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PRELIMINARY RESULTS ON HOLLOW CATHODE CHARACTERIZATION

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Abstract. *Hollow cathodes have been under development at the LAP (Associated Plasma Laboratory) of INPE (The National Institute for Space Research), aiming space applications, particularly for ion thrusters. The present hollow cathodes are built from a ¼ inch tantalum body with tungsten tips having orifices varying from 0.5 to 1mm diameter. Rolled tantalum foil inserts, coated with a mix of (Ba/Sr/Ca)O, are the primary thermal electrons source, and an enclosed keeper is used to startup and maintain the discharge. The experimental setup involves the cathode itself, installed in a vacuum chamber pumped two turbo molecular pumps, a Roots pump and a rotary pump, reaching a base pressure of* 3×10^{-8} *mbar and a working pressure around* 10^{-6} *mbar, depending on the gas load. A cylindrical Langmuir probe is the main diagnostics device to characterize the plasma parameters of the hollow cathode plume. The preliminary performance results were obtained as a function of the mass flow rate, and distance between keeper and probe.*

Keywords: *hollow cathode, plasma plume, ion thrusters, electric thrusters, electric propulsion*

1. INTRODUCTION

Hollow cathodes (HC) are key devices on plasma discharge generation in electric thrusters (ion and Hall). Their characteristics, such as reliability, long lifetime and capability of producing high electron current densities with low heating power consumption make these devices the best option for electron sources in electric propulsion, especially when compared to tungsten filaments (Goebel & Katz, 2008).The HC are used for producing the main plasma in the discharge chamber of electric thrusters and to neutralize the space charge in the ion beam ejected by ion thrusters with demonstrated lifetimes exceeding 30.000 hours (Sengupta, 2005a).

A clear explanation about the operating principle of hollow cathodes is given by Goebel and Katz, 2008, which is transcribed here: “A generic hollow cathode is shown in Fig. 1, where the cathode consists of a hollow refractory tube with an orifice plate on the downstream end. The tube has an insert in the shape of a cylinder that is placed inside the tube and pushed against the orifice plate. This insert is the active electron emitter, and it can be made of several different materials that provide a low work function surface on the inside diameter in contact with the cathode plasma. The cathode tube is wrapped with a heater (a co-axial sheathed heater is shown in the Fig. 1) that raises the insert temperature to emissive temperatures to start the discharge. The electrons emitted from the insert ionize gas injected through the cathode tube and form a cathode plasma from which the discharge-current electrons are extracted through the orifice into the thruster plasma”.

The hollow cathodes under study are equipped with oxides rolled tantalum foil inserts and built with technology entirely developed at LAP (Associated Plasma Laboratory) at INPE. This type of inserts was adopted because they are cheaper than the Barium-impregnated ones and they do not demand costly and special laboratory facilities to be produced. The LAP HC consists of a thin rolled tantalum foil covered with carbonates (Ba, Sr, Ca) forming a multilayer device that is then integrated into the cathode body. These cathodes have been tested with the ion thrusters under development at LAP, and so far no particular experiments were dedicated to them before in terms of performance characterization.

The motivation here is, thus, to study the axial plasma parameters variation along the distance from the keeper plate, inside the plasma plume located outside of the cathode and for different mass flow rates of Argon. Similar studies have

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been carried out by Martin, R.H., *et al. in* 2005 who employed a rapidly actuating Langmuir probe to measure the plasma properties near a hollow cathode. In this paper typical plasma environments were assumed to be represented by a 30 V plasma potential, 6.5 eV electron temperature, and 10^{13} cm^{-3} plasma density.

In the present paper, the plasma parameters that were under investigation are the plasma densities (electron and ion), electron temperature and both floating and plasma potentials. The post-processing results obtained were also compared amongst themselves as multiple raw data were processed with four different methodologies.

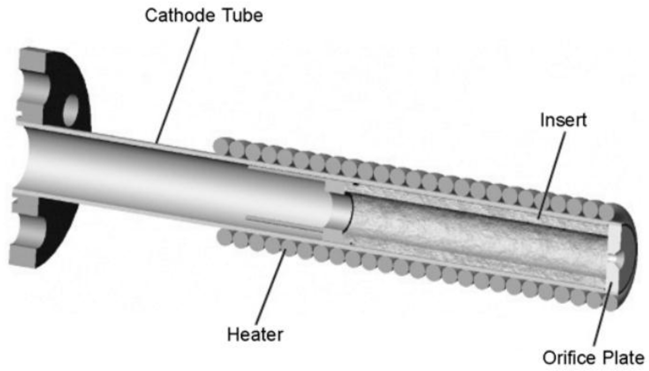

Figure 1. Typical hollow cathode geometry of a refractory metal tube with an emissive insert inside and a heater wrapped on the outside (Goebel & Katz, 2008).

