2D mapping of vacuum arc thruster plume plasma parameters

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Abstract: The vacuum arc thruster (VAT) appears to be a credible alternative to gas feed propulsion systems for nanosatellites and microsatellites. Among the advantages provided by this technology, we can point out a solid metal propellant and a high specific impulse. This paper gives a 2D mapping of the plume plasma parameters thanks to a triple Langmuir probe diagnostic. This experimental campaign is led on a VAT prototype developed by Comat.

Nomenclature

\[ V_p, V_{fl}, V_s = \text{plasma, floating and probe potential} \]
\[ n_e, n_i = \text{electron and ion density} \]
\[ m_e, m_i = \text{electron and ion mass} \]
\[ T_e, T_i = \text{electron and ion temperature (eV)} \]
\[ \lambda_D = \text{Debye length} \]
\[ r_D = \text{Landau length} \]
\[ \lambda_{th} = \text{Broglie thermal length} \]
\[ \lambda_{ii}, \lambda_{ie} = \text{ion-ion and ion-electron mean collision free path} \]
\[ v_{ii} = \text{ion-ion collision frequency} \]
\[ r_p = \text{probe radius} \]
\[ I_e, I_i = \text{electron and ion saturation current} \]
\[ V_d = \text{voltage difference between positive and floating probe} \]
\[ V_{bias} = \text{fixed voltage between positive and negative probe} \]
\[ R_{ip} = \text{thin sheath validation number for } p=i,e \text{ species.} \]
\[ K_{ip} = \text{Knudsen number for } p=i,e \text{ species.} \]
\[ c_p = \text{thermal velocity for } p=i,e \text{ species.} \]
\[ p = \text{pressure of plasma plume} \]

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I. Introduction

COMAT\textsuperscript{1} designs, manufactures, qualifies and commercializes equipment for space industry since 1977. Our company initially developed its activity in the microgravity field, in particular in designing and building science equipment for manned flight. Some years ago, COMAT enlarged its know how to satellite markets and particularly to space equipment such as mechanism and propulsion. COMAT is an integrated company with the ability to deliver a global offer for space equipments.

In this frame, the objective of COMAT is to commercialize a propulsion module:

- Plasma Jet Pack 0-30W for nanosatellites in 2018
- Plasma Jet Pack 0-150W for small satellites in 2020

The vacuum arc thruster (VAT) physics allows eroding solid metal propellant thanks to electrical discharge in vacuum. After an ignition process, an electric breakdown takes place between cathode and anode electrodes. During the arc, craters named “cathode spot” appear on the cathode surface; these spots result from heating process (Joule effect and ion bombardment) in the cathode sheath. The vacuum arc is driven by these spots allowing relatively high currents (10 - 100 A) with low arc voltages (10 - 50 V).

The cathode is ablated and solid metal is first transformed into vapor then into plasma by an electronic avalanche mechanism in the ionization region. Then, the plasma is accelerated thanks to electromagnetic mechanism and ejected from the thruster. For 1J energy discharge, the order of magnitude of ion exhaust velocity is roughly 50km/s (depending of the cathode material) and the mass eroded per pulse is about one hundred nanograms. These benefits, such as solid metal propellant and high specific impulse (>5000s), allow this electric propulsion technology to target the nanosatellite market.

The vacuum arc has been extensively studied by Boxman et al among others\textsuperscript{2,3} and has applications in metallic coating deposition, ion source, high current interrupters, etc.

However, in spite of numerous scientific researches on the vacuum arc physics, VAT suffers from a lack of experimental feedbacks and theoretical studies to better understand the physics phenomena, especially the acceleration mechanism. Testing requires specific probes and diagnostics in order to withstand the noisy VAT electromagnetic environment. Indeed, this environment is characterized by a high voltage/current breakdown (500V - 4kA) and a very short current rise time (1.7µs).

The purpose of this study is to estimate the order of magnitude of plasma plume parameters and finally determine the cone angle of the plasma jet in the frame of satellite accommodations.

Having reminded the basis of Chen & Sekiguchi TLP diagnostic, we will detail our experimental facilities as well as the circuit measurement and the custom shielded TPL achievement. Then, we will expose temporal and 2D ($r,\theta$) mapping plasma parameters results (electron temperature, electron and ion density, plasma potential, Debye length and plasma jet pressure) in order to discuss about VAT plume characteristics. Before concluding, we will make an error analysis by defining the working assumptions and the tools to validate them.

