3200 hours Endurance Testing of the Lisa Pathfinder FT-150 Thruster

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Abstract: The FT-150 micropropulsion thruster is being developed at Alta for use on-board the Lisa Pathfinder mission. After having demonstrated thrust performance in the range 0.3 to 200 µN, with a 0.1 µN resolution throughout the range, the cesium-fed slit-type Field Emission Electric Propulsion (FEEP) thruster had to demonstrate sufficiently extended operation. To this aim, two endurance tests were performed one after another in 2008. Both endurance tests were performed in a full flight-standard configuration. During first endurance test, the thruster cumulated 736 hours of firing time and a total impulse in excess of 260 Ns, before a facility failure interrupted the test. The second endurance test (performed on a thruster identical to the first one) immediately followed the first one. In this case the test went on until the thruster was no more able to drain propellant from its reservoir against gravity, due to the fixed geometrical setup. In the meanwhile, the thruster had cumulated 3228 hours of firing operation and it had generated a total impulse in excess of 950 Ns, i.e. very close to the qualification limit of 1100 Ns required for Lisa Pathfinder. The test results provided the means to predict lifetime, total impulse capability and end of life performance (e.g. thrust range and power consumption) of the thruster as it was. In addition, the information gained from test data analysis and thruster post-test inspection allowed some improvement to thruster unit design, focused to minimize thruster internal contamination and growth of parasitic currents, thus improving end-of-life power efficiency of the thruster. These tests provided also validation of Alta's "LFF" vacuum facility, in view of the upcoming Lifetime Test and full qualification for Lisa Pathfinder.

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Nomenclature

F	=	thrust
I_b	=	beam current
K	=	thrust constant
V_e	=	emitter voltage

I. Introduction

Alta is developing the FT-150 micropropulsion thruster under ESA funding in the frame of the joint ESA-NASA mission Lisa Pathfinder (technological precursor to the future Laser Interferometer Space Antenna). The thruster is currently baselined also for CNES' Microscope mission,[1,2] and for ASI's Galileo Galilei (GG) mission. Before undergoing formal qualification, the thruster had to go through a number of validation tests, aimed at completing its development phase.

After having demonstrated priming repeatability,[3] and thrust performance in the range 0.3 to 200 µN, with a 0.1 µN resolution throughout the range,[4] the cesium-fed slit-type Field Emission Electric Propulsion (FEEP) thruster had to provide demonstration of sufficiently extended operation. For this reason, two endurance tests were performed in sequence during year 2008. While previous record of 1'650 hours (and approximately 500 Ns total impulse),[5] was achieved with a thruster in a "naked emitter" configuration, in this case both endurance tests were performed in a full flight-standard configuration.

An overview of the application of the FT-150 thruster to the Lisa Pathfinder and Microscope missions is provided in Ref. 1, while the overall up-to-date development status of the thruster is presented in Ref. 6.

II. Test Description

A. Test Item

The test items that were subject to the two Endurance Tests (referred as ET#1 and ET#2 in the following) were two Engineering Model Thruster Assembly (TA) of the FT-150 FEEP thruster, almost identical in configuration to the flight and qualification models.

The TA includes:

- the Thruster Unit, in turn made of the emitter and accelerator electrodes and the core ceramic insulator;
- the Lid Opening Mechanism (LOM), protecting the thruster unit during non-vacuum phases;
- the propellant Tank, filled with about 90 grams of 6N grade cesium;
- two Heater Assemblies, installed on top of the propellant tank;
- all the required fittings, interfaces, and High Voltage and Low Voltage harness.

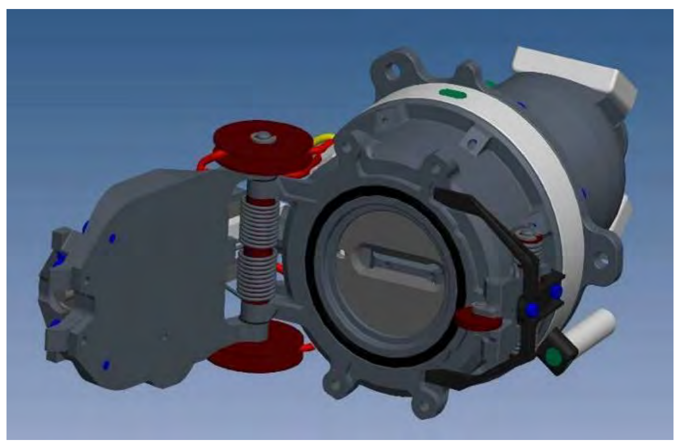


Figure 1. 3D view of the Test Item.

