Indium FEEP Endurance Test: Preliminary Results[*†]

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Three endurance tests have been carried out in order to investigate the long-term behavior of Indium FEEP microthrusters. The thruster tested is based on the Indium Liquid Metal Ion Source (LMIS), space-proven in a number of scientific satellites up to a thrust of 5 µN, developed by the Austrian Research Centers (ARC). The first endurance test was performed at a thrust of about 17 µN consistent with requirements for missions such as SMART 2, LISA, DARWIN and TPF. It lasted 820 hours at a mean mass efficiency of 45%, an extractor current of less than 1 µA and no sparks. Two more tests were run using profiles from 0-35 µN (plus calibration periods up to 60 µN) and 0-25 µN lasting for 460 and 470 hours respectively. In addition, a lifetime prediction model was developed and experimentally verified to estimate the behavior of microdroplet deposition on the extractor electrode.

Introduction

The Indium FEEP microthruster is under evaluation for several new scientific applications which need drag-free attitude control and ultraprecise pointing at µN level, such as GOCE, SMART-2, LISA, DARWIN and TPF. In view of these important application opportunities, it is mandatory to demonstrate the stability over time of the Indium FEEP and its wear-out resistance. In fact, typical mission applications of interest require operating times of several thousand hours. Hence, an endurance test would provide the confidence in this technology needed to open the way to such challenging applications.

The thruster tested is based on the Austrian Research Center (ARC) Indium Liquid Metal Ion Source (LMIS), space-proven on a number of scientific satellites up to a thrust of 5 µN accumulating more than 1,200 hours in space. A potential difference between 5 and 12 kV is applied between a needle emitter and an extractor electrode to ionize propellant directly out of a liquid Indium metal surface and accelerate it in the same electric field. It can provide a continuous thrust between 0.1 to 75 µN with an accuracy better than 0.1 µN and a very low thrust noise (< 0.1 µN over periods of more than 1000 s). This microthruster can also operate at a peak thrust of 100 µN for short periods. A complete description of the thruster can be found in the referenced literature[1-6].

This paper presents the experimental set-up of the Indium FEEP endurance testing (ion beam collector, beam diagnostics, thrust noise measuring system, on-line mass efficiency measuring system, data acquisition system,...), the results of three endurance tests, and a lifetime prediction model developed and experimentally verified to estimate the behavior of microdroplet deposition on the extractor electrode.

Experimental Set-up

Two vacuum facilities are available at ARC for endurance testing. The first one, the Large Indium FEEP Test Facility # 1 (LIFET 1), consists of a cylindrical, stainless steel vessel of around 1.0 m of diameter, 1.5 m of length and a volume of 1.2 m^3. The pumping system of the LIFET 1 consists of:

- fore-pump, Pfeiffer Balzers DUO 030 A (30 m^3/h)
- turbo-pump, Pfeiffer Balzers TPU 2200 (2200 l/s)

An automatic pumping unit controls both the fore-pump and the turbo-pump. To enhance the final vacuum, the vacuum chamber can be outgassed at about 100° C. Presently, the vacuum level obtained is in the order of 10^{-7} mbar. The pressure in the chamber is measured with a PENNING gauge (BALZERS IKR 010) and a hot-cathode Bayard-Alpert gauge (BALZERS IM 15).

An aluminium ion beam collector has been mounted inside the chamber. It has a chevron configuration, which results in large angles (typically greater than 50 degrees) between the expected ion trajectories and the direction normal to the aluminium surface. This allows to reduce both the collector sputtering yield and the amount of sputtered material directed back towards the thruster.

The current density distribution in the ion beam can be measured by electrostatic wire probes[7]. The Indium FEEP Microthruster is mounted on a special CF 150 UHV flange with the necessary low and high voltage UHV feedthroughs, installed centrally on the end flange, which allows to remove the emitter separately from the chamber (see **Fig. 1**).

The following data are recorded in 2.5 s intervals using BURR-BROWN PCI-20000 series interface cards and KEITHLEY - LABTECH - NOTEBOOK data acquisition software:

- Emitter Voltage
- Emitter Current
- Collector Current
- Chamber Pressure

Furthermore, the accelerator current is measured by an analogue amperemeter. An important improvement of the experimental set-up allows precise measurements of the actual ion beam current; **Fig. 2** shows that the collector current is about 50% higher than the emitter current when an open collector is used. This difference is due to secondary electrons that are released by the collector and are collected by the chamber walls. This can be avoided using a closed collector that completely shields the chamber walls. **Fig. 3** shows

that with a closed collector the difference between the two currents is less than 1% and is due to the accelerator current, that is those Indium ions that do not manage to escape from the accelerator hole. Hence, the collector current now represents a precise measurement of the ion beam current, and can be used for thrust and noise calculations.

Sampling precision of all inputs is 12 bit. The sampled data are stored on the PC's hard disk. Evaluation and presentation of the data is performed using Microcal ORIGIN data analysis and technical graphing software for Windows NT.

The second Large Indium FEEP Test Facility, LIFET 2, includes a cylindrical, stainless steel vacuum chamber of around 0.8 m of diameter, 1.8 m of length and a volume of 0.9 m^3. The pumping system of the LIFET 2 consists of:

- fore-pump, Balzers DUO 35 (35 m^3/h)
- turbo-pump, Pfeiffer TPU 510 (500 l/s)

Presently, the vacuum level obtained is in the order of 10^{-6} mbar. The pressure in the chamber is measured with a PENNING gauge (BALZERS IKR 010). An aluminium ion beam collector has been mounted inside the chamber. It has a closed configuration in order to completely shield the chamber walls; as mentioned before, this allows measurements of the actual ion beam current.

The Data Acquisition System consists of a KEITHLEY Data Acquisition Card and TESTPOINT software.

17 µN Endurance Test

The microthruster tested (V3L7 model) was of the needle type with a reservoir containing 1.2 g of Indium. **Fig. 4** shows the ion emitter which includes the Indium reservoir and the tungsten needle. This Indium FEEP Microthruster was mounted in the LIFET 1.

This endurance test started on the 21st of July, 2001, setting the emitter current (stabilised by a standard HEINZINGER HV power supply) to a constant value of about 150 µA (see **Fig. 5**), which corresponds to a

thrust of about 17 µN. This thrust level is consistent with the requirements of several new scientific missions, such as SMART 2, LISA, DARWIN and TPF.

Fig. 6 shows a comparison between the emitter current and the collector current, which is the actual ion beam current. The difference between these two currents, which represents the extractor current, was practically negligible over the whole test, as it can be seen in **Fig. 7** which shows that the collector current stayed very stable over more than 800 hours of continuous operation. In fact, the test ended on the 24th of August, 2001, with the total consumption of the propellant. This is a good indication of the effectiveness of the integrated Indium zero-g reservoir, which uses capillary forces in order to supply the needle with the liquid metal.

Fig. 8 shows the emitter voltage during the 17 µN Endurance Test. Post-test visual inspection found out no indication of electrode erosion and needle de-wetting (end of life - due to lack of In), but only a small decrease of the extractor hole due to Indium droplet deposition. This caused the 1 kV decrease in the emitter voltage after around 500 h of continuous operation. This is in line with the results of the lifetime prediction model, estimating a slow closing of the extractor due to microdroplet deposition (see **Fig. 28**).

Fig. 9 shows the calculated thrust during the 17 µN Endurance Test. The results show a good thrust stability even in current stabilised mode (open loop). In fact, the standard deviation is only 3.5% of the mean value (17.1 µN); however, in thrust stabilisation mode (closed loop) the standard deviation can be 10 times lower[5-6].

