Evaluation of various probe designs for measuring the ion current density in a Hall thruster plume.

IEPC-2017-336

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology – Atlanta, Georgia – USA
October 8–12, 2017

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This contribution deals with the comparison between various electrostatic probe designs for the measurement of the ion current density in the far-field region of the plasma plume of electric thrusters for spacecraft, in particular Hall thrusters. Following a thorough literature survey, three probe architectures have been selected: a planar probe (PP), a planar probe with a guard ring (PPGR) and a Faraday cup (FC). The geometrical ion collection area and the collector material are the same for the three instruments. The ion probes have been installed on a rotating arm in the PIVOINE-2G test bench of the ICARE laboratory, which allows data acquisition over a 180° angle. Measurements have been performed in the plume of the 1.5 kW-class PPS®1350-ML Hall thruster, a laboratory version of the PPS®1350-G developed and built by SAFRAN. Ion current density angular distributions have been acquired in the Hall thruster plume for a broad range of discharge voltages and xenon mass flow rates. The impact of the background pressure has also been investigated. The influence of the probe architecture upon ion profile and associated quantities will be discussed in this contribution. Recommendations for the design of an "ideal" ion current probe as well as methodology and guidelines for probe operation and data treatment are provided after the critical examination of all experimental outcomes. This works a first step towards the standardization of EP device plume measurements in simulated space environment, an essential phase towards improving the reliability of comparisons between different thrusters and different vacuum chambers and towards furnishing high-quality data for validation of numerical simulations.

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Nomenclature

A	Surface area	m^2	p	Pressure	Pa
d	diameter	m	r	Radius	m
ϕ	Latitude	rad	s	Sheath thickness	m
Φ_a	Anode mass flow rate	mg/s	T_e	Electron temperature	eV
ϕ_c	Cathode mass flow rate	mg/s	U_d	Discharge voltage	V
I_d	Discharge current	A	V_f	Floating potential	V
I_i	Ion current	A	V_p	Plasma potential	V
j_i	Ion current density	A/m^2	v	Ion velocity	m/s
λ_D	Debye length	m	θ	Longitude	rad
n_e	Electron density	m^{-3}	x, y, z	Coordinates	m

I. Introduction

Measurements of the ion current density in the plasma plume or ion beam of electric propulsion devices for spacecraft is of great relevance as the flux of ejected ions determines the thruster properties such as the thrust level, the specific impulse and the propellant utilization as well as the performances of the propulsion system. Moreover, an accurate and comprehensive knowledge about the ion current is critical for the validation of plume modeling and numerical simulations, for thruster acceptance tests, for the study of facility effects and for understanding the interactions between plasma and spacecraft. The ion current density can be measured using electrostatic probes that basically consists of a conducting electrode, termed the collector, polarized to a high negative voltage with respect to the local floating potential to repel electrons. There are various configuration of probes from a simple metal disk to architectures with collimators, filters, guard rings and highly technical materials.

This paper compares three different probe designs, namely a planar probe, a planar probe with a guard ring, also called a Faraday probe, and a Faraday cup for time-averaged measurements of the ion current density in the plume of Hall thrusters. All probes have the same geometrical collection area and use the same electrode material. Experiments reported in this paper have been performed in the plume far-field of the 1.5 kW-class PPS®1350-ML Hall thruster operated with xenon as fuel. The main objective of this study is to provide recommendations for the design of a high-quality ion current probe as well as guidance and methodology for probe operation and data treatment.

II. Measuring instruments

The ion current density measurements in the far-field region of a Hall thruster plasma plume have been performed with 3 types of electrostatic probes in this work: a planar probe (PP), a planar probe with a guard ring (PPGR), often termed a Faraday probe, and a Faraday cup (FC). Figure 1 shows a photograph of the 3 probes before wiring and mounting onto the rotating arm of the vacuum tank. The 3 probes share a number of characteristics that are summarized in table 1. The ion current collector is made in Molybdenum (Mo) to minimize the secondary electron emission under fast ion bombardment. Note that tungsten (W) is even better in terms of SSE,[1] however, it is difficult to machine. Covering the collector with a thin layer of W is one option but the lifetime of th coating is short especially when thrusters are operated in a high-voltage regime. The geometrical area that defines the ion current collection is a 15 mm diameter disk for the 3 instruments. The collection area is therefore 176.72 mm^2. The size of the collection area has been determined according to three criteria: the plasma sheath thickness in the plume, the spatial resolution required to resolve the gradient scale length and the amount of sputtered material. Parts for electrical insulation are either in alumina or in vacuum-compatible polymers such as PolyEther-Ether-Ketone (PEEK). Alumina exhibits good mechanical properties, it can stand high temperatures and its sputtering yield under high energy ion bombardment is low. PEEK offers excellent mechanical and chemical resistance properties that are retained to high temperatures. Its melting point is around 340C.

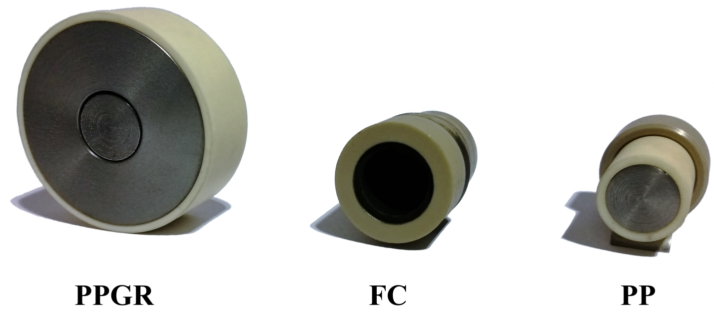

Figure 1. Picture of the 3 electrostatic probes used to measure the ion current in the plume of Hall thrusters: planar probe with a guard ring (PPGR), Faraday cup (FC) and planar probe (PP).

A. Planar probe

A planar electrostatic probe is simply a conducting plate whose thickness is negligible with respect to length and width.[2–5] Here the planar probe (PP) is a 15 mm in diameter and 3 mm in thickness Mo disk encapsulated in an alumina cylinder as can be seen in Fig. 1. The disk was polished to reduce the surface roughness below 0.01 mm. The Mo collector front face must be perfectly aligned with the edges of the ceramic cylinder to avoid collecting current on the sides, hence increasing the area of the collecting area. The length of the PP is 30 mm to facilitate handling and mounting.

