Experimental Investigations on the Influence of the Facility Background Pressure on the Plume of the RIT-4 Ion Engine

IEPC-2011-014

Presented at the 32nd International Electric Propulsion Conference,
Wiesbaden • Germany
September 11 – 15, 2011

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Abstract: It is known that the presence of residual gases during on-ground testing of electric propulsion thrusters can significantly influence the plasma parameters and the quantity of charge-exchange ions obtained in the backflow of the ion source. In the frame of an ESA study dedicated to the "Assessment of Interactions between Spacecraft and Electric Propulsion Systems" (AISEPS) a miniaturized µN-RIT thruster (RIT-4), developed by Giessen University, was tested in the Corona vacuum facility at the ESA Propulsion Laboratory (EPL), ESA-ESTEC. A single filament neutralizer was used for beam neutralization. The main ion beam and backflow properties of the thruster were investigated by means of Faraday probes (FP) and retarding potential analyzers (RPA). The Cathode Reference Potential (CRP) was also investigated. The background pressure in the vacuum facility was increased to assess the influence of the xenon residual neutral density on the plume of the thruster. Different electrical coupling configurations between the thruster and the ground were also studied. The µN-RIT was operated at three different thrust levels ranging from 100 to 500 µN while the neutralizer was operated with constant heating voltage during the entire test campaign to allow emission up to 12 mA depending on the electrical grounding configuration. The background pressure was increased in the main vessel of the Corona facility by injecting an auxiliary xenon flow ranging from 10 to 50 sccm. The influence of the neutralizer was clearly observed on the RPA measurements in the main ion beam. The divergence was also clearly correlated to the grounding configuration of the thruster. However, even if the xenon background pressure increased the backflow ion current it did not have a clear influence on the divergence of the thruster.

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Nomenclature

J_e = Electron current density
A = Richardson constant
T = Surface temperature of the material
k_B = Boltzmann constant
W_e = Work function of the material
j = Ion current density collected by the retarding potential analyzer
V = Filtering voltage
Z = Charge number density of the ion
e = Elementary charge
n = Ion density
m = Mass of the ion

I. Introduction

TO create the on-orbit environment in a ground-based laboratory facility is technically challenging and expensive. All ground-based vacuum facilities possess a low-density background neutral gas due to physical pumping limitations and to the leak rate of the facility. The facility background gas present in the vacuum chamber can have undesirable effects on the measurement of electric propulsion thruster performance and plume characteristics[1]. High-energy exhaust particles interact with the neutral background particles through charge-exchange collisions (CEX). In the plume, the effects of CEX products are more evident in the perimeter, where they lead to an increase in the measured current density. Thruster operation and performance are dependent on the backpressure of the facility[2].

Several investigation are underway to model thruster performance and the interactions between ion thruster plumes and spacecraft numerically[3]. For simulations of laboratory experiments, one of the most important auxiliary inputs required by these codes is the background pressure of the laboratory vacuum chamber. In the frame of a project funded by the European Space Agency (ESA) dedicated to the “Assessment of Interactions between Spacecraft and Electric Propulsion Systems” (AISEPS), a miniaturized radio-frequency ion thruster µN-RIT (RIT-4)[4,5], developed by Giessen University, was tested in the Corona vacuum facility at the ESA Propulsion Laboratory (EPL)[6], ESA-ESTEC. The objective of this test campaign was to provide data for the validation of numerical tools describing the interactions between a spacecraft and the electric propulsion system on board.

II. Test Setup and Methods

A. Test Articles and Facility

The 4 cm ion thruster RIT-4, shown in Fig. 1 is a miniaturized radio-frequency ion thruster (µN-RIT) built by Giessen University especially for the test. It is a 37-hole thruster able to produce a thrust up to 500 µN within its nominal range[7]. The unique feature of this type of engine is the electrodeless ionization of the Xenon propellant by electromagnetic waves. Figure 2 shows a principle drawing of the thruster. During the test campaign the engine was equipped with a conical ionizer designed by Astrium instead of the cylindrical one in the drawing.

Fig. 1. Miniaturiazed RIT-4 ion engine from Gieβen University.

