PLASMA MEASUREMENTS IN THE ESA ELECTRIC PROPULSION LABORATORY

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Abstract

Electric propulsion (EP) thrusters are highly important for both commercial and scientific applications due to their high specific impulse, high controllability and proven reliability. Europe is developing several types of EP thrusters that provide thrust levels between 1 μN up to 200 mN. Design, manufacturing and testing of such thrusters is a complex activity that requires a great effort, especially in the testing field. Full characterization, qualification and plume interaction tests are mandatory for the full assessment of this technology. The Electric Propulsion Laboratory at ESA has set up three facilities that are currently used in the preparation of several missions requiring electric propulsion thrusters. This paper will describe these test facilities, the diagnostics employed and some important results.

Introduction

ESA Telecommunications, Earth Observation and Scientific programs have several spacecraft with electric propulsion systems on board [1]. Two types of ion thrusters (RIT-10, UK-10) are operating on the ARTEMIS satellite[2] from this year, the GOCE satellite will operate ion engines to compensate atmospheric drag in 2005, the SMART-1[3] spacecraft will use the PPS-1350 hall thruster as a primary propulsion system to fly to the moon in 2002 and the MICROSCOPE (CNES) satellite will fly in drag-free mode by operating FEEP-5 field emission thrusters in 2004.

During the development of these thrusters, extensive ground testing in vacuum chambers is carried out to characterize the plume and to ensure the required lifetime. The Electric Propulsion Laboratory at ESTEC is currently being used to perform qualification tests of the RIT-10 (Radio-frequency Ion Thruster) engine that is flying on ARTEMIS and of the FEEP-5 (Field Emission Electric Propulsion) thruster that is the baseline in several ESA scientific missions (SMART-2, LISA, DARWIN, GAIA). Furthermore, some preliminary characterization tests are performed to assess the critical areas raised by both technology and mission developers. This paper will describe these test facilities, the diagnostics employed and some important test results.

Ion thruster testing

The RIT-10 system on ARTEMIS performs together with UK-10 ion engine the North South Station Keeping (NSSK) operations and, not planned for (due to a launcher malfunction), the orbit raising from 31000 km to GEO. This system relies on the Astrium ion thruster with the PROEL neutralizer and Alenia Defense (formerly FIAR) power supplies, and will operate at 15 mN consuming 600 W of power.

Figure 1: RIT-10 in operation

The operation of the thruster during the mission imposes a lifetime requirement of 10000 hours. This means that a long duration life testing of components subject to wear out (neutralizers and grids) must be performed.

Astrium (D) and the University of Giessen have developed this propulsion system. This technology is based on a three-grid concept. The Xenon propellant flows through the feed line via the isolator and the extraction anode, which also functions as gas distributor, into the discharge chamber. This chamber is surrounded by an induction coil that is connected to an RF-generator with a frequency of 1 MHz generating a high frequency electrical eddy field in the discharge chamber. Free electrons coming from the neutralizer collect energy from the induced electric field and ionize the neutral propellant atoms by inelastic collisions. When the discharge is ignited thrust is generated by the acceleration of ions in the electrostatic field applied to an extraction system comprising an extraction anode, an

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insulating plasma holder, an acceleration electrode and a deceleration electrode (see Figure 2).

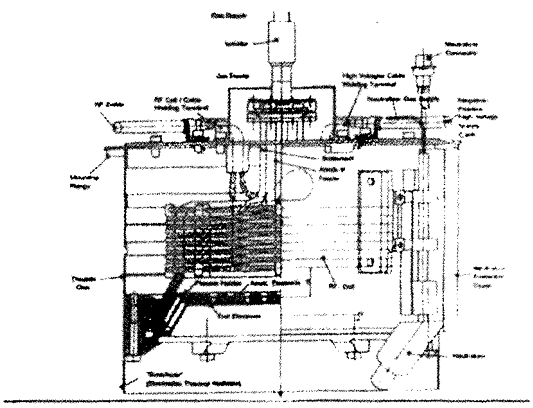

Figure 2: RIT-10 schema

The lifetime test will demonstrate the capability of the system to perform the required operation over the total mission time. Even if Ion Thrusters do not contain mechanisms with moving parts, they contain components that are subject to erosion by the ion beam, and thus can influence the operating parameters of the assembly during the lifetime or limit the lifetime itself. The main components influencing the lifetime of the thruster are the grid system of the thruster and the electron emitting material stored in the insert of the neutralizer tip.