B. Planar probe with a guard ring

The architecture of a planar probe with a guard ring, also called a Faraday probe, is more complicated as such a probe comprises an ion collector surrounded by a conducting ring,[6–8] as can be seen in Fig. 1. Although various guard ring designs are possible, the purpose of the ring is to maintain a flat plasma sheath on the collector in such a way the collection area exactly corresponds to the geometrical area, which is not the case for a simple planar probe due to sheath expansion.[3,9–13] A PPGR is a very common tool for the measurement of the local ion charge flux in the beam or plume of EP devices. Information about probe design and utilization as well as data treatment and analysis can be found in references[1,14–23]

In this work the disk-shape collector is surrounded by a 15 mm in width Mo ring. The guard ring width must be in the order of the local plasma sheath size to eliminate edge effects. The collector and the ring are electrically disconnected. The spacing between the two parts is 0.5 mm with a 10 mm depth throat. The gap must always stay far below the sheath thickness to avoid discontinuities in the potential distribution. The throat mitigates the occurrence of a short-circuit between the collector and the ring due to coating formation from sputtered compounds. The collector must be as thin as possible to prevent any ion current collection on the sides.[17] Here the collector thickness is 1 mm. The surface of the two components was polished to reduce the surface roughness below 0.01 mm. The guard ring is encapsulated into an alumina cylinder. The external diameter of the PPGR is 50 mm and its length is 18 mm. The collector and the ring each have their own electrical connection for polarization and current measurement.

Table 1. Main characteristics of the 3 ion current probes.

Probe	Diameter d	Material	Insulator
PP	15 mm	Mo	Al_2O_3
PPGR	15 mm	Mo	Al_2O_3
FC	15 mm	Mo	PEEK

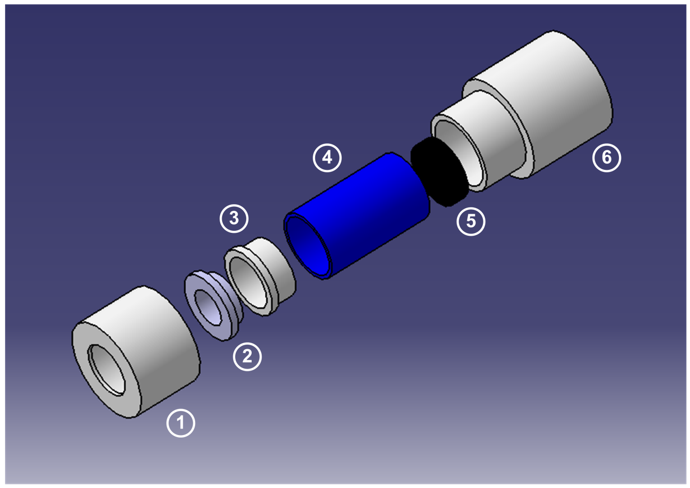

Figure 2. Exploded view drawing of the FC showing the main elements (see text for details).

C. Faraday cup

A Faraday Cup (FC) is a special kind of electrostatic planar probe; It is basically an isolated conductive cup dedicated to the detection of charged particles in a low-pressure or vacuum environment.[24–27] When a Faraday cup operates as an ion collector, which means the cup is negatively biased with respect to the floating potential, the ion current in the probe direction can be accurately measured. Contrary to a planar probe, edge effects due to plasma sheath formation are negligible with a FC.

In the frame of this study, a Faraday cup with a 15 mm in diameter collimator has been built. A large orifice collimator allows to minimize the impact of the neutral gas inside the cup. As a FC is collimated, the collection solid angle is below 2π str, contrary to a planar probe, therefore a fraction of the thermal ion current is not captured.[28] Nevertheless, a collimator allows to well define the velocity vector of ions entering the device. Besides, the collimator also limits the ion flux, which permits to avoid saturation of the measurement chain when the FC is placed in the center of the ion beam, especially for high-power EP devices. An exploded view drawing of the Faraday probe is shown in Fig. 2. The Faraday cup assembly is composed of 6 different parts.

The **collimator** (2) is used to reduce the amount of ion current and to accurately define the probe view angle; the diameter of the orifice is 15 mm. Graphite is used here due to its low sputtering yield under xenon and krypton ion bombardment. A very small orifice selects a narrow range of ion velocity vectors. When the aperture is infinitely small only ions with a velocity vector strictly parallel to the FC axis can enter the device. Although the collimator aperture acts as a velocity filter, having a narrow aperture has an unfavorable consequence: Ions that are not aligned with the probe axis, i.e. the thermal component of the flux, are not captured, that means the local ion current is underestimated. Moreover, a relatively large orifice diameter is preferred as the pressure inside is not much higher than the residual gas pressure in the vacuum chamber, which reduces charge-exchange and scattering collisions.

The **spacer** (3) acts as an electrical insulator. It electrically decouples the cup from the collimator as graphite is a conducting compound. The collimator is then at floating potential. The spacer is a 5 mm in length PEEK ring. The size is chosen to reduce the occurrence of short-circuit between the collimator and the cup.

The molybdenum **ion collector** (5) forms the back of the **cup** (4+5). The collector is mechanically attached to the cup without welding the two pieces. The diameter of the collector is 20 mm; The active length of the stainless-steel cup is 26 mm. The total volume of the cup is therefore $8.2\,\text{cm}^3$. The length should be longer than space-charge sheath thickness inside the probe to ensure the measurement outcomes are insensitive to the local plasma properties. The collector diameter, i.e. the cup diameter, is selected according to the sizes of the medium to be probed. In other words, the cup diameter must be lower than any gradient scale lengths to be able to correctly resolve the structures, the ion beam shape in this case. A small FC also reduces the amount of sputtered material in the plasma beam. The cylinder plus the collector are maintained at a potential well below the floating potential to capture positively charged particles. The cup

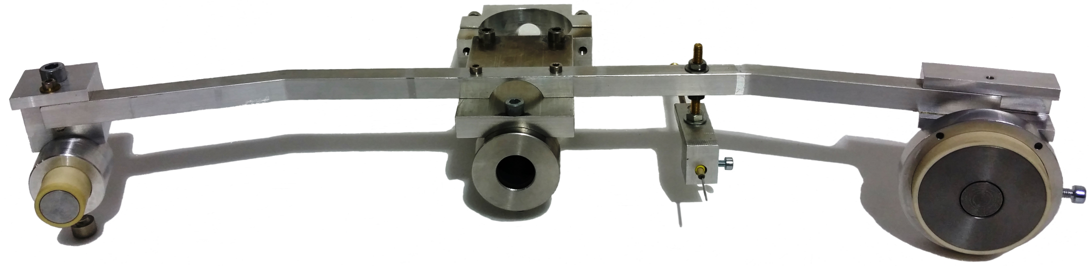

Figure 3. Probe support with the 4 instruments installed. From left to right: PP, FC, LP and PPGR. The FC is aligned with the rotating arm.

design limits the perturbation introduced by the SEE process: the cylindrical geometry allows to capture most of the secondary electrons emitted by the collector surface. As the collimator is floating, the high-voltage sheath of the cup does not play a role in the ion current collection.

