FEEP-5 Thrust Validation in the 10-100μN Range with a Simple Nulled-Pendulum Thrust Stand: Integration Procedures*†

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A micro-thrust stand developed by the National Physical Laboratory under ESA funding has been characterized and calibrated in different working environments, adapted to vacuum operations and interfaced with FEEP thrusters in the ESA Electric Propulsion Laboratory in ESTEC. A number of complex technical problems have been encountered, analyzed and overcome. Impacts of necessary set-up modifications on the stand measurement limits have been discussed. Direct thrust measurements in the 10-100μN range have been demonstrated to be possible in the current laboratory environment, though sub-μN thrust levels have been measured during calibration on a massive granite seismic block in the ESA Metrology Laboratory. Tests on a FEEP-5 EM adapted to fit on the thrust stand are under preparation and first results are expected soon.

Introduction

To support an important number of space missions that will require in the near future the use of extremely precise thrusters for satellite positioning, the Electric Propulsion Laboratory of the European Space Agency is sponsoring research and development of low thrust measurement techniques and systems.

A first prototype balance, commissioned to the National Physical Laboratory, is currently under operating test. Field Emission Electric Propulsion (FEEP) thrusters [1], because of their precisely controllable and continuos thrust level in the μN to mN range, appear as the most promising propulsion technology for fine-pointing and drag-free scientific spacecraft.

The extremely sensitive nature of the experiment and the thruster technological complexity impose the development of very delicate interfacing procedures. The definition and technical implementation of these procedures is an indispensable condition for a correct interpretation of experimental results, and will be helpful to set appropriate requirements for future diagnostic devices.

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Description of the balance

The prototype FEEP thrust stand operated in ESTEC is based on a simple nulled-pendulum principle. A picture of the system is shown in Figure 1. The design specification required to make measurements in the horizontal direction, in a thrust range of 0-100 μN, with a thrust resolution of 0.01 μN and a repeatability of 0.3%. The necessity to measure thrust in the horizontal direction (to allow the propellant external feeding) introduced significant measurements problems, because gravity acts on the thruster's mass in a direction nominally normal to the measurement axis.

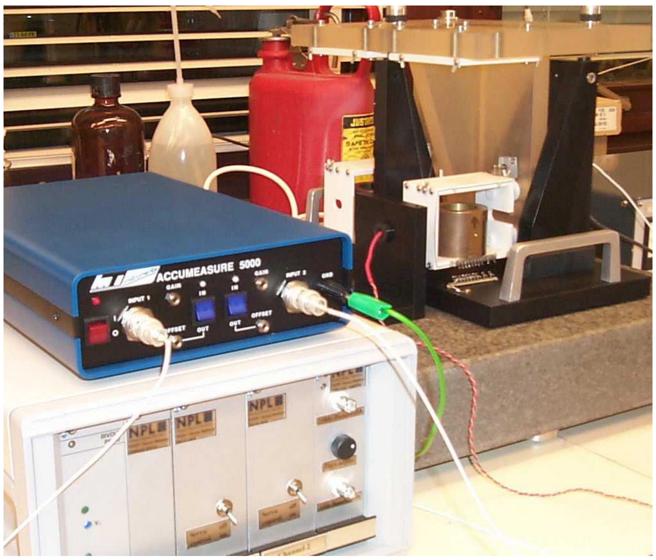


Figure 1 – NPL Micro-Newton Thrust Stand with the Control Electronics

A tilt in the thrust axis of only 6 mrad results in a horizontal force component of 30 mN for a 500 g mass. This tilt could be due to for example, tilt of the whole instrument or the supporting structure. Tilt could also be induced by differential thermal expansion within parts of the instrument. An additional serious source of signal noise is vibration. For a sinusoidal vibration of amplitude A and frequency f, the maximum acceleration is given by:

$$|a_{\max}| = 4 \cdot A \cdot (\pi \cdot f)^2$$

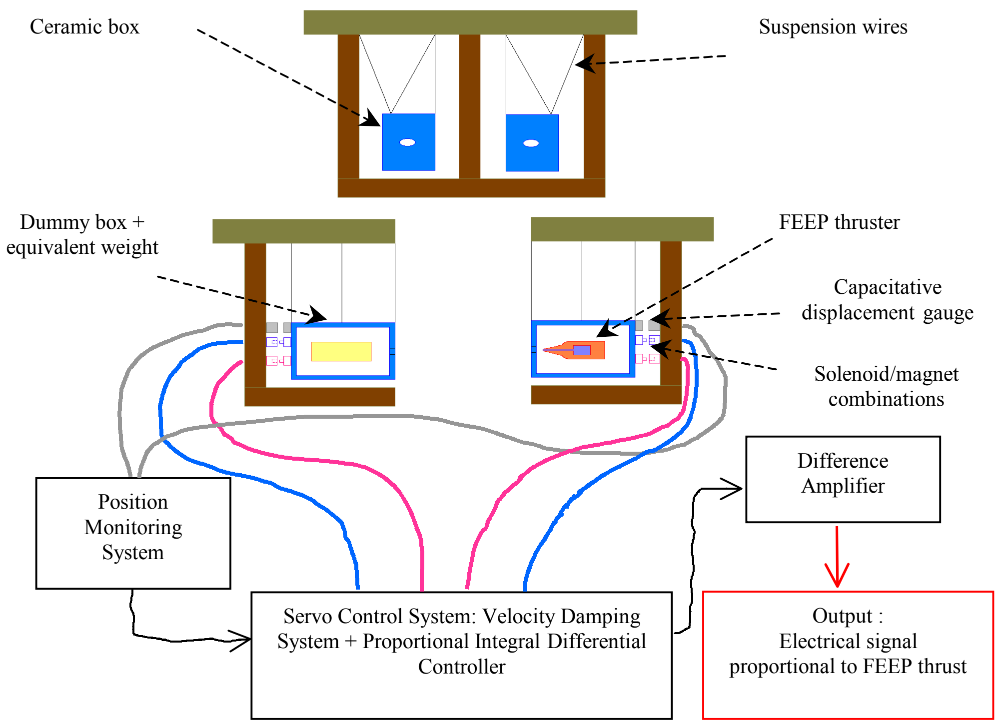
The corresponding force on a mass m is $F = m \cdot a_{max}$. Therefore, a 0.015 mm horizontal vibration at 10 Hz would apply a 30 μN force to the 500 g mass.

The extreme tilt and vibration sensitivity required a novel approach and careful choice of material properties to overcome possible thermal effects. In the final configuration the thruster is suspended as a constrained pendulum such that it is free to move in one direction only, that being along the line of thrust. A displacement transducer is used to measure movement of the thruster along the thrust axis as thrust is applied. A servo control loop then applies an equal and opposite force via a force actuator to the thruster to null the thruster's displacement. Given the known transfer characteristics of the force actuator, the servo gives an output voltage exactly proportional to applied thrust.

In order to overcome the tilt and vibration sensitivity, the balance is actually a twin balance consisting of two identical pendula. One carries the thruster under test; the other carries a dummy load. In principle, both balances are affected identically by external tilt and vibration sources and therefore give the same output signal. In order to eliminate the effect of tilt and vibration, the signal from the dummy balance is subtracted from that from the test balance. This principle goes a long way to eliminating noise caused by vibration, but torsional vibration can cause different signals in terms of amplitude and phase in each balance and such signals are not perfectly balanced. The resulting difference signal is then filtered and scaled to provide two final outputs. One output has a bandwidth of 1Hz, the other has a bandwidth of 10Hz. A simplified schematic diagram of the system is presented in the following page.

The displacement transducer used is a MTI Accumeasure 5000 dual channel capacitive system with two ASP-20-CTA transducers. Each servo controller block takes the displacement output form one channel of the Accumeasure 5000 as its input. This is the servo loop error signal. The role of the servo is to maintain this signal at 0 V, which represents zero displacement from the nulled position. The servos use velocity feedback to damp out the natural tendency of the balance to swing, and proportional, integral and derivative (PID) control to hold the error signal at zero volts. The servo block has two outputs, one is a voltage signal proportional to the thrust required to maintain the balance in its null position. This is converted to a current by the solenoid driver block. The current is then converted to force by the force actuator. The other output from the servo block is the raw output signal. The raw output signals from both servo channels are subtracted and filtered by the difference amplifier and filter block to provide the two filtered output signals. Each of these voltage signals is proportional to the applied thrust but bandwidth limited to either 1 Hz or 10 Hz. A detailed analysis of the servo system transfer function would show that the output signal is proportional to applied of gain or phase, from the two balances for the same input. As a result, imperfect cancellation will take place at the difference amplifier stage and hence some noise will feed through to the final outputs.