RF-ionization is known to be a very effective way to ionize neutral gases. The implementation of this ionization principle is simple as merely two components are necessary: an ionization chamber made of an isolating material and a RF-coil which surrounds this chamber. No other parts are required inside or outside the ionizer with respect to ionization of the propellant. This makes the overall concept very simple, robust and erosion free. When an RF-current is applied to the thrusters RF-coil a primary axial magnetic field is induced inside the ionizer. This field generates a secondary circular electric field (E).Whereas the effects of this electro-magnetic field on neutrals or ions is negligible, free electrons gain sufficient energy for impact ionization of the propellant. The propellant is set into the plasma state. Once the ionization process is initially triggered the process is self-sustaining. All electrons required for a steady state operation are generated in the discharge itself. There is no need for an additional electron source, e.g. a main cathode, inside the ionization chamber. By thermal movement ions from the bulk plasma find the way towards the grid system. Eventually the ions are accelerated in a system built up of two grids. Concentric holes in these grids form a large number of single extraction channels. Each of these channels represents a single ion optical system. The ion optical system properties are determined by the diameters of the holes, the grid spacing and the applied voltage.

For this test the RIT-4 was chosen to ensure a very low residual baseline backpressure in the vacuum chamber because the ratio between available pumping capacity on one hand and the maximum propellant flow through the thruster on the other hand is excellent.

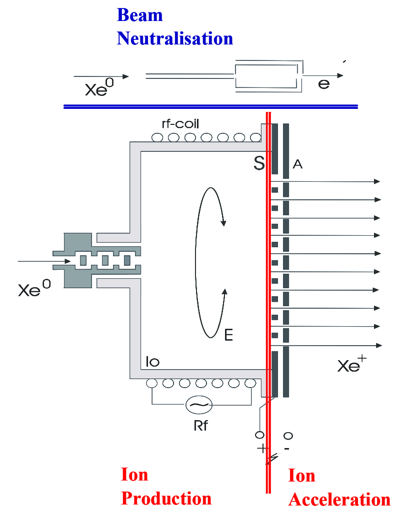

Fig. 2. RF-ion thruster function principle.

For beam neutralization a filament type neutralizer as shown in Fig. 3 was used. The filament is heated up by a DC-current. When a critical temperature is reached, thermal emission of electrons starts, following the Richardson equation

$$J_e = AT^2 e^{\frac{-W_e}{k_B T}} \qquad \text{Eq. (1)}$$

where J_e is the electron current density, A is the Richardson constant which depends on the material, T the surface temperature, k_B the Boltzmann constant and W_e the work function of the material. This temperature is dependent on the material used for the filament.

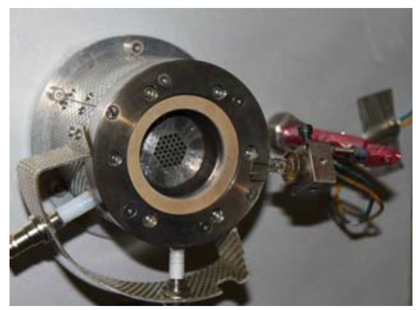

Fig. 3. RIT-4 and filament neutralizer used during the test.

Testing was performed in the Corona vacuum facility located in the ESA Propulsion Laboratory (EPL). The vacuum chamber is composed of a hatch of 1.5 m in length and 1 m in diameter and a main vessel of 5 m in length and 2 m in diameter. One cryopump and four cryopanels equipped the main vessel and were used for this test. The effective pumping speed was approximately 40,000 L/s of xenon. The thruster was located along the centerline of the chamber and fired towards the cryopanels located at the other end of the facility. To minimize the facility backsputter rates the interior back end of the vacuum facility is lined with graphite panels. Electrical power and xenon flow rate were both provided with dedicated systems built by Giessen University.

The power system and flow system were controlled and monitored by a Control Software from Giessen University written in Delphi whereas the facility telemetry was controlled and monitored with a Labview-based data acquisition and control system. The data systems recorded the thruster and neutralizer currents, voltages, flow rates and temperatures and facility pressure and temperatures at 1 Hz. The software used to record data was also used to control thruster power supplies and flow rate.

B. Diagnostics

1. Background pressure

Three hot-cathode ionization gauges (ITR90 from Leybold) were used to monitor the backpressure inside the vacuum test facility. Two of them were located in the middle (length) of the Corona main chamber and a third one was located 1 m under the thruster centerline approximately in the same plane as the thruster exit plane. Background pressure was corrected with a xenon correction factor of 2.87[8]. The base pressure in the Corona chamber was around 10^{-7} mbar. Chamber backpressure was increased by injecting xenon through an auxiliary flow line located approximately 2 m downstream of the thruster exit plane. The flow was controlled also with the Giessen's flow system. Injected flow of 10, 25, and 50 sccm corresponded to corrected xenon backpressures of 5×10^{-6} mbar, 1.1×10^{-5} mbar, and 2.3×10^{-5} mbar, respectively. The accuracy reported by the manufacturer in the 10^{-8} to 10^{-2} mbar range is 15 % of the measured value.

