Qualification of the AEPD System as a Standard On-Ground Tool for Electric Propulsion Thruster

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Abstract: **Any thruster needs to be qualified and tested in a representative environment before flying into space. The issues on the representativeness of the vacuum environment as well as the performance and accuracy of the diagnostic tools, raise concerns to many customers especially when comparing results obtained in different test facilities. A standardization of the on-ground diagnostic tools and procedures is therefore considered a key point for the qualification of the future European electric thrusters. The European Space Agency is devoting a large effort to meet this objective. In 2006 a first programme aimed at developing Advanced Electric Propulsion Diagnostics (AEPD) for thruster characterization was initiated. The results of that programme lead to the development of a number of advanced diagnostics. Recently, a new programme aimed at improving and qualifying the AEPD system as a standard on-ground diagnostics tool for EP thruster has been started by ESA, involving the participating institutions of the authors of this paper.**

Nomenclature

d	=	electrodes separation
B	=	magnetic field
E	=	electron charge
E	=	electric field
m_i	=	ion mass
v_i	=	ion velocity
V_{acc}	=	ion acceleration voltage
V_{probe}	=	voltage difference applied to the electrodes
z_i	=	ion charge state

I. Introduction

THE development of a diagnostic system for electric thruster characterization is not only of importance in order to measure the operating performance, but also to better understand and to predict their behavior in terms of the erosion of critical thruster components due to sputter-related processes, and spacecraft damage. The total impulse (lifetime) of the thruster is limited by ion impingement on exposed components of the system. This effect goes along with the erosion of ceramic walls for Hall Effect Thrusters (HET) and grid erosion for Gridded Ion Engines (GIE). Analysis of these phenomena could be also used to verify if the thruster is working properly. Another aspect to be considered to this end is the thermal load to which the different components of the thruster are subjected.

On the other hand the plume-spacecraft interactions may affect spacecraft operations by both damaging particularly important equipment and interfering with satellite communications. From this point of view, the characterization of the plasma is relevant. In particular, data on ion current density, ion energy, ion species composition and also power flux become crucial for developing models to describe these interactions and to optimize the design of spacecraft systems.

On one hand the aim of the present project is represented by the improvement of the diagnostics already developed during the former AEPD project by adapting the system to direct in vacuum operation in order to obtain better performances and developing new beam diagnostics.

The importance of such a diagnostic system is determined by its capability to provide a link between thruster performances (thrust) and plasma processes. In particular plasma diagnostic sensors are able to investigate crucial beam parameters, such as local current densities and energy distribution functions.

On the other hand another important aspect is to make this system a standard tool to investigate thrusters' performances. Although traceability to international standards may not be achieved for direct measurements of thruster plume particles, those measurements are of interest to allow for the investigation of complex processes in the thruster plume, and deliver together a well-defined, detailed picture of physical properties related to thruster performance parameters. The guidelines for standardizing measurements applying plasma diagnostic sensors involves:

- Design of the sensor with help of related modelling and experiments,
- Development of a consistent calibration strategy using different measurement principles to allow for a comprehensive, quantitative measurement error analysis,
- Validating the performance of the measured data with help of electrical measured thruster performance data like total current, grid voltages etc.

The developed diagnostic system will be tested at the University of Giessen and Aerospazio Tecnologie s.r.l. on two different types of EP thrusters: a gridded ion engine (Airbus Defense and Space RIT-µX) and a Hall Effect thruster (ICARE SPT-100ML).

II. Diagnostic System's Requirements

The most important step in the development of a diagnostic system able to investigate both HET and GIE thrusters is represented by the definition of the requirements determined by the quantities to be measured. A preventive analysis of the parameters to be measured must be carried out in order to evaluate the magnitude of these parameters and of the variations to be appreciated. It means also to decide where and when measurements will be performed: there is a strong dependence on the measurement position.

EP measurement techniques were analyzed in order to understand the potential and limitations in applying such techniques to characterize the plume produced by both Hall effect and ion thrusters. Table 1 summarizes the kind of measurements to be performed, the performance characteristic to whom each measurement is associated with and the diagnostic equipment chosen to carry out the measurement.

Table 1. AEPDII Diagnostic Measurement Objective and Performance Measure.

