# FEEP Thruster Performance at High Background Pressure

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## Abstract

SINCE the beginning of FEEP research, it was generally believed that the operational field of this thruster should be limited to high altitude orbits due to possible emitter contamination resulting from propellant interaction with the residual atmosphere. In fact, cesium reacts with water and oxygen forming compounds which may obstruct the emitter slit, causing performance degradation and eventually preventing ion emission. This concern is receiving much attention in view of the forthcoming FEEP flight demonstration on the Space Shuttle, whose gaseous environment is rich in contaminants.

This paper reports on the results of a series of high background pressure tests carried out at Centrospazio using an emitter with a 5 mm long, 1.4 μm high slit, and draws general conclusions on the suitability of FEEP emitters for LEO satellite applications. Experiments included tests at total pressure values as high as $10^{4}$ mbar, tests with a significant $H_2O$ partial pressure (up to $10^{-7}$ mbar), and tests carried out to investigate the effect of prolonged thruster shut-off periods (up to 15 hours).

As a result of this work, enhanced confidence in the use of FEEP at relatively high ambient pressures has been gained. It was concluded that the behaviour of the thruster is not as influenced by the background atmospheric environment as previously believed, even at relatively high water pressures, or at restart after prolonged inactivity. Of course this applies to proper thruster conditions, that can only be achieved if propellant filling, first wetting of the emitter internal surfaces and first firing are performed under the best possible vacuum conditions.

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## Introduction

In FEEP thrusters, field ionization of cesium occurs on the liquid metal surface at the outlet of a 1 μm slit. The main concern with this ionization mechanism is the possible clogging of the emitter slit due to oxidation of cesium. As an alkali metal, cesium reacts very rapidly with water, forming cesium hydroxide (CsOH), and with oxygen, forming cesium oxide ($Cs_2O$). These compounds melt or decompose at 272 °C and 400 °C, respectively. At the normal operating temperature of FEEP (about 35 °C), contamination by oxides may lead to partial obstruction of the slit by solid particles and to poor ion emission. This detrimental situation could take place in two different ways: first, because of interaction of the free liquid metal surface with the environment atmosphere; second, because of contact of liquid cesium with water vapour absorbed on the stainless steel internal surfaces of the emitter. As a consequence, special care must be devoted to the pre-flight emitter preparation procedure, and the operation of FEEP should be restricted to orbits at a sufficiently high altitude, where environment pressure and water content are below a certain limit.

However, recent tests show that this requirements have to be met only during the very first wetting of the emitter blades by the propellant, while much more unfavourable conditions may be tolerated after a new emitter has been successfully fired[1]. Since then, several other tests were carried out to investigate the effect of prolonged switch-off periods, and enhanced confidence in the use of FEEP at high pressure was gained.

Centrospazio is preparing for ESA a flight demonstration of the FEEP system, which will fly in 1999 on a Get Away Special canister onboard the Space Shuttle; hence, it is mandatory to demonstrate that FEEP is impervious to contamination from such substances as water, carbon dioxide, molecular and atomic oxygen, which are normally found surrounding the Shuttle, due to the spacecraft own outgassing and to the natural LEO environment.

The aim of this work is to address the problem of cesium contamination in FEEP and to summarize some recent, related experimental results.

### Internal Contamination

The problem of contamination of cesium internal to the emitter was thoroughly addressed in the past[2]. In fact, some ignition tests at relatively high pressure were already performed in the early 90's, with encouraging results[3]: for example, figure 1 shows a set of characteristic curves recorded at Centrospazio in 1990 using a 5 cm slit lenght emitter, ignited at different pressures. As a result of those activities, it was understood that contamination is avoided if the emitter undergoes a correct pre-flight procedure, i.e. outgassing at 350 °C for about 15 hours in a good vacuum just prior to propellant feed, where "good vacuum" means total pressure not in excess of $10^{-8}$ mbar and partial pressure of water of $5 \cdot 10^{-8}$ mbar or less. This results in complete wetting of the emitter blades by cesium and in prompt high quality ion emission. Obviously, cleanliness and perfect surface finish of the emitter blades are of the highest importance.

Once wetted, the emitter is much more resistent to contamination. In fact, even the formation of a crust of oxide on the liquid cesium surface may not result in a complete failure, as long as some portion (even very small) of the slit is still free. Ion emission from the unaffected zone will induce mechanical stresses in the remaining of the metal, until the crust is blown away. This self-recovering behavior, repeatedly observed in slit emitters, is one of the substantial advantages of linear FEEP ion sources with respect to single needle LMIS (Liquid Metal Ion Sources), which are more critical from the point of view of reliability.