2. *Beam diagnostics*

The Corona facility is equipped with a vertical diagnostic rake. It could be moved by means of a stepper motor which transmits rotation to the arm via a gear mechanism. This allowed for a full 180 º scan of the plume of the ion engine. Eleven Faraday Probes (FP) were used to determine the ion current density of the plume. They were placed on the arm at different angular positions. The maximum angle was chosen according to the divergence of the thruster. These probes gave a three-dimensional profile of the beam current and allowed for divergence calculation. Each probe consisted of a collimation electrode (collimator) which defined the reference entrance area (78.5 mm^2) and was connected to the external shield and a collecting electrode with an insulating body which supported both the collector and the external shield. The collector was biased to –20 V and the shield to 10 V for current density measurements.

A 3 kV Retarding Potential Analyzer (RPA) was used to measure the ion energy distribution of the plume of the thruster. It was based on a four grid configuration: an external shielding electrode (ESE), a primary electron repelling electrode (PERE), an ion repelling electrode (IRE) and a secondary electron repelling electrode (SERE). This configuration allowed (1) minimizing the electrostatic disturbances on the plasma flow thanks to the ESE which was left floating during the test campaign, (2) repelling electrons from the plasma flow by biasing negatively the PERE (-40 V during the test), (3), repelling ions which energy is below a threshold defined by the IRE positive biasing potential and (4) suppressing secondary electrons emitted by the collector by biasing the SERE negatively at -40 V with respect to the collector. The collecting area of the device was 155.5 mm^2. The 3 kV was mounted on the diagnostic arm, close to the centerline of the thruster (-7.5 º with respect to the centre of the arm) as shows Fig. 4. The FPs as well as the 3 kV RPA were located approximately 80 cm downstream of the RIT-4 engine.

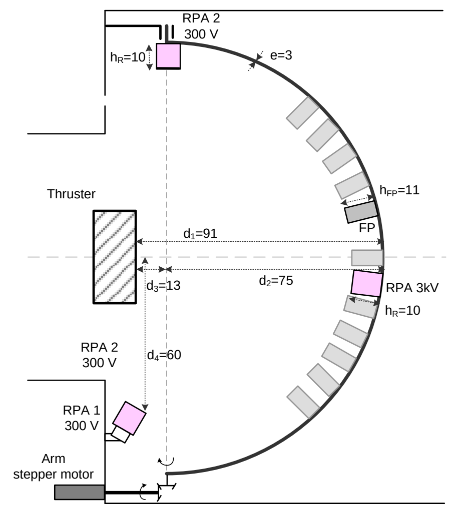

Fig. 4. Positions of the diagnostics during plume measurements.

Two low voltage RPAs placed in the backflow of the thruster were used to investigate the presence of CEX. The first RPA (probe 2) was installed on the diagnostic arm approximately at 90 º above the thruster exit plane. The second RPA (probe 1) was installed at 60 cm from the exit plane of the thruster (on the left side of the engine and in front of the neutralizer) and at about 70 º with respect to the thrust vector. The backflow RPA probes included a grid and a collector. The front grid was negatively biased at – 60 V to repel incoming electrons. The collecting area of the probes was 13.95 cm^2.

C. Electrical configurations

The test campaign offered the possibility to investigate the electrical coupling configurations of the RIT-4 thruster and the filament neutralizer (neutralization process). They were tested in “grounded” or “floating” mode. Figure 5 gives the baseline electrical test setup. Two power supplies were providing voltages to the grids of the ion engine. The RF-generator was fed by a dedicated power supply. It converted DC-electric power into RF-power. The net beam current was measured by the voltage drop over a shunt resistor. The amplified signal was compared with the reference beam current and a proportional-integral-derivative (PID) regulator set the input voltage to the RF-generator. In “grounded” mode the thruster secondary star ground (SSG) of the test system was connected to the facility ground: the ion current was in closed circuit via the chamber walls. The same applied for the electrons coming from the neutralizer. Even equivalent net electron and ion currents do not mean a neutralization of the ion beam by the electrons from the neutralizer. In “floating” mode, the electric connection between the SSG and the facility ground is opened. The electrons (ions) expelled from the neutralizer