Diagnostic Equipment	Measurement		Performance Characteristic
	GIE	HET	
Pyrometer	Grid Surface Temperature	Ceramic Wall temperature	Thermal stress, power loss distribution assessment.
Thermo-probe	Probe heating as a function of Beam Power at multiple sampling positions		Exhaust plume power, beam shape and energy distribution
Thermo-camera	Surface Temperature distribution of interesting part of the thruster in dependence on thruster parameter		Thermal stress as a function of thruster working conditions, power loss distribution
Tele-microscope	Grid hole erosion	Ceramic radial and axial erosion	Validation of life time wear calculations
Triangular Laser Head	*In situ* outer grid curvature and variation with thruster parameter, control of measuring head position	*In situ* ceramic radial and axial erosion and variation with thruster parameter, control of measuring head position	Validation of life time mechanical stress and wear calculations
Energy-Selective Mass Spectrometer	Mapping single and multiply charged particles energy and mass distribution in the exhaust plume, including ionized pollution from sputter material (ESMS resolution < 1°)		Thrust vector, Exhaust plume beam width and distribution
Faraday Probe	Mapping Ion current density distribution and space charge effects inside the plume,		Contributes to thrust vector and exhaust plume beam width and distribution calculation
E×B Probe	Separates ion species by velocity and measures multiple/charged ion composition and ion velocity distribution functions		Contributes to thrust vector and Exhaust plume beam width and distribution calculation
Retarding Potential Analyzer	Differential energy distribution of charged particles inside the plume in dependence on position		Contributes to thrust vector and Exhaust plume beam width and distribution calculation

A. Requirements Definition Approach

Once the parameters of interest have been defined and the techniques to be used have been chosen, we have to set the requirement that these techniques must satisfy. The first step for the assessment of diagnostics requirements for both HET and GIE thrusters is represented by definition of the operative conditions of the thrusters themselves including also the vacuum conditions. Indeed, these parameters determine the performances and thus the behavior of the connected quantities used to evaluate them. Thus, the operative conditions determine the magnitude of the quantities to be measured and the required accuracy.

Table 2. Thruster operative parameters and facility parameters.

Thruster Parameter	**HET (SPT100ML)**	**GIE (RIT-μX)**
Discharge Voltage	300 V	2000 V
Discharge current	4.5 A	TBD
Anode mass flow rate	5 mg/sec	3.8 mg/sec
Cathode mass flow rate	TBD	TBD
Facility Parameter		
Static Pressure	$< 1\times10^{-7}$ mbar	$< 1\times10^{-7}$ mbar
Dynamic Pressure	$< 2\times10^{-5}$ mbar	$< 8\times10^{-6}$ mbar

In principle the AEPD demonstration should be over the full operating range of the equipment under test and in different test environments to demonstrate full universal application. In practice such a large undertaking is likely to exceed both planned schedule and budget. The review of requirements is therefore based on the nominal operating criteria of the equipment. From a system point of view, characterizing thruster performances means to verify that the produced thrust corresponds to the nominal value within the specified tolerance.

In order to do that, thrust measurements should be performed with sufficient accuracy not only to measure the expected value but also high enough to appreciate their fluctuations.

In practice it may not be possible for the test set up to include a thrust balance and the sophisticated diagnostics for measuring beam performance. In such cases the thruster or system operating point should be measured in the same chamber separately and operated with the same electrical and propellant flow control settings for the subsequent plasma diagnostic testing. The measurement uncertainty attributable to not being able to measure both the operating point and the plasma diagnostic testing at the same time must then be assessed and included in the overall uncertainty associated with the plasma measurements.

The aim of the present project is to qualify the diagnostic system showing how it can be used effectively to fully characterize both Hall effect and ion thrusters allowing measuring parameters that are commonly used to do it. These parameters will be measured for nominal points independently from the thrust actually generated. It means to be able to measure with sufficient accuracy expected quantities when the thusters are operated in typical conditions at defined operating points.

These typical operative conditions are used to estimate the parameters to be measured on the basis of physical considerations and of data available for similar thrusters operating in similar conditions. This estimation is carried out taking also into account geometrical aspects of the measurement, because of the strong dependence of, for example, beam parameters (ion current, ion energy and thus energy flux) on the measurement point. This is true both for HET and GIE thrusters but with different effects' magnitude. Then the last point to be considered in the diagnostics' design process is the fact that the same probe must be used to measure a certain parameter in a quite wide range with sufficient accuracy.

Table 3 reports the requirements for the diagnostics as determined according to the described conditions.

Table 3. Summary of requirements for AEPD diagnostics.