B. Setup and GSE

1. Beam diagnostic

The TA was installed on the mounting plate of a beam diagnostic system in order to perform periodic beam scanning to determine the plume density profile. The system consists of two rotary single filament probes to measure the shape of the plume in both in-plane and out-of-plane directions.

The beam diagnostic system is shown in Fig. 2.

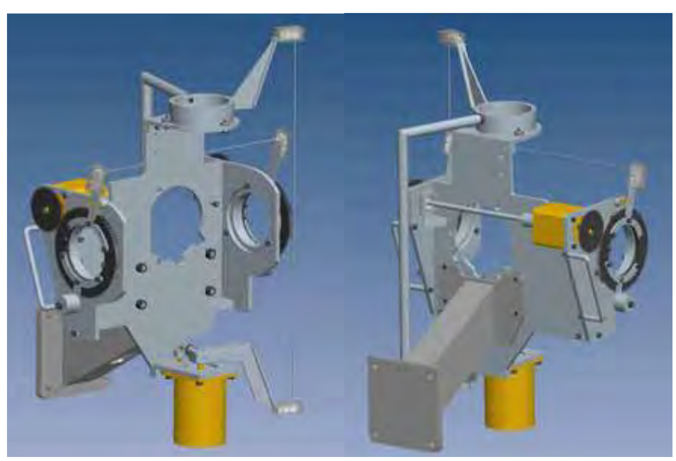


Figure 2. Beam diagnostic system.

The beam diagnostics support provides the interface between the TA and the vacuum chamber, and, at the same time, provides alignment of the TA axis with that of the beam diagnostic system.

2. Thermal shield

The propellant reservoir was thermally decoupled from the vacuum chamber walls by a gold-plated thermal shield installed on the rear of the diagnostic system and thruster support. The shield could be heated to reproduce the background thermal environment the tank would see during in-flight operation, especially for the activation and priming phases.

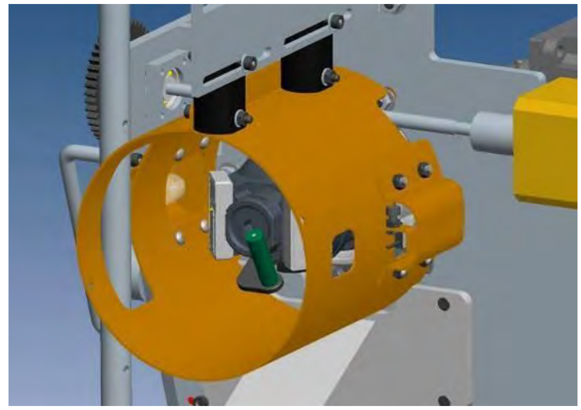


Figure 3. 3D view of the thermal shield.

3. Closing system

The TA was provided with a LOM Closing System GSE (Fig. 4) allowing to re-close the thruster sealing cover in case of facility maintenance operations or malfunctions, or in case the thruster was to be moved from one vacuum facility to another after activation.