2. EXPERIMENTAL SETUP

The main components of the LAP HC are shown in Fig. 2 and are basically the same as the one shown in Fig.1, except the enclosed keeper is different. This electrode is used for cathode ignition and discharge maintenance. It consists of a stainless steel body and a graphite plate with a 3 mm diameter orifice in the center located at its downstream end. The cathode consists of a 6.35 mm diameter tantalum tube equipped with a tungsten plate with a 0.64 mm diameter orifice in its center and an external wrapped sheathed heater. A 25 µm thickness tantalum foil covered with carbonates solution (Ba, Sr, Ca) is rolled to conform the insert in the shape of 5.2 mm external diameter and 2.5 mm internal diameter multilayer tube.

The experimental setup for hollow cathodes characterization in mounted on the door of the vacuum chamber, as shown in Fig. 3. It consists of a hollow cathode, cylindrical anode (110 mm diameter, 40 mm length and 3 mm thickness stainless steel) located at 94 mm from the keeper, and a cylindrical Langmuir probe. The probe can be moved along the cathode axis to measure the plasma parameters (in cathode plasma plume), placing it at different distances (d_p) from the keeper. A 80 cm diameter by 120 cm length vacuum chamber equipped with two turbo molecular pumps, with total pumping speed of 4600 l/s (for N_2), pumped by a 250 m^3/h Roots pump and an 80 m^3/h rotary pump, ensure running tests a base pressure of 3 x 10^{-6} Pa with no gas load and in the range of 2 to 5 x 10^{-4} Pa depending on the propellant gas mass flow rate.

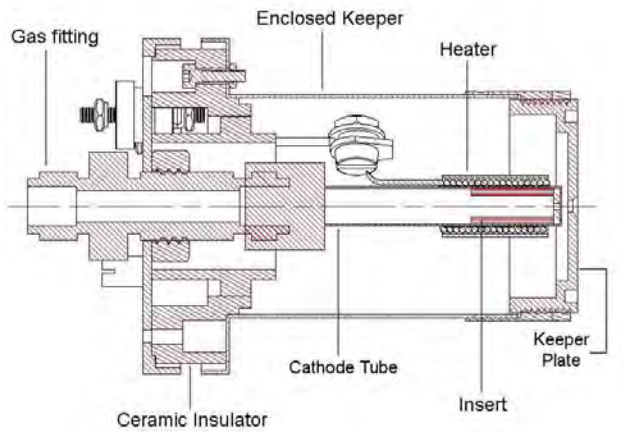

Figure 2. LAP hollow cathode schematics

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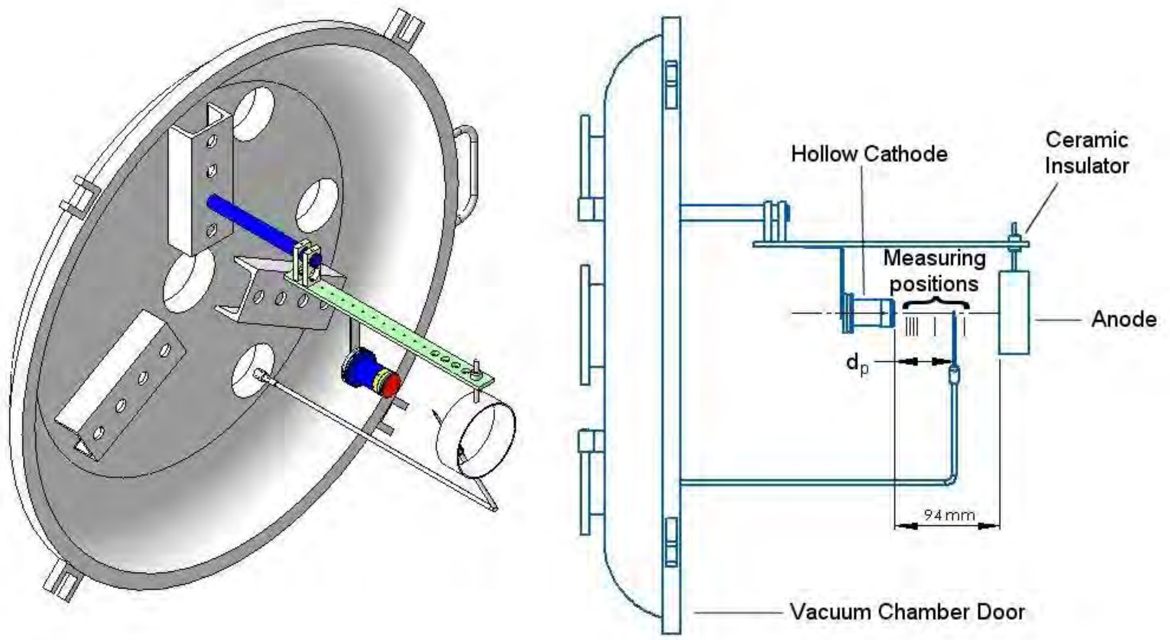