Characterization method	Requirements
Telemicroscope (IOM)	o Image size: >4.2 x 5.6 mm^2 o Resolution: 1280 x 960 pixel o Radial resolution/accuracy: < 0.01 mm o Vacuum compatibility: Is to be tested, not specified by the manufacturer o Operation temperature range: -5 °C to 45 °C (given by the manufacturer)
Triangular laser head (IOM)	o Spot size: < 0.2 mm (at a working distance of 150 mm) o Distance range: 110 mm – 190 mm o Distance repeatability: < 0.001 mm (as given by the manufacturer) o Distance resolution: < 0.01 mm (as result of previous tests in EP test campaigns in vacuum) o Vacuum compatibility: Is to be tested, not specified by the manufacturer o Operation temperature range: 0 °C to 50 °C (given by the manufacturer)
Pyrometer (IOM)	o Spot size: < 2mm (at a working distance of ~ 100 mm) o Temperature range: 150°C – 1000°C o Temperature resolution 0.1°C o System accuracy (at ambient temp. 23 ± 5°C): 0.3% of reading + 2°C (given by the manufacturer, does not consider uncertainties of the emissivity of the test object) o Repeatability (at ambient temp. 23 ± 5°C): 0.1% of reading + 1°C (given by the manufacturer, does not consider uncertainties of the emissivity of the test object) o Vacuum compatibility: Is to be tested, not specified by the manufacturer o Operation temperature range (given by the manufacturer): -20°C to 85°C (sensing head) 0°C to 85°C (electronics)
Thermocamera (IOM)	o Image size: ~ 0.05 m x 0.07 m (at a working distance of 500 mm) o Resolution: min. 160 x 120 pixel o Lateral resolution: 1.5 mm (at a working distance of 500 mm) o Temperature range: 0°C – 900°C o Temperature resolution 0.1°C o System accuracy: 2% of reading or 2°C (given by the manufacturer, does not consider uncertainties of the emissivity of the test object) o Vacuum compatibility: Is to be tested, not specified by the manufacturer o Operation temperature range (given by the manufacturer): 0°C to 50°C
Faraday probe (IOM)	o Measurement range: up to 50 mA/cm^2 o Accuracy: < 0.01 mA/cm^2 dependent on the required dynamic range o Vacuum compatibility: up to 10^{-8} mbar o Temperature stability: -10°C up to 500°C
Retarding potential analyzer (IOM)	o Measurement range: 0 eV – 2000 eV o Accuracy: better than 5 eV o Vacuum compatibility: up to 10^{-8} mbar o Temperature stability: -10°C up to 400°C

Table 3. Summary of requirements for AEPD diagnostics.

Characterization method	Requirements
ExB-probe (Aerospazio)	o Resolution: 1000 m/sec o Vacuum compatibility: up to 10^{-8} mbar o Temperature stability: -10 °C up to 200 °C
Thermoprobe (CAU)	o Measurement range: 0 W/cm^2 - 2 W/cm^2 o Accuracy: ± 1x10^{-3} W/cm^2 o Vacuum compatibility: up to 10^{-8} mbar o Temperature stability: -10°C up to 400°C

III. The Diagnostic System

A five-axis positioning system[1] developed by IOM will be used as test platform allowing positioning and orienting the thruster with respect to the diagnostics. The positioning system (Fig. 1) consists of a modular bar setup and uses in total three stepper-motor driven linear tables (maximum travel range 700 mm, maximum tested travelling speed 50 mm/s, positioning reproducibility better than 0.1 mm) and two stepper-motor driven rotation tables (360°, 3°/s, better 0.5°). By that, thruster and diagnostic tools can be positioned and oriented very precisely relative to each other. The *x*-axis allows adjusting the distance between thruster and diagnostic tools and the *y*-axis and *z*-axis define the observation spot on the thruster. In addition to single spot measurements, line scans along the *y*-axis at different *z*-axis positions or vice versa can be performed. By combination of *y*-axis scans at different *z*-positions, two-dimensional maps are possible.

