

Experimental Determination of the Plasma Properties in the Far-plume of an SPT-100 Hall Thruster

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Gabriel Giono*

KTH-Royal Institute of Technology, SE-100 44, Stockholm, Sweden

Stéphane Mazouffre

*ICARE, Centre National de la Recherche Scientifique, 1c, Av. de la recherche scientifique,
CS 50060, 45071 Orléans, France*

Dimitry Loubere, Lara Popelier, Christophe Théroude
*Airbus Defence and Space, 31 Rue des Cosmonautes,
31400 Toulouse, France*

Käthe Dannenmayer, Fabien Marguet
*ESTEC, European Space Agency, Keplerlaan 1,
PO Box 299, NL-2201 AZ Noordwijk, The Netherlands*

Jón Tómas Gudmundsson
*KTH-Royal Institute of Technology, SE-100 44, Stockholm, Sweden
Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland*

Nickolay Ivchenko, Georgi Olentsenko
KTH-Royal Institute of Technology, SE-100 44, Stockholm, Sweden

and

Mario Merino
*Aerospace Engineering Department, Universidad Carlos III de Madrid,
Avda. de la Universidad 30, 28911 Leganés, Madrid, Spain*

Understanding the expansion of the plasma plume created by an electric thruster is of crucial importance in order to assess the induced interactions with the surrounding spacecraft. An accurate modeling of the plasma behaviour is therefore required. However, a robust cooling model for the electron in the plume region is still lacking: the electron effective cooling rate represented by the γ parameter has been shown to influence the expansion of the plume but also the evolution of the ambipolar plasma potential, thus leading to unphysical results at infinity in the isothermal limit of $\gamma=1$. This indicates that a collisionless cooling mechanism might exist in the plume and more investigation is required to constrain the γ parameter. Despite the fact that extensive measurements in

*PhD., Department of Space and Plasma Physics, School of Electrical Engineering, email: ggiono@kth.se

thrusters' plasma plumes can be found in the literature, none provided satisfactory results to constrain the parameters affecting the electron cooling, especially for the electron energy distribution function (EEDF) and in the far axial part of the plume beyond 700 mm. Such measurements are crucial to assess the theoretical work currently ongoing to provide an adequate model for the electron cooling in an unmagnetized plasma thruster plume.

The presented work aims at filling this void, by providing the key plasma parameters (electron density, electron temperature, plasma potential and electron energy distribution function) inside the plume far-region of a SPT-100 Hall thruster. The plasma parameters were derived from cylindrical Langmuir probe measurements, performed along the plume axis at distances between 500 to 1550 mm from the thruster exit, as well as angularly from -20° to $+90^\circ$ at distances between 500 to 750 mm. Six different operating points of the thruster were investigated by changing its discharge voltage and its mass flow rate. Maps of the plasma parameters derived by fitting the current-voltage curves are presented and compared for the various operating points of the thruster. The axial variations of the electron energy distribution function in the far-plume are also discussed, as well as an estimation of the measurement error on the plasma parameters and a comparison between the current collected by Langmuir probes perpendicular and parallel to the ion streamlines.

Nomenclature

A	= Langmuir probe area
e	= electron charge
q_i	= ion charge
m_e	= electron mass
m_i	= ion mass (Xe : 131.293 amu)
k_B	= Boltzmann constant
n_e	= electron density
n_i	= ion density
T_e	= electron temperature
T_i	= ion temperature
V_p	= plasma potential
$\mathcal{E}$	= electron energy
v_i	= ion flow velocity
γ	= ratio of specific heats

I. Introduction

Understanding the expansion of the plasma plume created by an electric thruster is of crucial importance in order to assess the induced interactions with the surrounding spacecraft. Such interactions include erosion, contamination, electromagnetic interferences and spacecraft charging. These are important issues to be considered in a spacecraft design phase and an accurate modeling of the plasma behaviour is therefore required.¹⁻⁴ However, although state-of-the-art software such as the Spacecraft Plasma Interaction System code^{5,6} (SPIS) are available for simulating plume plasma, a robust cooling model for the electrons in the plume region is still lacking. The electron effective cooling rate represented by the ratio of specific heats γ has been shown to influence the expansion of the plume but also the evolution of the ambipolar plasma potential. But, in the isothermal limit $\gamma=1$ leading to the Boltzmann relation, unphysical results at infinity are obtained.⁷ This indicates that a collisionless cooling mechanism might exist in the plume and a kinetic approach is necessary to understand the electron cooling in this regime. More investigation is required to constrain the γ parameter and, despite the fact that extensive measurements in thrusters' plasma plumes can be found in the literature,⁸⁻¹¹ none provided satisfactory results to constrain the parameters affecting the electron cooling, especially for the electron energy distribution function (EEDF) and in the far axial part of the plume beyond 700 mm.

Filling this knowledge-gap is the goal of the ESA-supported MODEX project.¹² The project is a collaboration between the industry and research organizations, and aims at refining the modeling of the electron cooling in the far-plume by confronting it to experimental measurements. Theoretical work¹³⁻¹⁶ is ongoing to provide an adequate model for the electron cooling in an unmagnetized plasma thruster plume and a measurement campaign to obtain experimental data for the validation of the numerical model was conducted. Langmuir probes were used to estimate the key plasma properties; the electron density, the electron temperature, the plasma potential and the electron energy distribution function; inside the far-plume of a SPT-100 Hall thruster, in a region 500 mm to 1550 mm away from the thruster exit. Six different operating point of the thruster were investigated, where the discharge voltage and the mass flow rate were adjusted. Faraday cups (design similar to those discussed by Mazouffre et. al.¹⁷) were also used to estimate the ion current density, but their measurements are not presented in this article.

An overview of the experimental setup and analysis method is given in Section II. Maps of the plasma parameters derived from the fitting of the Langmuir probe current-voltage measurements taken at various operating points of the thruster are presented in Section III, and Section IV investigates the differences between the electron density and electron temperature obtained by two different methods: integration of the electron energy distribution and fitting of the current-voltage curve. Section V presents the results of the γ factor calculated along the plume using the plasma parameters derived with the two methods, and the shape of the electron energy distribution functions as well as its spatial variation along the plume axis are discussed in Section VI. The differences between the ion current collected by probes oriented perpendicular and parallel to the ion stream line, respectively, are discussed in Section VII. An estimation of the uncertainty of the plasma parameters induced by the measurement noise and by the hysteresis between up and down sweeps is presented in Section VIII. Finally, a comparison between the measurements recorded using a Keithley sourcemeter and KTH custom read-out electronics is made in Section IX.

II. Overview of the experimental setup and measurement analysis

The measurement campaign was conducted inside the large CORONA vacuum chamber (2 m in diameter and 4 m in length, see Figure 1(a) located at the ESA/ESTEC Propulsion Laboratory. The SPT-100 thruster used as a plasma source can be seen in Figure 1(b). Angular measurements were carried out using the large rotating arm installed inside the vacuum chamber: a cylindrical Langmuir probe was mounted on a small translation stage (350 mm range), allowing measurements at distances between 500 to 750 mm from the thruster and angularly from -20° to $+90^\circ$ ($x=0$ referring to the exit of the thruster and 0° on the plume axis). Axial measurements at further distances inside the plume were ensured by another cylindrical Langmuir probe mounted on a large translation stage (700 mm range), providing measurements at larger distances along the plume axis, between 850 mm to 1550 mm from the thruster exit. The tip of both Langmuir probes was made of a Tungsten wire (0.2 mm diameter, 5 mm length) and oriented parallel to ion stream lines, whereas the rest of the probe body was insulated by alumina tubes sealed with epoxy. A third Langmuir probe was installed on a second rotating arm of the chamber at a fixed distance from the thruster

