Measurements of plasma parameters in the plume of electric propulsion devices – Recent works performed at the ESA Propulsion Laboratory

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Abstract: **The experimental investigation of the plasma parameters in the plume of electric propulsion devices is essential for the validation and improvement of numerical plume models that are needed to assess plasma – spacecraft interactions. Furthermore, these measurements can be used to obtain improved performance models of electric propulsion devices thanks to a better understanding of the physical processes involved in the thruster operation. Electrostatic probes are widely used diagnostic tools for the experimental investigation of plasma parameters. At the ESA Propulsion Laboratory (EPL) different electrostatic probes are available, among them Faraday probes (FP), Retarding Potential Analyzer (RPA), Langmuir probes (LP) and emissive probes (EP). These probes allow measuring the ion beam current, the plume divergence, the ion energy distribution function, the plasma potential and the electron properties. EPL is constantly performing internal R&D works and collaborating with external partners in order to improve available probes and data analysis methods as well as to establish standardized measurement procedures for electric propulsion testing.**

Nomenclature

EPL	=	ESA Propulsion Laboratory
ESA	=	European Space Agency
ESTEC	=	European Space Research and Technology Centre
FP	=	Faraday probe
ICARE	=	Institut de Combustion Aérothermique Réactivité et Environnement
IRS	=	Institut für Raumfahrtsysteme
I_e	=	Electron current
LP	=	Langmuir probe
OML	=	Orbit Motion Limited
n_e	=	Electron density
R&D	=	Research and Development
RPA	=	Retarding Potential Analyzer

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T_e	=	Electron temperature
V_f	=	Floating potential
V_p	=	Plasma potential

I. Introduction

THE ESA Propulsion Laboratory (EPL) is an operational test facility at the European Space Research and Technology Centre (ESTEC) providing services to the ESA Propulsion and Aerothermodynamics Division that is responsible for R&D activities and support to projects in the field of chemical, electrical and advanced propulsion as well as aerothermodynamics[1]. The EPL is a reference for European propulsion companies in the field of standardization and procedures definition and it provides support for subjects related to propulsion testing and test facilities. The EPL provides support and services to ESA projects requiring a first independent and fast assessment of space propulsion technologies.

The underlying objective of electric propulsion terrestrial testing is to evaluate the performance that can be achieved by a given propulsion system in space. The required performances of an electric propulsion device are either a direct function of the commanded thrust or specific impulse or a function of the specific design of the equipment such as exhaust plume shape and content.

The electric propulsion community needs to demonstrate reliable, affordable processes to develop and qualify competitive products. But electric propulsion verification testing is complex and technically challenging. Therefore consistent, accurate and repeatable measurements are necessary[2]. Standardization and comparability of measurements are necessary to achieve these consistent measurements.

One of the major challenges using electric propulsion devices on board satellites are possible damages the plasma plume may cause to the host spacecraft[3]. The plume consists of charged particles (electrons and ions) which lead to electrical and mechanical interactions with the spacecraft. It is thus important to develop and improve numerical models of the plasma plume in order to help assessing spacecraft integration issues. Numerical models of the plasma plume need to be validated by comparison with experimental data. Therefore the entire plume needs to be mapped experimentally to obtain ion, electron and neutral properties. These parameters are also important in order to further improve the performance and lifetime of electric propulsion devices. Plasma parameters are usually measured using electrostatic probes.

At the EPL a series of different electrostatic probes are used to investigate the charged particle properties in the plume of electric propulsion devices. Among those probes are: Faraday Probes (FP), Retarding Potential Analyzers (RPA), E×B probes, Langmuir Probes (LP) and Emissive Probes (EP). EPL is continuously working on the improvement of the measurement devices available and setting up standardized procedures to be adopted by the European electric propulsion community.

The present contribution aims at introducing the different electrostatic probes available at the EPL, presenting recent results obtained with these probes and illustrating the current activities in terms of standardization of electrostatic probe measurements.