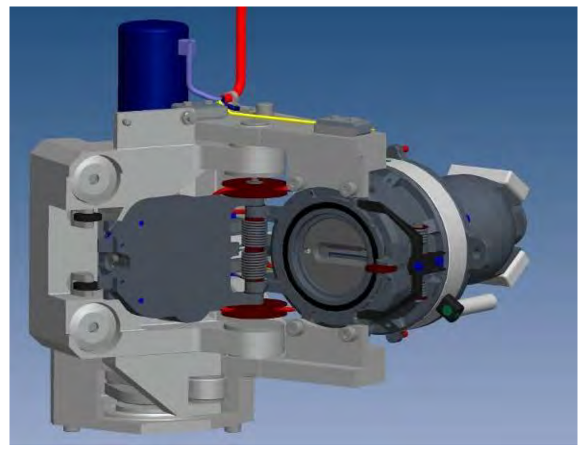
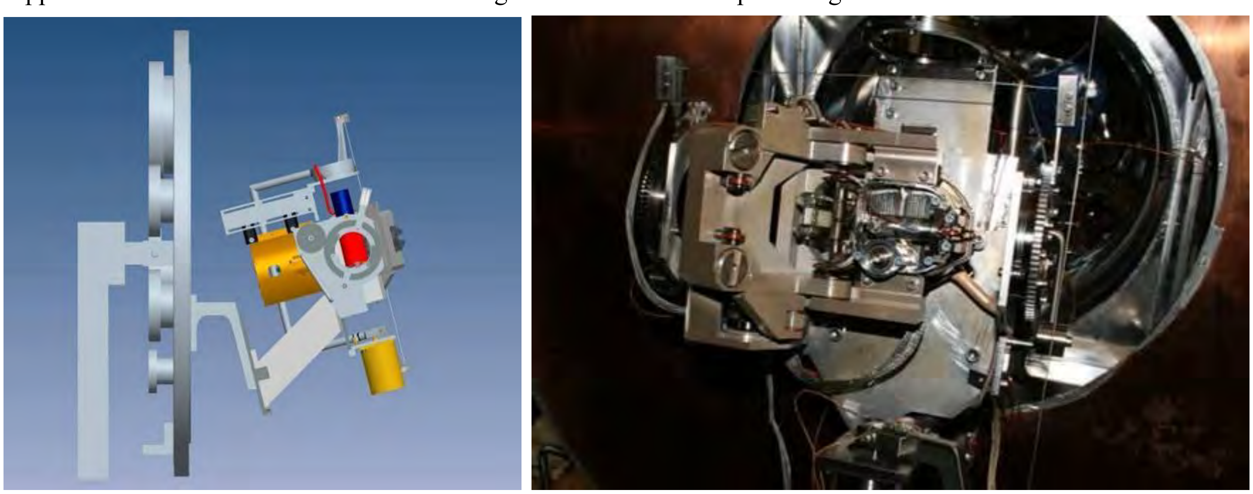


Figure 4. LOM Closing System GSE.

4. Thruster mount

In Endurance Test #1 the thruster was mounted horizontally. With this type of mounting, the level of the propellant within the tank was higher than that of the emitter tip, which may have contributed to an anomaly that will be described in section D. In Endurance Test #2 the beam diagnostics and thruster support system was assembled with a 15 deg upwards inclination to achieve a negligible (slightly negative) hydrostatic pressure in the emitter, i.e. the inclination was such that the level of the propellant in the tank (at the beginning of the test) was the same of that of the emitter tip. In this way, the effect of gravity on propellant drive was almost negligible at the beginning of the test, providing a close simulation of the actual in-orbit microgravity conditions. As the test went on, the level of propellant in the tank got lower and lower, up to the point where gravity became stronger than the capillary pull, and the test had to be interrupted. As it will be seen, this happened in Endurance Test #2 far after having achieved the total impulse target.



a) **b)**

Figure 5. Thruster mount relative to the vacuum chamber door. a) CAD picture. b) Actual setup in Alta's LFF facility.

C. Test objectives

The test objectives, common to Endurance Tests No. 1 and No. 2, were:

- to provide information about thruster performance in the long term, with particular regard to self-contamination phenomena, having the goal to reach a total impulse of 370 Ns (Lisa Pathfinder development phase target);
- to verify facility performance in the long term, and its suitability for life testing, mainly focusing on facility-induced contamination of the thruster.

Additional goals, albeit not mandatory for this test, were:

- to extensively characterize ion beam shape (plume divergence angles) and thrust direction;
- to collect data and information on thruster, facility and the set-up as input for future activities;
- to extend test duration past the 370 Ns target, to get further life performance information.

III. Test execution summary

D. Endurance Test No. 1 (ET#1)

Endurance Test No. 1 started on March 4th, 2008, in Alta's Lifetest FEEP Facility (LFF). The first part of the test was made of the priming and activation sequence, as well as initial performance characterization of the thruster. The priming procedure started by heating up the sealed propellant tank, up to the point where thermal expansion of cesium broke the calibrated sealing disk inside the tank. Disk rupture temperature (about 120 °C) was according to previsions. Further heating of the propellant allowed than the filling and priming of all capillary ducts up to the emitter, finally enabling thrust generation. Figure 6 shows a picture of the thruster shortly after ignition: emission starts from few spots on the emitter blade, and it extends progressively to the whole active part of the slit during the initial thrust stabilization phase. The final priming temperature was higher than analytical predictions: a review of the analytical model showed a bug in the model itself. Once the model was fixed, priming predictions for all the following tests proved sufficiently accurate.

