparatus will be described.

2 Experimental Apparatus

2.1 The Facility

The experimental rig consists of a stainless steel vacuum chamber of diameter $500mm$ and length $500mm$. This chamber is capable of achieving high vacuum ($10^{-7}mbar$) and provides access for the diagnostic equipment via optical fibre and electrical feedthroughs, see figure 1.

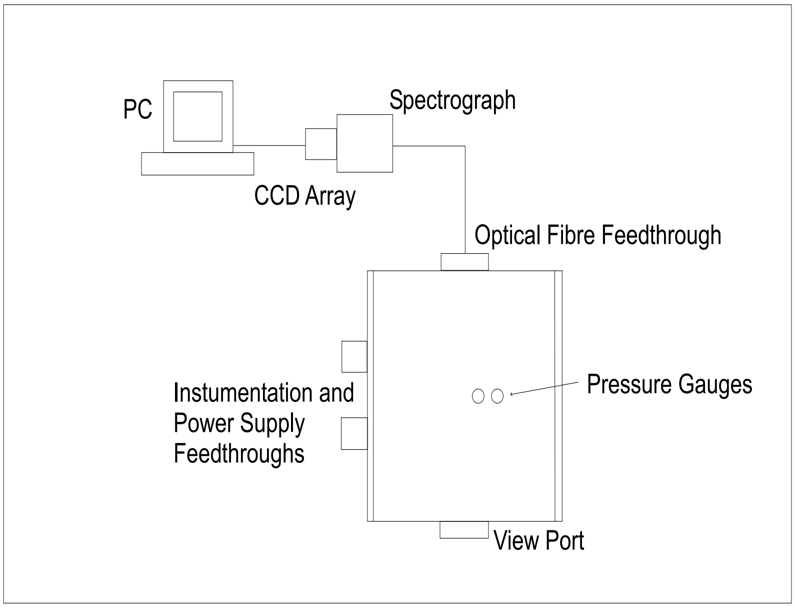

Figure 1: Experimental Facilities

2.2 Hollow Cathode

A modified T6 type hollow cathode has been manufactured by QinetiQ (Farnborough), with dimensions: $36.9mm$ length from tip to flange and $18.9mm$ radius. The instrumented hollow cathode has 14 axial holes with diameter of $0.6mm$ for probe access as shown in figure 2. When the probe access holes are not in use they are blocked off with tantalum pins to ensure there are no propellant leaks. This cathode configuration allows the spatial resolution of the internal plasma in the axial direction with a variety of diagnostic equipment. To the best of the authors' knowledge this type of measurement has not been previously attempted.