II. Standardization of electrostatic probe measurements

The key to standardization and comparability of tests in different facilities is to be able to make measurements of performance and properties of electric propulsion systems according to international or national standards of measurements. The calibration of all measuring instruments needs to be traced back to a primary standard through an unbroken chain of secondary calibrations. All measurements shall be fully compliant with ISO 17025[4] and follow the “Guide to the Expression of Uncertainty in Measurement”[5]. In order to meet these requirements, a strategy for assessing the measurement uncertainty associated with all diagnostic equipment is required.

No absolute calibration is currently possible for electrostatic probe measurements since no internationally accepted traceability route to a primary standard exists. For Faraday probes, for example, the parameter to be measured is the collected current. The current measurement device as well as the device to determine the exact size of the probe can be easily calibrated against traceable standards. However, the relationship between the measured current and the actual ion current in the plume as well as several other effects (e.g. facility effects) have to be considered in order to perform accurate measurements or to be able to calibrate the probe to a known traceable standard. For Langmuir probes the situation is even more complicated: The probe design and the analysis of the measured data depend on the plasma that is supposed to be investigated. This renders standardization very complicated if not impossible. Hence, in the case of electrostatic probes other measurement strategies must be adopted. One possibility is to base the uncertainty estimations on the largest known variability from published tests or on the comparison with computer models. Another possibility is to define standardized measurement procedures and to perform inter-diagnostic and inter-laboratory comparisons in order to evaluate, at least part of the uncertainty sources.

III. Plasma diagnostics at EPL

Electrostatic probes are simple and versatile diagnostic tools for the experimental investigation of different plasma parameters such as e.g. ion and electron density, plasma potential, electron temperature, ion energy and ion charge state. In the following the different probes available at the EPL are presented:

A. Faraday probes

A Faraday probe is an electrostatic probe that is polarized negatively in order to measure the ion beam current density distribution of the plasma plume. There are different types of Faraday probes such as nude, collimated, cupped or gridded probes. A standard Faraday probe is biased below the plasma potential in order to repel electrons and solely collect ions. The ions collected by the probe create a current that can be measured to obtain the ion current density. Moving the probe through the entire ion beam allows obtaining the ion current density distribution.

At the EPL both collimated and cupped Faraday probes are available to measure the ion current density. Several probes are mounted at different angles on a semi-circular arm that can be moved over 180° in order to obtain the 3D ion beam current profile. Figure 1 shows a collimated Faraday probe available at the EPL. A cupped Faraday probe is shown in Fig. 2.

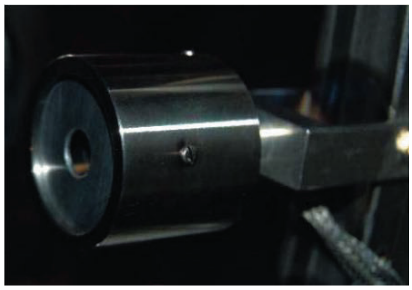

Figure 1 Collimated Faraday probe mounted on a diagnostic arm inside one of the EPL vacuum facilities.

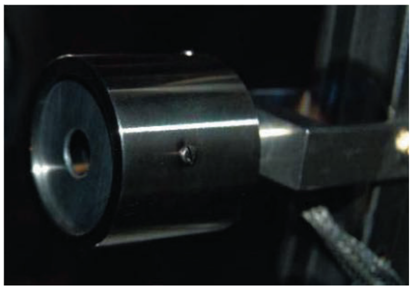

Figure 2 Cupped Faraday probe mounted on a diagnostic arm inside one of the EPL vacuum facilities.

B. Retarding potential analyzer

A Retarding potential analyzer (RPA) is an electrostatic probe that uses a series of grids to selectively filter ions and determine the ion energy distribution[6,7]. The first grid is used to shield the probe from the plasma. The second grid acts as primary electron filter so that only ions enter the analyzing section of the probe. The third grid is used as a filter so that only ions with an energy-to-charge state greater than the grid voltage can pass. The voltage of the ion retarding grid is swept over a certain voltage range to determine the RPA current-voltage characteristic. The derivative of this characteristic is proportional to the ion energy distribution function (IEDF). A forth grid may be used to suppress the effect of secondary electrons emitted by the collector.