Parts (1) and (6) correspond respectively to the front and the rear section of the **outer electrical insulator**. They are made of PEEK. The insulator shields the cup from the surrounding plasma. The FC is encapsulated into a cylindrical aluminum pod to protect the external PEEK insulator from ion bombardment. During measurements the pod is floating with respect to the local plasma potential. The pod is used to attach the probe to a mounting bracket.

D. Langmuir probe

A single cylindrical Langmuir probe (LP) was used to determine the electron properties and the plasma potential in the plume. The LP was made of a 1 mm in diameter tungsten wire . The non-collecting part of the wire was insulated from the plasma by a 50 mm long and 2.5 mm in diameter alumina tube. The length of the collecting part was 18 mm. The voltage sweep and the resulting probe current measurement were performed using the ALP System$^{\text{TM}}$ manufactured by Impedans.

E. Probe support and wiring

The three ion current probes and the Langmuir probe are installed on an aluminum support that is attached to the rotating arm of the PIVOINE-2G test bench. Figure 3 shows the probe holder with the 4 instruments before the experimental campaign. All probes are situated in the horizontal plane that contains the Hall thruster centerline. The center of each probe and the LP tip point towards the thruster axis. The collector of the PP and PPGR and the collimator of the FC are positioned at exactly 700 mm from the Hall thruster channel exit plane. The latter includes the pivot point of the rotating arm. The FC is the reference probe as its angular position coincides with the one of the rotating arm. The distance between the FC center and the center of the two other probes is 180.9 mm. The distance must be large enough to avoid any interference and perturbation between the probes. The angle between the two planar probes and FC is then 14.8°. The Langmuir probe is placed between FC and PPGR as shown in Fig. 3. The distance between LP and FC is 76 mm and the angle is 6.2°. All distances and angles are summarized in Tab. 2.

For the four probes, the collected current is transferred to the measurement chain by means of the core of a 50 Ω coaxial cable. The voltage is applied through the same cables. The cable is protected against plasma and heat by means of a Fluorinated Ethylene Propylene (FEP) polymer jacket and fiber glass hoses. Each cable is terminated with a 50 Ω male SMA plug connector to ensure good signal transmission. Electrical insulation between various probe components was checked at 250 V. All electrical resistance were above 100 MΩ. The value of the probe/cable/connector and vacuum feedthrough line resistance is given in Tab. 2.

Table 2. Distance to reference, angle and electrical resistance for the 4 probes. FC is the reference probe. PP, PPGR and FC are positioned at 700 mm from the thruster exit plane.

Sonde	Distance d	Angle	Rsistance
#	mm	°	Ω
PP	180,9	-14,8	4,0
PPGR (C)	180,9	+14,8	4,0
FC	0	0	4,2
LP	76	+6,2	4,0

III. Preliminary experiments

A. Hall thruster and vacuum chamber

1. PPS® 1350-ML thruster

Experiments have been carried out with the PPS®1350-ML Hall thruster, a laboratory version of the PPS®1350-G thruster developed, built and distributed by SAFRAN.[29–31] The PPS®1350-G is a 1.5 kW-class thruster that operates nominaly with xenon as fuel at 350 V discharge voltage. It delivers a thrust of 89 mN and a specific impulse of 1700 s with an anode efficiency in excess of 50 %. This Hall thruster demonstrated the ability to operate during 10530 hours at the nominal operating conditions. In 2005, the PPS®1350-G thruster propelled the European Space Agencys SMART-1 satellite to the Moon.[32] The PPS®1350-G thruster is currently used for north/south station keeping on telecommunications platforms. A 2.5 kW version has recently been developed and qualified for orbit transfer.[32]

The PPS®1350-ML thruster used in this work was equipped with BN-SiO_2 channel walls and a self-heated disk-shape LaB_6 external cathode. The thruster was fired with xenon as propellant gas. The cathode mass flow rate was 0.6 mg/s. The magnetic field topology was kept fixed whatever the operating parameters with a 4.5 A current through the external and internal magnetization coils.

2. PIVOINE-2G test bench

Plume measurements have been performed in the PIVOINE-2G test-bench at ICARE in Orléans. PIVOINE-2G is a cryogenically pumped 4 m long and 2.2 m in diameter stainless steel vacuum chamber. The bench allows testing Hall thrusters from 10 W up to 25 kW input power. The PIVOINE-2G test-bench was built in 1997 with the financial support of the French space agency CNES and the "Region Centre Council". It was upgraded in 2007 to achieve a pumping speed in excess of 200000 l/s, one of the largest within Europe. The current version is composed of two cryogenic stages optimized for xenon, although krypton and argon can also be efficiently evacuated. The cryogenic panels are shielded from the thruster thermal load and from the ion beam by means of LN2 cooled graphite tiles. When using the two stages, a background gas pressure of $2{\times}10^{-5}$ mbar can be achieved with 20 mg/s of xenon. A 2500 l/s turbomolecular pump is also used for removal of light gases like hydrogen and helium. The vacuum chamber is equipped with a large lock-chamber that permits inserting the thruster without disturbing the vacuum as well as with different observation windows and diagnostic ports. PIVOINE-2G has a set of diagnostics that includes a thrust balance, ion current probes and an energy analyzer. The probes can be installed either on a 2D translation stage or on a rotating arm that allows performing measurements in a hemisphere. The thrust balance is a pendulum stand, calibrated with a series of weights. The estimated accuracy of the measured thrust is 0.5 mN for a thrust ranging from 5 to 1500 mN. The discharge power is provided by two 500 V–30 A) supplies in parallel. During operation of a thruster, more than hundred parameters are monitored and continuously acquired. The PIVOINE-2G ground-test facility is dedicated to research and development activities in the field of Electric Propulsion. A fully automated version of PIVOINE-2G able to operate on a 24 hour/7 day basis is currently under development with an expected commissioning at the end of 2018.