It is particularly important that the masses on each balance are matched to better then 1 %. In all the cases, the feed-through of some noises is almost inevitable, and its amount is proportional to the average background noise level. For this reason, the



thrust, and the constant of proportionality is equal to the ratio of the gain of the voltage to current converter to the sensitivity of the solenoid/magnet combination.

Calibration Procedures

The background level of vibration limits the performance of the measuring equipment in terms of accuracy, resolution and repeatability. In fact, the performance of the overall system depends on how well the two servo channels are matched. Any slight differences result in slightly different outputs, in terms calibration of the balance and its operative characterization in different noise environments is the first fundamental step for a correct measurement procedure.

A test solenoid/magnet combination has been used to check the calibration of the balance. Its characteristic force constant has been experimentally estimated in local conditions in order to scale results obtained by a real thruster. The solenoid has been fixed to a rigid support while the magnet was laying on the plate of a Mettler-Toledo AT 400 balance (with a resolution of

0.0001 g). The measured force as a linear function of the applied current is shown in Figure 2. The calibrated force constant for the test solenoid/magnet combination was obtained with a linear interpolation of the collected data points, and resulted to be 35.193 µN/mA.

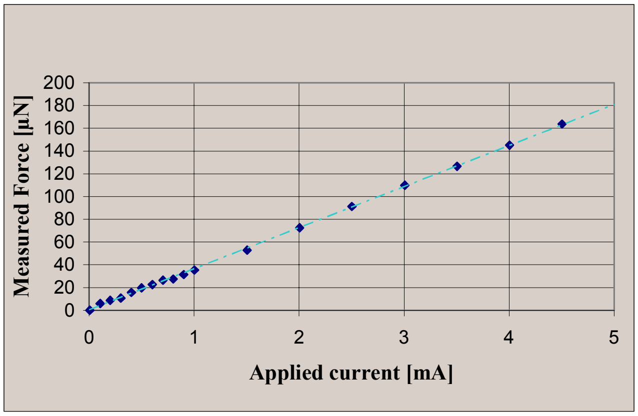


Figure 2 – Transfer Standard Calibration

The magnet has been successively installed in the beam exit slot of one of the platforms, while the solenoid was mounted on a bracket and aligned with the magnet (the solenoid front face was coplanar with the magnet holder shoulder, although the relative positioning should not be critical). In this way it has been possible to obtain an estimation of balance performances in different environments.

The best results have been obtained in an almost undisturbed environment, a big granite bench situated in ESTEC Metrology Laboratory, on the ground floor. The balance was protected against air convection with an apposite cover. As shown in the plots of Figure 3, the output signal resulted to be very stable and sensitive to any change in thrust level. It was possible, with a reasonably amount of approximation, to detect differences in the output signal voltage as small as 0.04 V. This corresponded to a thrust resolution of about 0.3 – 0.5 µN.

As predictable, results obtained on a normal desk on the first floor of the same building proved to be quite different: the output signal, acquired in average mode with an oscilloscope, required at least five minute observations to detect, with reasonable certitude, its unperturbed value. It was impossible to measure differences in the output signal below 1V, which corresponded to an effective thrust resolution of about 10 µN. However, the average trend resulted to be reasonably linear.