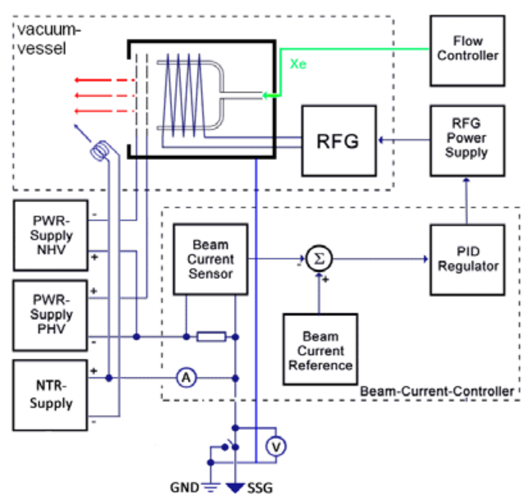

Fig. 5. Baseline electrical test setup.

(thruster) could not return via the chamber walls and the connection between the facility ground and SSG to the neutralizer power supply. A voltmeter was used to measure the Cathode Reference Potential (CRP) which is the voltage between the SSG and the facility ground.

Moreover, usually the housing of an electric propulsion thruster is hard-mounted to the spacecraft or to the test facility structure. In this configuration it is not possible to measure electron or ion currents to the thruster housing. To perform such a measurement the thruster was mounted electrically isolated and the direct measurement of the net current (sum of electron and ion current) was realized.

D. Test methods

Cathode reference potential (CRP) measurements and thruster plume characterization were conducted at three operating conditions shown in Table 1 and for each of the background pressures mentioned above. Test conditions are referenced in this paper by their nominal thrust level. To investigate the influence of backpressure on the plume of the miniaturized ion thruster, first a cold flow test was performed to determine the residual gas distribution in the Corona main vessel. Then, for initial ignition the RIT-4 was turned on and left running for 1 to 2 hours to allow it to be in stable conditions. During the warm-up phase the beam profile was measured on a regular basis. CRP and probe data presented here were collected over two series of five days of subsequent testing: during the first series the thruster body was grounded whereas it was electrically isolated for the second series. For each of the backpressure in the Corona chamber, the thrust level was chosen and then the electrical configurations of the thruster and neutralizer were modified.

Table 1. Set points for thruster plume investigations.

No	Regime	PHV [V]	NHV [V]	Mass flow [sccm]
#1	Low thrust 100 µN	800	100	0.147
#2	Medium thrust 250 µN	1200	120	0.158
#3	High Thrust 500 µN	1628	180	0.183

Thruster and vacuum facility telemetries were acquired continuously. Plume data were acquired after approximately 15 minutes after changing thrust level.

III. Test Results

Plume, backflow and CRP surveys data were acquired for each of the three nominal thrust levels and for each of the electrical configurations i.e. without neutralization, with neutralizer on and the system in "grounded" mode and with the neutralizer on and the system in "floating" mode. The influence of the backpressure was realized taking measurement for three different xenon auxiliary mass flow: 10, 25, and 50 sccm.

A. Cold flow test

The cold flow tests on the thruster line and/or on the xenon auxiliary line gave the distribution of the residual gases to be expected during the test such as to observe the influence of the backpressure on the thruster plume parameters. The pressure at the walls of the Corona vacuum facility was measured at three different positions. Xenon was fed into the vessel through the thruster and/or the auxiliary position. Firstly, gas was fed in through the thruster line only. During the second investigation the gas was fed through the auxiliary xenon line only. Finally the gas distributed via both lines into the vacuum chamber. The measurements were performed for thruster mass flow ranging from 0.2 sccm to 1 sccm and for auxiliary mass flow of 0, 25, and 50 sccm.

Those tests showed that the pressure inside the vacuum chamber and at the chamber walls was dominated by the high mass flow coming from the auxiliary line. It was nearly two orders of magnitude higher than the mass flow through the thruster. As expected we observed three major pressure levels with small variation of the pressure according to the mass flow through the thruster.

B. Ion energy distribution

The 3 kV RPA was used to determine the ion energy distribution in the thruster beam. It was positioned in front of the thruster exit plane 80 cm downstream of the engine. The low voltage RPAs were located in the backflow of the thruster.