Figure 3. Hollow cathode assembled on the vacuum chamber door. d_p: distance from cylindrical probe to keeper.

2.1 The cylindrical Langmuir Probe

A Langmuir probe is an electrostatic probe that performs basic diagnostics of main plasma parameters, which are: the electron plasma density n_e, electron temperature T_e and both floating and space potentials, such as floating potential and plasma potential, ϕ_f and ϕ_p , respectively (Conde, 2011). The probe can be simple or double type. The simple probe consists of an electrode that is introduced into the plasma and connected to a power supply that can be biased in several potentials either positive or negative in relation to the plasma, thus, an electric current is collected as function of these potentials. A return electrode at ground potential usually completes the circuit and the conductive portion of the vessel wall that is confining the plasma is used for this end (Merlino, 2007a) (Chung, et al., 1975). A typical current-voltage curve (I-V) is subdivided in three different regimes which are ion saturation (I), transition (II) and electron saturation (III), as shown in Fig. 4.

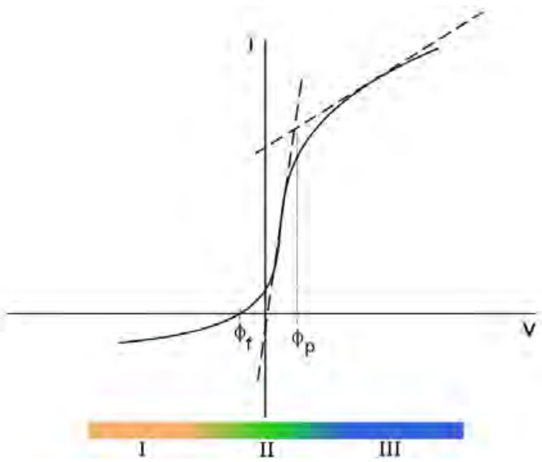

Figure 4. Typical I-V probe curves for different probe geometries. **I** is the ion saturation region; **II** is the transition region; and, **III** is the electron saturation region. ϕ_f: floating potential, ϕ_p: plasma potential.

The output of the Langmuir probe system generates I-V curves by using a data acquisition system that controls a programmable bipolar power supply to generate a triangular voltage ramp (from negative to positive voltages) and post process the data in terms of plasma parameters. The code for processing the probe signal was developed by ITA (Brazilian Technological Institute of Aeronautics) (Pessoa, et al., 2007b) in LabView™ platform and it was updated

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for hollow cathode characterization (Pereira, 2012). The following physical and numerical approaches are used to calculate the plasma parameters in the different regions of the characteristic curve:

- Orbital Motion Limited Theory - OML: is used in the ion saturation to estimate the ion density
- Classic Langmuir procedure: is used in both the transition region where the probe potential is $\phi_p < \phi_{sp}$ (ϕ_{sp} is the space potential) and in the electron saturation region for the determination of floating and plasma potentials, electron density, electron temperature and Debye length
- Exponential fitting: is used in addition to the Classic Langmuir procedure for both ion saturation and transition regions to estimate the same plasma parameters except the floating and plasma potentials.
- Druyvesteyn procedure: is used in the derivation the I-V curve to obtain the Electron Energy Distribution Function (EEDF) and further estimation of the effective electron temperature, electron density and plasma potential by the respective integration of the EEDF.