Mass efficiency is an important parameter describing the amount of propellant emitted in the form of unionised neutral microdroplets which do not contribute to thrust. In order to estimate this parameter on-line during thruster operation, a Quartz Crystal Microbalance (QCM) was installed in the LIFET 1, at the base of the collector aligned to the ion emitter. With proper calibration by standard mass loss measurement, the QCM can give real-time mass efficiency reading during long term test runs of Indium FEEP thrusters[6].
In a mixed ion/droplet beam, as for every Liquid Metal

Ion Source including FEEP thrusters, both material deposition and material erosion (sputtering) are taking place simultaneously on the QCM. The droplet component is responsible for the deposition (sputtering effect negligible) and the ion component is responsible for the sputtering, both from the original substrate and the droplets deposited by the beam itself.
Fig. 10 shows that the QCM reading decreased with a constant slope (-2.5 nm/day) during the first 6 days of continuous operation at 17 µN, i.e. ion sputtering was higher than droplet deposition. Then, the slope changed to about −1.3 nm/day, and it stayed constant for the rest of the test. This means that the instantaneous mass efficiency was constant over more than 800 hours of continuous operation, except for a small change after 6 days. Using the proper calibration for the QCM, we obtain mass efficiency values of 63% and 42% for the first and second part of the test run respectively.

Precision weighing of the microthruster before and after this endurance test showed that the mean mass efficiency was 45%. A short test performed with the same microthruster using the last milligrams of Indium left in the reservoir showed the same value for the mass efficiency.

0-35 µN Endurance Test

The second endurance test was started in the LIFET 1 on the 25th of August, 2001. The microthruster tested (V3R1 model) was of the needle type with a reservoir containing 1.2 g of Indium.

This test was performed commanding a sin^6 profile for the emitter current from 0 to 350 µA, with a period of 5000 s, as shown in **Fig. 11** (nominal operation). This leads to a thrust profile from 0 to about 35 µN. Furthermore, once per week a half-sinus profile with 0.1 Hz frequency and 250 µA amplitude was superimposed to the nominal profile for 6 hours (calibration phase). The total thrust peak of both is then about 60 µN. This was done according to the requirements of GOCE, which will soon choose the micropropulsion system needed for the mission.

Fig. 12 shows the thruster response in terms of emitter voltage. The two threshold voltages (ion emission on and off) are clearly visible. It is interesting to note that for this emitter the on-voltage (~4.6 kV) was higher

than the off-voltage (~3.4 kV).   Then, the emitter voltage followed the current according to the thruster characteristic; it ranged from 4.6 kV (1 μA) to about 6 kV (350 μA) and then down to 3.4 kV.

Fig. 13 shows the collector current, which is the actual ion beam current. **Fig. 14** shows a comparison between the emitter current and the collector current. The difference between these two currents, which represents the extractor current, was less than 10 μA at the maximum emitter current (350 μA), and it stayed below 5% of the emitter current over the whole endurance test.

Fig. 15 shows the thrust calculated from the emitter voltage shown in **Fig. 12** and the collector current in **Fig. 13**. The thrust ranges from 0 to about 35 μN with a good reproducibility. **Fig. 16** is an enlargement of the previous graph; it shows that very low thrust levels can be commanded, even below 0.1 μN.

Fig. 17 shows the start of the first calibration phase, that is once per week a half-sinus profile with 0.1 Hz frequency and 250 μA amplitude superimposed to the nominal profile for 6 hours. The total thrust peak of both is then about 60 μN, as shown in the enlargement in **Fig. 18**. A total of 6500 calibration cycles have been performed during this test (three calibration phases each of 6 hours).

Fig. 19 shows the emitter voltage during the 0-35 μN Endurance Test. The peak voltage corresponding to 350 μA fluctuated between 6 and 7 kV during the test. **Fig. 20** shows the collector current; the three calibration phases, each of 6 hours, are clearly observable.

Fig. 21 shows the calculated thrust over about 460 hours of continuous operation with the emitter current ranging from 0 to 350 μA. This means 330 on-off cycles without any significant performance degradation. The fluctuation of the peak thrust observable in **Fig. 21** is not real, but is due to a failure of the Microcal ORIGIN data analysis and technical graphing software in plotting so many data. In fact, this is not observable in the enlargement in **Fig. 22**. Here, the peak thrust stayed quite constant to a value of 35 μN and it increased up to 60 μN during the three calibration phases. However, in this test only the emitter current is controlled; hence, the thrust follows

the behaviour of the emitter voltage. This can be easily settled by controlling both the current and the voltage in a closed loop.

Precision weighing of the microthruster before and after this endurance test showed that the mean mass efficiency was 18%. %. This low value is due to the fact that it was not possible (due to time constraints) to start this test with an emitter being specially treated for high mass efficiency.

0-25 μN Endurance Test

The third endurance test was started in the LIFET 2 on the 20th of August, 2001. The microthruster tested (V3LOR2 model) was of the needle type with a reservoir containing 1.2 g of Indium.

This test was performed commanding a half-sinus profile for the emitter current from 0 to 250 μA, with a period of 5000 s. This leads to a thrust profile from 0 to about 25 μN, as shown in **Fig. 23**. **Fig. 24** shows the thruster response in terms of emitter voltage. The two threshold voltages (ion emission on and off) are clearly visible, and they have almost the same value for this emitter.

Fig. 25 shows the calculated thrust over about 470 hours of continuous operation with the emitter current ranging from 0 to 250 μA. This means 340 on-off cycles without any significant performance degradation. The peak thrust is not constant because in this test only the emitter current is controlled; hence, the thrust follows the behaviour of the emitter voltage. This can be easily settled by controlling both the current and the voltage in a closed loop. The sudden decrease of the thrust after 470 h of operation corresponds to the total consumption of the propellant.

Lifetime Prediction Model

In addition to the propellant reservoir size, lifetime of an In-FEEP thruster can be affected by microdroplet emission towards the extractor electrode. Those microdroplets can close the extractor hole, only counterbalanced by primary ion beam sputtering (see **Fig. 26**).

Using experimental measurements on microdroplet angular distribution[8] and ion beam profiles[9], the time dependence of the extractor hole diameter could be successfully modelled. The main input parameters are:

- Extractor geometry (hole diameter, emitter-extractor distance)
- Emitter current
- Mass Efficiency

Using these input data, the final extractor diameter at the end of several pre-endurance test runs were compared with the model. A comparison is shown in **Fig. 27**.

The lessons learned (geometry, mass efficiency) were implemented and the endurance tests were started as reported before. In order to predict lifetime for a profile, we need to implement a model for the mass efficiency dependence on the emitted current. Up to 20 μA (corresponding to about 2 μN) no microdroplets occur and the mass efficiency is 100%. This was verified in a number of tests and agrees with the literature[9]. Above 20 μA, mass efficiency decreases first sharply and then linearly with the emitted current. This decrease can be expressed as a polynomial function $y = A*x^B + C$. The parameters for the polynomial function are mainly dependent on the Indium film geometry and can be adjusted by proper wetting.

Using all these models, we can predict the extractor hole diameter even for temporal profiles. A comparison between the 17 μN Endurance Test (flat profile) and the two 500 hours profile tests with the model are shown in **Fig. 28**. The agreement is again very good which further increases confidence in the lifetime prediction model.

The model can now be used to extrapolate endurance test data to actual flight requirements. All parameters (mass efficiency, geometry) can be adjusted in order to fulfil both thrust and lifetime requirements. The predicted extractor hole for a 10,000 hours test using a 250 μA profile and a 4.5 mm extractor is shown in **Fig. 29**. The very good comparison of model predictions and measurements provide good confidence that such a configuration will exceed lifetime of 10,000 hours and has only propellant consumption as a limiting factor.

Conclusions

ARCS have carried out three endurance tests of the Indium FEEP Microthruster. These tests include the longest continuous test ever performed with a FEEP (820 h), at a thrust level (17 μN) consistent with the needs of the LISA mission. This has been done with only 1.2 g of Indium, that is with a mean mass efficiency of 45%.