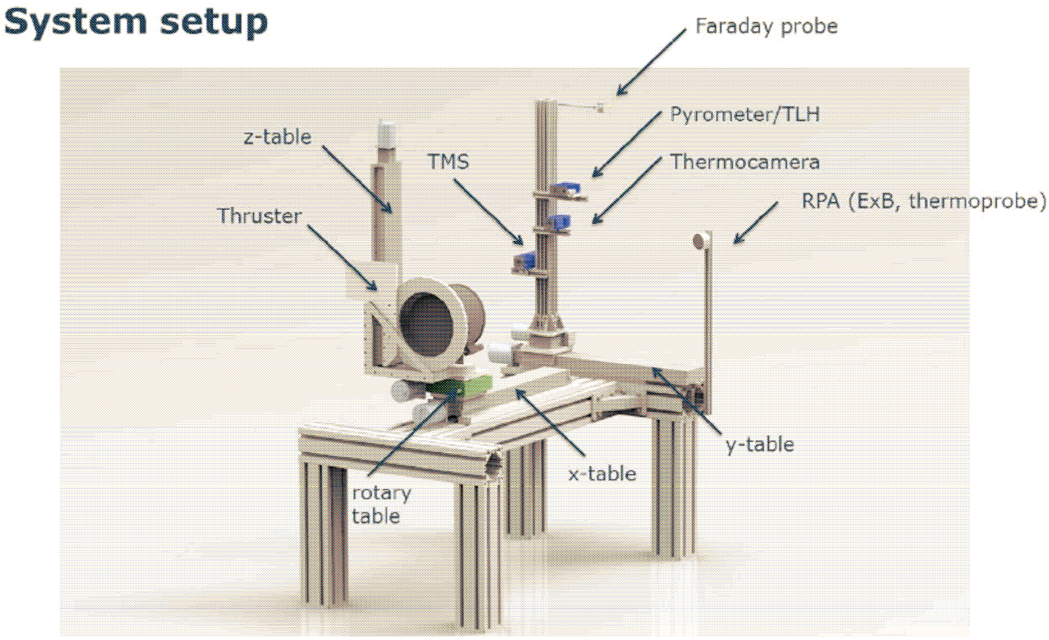

Figure 1. View of the overall diagnostic system.

Many of the diagnostics included in the system were developed in the framework of a previous ESA project named AEPD-1 and included: a triangular laser head (TLH), a telemicroscopy system (TMS), a pyrometer and a Faraday probe. The aim of the present project is represented by the improvement of the diagnostics already developed by adapting the system to direct in vacuum operation in order to obtain better performances and developing new beam diagnostics. The "old" diagnostics are well described in several papers[1-4], in the following we will focus on the new ones (Retarding Potential Analyzer, ExB probe and Active Thermal Probe).

IV. The New Diagnostics

The new beam diagnostics are represented by:

- a Retarding Potential Analyzer, developed by IOM, to measure the ion energy
- an ExB probe, developed by Aerospazio, for the determination of the plasma composition in terms of ion species
- a Thermoprobe, developed by Kiel University, used to determine the heat flux impinging the surfaces exposed to the plume.

A. Retarding Potential Analyzer

The probe acts as a high-pass filter selecting the ions reaching the collector by means of the voltage applied to a retarding grid: only ions with energy higher than the voltage applied to the grid will revealed. It is used to determine the Ion Energy Distribution Function and thus the mean ion energy[5,6]. The maximum expected ion energy must be taken into account to define the measurement range of the probe. It is obviously provided by the accelerating voltage experienced by ions. For HET it is given by the discharge voltage, instead for GIE it corresponds to the potential applied to the grids. This link between the accelerating voltage and the expected ion energy is valid in the central region of the plume; far from this region the ion energy is significantly lower. As indicated many times these spatial effects must be taken into account in the design process of the probe.

The first aspect to consider in analyzing data is represented by the fact that the retarding voltage applied to the retarding electrode is not the effective voltage felt by ions; this introduces a systematic error in the energy measurement. To overcome this problem a standard calibration procedure of the probe should be required. Unfortunately a standard calibration is not available but it can be performed exploiting a known ion source and/or a primary instrument. The calibration will provide a correction factor to be applied to the retarding voltage in order to determine the actual potential felt by ions

Another point to be considered is the influence that the plasma itself produces on the probe altering the potential distribution inside the probe. Moreover space-charge effects can occur as a function of the measurement position to which corresponds a different plasma density. This aspect is particularly critical if low ion energy (plume tails) must be measured. As for ion current measurement criticality can rise if also the current density is low.

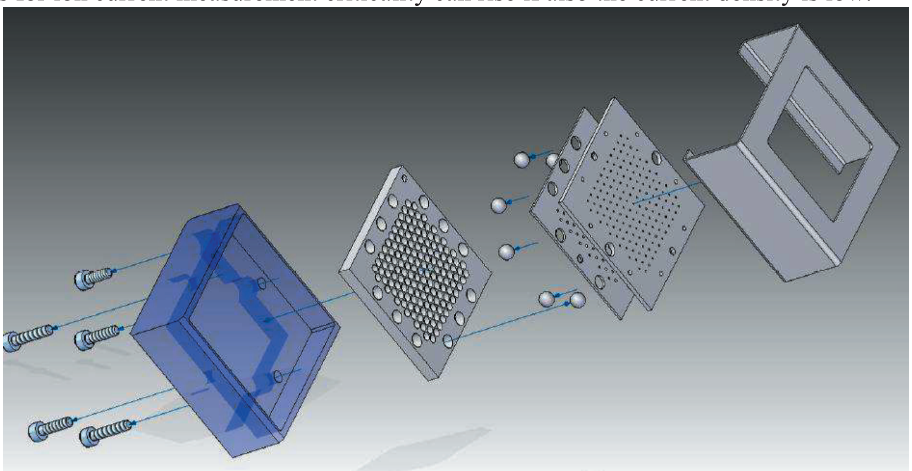

Figure 2 Retarding Potential Analyzer assembly.