The cylindrical Langmuir probe is shown in Fig. 5 and it consists of a 1 mm diameter and 120 mm length tungsten wire, with an exposed tip of 8 mm to the plasma plume. A 3 mm external diameter and 1.4 mm internal diameter alumina insulator is used to avoid electric current collection by the remaining conductive parts of the probe wire and its electrical connections. A motion leadthrough is used to transmit both rotation and translation movements to the probe stainless steel arm (a 6.35 mm external diameter stainless steel tube). Once the axial measuring position is set by translation movement, the probe is rotated until it is immersed into the plasma plume for I-V curve tracing. Afterwards, data acquisition stops and the probe is immediately moved out of the plume region to avoid the overheating and erosion of the probe tip. An external endstop is used to ensure the probe is always centered on the cathode axis after rotation to immerse it into the plume.

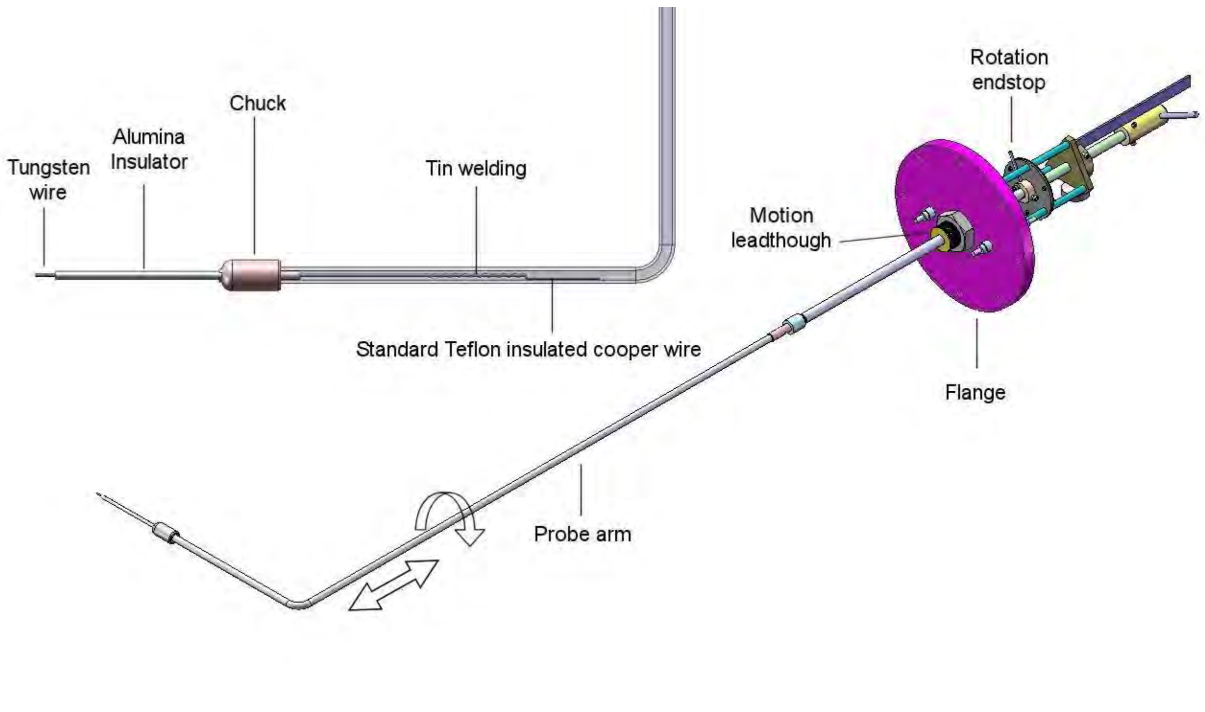

Figure 5. Cylindrical electrostatic probe schematics.

2.2 Experimental procedure

The chamber is pumped down to base pressure of 3 x 10^{-6} Pa and the cathode temperature is raised to about 800 ^{o}C by increasing the heater current up to 7 A in 1A/min steps. The discharge ignition takes place with the keeper at 200 V relative to the cathode and argon mass flow rate is set to the desired value (typically in range of 2 to 4 sccm). Once a steady electric discharge between the HC and the keeper is reached the heater is turned off and the keeper current is adjusted to 2 A, resulting in a keeper voltage in the range of 24 V to 30 V. At this point the measurements can then be carried out by either biasing the anode with a ground potential (0V) or by biasing the anode with a voltage of 200 V. In the latter case currents in the 500 mA to 700 mA range are recorded. The values of both keeper voltage and anode currents depend on the cathode operating parameters.

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The I-V curves were traced for different locations from the keeper, starting with a spacing of 2 mm and increasing it up to 20 mm in 2 mm steps, and to 50 mm in 10 mm steps. The spacing was set using a blade gauge. The probe is exposed to the plasma plume by rotating it up until the motion leadthrough reaches its endstop or before it if another measurement position is reached. The probe is then removed from the plume by rotating it back immediately after the data collection is completed. For each measuring distance a series of five I-V curves are taken for the sake of precision on data processing.