Other two endurance tests have demonstrated the capability of this microthruster to carry out on-off cycles with a good reproducibility of performance. These endurance tests increase the confidence in this technology needed to open the way to challenging applications like LISA, DARWIN and TPF.

The only limiting factor detected during these tests is the microdroplet emission towards the extractor electrode. A lifetime prediction model has been developed and experimentally verified to estimate the behavior of microdroplet deposition on the edge of the extractor hole. The very good comparison of model predictions and measurements provide confidence that the Indium FEEP Microthruster can exceed lifetime of 10,000 hours.

References

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[2]   M. Fehringer, F. Rüdenauer and W. Steiger, "Space-Proven Indium Liquid Metal Field Ion Emitters for Ion Microthruster Applications"*, 33rd AIAA Joint Propulsion Conference*, Seattle, AIAA 97-3057, July 1997

[3]   M. Fehringer, F. Rüdenauer and W. Steiger, "Indium Liquid-Metal Ion Sources as Micronewton Thrusters", *2nd International LISA Symposium*, Pasadena, California, 6-9 July 1998

[4]   M. Fehringer, F. Ruedenauer and W. Steiger, "Micronewton Indium Ion Thrusters"*, 16th International Electric Propulsion Conference*, Japan, 17–21 October 1999

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3rd European Spacecraft Propulsion Conference, Cannes, France, ESA SP-465, October 10-13, 2000

[6]   A. Genovese, W. Steiger and M. Tajmar, "Indium FEEP Microthruster: Experimental Characterization in the 1 – 100 µN Range", *Proceedings of the 37th Joint Propulsion Conference*, Salt Lake City, Utah, AIAA 2001-3788, July 2001

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[8]   M. Fehringer, F. Ruedenauer and W. Steiger, "WP 2000: Droplet Emission", Technical Note Nr. 2, Ultra-Precise Indium Thruster, ESTEC Contract 12376/97/NL/PA, 1998

[9]   V.V. Vladimirov, V.E. Badan and V.N. Gorshkov, "Microdroplet emission and instabilities on liquid-metal ion sources", Surface Sciences, **266**, 1992, pp. 185-190

Fig. 1 - Left image: ARC Large High Vacuum Chamber No. 1; right image: aluminium collector inside the vacuum chamber.
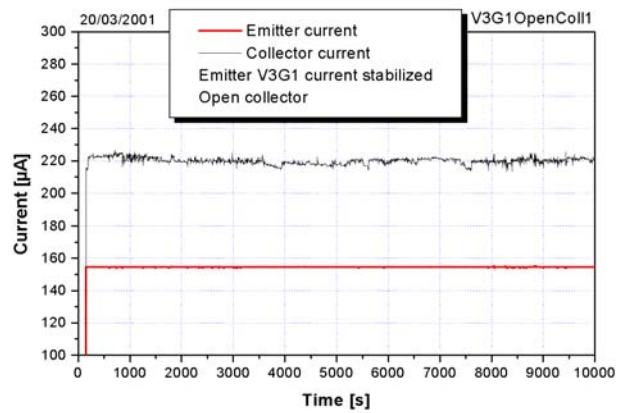
Fig. 2 - Comparison between the emitter and collector currents with an open collector
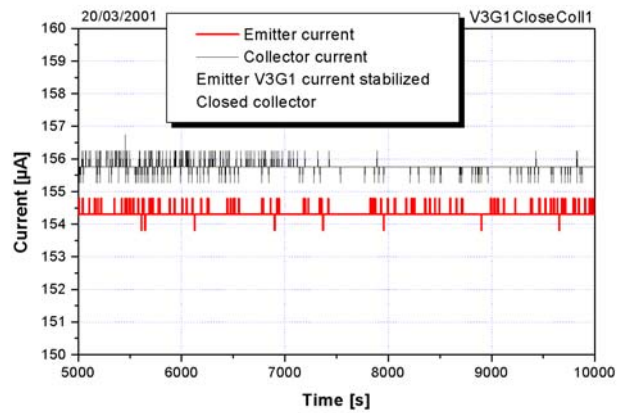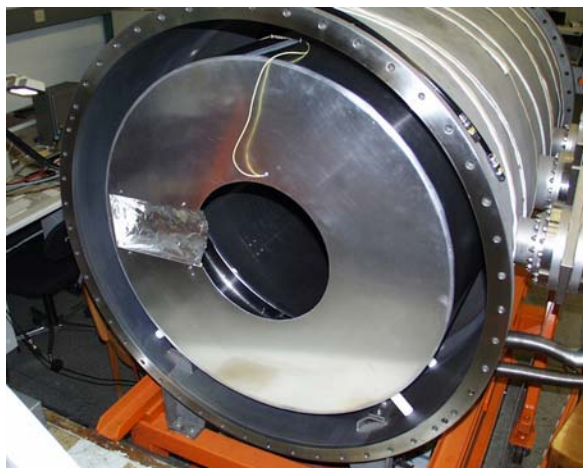
Fig. 3 - Comparison between the emitter and collector currents with a closed collector (small scale, 1 Bit resolution)
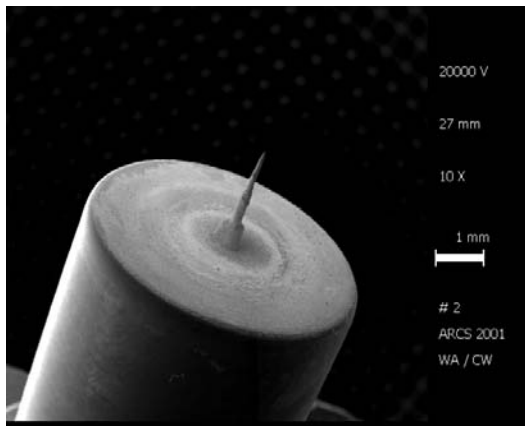
Fig. 4 - V3L7 Indium FEEP ion emitter.
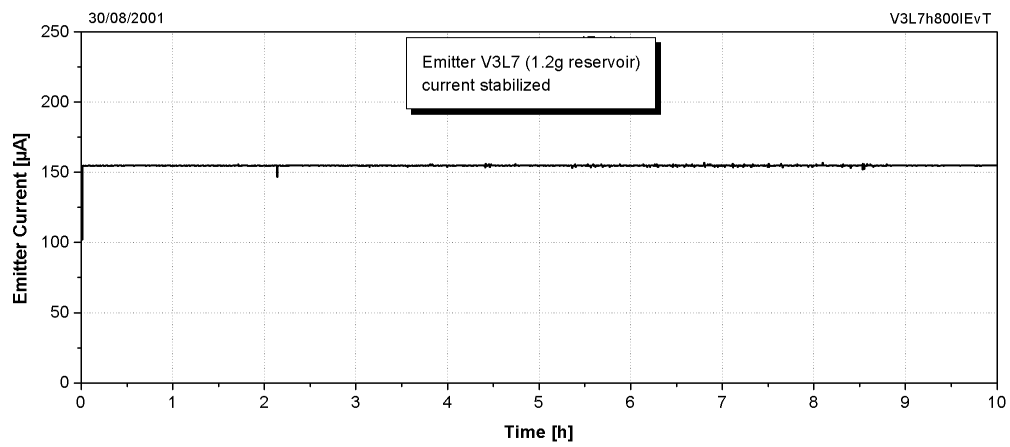
Fig. 5 – Emitter current versus time
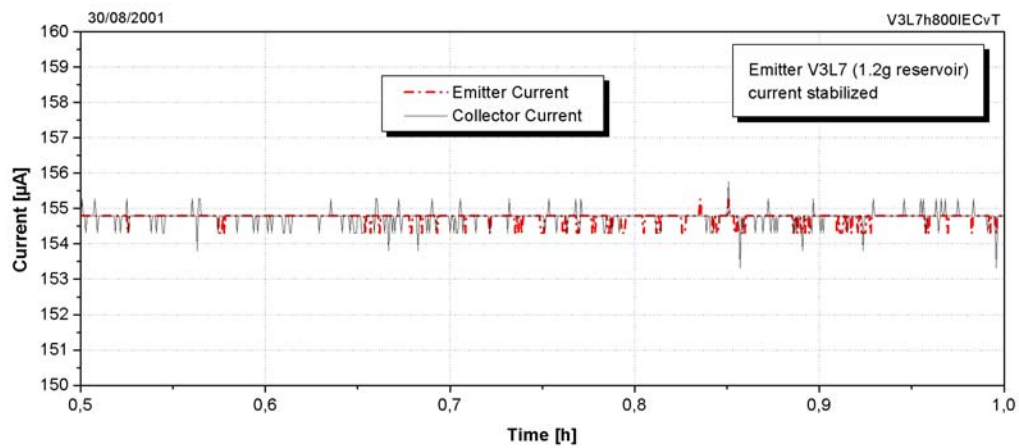
Fig. 6 – Comparison between emitter current and collector current (small scale, 1 Bit resolution).