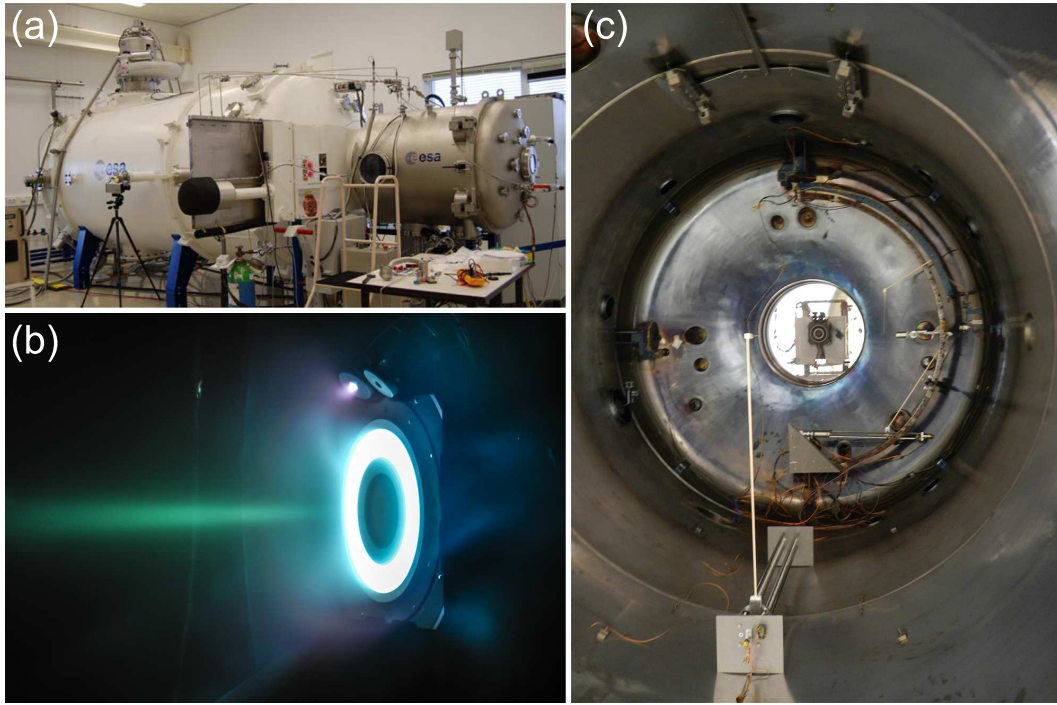


Figure 1. (a) The CORONA vacuum chamber at ESA/ESTEC. (b) The SPT-100 thruster working at nominal operating point. (c) The setup inside the vacuum chamber, including the chamber rotating arm, the two translation stages and the SPT-100 thruster in the background.

exit, with its tip oriented perpendicular to the ion stream lines. The purpose of this probe was to compare the different ion current collected depending on the orientation of probe with respect to the ion flow (see Section VII). An schematic of the configuration is shown in Figure 2 and the two translation stages installed inside the chamber can be seen in Figure 1(c).

Due to time constraints, angular measurements were only conducted at three radial distances: 550, 650 and 750 mm from the thruster. Axial measurements with the large translation stage were recorded every 100 mm, from 850 to 1550 mm. All measurements were performed in the horizontal plane located at the height of the thruster axis, and recorded using a Keithley 2440 sourcemeter sweeping the probe voltage from -15 V to $+35$ V. These measurements were recorded for six different operating points of the thruster by varying the discharge voltage and the mass flow rate of Xenon to (300 V, 4 mg/s), (300 V, 2 mg/s), (400 V, 2 mg/s), (225 V, 2 mg/s), (150 V, 4 mg/s) and (150 V, 2 mg/s), respectively. The current-voltage (IV) characteristic of the Langmuir probe was recorded at each location and an example is shown in Figure 3(a). The plasma potential was obtained by locating the maximum of the first derivative of the current dI/dV , smoothed using a Blackman window convolution (2 V width) to reduce the fluctuation induced by the measurement noise,¹⁸ as shown in Figure 3(b). The electron temperature T_e was derived from the slope of the IV curve in the transition region between the ion and the electron currents, taken from the plasma potential and extending towards the negative potential by 4 V, as

$$T_e^{-1} = \frac{d(\ln I)}{dV} \quad (1)$$

The electron density n_e was determined from the electron saturation current squared, taken starting from the plasma potential towards the positive potential, using the Orbital Motion Limit (OML) assumption

$$n_e = \sqrt{\frac{dI^2}{dV}} \sqrt{\frac{m_e}{2e}} \frac{\pi}{eA} \quad (2)$$

where m_e is the mass of the electron, e the elementary charge and A the area of the probe.

The Electron Energy Distribution Function (EEDF) $g_e(\mathcal{E})$ was then derived by taking the second derivative of the current d^2I/dV^2 from the plasma potential (example shown in Figure 3(c)), following the

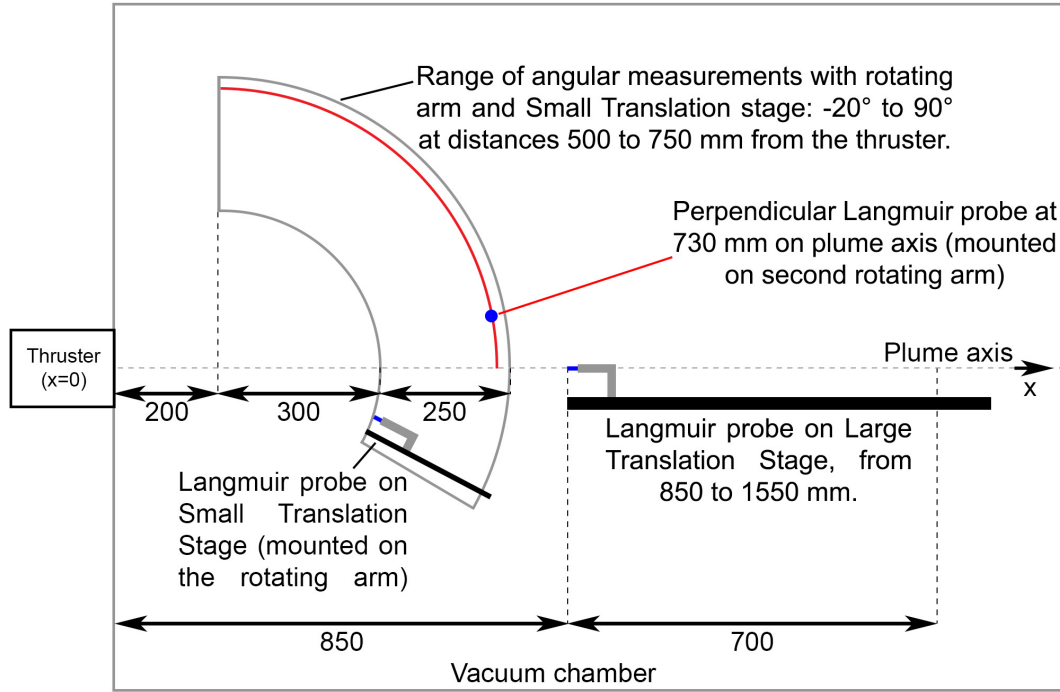


Figure 2. Schematic of the Langmuir probes configuration inside the vacuum chamber.