Data acquisition is set to the following parameters:

- Ramp voltage range: ± 100 V
- Number of points: 2.000
- Oversampling rate: 200 times
- Sampling period: 5 ms between samples

The power supply intrinsic noise must be subtract from the I-V curves in the post processing step in order to avoid obtaining incorrect plasma parameters. The power supply noise is traced with no plasma discharge and with the full probe circuitry. The noise generated by the Kepco™ BOP 200-1M (0 to ± 200 V, 0 to ±1 A) power supply is shown in Fig. 6a. An example of correction of I-V curve by noise subtraction is shown in Fig. 6b.

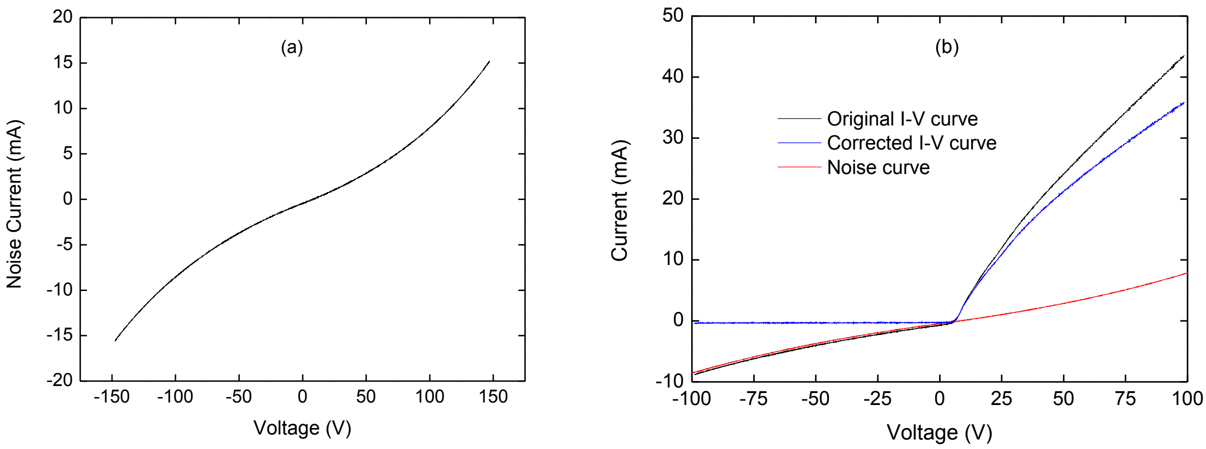

Figure 6. Power supply noise current (a) and example of I-V curve correction by noise subtraction (b).

3. RESULTS

The plasma parameters, computed using the four approaches described in Section 2.1, are presented and discussed in the next sections.

3.1 Plasma and floating potentials

The post processing code first calculates the plasma potential and the floating potential. The plasma potential estimated using the first and second derivation of I-V curve is then used to obtain the remaining parameters.

The plasma potential exhibits a remarkable difference comparing the output of the two procedures used, i.e., the first and second derivate of I-V curve and the Langmuir method (intersection of the asymptotes in transition and electron saturation regions in semi-logarithm I-V plot), as shown in Fig. 7.

It can be noticed that the plasma potential is nearly constant for the case studied where the anode is unbiased for both approaches as shown in Figs. 7a and 7b. For this last condition, the values obtained using derivation of I-V curve are lower than those obtained by Langmuir procedure and agreed with the values obtained by Martin, R.H., *et al.,*2005, where the anode was placed at 130 mm away from the hollow cathode.

The plasma potential increases for both approaches biasing the anode and they are even greater when calculated by the derivation procedure. In this case, the plasma potential grows rapidly up to a distance of 20 mm for both argon mass flow rates and is nearly constant for 4 sccm and a pronounced variation for 2 sccm as the distance increases. The larger values of the plasma potential can be explained by the space charge unbalancing in the plume by the electron drain towards the biased anode, resulting in both more positive floating and plasma potentials.

The floating potential is shown in Fig. 8 and it is independent on the procedure used, since it is the point in I-V curve where the electron and ion fluxes in equilibrium, i.e., where the probe current is zero. It was observed that the floating potential increases when biasing the anode and increases as the Argon mass flow rate increases.