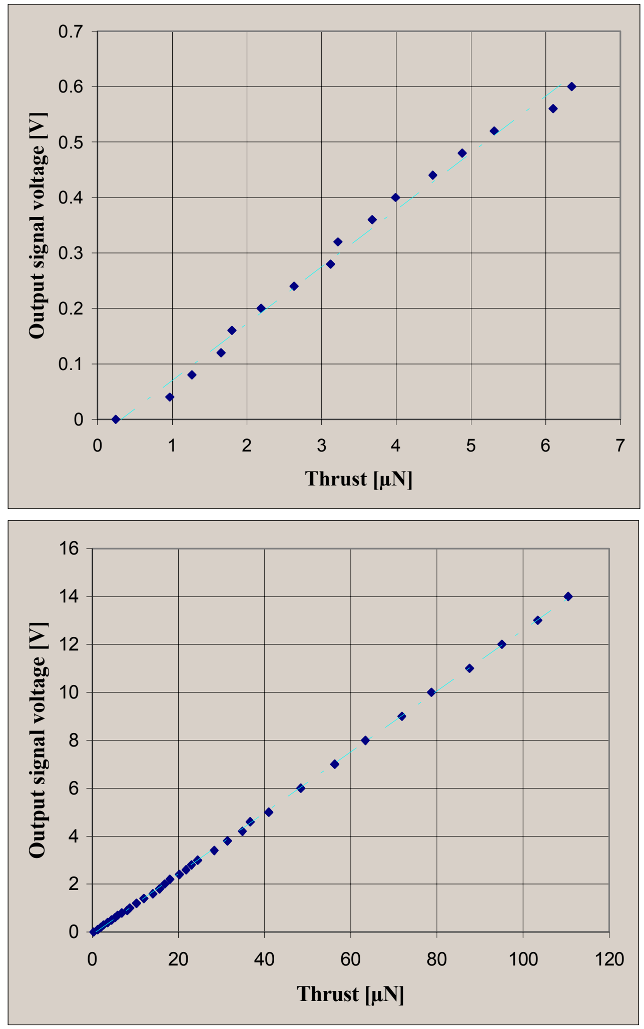
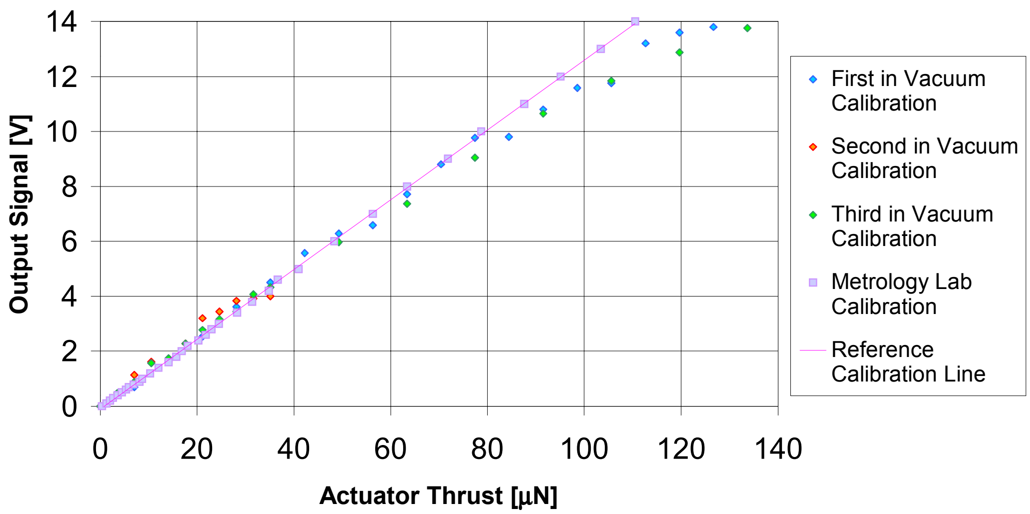


Figure 3 – Balance Calibration in Undisturbed Environment (ESTEC Metrology Laboratory): Full-range Data Set and Low-thrust Enlargement

As expected, installing the balance on a Newport vibration isolator breadboard with stabilizer pneumatic feet didn't improve sensibly overall system accuracy. Low frequency disturbances (because of the damping system's resonance frequency at 0.8 Hz) actually increased, with detrimental effects on the signal.

Finally, several system calibrations were performed inside vacuum facility n.2 in the Electric Propulsion Laboratory and compared with those executed in the Metrology Laboratory (Figure 4).