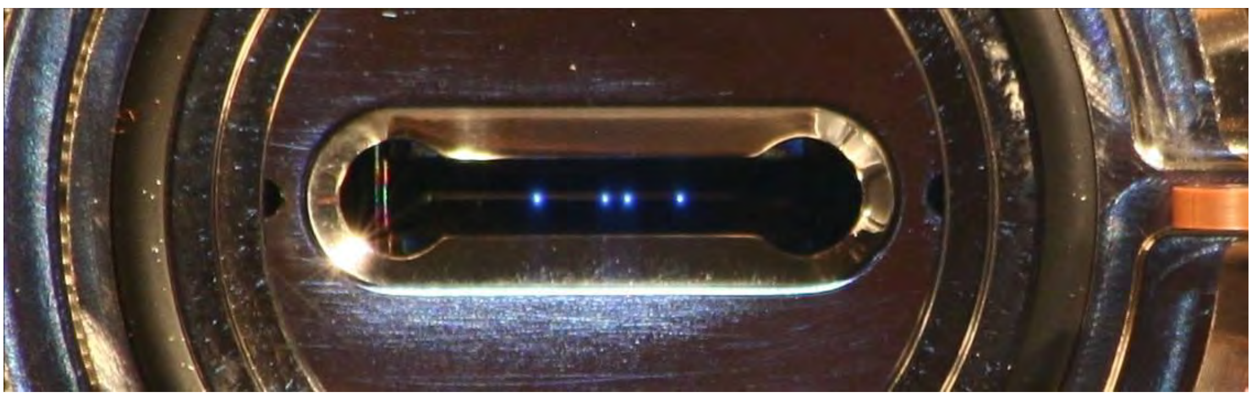


Figure 6. Emitter blade at thruster first ignition.

The thruster was fired for about 10 hours before starting characterization, to let performance stabilize. Nominal thrust level (150 μN) was gradually reached within an hour and a half from activation. The thruster performance in terms of electrical parameters (I/V curve) and beam shape was then characterized, according to test procedure, at different operational temperatures. During this phase, some spillage of cesium occurred, probably due to a combination of hydrostatic pressure, residual gas pressure in the tank, and temperature. This drop of cesium, then evaporated into the thruster, created a significant internal contamination of the thruster itself, resulting in parasitic currents flowing between the emitter and the accelerator electrode circuits (which, in turn, result in a poor power efficiency of the thruster).

This event, however, did not prevent the thruster from operating for another couple of months, up to totaling 736 hours of firing time. The test was interrupted on April 16th, 2008, by a failure in the vacuum facility: a short circuit in the thermocouple acquisition system switched off the pumping control system, and the pressure into the chamber suddenly rose to a level high enough to oxidize and contaminate the propellant.

E. Endurance Test No. 2 (ET#2)

Endurance Test #2 was started on mid April 2008, in Alta's IV1 facility (while the LFF facility was still hosting ET#1). The priming procedure was performed nominally, and both tank opening and priming occurred within the predicted temperature range (the priming analytical model had been fixed since ET#1). The thruster started firing on April 24th, 2008.

Thruster was operated and characterized for performance in IV1 facility up to 160 hours of firing operation and about 35 Ns total impulse. During this phase the thruster was operated with both the FUG laboratory power supplies and the flight-representative Power Conditioning Unit Elegant Breadboard (PCU-EBB), respectively 59 hours with FUG and 101 hours with PCU. The test allowed to record coupled thruster-PCU performance, and compare it with previous test data obtained with laboratory power supplies. A picture of the thruster during this test phase is provided in Fig. 7.

Figure 7. Thruster firing in IV1 facility @ 150 µN thrust (Priming Test No. 2 / Endurance Test No. 2).

At the end of these tests, the larger LFF facility had become available after the interruption of ET#1, and the thruster was moved into LFF for continuation of its endurance testing. Transferring the thruster from one facility to another did not affect its performance to a measurable extent, and the maximum thrust value of 150 µN could be reached within few hours since thruster restart in the new facility.

As anticipated above, the test went on as far as the capillary forces were able to drive the propellant to the emitter against gravity, considering the upwards tilt of the thruster. The interruption of flow occurred on December 19th, 2008. Up to then, the thruster had cumulated a total firing time of 3228 hours.