At the EPL both 3- and 4-grid configuration RPAs are available to measure the ion energy distribution function in the plume but also in the backflow of electric propulsion devices. For the plume measurements a RPA is mounted on a moving arm in order to perform measurements at different positions in the plasma plume. A picture of a 4-grid RPA is shown in Fig. 3.

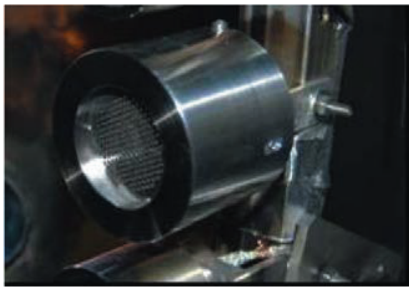

Figure 3 Four-grid RPA mounted on a diagnostic arm inside one of the EPL vacuum facilities.

C. E×B probe

An E×B probe is an electrostatic probe that uses perpendicular applied electric and magnetic fields to determine ion charge states. It is also known as Wien filter. The probe acts as velocity filter that separates ion species according to their velocity. An E×B probe uses uniform, perpendicular electric and magnetic fields that are both perpendicular to the velocity vector. Consequently, the two fields create opposing forces on the particles. For a given velocity, these fields can be adjusted so that there is no net force on the particle, which will then travel to the detector without being redirected by the fields. Since particle acceleration in electric propulsion devices is dependent of the charge, the ion speed will be proportional to its charge state. Because of this, an E×B probe can distinguish the ions with different charge states. By varying the electric or magnetic field, one can select the ions to be collected by the probe's particle detector. The current fraction of each species must be determined from the E×B spectrum to quantify their relative population.

An E×B probe is available at the EPL. This probe was designed and built by the ICARE laboratory in Orléans, France[8]. A picture of the probe is shown in Fig. 4.

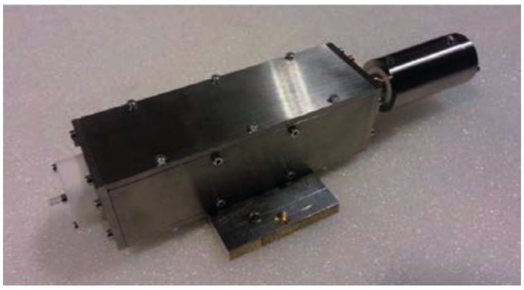

Figure 4 E×B probe designed by ICARE.

D. Langmuir probe

A Langmuir probe is an electrostatic probe that is comprised of one or more conducting elements inserted into the plasma and connected to an external electrical circuit. Different types of Langmuir probes exist depending on the number of probe tips: single, double and triple probes are commonly used. For a single Langmuir probe, the probe bias is varied by the external electrical circuit and the collected probe current is measured as a function of the probe bias in order to obtain the current-voltage characteristic. This characteristic can be used to obtain the electron and ion density, the electron temperature as well as the plasma and the floating potential using the standard Langmuir probe theory assuming a Maxwellian electron distribution function[9,10]. A triple Langmuir probe is composed of a floating double probe system and a third independently floating probe tip. It can be used to obtain the electron temperature and the electron density from the floating potential of the third probe tip and the current collected by the double probe system using an adequate theory[11,12].

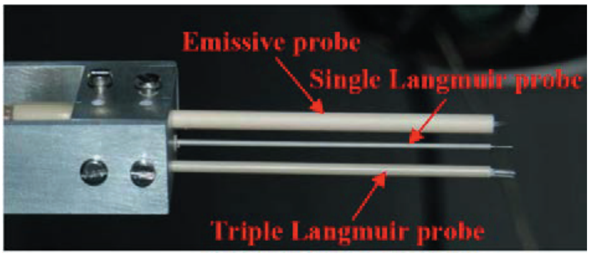

Figure 5 Single and triple Langmuir probe as well as an emissive probe installed on a common interface for a test at the EPL.