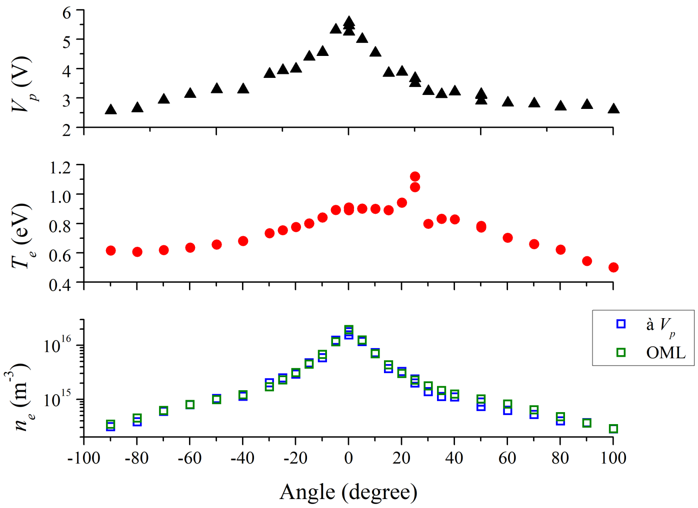

Figure 4. Angular distribution of V_p (top), T_e (middle) and n_e (bottom) at $x = 70$ cm. The electron density was calculated using two different methods. $\theta = 0°$ corresponds to the PPS®1350-ML thruster axis. Operating conditions: 350 V, 5 mg/s and 4.28 A.

B. Electron properties

The electron density n_e, the electron temperature T_e and the plasma potential V_p have been obtained from the analysis of the cylindrical Langmuir probe current-voltage characteristics curve using the standard Langmuir probe theory in a collisionless and magnetic field free plasma assuming a Maxwellian electron distribution function.[3,9–13] The floating potential V_f is the potential for which the net current is zero. In other words the ion current matches the electron current at V_f. The plasma potential is obtained from the maximum of the first derivative of the probe characteristic. The electron temperature T_e corresponds to the slope of the logarithm of the electron current against potential in the transition region between V_f and V_p. The electron current trace is obtained from the I-V curve after subtracting the ion current. The latter is estimated using a linear fit to the ion branch. The electron density n_e has been determined with two methods. The density was inferred from the electron current value at V_p as the plasma sheath vanishes at this specific potential. One can then use the probe geometrical area to compute n_e. The density was also calculated using the orbital motion limited (OML) assumption: In the OML regime the slope of I_e^2 versus V_s plot is proportional to n_e^2. The angular distribution of V_p, T_e and n_e in the far-field plume ($x = 70$ cm) of the PPS®1350-ML Hall thruster firing at 350 V discharge voltage with a xenon mass flow rate of 5 mg/s through the anode is displayed in Fig. 4.

The angular distributions are symmetrical with respect to the thruster axis with a bell-curve shape as expected. The values of electron properties and plasma potential are in agreement with the ones obtained during previous campaigns in the PIVOINE-2G chamber with the SPT100-ML and the PPS®1350-ML Hall thruster.[33–37] The profiles are also in agreement with the ones measured at Aerospace Corporation with the PPS®1350-G thruster.[31]

C. Plasma sheath thickness

The plasma sheath thickness in the case of a high-voltage sheath, or space-charge limited sheath, can be determined from n_e and T_e using equations derived from a fluid model of the plasma.[38–42] Detail calculations of the size of a high-voltage sheath using various approaches and assumptions can be found in reference.[7]

Figure 5 shows the evolution of the Debye length λ_D and the sheath thickness with the angle in the plume ($x = 70$ cm) of the PPS®1350-ML Hall thruster operating at nominal operating conditions. The thickness of the space-charge limited sheath has been calculated with two different assumptions for the ion velocity at the sheath edge:[7] Bohm velocity (s), which is a common assumption for plasma discharges, and beam velocity (s_v). In the latter case the ion velocity directly depends upon the accelerating potential, i.e. the potential drop experiences by ions. Here we considered a 50 V loss term. Moreover, the ion kinetic energy is

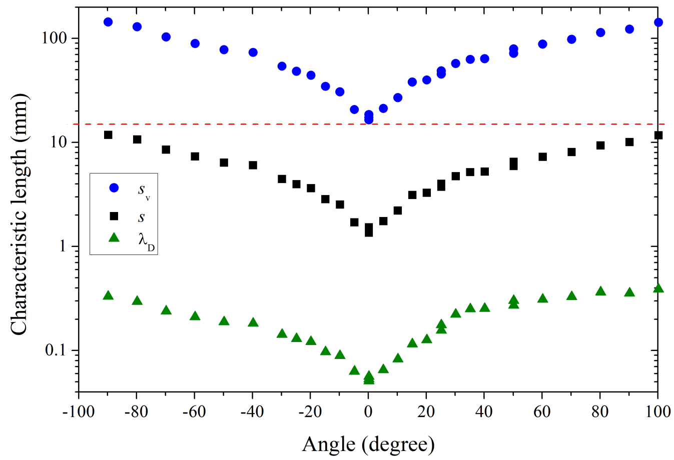

Figure 5. Plasma sheath thickness s and s_v and Debye length against the angle in the plume ($x = 70$ cm of the PPS®1350-ML thruster operating at 350 V, 5 mg/s and 4.28 A. The red dashed line represents the probe collector/collimator diameter.

assumed independent of the angle.[31] Therefore the ion energy is 300 eV. In Fig. 5, sizes have been computed for a probe potential $V_s = -70$ V, which correspond to the potential selected for our measurements, see next section.

The red dashed line in Fig. 5 indicates the collector, collimator and guard ring size (15 mm). For the high-voltage sheath calculated under the fast ion assumption, the thickness is always above the probe characteristic size. The thickness is smaller when the Bohm velocity is used, however, it approaches the probe collector diameter at large angles. When s is well above the characteristic dimensions, probes do not operate properly and give erroneous values. Notice in many studies the guard ring of the planar probe is not wide enough and the sheath effect is not compensated correctly, especially at large angles.

D. Probe I-V characteristic curve

1. Current measuring system

A calibrated Keithley 2410 sourcemeter has been used to measure the ion current collected by the PP, PPGR and FC probes. The unit was operated in voltage source to apply the DC voltage to the probe collector. The Keithley 2410 device offers a broad range of currents [1 A – 10 pA] and voltages [$\pm$ 1100 V – $\pm$ μV] with a high degree of stability and accuracy. The potential of planar probe guard ring was applied using a TTI EX752M dual output 300 W power supply that can delivers up to $\pm$ 75 V in single output mode and $\pm$150 V in dual output mode. During measurements with the PPGR the potential applied to the collector and to the guard ring must be exactly the same to avoid creating a discontinuity in the sheath structure above the probe.

The two instruments are by default floating. They must therefore be connected to the ground to warrant a common reference with all other potentials (thruster, cathode, LP and vacuum tank).

2. Guard-ring impact

The impact of the guard ring polarization of the PPGR is illustrated in Fig. 6. The ion branch of the I-V curve of the probe has been measured in the plume of the PPS®1350-ML thruster with the guard ring polarized at the collector potential and floating. The experimental conditions were: 350 V, 4.8 mg/s and 4.08 A. Measurements have been performed at two angle to vary the plasma sheath size. It is clear from plots in Fig. 6 that applying the voltage to the guard ring makes the collected current independent from the probe voltage V_s. Without a guard ring, or with a floating guard ring, the current collected by a planar probe increases with the voltage as the sheath thickness increases with V_s. As can be seen in Fig. 6, the PP current to PPGR current ratio is larger at -45° as s is longer.