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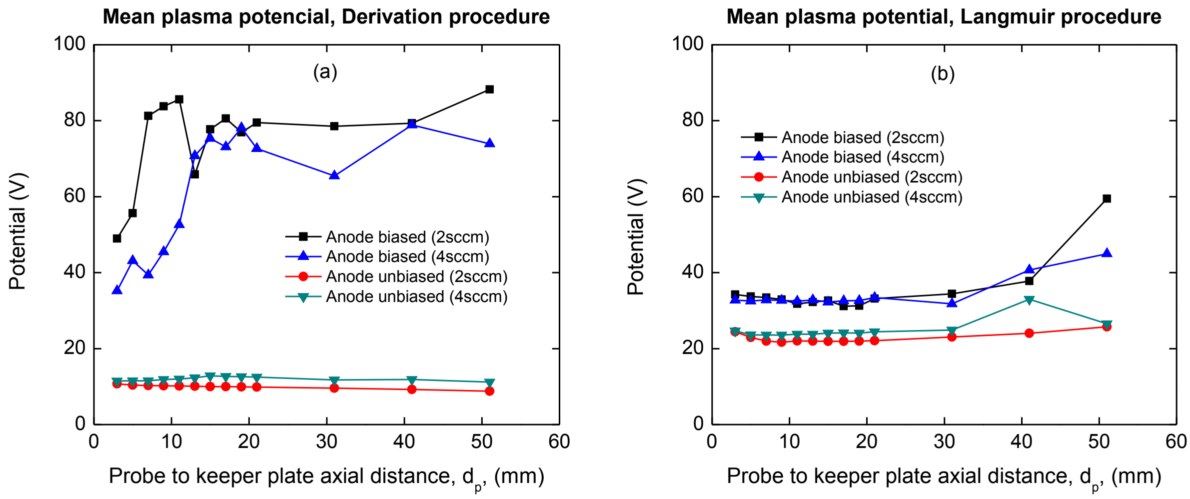

Figure 7. Plasma potential obtained using I-V curve derivation procedure (a) and Langmuir procedure (b)

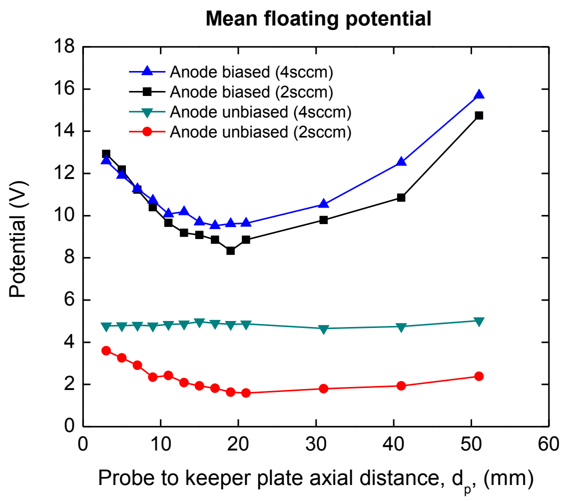

Figure 8. Floating potential.

3.2 Electron density

The results obtained for the mean electron density, shown in Fig. 9, reveal that none of the procedures described in section 2.1 produce results in good agreement amongst themselves. The only agreement observed is the same order of magnitude of all plots (in the range of 10^{12} – 10^{13} cm^{-3}). Nevertheless, the exponential fitting method results in larger values for the mean electron density with a similar profile obtained by the Langmuir procedure, as shown in Figs. 9c and 9a.

Increasing the Argon mass flow rate from 2 sccm to 4 sccm, keeping the anode unbiased, yields an increase and decrease of the mean electron density as the probe is placed farther from the keeper plate, as shown in Figs 9a, 9b and 9c. However, there is no regular behavior as the mass flow rate is increased if the anode is biased.

The order of magnitude obtained for the plasma densities prove that this device is indeed providing a typical hollow cathode plasma environment, as declared by Martin, R.H., *et al.,*2005.