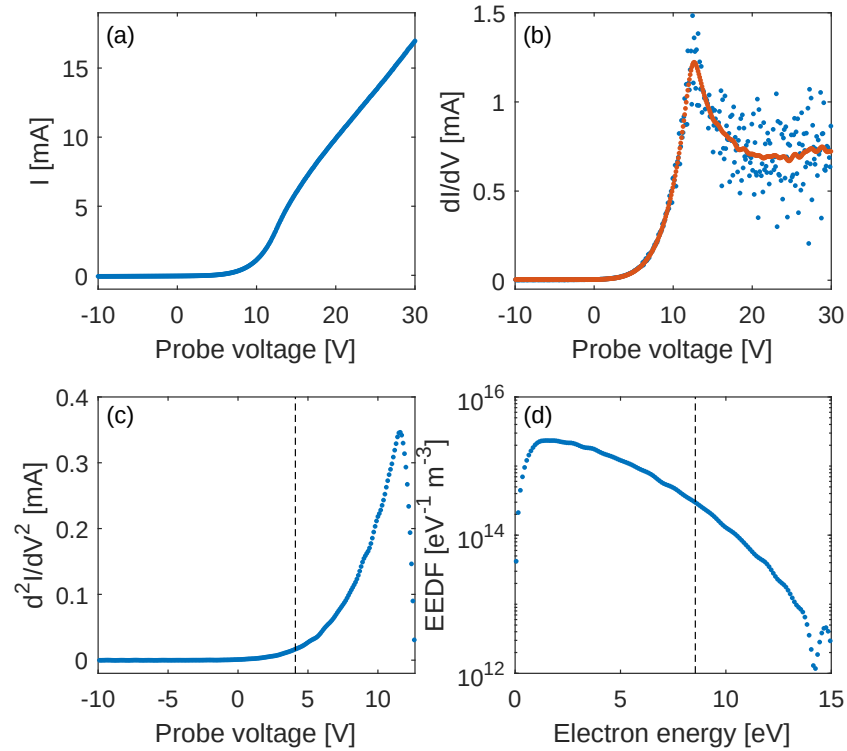


Figure 3. Example of a measurement taken along the plume axis at 500 mm from the thruster exit, for a discharge voltage of 300 V and a mass flow rate of 4 mg/s. (a) raw IV curve. (b) raw dI/dV (blue) and smoothed dI/dV after convolution with a 2 V width Blackman window (orange). (c) d^2I/dV^2 derived from the smoothed dI/dV . Black vertical dash line shows the location of the floating potential. (d) EEDF obtained from the d^2I/dV^2 using the Druyvesteyn formula. Black vertical dash line shows the location of the floating potential energy.

Druyvesteyn formula¹⁹

$$g_e(\mathcal{E}) = \frac{2m_e}{e^2 A} \sqrt{\frac{2e\mathcal{E}}{m_e}} \frac{d^2 I}{dV^2} \quad (3)$$

and using the smoothed dI/dV . An example of EEDF is shown in Figure 3(d).

III. Maps of the plasma parameters

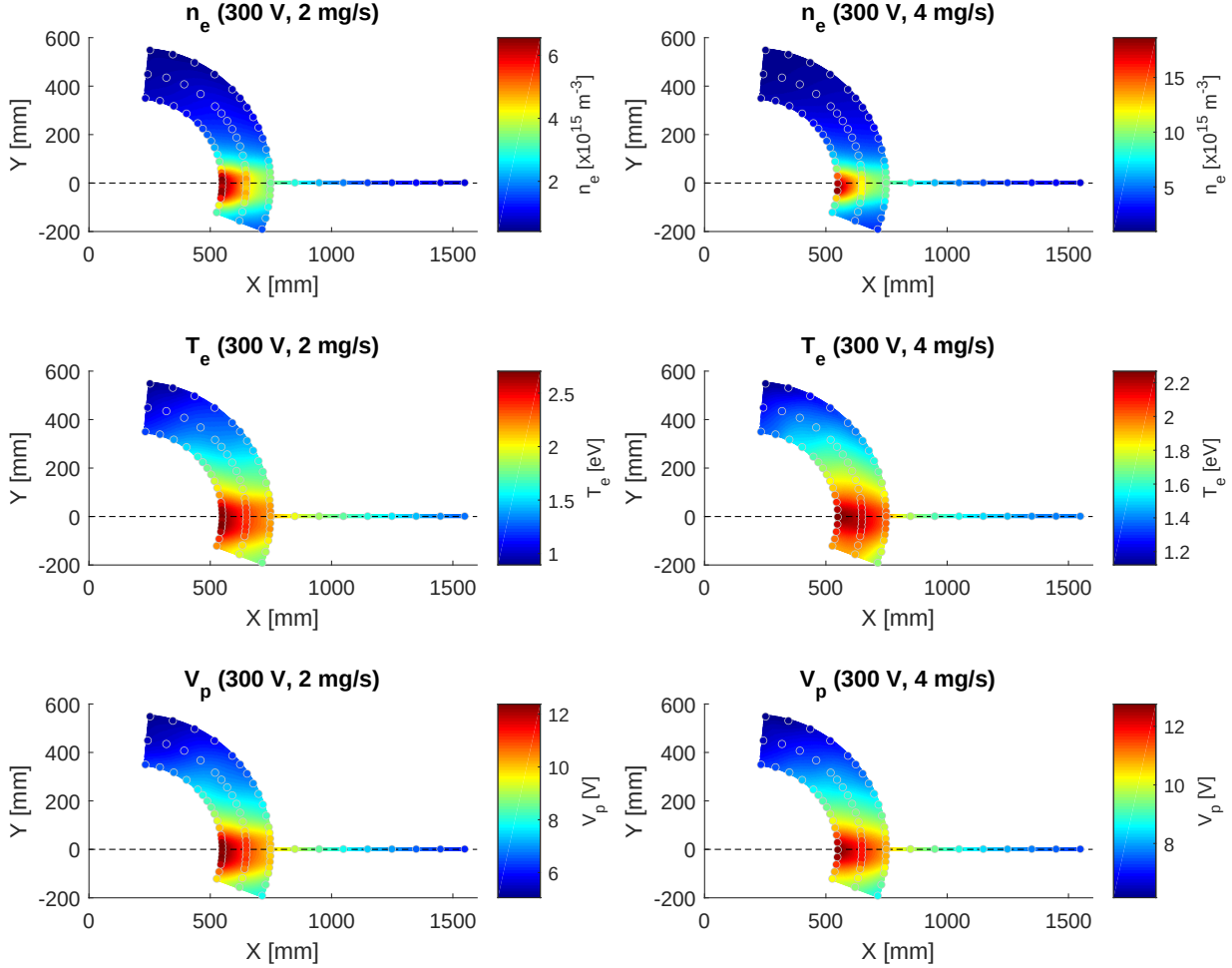


Figure 4. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) for a discharge voltage of 300 V and a mass flow rate of 2 mg/s.

Figure 5. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) for a discharge voltage of 300 V and a mass flow rate of 4 mg/s.

Maps of the electron density, electron temperature and plasma potential are shown in Figures 4–9. Circles show the location of each measurement and the color is scaled with the magnitude of the corresponding parameter. Regions in-between the measurement points are colored based on a 2D interpolation, to better visualise the spatial variation of each parameter. The effect of the mass flow rate on the plasma parameters can be seen by comparing Figure 4 and Figure 5. Increasing the flow rate by a factor of two results in a larger plasma density by a factor of roughly three, and in a slightly lower electron temperature and plasma potential. On the other hand, the effect of the discharge voltage is seen by comparing Figure 4 with Figure 6 and Figure 7: a larger discharge voltage leads to an increase in plasma density, electron temperature and plasma potential. It is important to mention that the IV curves recorded at (225 V, 2 mg/s) and (150 V, 2 mg/s) had significantly larger noise compared to the other operating points of the thruster. An explanation might be because the thruster was less stable at low discharge voltage and flow rate, hence increasing the fluctuations on the recorded current.

As a results, the electron density and electron temperature obtained by fitting the IV curves was less consistent, and a stronger smoothing was performed on the first derivative of the current for these two operating points (i.e. 4 V width Blackman window instead of 2 V width) in order to get the plasma potential and the EEDF. One can also see a significantly different shape of the plume for the measurements recorded at a discharge voltage of 150 V, illustrated in Figure 8 and Figure 9. The thruster entered a different current oscillation mode for these low discharge current compared to the nominal oscillation mode seen in the other operating points of the thruster, resulting in a less collimated plume which could even be seen by naked eye when looking at the thruster. Regardless of this effect, the same differences in the plasma parameters when doubling the mass flow rate were observed at 150 V compared to 300 V.