In orbit, the RIT-10 system performs operations in cycles of 3 hours firing every 12 hours for the 10-year mission. This corresponds to about 10000 hours of firing. For a lifetime qualification test, a safety factor of 1.5 is applied to the nominal thruster life, which brings the total needed firing time of the RIT-10 to 15000 hours. At the ESA Electric Propulsion Laboratory in ESTEC, the lifetime test was set-up so that the thruster operates in cycles of 3 hours on and 1 hour off (the minimum time necessary to bring the thruster again to the nominal temperature at starting conditions). This allows reducing the overall testing time to about 2.5 years. At this moment the thruster has reached the 15000 hours of operation required for qualification and will complete soon the 600 cycles requested (they were not reached simultaneously because after the launch failure the thruster was fired in continuous mode for several hundred hours to simulate the orbit transfer operation).

The vacuum facility has been equipped to perform a fully automated test (24-7) and is monitored remotely from Munich via ISDN. The schematic of the main vacuum components is shown in Figure 4. The RIT thruster and the neutralizer are mounted on a plate inside the hatch of the vacuum chamber that is always under vacuum and can be separated from the main vacuum chamber by a valve, if repairs or reconditioning of the cryopanels are needed. The PSCU (Power Supply and Conditioning Unit) and the other equipment necessary for the performance of the test (translator box, main bus simulator, computers, xenon bottle etc.) are located outside the vacuum chamber. Tubing and electrical connections go inside the vacuum chamber via feedthroughs.

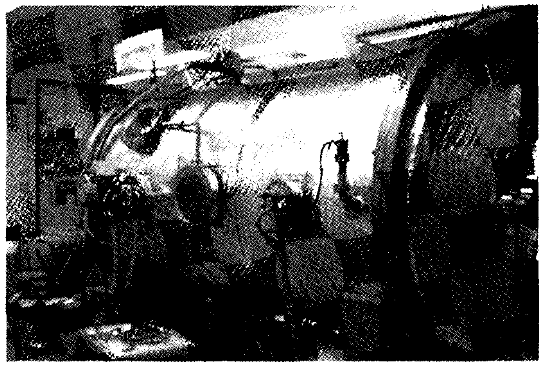

Figure 3: Vacuum Facility 3

The main requirements used in the preparation of the vacuum chamber were:

- Background pressure in the area of the beam during RIT operation at 15 mN: 5 * 10^{-5} torr
- Free length of the ion beam: > 1.5 m
- Inner diameter: > 1m
- Temperature of the thruster flange < 40 ^{0} C
- Automatic operation and control

This facility fulfils these requirements. A set of vacuum pumps, including six cryopumps, one graphite-coated collector at the end of the chamber and a set of diagnostic measurements are used in this effort.

The nominal test set-up has the following test components: PSCU, Main Bus simulator-translator box, data handling system, data acquisition system and Xenon supply system.

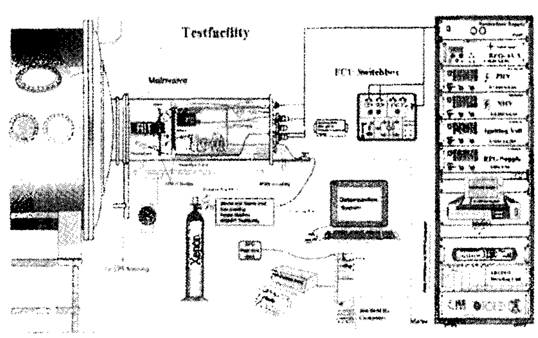

Figure 4: RIT lifetime test set-up

In case of failure of the normal set-up, a back-up set-up is foreseen with laboratory power supplies and commercial flow controllers that will allow continuing the test until the units are repaired.