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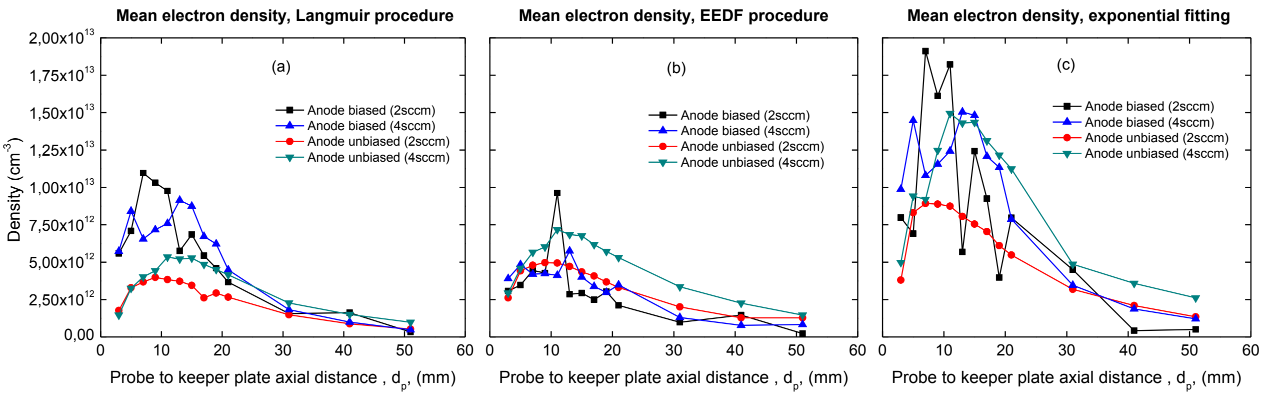

Figure 9. Mean electron density obtained by Langmuir (a), EEDF (b) and exponential fitting (c) procedures.

3.3 Electron temperature

The mean electron temperature is nearly constant and is lower for the different procedures for unbiased anode with both argon mass flow rates, as shown in Figs. 10a to10c. These values confirm again that the experiments were carried out on a typical plasma environment.

Nevertheless, the mean electron temperature increases for distances greater than 20 mm in the case of biased anode with the Langmuir method (Fig.10a) and exhibits values remarkably greater when the EEDF procedure is adopted, as shown in Fig. 10b. The plasma temperature increases for distances closer to the anode, and this can be attributed to the charge unbalancing produced by a more effective electron flux accelerated toward the anode.

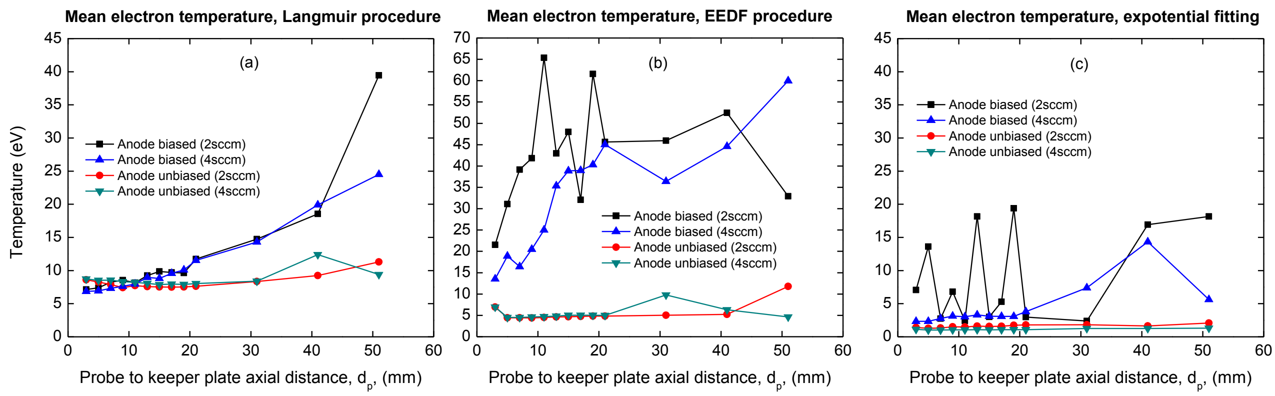

Figure 10. Mean electron temperature obtained by Langmuir (a), EEDF (b) and exponential fitting (c) procedures.

3.4 Debye length

A similar plot profile for the Debye length is observed for both Langmuir and EEDF procedures for unbiased anode, as shown in Figs. 11a to 11c, being slightly lower for EEDF procedure and remarkably lower for exponential fitting approach. Notice that in these cases increasing the argon mass flow rate minor variations are produced only for distances greater than 20 mm from the keeper plate and, also, that the Debye length increases for larger distances from the keeper plate.