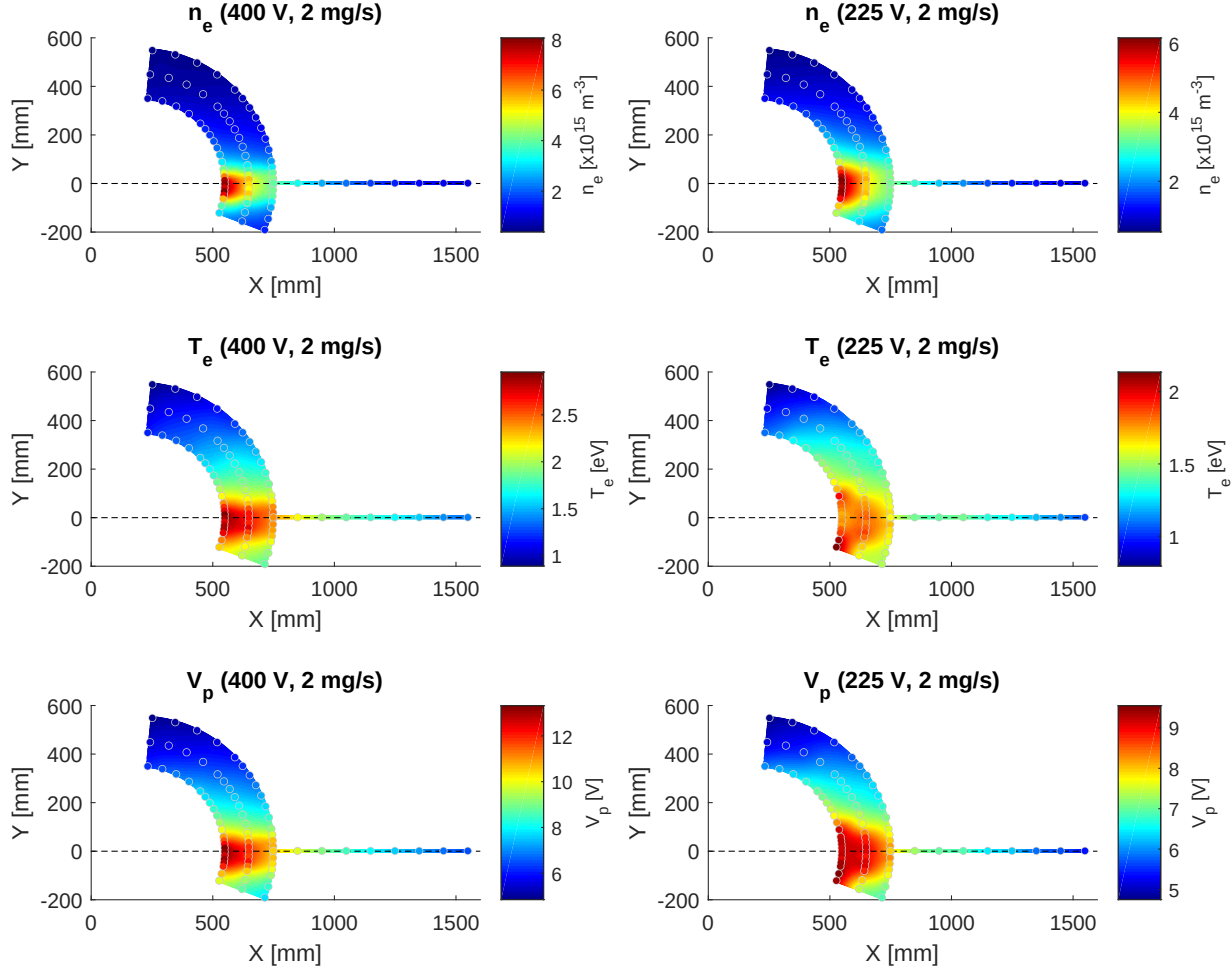


Figure 6. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) for a discharge voltage of 400 V and a mass flow rate of 2 mg/s.

Figure 7. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) for a discharge voltage of 225 V and a mass flow rate of 2 mg/s.

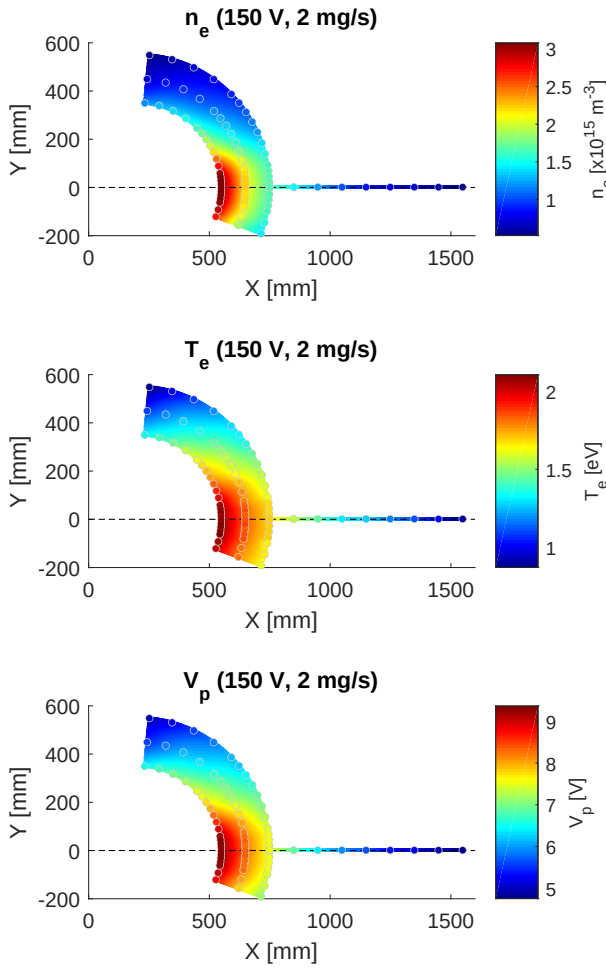


Figure 8. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) for a discharge voltage of 150 V and a mass flow rate of 2 mg/s.

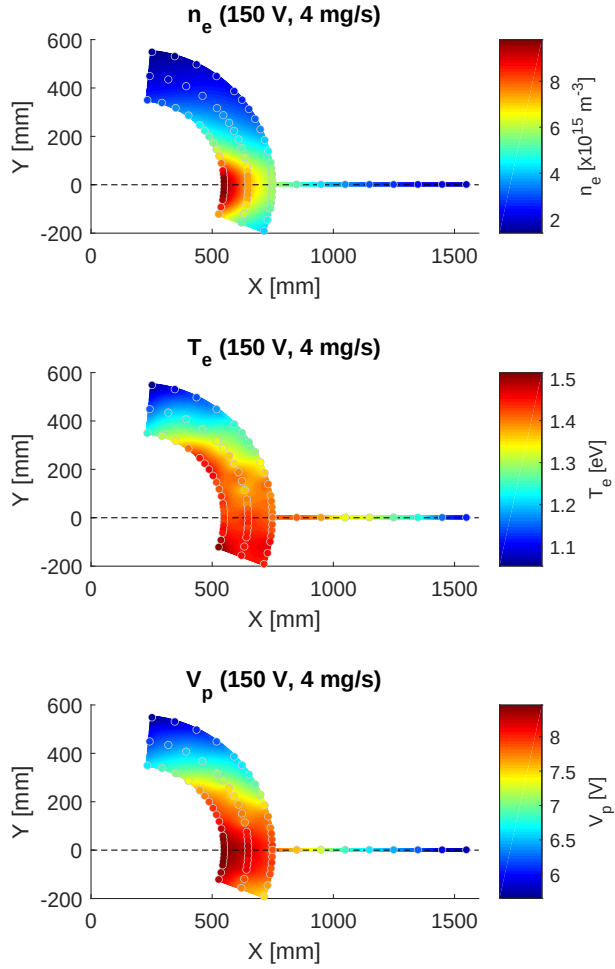


Figure 9. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) for a discharge voltage of 150 V and a mass flow rate of 4 mg/s.