The diagnostic equipment comprises the diagnostic arm, the backsputtering sensors and the mass spectrometer[4].

- The diagnostic arm monitors the thrust vector stability during the mission time. This arm has been designed and manufactured at ESTEC. The arm, installed inside the vacuum chamber, is raised at predetermined intervals in front of the ion beam, where sensors detect the intensity of the ion beam itself.

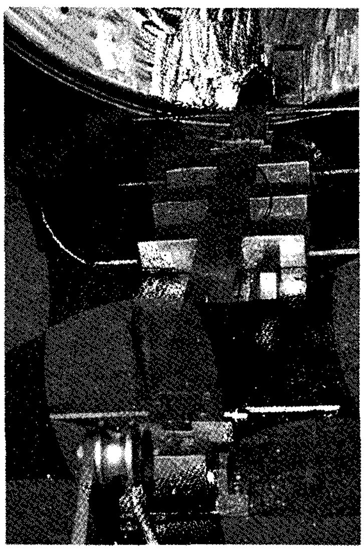

Figure 5: Diagnostic arm in down position during maintenance

The arm has a square cross section and contains in its case a row of 48 target plates, made of stainless steel. The ion beam passes the entrance slit where electrons coming from the neutralizer are suppressed, and finally hit the sensor plates (Figure 6). The current signal produced is fed into filtering and amplification circuits, mounted on printed circuit boards, in the rear section of the arm. The current signal is converted into a voltage, then is amplified by a factor of 10 and finally provided as a low impedance output. The readings of the sensors are multiply by 3 using a movable strip carrying the holes in front of the sensors, in order to reduce the uncertainty in the thrust vector measurement. 18 additional sensors are mounted on 3 lateral arms with fixed hole positions, which provide indications on the ion beam distribution in the horizontal plane. The maximum time this arm is in the beam is two minutes; this time had to be short in order to avoid the destruction of the probe and the backsputtering of materials coming from the arm towards the thruster. The arm is calibrated at the start of the measurements and is re-calibrated twice a year during testing time. Figure 5 shows the diagnostic arm and a typical curve obtained at one measurement is shown in Figure 7. The evolution of this curve with time allows us to characterize the thrust vector migration.

- The backsputtering monitor devices are Quartz Crystal Microbalances that are placed in the main chamber closed to the thruster exit plane. These devices quantify the material backsputtered in the direction of the thruster by the chamber walls and the beam target. In addition, two metallic plates, one shielded and one unshielded are also near the thruster mouth. The weight of both plates are measured a certain intervals to compare the material deposition quantity on the uncovered with respect to the covered plate[5].

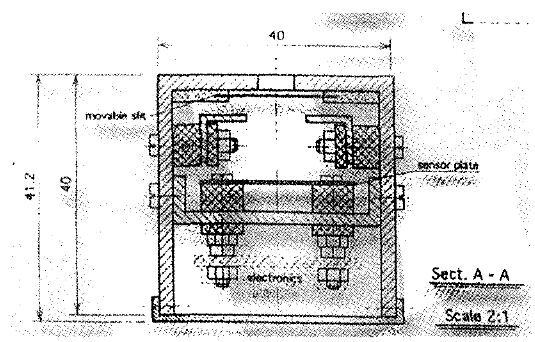

Figure 6: Mechanical drawing of plasma sensor

- A mass spectrometer is used to detect materials coming from the thruster, mainly the grids, and to assess a possible failure of the thruster due to the erosion or deposition of thruster material on the thruster itself.