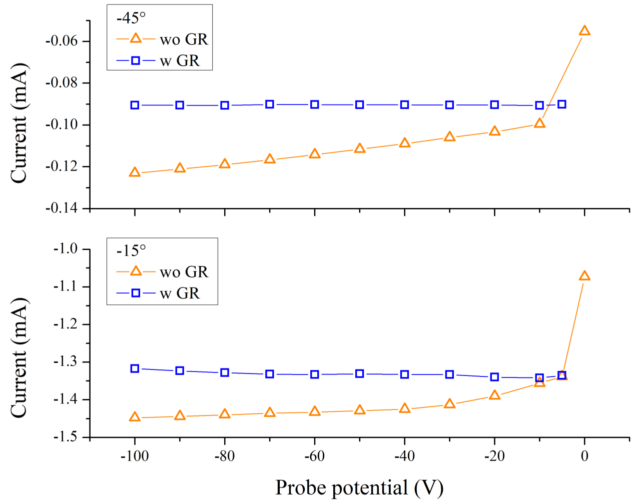

Figure 6. Current-voltage curve of the PPGR obtained at two angles in the plume of the PPS®1350-ML thruster with the guard ring polarized (square) and floating (triangle).

3. Comparison between the 3 probes

A comparison between the ion branch of the I-V curves of the three probes is given in Fig. 7 for two angles. Curves have been acquired at the beginning of the campaign during the instrument and process validation phase at $x = 70$ cm in the plume of the PPS®1350-ML thruster fired at 350 V, 4.8 mg/s and 4.08 A. The background gas pressure in the chamber was 1.93×10^{-5} mbar-Xe. The probe bias voltage is referred to ground. The guard ring voltage follows the collector voltage during measurements. The Faraday cup and the planar probe with guard ring collect a constant current below -10 V, i.e. when all electrons are repelled. The current magnitude is the expected one. The FC give a lower current as its collection solid angle is below 2π str. The PP gives the larger current as its collection area increases with the bias voltage. The effect is more pronounced at large angles as the sheath thickness increases with the angle, as shown in Fig. 5.

Figure 8 shows the ion current density angular profile measured with the three probes at $x = 70$ cm for two values of the bias voltage. The difference between the profiles amplifies at large angles for two reasons: the plasma sheath thickness and the thermal current component increase.

In this study, the bias voltage was fixed to -70 V after analyzing all data. V_s has to be far enough from V_f to ensure a marginal influence of electrons on the measured current. The value of V_s must be selected in such a way the plasma sheath size is not much larger than the probe characteristic dimensions.

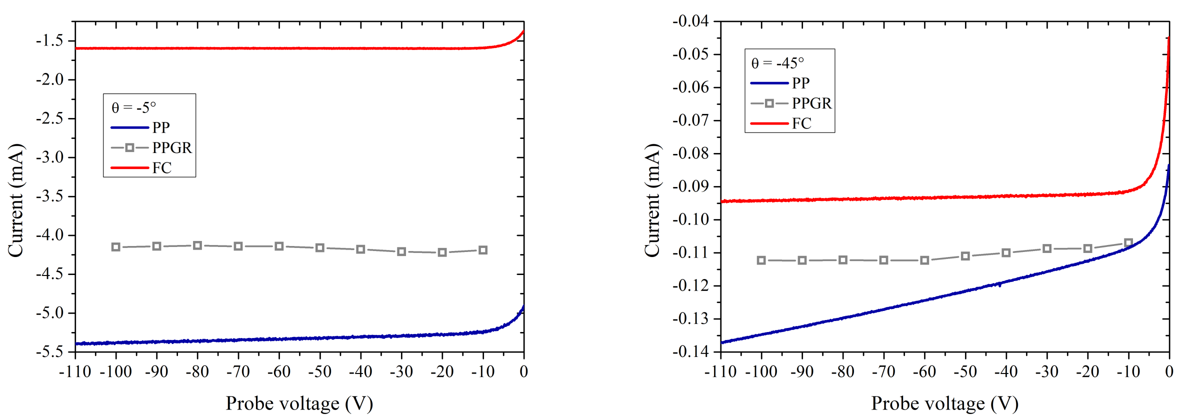

Figure 7. Current-voltage curve of the 3 probes measured at two angles in the plume of the PPS®1350-ML thruster.

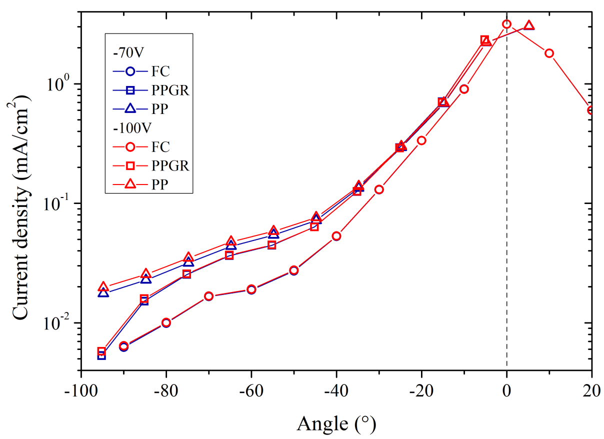

Figure 8. Angular distribution of the ion current density measured with the 3 probes for two bias voltages in the plume of the PPS®1350-ML thruster (350 V, 4.8 mg/s, 4.08 A).

IV. Ion current density angular distribution

A. Coordinate system and configuration

The spherical coordinate system used in this work to measure the ion current in the far-field plume of Hall thrusters is illustrated in Fig. 9. θ is the longitude, which can varied in the range $[0 - -2\pi]$. Here θ corresponds to the angular position from the thruster centerline. ϕ is the latitude, which can varied in the range $[-\pi - -\pi]$. The thruster centerline correspond to the y axis. The external cathode is placed below the (x, y) plane with its orifice in the (x, z) plane. The axis of rotation of the measuring instruments is z. The thruster exit plane contains the pivot of the rotating arm.