II. Triple Langmuir Probe theory

A. TPL description
Obviously, such a pulsed plasma thruster requires a high sampling rate in order to draw temporal plasma parameters. The most straightforward way to characterize plasma would be the single Langmuir probe (SLP) diagnostic due to the simplicity of its measurement circuit. However, application of SLP diagnostic on pulsed plasma thruster have some major drawbacks that are difficult to overcome, particularly when the floating electrode is absent or when plasma potential is not well defined. Moreover, unless the probe area is sufficiently small, SLP may draw large electronic currents and become intrusive when operated close to the plasma potential. Consequently, the SLP method is not suitable for studying pulsed plasma.

In order to overcome these difficulties, the double and triple Langmuir Probe methods are developed. The triple Langmuir probe (TLP) diagnostic provides an advantage over single and double probes, allowing simultaneous measurements of plasma parameters without the need to sweep bias probe voltage. This technique proves to be an adapted tool for stationary and non-stationary plasmas such as pulsed plasma thruster\textsuperscript{2,3,4,5,6}.

The current drawn by a Langmuir probe depends on the probe voltage and plasma parameters. The total current received by one probe is the sum of ion and electron current. The typical I-V Langmuir curve shown in Fig. 3\textsuperscript{a}) is characteristic of the plasma and allows the determination of plasma parameters\textsuperscript{4}.

The triple probe diagnostic consists in three exposed wires in the plasma. The “voltage mode” is the traditional method of operation. This mode consisting to put one floating probe (\(P_f\)) in the plasma, while an external voltage is fixed (\(V_{bias} = V_p - V_e\)) between the probes \(P_+\) and \(P_-\). By measuring the voltage difference \(V_d\) between \(P_+\) and \(P_f\) and the current \(I\) in the closed-loop, electron temperature \(T_e(t)\) and electron density \(n_e(t)\) can be found as a function of time for each plasma pulse.

![Characteristic Langmuir I-V curve](image1)

**Figure 3.** Triple Langmuir probe theory and circuitry

The TPL design imposes that the positive probe can draw at most a current \(I\) only equal in magnitude to the ion saturation current drawn by the negative probe. Finally, neither electrode is ever very far above floating, so the theoretical uncertainties at large electron currents are avoided (see Fig. 3\textsuperscript{a}).

In order to simplify current measurement in the closed-loop, the voltage bias should be high enough to scan the maximum ion saturation current. Common rule of thumb for satisfy this criterion is to fix the bias voltage at minimum three times the expected electron temperature.

**B. TPL Assumptions**

The following assumptions have to be made in order to use TPL theory:

1. Thin sheath assumption: the mean free path for ion-ion, \(\lambda_{ii}\), and ion-electron, \(\lambda_{ie}\), collisions must be greater than the Debye length \(\lambda_D\).
2. Free molecular flow assumption: The probe radius $r_p$ must be smaller than the mean free path of plasma species.
3. The electron energy distribution in the plasma is Maxwellian.
4. The distance between each probe must be greater than the sheath thick.
5. All exposed tips have the same area.
6. The electron temperature is higher than ion temperature in the plasma ($T_e > T_i$).

C. TPL model theory

Considering that the assumptions part II.B are verified, the current for each probe (see Fig. 3b) can be written as (with $T_e$ in eV$^7$):

$$I_+ = I_e e^{\frac{|V_4-V_p|}{T_e}} - I_i \quad (1)$$

$$I_- = I_e e^{\frac{|V_5-V_p|}{T_e}} - I_i \quad (2)$$

$$I_{fl} = I_e e^{\frac{|V_{fl}-V_p|}{T_e}} - I_i \quad (3)$$

If the eqs. (1) and (3) are subtracted and then divided by the sum of eqs. (1) and (2), the resulting equation is:

$$\frac{I_+ - I_{fl}}{I_+ - I_-} = \frac{1 - e^{\frac{V_d}{T_e}}}{1 - e^{\frac{V_{bias}}{T_e}}} \quad (4)$$