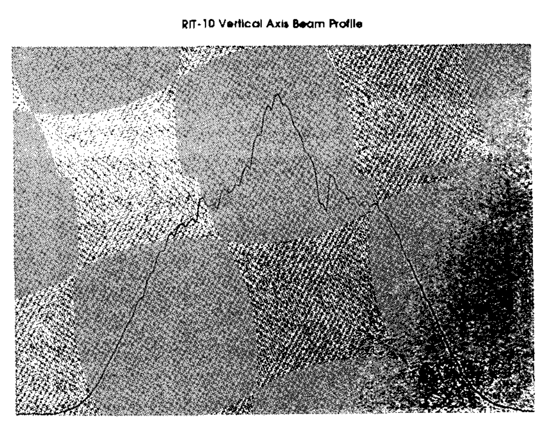

Figure 7: RIT-10 beam profile after 14000 hours of operation

This vacuum chamber has been designed to minimize the interaction of the thruster beam with the chamber walls. Vacuum pumps and collector are the means to ensure this task. The diagnostic devices monitor the evolution of the different thruster parameters and to identify any cause of any problem related to the interaction of the thruster beam with the chamber. How to separate the effects due to the chamber plume-interaction from the effects due to the thruster lifetime has been our major goal.

Field emission thruster testing

The FEEP-5 thruster will have its first application on the CNES mission MICROSCOPE. ESA will supply to CNES the FEEP propulsion subsystem developed by Alta (industrial spin-off of Centrospazio). The thruster will perform the drag-free control of the satellite, in order to allow the verification of the equivalence principle up to a 15-digit precision, by thrusting in the 1 – 100 μN range at an average of 15 μN consuming 8 W of power per cluster of three. The FEEP-5 is also currently under an ESA extensive verification and qualification program in view of its possible application on the ESA missions SMART-2, LISA, and DARWIN. The same applies for the mN-level FEEP-50 candidate for the ESA missions GAIA and GOCE.

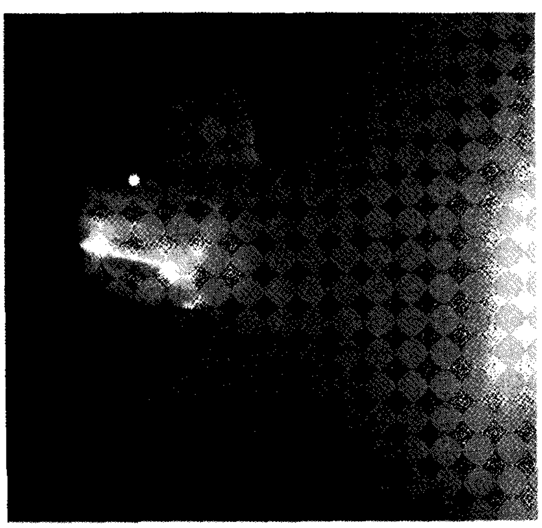

Figure 8: FEEP-50 in operation

Testing on FEEP at the ESA Electric Propulsion Laboratory includes lifetime testing, direct thrust measurements, performance tests, advanced plume diagnostics, contamination measurements, and direct mass flow measurements (not trivial for FEEP due to the liquid metal propellant, Cesium, and to the very low mass flow figures, down to 0,1 μg/s). Two facilities are dedicated for these tests, of which one fully automated and remotely controllable for lifetime testing[6].

An advanced diagnostic system capable of generating 3-D plots of the beam distribution and intensity was developed in the laboratory in cooperation with Alta[7]. The system is based on two simple wire probes that scan the plume density distribution along the three axes and on a triple Langmuir probe that measures plasma density, electron temperature and plasma potential along the thrust direction. Furthermore, the two wire probes can be used to instantaneously identify the position in space of the thrust vector.