After having undergone the first wetting - first firing procedure, the FEEP emitter is ready for operation and may be kept in an idle state for prolonged periods. Protection from contamination is necessary but not more demanding than what is normally required by sensitive space instrumentation. A dedicated sealed container, with an openable lid, has been recently designed, manufactured and tested at Centrospazio, and will be used in the flight demonstration to protect the emitters from the laboratory to start of operation in orbit.

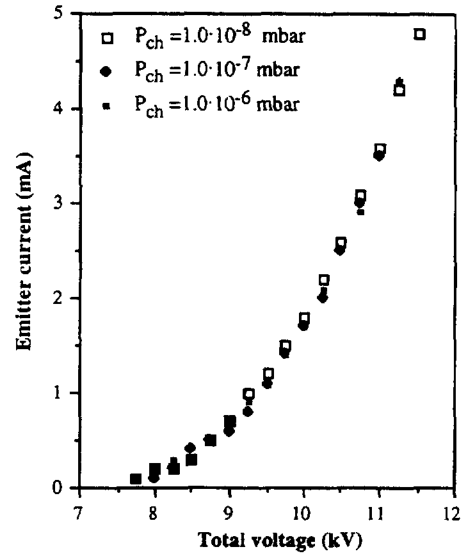


**Fig. 1 - I/V characteristic curves of a 5 cm FEEP emitter**

### Experimental Setup

The experiments were carried out in Centrospazio's IV1 vacuum chamber. This facility consists of a stainless steel vessel with an overall length of 1.8 m and an inner diameter of 0.6 m, and is equipped with a pre-vacuum rotary vane pump, a turbomolecular pump and a cryopump. The ultimate pressure of the vacuum plant is in the range of $10^{-9}$ mbar. The chamber pressure and the composition of the residual atmosphere are controlled by a complete pressure measuring instrumentation, including low- and high-vacuum pressure gauges and a quadrupole mass spectrometer (Balzers QMG 064) for the mass range 1 - 64 amu.

The vacuum chamber is equipped with a flange that supports the emitter-accelerator assembly, an emitter heater, the propellant feeding system, electrical wirings, temperature sensors and two motorized electrostatic probes for ion beam scanning. The flange can be removed from the vacuum chamber by means of a movable undercarriage. This arrangement allows full accessibility to the experimental support plate during assembly and bench testing. The propellant feeding system consists of a glass siphon containing a sealed ampoule filled with 2.5 g of cesium. The experimental assembly is shown in fig. 2, just prior to installation in the vacuum chamber.

During this experimental activity, several diagnostic devices and a set of low and high voltage power supplies were employed. The data acquisition arrangement is shown in fig. 3; in particular, $I_e$ acquisition on the HV emitter line was performed by a Keithley 2001 digital multimeter connected to the computer via fiber optic cables. Fiber optic trasmission provides high noise immunity, low RFI emissions, long-distance capability and HV insulation. Acquisition of $V_e$ and $V_a$ was performed by a P6015 HV probe (1000 × attenuation) and a HP 44702B 13-bit high speed voltmeter; the latter is installed on a HP 3852A Data Acquisition/Control Unit together with a HP 44711A 24 channel High-Speed FET Multiplexer. In addition to manually operated, standard laboratory HV power supplies (FUG HCN 700-20000 and FUG HCN 14-12500), a more sophisticated power supply was used, in order to investigate the settling time of the ion beam current. This power supply (CAEN Mod. N 570) is a device especially designed for high energy physics particle detectors. It features a