Single and triple Langmuir probes are available at the EPL. Both probes can be mounted onto a moving arm in order to perform measurements at different locations in the plasma plume. Figure 5 shows a single and a triple Langmuir probe used at EPL for far-field plume measurements. The probe tips are made of 0.38 mm in diameter tungsten wire. The active length of the probe tips is 5 mm.

E. Emissive probe

An emissive probe is an electrostatic probe that can be used to obtain a direct measurement of the plasma potential[13]. The probe filament is heated, by applying a current to it, into thermionic electron emission. The emitted electrons essentially neutralize the sheath surrounding the filament causing the probe to float at the local plasma potential, which can therefore be measured directly.

At the EPL, emissive probes are used simultaneously with Langmuir probes in order to cross-validate the results. As the Langmuir probes, the emissive probes are mounted on a movable arm. A picture of an emissive probe used at EPL is shown in Fig. 5. The emitting part of the probe consists of an 8 mm long loop of 0.15 mm in diameter thoriated tungsten wire.

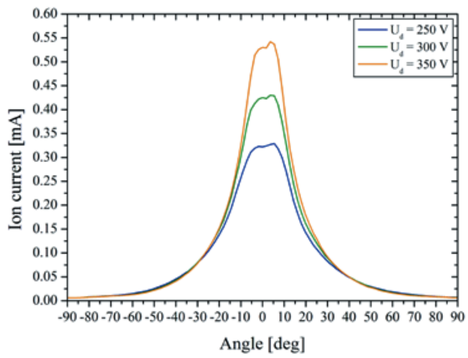

Figure 6 Faraday cup measurements performed in the far-field plume of a 1.5 kW Hall effect thruster operating at 3.5 mg/s and different discharge voltages. The ion current is measured as a function of the scan angle at a distance of 70 cm from the thruster exit plane.

F. Measurement examples

Different measurement campaigns have been carried out over the last years involving EPL electrostatic probes. In the following some of the results will be presented.

A series of Faraday cup measurements has been performed in the plume of 1.5 kW Hall thruster. The Faraday cup was moved from -90º to +90º, where 0º corresponds to the thruster axis, in order to obtain a complete scan of the far-field ion current profile. The Faraday cup was positioned at 70 cm from the thruster exit plane. An example of three Faraday cup scan in the plume of the 1.5 kW Hall thruster operating at a constant mass flow rate of 3.5 mg/s of Xenon and three different discharge voltages (250 V, 300 V and 350 V) is shown in Fig. 6.

Measurements with a 4-grid RPA have been performed in the far-field plume of a 200 W Hall effect thruster. An example of a current-voltage characteristic and the corresponding ion energy distribution function measured with the 4-grid RPA is shown in Fig. 7. The thruster was operated at 250 V and 1.0 mg/s of Xenon. As can be seen, the most probable ion energy E_{max}, which corresponds to the maximum of the IEDF, is 229 eV in this case. The mean ion energy E_{mean} corresponds to the first order moment of the IEDF and is 203 eV in the present case.

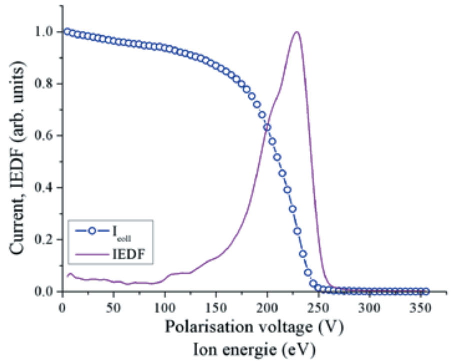

Figure 7 RPA current-voltage characteristic (circle) and corresponding ion energy distribution function (line). Measurements were performed in the far-field plume of a 200 W Hall thruster at 83 cm downstream the thruster exit plane.