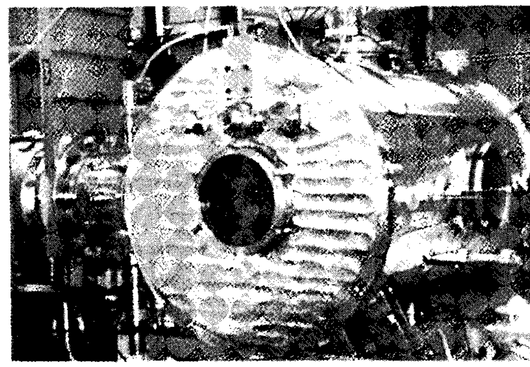

Figure 9: Vacuum facility for FEEP performance, plume analysis and lifetime testing.

The two wire probes are mounted on a frame structure, perpendicular to each other, and are moved by two stepper motors via four chains. The structure, supported on four ultra high vacuum bearings used as wheels, slides on two guides, allowing the probes to be positioned at a maximum distance of 50 cm from the thruster. On the same structure is mounted the triple probe, which is normally kept out of the beam and can be put in place, when needed, in by another stepper motor. The structure is made of aluminum mainly because of its low sputtering yield.

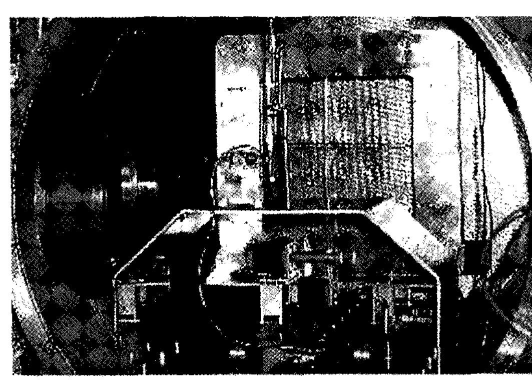

Figure 10: The diagnostic system for 3-D ion beam analysis

The two probes orthogonal to each other, used to determine the plasma distribution, are simply two cylindrical filaments made out of a conductive material (steel or tungsten), long enough to contain the cross section of the ion beam, which is connected to ground in the course of an ammeter. By measuring the current flowing through the ammeter as a function of the position of the probe in the plume, the ion density distribution can be derived, being proportional to the current collected by the probe. The current measured is mainly due to the ions that hit the probe at high speed.

generating a direct ion current plus a small current caused by the electron secondary emission from the impinged probe. The current collected by the probe is not directly related to the plasma density, but it can be very useful to estimate the ion density distribution in the plume, which is responsible for the thrust generation. Together with the two simple wire probes, a triple Langmuir probe is used to give a quantitative measure to the plasma distribution measurement. The triple probe has the great advantage that the voltage swapping is not required to derive the needed parameters, thus making it possible to measure instantaneously plasma density, plasma potential and electron temperature. The equations from which the plasma properties are calculated are shown below:

$$\frac{1}{2} = \frac{1-\frac{\eta_3}{\eta_1}e^{\frac{q(V_3-V_1)}{kT_e}}}{1-\frac{\eta_2}{\eta_1}e^{\frac{q(V_2-V_1)}{kT_e}}} = \frac{1-\frac{\eta_3}{\eta_1}e^{\frac{q\Delta V_{31}}{kT_e}}}{1-\frac{\eta_2}{\eta_1}e^{-\frac{q\Delta V}{kT_e}}};$$

from which the electron temperature can be implicitly derived, and

$$n_\infty = \frac{I_{12}}{(1+\gamma)qU_\infty A_p\left(\frac{\eta_1}{\eta_3}e^{-\frac{q\Delta V_{31}}{kT_e}}-1\right)};$$

from which the plasma density, and

$$Vp = V_3 - Ln\left(\frac{4A_pU_\infty}{\eta_3 Av_e}\right);$$

from which the plasma potential. $\eta_{1,2,3}$ are coefficients that take into account the presence of the sheath around the filaments.