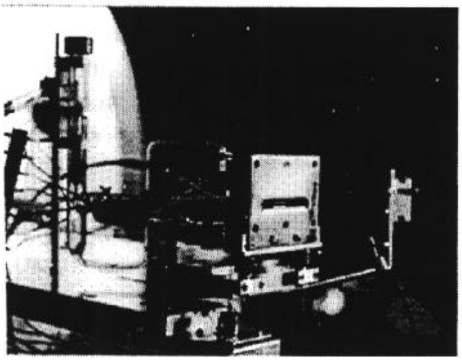

Fig. 2 - Experimental setup

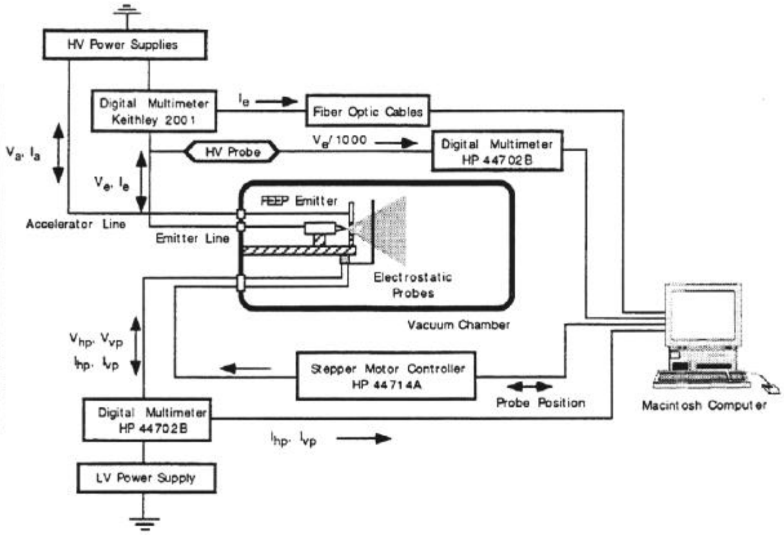


Fig. 3 - Data acquisition arrangement

very low ripple (250 $mV_{pp}$ at full load) and a very good long term stability (0.1 %). The output voltage can be set with a 1 V resolution, the amplitude of the required voltage step can be programmed, and the rise or fall voltage ramp is subsequently executed at a constant ratio (1 - 500 V/s).

## Test Procedure

The tests were performed on a FEEP emitter with a 5 mm long and 1.4 μm high slit manufactured at ESTEC; the nickel layer deposition was performed at the Department of Electronics of the University of Pisa by Centrospazio's specialists. The test procedure included:

- a preliminary phase, during which the experiment is assembled and mounted on the vacuum chamber flange and pumping is turned on. Then the vacuum facility is baked out at about 80 °C for about 2 days in ultra-high vacuum, to get rid of water absorbed on the chamber walls, and emitter and feeding system outgassing is performed. The outgassing procedure is accomplished by heating the emitter to 350 °C for about 15 hours, while the propellant feeding system is heated to 150 °C. After the bakeout, HV insulation of all the relevant components is checked;

- the test phase, starting with propellant filling in the best possible vacuum. For all of the tests here reported, propellant filling was performed at a total pressure between $7.0 \cdot 10^{-9}$ and $1.0 \cdot 10^{-8}$ mbar;

- the post-test phase, including residual propellant evaporation, chamber venting, experimental assembly dismount, thruster dismount and inspection, and vacuum chamber cleaning.

The following quantities were recorded:

- emitter current, $I_e$ (with 0.05 % accuracy);
- accelerator current, $I_a$ (resolution of 0.5 μA);
- vacuum chamber pressure, $P_{ch}$;
- partial pressures of several gases: $P_{H2O}$, $P_{O2}$, $P_{N2+CO}$, $P_{Ar}$, $P_{H2}$, $P_{CO2}$, $P_{He}$;
- emitter temperature, $T_e$, measured by a type K thermocouple.

## Experimental Results

### High total pressure tests

All tests were carried out at constant emitter voltage; therefore, as the current extracted from a FEEP emitter is a function of total voltage difference between emitter and accelerator, the accelerator voltage acted as the thruster control parameter. In all pictures below, the upper graph shows the accelerator voltage, i.e. the input quantity imposed by the experimenter, and the lower graph shows the thruster response to the voltage input in terms of emitter current. The values of $V_a$ and $I_e$ were sampled at 1 Hz. Prior to all tests, a set of characteristic curves (emitter current vs. total voltage) was recorded to check proper operation of the emitter.

A first test was made as soon as stable ion emission was obtained after first ignition of the emitter, at $P_{ch} = 10^{-8}$ mbar. After having let the emitter run at high current for several tens of minutes, chamber pressure increased to $P_{ch} = 10^{-7}$ mbar. This rise with respect to the pre-firing value is due to gas release from the chamber walls, as a consequence of energetic ion impacts. Pressure was then gradually increased from $10^{-7}$ to $10^{-4}$ mbar, throttling the cryopump valve. The subsequent variation of emitter current with time (fig. 4) shows that no appreciable effect on emitter performance appeared until pressure reached $10^{-4}$ mbar: from that moment on, an increase in emitter and accelerator currents was recorded. This was probably due to a local loss of insulation of the electrode mounts, and is not to be related to the mechanism of ion emission. Test was carried out at constant electrode voltages (note the scale of $V_a$ in fig. 4). Thus, emission was satisfactory at a pressure as high as $10^{-5}$ mbar, which is higher than the total pressure around the Shuttle[4].