In order to adapt the balance to in-vacuum operations, all the components that could out-gas were removed and suitable feedthroughs were prepared to carry the servo-control and the output signals. A middle size granite block was introduced in the chamber to be used as passive damping support, and the balance itself was laid on three small surface shockproof washers. During the capacitance sensors installation it was necessary to take into account the change in the dielectric constant of the medium. In fact, normal set-up procedures had been defined for air operation, and the static dielectric constant of the air is slightly greater than one (it is 1.00059 at 25°C). Due to the extremely sensitiveness of the system, the decrease of sensor capacitance during air pumping had to be compensated with an initial suitable variation of



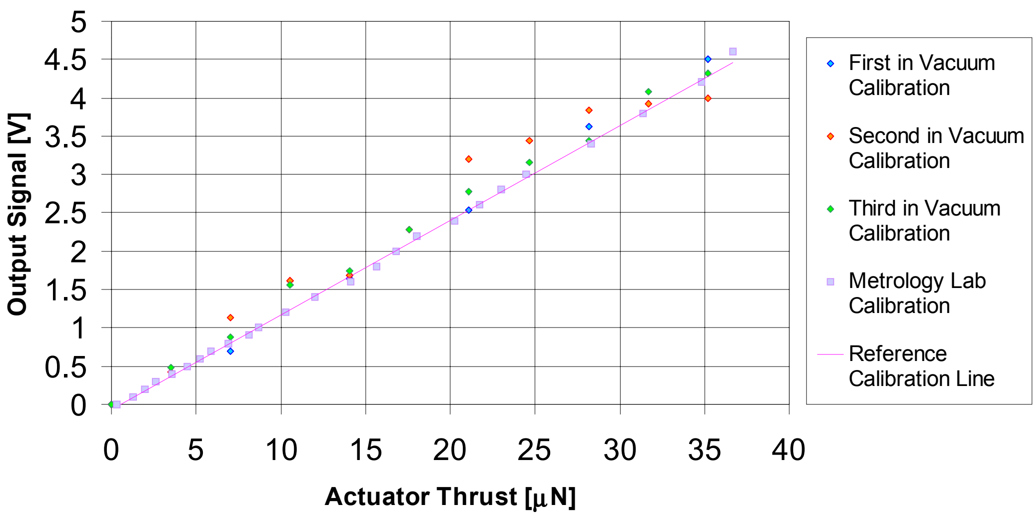


Figure 4 - Balance Calibrations in Vacuum Facility n.2 (ESA Electric Propulsion Laboratory): Full-range Data Set and Low-thrust Enlargement

sensor capacitance components distance. Fortunately, the magnetic permeability for vacuum and air is strictly the same, so that no compensations were required for the electromagnetic actuators.

ESA Electric Propulsion Laboratory Vacuum Facility n.2, in the split configuration (half chamber), is equipped with a system of two root pumps, one turbo-pump and one cryopump, which allows reaching pressures in the 10^{-8} mbar range with facility bake-out. From the noise point of view, the cryopump system produces a vibration level capable to completely overcome the balance signal; the turbo-pump system proved to be compatible with low-resolution measurements, but introduced an important disturbing effect. For this reason, the adopted strategy consisted in deactivating the cryopumps at the beginning of the calibration. This procedure restricted the effective measurement time to the interval required by the cryopanel to warm up (about 20 minutes), but allowed to limit the information loss caused by background noise.

The progressive increase of chamber pressure during the experiment (it increased of about two orders of magnitude, from 10^{-6} mbar up to 10^{-4} mbar) is clearly reflected on the higher thrust calibration curves loss of linearity (Figure 4). A part from this effect, the deviation from the reference calibration line of the straight lines fitted in a least-squares sense to each data set appears to have an effect, on the global measurement accuracy, comparable with the output signal noise. Therefore, without eliminating vibration sources, a maximal achievable resolution of 5 μN can be anticipated.

