TEST OF A NOVEL FEEP EMITTER WITH LISA PF HARDWARE

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The focus of the Austrian FEEP system developed in the framework of the LISA PF program was the so-called needle FEEP technology. In all the qualification tests conducted within the LISA PF program, this technology was shown to be compliant with all LISA PF and LISA performance requirements. However, the needle FEEP development program suffered from several setbacks. The needle FEEP technology requires highly accurate manufacturing processes on a µm scale. The control of those processes was never fully achieved to ensure proper and timely manufacturing rates for the flight hardware. At this point, another technology was re-introduced, the capillary liquid metal ion source (LMIS). This technology was developed by FOTEC and is the only flight proven liquid metal ion source (LMIS) technology (Cluster, Double Star etc.). The only major difference between flight proven capillary emitters and the one necessary for a FEEP system for LISA PF is the size of the tank. LMIS normally have tanks in the range of 1 g. For LISA PF a tank size sufficiently large to hold 15 g of propellant is necessary. However, due to the lower performance of capillary emitters compared to needle emitters, they were discarded in the very beginning of the LISA PF program. In hindsight, one of the great advantages of capillary type emitters is their rather simple manufacturing process – a feature which, from a programmatic view point, might balance the lower performance. In order to demonstrate the feasibility to use the capillary emitters, FOTEC was asked to manufacture 9 emitters and test them with LISA PF thruster hardware. In order to maximize the amount of information with regard to performance and general functionality of the capillary technology, it was decided to conduct a thermal vacuum test (TVT) combined with an endurance test.

The test was run for 930 hours, generating a total impulse of 114.7 Ns. During the 230 hours of the thermal vacuum test, compliance with all the LISA PF thermal requirements has been demonstrated. Thruster characterizations conducted throughout the test showed a very stable operation. In total, the necessary thruster voltage at 100µN increased only 2.8% over the complete test. A thrust range from <1 µN up to 135 µN has been demonstrated The average specific impulse of the thruster was 5018 s, exceeding by far the 4000 s requirement of LISA PF. In conclusion, integrated in the LISA PF hardware, capillary emitters showed a surprisingly good performance and can indeed be considered as a workable alternative to the needle technology.

1. Introduction

The Laser Interferometer Space Antenna (LISA) is a co-operative program between ESA and NASA to detect gravitational waves by measuring distortions in the space-time fabric. The program consists of two space missions: LISA Pathfinder (LISA PF), to be launched in 2016, and LISA itself. There is no launch date for LISA presently. However, the LISA mission shall consist of three spacecrafts flying in a triangular formation with a side length of several million kilometers. The position of each satellite with respect to its two counterparts has to be controlled with an accuracy of 10^{-9} m to ensure sufficient accuracy of the scientific measurements. The extreme challenge in position control can only be satisfied with an ultra precise propulsion system such as an Indium FEEP thruster. LISA will demonstrate for the very first time a near perfect gravitational free fall to detect gravitational waves.

LISA Pathfinder (LISA PF) is the precursor mission to LISA designed to validate the core technologies intended for LISA. In general most of the challenging propulsion requirements of LISA are also valid for LISA PF (see table 1). The micro-propulsion system is one of the enabling technologies for LISA as well as for LISA Pathfinder. In 2006, a consortium consisting of SELEX Galileo S.p.A, Astrium ST, FOTEC (originally the Space Propulsion & Advanced Concepts Business Division of the Austrian Institute of Technology-FOTEC was commissioned by the ESA to develop the micro-propulsion system for those missions. The micro-propulsion system under development is based on a Liquid Metal Ion Source (LMIS) technology which was developed by FOTEC over the last three decades and the technological maturity and lifetime capability of the LMIS technology has been shown in the past decade[i,ii,iii,iv].

Still up to this date, the FOTEC LMIS technology is the only LMIS technology ever operated under space conditions and has logged more than 15,000 hrs in-space operational hours in various applications such as massspectrometry and space-charge compensation[v] but not yet for propulsive purposes (i.e. Field Emission Electric Propulsion, FEEP)

2. In-FEEP Cluster Assembly

LISA and its precursor mission, LISA PF, have propulsion requirements unprecedented in the history of space propulsion. Highly challenging propulsion system requirements (see Table 1) in terms of thrust range, controllability and thrust noise, to name only some of the challenging requirements make the FEEP technology presently the only propulsion system capable to satisfy the needs for LISA.

