Field Emission Electric Propulsion: Experimental Investigations on Microthrust FEEP Thrusters

J. Gonzalez *, G. Saccoccia *, H. von Rohden
ESA/ESTEC, Noordwijk, The Netherlands

The recent interest of several scientific missions on the micro thrust FEEP capabilities for "fine attitude control" has changed the orientation of the FEEP development activities from the milli-Newton towards the micro-Newton operation range. In order to obtain a FEEP system ready to fulfill the requirements of this kind of missions, the ESTEC Electric Propulsion Test Laboratory has carried out several performance tests to identify the best FEEP emitter geometry working in the micro-Newton range. Taking into consideration the requirements of these scientific missions interested in the micro-Newton FEEP system, the main operation drivers have been identified and thus the relevant electric parameters trends have been studied. A complete electric characterization of the emitting units and the analysis of the results are presented in this paper. Points of enhancement in the micro-thrust FEEP system operation and future activities in this direction at the ESTEC Electric Propulsion Test Laboratory are also highlighted.

Introduction

Liquid metal FEEP research has been carried out by ESA since 1972; the thruster has evolved from a single pin emitter configuration in 1972, through linear arrays of stacked needles in 1975, to the high efficiency solid slit emitter in 1979. During the past phases of the development programme all the components of the system have been designed and tested, and the emitter manufacture problems have been solved. At that moment, development had entered the industrialization phase, and research was devoted to the testing of the whole system in view of an application in the milli-Newton range.

At this point, the international scientific community interest on "Gravity Wave Missions" highlighted the concept of "ultra fine position keeping" requiring thrusts in the range 0.5+100 μN, which could only be fulfilled by the FEEP system operating in the micro-Newton range.

As main exponent of this interest, JPL and European scientists are currently working on SAGITTARIUS (Space-borne Astronomical Gravity-wave Interferometer for Testing Aspects of Relativity and Investigating Unknown Sources) mission which has been presented to NASA and ESA in parallel during this year. The SAGITTARIUS mission team has confirmed the FEEP thrusters as the base-line attitude and reaction control system for this mission.

Mission designer of other scientific missions like LAGOS, OGRE, STEP, LARF# are also interested in the micro-Newton FEEP operation capabilities. Therefore, in order to obtain a FEEP system ready to fulfill the requirements of this kind of missions in the micro-Newton range, the FEEP activities under the ESA Technical Research Programme have been reoriented. As part of these activities the ESTEC Electric Propulsion Test Laboratory has carried out performance tests on several emitters with different slit lengths (1, 5, 10 mm) to identify the best FEEP emitter geometry for the micro-thrust operation.

In all the three sets of tests, the electric parameters have been measured in order to obtain a complete characterization of the electric performance of the unit (such as voltage-current characteristics) and to calculate most of its propulsive performance parameters (such as thrust, specific impulse and specific power). Based on the analysis of these results a slit length emitter has been chosen.

Main experimental goals: the FEEP thruster

The physical principle underlying FEEP thrusters is the so-called "field effect". Under a strong electric field, the surface of a liquid metal distorts itself, creating a series of protruding cusps; the local electric field on the tip becomes larger and larger as the radius of curvature of the cusps decreases. When the electric field has a value around $10^{10}$ V/m, the atoms of the tip are ionized and accelerated by the same electric field, while electrons are rejected in the bulk of the liquid. The particles extracted are replaced by the hydrodynamic flow.

The FEEP system comprises a thruster, a neutralizer, a propellant feeding system and a power control unit.

Fig. 1 shows the thruster arrangement with the electrodes used to create the strong electric field: emitter and accelerator. Photograph and schematic of the microthrust FEEP emitter are shown in Fig. 2. The emitter halves are separated by a thin sputter-deposited Ni layer; when clamped together, the halves form a narrow slit, of elongated elliptical, near rectangular shape.