Fig. 5 shows an ignition test after a switch-off period of two hours, during which the chamber pressure was set to the high value of $10^{-4}$ mbar. However, the partial pressure of water vapour, which is the main contamination source of cesium, was only $5.0 \cdot 10^{-9}$ mbar. This was due to the getter effect of the cesium deposited on the chamber walls as a result of the previous thruster activity. According to Mitterauer[5], the time necessary for the adsorption of a monomolecular layer of CsOH by the free Cs surface at the

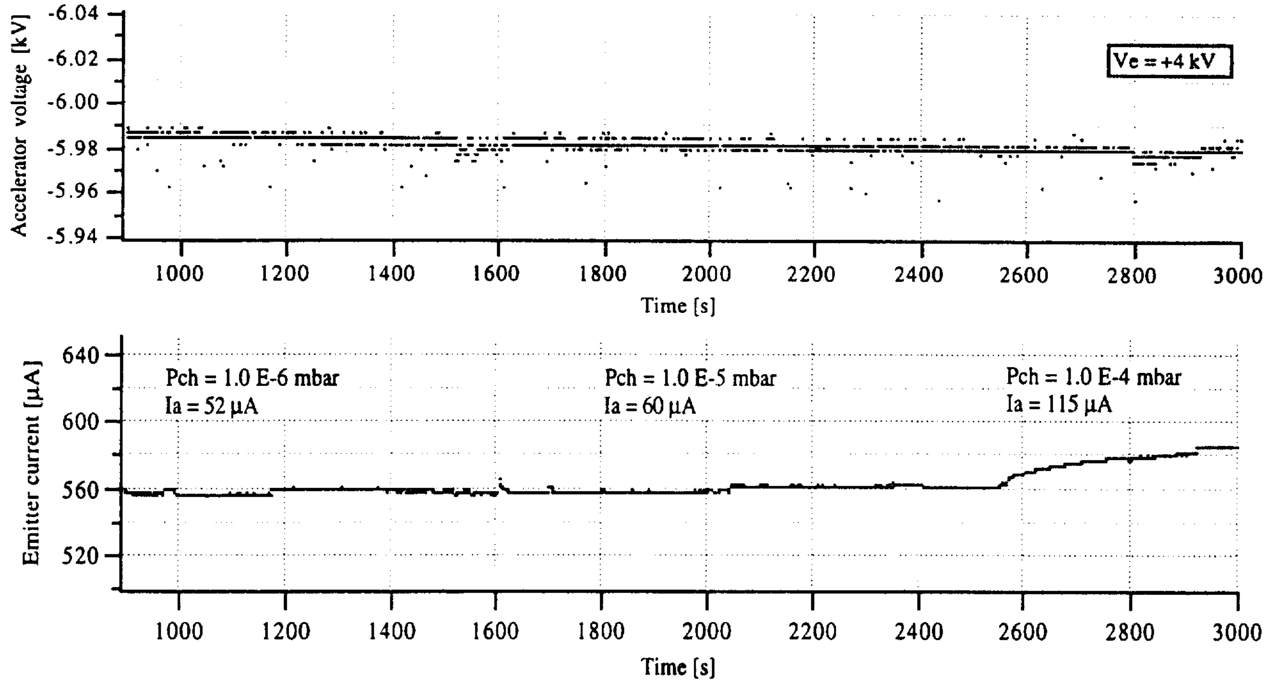


**Fig. 4 - Effect of a gradual total pressure rise**

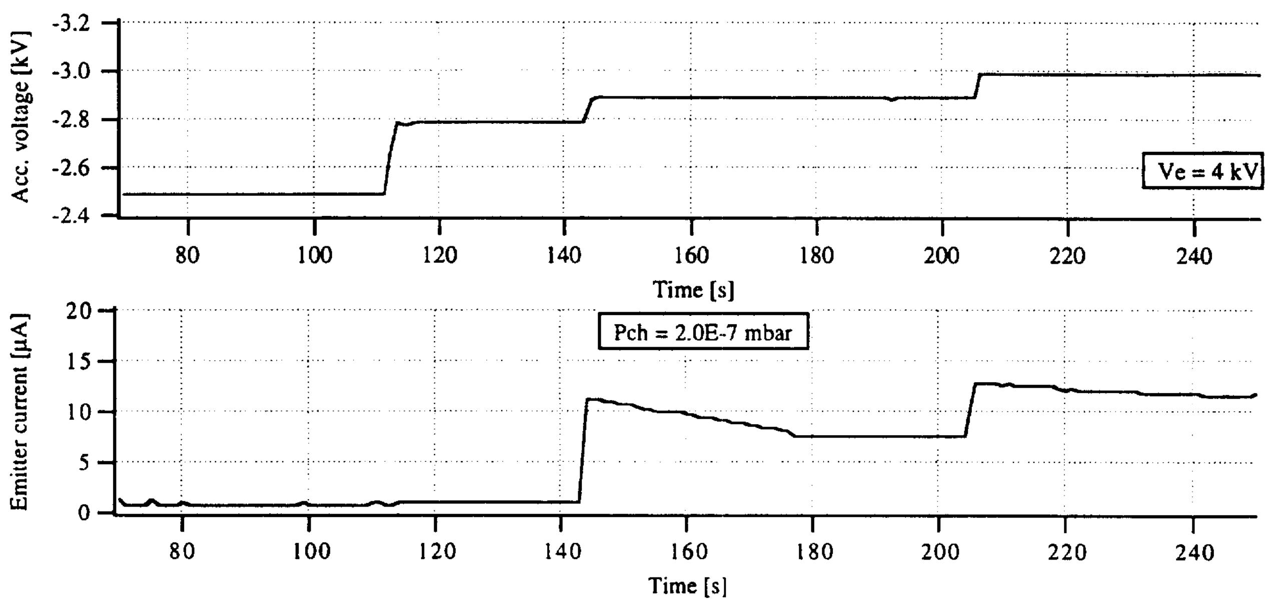


**Fig. 5 - Ignition test after a two hours shut-off period at1.0·10$^{-4}$ mbar**

emitter slit edge is about 10 minutes at $P_{H2O} = 5.0 \cdot 10^{-9}$ mbar. Hence, if an originally chemically clean Cs surface is exposed under these conditions to the background atmosphere for several hours, it is realistic to assume that emitter performance will somehow change due to the growth of multilayers of CsOH. In spite of this, when pumping was resumed and pressure was lowered to $10^{-7}$ mbar, the emitter ignited immediately at voltage switch-on. The emission threshold voltage was found to be 6.9 kV, that is pratically the same value which was measured prior to switch off in optimal pressure conditions[4]. For comparison, ignition voltage in best vacuum is shown in Fig. 6.

Fig. 7 shows an ignition test after a 15 hours period with pumps off. Chamber pressure reached $1.0 \cdot 10^{-3}$ mbar a few hours after pumps shut-off, while the water partial pressure did not exceed $6.0 \cdot 10^{-9}$ mbar. Again, the thruster was easily ignited at the first attempt, but the threshold voltage was slightly larger than in previous case (7.3 kV): this may suggest that the emitting region geometry had