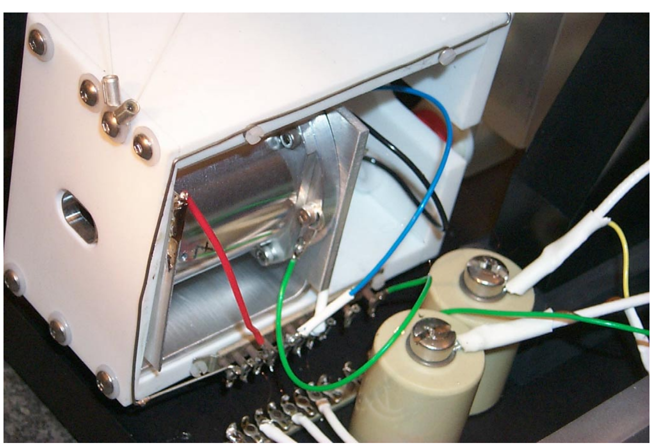


Figure 5 – InFEEP module as first installed

Thruster-Balance Interfacing procedures

At first an ARCS Indium LMIS Engineering Model (InFEEP) [4] was interfaced with the balance in order to validate the thrust stand with a thruster due to the InFEEP's simpler testing conditions. Afterwards the slightly modified (in order to fit in the ceramic slot) Alta FEEP-5 Engineering Model was installed on the thrust stand. In both cases special integration procedures were adopted. An ion collector was applied to the inner surface of the pendulum holed back wall in order to get a drain current measurement (to be subtracted from total thrust calculations) in both cases.

The InFEEP was mounted on an aluminum support designed to hold the emitter in front of the beam exit slot with high geometrical precision.

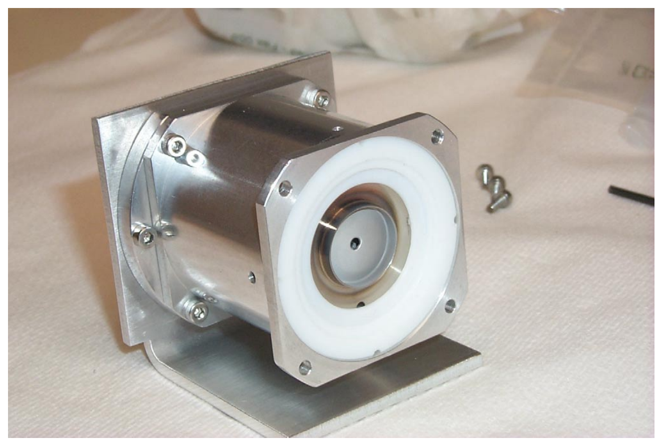


Figure 6 – InFEEP on aluminum support for thrust stand

The electrical power was supplied to the heater (low voltage) and to the emitter (high voltage) through very thin (25 μm diameter) copper wires, in order to reduce system rigidity. This kind of connections proved to be a major source of implementation problems, because of their extreme weakness.

An significant number of failures related to the 25μm wires have shown the necessity to isolate every electrical connection with Teflon screens to avoid the thin wires to get in contact due to the electrostatic attraction. Subsequently it was deemed necessary to reduce high voltage hair-wires length by using thruster pin shielded extensions, and to modify the feeding circuit with the introduction of a 10 kOhm security

resistance on the HV line, to prevent wire burning caused by sudden sparks.
In the initial configuration (Figure 5), the high voltage was taken from the power supply to the corresponding hair-wire passing from a ceramic cylindrical connector provided with a fixing steal bolt. This simplified arrangement later on had to be modified to face the disturbance of the electric interactions.

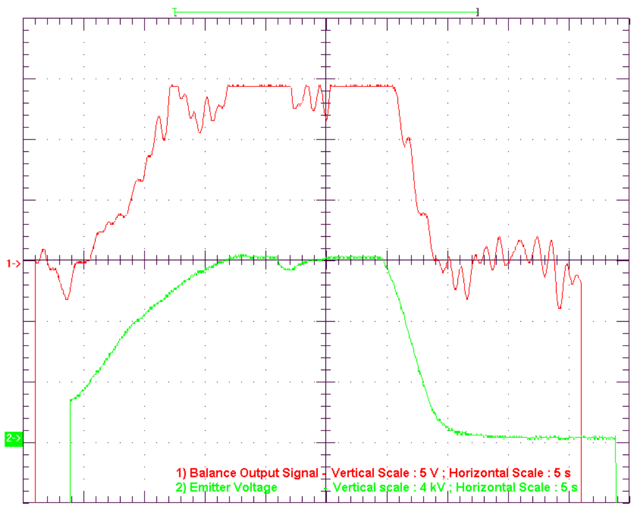


Figure 7 – Global electric interaction of the unshielded high voltage cables on the thrust stand output

In fact, important disturbances of the balance output signal appeared when high voltage was supplied to the thruster. This interaction was expected, but not in such magnitude. In first approximation, the signal from the balance resulted to increase proportionally with the emitter voltage (while no emission and thus no thrust was produced), until it reached saturation for an emitter voltage of about 10 kV. This behavior has been recorded directly with an oscilloscope Tektronix TDS224 connected with an automatic data acquirement system (Figure 7). Most probably this large-scale phenomenon is the consequence of several different components superposition. If a significant crosstalk resulting from mutual inductance [2] could be excluded cause strong magnetic fields were absent, an electric field coupling (mutual capacitance) between the balance circuit and the thruster circuit was more likely to be important.

