Endurance Tests of 150 μN FEEP Microthrusters

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Abstract: The FEEP-150 micropropulsion subsystem is presently being developed by Alta for application on CNES Microscope mission as well as in the framework of technology pre-development for ESA LISA Pathfinder and Gaia missions. The subsystem is composed by 150 μN field emission propulsion units (operating on cesium), by thermionic neutralizers and by high voltage power supplies. During 2004 and the first half of 2005, a number of important milestones were achieved, including the first coupled firing test between EM thruster unit and power supply (which allowed to demonstrate subsystem-level dynamic response of more than 200 Hz and thrust noise of less than 0.1 $\mu N^2/Hz$), and two 1,500 hours continuous firing tests (totaling 3,000 hrs on two EM thrusters) which logged a total impulse of more than 600 Ns, with thrust modulated between 0.1 and 225 μN.

I. Introduction

Field Emission Electric Propulsion (FEEP) is a breakthrough technology in ultra-fine pointing and position control. Due to its unique thrust modulation and control features, FEEP is the only viable solution for very demanding missions, such as those for fundamental physics (CNES MICROSCOPE and NASA/ESA LISA) and astronomy (ESA Gaia and Darwin). Due to its compactness and extremely high Isp, FEEP can also be successfully adopted to perform orbital control on microsatellite platforms, and be therefore used for very precise remote sensing missions and formation flying.

Since 2001 Alta has been responsible for the MICROSCOPE micropropulsion subsystem definition and development under ESA contract; since 2002 Alta is also working on similar subsystem elements as technology demonstrators in preparation of ESA LISA Pathfinder mission; since 2003 the pre-development activities were extended under ESA contract to cover the Gaia mission requirements.

Although the various micropropulsion subsystem elements were initially supposed to respond to different requirement specifications, during 2004 ESA and Alta completed a harmonization effort aimed at the consolidation of the various development programmes towards a single highly capable product, fulfilling the needs of the various missions and with growth capability for future applications. The result of this consolidation effort is Alta's FEEP-

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150 subsystem, which modular design allows for application to the full range of European microthrust missions over the next decade.

II. FEEP-150 General Information

Operated on 99.9999% (grade 6N) pure cesium, the FEEP-150 thruster provides a thrust level between 0.1 and 150 µN (nominal, 0.1-200 µN off-design), with a 0.1 µN thrust resolution capability. The specific impulse ranges between 5,000 and 8,000 s, while specific power is in the order of 60 W/mN. The FEEP-150 sub-system is made up by self-contained thruster clusters (EPSAs), each composed by 3 or 4 independent Thruster Assemblies (TA, including thruster unit and propellant tank), two neutralizers (one active + 1 cold redundant) and a common PPCU. With its integrated 76 g (175 g for Gaia) surface tension propellant tank, each TA is capable of delivering a total impulse in excess of 3,500 Ns (8,500 Ns for Gaia). The mass of each EPSA is about 10 kg (1.23 kg for each TA). The subsystem power consumption (including PPCU power dissipation and neutralizer operation) does not exceed 20 W per thruster at maximum thrust.

The FEEP-150 propulsion subsystem is presently being qualified by Alta for CNES Myriade platform under ESA contract, with subcontractors Galileo Avionica (with responsibility for the high voltage power supply and emitter micromachining), Alcatel Alenia Space (with responsibility for the neutralizer), Contraves Space (with responsibility for the sealing and opening mechanism) and EADS Astrium (with responsibility for surface tension tank verification).

Figure 1. The FEEP-150 thruster assembly

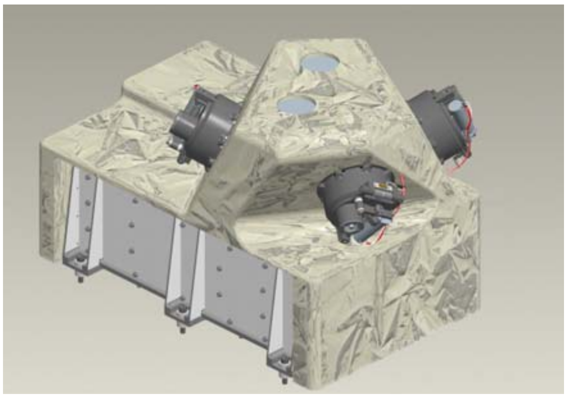


Figure 2. Microscope FEEP-150 EPSA

III. FEEP-150 Development and Qualification Activities

During 2004 and the first half of 2005, several FEEP-150 thruster units and thruster assemblies were tested in various conditions, including environmental, extended firing and integrated tests. The environmental tests (shock and vibration) demonstrated the design compliance with the launch stresses; the extended firing tests demonstrated the performance stability and long term behavior; the integrated (subsystem level) tests demonstrated the end to end performance level.