IV. EEDF integration versus IV fitting

Maps of the electron density and electron temperature presented in Section III were derived by fitting the measured IV curve. However, this method is not optimal, as OML assumption are taken for the collected electron current and the contribution of the ion current to the transition region is not taken into account. A more accurate method is to integrate the EEDFs,¹⁹ as

$$n_e = \int_0^\infty g_e(\mathcal{E}) d\mathcal{E} \quad T_{\text{eff}} = \frac{2}{3n_e} \int_0^\infty \mathcal{E} g_e(\mathcal{E}) d\mathcal{E} \quad (4)$$

where $T_{\text{eff}} = \frac{2}{3}\langle\mathcal{E}\rangle$ is the effective electron temperature and $\langle\mathcal{E}\rangle$ is the average electron energy. The effective electron temperature is, by construction, equal to the electron temperature when integrating the EEDF from zero to infinity. This method only relies on the measured EEDF but requires a good measurement of the distributions. Reliable EEDFs measurements were obtained for four out of the six operating points, and a comparison between the plasma parameters obtained by fitting the IV curves and by integrating the EEDFs are shown in Figure 10 and Figure 11, respectively. In this example, fitting on the IV curves seems to overestimate the electron density by a constant of $2.5 \times 10^{15} \text{ m}^{-3}$ while underestimating the electron temperature by 0.36 eV on average. In addition, the spatial variation of the electron temperature derived from integration is slightly less consistent compared to the electron temperature obtained by fitting on the IV curve. This is particularly seen in the measurements taken at (225 V, 2 mg/s) and (150 V, 4 mg/s)

where the noise was higher, making the EEDFs less reliable (i.e. noise on the IV curve is amplified by the double derivative). In conclusion, fitting the IV curve gives more reliable maps for the spatial variation of the electron density and electron temperature but the obtained values are slightly different from the ones obtained by integrating the EEDFs.

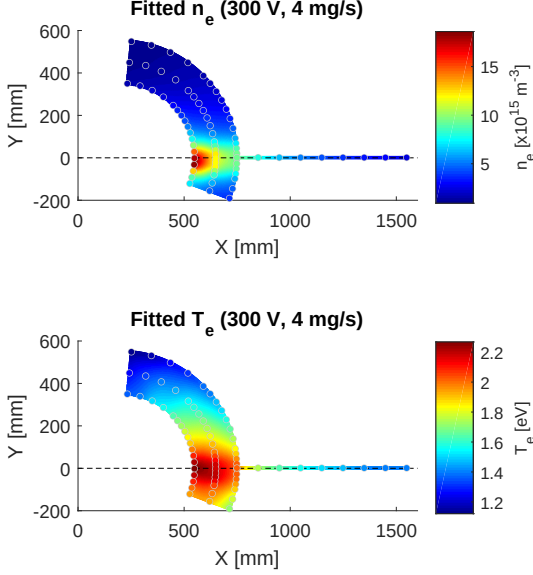


Figure 10. Electron density and electron temperature calculated by fitting the measured IV curves.

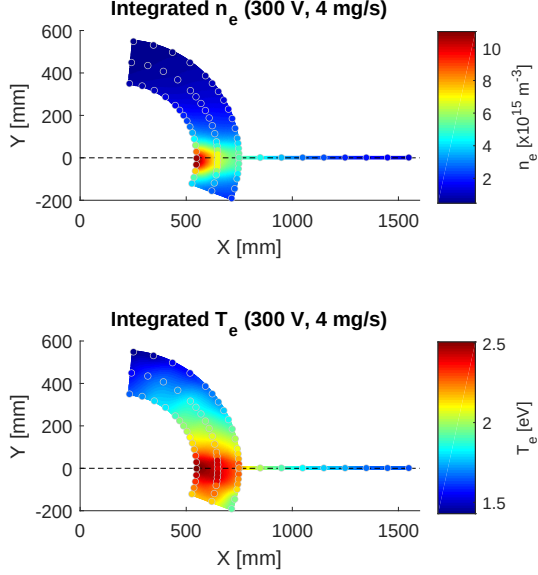


Figure 11. Electron density and electron temperature calculated by integrating the EEDFs.

V. Ratio of specific heats γ

The ratio of specific heats γ establishes a relationship between the electron temperature and plasma density and is an important parameter for the fluid-type models of the plume. The γ factor is expressed as³

$$\left(\frac{n_e}{n_e^*}\right)^\gamma = \left(\frac{T_e}{T_e^*}\right)^{\frac{\gamma}{\gamma-1}} \quad (5)$$

where * indicates a reference state. In a collisional gas plume, local thermodynamic equilibrium is expected and a γ value of 5/3 is anticipated due to adiabatic cooling. However, in a nearly-collisionless plasma plume, local thermodynamic equilibrium conditions are not expected and no simple physical argument leads to a γ equal to 5/3. A γ lower than 5/3 in an otherwise isentropic expansion indicates the existence of non-trivial electron kinetic heat-fluxes. The γ parameter was fitted between the electron density and electron temperature obtained along the plume axis from fitting the IV curves, as well as integrating the EEDFs, are shown in Figure 12. Both methods for obtaining the parameters provide similar values of γ , even though the electron density and electron temperature are slightly different. For the three operating points of the thruster considered, the derived γ is lower than the adiabatic value. Similar values were reported by,^{11,20,21} and indicate that the medium is far from thermodynamic equilibrium and the existence of non-trivial kinetic heat-fluxes.

VI. Spatial variations of the Electron Energy Distribution Functions

The detailed analysis of the measured EEDFs is discussed in a separate article by Giono et. al.²² Nevertheless, parts of the results are recalled here for the convenience of the reader. The EEDFs were measured for each of the operating point tested. However, the higher noise seen at (225 V, 2 mg/s) and (150 V, 2 mg/s) impeded accurate EEDFs to be determined for these two operating points. Hence, only results from the EEDFs recorded at (300 V, 4 mg/s), (300 V, 2 mg/s) and (400 V, 2 mg/s) are discussed here, as comparing these three operating points gives an indication on the effect of the discharge voltage

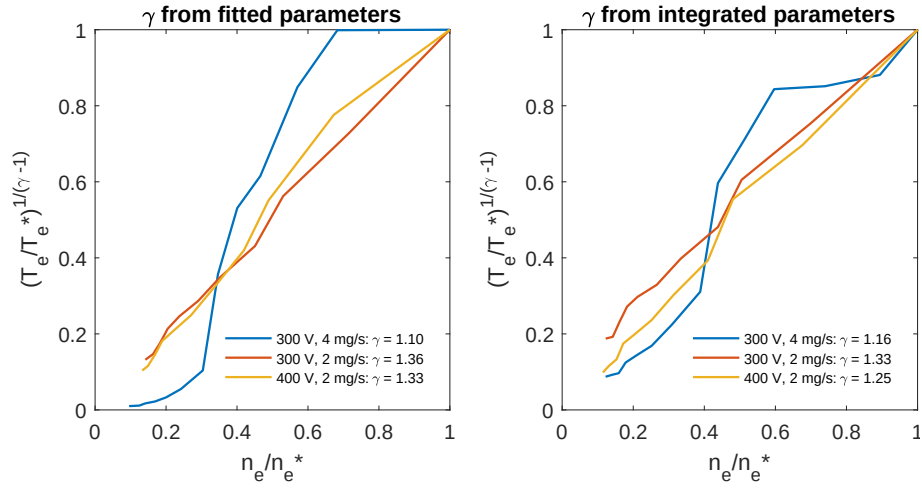


Figure 12. Ratio of specific heats along the plume axis for three operating points of the thruster, derived from the fitted parameters (left) and from the integrated parameters.

and mass flow rate. The Electron Energy Probability Function (EPPF) $g_p(\mathcal{E})$ is obtained from the EEDF as $g_p(\mathcal{E}) = \mathcal{E}^{-1/2}g_e(\mathcal{E})$, and Figure 13 shows its spatial variation along the plume axis for three operating points of the thruster.