F. Thrust profile

During both tests, with the exception of the initial characterization phase, thrust level was controlled following system-specified cycles, whose template is shown in Fig. 1. Each cycle, lasting 1 week, is made of three initial blocks of sinusoidal thrust (levels of 5-30 µN, 30-55 µN, and 55-80 µN, and frequencies of 1 mHz and 0.1 Hz), followed by two longer constant thrust legs, at levels of 100 µN and 75 µN, respectively. At the end of each cycle, I/V characteristics of the thruster were collected (sect. 5) and the cycle was then repeated. During the constant thrust phases ion bean scans were also performed using single filament Langmuir probes, allowing an evaluation of beam divergence and of thrust vector evolution (sect. 0 and 7).

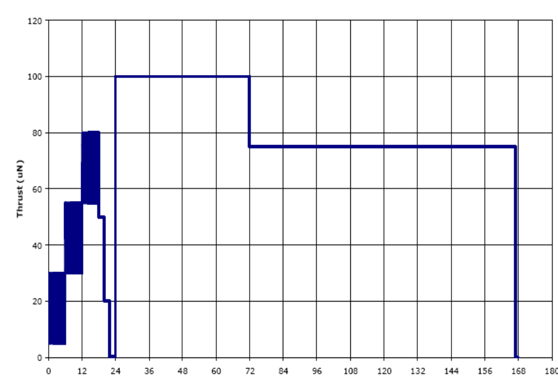


Figure 8. Thrust profile during endurance test.

IV. Main test results

G. Total impulse achievement and specific impulse evaluation

Thrust in FEEP thrusters is calculated on the basis of electrical parameters according to the following Eq. (1):

$$F = K \cdot I_b \cdot \sqrt{V_e} \qquad (1)$$

where F is thrust, K is a constant, I_b is "beam" current (equal to emitter current minus accelerator current), and V_e is emitter voltage.

The value for the thrust constant K was established by the direct thrust measurement test,[4] and its value, made applicable to the evaluation of the test results, is $1.868 \cdot 10^{-3}$ N A^{-1} $V^{-1/2}$, with a relative uncertainty of ± 2%. The electrical parameters I_b and V_e were acquired during the endurance tests at a frequency of 1 Hz, independently from the commanded thrust value and the programmed thrust profile. Once the value of K is known, the total impulse produced by the thruster is therefore obtained by integrating Eq. (1) over time.

During 736 cumulated hours of firing, the thruster of Endurance Test #1 had produced a total impulse of 270 Ns ± 2%. The propellant reservoir was weighted after the test, and it was estimated that about 10 grams of cesium were consumed during the test. This leads to a calculated average specific impulse of 2750 s. This value is quite lower than the expected one because, as explained in section D above, a certain amount of propellant had been ejected by the thruster, and it was not possible to make a distinction between the propellant that was effectively fired by the thruster and the one that spilled out.

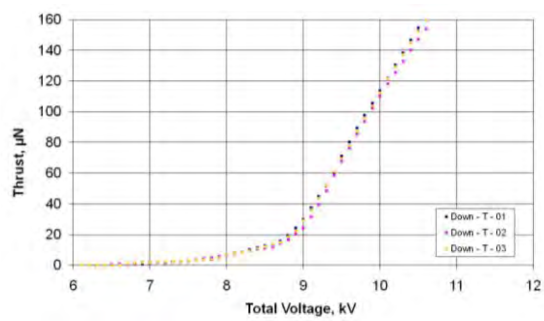
In Endurance Test #2, the thruster fired for a total time of 3228 hours, achieving a total impulse of 975 Ns ± 2%. The missing mass of cesium after the test was about 43.7 grams, and the average specific impulse was then 2275 s. Also in this case, the value was lower than expected. The neutral flow measurement test (Ref. 7) showed that the evaporation of neutral flow is very strongly dependant on emitter temperature. During the ET#2, a progressively increasing internal dissipation current (not described in this paper, as the analysis work for its full understanding is still ongoing) kept the average emitter temperature during the test much higher than nominal operative level (up to 130 °C vs. the nominal 45 °C). This is believed to have improved the neutral cesium evaporation rate to an extent that explains the relatively low specific impulse. Following the results of this test, the design of the thruster was slightly modified to minimize such behavior during flight operation. It has to be noted, however, that even considering this worst-case Isp value, the propellant in the tank is sufficient to fulfill the mission requirement (2045 Ns including all the required margins).