A. Integrated thruster/power supply tests

In early 2004 various test campaign were performed to assess the coupled static and dynamic behavior of FEEP-150 thruster units and high voltage power supplies manufactured (in the framework of the various parallel programmes) by Galileo Avionica, Alenia Spazio/LABEN and Carlo Gavazzi Space. All the tests showed the dominant effect of the power electronics in the subsystem level dynamic response, and satisfactory thrust stability and overall performance was achieved in all the cases.

The Galileo Avionica power supply (later selected as the baseline unit for the FEEP-150 subsystem) was thoroughly investigated in terms of step response and spectral characteristics. During coupled operation with a FEEP-150 EM unit, the power supply showed a response of less than 5 ms for a commanded step from less than 2 to 125 µN, therefore exhibiting a dynamic bandwidth in excess of 200 Hz. Thrust stability was demonstrated to be better than 0.1 µN over 24 hrs, and the subsystem-level power efficiency was never below 90%.

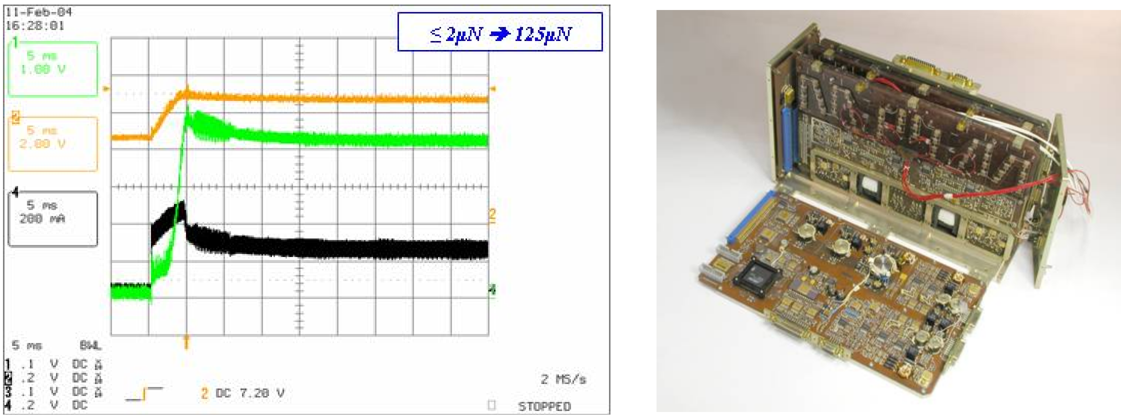


Figure 3. Commanded step response at subsystem level (left) of FEEP-150 unit with Galileo Avionica power supply (right).

B. Extended Firing Tests

From August until October 2004, a FEEP-150 thruster unit underwent a continuous firing test in Alta's IV9 test facility (1.2 m dia., 2.5 m length). The average thrust level during the test was in the order of a few tens of µN (with a large number of thrust modulation cycles), and was progressively increased during the test: for short durations the thrust was pushed to as much as 225 µN. The first extended firing test was continued for over 1,500 hrs, after which the thruster had logged a total of 110 Ns. The test was stopped at the end of October 2004 because of a high voltage cable/connection failure.

A new test was set up and started in January 2005, again in Alta's IV9 test facility. A more demanding test plan was prepared, with the aim of maximizing the delivered total impulse in the shortest possible time: according to the test plan the thruster was continuously fired for up to 200 hrs at the maximum nominal thrust (150 µN), although occasionally the thrust level was pushed for a short duration to 200 µN. Relatively short thrust modulation phases were also performed every few hundred hours. The second extended firing test continued until May 2005, with a total duration of more than 1,650 hrs and a delivered total impulse of more than 500 Ns. A cesium propellant mass of 8.7 g was consumed during the test, equivalent to an average specific impulse of 6060 s. The second extended firing test was stopped in mid-May 2005 because of the total consumption of the propellant contained in the small experimental tank.

At maximum thrust level the accumulation of cesium on the test facility walls was considerable, and firing had to be stopped on a few occasions for 2-4 hours, waiting for a drop in the cesium partial pressure in the vacuum chamber. After about 700 firing hrs the cesium partial pressure started to increase rapidly, signaling a "saturation" condition of the facility walls. Without breaking the vacuum, the thruster was therefore retracted in the IV9 lock chamber which was then sealed from the main chamber by means of a large gate valve. The main chamber was then decontaminated and vacuumed again down to 1e-8 mbar, the lock chamber was reconnected and the thruster was reignited for the rest of the test.