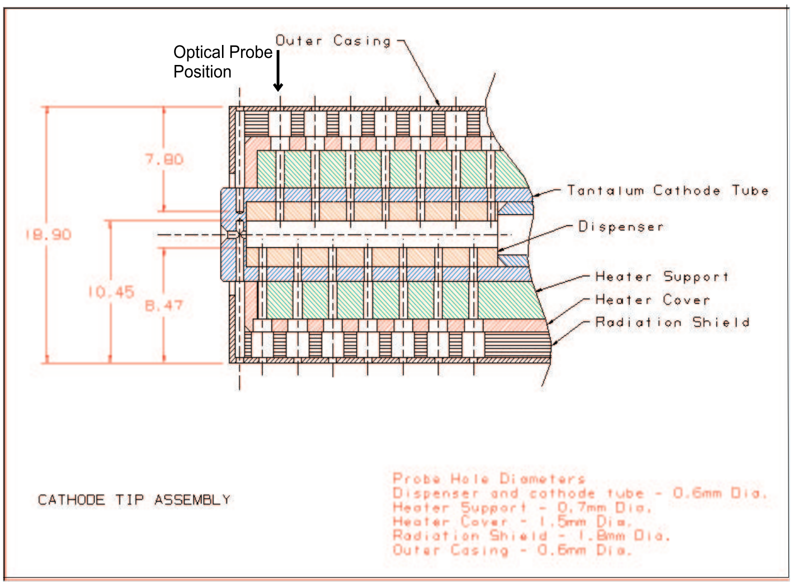

Figure 2: Cathode with Probe Access

2.3 Optical Probes

The optical probes used in this investigation were designed by I. Rudwan of the University of Southampton in collaboration with Dr. D. Fearn. The probes consist of a sapphire fibre (UV grade) surrounded by a tantalum tube of outer diameter $0.5mm$ and inner diameter $0.2mm$. A stainless steel tube of diameter $1.1mm$ provides the protective outer casing as shown in figure 3. These probes have a field of view of 30° half angle which allows an approximate area of $4mm^2$ to be seen by each probe. A multichannel imaging spectrograph was used to display and record the spectra produced. A grating

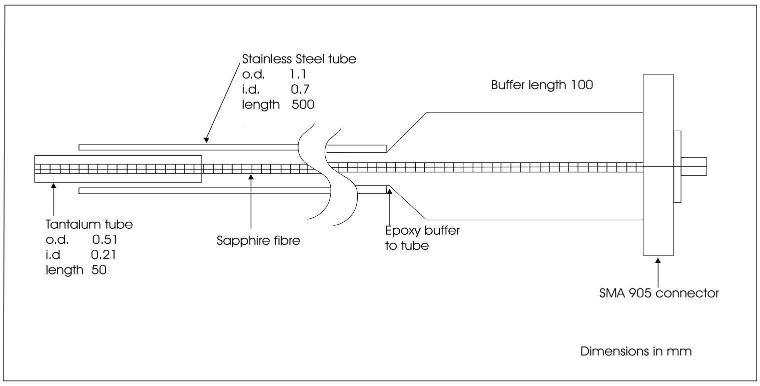

Figure 3: Optical Probe

was installed with a line density of $300l/mm$ and a primary wavelength region of $200 - 750nm$. This grating allows the maximum coverage of the region of the spectrum of interest.

2.4 Cathode Geometry

The experiments were carried out with the cathode and keeper electrode in an open diode configuration. The cathode keeper separation was $3.0mm$. This distance was chosen in order to minimise the noise and oscillation characteristics of the cathode while enabling breakdown to occur at relatively low keeper voltages [9], [10]. The anode was placed $60mm$ from the keeper.

2.5 Experimental Procedure

The experimental results presented in section 3 were collected with the cathode in the geometry described above. The optical probe was placed at a distance of $4.70mm$ from the cathode tip in the second probe access hole as shown in figure 2. Conventional experimental procedures were followed throughout this investigation. One parameter was varied and the effect on the remaining parameters was monitored. The parameters that were varied in this study were the mass flow rate and the anode current. The keeper voltage was set to $0.5Amp$.

3 Experimental Results

3.1 Cathode Characterisation

The voltage current characteristics for the cathode were tested over a range of mass flow rates from $1.0mg/s$ to $4.75mg/s$ and for anode currents of $2.0 - 10.0Amp$. It was found that the plasma discharge became less stable for mass flow rates of $1mg/s$ and below. It was also observed that the discharge became less stable for anode currents of $1Amp$ and below. As can be seen from figures 4 and 5 the following general trends occur:

- For a given mass flow rate, increasing the anode current causes a decrease in anode voltage and keeper voltage.

This trend becomes more evident at low mass flow rates (below $1.5mg/s$) and high rates (above $2.5mg/s$). For mass flow rates between $1.5mg/s$ and $2.5mg/s$ there is little variation in anode voltage with changing anode current.

- For a given anode current, increasing the mass flow rate results in a decrease in anode and keeper voltages.