* Staff Member Electric Propulsion Unit, Technical Directorate
* Member AIAA
done on three emitters with different slit length: 1, 5 and 10 mm. The slit width was fixed at 1.2 μm and a continuous mode of operation with thrust levels of 1, 10 and 25 μN was set for each emitter.

Experimental setup

The testing of the FEEP thrusters was performed in the vacuum facility number 1 of the ESTEC Electric Propulsion Test Laboratory. This facility consists of a cylindrical, stainless steel vessel of 0.8 m of diameter, 1.3 m of length and a volume of 0.65 m³. Fig. 3 shows a photograph of the chamber.

Within the chamber, there is an Aluminium honeycomb collector which acts as a getter for the ion beam. The getter effect is further enhanced by the fact that the collector is mounted on a liquid nitrogen (LN₂) cold shroud which freezes the emitted Cs propellant onto the collector. The LN₂ cold shroud is maintained at 80 K.

The pumping system of the vacuum chamber ensures a low background pressure (=10⁻⁹ mbar).

The pumping system consists of:
- fore-pump, Leybold Heraeus (40 m³/h)
- roots-pump, Leybold Heraeus (150 m³/h)
- turbo-pump, Leybold Heraeus (450 l/s)
- cryo-pump, Balzers (5500 l/s).

The first vacuum is obtained with the fore-pump and the roots-pump. These pumps can reduce chamber pressure from atmospheric pressure to 10⁻⁸ mbar in about 30 minutes.

The high vacuum is obtained with the turbo-pump and the cryo-pump. To enhance the final vacuum, the vacuum chamber can be outgassed at =100 °C. Presently, the vacuum level obtained is of =10⁻⁹ mbar.

Both the turbo-pump and cryo-pump are rigidly attached to the vacuum chamber and the chamber/pump assembly is mounted on thick rubber pads.

Fig. 4 shows the experimental set-up inside the chamber.
An electron shield is used to protect the emitter against electron back-bombardment. Apart from the accelerator itself, the shield consists of two lateral plates and a top and bottom plate. These plates, like the accelerator, are made of Al and are directly, without insulation, bolted onto the accelerator. Thus if the accelerator is on high tension, the whole shield is on high tension.

An external reservoir connected to the emitter via a small capillary of several cm long and 0.5 mm inner diameter is placed between the feeding system and the emitter module. Fig. 5 shows the experimental feeding system employed which consists of a rotating syphon containing a sealed ampoule with Cs. The main body of the syphon and its capillary terminal part are temperature controlled. This allows for the heating of the Cs to 30-40°C. The ampoule is opened by a seal breaker and the liquid Cs is allowed to flow in the capillary terminal part. The Cs is pressure-fed, by spectroscopically pure Argon into the external reservoir.

A power and control system (PCU) provides the power needed for the operation of the emitter accelerator, grid, heaters and ensures the good operation via measurements on emitter current, accelerator current, and several temperatures. The adjustment of the operational parameters such as emitter and accelerator voltage over the full operational range is also provided by the power and control system.

In order to measure the operation parameters of the FEEP several diagnostic devices have been placed in the chamber. Most measurements can be done with standard laboratory equipment:

- Most of the voltage and currents can be directly read from their respective power supplies. As an exception, emitter voltage is obtained via a separate electrostatic voltmeter because the reading on the emitter power supply is influenced by the high ohmic resistor (arc protection) in the power feed line.

- Since the collector is at ground potential, no separate power supply is needed. The collector current is measured by simple mA-meter in the ground line.

- Emitter temperature is measured from a Copper/Constantan (T-type) thermocouple connected to a mV-meter. Via standard tables the emitter temperature can then be determined.

- Thrust and mass flow rate can be measured simultaneously with a microbalance sketched in Fig. 6. This double beam electro-mechanical micro-balance consists basically of two balance beams each with a torsion wire suspension. The thrust balance which supports the mass flow balance is suspended on vertical wire while the mass flow balance is suspended on a horizontal wire. The emitter is mounted on one side of the mass flow balance and is counter-balanced by weight at the other end. On each beam a differential plate capacitor is used to sense balance movement. Beam position is recorded on a chart recorder by utilizing a capacitor output.