In order to produce the maximum thrust level of 100 µN as required for LISA Pathfinder, nine LMIS are operated in parallel by a single high voltage power supply in one, so-called Thruster Cluster Assembly (TCA). The number of 9 emitters is the result of a trade-off between lifetime and available power. By this clustering approach the Indium FEEP thruster assembly provides an inherent redundancy. In case one LMIS element fails, the remaining 8 LMIS continue to provide the commanded thrust as the cumulative beam current is still equivalent to the selected voltage. Especially during science mode, when the thrust level is expected to be between 0.3 µN and about 30µN even a failure of up to 6 emitter would have no significant effect in terms of required thrust.

In order to transfer the FOTEC FEEP technology into a flight model, FOTEC joined forces with Astrium ST as industrial partner covering the experience from electric propulsion flight programs to optimized mechanical/thermal design and space qualified high voltage experience[vi]. A flight cluster assembly (FCA) (shown in Figure 1) consists of 4 Thruster Cluster Assemblies (TCA), each containing 9 LMIS and assembled in a truncated pyramid shape structure.

Table 1: LISA PF Key Thruster Requirements.

Minimum Thrust	0.3 µN (Target 0.1 µN)
Maximum Thrust	100 µN (Target 150 µN)
Total Impulse	2920 Ns (Target 4000 Ns)
Thrust Noise	< 0.1 µN/Hz (from 0.01 – 10 Hz)
Thrust Resolution	1 µN
Specific Impulse	> 4000 s
Beam Divergence	< 35°

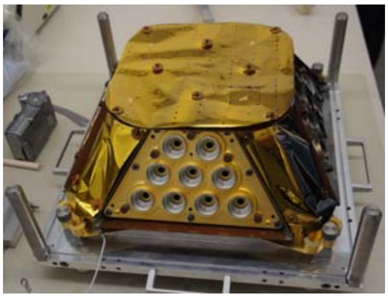

Figure 1: Complete FCA showing one TCA with 9 emitter

Verification and qualification of the In-FEEP technology and the TCA/FCA design was conducted in a series of tests within the LISA PF program. This included performance evaluations on LMIS level but also on TCA and FCA level, environmental test such as shock and vibration test as well as acoustic noise tests (see Figure 2). All those tests were passed with a very comfortable margin[vii].

However, the needle FEEP development program suffered from several setbacks. The needle FEEP technology requires highly accurate manufacturing processes on a µm scale. The control of those processes was never fully achieved to ensure proper and timely manufacturing rates for the flight hardware. This resulted in a very large rate of rejected emitters which again caused a significant increase in manufacturing efforts with a very detrimentally impact on project schedule as well as project budget. Facing the manufacturing problems it became clear that in spite of the good performance of the In-Needle FEEP system this technology has not yet achieved sufficient maturity for a flight mission such as LISA PF.

At this point, another technology was re-introduced, the capillary LMIS. Due to the lower performance of capillary emitters compared to needle emitters, they were discarded in the very beginning of the LISA PF program. In hindsight, one of the great advantages of capillary type emitters is their rather simple manufacturing process – a feature which, from a programmatic point of view, might balance the lower performance. This technology was developed by FOTEC and is the only flight proven liquid metal ion source (LMIS) technology (Cluster, Double Star etc.). The only major difference between flight proven capillary emitters and the one necessary for a FEEP system for LISA PF is the size of the tank. LMIS normally have tanks for propellant in the range of 1 g. For LISA PF a tank size for 15 g of propellant is necessary. In order to demonstrate the feasibility to use the capillary emitters, FOTEC was asked to manufacture 9 capillary emitters on standard LISA PF (15g) tanks and test them with LISA PF thruster hardware. In order to maximize the amount of output of such a test, it was decided to conduct a thermal vacuum test (TVT) combined with an endurance test.

With regard to the manufacturing difficulties experienced within the LISA PF program, it is very important to note that all 9 emitters were manufactured in a matter of 1 week and were not pre-tested or pre-selected prior to integration into the TCA.