In order to investigate the contribution on the perturbation of the electric field generated by the feeding line segment located between the chamber feedthroughs and the ceramic connector bolt, the hair-wire connecting the thruster to the bolt was removed and a tension up to 12kV was applied.

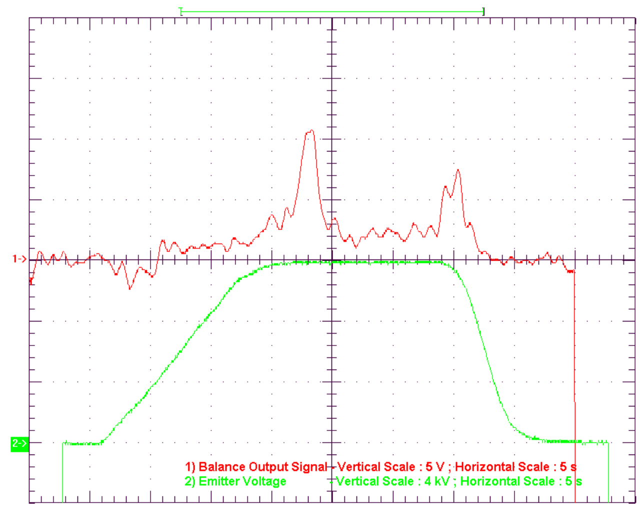


Figure 8 - Electric Field Coupling Component

The resulting trends are shown in Figure 8. A small increment of the average signal can be noticed, but it is small compared to the global interaction. The side spikes might be [3] time-domain (transient) crosstalks. It may be therefore assumed that the most important contribution to the observed perturbation is not an electromagnetic interference but an electrostatic interaction between the electrically charged unshielded copper hair-wire and the ground potential surrounding environment.

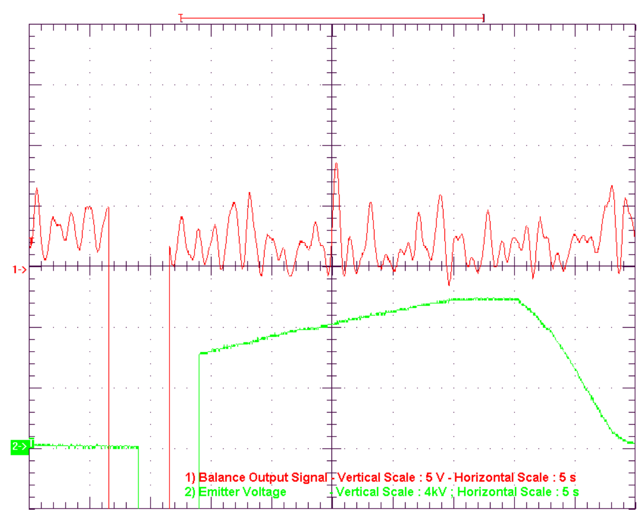


Figure 9 – Shielded Solution Efficacy

In order to suppress this perturbation, the ceramic connector bolts were removed and a complex multi-layer cylindrical structure (made of Teflon sheets and grounded shields) was built around the hair-wire uncovered tips, granting at the same time electrical insulation and freedom of movement. This solution proved to be effective, as it is possible to infer from Figure 9.

Thanks to the implementation of these changes, it has been possible to fire the InFEEP thruster for a short period; unfortunately the emission never reached measurable levels (the thrust calculated on the base of the emitted current was about 2–3 µN). The thruster model, already used for characterization tests [5], underwent a total extinction after a few minutes of operation (likely for fuel depletion).

