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ENDURANCE TEST OF THE MICRONEWTON FEEP THRUSTER

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This paper present the experimental setup of the Endurance Test of a Field Emission Electric Propulsion (FEEP) thuster presently underway at the ESTEC Electric Propulsion Laboratory. The setup includes a fully automated 3-D ion beam scanning system to assess the plume current distribution and a triple filament Langmuir probe. The test is aimed at totalling 2000 hours of operation. The criteria behind the test setup are discussed and the experimental arrangement is presented. First operational results are shown.

Introduction

Field Emission Electric Propulsion (FEEP) is currently considered for short and medium term application on scientific spacecraft to perform drag compensation, formation flying and fine pointing or attitude control. Some examples of scientific missions which will need FEEP thrusters to be enable are LISA [1] (Laser Interferometer Space Antenna), GAIA [2], IRSI-DARWIN and GOCE [3] (Gravity and Ocean Circulation Explorer). The use of FEEP thrusters is also being considered as propulsion system for microsatellite platforms. In particular, the application of FEEP is being investigated on the Italian microsatellite platform MITA, developed by Carlo Gavazzi Space, which will be used for scientific and commercial applications.

Many studies and tests have been performed by Centrospazio during the last few years on the FEEP system, which have both defined its operational features and demonstrated its capabilities. Specifically, utilization of this system at the microthrust level could offer great advantages over more traditional systems. Next steps required in the qualification of FEEP thrusters and in the perspective of the envisaged applications are represented by a flight demonstration and by more comprehensive laboratory testing, as an endurance test and a lifetime test.

The possibility of performing such tests emerged from the co-operation between the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). It will be achieved within a Get Away Special (GAS) experiment during a Space Shuttle mission (scheduled for the year 2001), and with an endurance test in the Electric Propulsion Laboratory of the ESA European Space Research and Technology Center (ESTEC).

The endurance test is being carried out on a 5 mm slit FEEP thruster. This slit length and the associated levels of thrust (about 100 μN) and power (about 6 W) were chosen as representative of thrusters to be used on envisaged scientific and commercial missions with lifetime requirements ranging from 6 months to 5 years.

The FEEP Thruster

FEEP (Field Emission Electric Propulsion) is an advanced electrostatic thruster capable of delivering very low thrust with very high accuracy and controllability. The application range of FEEP covers the 1 μN–several mN thrust range. Some of the thruster's main features are:

- Very low thrusting capability (thrust range 0.1 – 2000 μN);
- Ultra-fine thrust modulation capability with high accuracy and resolution; the thrust level is finely tunable allowing linear control, while instantaneous switching capability permits pulsed mode operation (with frequencies up to several kHz);
- Very high specific impulse (I_{sp}= 6000–11000 s);
- Absence of moving parts;
- Simple satellite integration.

The main difference between FEEP and the other

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electrostatic thrusters consists in the fact that the same field that accelerates the ions is the one responsible for the propellant ionization. Furthermore, since a conductive liquid is needed for the field emission, a liquid metal (Cs or Rb) is used as a propellant. This leads to a very simple system, because there is no need of a separate ionization system or a separate feeding system, thus reducing the chances of failure.

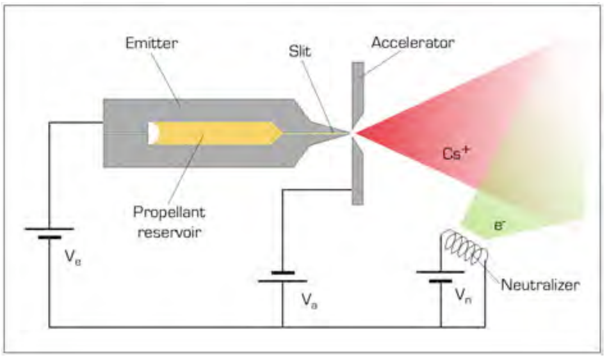

Fig. 1-Schematic representation of the FEEP system

Referring to Fig. 1, V_e - V_a controls the emission process (I_e), thus the thrust level, while V_n regulates the current through the filament, that generates the electron emission because of the joule effect, and thus controls the neutralization process (thermo-ionic neutralizer). The FEEP system includes also a heater, to keep the cesium in liquid form (>28 °C), and a power control unit (PCU), that regulates all the voltages and currents required. The specific power of the FEEP emitter is about 60W/mN, with the atual value depending on the emitter voltage chosen.

Goals of the Endurance Test

The endurance test is the first step for the qualification of a space propulsion system. Operating the thruster for a fraction of its operational life, important information on its overall performance may be extrapolated, as the wear the system may encounter or the stability of the thrust level.

Endurance and lifetime tests on electric propulsion systems have been carried out since the early '60s in Europe, Russia, United States and Japan on different types of thrusters. The methodology can finally be considered as consolidated on ion engines, Hall thrusters and arcjets, and most of it can be applied to field emission thrusters. In general, the experimental approach is driven by consideration of the effects of the ion beam on the vacuum chamber's walls; furthermore, the back-sputtering generated by the ions collisions and the surface contamination caused by the propellant deposition can make it very difficult to maintain ambient conditions that are comparable to the ones encountered during space operation, forcing the thruster to operate in conditions much worse than it's designed for. In addition, in the case of the FEEP thruster, we have to deal with:

- Very low thrust levels (μN level), thus very hard to measure;
- Very high propellant exhaust speed (about100,000 m/s), thus very energized ions;
- Very high operation voltages (up to 10 kV), that must be handled carefully to avoid sparks and leaks.