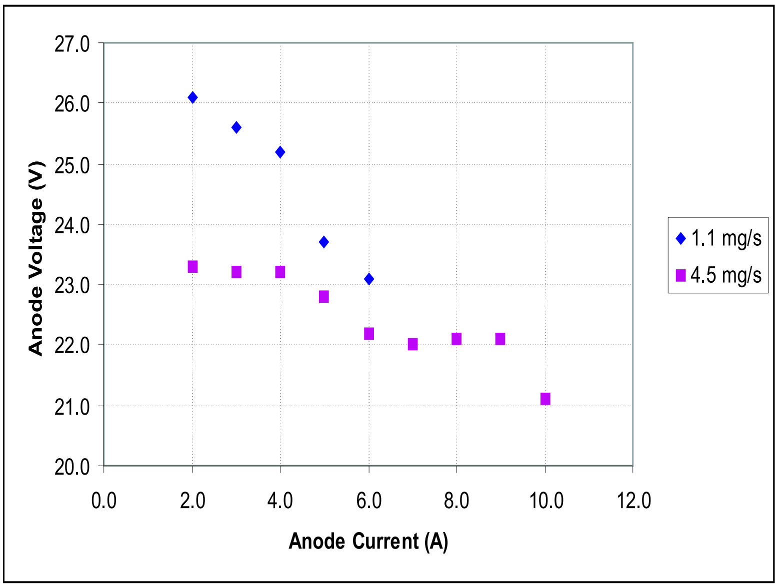

Figure 4: Voltage - Current Characteristic for high and low mass flow rates

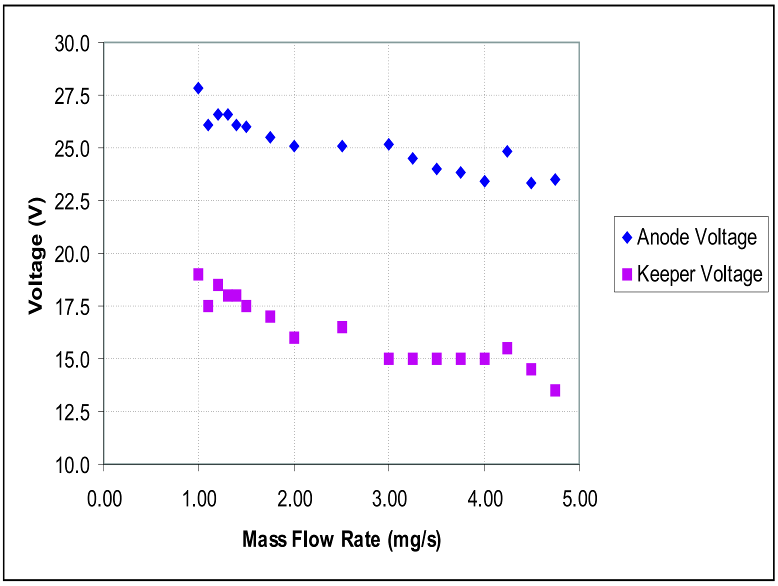

Figure 5: The dependence of anode voltage mass flow rate for a 2 ampere anode current

This trend becomes less pronounced for higher mass flow rates (between $2.5 mg/s$ and $4.75 mg/s$. This implies that electrode voltages are less dependent on mass flow rates after a certain propellant flow rate has been exceeded. These trends are in agreement with those stated by Delcroix and Trindade [11] for a plasma operating in the "N–Regime" or normal regime. Comparisons of the performance of the instrumented cathode with those in literature [12], [13] shows good agreement with the trends stated above.

The voltage current characteristic of the instrumented cathode as shown in figure 4 was compared with those obtained by Edwards [14] and Rudwan [15]. Edwards carried out experiments on a hollow cathode in a UK–25 ion thruster configuration. Argon propellant was used and a magnetic field was present with magnetic current of $0.5 Amp$, a mass flow rate of $0.5 mg/s$ was used. Despite these differences the values for the discharge voltage are comparable. The largest difference of $4.6 V$ occurs for an anode current of $6.0 Amp$. The largest difference in keeper voltages is $8.5 V$ which corresponds to an anode current of $6.0 Amp$. Both the anode and keeper voltages for the instrumented cathode are higher than those obtained for the non instrumented cathode. Rudwan has used an enclosed keeper configuration. Xenon propellant was used at a mass flow rate of $1 mg/s$. Higher anode voltages are displayed for the cathode in enclosed keeper configuration with a maximum difference of $4.1 V$ at $2.0 Amp$. As before the keeper voltages are higher for the instrumented cathode and show little variation with changing anode current.