To obtain the ion energy distribution the current density measured by the collector was derivated and smoothed. This derivative is related to the ion voltage distribution function *f* as given in Eq. (2).

$$-\frac{dj}{dV} = \frac{Z^2 e^2 n}{m} f(V) \qquad \text{Eq. (2)}$$

where j is the collected current density, V the filtering voltage, Z the charge number density of the ion, e the elementary charge, n the ion density and m the mass of the ion. As the multiply charged ions in a RIT thruster are scarce[9], the filtering voltage (V) is equal to the ion energy (eV) and the voltage energy distribution to the energy distribution. All ion voltage distributions measured with the 3 kV RPA showed a main peak at a voltage close to the positive grid polarization voltage (PHV). Figure 6 shows the voltage of the main peak of different ion voltage distributions measured with the 3kV RPA as a function of mass flow. Each color corresponds to a thrust operation regime: 100 µN (blue), 250 µN (magenta), and 500 µN (green). It can be seen that the peaks drift towards higher voltages when the thrust increases. This is consistent with the increase of the PHV of the thruster. The difference between the voltage of this peak and the PHV is explained by the plasma potential (a few tens of Volts at most) but also by the uncertainty in the measurement.

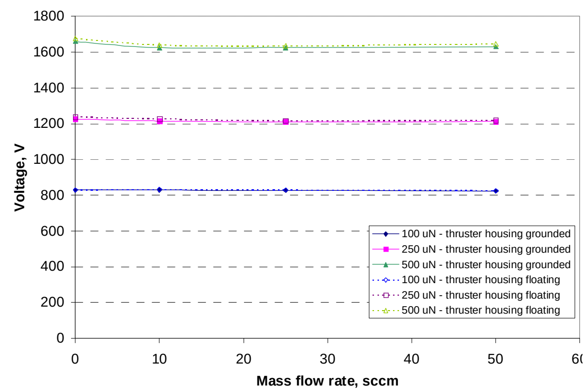

Fig. 6. Voltage of the main peak in the ion energy distribution (3 kV RPA measurements) as a function of the background pressure (mass flow rates) and for different electrical configurations of the thruster and for the three operating regimes (blue for 100 µN, magenta for 250 µN, green for 500 µN) with neutralizer off.

The influence of the neutralization of the beam was also investigated. For all thrust levels, the beam ion distribution became narrower when the neutralizer was on. It did not change when the neutralizer was left floating or when the housing of the thruster was grounded as given in Fig. 6.

The influence of the backpressure on the ion energy distribution was also investigated. Figure 6 shows the voltage of the ion voltage distribution peak for different auxiliary xenon mass flows (for 100 µN, 250 µN, and 500 µN). The voltage of the main peak did decrease slightly with the backpressure (up to 6 V difference for 100 µN and up to 30 V for 500 µN). However on the whole the background pressure had only a slight influence on the ion distribution in the beam.

Regarding the backflow RPAs (probe 1 corresponds to the RPA positioned on the left of the thruster and probe 2 to the probe above the thruster), the post processing method applied was the same as for the 3 kV RPA. Most measurements from probe 1 were not interpretable because they clearly showed that many electrons were not repelled by the grid of the probe even though the biasing voltage was at -60 V. The collected electron current varied with the polarization voltage of the collector which made it difficult to interpret the corresponding plots. For the measurements from probe 2, on the whole, all measured current density profiles were similar. Even though the thrust was multiplied by five, the collected current was at most doubled. A bulk of ions was generally seen between 0 and 20 to 30 V. Both thrust and electrical configuration did not seem to have a major impact on the energy of the CEX collected by the probes. It did seem that their energies decreased slightly when the neutralizer emitted electron current increased (which increased when the neutralizer was turned on but also when it was left floating) as shown in Fig. 7. The grounding of the thruster housing had little effect on these measurements.

To check the influence of the background pressure on the ion energy distribution in the backflow, the measurements were performed with the neutralizer turned off to avoid high electron currents on probe 1. Increasing the auxiliary xenon mass flow increased significantly (more than one order of magnitude) the collected current by both probes. This current could reach a few 10^{-5} A/m^2. The xenon pressure in the chamber was clearly the driver for the collected CEX current because thrust had little influence on it as both probes collected similar currents. Another interesting change was the decrease of the ion energy: at higher backpressures, most collected CEX ions have energies below 5 eV against 10 eV and 20 eV with no auxiliary mass flow.