H. ET#2 Performance

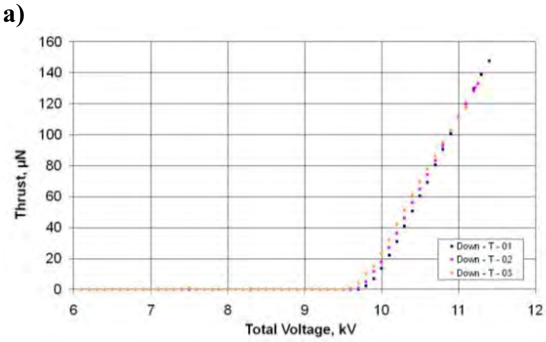
This section summarizes the main performance data that were collected and successively analyzed in the frame of the Endurance Test No. 2, which is the main topic of this paper.

5. *Thrust characteristics*

As in all ion thrusters, the thrust performance of FEEP is evaluated by monitoring its electrical parameters. The major achievement of the ET#2 was to observe the evolution of such parameters with time. The fundamental plot for the assessment of the thrust performance is the thrust vs. total voltage* characteristic curve, where two basic parameters are of interest: threshold voltage, i.e. the total voltage required to



a)



b)

Figure 9. Thrust vs. total voltage characteristic curves for ET#2. a) Beginning of test, 29/04/08. b) End of test, 15/12/08.

* The "total" voltage in FEEP is the voltage difference between the emitter and the accelerator electrodes.

let emission begin and to obtain a non-zero amount of thrust, and total voltage for a given thrust level, typically maximum thrust (100 μN for Lisa Pathfinder).

Figure 9 shows six of such characteristic curves. Three of them (Fig. 9-a) were recorded close to the beginning of the test, and the other three (Fig. 9-b) were recorded few days before the test conclusion. The comparison of these two plots shows that:

- the threshold voltage increased from about 7.5 kV at the beginning of the test to about 9.5 kV at the end of the test. This effect is believed to be a consequence of a progressive reduction in residual pressure inside the propellant tank[†], due to both propellant depletion and gas ejection by diffusion;
- the total voltage required to produce 100 μN of thrust increases from about 9.8 kV at the beginning of the test to about 10.8 kV at the end of the test. This is a combined effect of the increase in the threshold voltage describe above, which increases the required voltage for a given thrust, and of the square root contribution of voltage to thrust in Eq. 1, which reduces the required beam current to get the same thrust at an higher voltage.

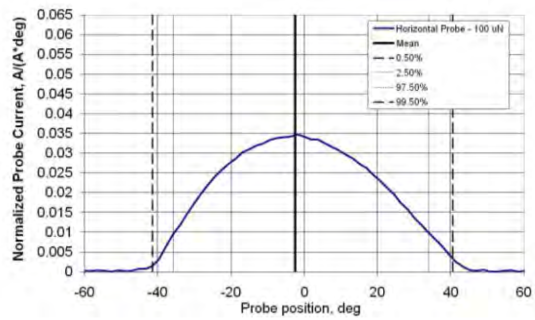
It is remarked that the observed variation is not preventing the thruster from being operated at full performance, in particular with respect to thrust range and resolution. The flight Power Control Unit (PCU), in fact, is designed to provide a maximum total voltage value of 13.7 kV, which means that about 3 kV of margin where still available at the end of the test in terms of operational voltages.

6. Beam divergence

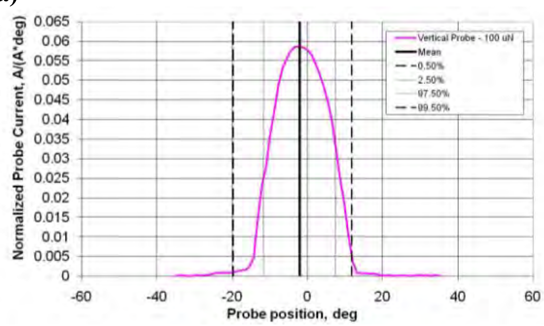
The beam geometry and divergence are evaluated by means of scans performed with two single filament Langmuir probes, perpendicular to one another, and being parallel and perpendicular to the emitter slit, respectively ("horizontal" and "vertical" probes, respectively). An example of such scans is provided in Fig. 10, for the 100 μN thrust level. It can be noted that the beam is quite broad (about 40 deg half angle) if sectioned with a plane which is perpendicular to the slit, while it is well focused (about 15 deg half angle) in the emitter slit plane. This feature is typical of the slit-emitter FEEP.