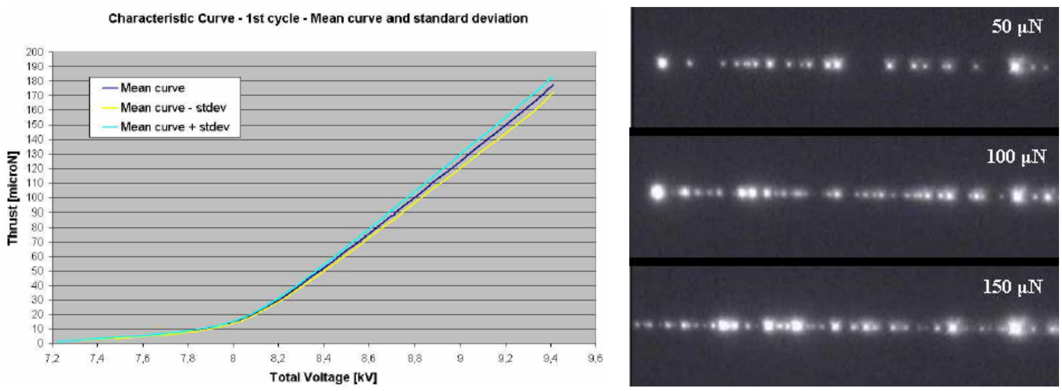


Figure 4. FEEP-150 V-T characteristic curve (left) and slit emission at various thrust levels (right).

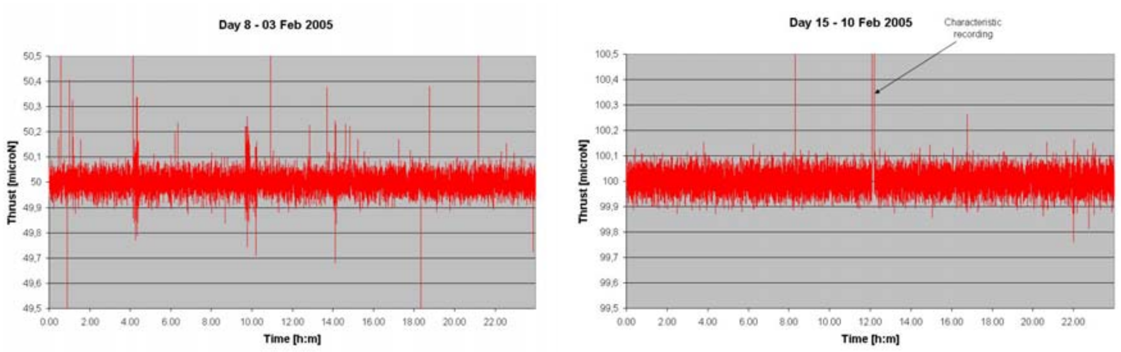


Figure 5. Thrust stability of FEEP-150 at 50 µN (left) and 100 µN (right).

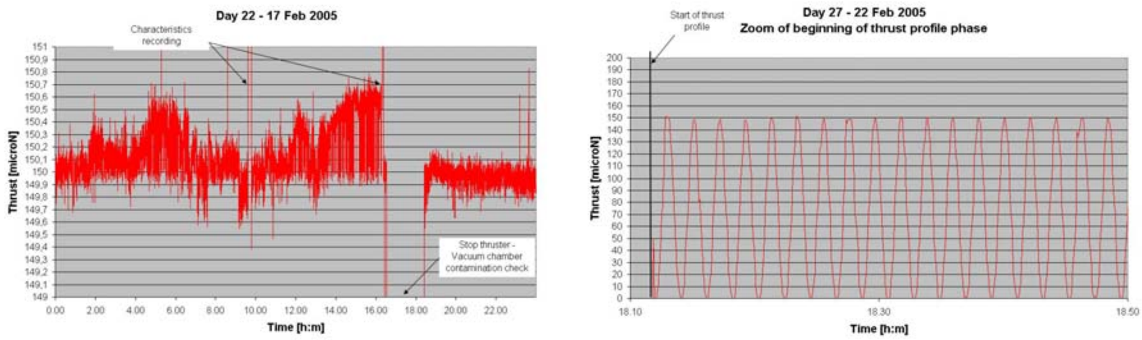


Figure 6. Thrust stability of FEEP-150 at 150 µN (left) and sine-commanded thrust phase (right).

Plume scans were performed at various times during the first and second extended firing tests, in order to verify stability of the plume shape and thrust direction. Good overall repeatability was found, with standard deviation between different measurements always within the error boundaries. Plume measurements could be obtained also at the minimum thrust of 1 µN, therefore showing that ion emission (and therefore thrust generation) indeed occurs even at this low current level (which is quite difficult to explore by means of thrust balance tests).