Electrostatic probes are swept in a 180° arc at a constant distance r to thruster. The ion collector or collimator face point toward the rotation axis at all angular locations. The ion current is acquired during the entire sweep. Here the probe angle is not varied continuously but step by step and data is recorded at each angular position. In fact measurements are performed in an hemisphere ($\phi = 0$), i.e. the (x, y) plane, and the plasma plume is assumed to be axisymmetric about the y axis. Although the longitude θ cannot have negative values we apply here the convention that θ varies from -90 to +90 degrees with the negative

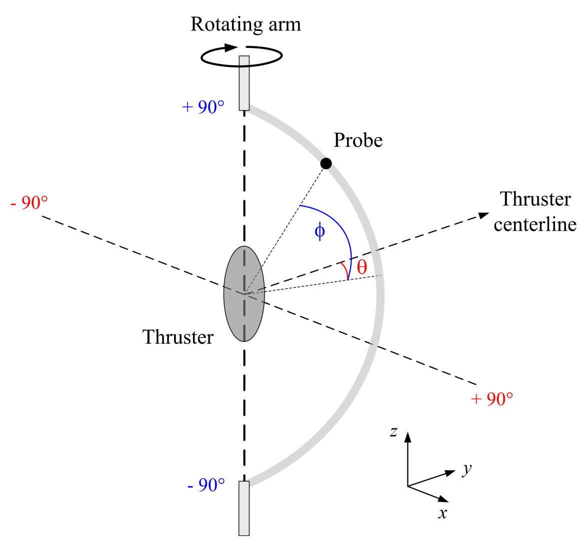

Figure 9. Hemispherical coordinate system used for far-field plume measurements.

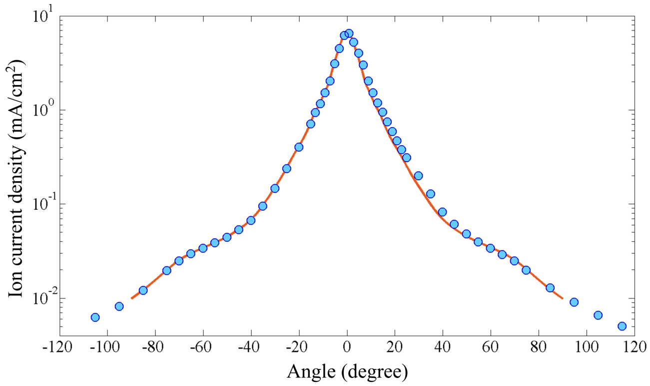

Figure 10. Angular distribution of j_i acquired with the PPGR in the PPS®1350-ML plume at 350 V and 5 mg/s (circle). The red line is a symmetrical distribution reconstructed from the negative angle part of the original profile.

angular positions $-\theta$ representing the left side of the thruster plume pointing to the **y** vector direction. The distance r is fixed to 70 cm, which is about 7 thruster outer channel diameters. The far-field plume is usually defined as the region where r is greater than four thruster diameters.[17,43] In the far-field plume domain the thruster is assumed to be a point ion source.

Figure 10 shows an ion current density profile measured with the planar probe with a guard ring in the plume of the PPS®1350-ML thruster firing at 350 V and 5 mg/s. The ion current density is the highest on the thruster axis with a value of several mA/cm^2, which is typical for such a Hall thruster at moderate discharge voltage.[4,5,31] The overall shape of the angular profile of j_i is standard with wings at large angles ($\theta > \pm 40°$) due to charge-exchange and momentum exchange (scattering) collisions. The amount of ions at the plume periphery drastically depends upon the background pressure, as we shall see in section D.

As can be seen in Fig. 10, the angular distribution is not perfectly symmetrical about the thruster axis. Many reasons can explain the asymmetry such as probe misalignment, inhomogeneous thruster discharge and cathode effects.

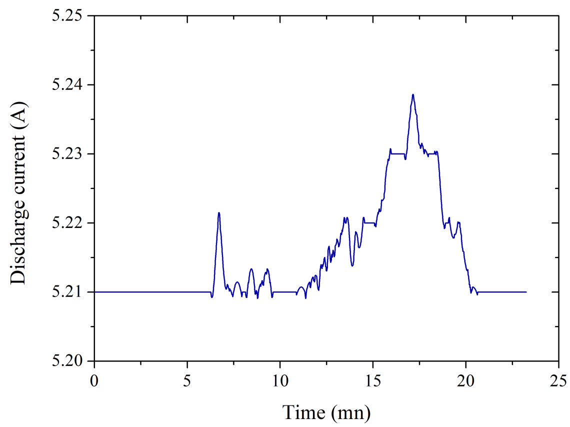

Figure 11. Trace of the PPS®1350-ML thruster discharge current I_d recorded during a sweep over a 180° arc. The operating parameters were 300 V and 6 mg/s. The change in the magnitude of I_d is a consequence of sputtering of the measuring system components.

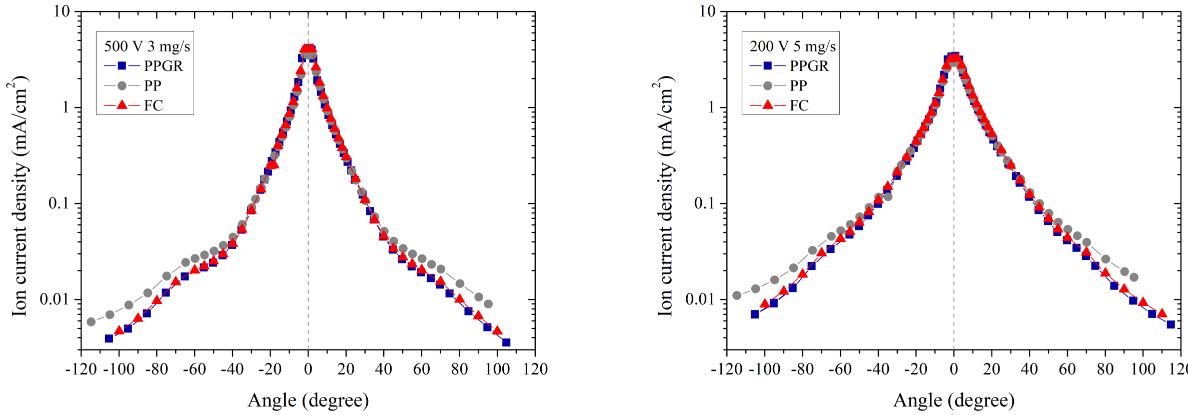

Figure 12. Ion current density as a function of angular position measured with the three probes for two different discharge voltages.

B. Perturbations

In Fig. 11, the Hall thruster discharge current I_d trace reveals perturbations during far-field plume ion current measurements with our instruments. The time interval shows in In Fig. 11 corresponds to a sweep from -90° to +90°. The current magnitude increases slightly in the course of the measurements, whatever the operating conditions. In the present example (300 V, 6 mg/s), the increase reaches at most 0.6 % of the current base level. The perturbation is observed when the probe assembly is nearby the thruster axis. The perturbation originates in sputtering of the measuring system by fast ions of the beam. A fraction of the sputtered atoms enter the thruster discharge where they are ionized, which induces a rise of I_d. In order to limit the perturbation of thruster conditions, the dimensions of all components, including the probes, support and rotating arm, have to be small and materials with a low sputtering yield under ion bombardment must be employed when possible.