Hereafter are listed the aspects that are of major concern in the FEEP's performance, and that will be more carefully monitored during and after the test operation.

1. The wear of the FEEP electrodes was not evaluated in detail in the past. All the tests carried out in the past were not long enough to evaluate the degradation of the electrodes, being mainly aimed in the determination of the thruster's characteristics. Theoretically, the FEEP system has a low wear rate. This is because the accelerator erosion, very critical in the gridded ion engines, is negligible because of the particular electrode geometry and ion beam characteristics. Throughout the endurance test it will be possible to analyze more exhaustively this and other wears typical of the thruster.

2. The evaluation of the thruster stability is one of the main goals of the test. More precisely, we will look after the stability of:

- thrust, as a function of the voltage applied, i.e., repeatibility of the V – I characteristics;
- thrust vector direction;
- beam divergence and plasma density.

3. Another main goal, important for the thruster's satellite integration, is the determination of the entity of the surface contamination generated by the liquid metal and the localization of the zones that most likely will be contaminated. This is very important because propellant (in particular metallic propellant) deposition on a generic surface of the satellite can alter its physical properties (like reflection, electrical isolation and so on). More than in other cases, it has to be taken into account that the effective conditions of operation in space are hardly comparable with the ones created on earth, because of the presence of the

chamber's walls that both influence the electromagnetic field and the plasma conditions.

Therefore, the main goal of the test is to prove the performance stability and wear resistance of the FEEP thruster in sight of its imminent space application. The typical missions of interest need several thousand hours of operation at different thrust levels and often cyclically. The endurance test has to be representative of this kind of operation.

Endurance Test Parameters

Test Duration

The classical failure rate dependence on time is shown in Fig. 2. The early failures, occurring between time zero and time T_B, can in general be reduced by quality control and design improvement as they are uncovered by tests. Such failures in an ion thruster include those defects caused by poor workmanship, heater burnout, electrical connection open or short, etc. Time T_B is in the order of 10 to 100 hours; this means that a modest "burn-in" of the engine system should be able to reveal these failure modes. During the time interval between T_B and T_W, the failures are random, being influenced, for example, by the degree of conservatism in the component design, the stress of the components relative to their limit, etc. The objective of system design and quality control is to have enough thruster reliability, so that the system has a high probability to survive these random failure modes for a time significantly greater than the duration of the intended mission. After time T_W wear is the major responsible for system failure and represents in this case the lifetime limitation of the ion propulsion systems.

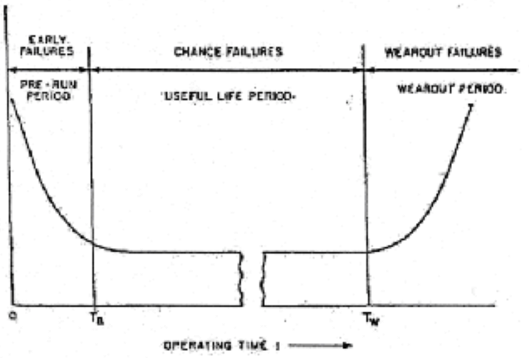

Fig. 2-Typical dependence of component failure rate on operating time.

On the basis of these considerations, the endurance test duration is fixed at 2000 hours, sufficient to extrapolate the wear condition at EOL (End Of Life) and evaluate if it is critical for the thruster operation.

The FEEP Emitter

The thruster is a FEEP emitter developed by Centrospazio. The module in the whole is identical to those tahat will be used on the flight test, except some components optimized specifically for the test on ground. The emitter and the accelerator are identical to the flight model: emitter slit length is 5 mm, resulting in a thrust level in the interval 0.1 – 100 µN.

Test Plan

The endurance test will start with the initial wetting of the emitter slit and initial manual start up of the thruster. When the thruster is fully functional, it will operate at two thrust levels: 50 ∝N and 100 ∝N. These thrust levels will recur every hour and every four hours the thruster will be shut off for 20 minutes, running 500 cycles on/off and 2000 hours of thruster-on time. During these cycles I-V characteristic curves will be measured and the ion beam will be scanned measuring plume geometry, plasma density, thrust vector direction and more.

Operating point at maximum thrust:

Thrust	100 µN
Emitter current	0.5 mA
Emitter voltage	7 kV
Accelerator voltage	-3 kV

Operating point at half thrust:

Thrust	50 µN
Emitter current	0.25 mA
Emitter voltage	6.25 kV
Accelerator voltage	-3 kV

The FEEP thrust is analytically derived according to the following relation:

$$T = 1.67 \cdot 10^{-3} I_e \sqrt{V_e} \frac{\sin\alpha}{\alpha} \frac{\sin\beta}{\beta},$$

that was experimentally validated in ESTEC at the millinewton level.