Because $V_{bias}$ is a constant input and $V_d$ is measured output, eq. (4) can be solved to provide $T_e$. When $V_{bias} > 3T_e$ the eq. (4) becomes simply:

$$V_+ - V_{fl} = T_e \cdot \ln(2)$$

Finally, the voltage difference between the positive and floating electrodes is proportional to the electron temperature. The electron density can be found by using two different expressions of the ion saturation current. The first comes from Chen and Sekiguchi theory using this equation:

$$I_{sat} = 0.6 \cdot A e n_e \cdot \frac{eT_e}{m_i} \quad (5)$$

The second can be found after some manipulations of the three eqs. (1), (2) and (3):

$$I_{sat} = \frac{I}{e^{V_d/T_e} - 1} \quad (6)$$

Finally, the resolution of system given by eqs. (5) and (6) leads to the electron density in the plasma:

$$n_e = \frac{I}{0.6 \cdot A \cdot \sqrt{e^2T_e/m_i} \cdot [e^{V_d/T_e} - 1]} \quad (7)$$

III. Experimental TLP circuit measurement and facilities

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A. Comat facilities

Comat propulsion laboratory is set in an iso7 clean room. In this clean room, a 1m³ vacuum chamber allows to have a space representative vacuum environment of 10⁻⁶ mbar. The propulsion setup is composed of one thrust bench, several homemade Langmuir probes, 2D translation table and 4 channels Rode & Schwartz RTE 1024 high speed oscilloscope (200MHz bandwidth, 5 Gsample/s per channel).

B. TPL construction

Proper circuitry of TLP is required to reduce electromagnetic noise and simplify the measurement. Home-made TLP has been designed and manufactured with three tungsten wires aligned with the plasma flow. These wires have 0.3mm diameter fed through four bore alumina tubing with holes of 0.8mm diameter. The exposed length of the tips in the plasma is fixed to 9mm and the distance between each probe is 1.4mm (2mm for the floating and negative tips). The alumina tubing of 4mm diameter serves to insulate the wire from the probe supports, keeping tips parallel to each other and holds them at the same distance. The alumina tubing is surrounded by an aluminum sheet connected to the ground and fed through a glass tube in order to hold the entire system (see Fig 4). The TLP is finally mounted on a translation table in order to sweep the radial and angular positions (r = [0,20] cm, θ = [0,90] degrees).

C. TPL circuitry and measurement

At the extremity of the alumina tubing, each wire is connected to a BNC 50Ω coaxial cable core to be finally linked to the BNC feedthrough of the chamber wall. By doing so, the shields of BNC and aluminum sheet of TLP are common with the ground, as well as the Faraday cage outside of the vacuum facility (see Fig. 5). Notice that the TLP circuitry is enclosed in a Faraday cage to reduce the radiated noise naturally picked up by the components. In this box, the bias between the positive and negative probes is supplied by a Pb battery pack and the current is provided by both battery and a 1μF ceramic capacitor loaded in parallel of the loop. This capacitor helps the battery to provide a high current rate in the loop in order to maintain constant the bias voltage during the pulse. Then, this current I (see Fig. 5) is measured by a non-intrusive Tektronix CT1 AC current probe.

Positive and floating potential are measured thanks to Rode & Schwartz 1/10 divider probes. The difference $V_d$ is made numerically in the scope. The bandwidth of the scope is set to 10MHz and noise rejection is applied on each channel.

For each pulse, the arc current is measured with Pearson tore in the discharge loop of the thruster. This high repeatability signal serves as trigger for the scope.

The thruster propellant has been chosen in tungsten in order to reduce the contamination of the probe’s tips. Indeed, tungsten plasma deposition on the tungsten tips does not change drastically the electrical properties of the probes.

D. TPL procedures and data reduction

In order to estimate the signal to noise ratio, the TLP procedure is separated in two stages: with polarization (ON - $V_b=24V$) and without polarization (OFF - $V_b= 0V$, battery and capacitor disconnected after discharging the capacitor by short-cutting it). For one position (r,θ), each step recorded 20 pulses, and for each pulse, current, positive, negative and floating probe are recorded on the scope. Finally a Labview routine generates .txt files for the data post processing, then, this procedure restarts for another probe’s position. Note that a preliminary study has been made in order to estimate the TLP parameter’s range of variation. Then, it was deducted that only the range $r = [2,8]$ cm, $θ = [0,25]$ degrees is appropriate for the mesh and also that under $r=2$cm, the probe becomes intrusive and the TLP diagnostic is no longer applicable.