Fig. 11 shows the summary of beam divergence angles (defined as the half-cone aperture angle including 99% of the beam) recorded during Endurance Test No. 2. The plot shows how the beam divergence increases at very low thrust values (higher average values at 150 μN, besides being outside the nominal thrust range, are due to the lower numerousness of the data sample).

Since the beam divergence information is mainly applicable to contamination effects, the average value is that of concern. The plot shows that the Lisa Pathfinder mission requirement is met by the average beam divergence on both planes of measurement, down to a thrust value in the order of 10 μN. At lower thrust values, the average divergence angle is higher than the specified limit. However, also the ion current is reducing for lower thrust, which means contamination is still very low, and acceptable.



a)



b)

Figure 10. Normalized scans at 100 μN thrust. a) Horizontal probe. b) Vertical probe.

It is also worth noticing that beam divergence is always lower than 60 deg at all times and in all test conditions.

7. Thrust vector errors

Thrust vector is also evaluated on the basis of the plume scans described above, by applying the suitable trigonometry, and a certain degree of simplifying assumptions on beam uniformity. Figure 12 shows a summary of thrust vector angle measurements collected during ET#2. The measured thrust angle is plotted as a function of thrust level, showing the deviation from nominal direction is lower for increasing thrust levels.

[†] The dependence of threshold voltage on propellant pressure has been observed in several other tests before.

The recorded values are the result of both the geometrical errors (due to tolerances in internal thruster alignment and in alignment of the thruster w.r.t. the beam probes system), providing a certain bias, and the fluctuations of the beam due to the inherent behavior of the thruster. The plot shows that these fluctuations are more evident in the very low thrust region, with a vector error that can exceed 6 deg when thrust is lower than 10 μN.

If one considers the vector error in terms of lateral disturbance, i.e. the lateral force that has to be compensated by actuating another thruster in the reaction control subsystem, it is easily understood that the higher error at low thrust is mitigated by the low value of thrust itself. In fact, lateral disturbance is obtained by multiplying the thrust level by the sine of the thrust vector angle. Figure 13 shows that, even if the angular deviation is higher, the lower thrust levels are still less critical than the higher ones w.r.t. lateral force.

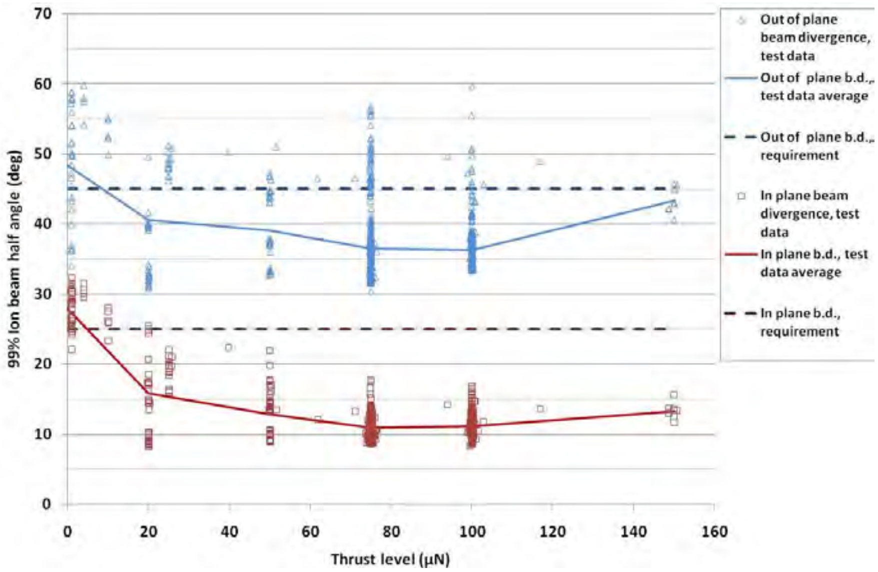


Figure 11. Beam divergence (99% of beam), from ET#2, vs. thrust level.