Experimental Setup

The FEEP microthruster endurance test will be performed in the Vacuum Facility No. 1 in the Electric Propulsion Laboratory of the ESTEC at

Noordwijk, the Netehrlands. This chamber is already equipped with a set of vacuum pumps able to simulate the space conditions for the test, also during thruster firing. In particular, the facility features two cryopumps that assure redundancy in the maintenance of the high vacuum necessary for the FEEP operation. Although the FEEP thruster has been operated successfully at 10^{-3} mbar an more, it was decided to perform the endurance test at a background pressure not exceeding 10^{-5} mbar, to reproduce the conditions that are likely to be enciuntered in most space missions in LEO.

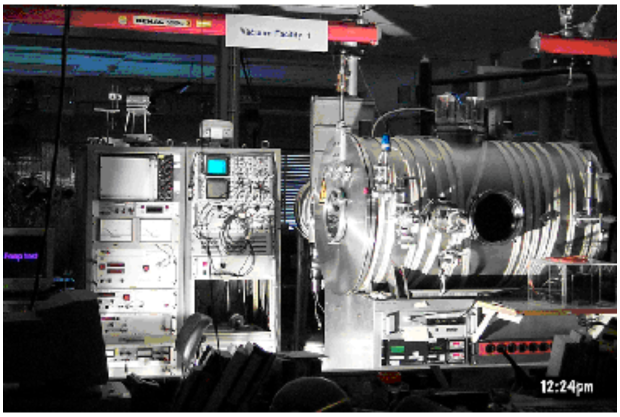

Fig. 3 - Vacuum facility No. 1 at ESTEC EP Lab.

This facility consists of a cylindrical, stainless steel vessel of 0.8 m of diameter, 1.3 m of length, thus a volume of 0.65 m^3. The pumping system includes:

- fore-pump, Leybold Heraeus (40 m^3/h);
- roots-pump, Leybold Heraeus (150 m^3/h);
- turbo-pump, Leybold Heraeus (450 l/s);
- two cryo-pumps, Balzers (3200 l/s and 6500 l/s respectively).

The rough vacuum is obtained with the fore-pump and the roots-pump. These pumps can reduce chamber pressure from atmospheric pressure to 10^{-3} mbar in about 15 minutes. The high vacuum is obtained with the turbo-pump and the cryo-pumps. To enhance the final vacuum, the vacuum chamber can be out-gassed at about 100° C. Presently, the vacuum level obtained is in the order of 10^{-9} mbar. Both the turbo-pump and the cryo-pumps are rigidly attached to the vacuum chamber and the chamber/pump assembly is mounted on thick rubber pads. Furthermore, there is a beam target (aluminum honeycomb structure) on the end of the chamber that can be cooled with liquid nitrogen.

The facility was recently internally covered with Grafoil®, drastically reducing back-sputtering and electron secondary emission, and several new low voltage and high voltage feedthroughs were added. All the valves, pumps, pressure and temperature sensors had to be interfaced with the system controller to operate the facility autonomously via a LabVIEW® program.

The experimental platform was designed in order to integrate with the existing guides that allow it to be mounted in the chamber using a moving structure. The platform includes:

- the thruster module;
- two thermionic neutralizers;
- the feeding system;
- the heaters for the thruster and for the propellant feeding system;
- the diagnostic equipment.

The diagnostic equipment includes:

- two passive electrostatic probes and a triple probe, mounted on an aluminum structure coated with Grafoil® sheets (99% carbon) in order to reduce backsputtering and secondary electron emission;
- a photovoltaic cell, to evaluate its eventual performance degradation because of the propellant contamination;
- Quartz Crystal Microbalances (QCM) to monitor the amount of material back sputtered in the direction of the thruster by the chamber walls and the ion beam collector.

The structure is capable of moving the two wire probes perpendicular to each other on a plane orthogonal to the thrust direction while it moves them long the thrust vector direction together with the triple probe. Two neutralizers are provided to guarantee redundancy in case of failure; however, the test is not intended to qualify the neutralizer. Fig. 4 shows a representation of the designed experimental platform, rendered directly from the mechanical drawings of the parts.

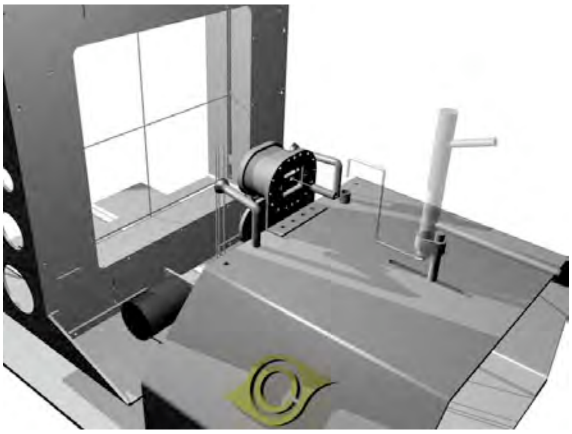

Fig. 4 - Schematics of the experimental platform designed for the FEEP endurance test.