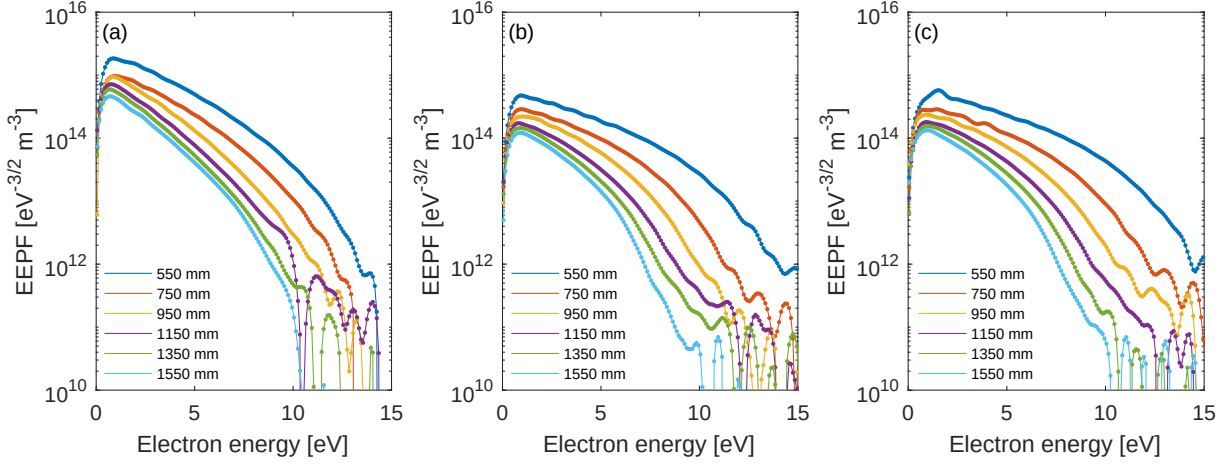


Figure 13. EPPFs measured along the plume axis, for (a) 300 V, 4 mg/s, (b) 300 V, 2 mg/s and (c) 400 V, 2 mg/s. Not every axial measurements are shown. Figure adapted from Giono et. al.²²

The EEPFs can be seen to drop faster at higher energy, and it does not follow a typical Maxwellian distribution. A general formulation for the EEPF is

$$g_p(\mathcal{E}) = n_e \frac{3\alpha}{T_{\text{eff}}^{\frac{3}{2}}} \frac{\left[2\Gamma\left(\frac{5}{2\alpha}\right)\right]^{\frac{3}{2\alpha}}}{\left[3\Gamma\left(\frac{3}{2\alpha}\right)\right]^{\frac{3}{2\alpha}}} \exp\left\{-\left[\frac{2\Gamma\left(\frac{5}{2\alpha}\right)}{3\Gamma\left(\frac{3}{2\alpha}\right)} \frac{\mathcal{E}}{T_{\text{eff}}}\right]^{\alpha}\right\} \quad (6)$$

where α is an exponent describing the curvature of the EEPF.^{23,24} This expression reduces to a Maxwellian distribution for $\alpha=1$, whereas $\alpha=2$ leads to a Druyvesteyn distribution. Equation (6) was fitted onto the measured EEPF and the spatial variation of the exponent α along the plume axis is shown in Figure 14. The exponent α can be seen to be between 1 and 2, indicating that the EEPFs are in-between a Maxwellian and a Druyvesteyn distribution. Figure 14 also revealed that the shape/nature of the EEPF is independent of the distance from the thruster, but seems to be influenced by the mass flow rate of the thruster. This might indicate a correlation between the shape of the EEPFs and the plasma density inside the plume.

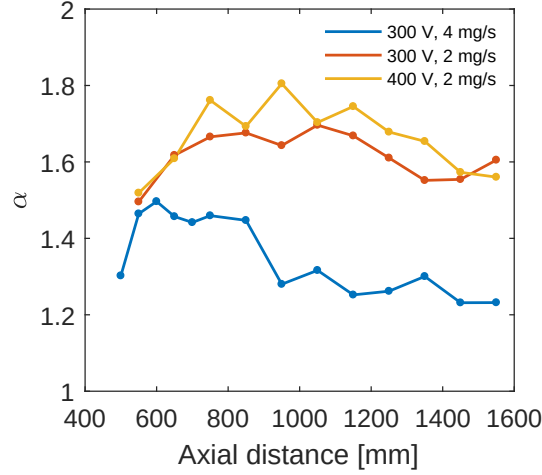


Figure 14. Axial variation of the exponent α for each of the three operating points of the thruster. Figure adapted from Giono et. al.²²

VII. Langmuir probe perpendicular to the ion flow

Only few measurements were recorded using the perpendicular Langmuir probe (mounted on the second rotating arm, see Figure 2). Nevertheless, Figure 15 presents two measurements taken along the plume axis for a discharge voltage of 300 V and a mass flow rate of 4 mg/s, one taken with the parallel probe and one taken with the perpendicular probe, respectively 700 and 730 mm away from the thruster exit. The main difference can be seen in the ion current: the perpendicular probe collects a significantly larger number of ions due to its larger cross-section in the plane perpendicular to the ion flow. A slight difference can be seen in the electron density, electron temperature and plasma potential as well, but this is most likely due to the different location of the two probes (i.e. perpendicular probe further away and slight above the parallel probe).

The ion current collected by the perpendicular probe can be modelled using the theory developed for moving probes^{25,26} assuming a OML regime, i.e. large enough sheath compare to the probe size. In this theory, the collected ion current by a cylindrical probe is

$$i = An_i q_i v_i \pi^{-1} \sqrt{1 + \frac{k_B T_i}{m_i v_i^2} + \frac{2e(V_p - V)}{m_i v_i^2}} \quad (7)$$

where A is the probe area, n_i the ion density, q_i the ion charge, T_i the ion temperature, m_i the ion mass and v_i the speed of the spacecraft through a non-moving plasma. In the presented case where the probe is fixed, v_i corresponds to the ion flow velocity. An examination of the three terms under the square root reveals

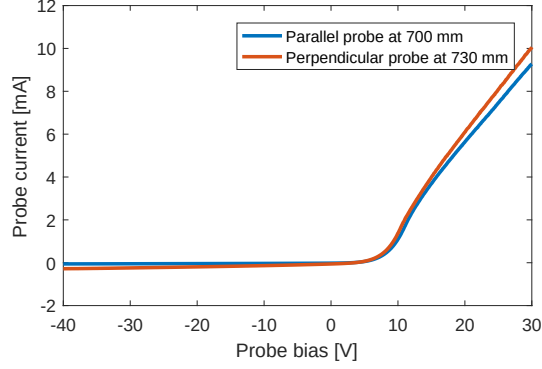


Figure 15. IV curves from the probe parallel to the ion stream line (blue) and a probe perpendicular to the ion stream line (red).

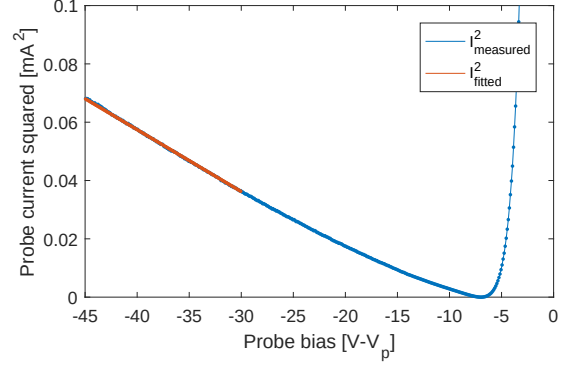


Figure 16. Squared ion current from Figure 15 (blue) and example of fitting on the squared ion saturation current (red).

their origin: the first corresponds to the current collected from the moving ion due to their flow, the second to the current collected from the thermal motion of the ions, and the last one to the current collected from the ions attracted by the probe potential in the OML regime. Yet, all terms do not compete equally and one can see that the thermal term requires a large ion temperature in order to compete with the potential term. For example in the present case, an unrealistic 60 eV ion temperature would be required to compete with a -30 V potential. Hence, the thermal term can be neglected in the equation for the ion current. Squaring the simplified equation, one can see that the squared current should have a linear trend depending only on the ion density, with an offset depending on both the ion density and their velocity. Figure 16 shows the squared ion current recorded by the perpendicular probe after removing the plasma potential, with a linear fit onto the ion saturation part for negative potential. Fitted values for the ion density and velocity are $1.1 \times 10^{17} \text{ m}^{-3}$ and 4.35 km/s , respectively. The retrieved ion density is larger by about one order of magnitude compared to the corresponding the electron density of $1.3 \times 10^{16} \text{ m}^{-3}$, also obtained from OML theory in the electron saturation region. In addition, the ion flow velocity is lower than the expected exhaust velocity ($10\text{-}80 \text{ km/s}$). These two unexpected results might suggest that the theory used does not match the actual plasma regime: a linear squared ion saturation current does not directly imply an orbital motion limit regime. Furthermore, the transition region between the ion and the electron currents cannot be simply modelled as the sum of the discussed ion saturation current and an exponentially-growing electron current, indicating that a more complicated regime operates in this region (e.g. sheath of intermediate size, collisions, etc...).