It becomes difficult to make direct comparisons of voltage current characteristics due to the fact that different cathode geometries and propellants have been used. We are confident that the instrumented hollow cathode displays characteristics similar to those of a non instrumented cathode. The differences shown in the comparisons of various voltage current characteristics are small and all values display the same general trends. Any variations in performance may be attributed to differences in cathode geometry and cathode design e.g. cathode length, radius and aspect ratio or the propellant used. The effect of external parameters on the internal plasma is not clear. It is not known whether these factors will influence what is observed by the diagnostic equipment.

3.2 Optical Spectra

Optical emission spectra were recorded for mass flow rates of $1.0 mg/s$ to $4.5 mg/s$ for argon. The anode current was restricted to $2.0 - 10.0 Amp$, as in the cathode characterisation procedure. Background corrected spectra have been collected over a variety of experimental conditions and display a high degree of consistency. Examples are shown in figures 6, 7, and 8. Spectral lines are visible at the same wavelengths for all experimental conditions. A decrease in line intensity has been observed for $10 Amp$ anode currents at a wavelength of $811nm$. For anode currents of $10.0Amp$ there is an increase in counts from continuum radiation for longer wavelengths ($\lambda > 700nm$). This corresponds to the near infra red region of the spectrum and may be attributed to an increase in temperature of the cathode wall for higher discharge currents. Initial estimates of this temperature have been determined using black body theory. A temperature of $\sim 1500K$ was calculated, this value agrees with cathode tip temperature measurements made by Fearn et. al [13] and Domonkos [12]. Table 1 shows the wavelengths of the strongest spectral lines[1]. It can be seen that transitions within neutral argon atoms are responsible for the majority of intense lines that have been observed.

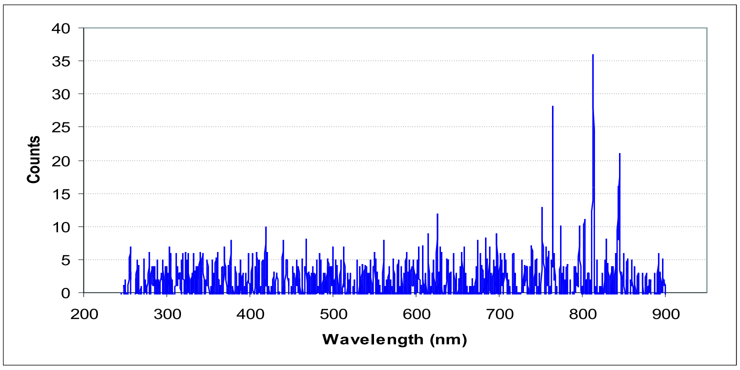

Figure 6: Optical emission spectra for a 2 ampere anode current and mass flow rate of 1.1 mg/s

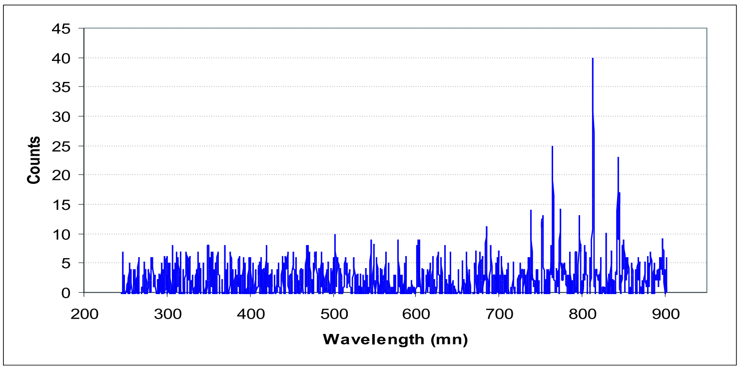

Figure 7: Optical emission spectra for a 5 ampere anode current and mass flow rate of 1.1 mg/s

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[1] Spectral line information was obtained from NIST Physics Laboratory Atomic Spectra Database.