The amount of propellant required by a 2000-hour endurance test of a 100 µN FEEP may be calculated from experimental data obtained by measuring the total mass of cesium emitted per unit time (propellant flow rate). As a first estimate, we can calculate an upper bound to the total quantity of propellant required assuming that the thruster fires at T = 100 µN for the half duration of the experiment and at 50 µN for other half. Assuming an average specific impulse I_{sp} = 8000 s, we have for the 50 µN level:

$$\dot{m} = \frac{T}{g_0 I_{sp}} = \frac{5 \cdot 10^{-5} N}{9.8 ms^{-2} \cdot 8 \cdot 10^{3} s} = 6.4 \cdot 10^{-10}\, kg/s$$

where $\dot{m}$ is the mass flow rate and g_0 is the standard gravity acceleration. The propellant flow rate at a thrust level of 100 µN is calculated to be $1.3 \cdot 10^{-6}$ g/s. Considering 500 cycles of 4 hours each, two at 100 µN and two at 50 µN, yielding a firing time $3.6 \cdot 10^{6}$ s each, the propellant needed is found to be 7.4 g (4.8 g + 2.6 g). Allowing for some margin, a 10 g cesium ampoule is enough for the whole test. This amount of cesium still fits in the existing feeding system, hence it can by used with no substantial modification for test.

Fig. 5 is a view of the FEEP thruster configuration.

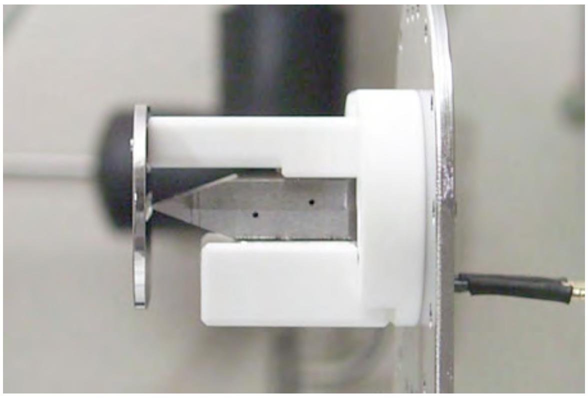

Fig. 5 - The FEEP emitter used in the test

The thruster will be operated with the present standard laboratory power supplies, controlled by the system controller via GPIB interface. These are principally a *FuG HCN 1400 – 20000*, 0 – 20 kV, 0 – 60 mA, used for the emitter, and a *FuG HCN 35 – 20000*, 0 – 20 kV, 0 – 1.5 mA, used for the accelerator. The neutralizers use power supplies built by Centrospazio, while standard power supplies are used for the remaining needs (emitter heater, feeding system heater, etc.).

The Diagnostics System

The principal requirements on the diagnostics can be summarized as:

- possibility to move the electrostatic probes on a plane orthogonal to the ion beam's axis and orthogonal to themselves, and simultaneously to move the scanning plane long the beam;
- precise definition of the position of the probes in any moment, without the possibility of slipping or loss of position;
- possibility to repeat the measurements as many times as needed in an identical way.

The main problem of motion in ultra high vacuum applications is the high friction due to the absence of air. Furthermore, the impossibility to use most of the common materials used in these applications (as lubricants or plastic parts) because of their high outgassing, makes it even more complicated. In addition, the electric motors have to be carefully dimensioned to avoid overheating; the absence of air nulls the convective heat transfer, addressing all the thermal power to the conductive transfer.

Shielding of the lubricated transmission chains from the highly energized ion beam is another critical task. The cesium ion beam can substantially erode the components of the diagnostic structure, crucial for the motion of the probes, if direct impingement is not avoided.

The diagnostic system was designed considering the requirements and taking into account the difficulties illustrated above. It followed that all the solutions that implicated high friction were excluded (as sliding) by adopting spherical bearings for ultra high vacuum applications. For the positioning of the passive probes on the scanning plane, four precision chains ISO 04-1 lubricated with a ultra high vacuum lubricant (vapour pressure at 20 °C > 10^{-12} mbar, 10^{-8} at 150 °C) were used, kept in tension by four ¼ inch steel shafts. Two stepper motors power the shafts through a bellows coupling (Fig. 6).

For the motion of the structure, a rack and pinion solution was adopted because of its low friction, good precision and perfect repeatability (Fig. 7). The structure slides on four bearing (the same used for the shafts) over two Teflon guides, which is characterized by a low friction coefficient and is suitable for vacuum applications. Most of the structure is made out of aluminum 6061, because of its low sputtering yield and low weight; in fact, the structure has both a structural function and a shielding function, of the transmission parts against the impinging ions. The passive electrostatic probes are mounted on Teflon blocks, to guarantee electric isolation against the structure, while the triple probe is mounted on a rotating aluminum cylinder.

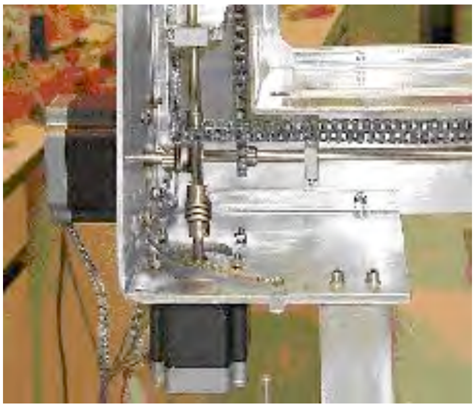

Fig. 6 - Close view of the chains and stepper motors

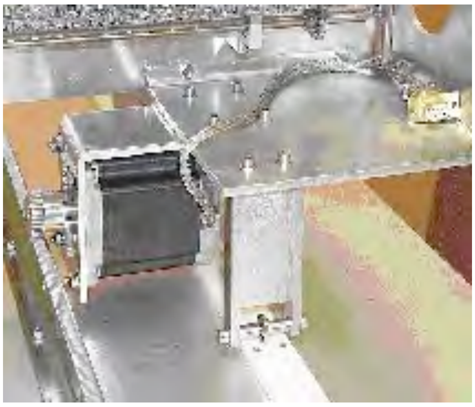

Fig. 7 - Close view of the rack and pinion, and the bearings over the Teflon guides.