The design of RPA is sketched in Fig. 2 and consists of:

- Orifice (diameter 0.4 mm +/- 0.05 mm) (limits the particle current)
- Electron repeller (repels electrons from outside the RPA and secondary electrons from the ion counter)
- Ion Counter (retards charged particles depending on energy)

The grid and ion counter material is made of graphite, because graphite has the following advantages compared to other materials:

- Low sputter yield

- Low secondary electron coefficient
- High thermal stability
- Good machinability

The diameter of the orifice hole should be in the Debye length to minimize the electron flow from the outside plasma into the RPA. This is especially important for measuring Hall thrusters, because the plume of a HET contains more electrons than the ion beam of the GIE

B. ExB Probe

The goal of the ExB probe is first of all to provide information on the plasma in terms of ion species composition (Xe^{+}, Xe^{2+}, Xe^{3+}, etc.)[7,8]. It exploits the action of a magnetic and an electric field to select ions on the basis of their velocity: only ions whose velocity satisfies the Wien condition (Eq.1) are able to reach the collector.

$$v_i = \frac{E}{B} = \frac{V_{probe}}{B \cdot d} \tag{1}$$

Thus, different ion species are separated according to their charge state, mass and energy as clear Eq.2 expressing the voltage difference associated with each peak in the spectrum:

$$V_{probe} = B \cdot d \cdot \sqrt{\frac{2 z_i e V_{acc}}{m_i}} \tag{2}$$

The magnetic field is kept constant while the electric field is changed according to voltage ramp applied to the electrodes. The spectrum is obtained by measuring the current reaching the collector plate as a function of the electrodes' voltage as for the RPA measurements.

The difference consists in the fact that for the RPA the required voltage ramp applied to the retarding grid is directly connected to the accelerating voltage of the thruster, instead in the case of ExB probe it depends also on the constructive parameters of the probe (magnetic field, electrodes separation). It means that the maximum voltage difference to be applied to the electrodes in order to collect different ion species is determined by these parameters and obviously by the ion energy.

The peak separation determines the probe resolution and it is affected by the magnetic field. In particular the probe must be able to separate the ionic species of interest in the energy range defined by the operating point of a typical HET (300 V) and a typical GIE (2000 V).

During the design process two aspects was taken into account that can be considered conflicting represented by the minimization of the invasiveness of the probe and the maximization of the magnetic field in order to improve the probe performances. Indeed, increasing the magnetic field usually means to use larger magnets. This problem has been overcome by exploiting a particular magnetic configuration known as Stelter dipole[9] (Fig. 3). It is constituted by 8 SmCo magnets characterized by a high energy product, enclosed in a iron chassis with a central cavity where the electrodes assembly are located. The magnetic material has been chosen also for its high thermal stability allowing using it up to 350°C. The expected magnetic field is 0.54 T, thus almost 3 times the magnetic field produced by a "traditional" dipole. A high magnetic field determines an increase in the separation between the peaks associated with the ion species, thus affecting the resolution. This is more important for the measurements to be performed on Hall thruster: indeed, resolution is not constant but depends on the accelerating voltage. On the other hand, higher the magnetic field higher the electric potential difference required to satisfy the Wien condition. This is clearly evident looking at data reported in Tables 4 and 5 showing the Larmor's radius and the peak voltage difference for Xe^{+}, Xe^{2+} and Xe^{3+} for the typical accelerating voltage of Hall effect (300 V) and Gridded ion (2000 V) thrusters.