Emitter V3L7 (1.2 g reservoir)
current stabilized

Mean value = 156,6 μA
Standard deviation = 0.7%
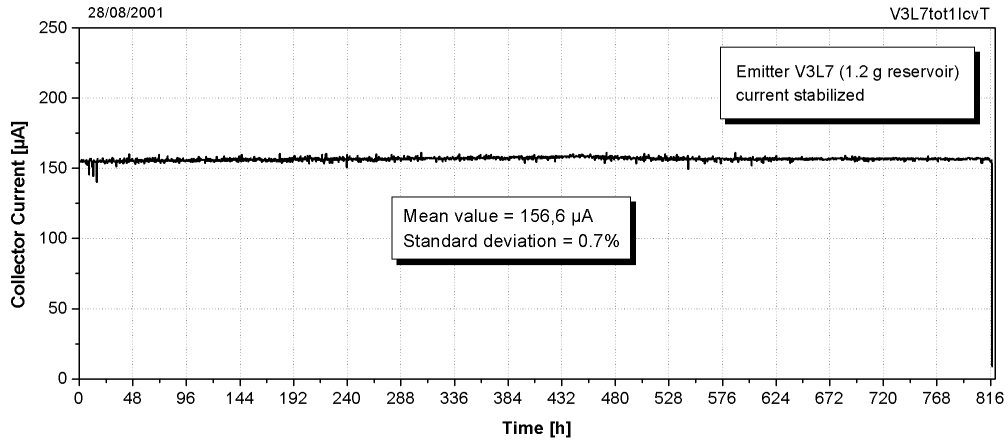
Fig. 7 – Collector current during the 17 μN Endurance Test

Emitter V3L7 (1.2 g reservoir)
current stabilized

Fig. 8 – Emitter voltage during the 17 μN Endurance Test.