Fig. 8 shows a picture of the experimental platform inside the vacuum chamber.

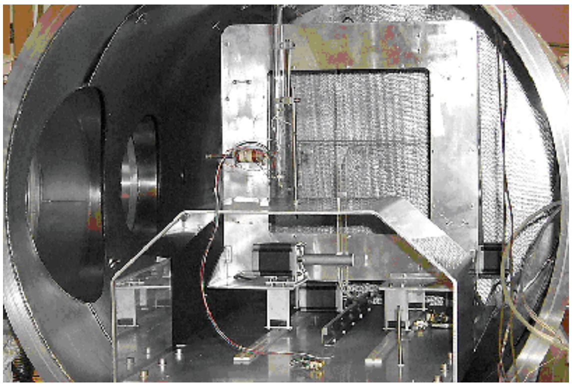

Fig. 8 - The experimental platform of the FEEP endurance test.

Data Acquisition and Control System

Since it will not be possible for Centrospazio personnel to attend the test for its whole duration, an adequate control equipment must be provided for the test to operate autonomously. A remotely controlled system was developed to perform data acquisition and to monitor and control the experiment from Centrospazio premises in Italy. The system is composed of the following parts:

- Data Acquisition Section (DAS) capable of monitoring 32 low voltage & 16 high gain / high isolation channels with a nominal sample rate of 0.1 - 1 kHz on each channel.
- Digital Output Section (DOS) capable of controlling 32 digital I/O channels.
- Diagnostic Processing Section (DPS) capable of performing simple emergency tasks and routine actions, triggered by acquired data.
- Remote Control Section (RCS), for full remote control and emergency operation, via an Internet connection to Centrospazio.

The Data Acquisition Section is based on a National Instruments PXI-8156 running the Windows NT operating system, equipped with a data acquisition module (National Instruments PXI-6030E), a motion controller (National Instruments PXI-7324), a Ethernet interface (National Instruments PXI-8210) and a GPIB interface. The data acquisition module acquires the signals through two signal conditioning boards and controls the DOS. The system is programmed using the National Instruments LabVIEW™ platform.

The DOS is interfaced to the Diagnostic Processing module, which executes pre-determined actions on the occurrence of certain conditions on input channels. The Diagnostic Processing Section processes acquired data in real-time, executing pre-programmed actions at pre-determined times and performing simple emergency tasks. In the event of failure in absence of a human operator at the local or remote system, the DPS is capable of operating in such a way to minimize damage. The control is performed on a sub-set of the input channels. The occurrence of pre-determined conditions triggers alarms on the local and the remote system. The Remote Control Section allows the remote operator to control and act on the local system as if he was present. RCS is implemented as an Internet Protocol application, taking full advantage of modern telecommunication technologies. A direct Internet connection is available at both the experiment and the remote control locations. A schematic drawing of the system is shown in Fig. 9.

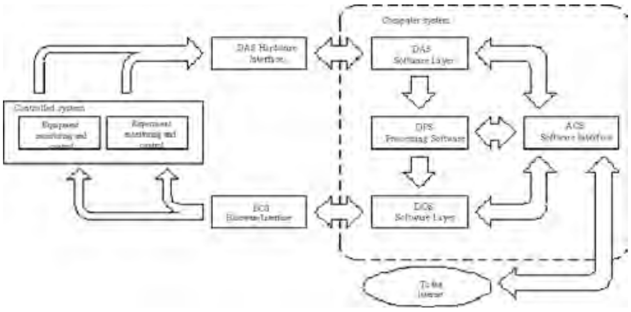

Fig. 9 - DACS block diagram.

The experimental set-up and the test procedure is designed in accordance with a fail-safe philosophy. A permanent check of 8 selected parameters is included in the monitoring system, so that any value in excess of the assigned levels will immediately start an alarm warning. If a major failure occurs, the FEEP microthruster endurance test will be interrupted, waiting for the intervention of an human operator at the local or remote control system. The following failure possibilities can be considered:

- A thruster parameter exceeds specifications:

In this case the DACS will switch off the thruster, the feeding system and the emitter heater power supplies and trigger alarms on the local and the remote control system.

- Cryo-pump temperature increases beyond a critical value:

The DACS will switch the cryo-pump off and will close the relevant gate valve. In this case thruster operation will continue, as the required vacuum level can be maintained even by only one cryo-pump. A rough pumping system will regenerate the saturated cryo-pump.

- Vacuum chamber pressure exceeds its upper limitation:

The DACS will switch off the thruster, will close the two cryo-pump gate valves and will vent the chamber with nitrogen in order to prevent the cesium contamination.