- Beam profile is measured with two wire probes, one horizontal and one vertical. The horizontal probe provides information on the beam distribution around the horizontal...
plane containing the emitter. The vertical probe which translate in front of the emitter, parallel to the slit, gives the emission profile along the slit.  

Test Procedure  
To prevent any obstruction of the slit by dust particles, the emitter is cleaned carefully before being assembled with the accelerator electrode. Then the emitter is placed inside the chamber and the electric wires are connected. Once the desired pressure is reached inside the vacuum chamber, the bake-out phase starts. In this phase the emitter body temperature is raised to 350°C in order to outgas the various substances that may have been absorbed by the inner surfaces of the two halves of the emitter body. After the maximum temperature has been reached, the emitter is allowed to cool down to about 30°C, slightly above the melting point of Cs. At this moment the unit is moved to a position in which the funnel underneath the nozzle of the feeding system. Liquid Cs is then fed to the emitter reservoir. At this point the emitter is moved again to its fully forward position and is ready for its operation. Upon the application of suitable voltage difference above a threshold value, the emission of Cs ions begins and after some minutes a steady emission is achieved. During the operation of the thruster, it is necessary to keep the temperature of the emitter body between the melting point of Cs (28.4°C) and 40°C in order to minimize the propellant losses by evaporation and avoid the forming of an electric arc between the two electrodes.

Experimental Results and Discussion  
The new re-orientation of the FEEP activities has been based on the scientific missions interest in the microthrust operation capabilities of the FEEP system for fine attitude control. Therefore all the current activities on FEEP have as main goal to achieve a FEEP system ready to fulfil the requirements of this kind of missions.  
Within these scientific missions, the SAGITTARIUS mission has been identified as the most likely mission to be accepted in the near future and thus its requirements have been taken as main guide for the current development of the new activities. The SAGITTARIUS mission drivers of low thrust (1+50 pN) in continuous mode, high accuracy and long life-time, rise the FEEP thruster controllability and lifetime requirements for this mission. These tests, performed, on three emitters with different slit lengths (1, 5, 10 mm) and 1.2 μm slit width, had as main goal the selection of the optimum slit length of FEEP emitters operating in the micro-thrust range 1+50 μN.

Test on 1 mm Slit Length Emitter  
Performance tests in continuous mode on the 1 mm slit length and 1.2 μm slit width emitter were performed varying the emitter voltage for different accelerator voltage. Fig. 7 shows the emitter current versus emitter voltage for different accelerator voltage in two different sets of tests to demonstrate the repeatability.
The thrust level was obtained indirectly from the mathematical equation 1:

\[ F = 1.67 \times 10^4 \times I_e \times (V_e)^{1/2} \sin A/A \times \sin B/B \]  

(1)

where \( I_e \) and \( V_e \) are the emitter current and voltage, and \( A \) and \( B \) the vertical and horizontal divergence angles.

The experimental microbalance can measure with good reliability only over 50 \( \mu \)N.

Fig. 10 to 14 shows the emission distribution in the horizontal plane taken by the vertical probe located in front of the emitter for several accelerator voltage. An improvement of the performance with the decrease of the accelerator voltage in absolute value is observed. This is due to the increment of the beam divergence with the increment of the accelerator voltage in absolute value because of the higher attraction of the slow positive ions towards a higher negative electrode. This effect can be seen in the Fig. 15 to 19 which show the vertical divergence of the ion beam measured with the horizontal probe.

Therefore the use of a lower accelerator voltage in this thrust range for this small slit length emitters is needed.

Although a steady current was achieved in the beginning of the test, there was a growth in the Cs deposit on the accelerator due to the divergence of the beam when increasing the accelerator voltage. Even in the case of low accelerator voltage the divergence is high enough to have Cs deposit in the accelerator which has induced sparks between the two electrodes. We suspect that the Cs exceeds the slit borders and is ionized outside the slit, increasing the divergence and therefore the Cs deposit on the accelerator.