Emitter V3L7 (1.2 g reservoir)
current stabilized

Mean thrust = 17.1 μN
Standard deviation = 3.5%
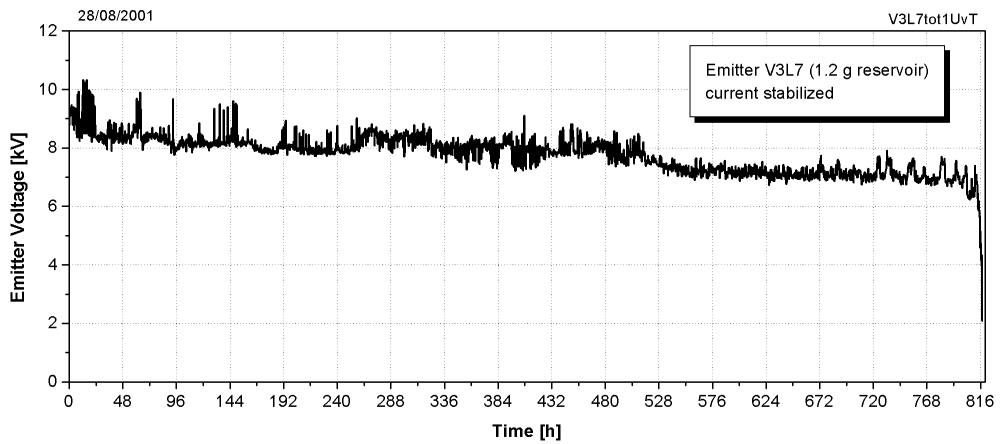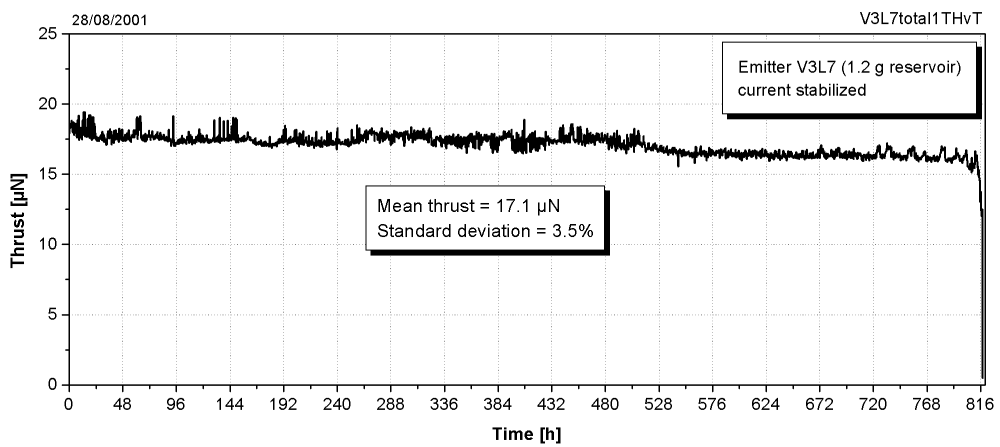
Fig. 9 – Calculated thrust during the 17 μN Endurance Test.
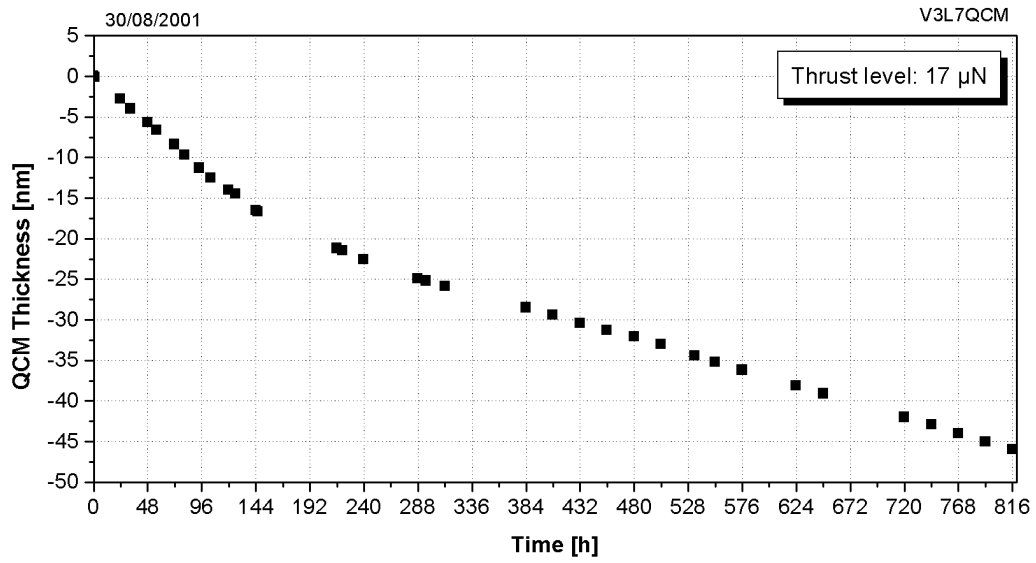
Fig. 10 – QCM reading during the 17 μN Endurance Test.
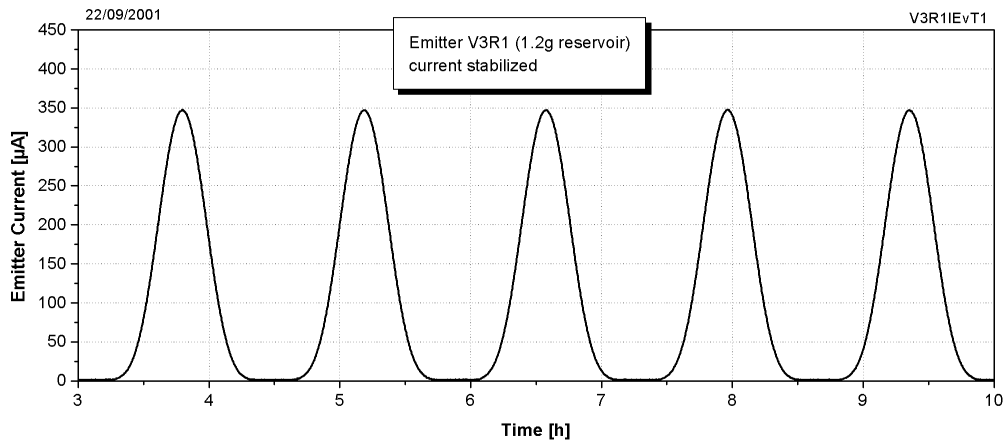
Fig. 11 – Emitter current versus time
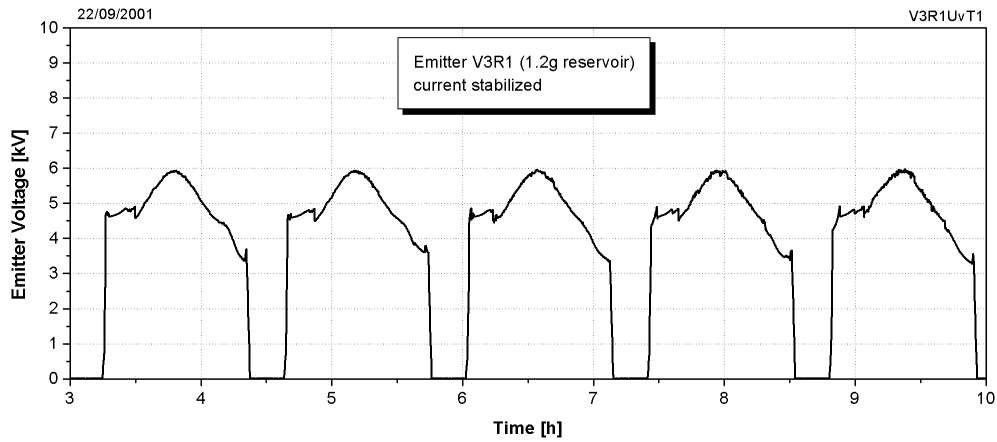
Fig. 12 – Emitter voltage versus time
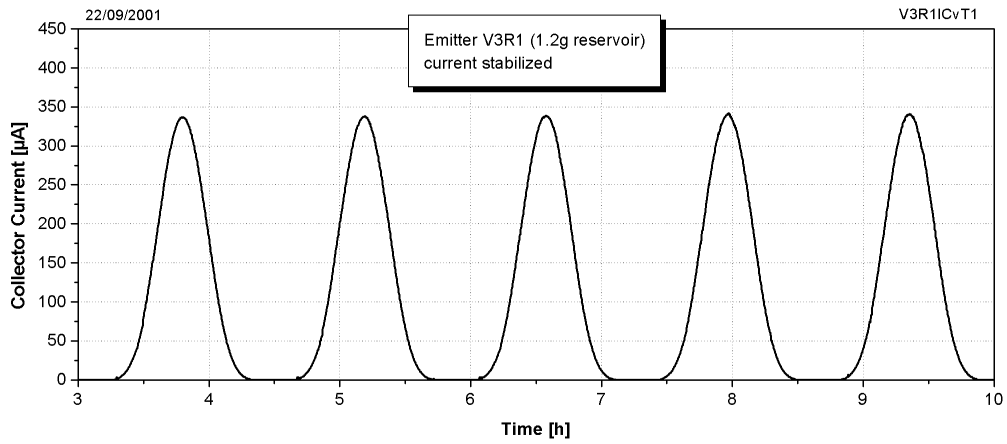
Fig. 13 – Collector current versus time
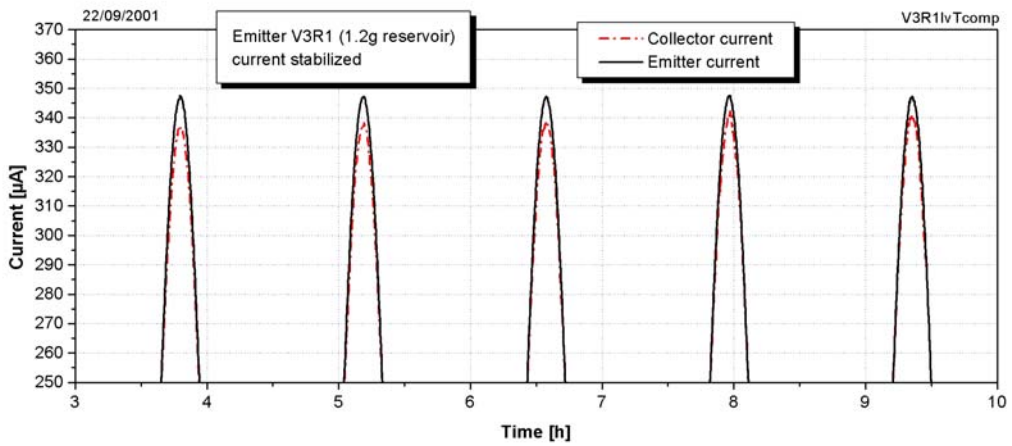
Fig. 14 – Comparison between emitter current and collector current