- Computer failure:

The DACS will send a change-of-state signal every 15 seconds to an electronic timer. In the event of a computer failure, the timer will activate a series of relays to turn off the thruster power supplies and trigger alarms.

Experimental Data

Before performing the endurance test of the FEEP thruster, it was considered useful carrying out a qualification test of the whole experiment equipment in order to verify the correct operation of the diagnostic and control system. The test equipment operations to be checked by simulating the experiment condition are as follows:

- Control of the vacuum chamber pumps, temperature and pressure sensors;
- Control of high voltage and low voltage power supplies,
- Movement and position control of the diagnostic structure;
- Acquisition of data coming from FEEP thruster, diagnostic structures, temperatures and pressure sensors, power supplies and facility pumping system.

This qualification tests was carried out on a laboratory FEEP thruster with an emitter slit length of 10 mm, capable of delivering 200 ∝N of nominal thrust (fig. 10). The propellant used was cesium.

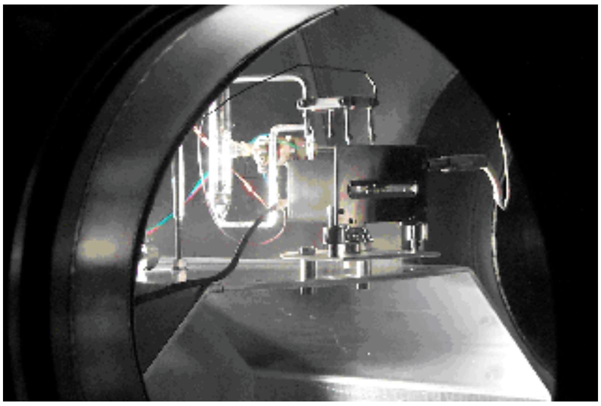

Fig. 10 - Laboratory FEEP thruster during the qualification test

This test lasted three months and during this span of time the test equipment was checked accurately and, when needed, calibrated. The new diagnostic system functioned correctly from the beginning and a certain quantity of data coming from ion beam scans and measurements were collected. These data are important because new information about the functioning features of a laboratory thruster were obtained and, furthermore, they gave the possibility to make a comparison with those acquired in the endurance test. After that, the chamber was opened, the diagnostic equipment was dismounted and an accurate checking and cleaning of the parts were accomplished. No evidence of damages was found, so the equipment was mounted again inside the vacuum chamber.

The Endurance Test

As of writing, the endurance test is underway and only a part of data has been processed and analyzed. However this first set of data is significant and representative of the FEEP thruster operation and characteristics.

The results presented hereafter are referred to the initial operation of the FEEP thruster, that is to say the starting phase of the endurance test, and a time of overall 8 hours of thruster operation was taken as example of this first part of the endurance test execution. During this time the test plan has not been taken in consideration because the start up of the thruster occurred manually and only after checking the full functionality of the thruster the test plan path will be followed.

After switching on, the procedure of acquisition of the main emitting features of the thruster was started. The operation of the thruster resulted excellent since the start up: a complete and immediate wetting of the emitter slit was noticed along with complete absence of sparks or glows on the electrodes. The analysis of the first emitting data revealed a small difference between the thrust vs emitter voltage curve of the thruster taken as referenceand the endurance test thruster, so the operating point figures reported in the above mentioned paragraph were slightly changed to meet the new emitting features, as it will be shown subsequently.

The chosen reference operation time (8 hours) is the sum of two sub-periods, each one characterized by a set of thruster parameters and illustrative of a particular FEEP operating points. The operating points were selected on the base of the test plan thrust levels (50 and 100 ∝N).

The main parameters of the two operating points are as follows:

- First Operating Point

- Thrust	96.7	μN
- Emitter Voltage	9.0	kV
- Accelerator Voltage	-2.0	kV
- Emitter Current	0.687	mA

- Second Operating Point

- Thrust	46.9	μN
- Emitter Voltage	6.6	kV
- Accelerator Voltage	-3.5	kV
- Emitter Current	0.388	mA

and the time elapsed by the FEEP thruster in each operating condition is:

▪ First Operating Point	5 hours
▪ Second Operating Points	3 hours

At the end of each period, the thruster was shut off for some minutes, then switched on again and positioned in the corresponding operating point parameters. In this way the response of the thruster to on/off cycles was checked, too. This response was very satisfactory; in fact each time the voltage was applied, the thruster started emitting immediately and no transient was recorded.

The data recorded during the thruster operation are divided in two sections, for each of the operating points. The main performance parameters that will be analyzed hereafter are:

- Thrust (T), calculated analytically according to (3.1)
- Emitter Current (Ie)
- Accelerator Current/Emitter Current Ratio (Ia/Ie).

The emitter current is important because the thrust is proportional to it, so the stability of this parameter affects strongly the stability of the FEEP thrust. The accelerator current /emitter current ratio gives evidence of the efficient operation of the thruster, in fact the accelerator current is a negative effect in a FEEP thruster, that is to say a loss, so its value should be as small as possible. A ratio below 15 – 10% indicates an efficient operation of the thruster.

First Operating Point

The thrust, emitter current and accelerator current/emitter current ratio vs time curves are shown in figures 11 to 13.