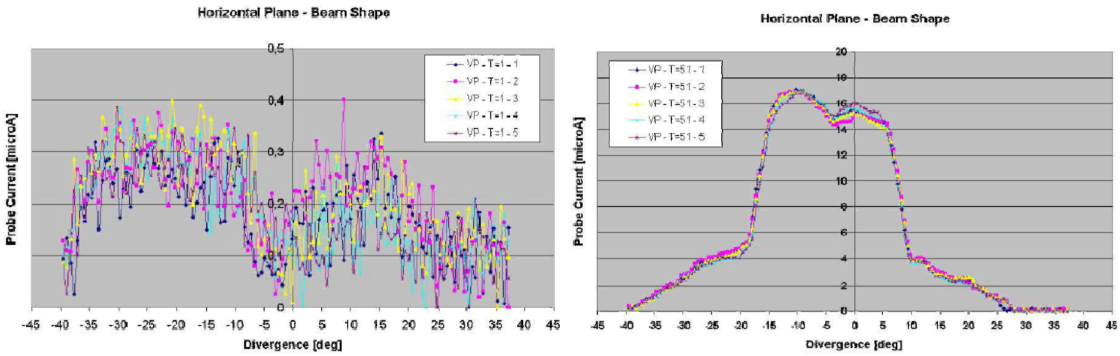


Figure 7. FEEP-150 plume divergence at 1 µN (left) and 50 µN (right).

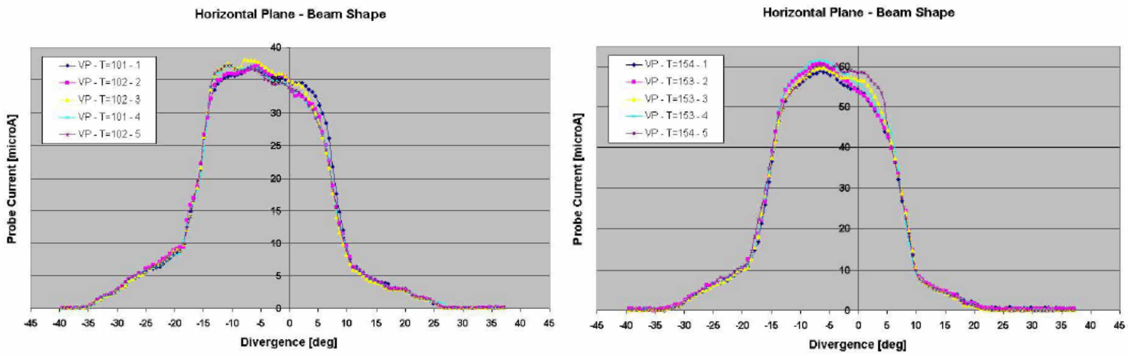
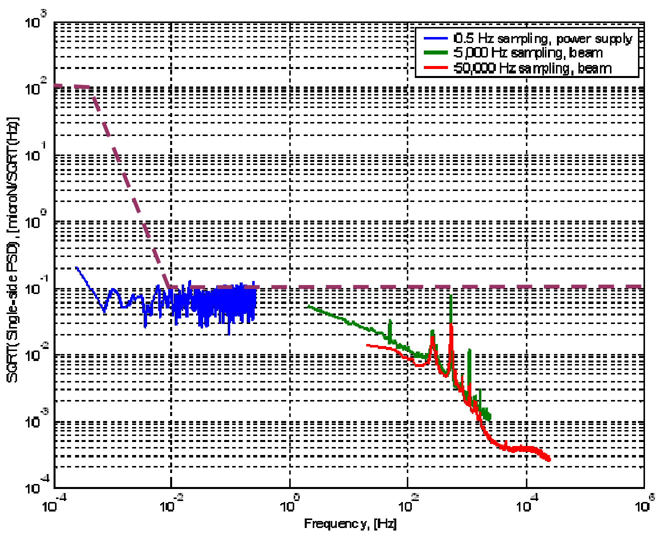


Figure 7. FEEP-150 plume divergence at 100 µN (left) and 150 µN (right).

C. Spectral Characterization

Characterization of the thrust noise spectra was performed over different frequency ranges in order to verify the noise characteristics and check their compliance to Microscope, LISA and Gaia requirements. Indirect thrust noise measurements were performed by acquiring the thruster emitted current both through the power supply (upstream) and beam probes (downstream), although no transfer function assessment could be performed as these measurements could not be performed on overlapping frequency ranges. The compliance to the stated requirements was found to be satisfactory over the full spectral range of interest, and the noise content was verified to fall off significantly at high frequency as expected from analytical solutions.

Comparison of the indirect thrust noise measurement with the open circuit noise of the laboratory power supplies confirmed that most of the low frequency noise contribution is indeed generated by the electronic components of the test setup. Higher frequency peaks in the spectral distribution were verified to be induced by electromagnetic interference from facility turbopumps.



Acknowledgments

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