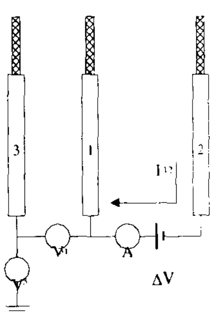

Figure 11: Triple Langmuir probe schema

The ion density in the plume is mapped simply by measuring the current flowing between ground and the wire probe while the probe is scanning the plume. Alternatively, the probes can be polarized negative with respect to ground, to reduce the plasma sheath thickness and simultaneously reduce secondary ion emission and the electron current collected on the probe. The wire probes can scan the plume one at a time simply by crossing it, thus yielding the 1-D envelope of the integral along the probe of a quantity proportional to the ion density. The probes can also scan the plume simultaneously and take advantage of their mutual interaction to retrieve the 2-D ion density distribution on the scanning plane. Repeating this scanning procedure at various distances from the thruster, a 3-D map of the plume can be obtained. More precisely, the first probe invested by the ion beam creates a *wake region* behind itself that extends for a distance that depends on the mean ion velocity (energy). If the second probe is in the zone of influence of the first probe, it will collect an ion current that is smaller by an amount proportional to the size of the wake region and to the ion density in that region.

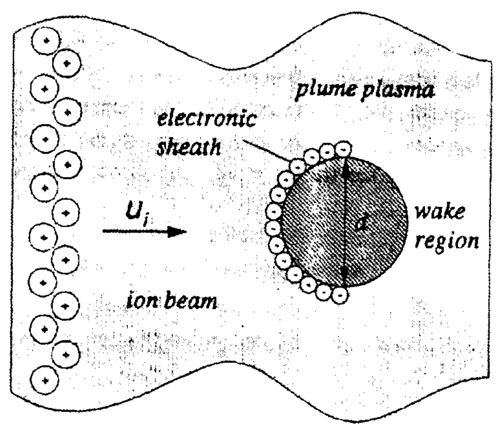

Figure 12: *Wake region* created in the ion beam by the probe.

By applying this procedure for different points on the scanning plane, and consequentially by repeating it on other scanning planes, a three dimensional ion distribution in the plume can be obtained.

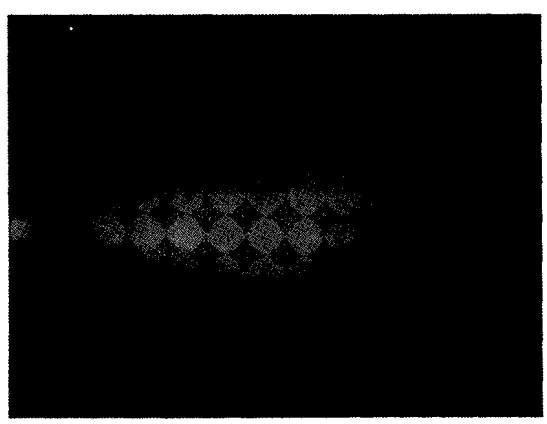

Figure 13: FEEP-5 plume image generated with the FEEP's facility diagnostic system (top view, normal to slit plane)

Combining this qualitative density distribution with quantitative triple probe measurements of the plasma density along the plume center axis, a quantitative 3-D image can be obtained.

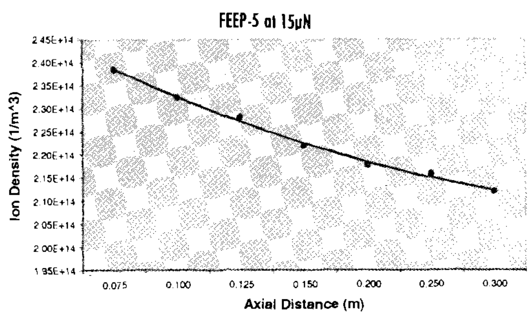

Figure 14: Triple Langmuir probe measurement on a FEEP-5

The complete scanning cycle takes not more than a few minutes, unless when operating at high spatial resolution.

Acknowledgements

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