Figure 4. Triple Langmuir probe in vacuum tank

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The complete mapping consists in sweeping the axial position from 2 to 8 cm and the angular position from 0 to 25 degrees for a total of 42 positions and 1680 pulses.

Because impurities, varnish, oxidation and insulator vapor deposition on the probe’s tips can shift the current-voltage characteristics, it is necessary to apply a cleaning process in order to keep the diagnostic in the same condition for each plasma pulse. In this field, it was shown that the electronic bombardment of the tips surfaces and its ohmic warm-up lead to a very effective cleaning of the probe. The cleaning needs have been quantized by a secondary study and a rule has been stated: if the roles (floating, positive or negative) of the tips can be exchanged without affecting the measure, the diagnostic is valid, if not, the cleaning is necessary. In our case, this study showed that this criterion is satisfied up to 4000 pulses without breaking the vacuum. Finally, the cleaning process takes place only one time, before the beginning of the complete mapping.

Figure 5. Electrical diagram of experimental facility
IV. Results and discussion

A. TLP temporal results

The arc current discharge generated by the thruster draws two repeatable oscillations (positive and negative – see Fig. 6a) for a total pulse duration of 6µs. For 1J energy discharge thruster operation, the arc current peak is 3900A and the rise time is around 1.7µs (588kHz).

In OFF configuration (without polarization), the TLP current is close to zero (see Fig. 6b and 7a) which confirms that zero current is collected if all the probes are floating (see Fig. 3a). Moreover, because the probes are close enough to scan the same part of the plasma, the difference between the positive and the floating probes is negligible ($V_d \sim 0$ V). Finally, in OFF configuration, the remaining noise signal is negligible for both parameters.

In ON configuration, the TLP draws a positive current during the same time length than the arc current (6µs). Nevertheless, while the TLP current should stay at zero 6µs after the beginning of the collection, a negative current is observed (see Fig. 6b, 14-25µs). This phenomenon is probably linked to an oscillation response of the measurement circuit (RLC discharge). In this period, Fig. 7b underlines that the positive potential keeps a constant value (~5V) during 30µs before falling to zero. Secondary studies are in progress to understand these measurement issues.

Because the positive potential is always higher than the floating one ($V_d > 0$) during the pulse, the results are conform to the theory predictions (see Fig. 3b). Note that a negative pulse is observed on a $V_d(t)$ curve (see Fig. 7d), exactly when the TLP current appears. This noise peak on $V_d(t)$ is obviously due to the first probe/plasma interaction and takes place when the floating and the positive voltage are maximum (~140V).
These temporal results show that TLP current is exploitable for the calculation of the density and the TOF measurement. Nevertheless, this $V_d(t)$ shape cannot allow a temporal simulations on $T_e$. Therefore, only a $V_d$ time averages (after the negative noise peak) could be made in order to get the spatial $(r,\theta)$ trend line of $T_e$. The resulting relative error on $n_e(t)$ calculation has been estimated and does not exceed 20%.

In ON configuration, the TLP draws a positive current but slightly out of phase with the arc current (see Fig. 8a). This time difference between arc current peak and TLP current peak corresponds to the plasma time of flight (TOF) between the thruster exhaust and the probe’s tips. In fact, this TOF is often used to estimate the mean ion velocity\textsuperscript{12,13,14}.

Figure 8a shows the arc current and the TLP current as a function of time for different distances $r$. For $r=2$ and $r=3\text{cm}$, even if the arc current changes of sign (for $t=10.5-13\text{ ms}$, see Fig. 8a), the probe continues to collect current. This fact proves that a negative arc current generates plasma, while in this case, plasma is supposed to go in the opposite direction (because when arc current is negative, the roles of the cathode and the anode are inverted). Nevertheless, this plasma is only present in the vicinity of the thruster exhaust and the anode geometry limits its participation to the total axial thrust.