Fig. 15 – Calculated thrust versus time

22/09/2001   V3R1THvT2

Emitter V3R1 (1.2g reservoir)
current stabilized
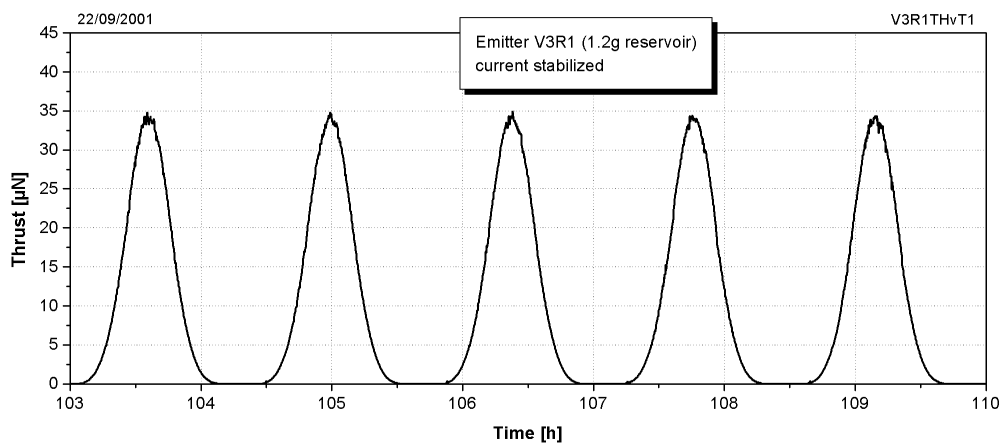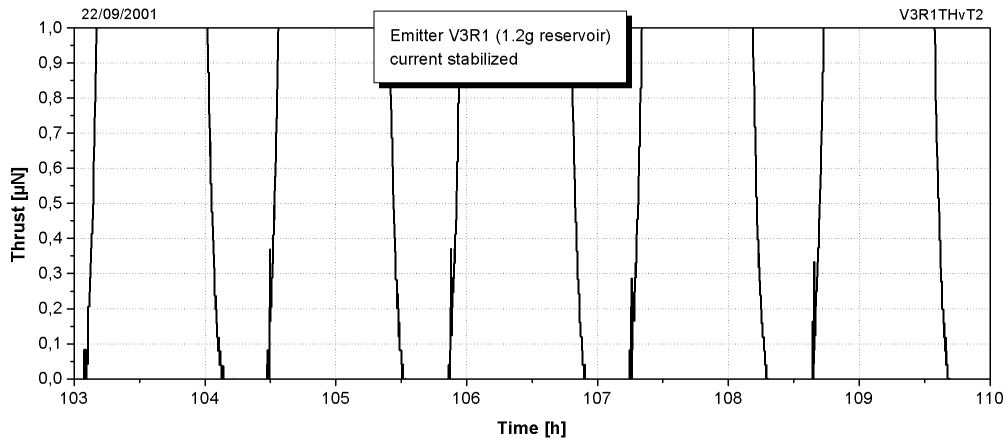
Fig. 16 – Calculated thrust versus time; enlargement.

22/09/2001   V3R1G2THvTcal1

Emitter V3R1 (1.2g reservoir)
current stabilized

Fig. 17 – Calculated thrust versus time during the calibration phase.