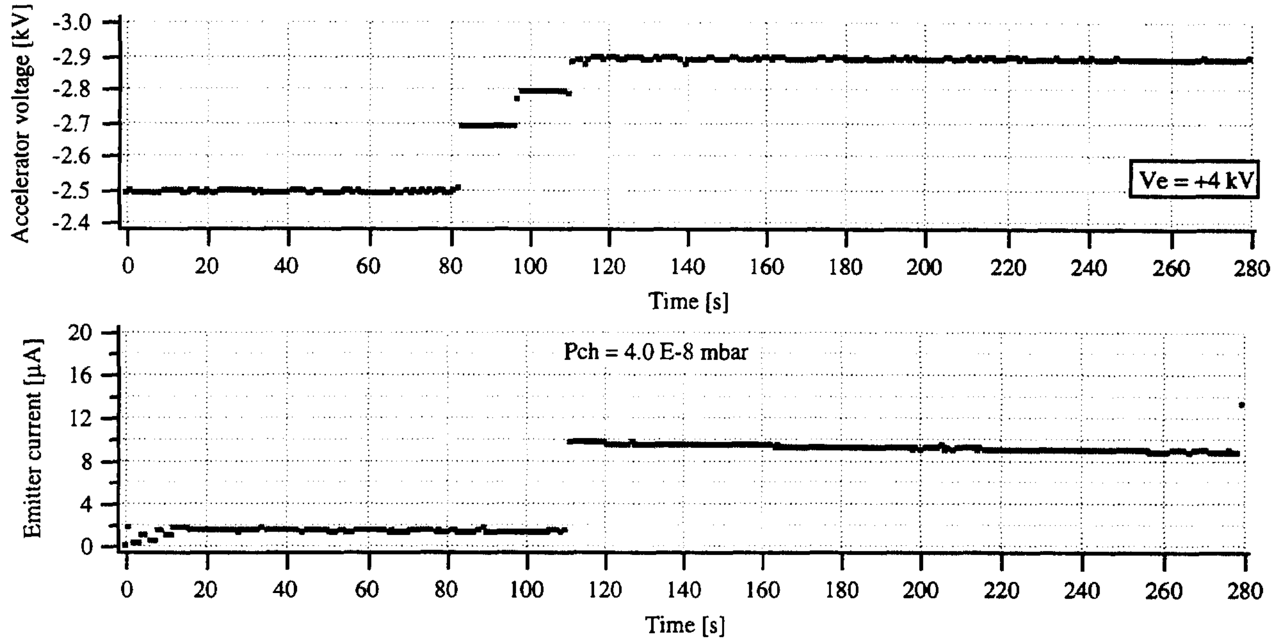


**Fig. 6 - Ignition test at $4.0 \cdot 10^{-8}$ mbar**

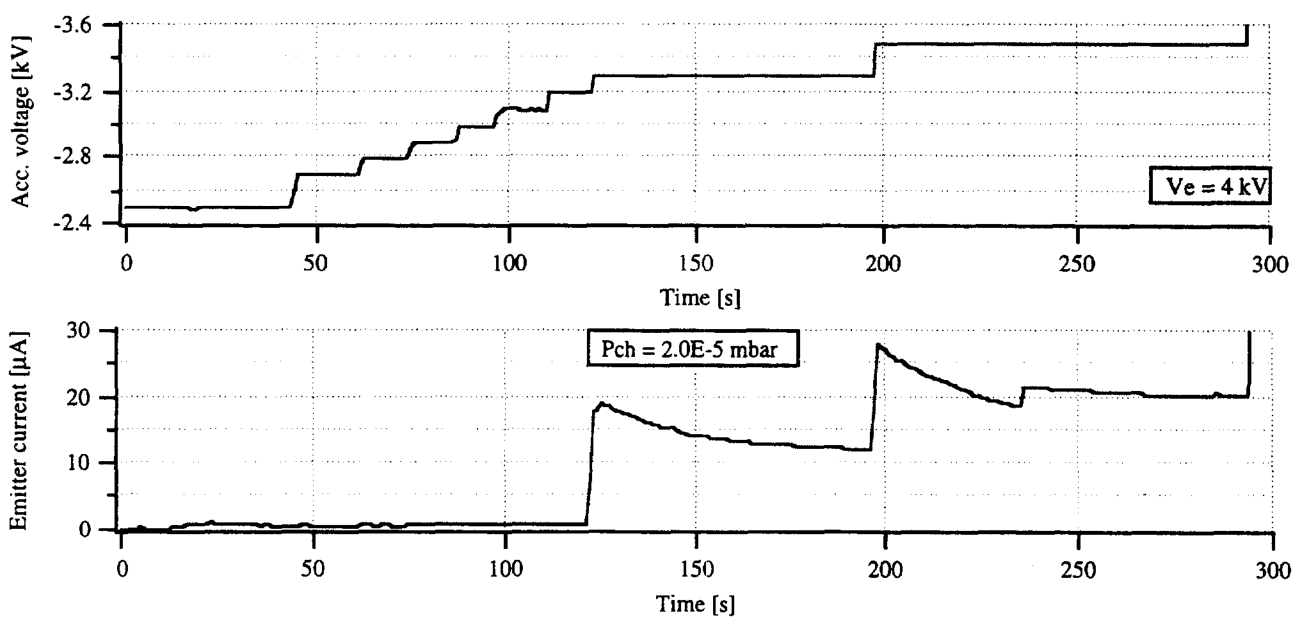


**Fig. 7 - Ignition test after a 15 hours shut-off period without pumping**

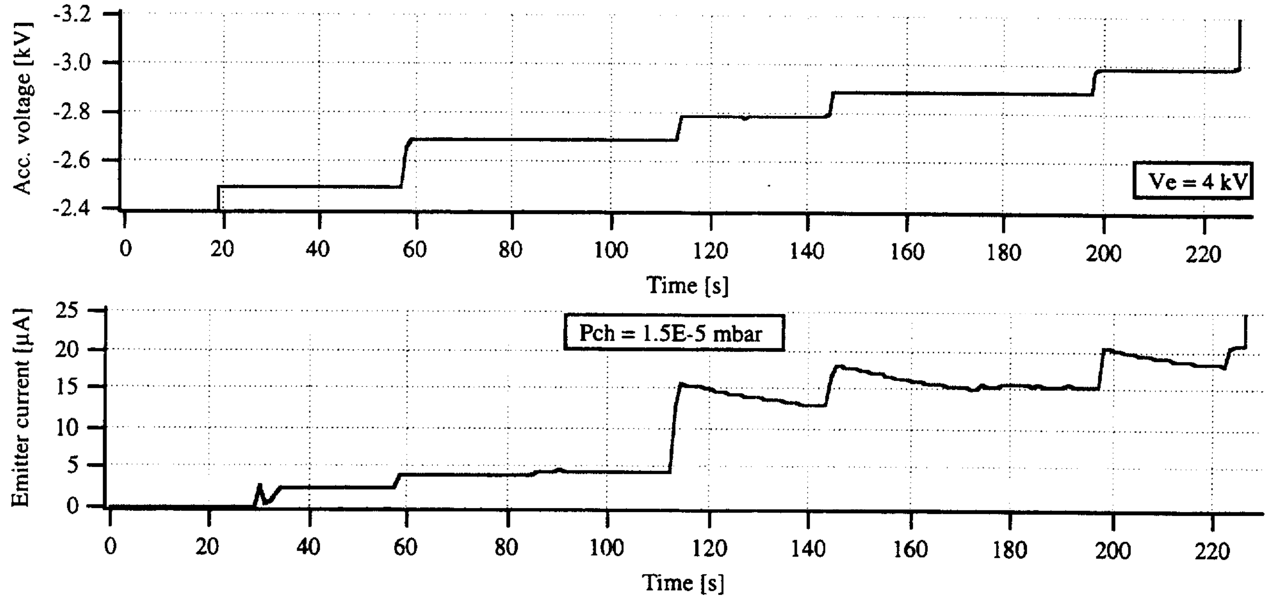


**Fig. 8 - Ignition test after a 6 hour shut-off period ($P_{H_2O}$ = 4.0 $\cdot 10^{-7}$ mbar)**

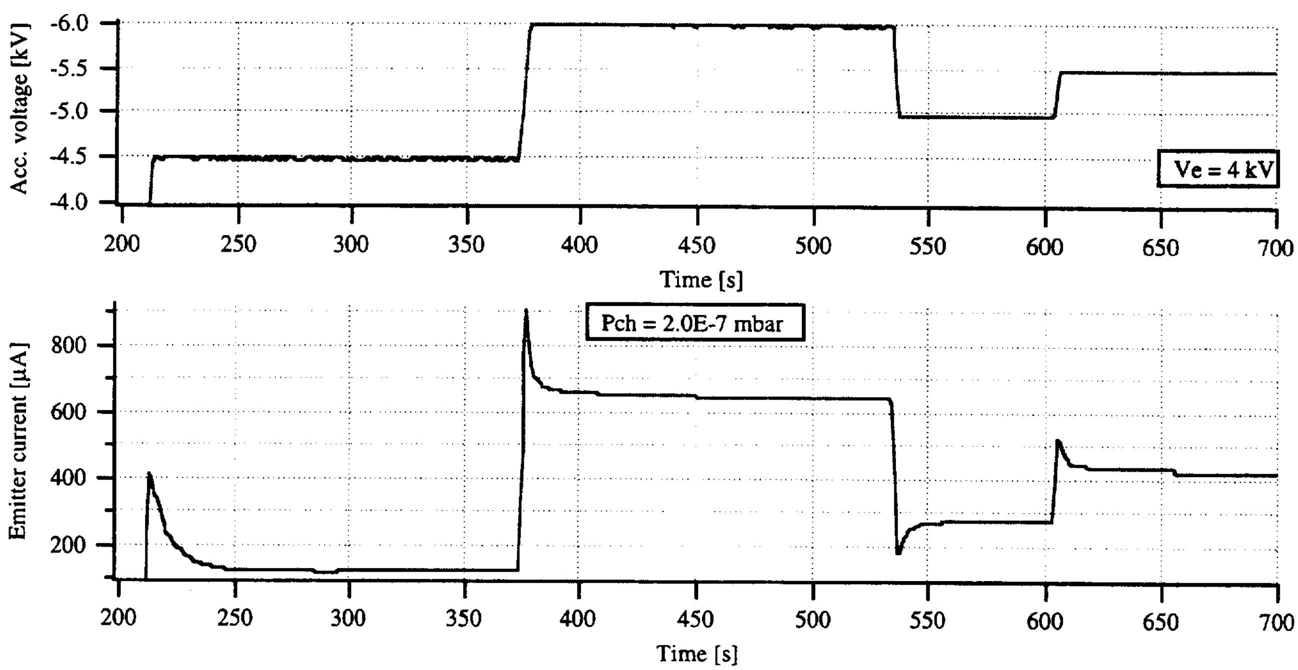


**Fig. 9 - Emission test after a 15 hours shut-off period without pumping**

been altered by the formation of multilayers of CsOH on the cesium surface. Threshold voltage reverted to 6.9 kV a few minutes after, when the impurities were blown away and good slit wetting condition was established again. Further emission tests showed no significant performance degradation. As an example, fig. 8 shows the thruster response to rapid, step-like variations of $V_a$, at constant $V_e$ = 4.0 kV (notice the marked current overshoot, which is discussed in detail in Ref. 6).

### Tests in presence of water vapour

All of the above reported tests were carried out in an almost water-free environment, since the cesium exhausted by the thruster acted as a getter. The partial pressure of water was in the 2.0 - 6.0$\cdot 10^{-9}$ mbar range throughout the tests, even at high total pressure. As water is the most dangerous and most common potential contaminant, it was decided to perform other