VIII. Error due to measurement noise and hysteresis

All measurements previously presented were derived from a single up-sweep IV curve (i.e. from negative to positive potential). However, differences in the IV curves can be seen depending on the direction of the sweep, from negative to positive potentials (i.e. up sweep) or from positive to negative potentials (i.e. down sweep). In addition, noise on the recorded current can also affect the derived plasma parameters. For this reasons, several IV curves were measured at a fixed location along the plume axis, and for a fixed operating point of the thruster. Five up-sweeps and five down-sweeps were recorded, as a way to estimate the measurement error (i.e. between the five up and five down measurements, respectively) and the hysteresis error (i.e. difference between up and down sweeps). Errors were derived as the maximum deviation from the mean plasma parameter, namely electron density, electron temperature and plasma potential, derived for all ten measurements. The error on the electron density and electron temperature were derived for the two methods described before: IV curve fitting and EEDF integration. Figure 17 shows an example of hysteresis between an up and a down sweep, and the errors are summarized in Table 1. The total uncertainty on the measurements can be obtained as the root sum square (RSS) of the measurement and hysteresis errors. The uncertainty on the electron density and electron temperature is about 5% of the derived values, for both parameters. The uncertainty on the plasma potential is about 3% of the derived values.

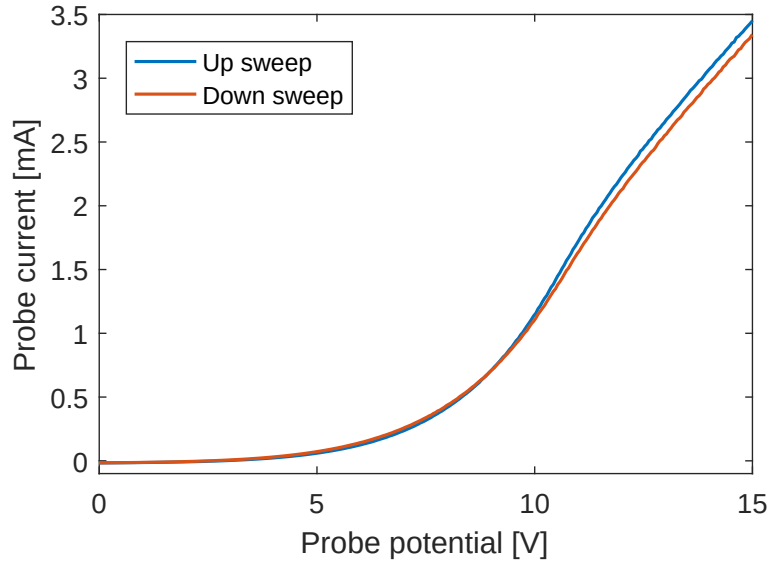


Figure 17. Example of hysteresis between up (blue) and down (red) sweeps.

Table 1. Error on the plasma parameters.

	Measurement error	Hysteresis error	RSS	Unit
n_e (IV fitting)	9.88×10^{13}	1.89×10^{14}	2.13×10^{14}	m^{-3}
n_e (EEDF integration)	8.26×10^{13}	2.45×10^{14}	2.58×10^{14}	m^{-3}
T_e (IV fitting)	0.027	0.204	0.206	eV
T_e (EEDF integration)	0.049	0.251	0.256	eV
V_p	0.08	0.30	0.31	V

IX. Comparison with the measurements recorded using KTH read-out electronics

A custom read-out system for operating the probes was developed by KTH, and is shown in Figure 18. The sweeps are operated by a FPGA, back and fourth from -45 V to $+45$ V (i.e. multiple up and down sweeps) with 1.6 mV steps. The probe voltage bias was imposed using a 16-bits Digital to Analog Converter (DAC), and the probe current recorded with a 16-bits Analog to Digital Converter(ADC). During the sweep, data is temporary stored on a 2 Mb RAM storage, and then written onto a SD card once the sweep is completed. This system has the advantage of being one order of magnitude faster than the Keithley sourcemeter: a half million points measurement with multiple up and down sweeps was recorded in 10 s compared to 1.5 min for a thousand points single up sweep with the Keithley. An example of recorded IV curve is shown in Figure 19. However, accurate EEDF measurements could not be derived from these measurements due to a too large electric noise and the Keithley sourcemeter was used for the measurements instead. Nevertheless, a set of measurements was performed with the KTH read-out for a 300 V discharge voltage and a 2 mg/s mass flow rate. The plasma parameters derived from fitting on these IV curves is shown in Figure 21 and compared to the corresponding measurement set taken with the Keithley recalled in Figure 20. The obtained electron density and plasma potential are similar in both cases, and only the estimation of the electron temperature appears to be less consistent in case of the KTH read-out electronics. This is an

encouraging results considering that each measurement was taken during a fraction of the time taken by the Keithley, but also considering the cost of such read-out electronics. The system is planned to be improved upon and could provide for more flexible sweeps (i.e. variable steps and boundary) as well as time-resolved measurements.

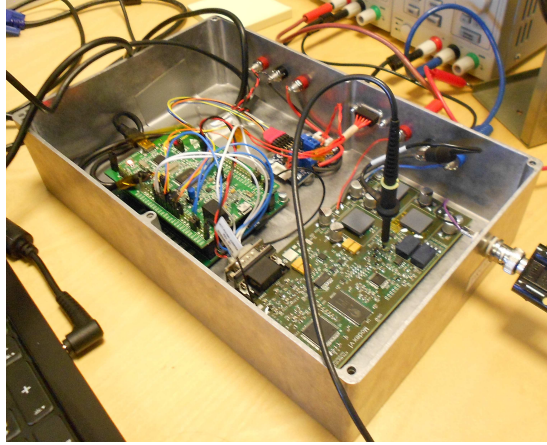


Figure 18. KTH read-out electronics. The dark green PCB on the right operates with probe : a 16-bits DAC imposes the voltage bias and a 16-bits ADC records the current. The sweeps sequence is controlled by a FPGA on the board. User commands are send to a STM32 board (light green PCB on the left) via USB, which then transferred them to the FPGA. The blue PCB in the middle is the motor controller for the translation stage, allowing for the automation of the translation/sweeps.