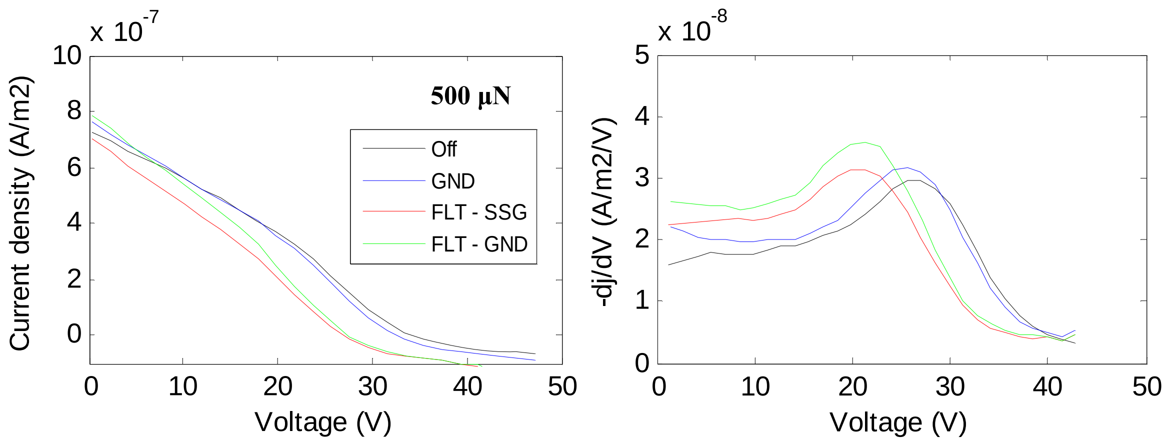

Fig. 7. Current densities (A/m^2, left) and backflow ion distribution function (A/m^2/V, right) measured by probe 2 at 500 µN and neutralizer conditions: off (black), on and grounded (blue), on and floating (red) and with the thruster housing floating (green).

C. Ion beam profile and divergence

The FP's were scanned radially across the beam allowing a 3-D mapping of the current density of the plume. The FP's were located at 80 cm from the thruster exit plane. Figure 8 shows the current densities measured at 500 µN, no neutralizer was used and the thruster housing was grounded. FPs were used to characterize the engine beam divergence as a function of operating conditions (thrust levels, electrical configurations and background pressures). The divergence angle was calculated as the half-cone including 95 % of the high energy ions exiting the thruster. During the experiments when the thrust level was increased the maximum current density increased while the beam divergence decreased.

The influence of the electrical configuration of the system thruster/neutralizer was also investigated. Except for the 100 µN thrust level, when the thruster housing was grounded to the facility ground the divergence decreased when the system was in "floating" configuration. The same results were obtained when the housing was electrically connected to the SGG. All the results are summarized in Fig. 9 which gives the divergence angle for three thrust levels: 100 µN, 250 µN, and 500 µN and for all the different electrical configurations.

The influence of the xenon residual neutral density on the plume of the thruster was assessed increasing the backpressure of the Corona vacuum facility and results are also given in Fig. 9. The mass flow rate of the auxiliary xenon line was set at 10, 25, and 50 sccm. A trend of the divergence of the plume with increasing background pressure was not very clear as the calculated divergence angles were very close to each other and they could be in the uncertainty of the FP's measurements.

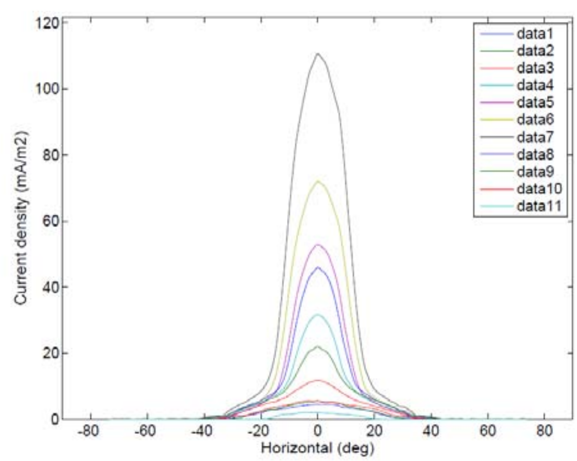

Fig. 8. Ion beam profile measured for a thrust level of 500 µN, neutralizer off and thruster housing grounded