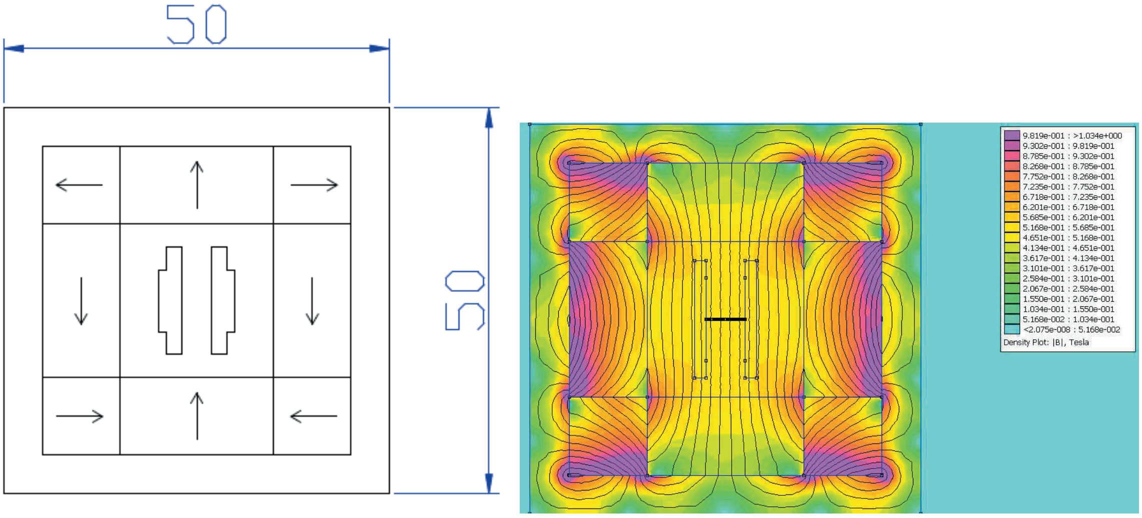

Figure 3. Stelter dipole section and the corresponding magnetic field (Dimensions are in millimeters).

Table 4. Larmor radius and plate voltage difference corresponding to the peaks position for B=0.160 T.

V_{acc} (V)	z_i	v_i (m/sec)	Larmor radius (cm)	Peak voltage difference (V)
300	1	20942	17.9	13.4
	2	29616	12.7	18.9
	3	36273	10.3	23.2
2000	1	54072	46.2	34.6
	2	76740	32.7	48.9
	3	93656	26.7	59.9

Table 5. Larmor radius and plate voltage difference corresponding to the peaks position for B=0.54 T.

V_{acc} (V)	z_i	v_i (m/sec)	Larmor radius (cm)	Peak voltage difference (V)
300	1	20942	5.3	45.3
	2	29616	3.8	64.0
	3	36273	3.1	78.4
2000	1	54072	13.7	116.8
	2	76740	9.7	165.2
	3	93656	7.9	202.4

Previous considerations on electric and magnetic fields are based on the assumption that both fields decay instantaneously at the entrance and at the exit of the space region occupied by the magnets and the electrodes. Actually, fields do not decay instantaneously and moreover this decaying is faster for the electric field than for the magnetic one. The final result is that the Wien condition is no more satisfied at the entrance and exit of the probe affecting the performances of the probe.

This point represents the second aspect taken into account in the design process, i.e. making the electric fringing field matching the magnetic one as close as possible. The first action is represented by the minimization of the extension of the magnetic fringing field by means of appropriate shunts[10] and then the optimisation the electrode shape in order to obtain the same profile for the electric and the magnetic field. Figure 4 reports a comparison between the normalized measured magnetic field and the normalized electric field along the probe axis for the plane electrodes and for optimized shape electrodes.

We said that the probe is used first of all to determine the plasma compositions in terms of ion species fraction. The area under each peak gives the current carried by each ion species, thus the ratio between this area and the area under the overall spectrum provides the current fraction (neglecting secondary emission effects). On the other side the position of the peak is directly connected to the ion velocity through the constructive parameters of the probe: in particular the ion velocity distribution function for each ion species could be determined. As for RPA measurements, this application requires a calibration of the probe providing a correction factor to be applied the measured ion velocity in order to obtain the real ion velocity.