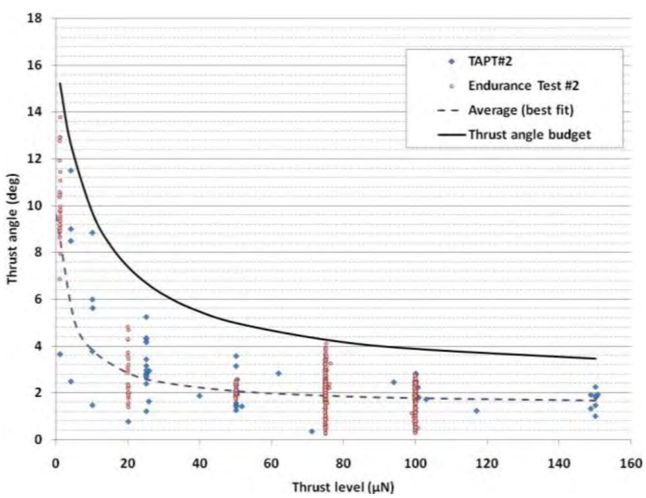


Figure 12. Thrust angle vs. thrust level.

Finally, Fig. 14 shows how the thrust vector angle (at the reference thrust value of 100 μN) varied during the test. It can be seen that the thrust vector lies inside a cone having a 3 deg half angle at all times.

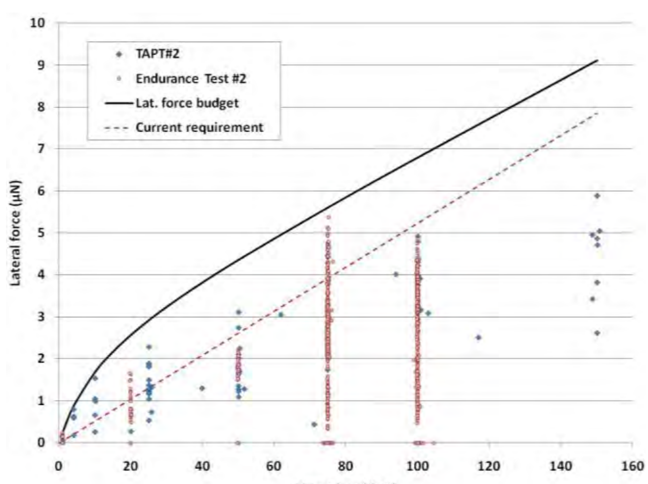


Figure 13. Lateral force vs. thrust level.

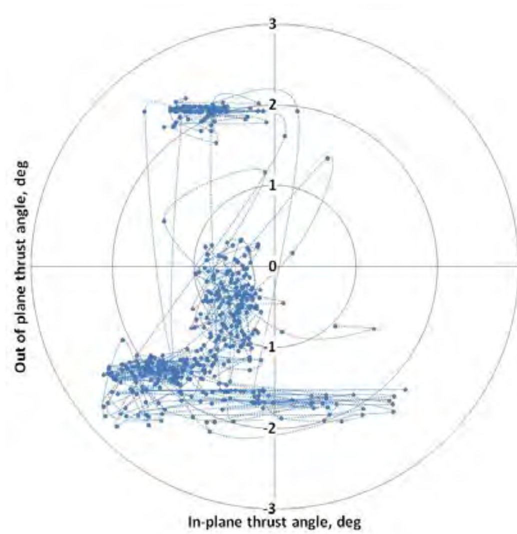


Figure 14. Evolution in time during ET#2 of thrust vector angle at 100 μN.

V. Conclusion

For the first time ever, a complete, flight design FEEP thruster was tested for about 8 months, cumulating a total firing time in excess of 3200 hours and producing a total impulse of almost 1000 Ns.

The long duration test provided a huge amount of data that allowed thruster characterization with respect to some features that were never assessed before. Among these are:

- thrust vector errors and their dependence on thrust level and time;
- evolution with time and delivered total impulse of electrical characteristics;
- assessment of average effective specific impulse;
- aging phenomena, including growth of internal dissipation currents and consequent reduction of power efficiency.

The information gained from post-test data analysis and thruster inspection allowed some improvement to thruster design, in order to minimize thruster internal contamination and self-sputtering. On the basis of current subsystem specifications, the test results provide the means to predict lifetime, total impulse capability and end of life performance (e.g. thrust range and power consumption) of the thruster *as is*. A significant enhancement of the above mentioned features is expected as a result of the planned design upgrades and of optimization of thruster operation modes, based on the lessons learned.

In addition, these tests also provided a validation of Alta's LFF vacuum facility in view of the upcoming lifetime test, to be performed in the frame of the full qualification of the FT-150 FEEP microthruster for Lisa Pathfinder.

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