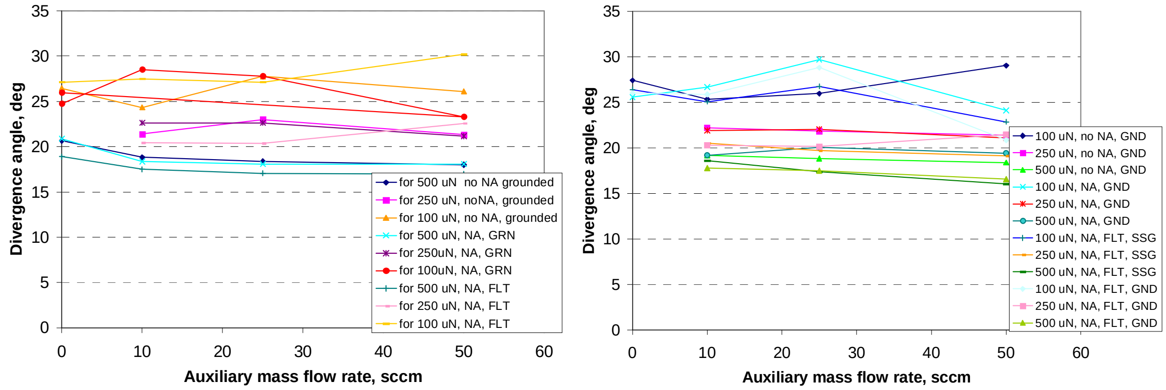

Fig. 9. Influence of the auxiliary mass flow rate (residual neutral backpressure) on the thruster divergence for 100 µN, 250 µN, and 500 µN. The thruster housing was grounded (left) or electrically isolated (right).

E. Cathode reference potential

For the lowest thrust level (100 µN) the heater current through the neutralizer was adjusted so that the emitted electron current was equal to the beam current. During the measurement using the RPAs and the FPs the emitted current increased when one of the devices was in the vicinity of the thruster ion beam. This behavior was observed for all thrust levels. When the thruster was operated in "floating" mode a slightly positive voltage was measured. This indicated that the emitted electron current was slightly higher than the beam current.

The maximum electron current of the neutralizer in grounded mode was limited to approximately 3 mA. This was not sufficient for a full neutralization of the beam. However, when the thruster was operated in "floating" mode the CRP ensured that the electron current and ion current became exactly equal. Figure 10 and Fig. 11 give the influence of the electrical configuration of the neutralizer on the ion beam and neutralizer currents, and the cathode reference potential, respectively for a thrust level of 500 µN. Compared with a plasma bridge neutralizer which has a typical CRP of 10 to 20 V, the maximum observed CRP was considered high (-34.6 V @ 500 µN) for the filament neutralizer. But the system operated also with the filament self adjusting as known from plasma bridge neutralization. Figure 12 shows the observed dependency between beam current and CRP.

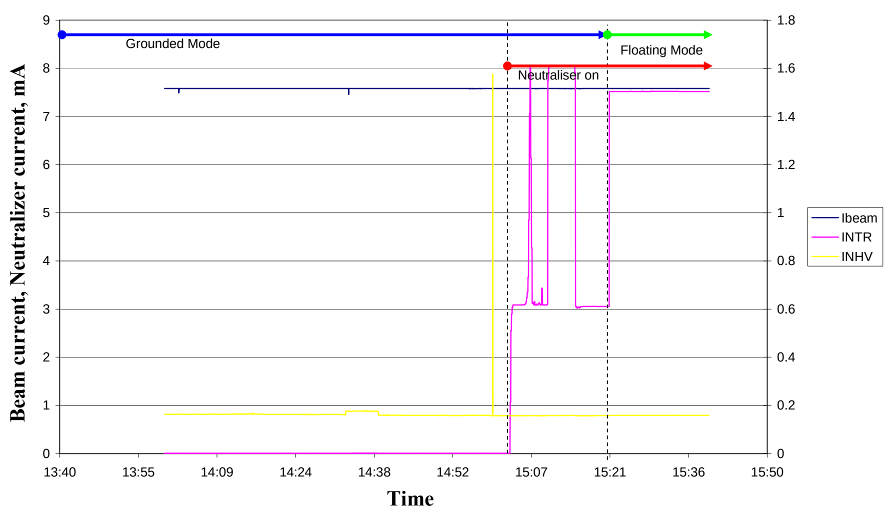

Fig. 10. Ion beam (blue) and neutralizer (magenta) currents evolutions in function of the electrical configuration of the neutralizer, for a thrust level of 500 µN. The thruster housing was grounded.