The emitter current curve is very flat, apart from random small deviations from the mean current value. This noise can be evaluated calculating the maximum superior (DIu) and inferior (DId) deviation respect to the mean value. According to the following equations:

$$DIu = \frac{Ie\max - Iem}{Iem} \cdot 100$$

$$DId = \frac{Iem - Ie\min}{Iem} \cdot 100$$

where:

Iemax: maximum value of the emitter current
Iem: mean value of the emitter current
Iemin: minimum value of the emitter current

The results are:

- DIu = 1.1 %
- DId = 1.3 %

This emitter current variations affect the thrust and the corresponding maximum superior (DTu) and inferior (DTd) thrust deviation respect to the thrust mean value are:

- DTu = 2.8 %
- DTd = 2.4 %

As regards the accelerator current-emitter current ratio, its value is constantly lower than 13% and it shows a stability point at 9% after 1.5 hour of thruster operation.

Second Operating Point

The thrust, emitter current and accelerator current/emitter current ratio vs time curves are shown in figures 14 to 16.
The emitter current curve shows a almost constant value. The per cent deviation value respect the mean current, using the same notations as before, are:

- DIu = 0.5 %
- DId = 1.0 %

The corresponding thrust deviations are:

- DTu = 5.3 %
- DTd = 2.3%

During this phase of thruster operation a slightly high value of DTu and of accelerator current/emitter current ratio (about 17.5 %) were recorded.

Conclusions

The FEEP thruster endurance test setup has been validated with a series of tests. The test equipment is performing nominally, as shown by the first data analyzed. The test is underway and the envisaged goal of 2000 hours is likely to be achievable.

Acknowledgments

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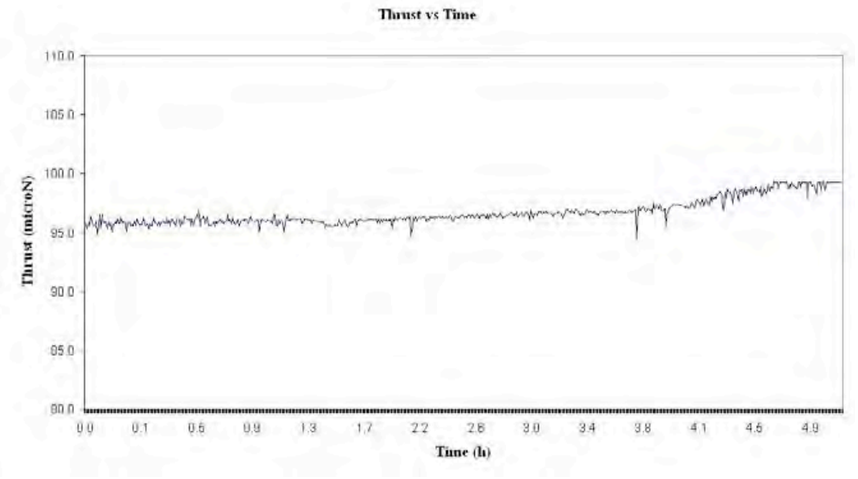

Fig. 11 -Thrust vs. time (1)

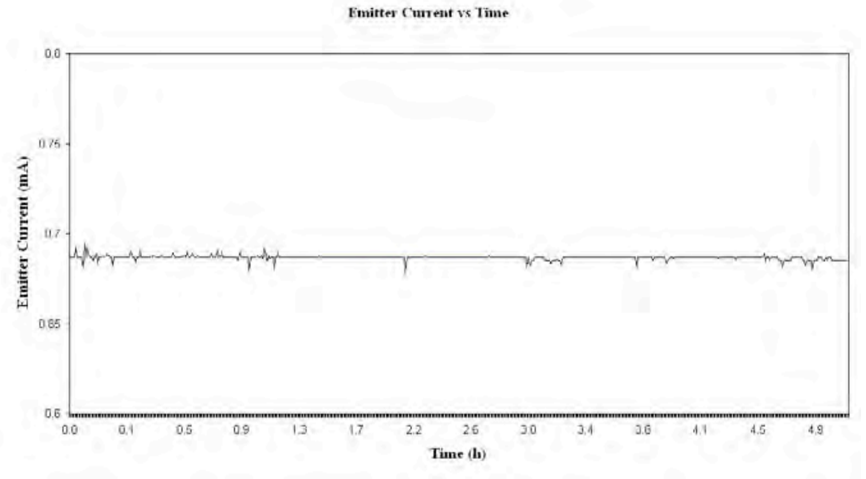

Fig. 12 -Ie vs. time (1)