Besides a blue glow between the emitter and the shield took place due to ionization of neutral particles “captured” between the emitter and the shield, thereby causing enhanced electron back-bombardment. Because of this unsteady behaviour it was decided to explore other emitters with different slit lengths.

**Tests on 5 and 10 mm Slit Length Emitters**

After this preliminary experience, a compared study between two emitters of 5 and 10 mm slit length with 1.2 \( \mu \)m slit width both was performed. The thrust levels were adjusted by varying the emitter voltage to 1, 10 and 25 \( \mu \)N, maintaining the accelerator voltage at a fixed value of -3 kV in order to reduce the divergence of the ion beam. To observe the controllability of the FEPE system, several rounds of 24 hours with each of these thrust levels in continuous mode were performed.

Figs. 20-23 give the emitter current as a function of the emitter voltage at the beginning and at the end of the tests performed on both emitters. As equation 2 shows, the flow impedance increases when the slit length diminishes:

\[ Z = d/t^2 \]  

(2)

where, \( Z \) is the impedance, \( t \) is the slit width, \( I \) the slit length and \( d \) the emitter depth) making more difficult to extract an ion, thus the threshold voltage increases.

This phenomena can be seen in Figs. 20-23. On the other hand the mass flow-rate increases when diminishing the flow impedance (see eqn 3):

\[ dm/dt = \Delta P/Z \]  

(3)

d therefore, for a constant force, the ion velocity will decreases
Fig. 15-19  Horizontal Probe Runs for Different Accelerator Voltage of a 1 mm Slit Length Emitter

Fig. 20  Emitter Current vs. Emitter Voltage for a 5 mm Slit Length (beginning of the test)

Fig. 21  Emitter Current vs. Emitter Voltage for a 5 mm Slit Length (end of the test)

Fig. 22  Emitter Current vs. Emitter Voltage for a 10 mm Slit Length (beginning of the test)

Fig. 23  Emitter Current vs. Emitter Voltage for a 10 mm Slit Length (end of the test)
following the equation 4:

\[ F = \frac{dm}{dt} v_e \]  

(4)

where \( v_e \) is the exhaust velocity and \( F \) the thrust.

In any case taking in consideration that the thrusts involved in the SAGITTARIUS mission are not very high, we can conclude that from this point of view a smaller exhaust velocity should not be a problem.

Four rounds of 24 hours with each of the thrust levels in continuous mode on each emitter were performed and the measurements effectuated were used to study the trends of the followings parameters:

- The minimization of the drain current of the FEEP thrusters is an essential requirement for a long term operation mission like SAGITTARIUS, as drain leads to localized heating of the emitting edge because of electron back-bombardment. This in turn leads to propellant vaporization, with the consequences of neutral losses, charge-exchange processes, isolator contamination, etc. Therefore a study of the \( I_{ac} / I_{em} \) (\( I_{ac} \) is the accelerator current) was performed in order to observe the proportion of emitter current that is transferred from the emitter to the accelerator without contributing to the ion beam current. Tab. 1 shows the trends of this parameter through the whole test. It can be observed that the 10 mm slit length emitter presents a higher \( I_{ac} \) than the 5 mm when firing at 10 and 25 \( \mu \)N. For 1 \( \mu \)N the difference between both emitters is smaller. Therefore the 5 mm slit length emitter has lower accelerator current than the 10 mm when operating at these low thrust levels.

- The beam divergence of the FEEP thrusters will increase the probability of interaction with other subsystems of the spacecraft (optical, chemical and electromagnetic contamination) and will reduce the accuracy and performance of the thrust operation itself (see equation 1). Therefore the cause of this divergence, a high accelerator voltage, must be taken in consideration. The trends of the parameter \( V_{acc}/V_{em} \) (\( V_{acc} \) is the accelerator voltage, \( V_{em} \) is the emitter voltage) have been studied. Tab. 2 shows that the 5 mm slit length emitter has lower \( V_{acc}/V_{em} \) when operating at 1, 10 and 25 \( \mu \)N than the 10 mm slit length emitter. Therefore the 5 mm slit length emitter is preferred from this point of view. The measurements performed with the horizontal probe, Figs. 24 and 25, confirm the higher beam divergence in the 10 mm slit length emitter.