When the anode is biased the Debye length starts at lower values compared to the unbiased but it greatly exceeds the unbiased as the axial distance increases, as shown in Fig.11a for the Langmuir method. The profile and magnitude of the Debye length is notably altered for EEDF procedure in which larger values and distinct differences are observed for the different mass flow rates used, as shown in Fig. 11b. When the exponential fitting method is used, the lowest values for the Debye length are obtained and rugged profiles are observed for a mass flow rate of 2sccm, as shown in Fig.11c. As the Debye length can be estimated in practical units by Eq.(1):

$$\lambda_D = 745\left[T(eV)/n_e\left(cm^{-3}\right)\right]^{1/2} \tag{1}$$

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where T is the electron temperature and n_e is the electron density, then a more dramatic increase in electron temperature, while keeping a smooth decay in electron density, produces a remarkable increase in the Debye length for distances larger than 40 mm, as shown in Figs 11a and 11b.

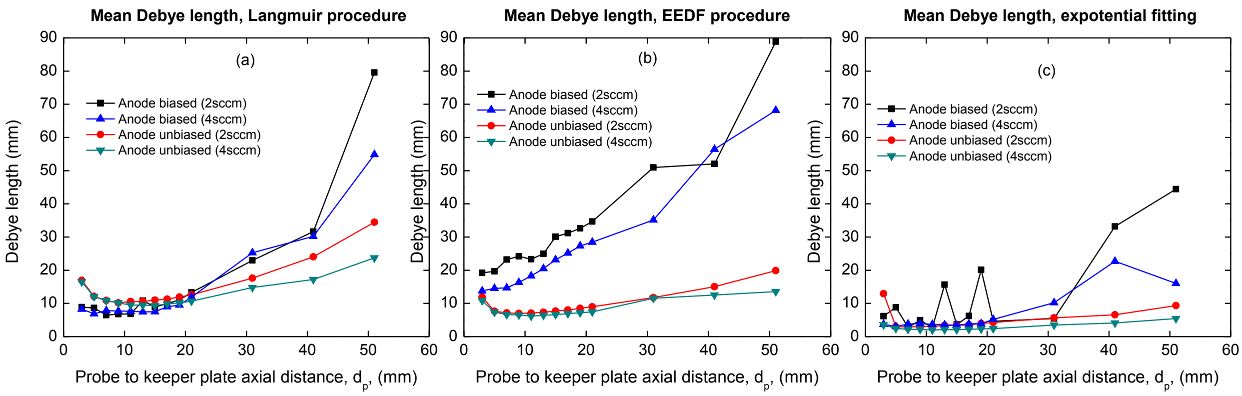

Figure 11. Mean Debye length obtained by Langmuir (a), EEDF (b) and exponential fitting (c) procedures.

3.5 Ion density

The mean ion density was obtained by using the OML approach and it was observed that the mean ion density decreased as the distance from the keeper plate increased for all tested cases, as shown in Fig. 12. It can be seen that the results are of the same order of magnitude of the mean electron density discussed in section 3.2 and there is no remarkable difference between biased and unbiased anode results and also no remarkable differences for results of the two different mass flow rates used.

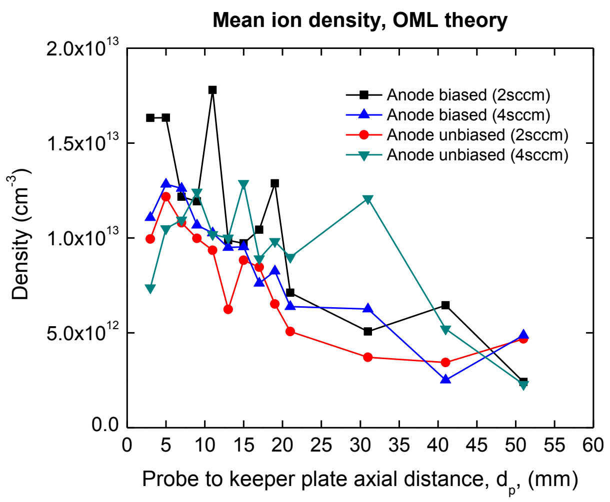

Figure 12. Mean ion density obtained by OML theory.

4. CONCLUSION

The preliminary study involving the hollow cathode with rolled tantalum oxide foil insert have demonstrated the capability of such cathode for producing both high electron and ion densities along the plasma plume propagation region. The plasma parameters confirmed that the hollow cathode under investigation does indeed produce a typical hollow cathode plasma environment, especially for the situation when the anode is unbiased. All the results obtained biasing the anode revealed that this electrode plays a strong influence on the plasma charge balance in the plume. Future work will include measurements of plasma properties for different locations of the anode.

The physical and numerical approaches adopted to compute the plasma parameters indicate that a more detailed investigation should be carried out in terms of data post processing in order to obtain results in a closer agreement.

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