A series of measurements using a single Langmuir probe has been performed in the far-field plume of a 200 W Hall effect thruster. An example of a current-voltage characteristic measured with a single Langmuir probe in the far-field plume of a low power Hall effect thruster operating at 150 V and 2.1 mg/s of Xenon is shown in Fig. 8. The measurement was performed on the thruster axis. The upper graph shows the measured characteristic as well as the first derivative. The lower graph shows the logarithm of the electron current as well as the square of the electron current. The plasma potential is obtained from the maximum of the first derivative. The electron temperature is determined from the slope of the logarithm of the electron current in the transition region. And the electron density is calculated using the Orbit Motion Limited (OML) assumption. In the OML regime the slope of I_e^2 vs V plot is proportional to n_e^2.

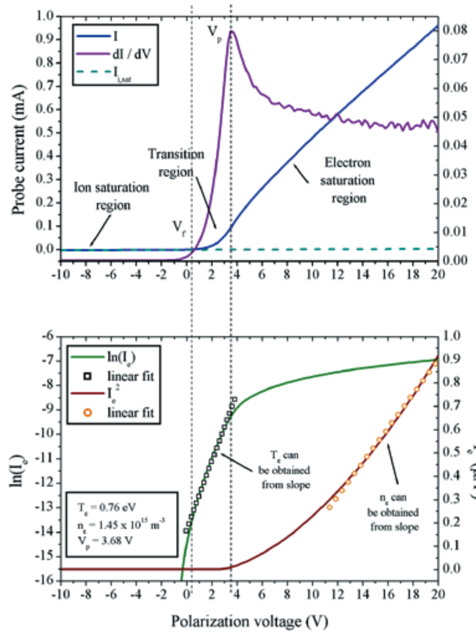

Figure 8 Example of a current-voltage characteristic recorded in the far-field plume of a low power Hall effect thruster operating at 150 V and 2.1 mg/s. The probe was located at 83 cm downstream the thruster exit plane on the thruster axis.

IV. Standardization activities at EPL

EPL is constantly working on the improvement and standardization of electrostatic probe measurement procedures. The final goal is to obtain a specific ISO 17025 accreditation and to establish standardized procedures that will be applied for all electric propulsion testing activities in Europe. EPL is coordinating several activities in order to establish standardized procedures for electrostatic probe measurements. Recently an activity has been performed in collaboration with the ICARE laboratory in Orléans, France in order to define standardized procedures for electrostatic probe measurements to be applied for electric propulsion activities. In a first step the different error sources for electrostatic probe measurements were evaluated and dedicated test procedures defined for the different probe types (FP, RPA, LP and E×B probe). During an extensive test campaign with a 1.5 kW thruster at the EPL these procedures were tested and the capacity of the EPL to perform high resolution electrostatic probe measurements was confirmed.

Furthermore an activity focused on Langmuir probe measurements is performed together with the IRS, University of Stuttgart. This activity aims at the development of specific procedures for the use and the uncertainty assessment of Langmuir probes. An inter-laboratory comparison is also foreseen during this activity.

In the near future EPL plans to perform an inter-laboratory comparison of a Faraday probe in two different vacuum facilities using the same plasma source.

V. Conclusion

Different electrostatic probes are available at the EPL to perform measurements of the plasma parameters in the plume of electric propulsion devices. Among those probes are Faraday probes, retarding potential analyzers, E×B probe as well as Langmuir and emissive probes. Accurate measurements of the plasma parameters are essential for the understanding of plasma-spacecraft interactions and the improvement of electric propulsion performance models.

Standardization and comparability of measurements are necessary to achieve accurate, reliable and consistent measurements. Therefore it is important to establish standardized measurement procedures to be adopted by the European electric propulsion community. The EPL is constantly working on the improvement of available measurement devices. The aim of EPL is to set up the required standardized measurement procedures and to perform inter-laboratory comparison of different electrostatic probes.

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