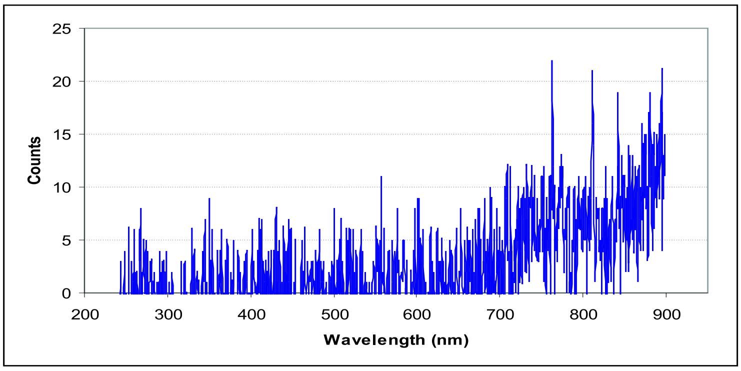

Figure 8: Optical emission spectra for a 10 ampere anode current and mass flow rate of 4.0 mg/s

Atomic Species	Wavelength (nm)	Energy Levels (eV)	Term
Ar I	842.46	11.62359 - 13.09487	2[3/2]*-2[5/2]
Ar I	811.53	11.54835 - 13.07572	2[3/2]*-2[5/2]
Ar I	772.38	11.54835 - 13.15314	2[3/2]*-2[3/2]
Ar I	763.51	11.54835 - 13.17178	2[3/2]*-2[3/2]
Ar I	751.47	11.62359 - 13.27304	2[3/2]*-2[1/2]
Ar II	624.31	17.69467 - 19.68005	4F-2D*
Ar I	419.10	11.72316 - 14.68065	2[1/2]*-2[3/2]

Table 1: Identified argon spectral lines

4 Future Work

The optical emission spectra collected have shown good consistency under varying conditions. This may be further demonstrated by repeating measurements in the same conditions and comparing the resulting spectra to formally assess the repeatability of the data collected. Improvements may be made on the spectra presented above by attempting to increase the signal to noise ratio. This may be achieved by increasing the integration time of the signal or by averaging a number of spectra. A detailed identification of spectral lines will be carried out and an attempt will be made to identify any contaminant lines present such as barium, tungsten or tantalum. It is hoped that the plasma parameters of the internal plasma can also be calculated. Spectral line data as well as the continuum data will be used for the calculations and an appropriate model e.g. local thermodynamic equilibrium (LTE) models or coronal models will be applied.

In the long term, the main objective of this investigation is to spatially resolve the internal plasma of the hollow cathode. This would enable an accurate model of the processes occurring within the hollow cathode to be developed. This work may also verify or contradict the existence of an active emitting region near the cathode tip. Electrical probes are being developed which would be inserted into the cathode probe access holes in order to provide an independent method of determining the plasma parameters. These results will then be compared to those obtained using optical probes. A variety of inert gas propellants will be used through out the study, these include xenon and krypton.

The modified T6 hollow cathode enables a wide variety of diagnostic techniques to be used. It will be possible to produce a thermal characterisation of the cathode with the use of infra red fibres or thermocouples. Experiments concerning the effect of external factors such as keeper electrode and anode geometry on the internal plasma may also be carried out.

5 Conclusion

A modified T6 hollow cathode was developed in order to allow probe access to the cathode internal plasma. Initial results suggest that the modifications made did not adversely effect the performance of the cathode.

Optical probes were used to characterise the plasma near the cathode tip. Optical emission spectra were recorded for a variety of experimental conditions. Strong spectral lines were observed for $\lambda > 750nm$ and less intense lines were present at shorter wavelengths. Further work will be carried out on line identification.

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