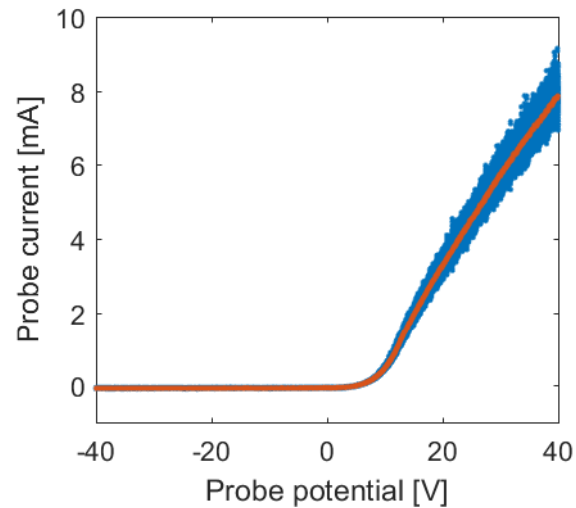


Figure 19. Example of IV curve recorded with the KTH read-out electronics, along the plume axis at a 500 mm distance from the thruster exit, for a discharge voltage of 300 V and a mass flow rate of 2 mg/s. Blue shows the raw measurements: half-million points recorded with a 1.6 mV steps from -45 to 45 V. Red shows the IV curve after averaging with 0.05 V bins.

X. Conclusion

Extensive measurements of the plasma properties were conducted in the plume far-region of a SPT-100 Hall thruster using cylindrical Langmuir probes. The electron density, electron temperature, plasma potential and electron energy distribution functions were successfully derived by fitting the recorded current-voltage characteristics at axial positions 500 to 1550 mm away from the thruster exit ,as well as at multiple angular positions (500 to 750 mm from the thruster exit). Measurements at these positions were conducted for six different operating points of the thruster, with discharge voltage from 150 to 400 V and mass flow rate from 2 to 4 mg/s. A comparison between the electron density and electron temperature obtained by fitting the IV curves and by integrating the corresponding EEDFs showed that the first method overestimated the density while slightly underestimating the temperature, and it was more reliable for deriving consistent spatial maps. The ratio of specific heats γ was computed along the plume for the parameters derived with both methods, and no significant differences between the two were noticed. In both case, a γ factor lower than the adiabatic value of 5/3 was found, which seems to decrease further when increasing the mass flow rate. A more detailed analysis was performed on the axial EEDF for three different operating points: the shape of the distribution was determined to be between Maxwellian and Druyvesteyn like distributions, with an exponent α between 1.2 and 1.6. The mass flow rate seems to influence this exponent α , with its lower value of 1.2 for the larger mass flow rate of 4 mg/s and its high value of 1.6 for the lower mass flow rate of 2 mg/s, suggesting an possible influence of the plasma density on the shape of the EEDF. The spatial variation of the exponent α along the plume axis was seen to be roughly constant, indicating a global property of the plasma inside the plume which might be imprinted by the plasma condition closer to the thruster exit, where the collision rate is higher. A clear difference was observed in the ion current collected by the probe perpendicular to the ion stream lines compared to the current collected by the parallel probe at a similar distance from the thruster exit. Based on OML theory, an estimation of the ion density and ion velocity was made using the ion saturation current collected by the perpendicular probe. As a results, a larger ion density was obtained

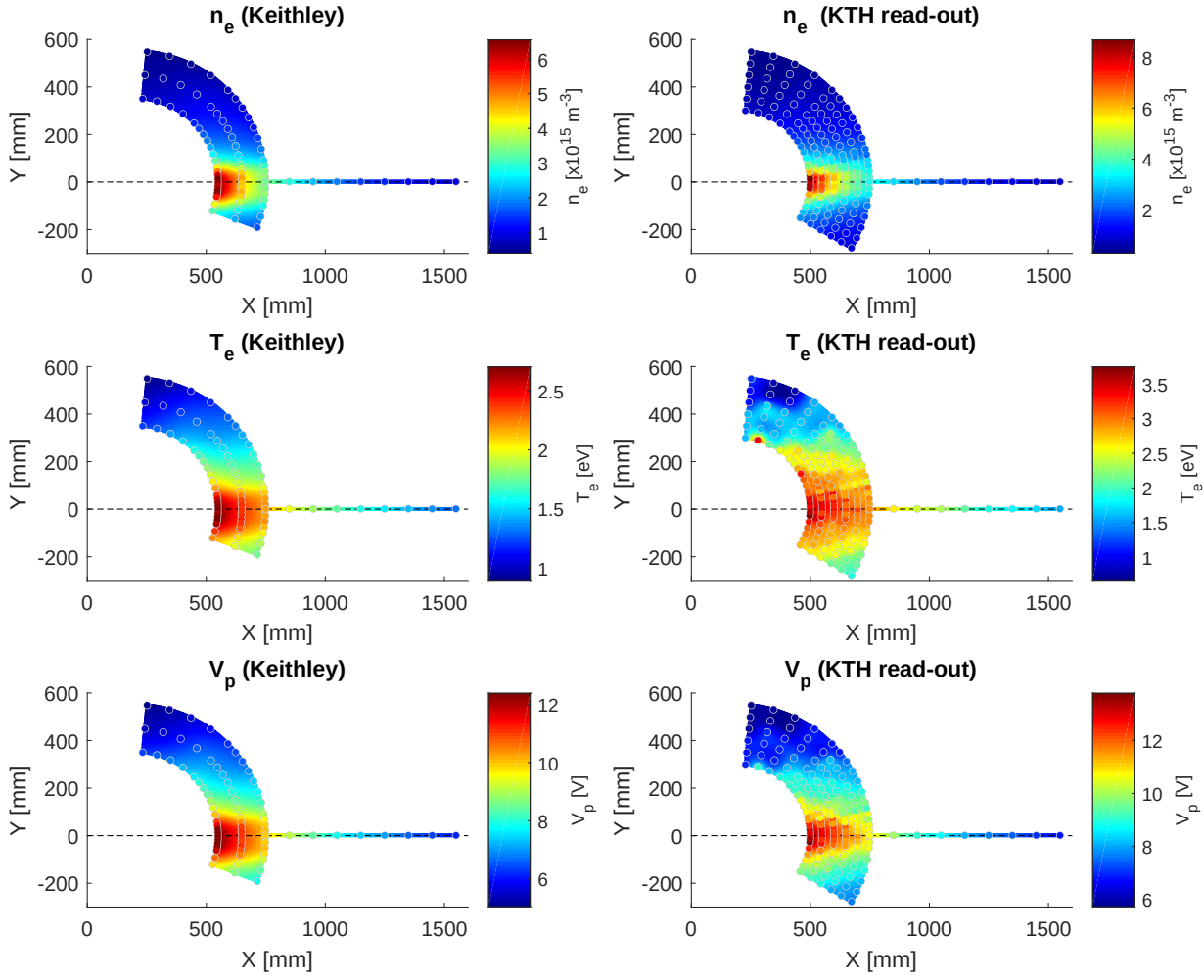


Figure 20. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) derived by fitting on the IV curves recorded using the Keithley sourcemeter, for a discharge voltage of 300 V and a mass flow rate of 2 mg/s.

Figure 21. Maps of the electron density (top), electron temperature (middle) and plasma potential (bottom) derived by fitting on the IV curves recorded using the KTH read-out electronics, for a discharge voltage of 300 V and a mass flow rate of 2 mg/s.

compared to the corresponding electron density, and a lower ion velocity compared to the expected exhaust velocity was also obtained. This indicates that the theory used might not be adequate to the plasma regime encountered, even though a linear squared ion saturation current was observed. Finally, the error on the obtained plasma parameters was estimated using dedicated measurements with both up and down sweeps, indicating that the derived plasma parameters for each method are within a $\pm 5\%$ uncertainty. In addition, the plasma parameters obtained using KTH read-out electronics were comparable with the ones recorded with the Keithley sourcemeter. This is an encouraging results and further improvement of the read-out system could lead to a better and more affordable alternative to sourcemeter.

Results from this experiment will be used as a reference point to better constrain the modelling of the plasma plume.

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providing experimental measurements to better constrain the modelling, and therefore includes both the theoretical/modelling aspect (UC3M and ONERA) and the experimental aspect (KTH, CNRS, ESA and Airbus-DS). The test campaign was conducted at ESA/ESTEC in April-May 2017, using a SPT-100 Hall thruster provided by Airbus-DS. The project was partially supported by the Swedish Government Agency for Innovation Systems (VINNOVA) contracts nos. 2014-0478 and 2016-04094.

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