22/09/2001   V3R1G2THvTcal

Emitter V3R1 (1.2g reservoir)
current stabilized
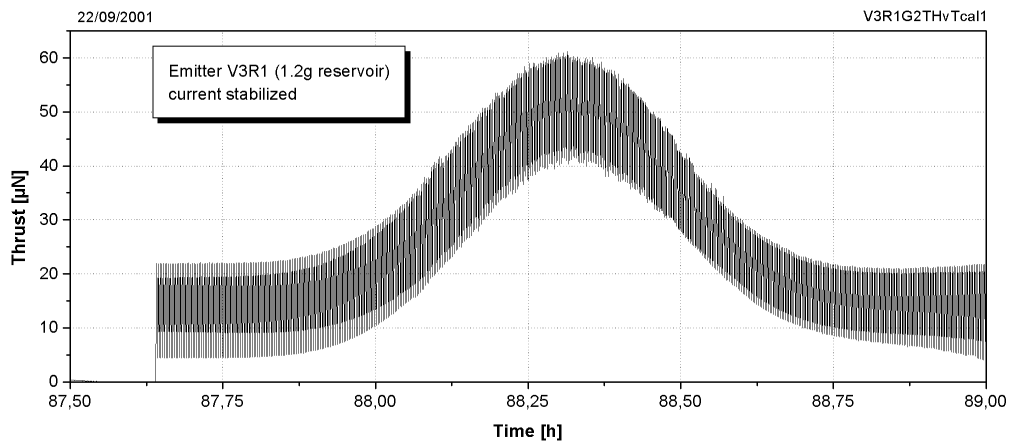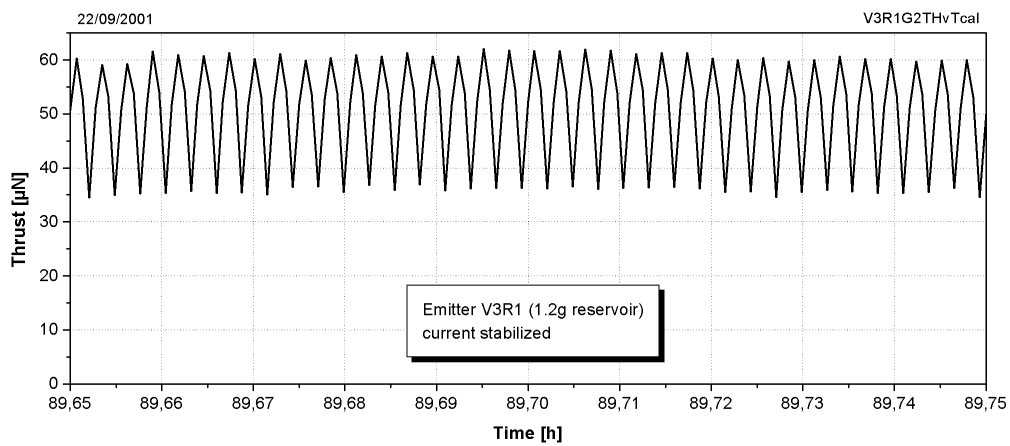
Fig. 18 – Calculated thrust versus time during the calibration phase; enlargement.
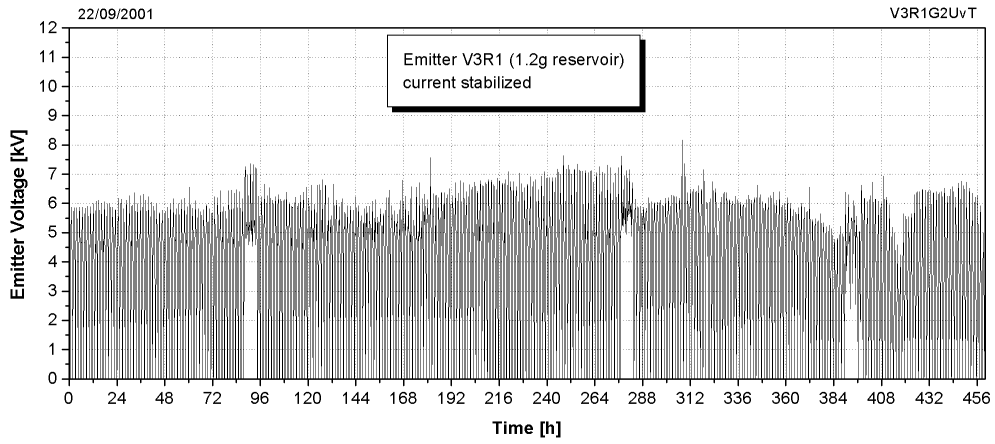
Fig. 19 – Emitter voltage during the 0-35 µN Endurance Test.
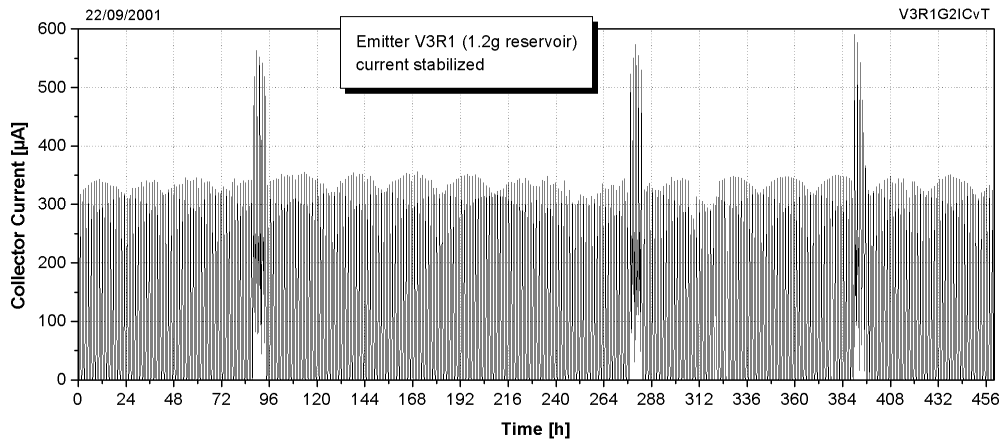
Fig. 20 – Collector current during the 0-35 µN Endurance Test.
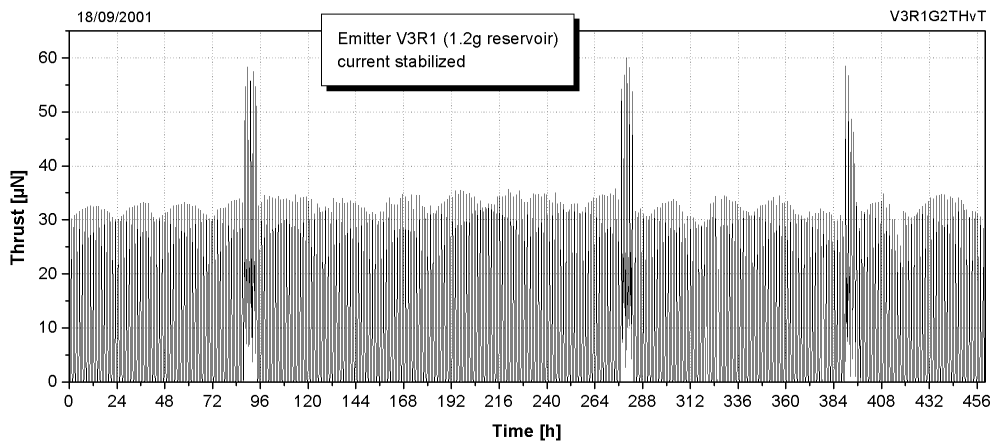
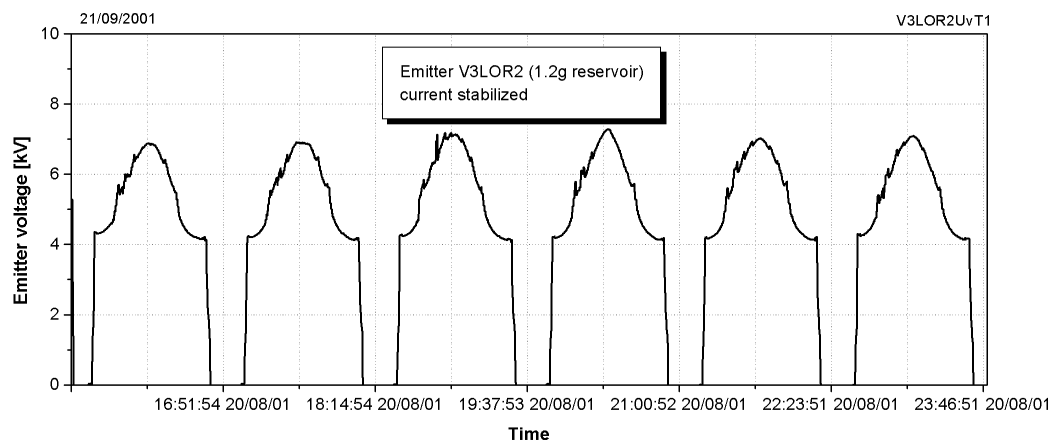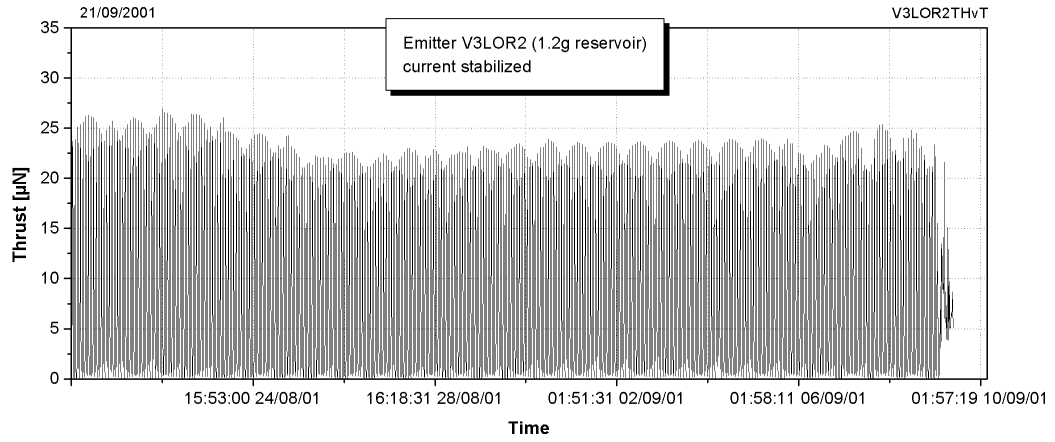**Fig. 21** – Calculated thrust during the 0-35 µN Endurance Test.
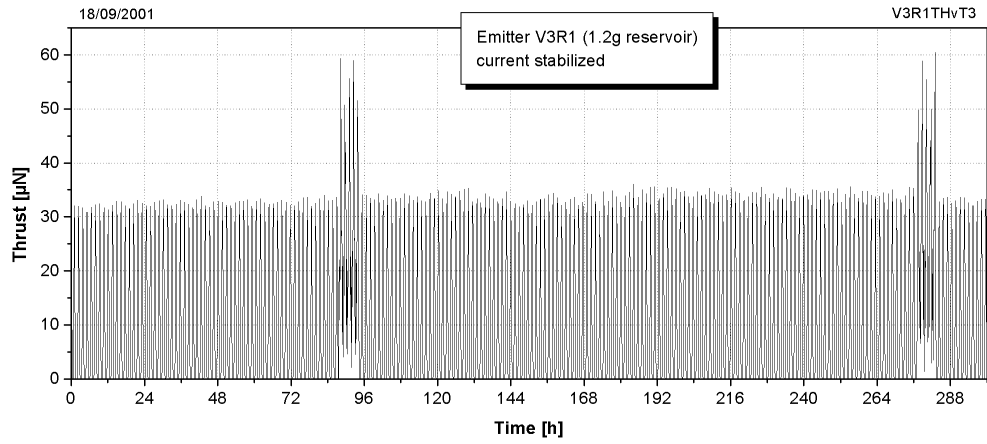
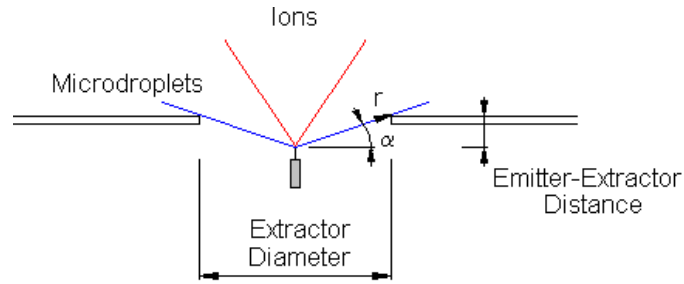**Fig. 22** – Calculated thrust during the 0-35 µN Endurance Test; enlargement.
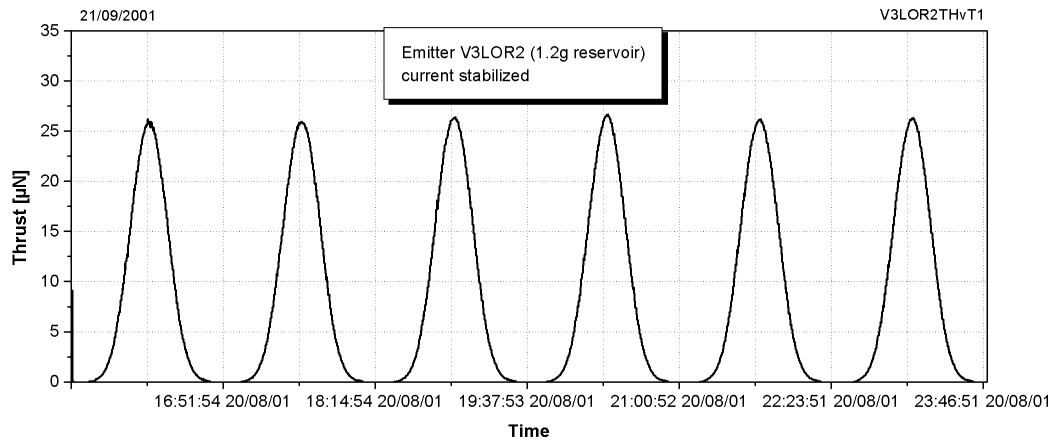
Fig. 23 – Calculated thrust versus time (0-25 µN Endurance Test).