<table>
<thead>
<tr>
<th>( V_{acc}/V_{em} )</th>
<th>THRUST = 1( \mu )N</th>
<th>THRUST = 10( \mu )N</th>
<th>THRUST = 25( \mu )N</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm slit length</td>
<td>0.05 0.06 0.06</td>
<td>0.015 0.03 0.03</td>
<td>0.03 0.04 0.04</td>
</tr>
<tr>
<td>10 mm slit length</td>
<td>0.06 0.08 0.08</td>
<td>0.016 0.03 0.03</td>
<td>0.037 0.05 0.05</td>
</tr>
</tbody>
</table>

Tab. 1 \( I_{ac}/I_{em} \) for 5 and 10 mm Slit Length Emitters Operating at Micro-thrust Levels

- As part of the attitude and reaction control system, the FEEP thrusters must provide a high accuracy in the correction of the disturbances under which the spacecraft is operating. Taking in consideration the equation 1, it is very important to study the trends of the difference between \( \langle V_{em} \rangle_{max} \) and \( \langle V_{em} \rangle_{min} \) in each of the rounds of 24 hours. This parameter will give information about the thrust variation in a period of operation with a particular thrust level. Tab. 3 shows clearly a higher difference of this parameter for the operation with the 10 mm slit length emitter than with the 5 mm emitter. On the other hand the measurements taken with the vertical probe, Figs. 26 and...
27, show how the distribution of the ion current is more regular and symmetric in the 5 mm slit length emitter than in the 10 mm, with better performance from the accuracy point of view.

Therefore we can conclude that the 5 mm slit length FEEP emitter fulfils the micro-thrust operation requirements of scientific missions such as SAGITTARIUS in a better way than the 1 and 10 mm slit length emitters. Several points of enhancement for the micro-thrust FEEP operation have been detected and will be taken into consideration in the future activities on this system at the ESTEC Electric Propulsion Test Laboratory:

- Because of the low thrust involved, the voltage needed to obtain this micro-thrust level can be reduced and thus it will be possible to diminish the accelerator voltage which will decrease the beam divergence. Future activities at the Electric Propulsion Test Laboratory will test several emitters with 5 mm slit length under different "low" accelerator and emitter voltage.

- On the base of optimised parameters obtained as output of the already mentioned tests, a life-time test of one year of duration will be carried out at the ESTEC Electric Propulsion Test Laboratory and any possible operation problem will be assessed.

Conclusions

An experimental investigation on three different slit length emitters (1, 5, 10 mm) has been carried out at the ESTEC Electric Propulsion Test Laboratory. Micro-thrust levels of 1, 10 and 25 μN in continuous mode were explored. Taking in consideration the requirements of the scientific missions such as SAGITTARIUS interested in the micro-thrust FEEP system, the main operation drivers have been identified and in consequence, the relevant electric parameters trends have been studied for each emitter in each of the thrust levels already mentioned.

After evaluating the trends of the parameters which could influence the future operation of a micro-thrust FEEP system in scientific missions, it was demonstrated that a 5 mm slit length emitter was able to fulfil the requirements of this kind of missions in a more efficient way than the other two candidates.

Points of enhancement in the micro-thrust FEEP system operation and future activities in this direction at the Electric Propulsion Test Laboratory were presented.

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# LAGOS (LAser Gravitational-wave Observatory in Space)
OGRE (Orbiting Gravitational Red-shift Experiment)
STEP (Satellite Test of the Equivalence Principle)
LARF (Low Acceleration Research Facility)
REFERENCES