tests at higher water partial pressure. To this end, a simple but effective water vapour generator was setup, using a calibrated valve to put a boiler in communication with the vacuum chamber. In this way, it was possible to control the partial pressure of water within a wide range.

Water pressure was raised from $4.0 \cdot 10^{-9}$ mbar to $4.0 \cdot 10^{-7}$ mbar and kept at that level, with emitter idle, for 6 hours. This value of $P_{H2O}$ is about the one reported for the normal Shuttle environment. At the end of that prolonged exposition to water, total pressure had reached $1.5 \cdot 10^{-5}$ mbar. In spite of all that, thruster ignition was immediate, and at the same threshold voltage as in previous tests (fig. 9).

## Conclusions

This experimental work included tests at pressures as high as $10^{-4}$ mbar, tests with a significant $H_2O$ partial pressure (up to $10^{-7}$ mbar), and emitter ignition test performed after prolonged switch-off periods. The results have shown no significant thruster performance degradation up to a total pressure of $10^{-5}$ mbar. Furthermore, thruster restarting was found to be not as difficult as previously believed, even after 15 hour switch-off periods at high water vapour pressures.

In conclusion, the thruster was found to operate smoothly and reliably in a LEO-like environment, even at restart after a prolonged switch-off. These results are of extreme importance in view of the forthcoming FEEP flight demonstration on the Space Shuttle. Of course additional, systematic tests shall be performed to investigate all possible operational scenarios. Among others, planned thruster tests include emitter firing in a simulated atomic oxygen environment.

## References

1. Marcuccio, S., Genovese, A., "FEEP Thruster Operation in LEO", TN F1/95, Centrospazio, 1995.

2. Mitterauer, J., "Field Emission Electric Propulsion - Spectroscopic Investigations on Slit Emitters", Final Report to ESTEC Contract 5051/82/NL/PB (SC), 1985.

3. Andrenucci, M., Marcuccio, S., Spagli, L., Genovese, A., Repola, F., "Experimental Study of FEEP Emitter Starting Characteristics", IEPC 91-103, Proceedings of the 22nd International Electric Propulsion Conference, Viareggio, Italy, October 1991.

4. Carignan, G. R., Miller, E. R., "The Shuttle Induced Background: Gaseous Constituents", Adv. Space Res. Vol. 7, No. 5, pp. (5)153-(5)160, 1987.

5. Mitterauer, J., "FEEP: Emission Performance of Slit-Type Liquid Metal Ion Sources", IEPC 88-021, Proc. 20th International Electric Propulsion Conference, Garmisch-Partenkirchen, Germany, 1988.

6. Genovese, A., Marcuccio, S., Andrenucci, M., "Experimental Characterization of FEEP Emitters", ESA SP-398, Proc. 2nd European Space Propulsion Conference, Noordwijk, The Netherlands, 1997.