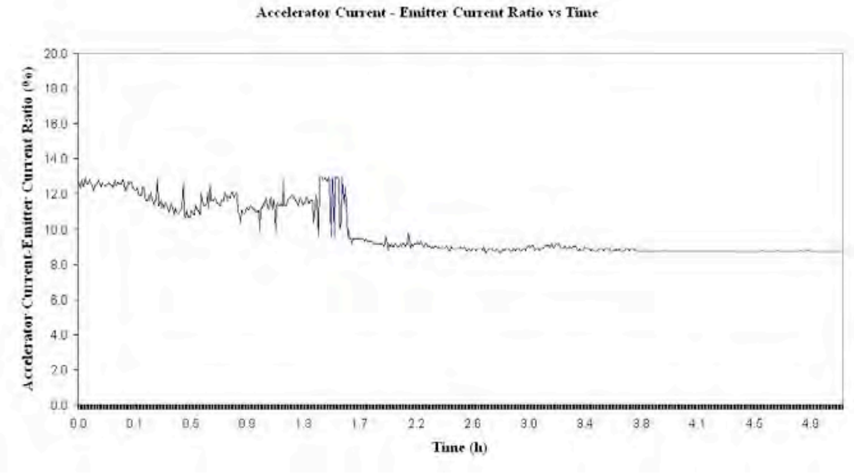

Fig. 13 -Current ratio vs. time (1)

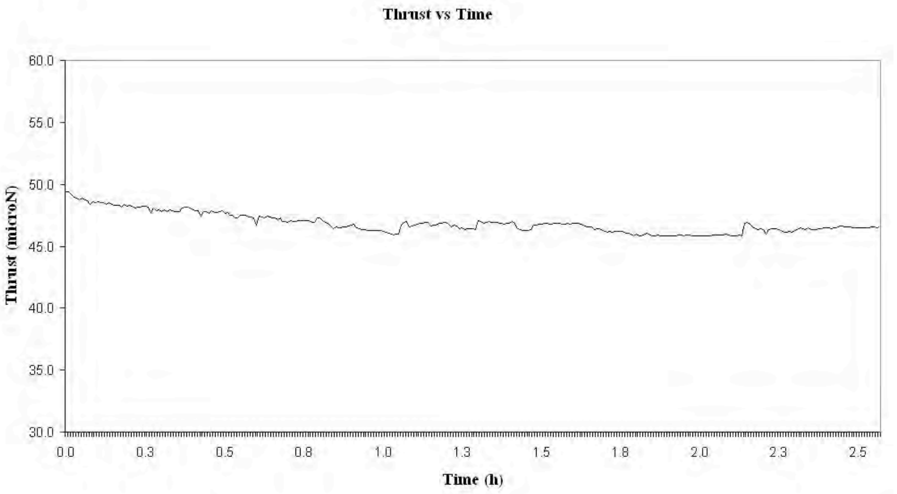

Fig. 14 -Thrust vs. time (2)

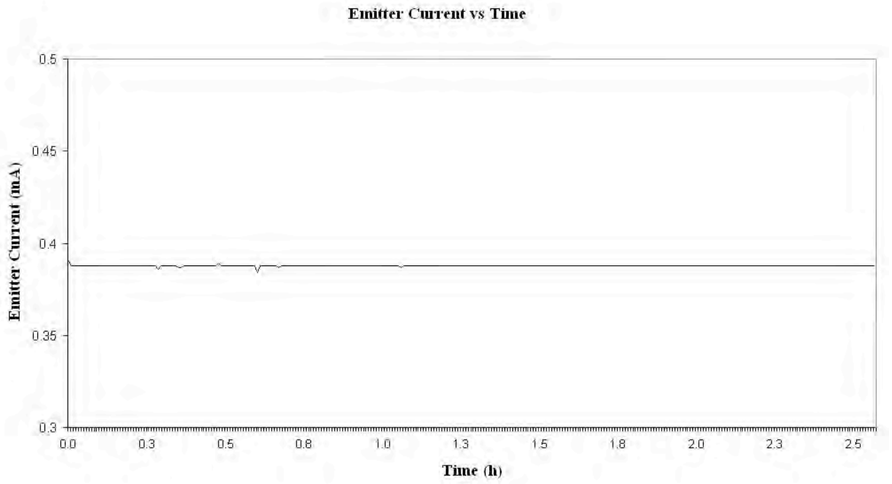

Fig. 15 -Ie vs. time (2)

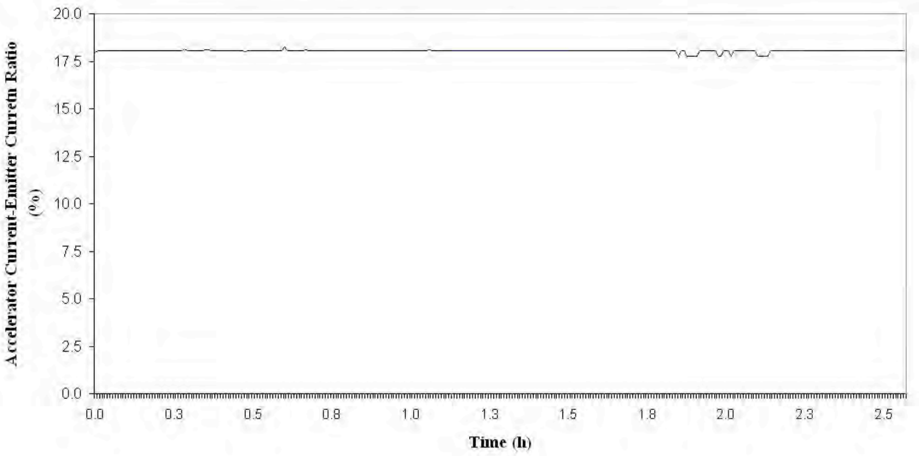

Fig. 16 -Current ratio vs. time (2)