It can be noticed that for the rising $r$; the peak TLP current moves towards the right. As we said in the previous part, this fact is easily explained by the TOF. For example, there is $1.05\mu$s elapsed between $r=2$ and $r=8\text{ cm}$ (see Fig. 8a), so the mean ion exhaust velocity can be estimated to 57 km/s in the axis for tungsten cathode material. A more complete study comparing TOF between the arc peak current and TLP peak current has shown in Fig. 8b. The total range of ion velocity variation is between 22 to 120 km/s. Despite this high dispersion on the 20 curves/positions, we can notice that the mean ion velocity slowly decreases in function of $r$, falling from 67 to 58 km/s.

**Figure 8.** $I(t)$ and TOF measurement of $v_i(r)$ for each $r$ positions and 20 points
B. TLP spatial results

Figures 9 and 10 show the distribution of the plasma plume. These spatial results show $n_e$ peak behavior in function of $r$ (see Fig. 9a). We can see that for low $r$, the $n_e$ parameter follows a $1/r^2$ decreasing rule, but has a more slowly decrease for high $\theta$ values. Consequently, the plasma plume is very focused close to the thruster exhaust and becomes diffuse after several centimeters. We can also notice that the measured maximum $n_e$ peak is around $6\cdot10^{20}$ at/m$^3$.

Figure 9b shows that the mean $T_e$ decreases very slowly as a function of $r$, so $T_e$ is weakly dependent on the distance. For example, at $\theta=0$ degree, the mean $T_e$ decreases slowly from 6.5 to 5.2eV on a length scale of 6cm.

Figure 10 shows the angular dependency of these parameters. Note that for $n_e$, the rule of decreasing depends more on probe distance from the thruster exhaust than on angular position. Finally, for mean $T_e$, the measures reveals an increase in function of angular position and they both reached a constant value after $\theta=20$ degrees (see Fig. 10b). We cannot explain why $T_e$ is lower for low $\theta$ values than for high $\theta$ values. In fact, this observation could reflect the real nature of the plasma or be an artefact due to the angular position of the probe’s tip. For example, at $\theta=0$, the tips are parallel to the thrust axis and at $\theta=90$ the tips are perpendicular to the thrust axis. Therefore, one tip can screen the others with different orientations for each angular position. Moreover, the thrust aperture (1cm) and the axial length have the same order of magnitude than the probe’s tip length (0.9cm).

![Figure 9. TLP parameters as function of $r$ for $\theta=0,5,10,15,20,25$ degrees](image)

![Figure 10. TLP parameters as function of $\theta$ for $r=2,3,4,5,6,7,8$ cm](image)
C. TLP spatial and temporal results – 2D mapping

For the display, the 2D spatial polar mesh ($r, \theta$) has been transformed into a cartesian one (X,Y), where the X coordinate defines the thrust axis. It should be recalled that points $r=0$ and $r=1$ are missing and noted that the diameter of the thruster exhaust is 1cm ($Y=\pm0.5$ on Fig. 11b).

Figure 11b shows the mean $T_e$ spatial distribution and illustrates the Fig. 10 results. Only the mean of $T_e$ for each X,Y positions has been retained for the temporal mapping. In this case, the $n_e(t)$ variations follow those of $I(t)$. $n_e$ and $T_e$ are also used to calculate pressure and Debye length of the plasma expressed as follow:

$$\lambda_D = \sqrt{\frac{\varepsilon_0 T_e}{en_e}}; \quad p = en_e \cdot \left(\frac{T_e}{Z} + \frac{T_i}{Z}\right)$$

For a vacuum arc, $T_i$ is estimated as cathode spot temperature that is between 0.1 and 1eV depending on the cathode material. For a tungsten cathode, a good approximation of $T_i$ is 0.8eV and the mean ion charge $Z$ can be estimated as 3.1. Figures 12, 13 and 14 show the 2D temporal reconstruction of the TLP measurements for the electron density (at/m$^3$), the Debye length (µm) and the plasma pressure (mbar). Each time step corresponds to the Fig. 11a time step during the arc discharge.