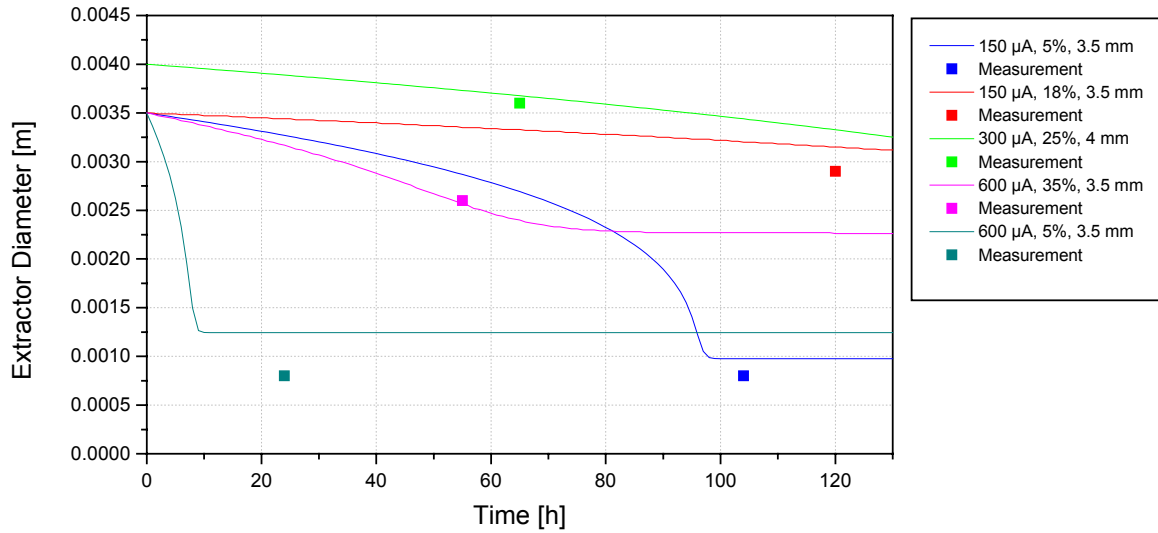**Fig. 24** – Emitter voltage versus time (0-25 µN Endurance Test).
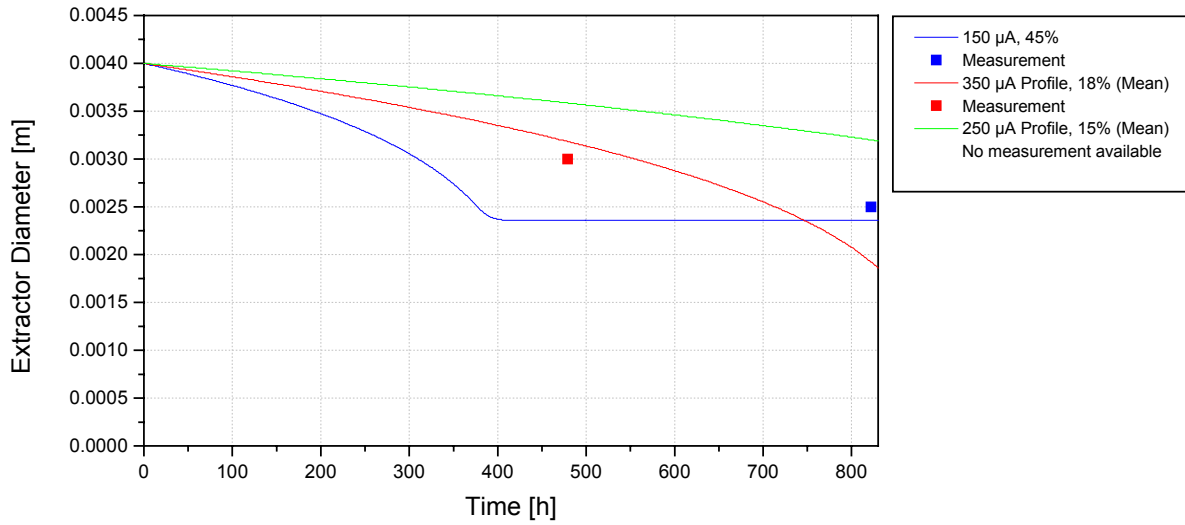
Fig. 25 – Calculated thrust during the 0-25 µN Endurance Test .
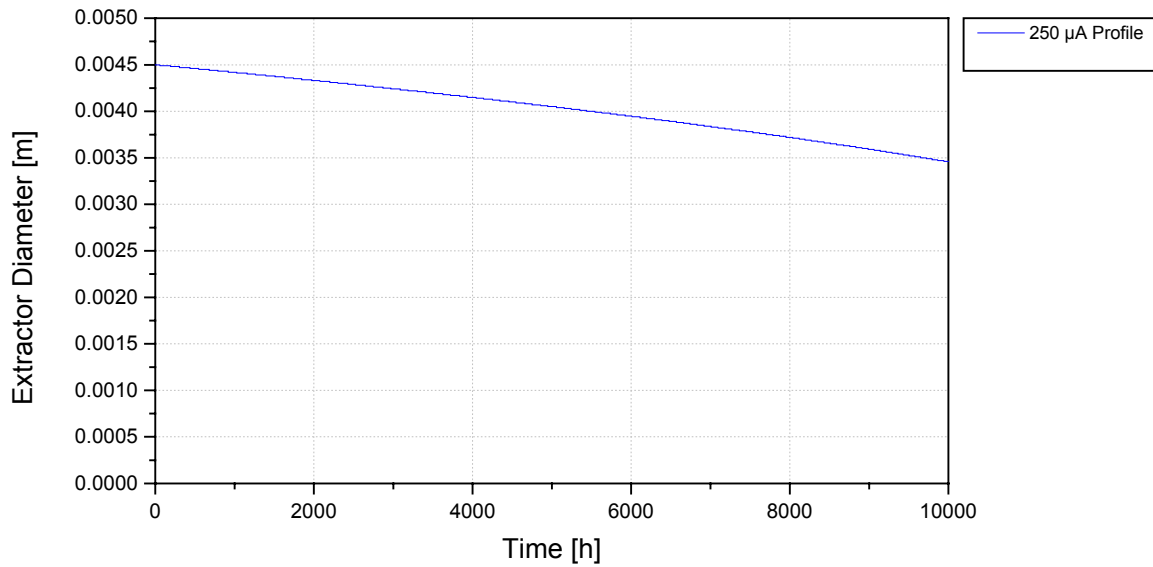

Fig. 26 - Microdroplet Deposition and Ion Beam Sputtering on Extractor Electrode

Fig. 27 - Lifetime Prediction Model Comparison with Experimental Data

Fig. 28 - Comparison of Model with Endurance Tests in this Report

Fig. 29 - Model Prediction for a 10,000 hours Test using a 250 µA Profile