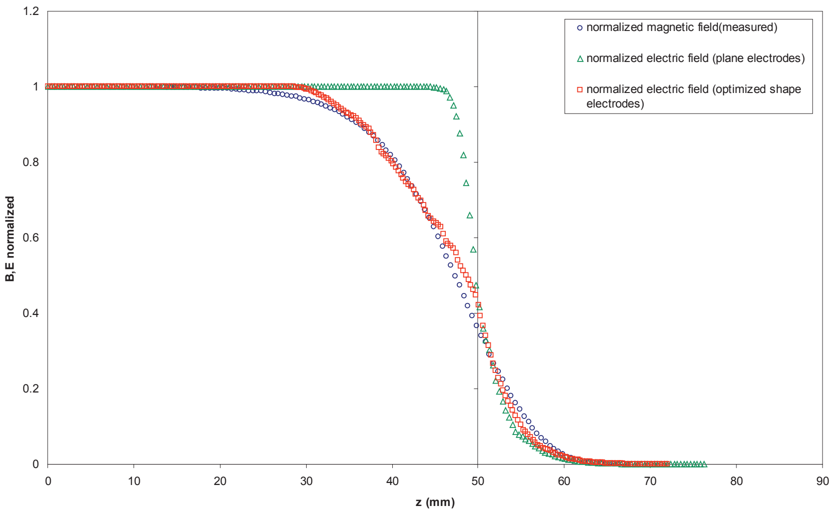

Figure 4. Comparison of the normalized magnetic and electric fields for plane electrodes geometry and optimized electrodes geometry.

C. Active Thermal Probe

The damage due to the plume impingement on exposed surfaces is determined not only by the physical action of energetic ions but also by the energy influx from the plasma. Passive probes[11] allow measuring this energy flux by measuring the temperature. However, this kind of measurement is affected by different sources of uncertainty as the necessity to know exactly the heat capacity of the probe. A different approach is represented by the use of an active devices[12,13] operating continuously. The probe is heated up to a well-defined temperature by means of an electrical current. When the probe is exposed to the plasma plume, an additional influx occurs, thus to keep the current constant the electrical power must be reduced. The variation of the electrical power corresponds to the energy influx by the beam.

For accurate measurements of the energy influx all incoming and outgoing heating fluxes not involved in the measurement must be constant as a function of time. It means that a special probe holder is required in order to make the heat flux between the probe and the holder equal to zero or constant.

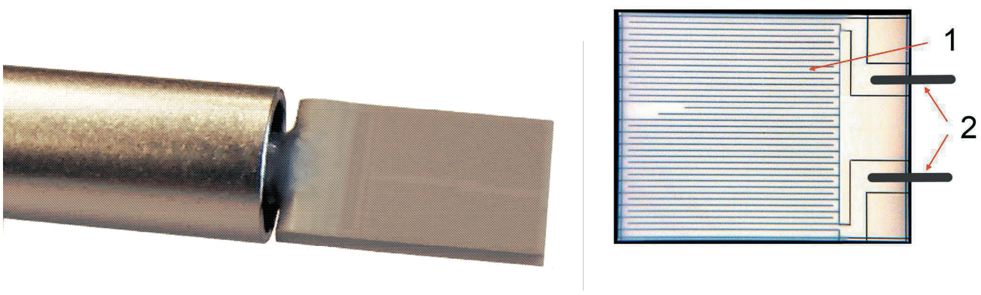

Figure 5. View of the active thermal probe and scheme of the heating resistance.

Figure 5 shows a picture of the probe and a scheme of the heating resistance. In the following the parameters of the probe are summarized:

- Dimension of the sensor: 7 mm × 10 mm × 0.3 mm
- Active measurement area: 0.47 cm^2
- Maximum working temperature: 400 °C

- Maximum detectable energy flux: 2 W/cm^2
- Sensitivity: 1 mW/cm^2

Figure 6 shows the temporal behavior of temperature and heating power during measurements carried out on an ion beam source.

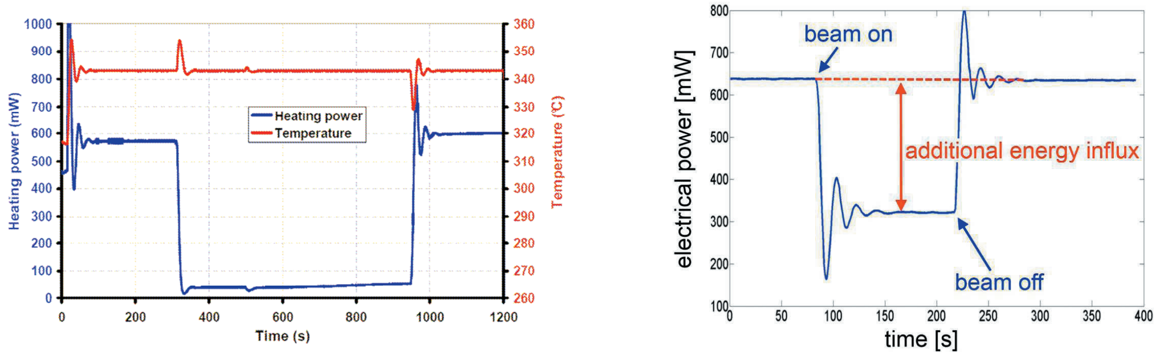

Figure 6. Temperature and heating power as a function of time during the measurements performed on an ion beam source.