The installation procedures for the FEEP-5 thruster were significantly different. The thruster model (Figure 10) is an EM FEEP-5 (slit length of 5 mm), capable of delivering 1 – 100µN of nominal thrust [6].

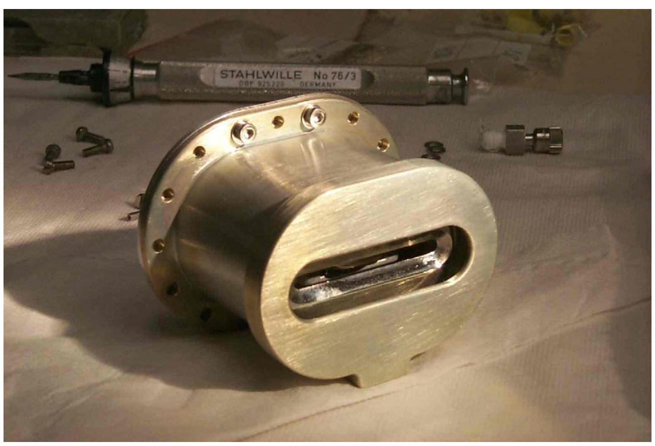


Figure 10 – Alta FEEP-5 model for thrust measurements on the NPL thrust stand

The external nominally cylindrical housing, approximately 55 mm long and 60 mm in diameter was explicitly designed in order to fit into the balance pendulum. The thruster coverlid of the device normally should seal the unit from the atmosphere to prevent the cesium propellant from oxidizing. This lid cannot be operated while the thruster is on the balance, hence the modified container design. This involves that the thruster must be baked whilst on the thrust stand in the vacuum chamber and subsequently filled with liquid cesium. Provision for the filling of the thruster with cesium has been made by the inclusion of a slot in the rear of the FEEP free-swinging box and in the Zerodur main plate. A 30 cm long and 2mm diameter thin capillary equipped with a final filling funnel was predisposed to feed propellant to the emitter. The feeding system can in such a way be kept at security distance from the delicate balance apparatus, minimizing electrostatic interference from the not shielded filling funnel. Since all the propellant and the capillary pipe, during operation, is going to be kept at the emitter high positive voltage, an efficient shielding was indispensable. The capillary has consequently been wrapped with a 4-layer protection made of a ceramic insulator, two heat shrinks and a wire mesh twist tie grounded to the thruster housing.

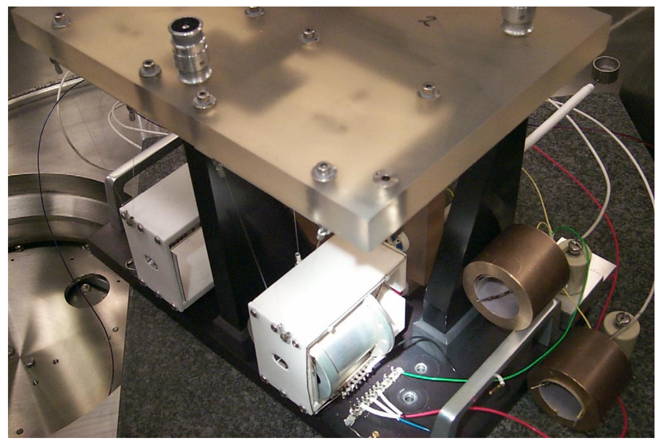


Figure 11 – FEEP-5 installed on the thrust stand

Furthermore, the necessity to feed the thruster with two independent high voltage lines imposed the necessity to take special precautions against EMI and electrostatic coupling between feeding cables. Tentative solutions are currently being implemented (Figure 11); a thick rigid cylindrical brass wall has been for the moment retained as the best compromise between shielding requirements and the necessity to permit delicate wire welding operations.

Conclusions

Two different FEEP thruster models have been successfully interfaced with the simple nulled-pendulum thrust balance for micro-Newton measurements.

Reliable thrust measurements in the 10 (or less) - 100 μN range in an average noisy laboratory environment have been demonstrated to be feasible with this kind of apparatus, although technical constraints make the operation complicated to perform and difficult to reproduce without appropriate interfacing procedures.

The thrust stand set-up with the FEEP-5 is under final optimization and direct thrust measurements at sub 100 μN levels are expected soon.

Acknowledgments

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