Besides, sputtered particles can be ionized in front of the probes and they can collide with fast incoming ions, which modifies the local plasma and beam properties. A direct consequence may be a substantial alteration of the measurement outcomes. Finally, a large instrument is detrimental to measurement as it generates a local pressure increase that can change the beam properties through charge-exchange collision events and scattering.

C. Impact of U_d and Φ_a

1. Discharge voltage series

Measurements of the ion current density have been performed with the three probes biased at $V_s = -70\,\text{V}$ for Hall thruster discharges voltages ranging from 200 V up to 500 V. The ion current density angular profiles measured at 200 V and 500 V are shown in Fig. 12.

All distributions are almost symmetrical with the largest magnitude obtained on the thruster centerline and with charge-exchange collisions wings at large angles ($\theta > \pm 40°$). Values of j_i are slightly above the ones obtained at Aerospace Corporation with the PPS®1350-G thruster.[31] The difference might be due to the fact that measurements at Aerospace Corp. were carried out at 1 m from the thruster exit plane against 70 cm in this work. The planar probe always gives larger value of j_i at large angles due to plasma sheath effects. The on-axis j_i magnitude is slightly below the one given by the guarded planar probe and the Faraday cup. As can be seen in Fig. 12, PPGR and FC give similar values of j_i for all angles while one would expect lower ion flux values for FC as its collection solid angle is below 2π str. One possible explanation is a change in the spacer electrical resistance. The spacer could depart from a perfect electrical insulator due to the formation of a coating from sputtered materials. In that case, an additional current can be delivered by the spacer and the collimator.

Our study indicates that when the discharge voltage U_d is ramped-up the ion current density increases

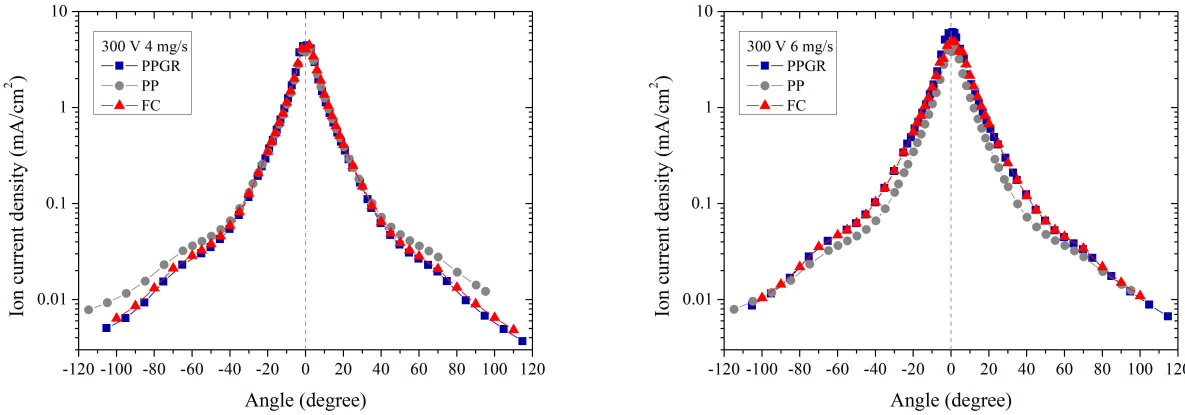

Figure 13. Ion current density as a function of angular position measured with the three probes for two different xenon mass flow rates at $U_d = 300\,\mathrm{V}$.

on axis while it decreases at large angles, similarly to what was observed at Aerospace Corp with the Busek BHT-1500 Hall thruster.[5] The ion beam divergence could decrease due to a better focusing of the ion flow by the electrostatic lense at high voltages. As the charge-exchange cross-section decreases with the ion energy, the number of charge-exchange collision event diminishes when the voltage increases, hence a narrower j_i profile.

2. Mass flow rate series

Measurements of the ion current density have been performed with the three probes biased at $V_s = -70\,\mathrm{V}$ for xenon mass flow rates ranging from 4 mg/s up to 6 mg/s ate a fixed discharge voltage of 300 V. The ion current density angular profiles measured at 4 mg/s and 6 mg/s are displayed in Fig. 13.

The ion flux profile peaks on the thruster axis and exhibits wings at large angles. PPGR and FC give almost identical j_i values for all angular positions. The planar probe gives greater current densities at large angles but at $\Phi_a = 6\,\mathrm{mg/s}$, as can be observed in Fig. 13. We have no satisfactory explanation at that time; a defect in the data acquisition chain is an assumption. As expected, measurements indicate the ion current density increases with the propellant mass flow rate whatever the angular position.

D. Influence of the background pressure

The residual gas pressure in the vacuum chamber strongly influences ion charge flux angular distributions and, consequently, thruster properties such as propellant utilization, current utilization, divergence angle, thrust and anode efficiency. The background pressure effect has been studied by many authors with various Hall thrusters in different vacuum chamber and it is well documented, see e.g.[4,5,16,22,31,43–45]

Figure 14 shows ion flux angular profiles recorded with a planar probe in the plume of the PPS-Flex Hall thruster fired with xenon in the PIVOINE-2G test bench for several background pressure levels.[46] The probe was positioned at 70 cm from the thruster front panel. This measurement series was realized with a magnetic field topology similar to the SPT100 topology with a the maximum magnitude of the field at the outlet of the channel straight section. The background pressure was varied from 5×10^{-5} down to 4.8×10^{-6} mbar-Xe keeping the PPS-Flex thruster parameters unchanged at 250 V and 3.5 mg/s. Also presented in Fig. 14 is a linear extrapolation to perfect vacuum conditions. The ion current density decreases when the residual gas pressure is reduced, especially at large angles where the diminution typically reaches one order in magnitude.

In Fig. 15 the evolution of the discharge current of the PPS-Flex thruster with the background pressure indicate that the pressure effect are negligible below 8×10^{-6} mbar in agreement with other studies. The same trend was observed with the total ion current, the plume divergence angle and the thrust. For the latter the change reached several mN.