The electron density and the plasma pressure have almost the same distribution in time, therefore, we can describe them together (see Fig.12 and 13). At 8µs, the plasma has not yet reached the probe (see Fig. 8a), so zero density and pressure are recorded after $r=2$ cm. At 8.5µs, we can see the formation of the plume on the left part. At 9.5µs, the plasma has moved forward and we see that the jet is very focused, in fact above $\theta=15$ degrees, $n_e$ and $p$ are divided by 5 compared with the centerline ($\theta=0$). At 10µs, the arc current has already initiated its falling down and the plasma becomes more diffuse ($n_e \sim 10^{19}$ at/m$^3$ and $p \sim 1$ mbar). At 10.5µs, the plasma plume intensity decrease and it remains focus plasma in the centerline, note that arc current is going to be negative. At 12µs, the arc current is negative and extinguishes. Nevertheless, the plasma remains close to the thruster exhaust and the phenomenon described in Fig. 8 is well illustrated.

Debye length defines the limit of penetration of an external electric field in the plasma. In fact, this parameter is used to determinate the type of plasma and it’s necessary to estimate it for future numerical simulations on VAT. For our tungsten plasma, Fig. 14 shows that $\lambda_D$ is between 0.5 to 3µm during the pulse (see Fig. 14).
These results lead to the following order of magnitude at the centerline: \( n_e \sim 10^{20} \text{ at/m}^3 \), \( T_e \sim 6 \text{ eV} \), \( \lambda_D \sim 1 \mu\text{m} \). By compares the distance between two particles \( d_e(n_e^{-1/3}) \) with the Broglie thermal length \( \lambda_{th} \), the Landau length \( r_0 \) or the Debye length \( \lambda_D \) we can determine more precisely our plasma.

- \( \frac{d_e}{\lambda_{th}} \) ratio reports the weight of quantum effect (it compares plasma temperature to the Fermi temperature).
- \( \Xi = \frac{r_0}{d_e} \) ratio compares thermal agitation and coulombian interaction (ratio between kinetic energy and potential energy of the plasma).
- \( \Lambda = \left(\frac{\lambda_D}{d_e}\right)^3 \) ratio compares collective and individual interactions.

### Table 1. Plasma type in function of plasma ratio

<table>
<thead>
<tr>
<th>Plasma Ratio</th>
<th>(&lt; &lt; 1)</th>
<th>(\geq 1)</th>
<th>VAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{d_e}{\lambda_{th}} )</td>
<td>Degenerated gaz (arc, metal plasma, etc.)</td>
<td>plasma with high temperature or low density</td>
<td>( \sim 10^{-15} )</td>
</tr>
<tr>
<td>( \Xi = \frac{r_0}{d_e} )</td>
<td>Kinetic or classic plasma (disorder dominates)</td>
<td>Plasma strongly correlated (Coulombian interaction dominates)</td>
<td>( \sim 10^{-3} )</td>
</tr>
<tr>
<td>( \Lambda = \left(\frac{\lambda_D}{d_e}\right)^3 )</td>
<td>Plasma weakly correlated</td>
<td>Ideal or Kinetic plasma (collective interactions)</td>
<td>( \sim 10^{-108} )</td>
</tr>
</tbody>
</table>

The calculation of these ratios allows a first classification of our plasma VAT. We can deduct from table1 that such a plasma is difficult to simulate because of its high density \( (10^{14} \text{ at/cm}^3) \) and its collective interactions.
Figure 12. Electron density (at/m³) 2D temporal simulations for the 6 time steps of Fig. 11a
Figure 13: Plasma pressure (mbar) 2D temporal simulations for the 6 time steps of Fig. 11a
Figure 14: Debye length (µm) 2D temporal simulations for the 6 time steps of Fig. 11a
D. Assumptions and validation

The seven assumptions given in part II.B have to be validated in order to use the TPL theory. Several equations and specific numbers enable to validate these assumptions properly. In this section, we shall detail the validation tools for each assumption given in the part II.B and with the same order.

1. The mean free paths for ion-ion and ion-electron collisions are given by:

$$\lambda_{ii} = \frac{c_i}{\nu_{ii}}$$

$$\lambda_{ie} = \frac{c_e}{\nu_{ii}} \sqrt{\frac{m_i}{2m_e}} \left(\frac{T_i}{T_e}\right)^{3/2}$$

Where the mean thermal speed for species \( p=i,e \) is:

$$c_p = \sqrt{\frac{8eT_p}{\pi m_p}}$$

and the ion collision frequency is given by:

$$\nu_{ii} = n_i c_i 6\pi b^2 \ln\left(\frac{A_D}{b}\right).$$

In the previous expression of \( \nu_{ii} \), b is the impact parameter defined as:

$$b = \frac{e^2}{4\pi \varepsilon_0 m_i c_i^2}.$$

Thin sheath number could be defined as:

$$R_{ii} = \frac{\lambda_{ii}}{A_D} ; R_{ie} = \frac{\lambda_{ie}}{A_D}$$

To ensure that the “thin sheath approximation” holds, \( R_{ip} \) number has to verify \( R_{ip} >> 1 \) for each species \( p=i,e \).