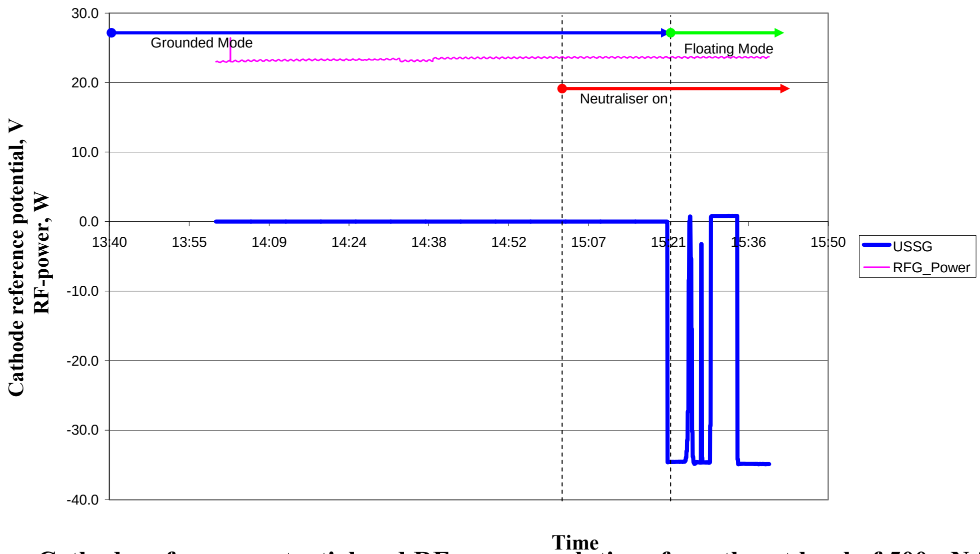

Fig. 11. Cathode reference potential and RF-power evolutions for a thrust level of 500 µN in function of the electrical configuration of the neutralizer. The thruster housing was grounded.

For evaluation of the CRP with background pressure the potential was regarded as a free expanding plume in front of the thruster. The results are summarized in Fig. 13. On all thrust levels the CRP decreased when the backpressure increased. Evidently an increased background pressure resulted in a higher electric conductivity between neutralizer and thruster plume.

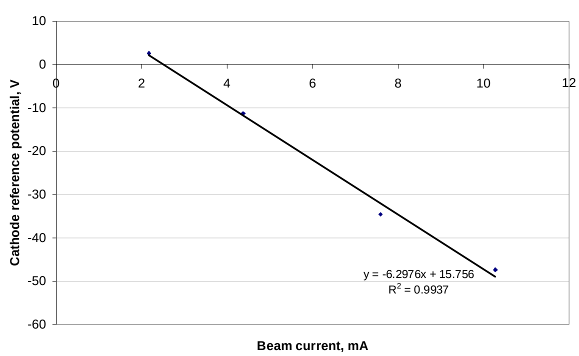

Fig. 12. Influence of the beam current on the Cathode reference potential.

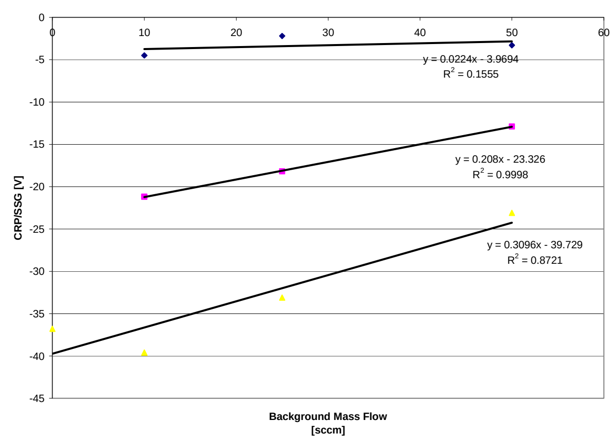

Fig. 13. Influence of the backpressure on the CRP for three different thrust levels: 100 µN (blue), 250 µN (red), 500 µN (yellow).

IV. Conclusion

This test campaign supplied valuable plume and cathode reference potential data for the validation of numerical tools in the frame of the AISEPS (Assessment of Interactions between Spacecraft and Electric Propulsion Systems) project. Measurements of beam divergence, ion beam energy as well as energy of CEX ions in the backflow of the RIT-4 thruster were performed for different thrust levels (100 µN, 250 µN, and 500 µN) and residual xenon gas pressures ($5x10^{-6}$ mbar, $1.1x10^{-5}$ mbar, and $2.3x10^{-5}$ mbar), and this for different electrical configurations. The influence of the neutralizer was clearly observed on the RPA measurements in the main ion beam. The divergence was also clearly correlated to the grounding configuration of the thruster. However, even if the xenon background pressure increased the backflow ion current, it did not have a clear influence on the divergence of the thruster or on the energy distribution.

Acknowledgments

The authors would like to thank M. Wartelski and C. Theroude from Astrium Toulouse and E. Gengembre from ESA-ESTEC for the fruitful discussions during the preparation and the test campaign.

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