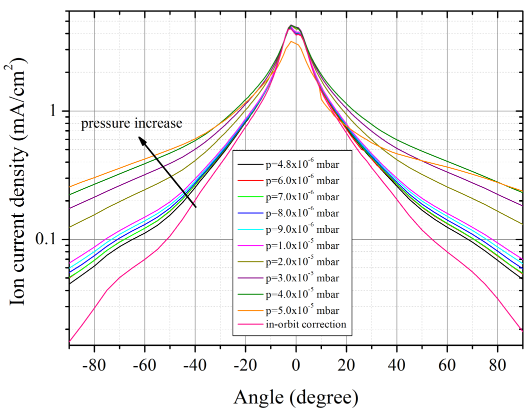

Figure 14. Ion current density distribution in the plume of the PPS-Flex Hall thruster for several background pressures (250 V, 3.5 mg/s). Also shwon is the extrapolation to $p = 0$.

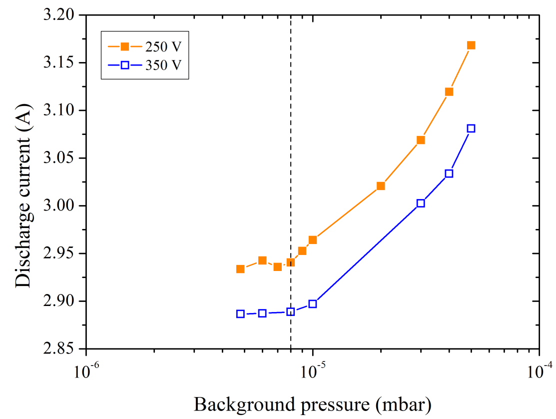

Figure 15. Discharge current of the PPS-Flex Hall thruster as a funtion of the background pressure for two discharge voltages ($\Phi_a = 3.5$ mg/s).

The ion current density profiles have been measured in the plume of the PPS®1350-ML thruster with PP, PPGR and FC probes at two different background pressures, namely 2.1×10^{-5} mbar-Xe and 5.5×10^{-6} mbar-Xe. The lowest pressure is achieved when all the cryo-panels are functioning. Figure 16 shows the ion current density angular profiles acquired with PPGR for the two background pressures at 350 V and 5 mg/s. The thruster discharge current drops from 4.29 A down to 4.23 A when the pressure decreases mainly because the fraction of residual gas atoms ingested into the channel, and subsequently ionized, decreases. In Fig. 16, the central part of the plasma plume is not affected by the pressure change. The ion current density decreases in the wings, i.e. at $\theta < 40°$, when the pressure is lower due to a reduction is charge-exchange and scattering collision events. A similar tendency is observed with PP and FC.

As previously explained, a change in Hall thruster characteristics goes along with a change in background pressure. In this example (Fig. 16), the ion plume divergence half-angle, calculated for the 95 % of I_d, drops from 53.8° to 43.1°.

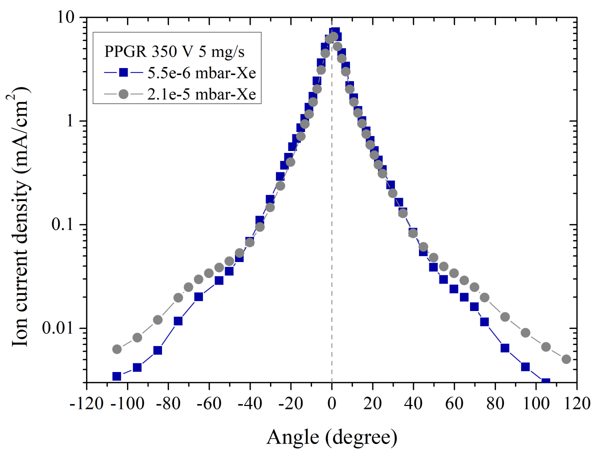

Figure 16. Ion current density distribution measured with PPGR in the plume of the PPS®1350-ML thruster at two background pressure (350 V, 5 mg/s).

V. Conclusions and recommendations

The experimental campaign performed with the xenon-fueled PPS®1350-ML Hall thruster in the PIVOINE-2G ground test-chamber allowed to compare three types of electrostatic probes for measuring the ion current angular profile, namely a planar probe, a planar probe with a guard ring and a Faraday cup. The study was also focused on the investigation of the impact of the thruster operating parameters on measurement outcomes and on the effect of the background gas pressure. This work, in combination with previous works carried out within the ICARE laboratory with other thrusters, enables to provide a list of guidance, recommendations and good practice rules for ion current density measurements in electric thruster far-field plumes. This list, certainly non-exhaustive, must be considered as a further step forwards for the standardization of EP devices plume property measurements in space environment. It is complementary to the recommended practices and guidelines described in a recent article written by Brown and co-workers.[22]

List of recommendations, guidance and practice rules (random order):

- A planar probe is not appropriated for measuring the ion current density as it is sensitive to plasma sheath expansion. An elaborated sheath model could be used to correct the sheath effect data but at the expense of accuracy.
- A planar probe with a guard ring, often termed a Faraday probe, and a Faraday cup are insensitive to the existence of a plasma sheath when well designed and when operated at the right bias voltage. Those two instruments are therefore recommended for ion current density measurements.
- The sizes and architecture of the measuring instrument are critical for obtaining accurate and high-quality data. In particular, the instruments must warrant the resolution of gradient scale lengths and reduced surface sputtering yield and ion flow perturbation.
- In like manner the design of the probe support and rotating arm is critical: interactions with the plasma jet have to be minimized
- A simple Langmuir probe must be used to determine the local electron properties n_e and T_e in the measurement domain in order to assess the sheath thickness. The latter must then be compared to the probe characteristic dimension while keeping in mind that $d << s$.
- The angular sweep can be continuous or performed step by step with a small step size. The sweep over a 180° arc must however be fast to reduce exposure of the probe to the fast ion beam.
- The selection of materials is critical, especially for the ion collector and collimator. Materials must have a low secondary electron emission, they must withstand fast ion bombardment and ion recombination (neutralizaion) at the surface has to be high (low reflection probability).
- Measurements must be carried out at a very low background pressure (stay below 10^{-5} mbar). The vacuum quality is also a relevant criterion.
- A large vacuum chamber is preferred to minimize facility effect: thruster diameter << chamber radius and length.
- The chamber walls have to be grounded (potential reference).
- Measurement have to be performed at a significant distance from the thruster front face in such a way the ion point source assumption is valid.
- Alignment of the instruments with respect to the thruster must be carefully checked.
- A high cleanliness level of the measuring instruments is required. Electrical insulation must be verified before and after measurements. All wire must be protected against the plasma.
- The measurement chain and the DAQ system must be calibrated (voltage source, current meter, analog-to-digital converter).
- The thruster has to be operated in steady state (thermal equilibrium of main components, stable discharge current and power spectrum).

Acknowledgments

This research was financially supported by the CNES under contract 150971/00-2015 and by the ESA-ESTEC under grant PO-5401002960. This project has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement 730135 CHEOPS.

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