2. Knudsen number is defined as:

$$K_{ii} = \frac{\lambda_{ii}}{r_p} ; K_{ie} = \frac{\lambda_{ie}}{r_p}$$

To ensure that the “molecular flow approximation” holds, \( K_{ip} \) number has to verify \( K_{ip} >> 1 \) for each species \( p=i,e \).

Figure 15 shows that all ratios given in the previous part (Kii, Kie, Rii, Rie) validate the assumptions given in part II.B (>>1) except for the ratio Kii. Indeed, Kii increase from 0.25 (at \( r=2\text{cm} \)) to 2.31 (at \( r=8\text{cm} \)) so it cannot

![Figure 15. Kii, Kie, Rii and Rie ratio in function of r at centerline.](image)
validated the “molecular flow assumption” and an error occurs. It can be noted that more the distance is small, more the assumptions are invalidated. In fact, the TLP diagnostic is more accurate far from the thruster exhaust. Because our measurements of $I$ and $V_d$ is very repeatable (see Fig. 7) the main error in $n_e$ calculations is due to the fact $Kii \sim I$ as discussed above and this introduces a relative error of $\sim 60\%$ on $n_e$ (Tilley et al., 1990).\(^\text{15}\)

3. The electron energy distribution in the plasma is considered as Maxwellian.

4. If the “molecular flow approximation” is validated, the sheath thickness is much smaller than the probe radius. In our experimental setup, the distance between tips is fixed to 1.4mm, because this distance is much higher than the probes radius ($r_p = 0.15\text{mm}$), the “molecular flow approximation” also validated this assumptions.

5. In our experimental setup, all the cylindrical tips have the same exposed length and the same radius.

6. It is well known that in cold vacuum arc plasma, electron temperature is higher than ion temperature.\(^2,3\)

E. Dispersion analysis

Figure 16. $n_e$ and Mean $T_e \pm \sigma$ error bars in function of $r$ at centerline ($\theta=0\text{ degree}$)

Figure 16 shows the measurement dispersion resulting from 20 curves statistics. The maximum electron density and mean electron temperature are plotted at $\pm \sigma$ (standard deviation – errors bars amplitude). These standard deviation varies from 29$\%$ (at $r=2\text{cm}$) to 3$\%$ (at $r=8\text{cm}$) for $n_e$ and remains almost constant at 9$\%$ for $T_e$. For 2D temporal animation, it can be recalled that the resulting relative error on $n_e(t)$ due to the $T_e$ time averaging calculation has been estimated and does not exceed 20$.\%$.
V. Conclusions

We showed that TLP diagnostic applied to a pulsed VAT allows estimating the order of magnitude of the plasma parameters as well as its spatial and temporal distribution. For 1J discharge energy, even if all hypotheses of the calculations are not verified, especially for the measures close to the thruster exhaust (where the density is higher), this diagnostic quantifies the trend of the parameters up to 20 cm (where the S/N current signal becomes close to 1). Moreover, for 1J discharge energy, the TOF measurements on this thruster lead to an ion velocity around 60 km/s, which gives additional information on the thruster’s specific impulse.

More experimental campaigns are needed to entirely validate the diagnostic and clarify several critical points such as: the peak noise on $V_A$ resulting on the first plasma/probe interaction, the non-null signal on the positive probe after the pulse end, and the understanding of the negative current $I$ after the arc pulse duration.

Such improvements shall allow us to obtain better $T_e(t)$ curves and minimize the error committed on the hypothesis express in part IV.A.

This TLP–TOF diagnostic on VAT turns to be essential to get the plasma plume distribution and compare the cone angle obtained by other technologies (ion thruster, Hull effect, LPPT, etc.). Moreover, such a diagnostic helps to feed theoretical models of vacuum arc thruster and clarifies the physical phenomena in the plasma plume.

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