V. Conclusion

The AEPD system has been upgraded in order to improve its performances and reduce the invasiveness of the single equipment on the thruster behavior through their direct in-vacuum operation. This upgrading concerned the triangular laser head (TLH), the telemicroscopy system (TMS) and the pyrometer. Moreover new diagnostics have been developed including a retarding potential analyzer, an ExB probe and a thermoprobe. A big effort has been devoted to the analysis of the parameters to be measured and of the variations to be appreciated in order to define the requirements for all the equipment. The analysis was performed on the basis of the operative parameters of the thrusters (HET and GIE) to be tested.

All the diagnostics have been manufactured when this paper is written and testing activities are beginning.

Acknowledgments

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References

[1]Bundesmann, C., Tarz, M., Scholze, F., Leiter, H. J., Scortecci, F., Gnizdor, R. Y. and Neumann, H., "Note: An advanced in situ diagnostic system for characterization of electric propulsion thrusters and ion beam sources," *Rev. Sci. Instrum.*, Vol. 24, 2010, pp. 046106-1, 046106-3.

[2]Bundesmann, C., Tarz, M., Scholze, F., Neumann, H., Leiter, H. J., Scortecci, Feili, D., Frigot, P.-E., Gonzalez del Amo, J., "In-situ temperature, grid curvature, erosion, beam and plasma characterization of a gridded ion thruster RIT-22," *31st International Electric Propulsion Conference*, IEPC-2009-160, University of Michigan, Ann Arbor, September 20-24, 2009.

[3]Bundesmann, C., Tarz, M., Scholze, F., Neumann, H., Leiter, H. J., Scortecci, F., Feili, D., Frigot, P.-E., Gonzales del Amo, J., "In-situ temperature, grid curvature, erosion, beam and plasma characterization of a SPT-100D EM1 with an advanced electric propulsion diagnostic system," *31st International Electric Propulsion Conference*, IEPC-2009-141, University of Michigan, Ann Arbor, September 20-24, 2009.

[4]Bundesmann, C., Tartz, M., Scholze, F., Leiter, H. J., Scortecci, F., and Neumann, H., "In Situ Characterization of the Accelerator Grid of an Ion Thruster," *Journal of Propulsion and Power*, Vol. 27, No. 3, 2011, pp. 532-537.

[5]Azziz, Y., "Experimental and Theoretical Characterization of a Hall Thruster Plume," Ph.D. Dissertation, Massachusset Institute of Technology., Cambridge, MA, 2007.

[6]Hofer, R. R., Haas, J. M., Gallimore, A. D., "Ion Voltage Diagnostics in the Far-Field Plume of a High-Specific Impulse Hall Thruster," *39th Joint Propulsion Conference and Exhibit*, AIAA-2003-4556, Huntsville, Alabama, July 20-23, 2003.

[7]Kim, S.-W, Gallimore, A. D., "Plume Study of a 1.35-kW SPT-100 Using an ExB Probe," *Journal of Spacecraft and Rockets*, Vol. 39, No. 6, 2002, pp. 904-909.

[8]Reid, B. M., Shastry, R., Gallimore, A. D., Hofer, R. R., "Angularly-Resolved ExB Probe Spectra in the Plume of a 6-kW Hall Thruster," *44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA-2008-5287, Hartford, CT, July 21-23, 2008.

[9]Zhang, B., "Field Analysis and Comparison of Several Permanent Magnet Dipole Structures," *IEEE Transactions on Magnetics*, Vol. 45, No. 10, 2009, pp. 4395-4398.

[10]Liebl, H., *Applied Charged Particle Optics*, Springer-Verlag, New York, 2008, Chap. 5.

[11]Steffen, H., Kersten, H., Wulff, H., "Investigations on the energy transfer to the substrate during titanium deposition in a hollow cathode arc," *J. Vac. Sci. Technol. A*, Vol. 12, 1994, pp. 2780-.

[12]Kersten, H., Rohde, D., Berndt, J., Deutsch, H., Hippler, R., "Investigations on the energy influx at plasma processes by means of a simple thermal probe," *Thin Solid Films*, Vol. 377-378, 2000, pp. 585-591.

[13]Cormier, P. A., Stahl, M., Thomann, A. L., *et al.*, "On the measurement of energy fluxes in plasmas using a calorimetric probe and a thermopile sensor," *J. Phys. D: Appi. Phys.*, Vol. 43, 2010, pp. 465201.