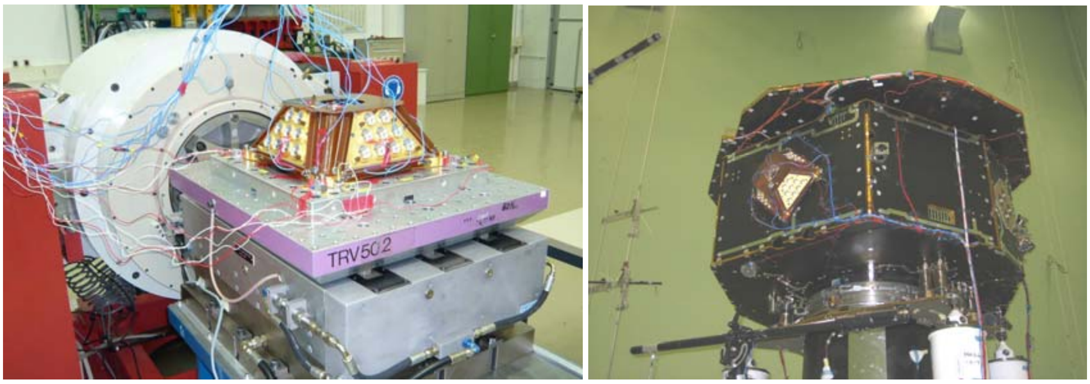

Figure 2: FCA during vibration and shock test at IABG (left) and integrated on the LISA PF Spacecraft Structure during Acoustic Noise Test (right)

3. Test plan and test equipment

The test plan foresaw to start with the TVT test and proceeding with the endurance testing without test interruption (see table on the right). The detailed test plan can be seen in the table on the right. The test set-up was identical to the one used in previous testing (shown in Figure 3). Figure 4 shows the FCA mounted on the thermal interface plate (simulating the satellite surface) and the thermal conditioning plate (cooled with LN2). The temperature of the thermal interface plate can be controlled by the mass flow rate of LN2 through the thermal conditioning plate, an independent set of two high power ohmic resistive loads and a set of four Peltier elements. Unfortunately the ohmic resistors and the Peltier elements suffered damage during the test.

Capillary FEEPS	
Phase no.	**Test Phase Description**
0	Initial Check-out
1	Pump Down
2	Outgassing and Heat-Up
3	FEEPs ambient test (performance testing)
4	Conduct cycling
5	Recovery of TVT to ambient temperature
6	FEEPs ambient test (performance testing)
7	Initiate endurance testing
8	Recovery Thruster to Ambient Temperature
9	Recovery to Ambient Pressure
10	Post Test Check-out
	Total (phases 1 to 10)

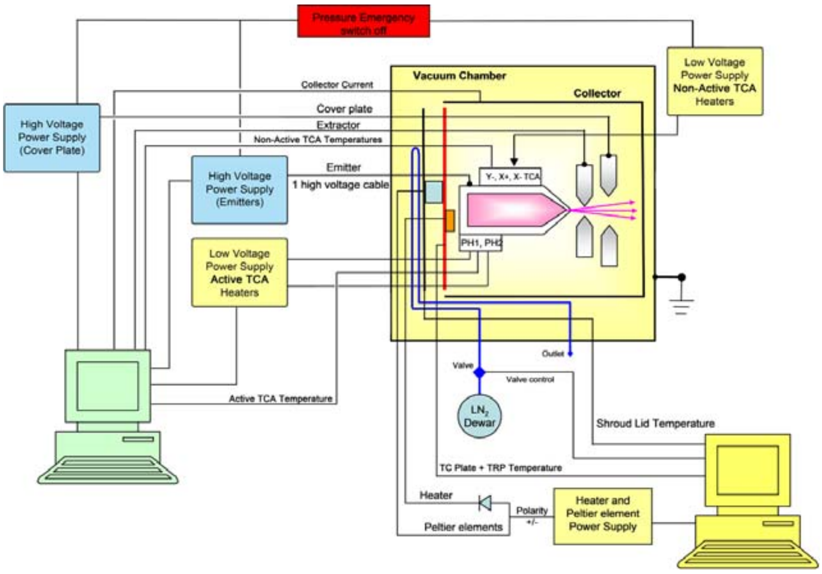

Figure 3: Schematic of the electrical set-up for the TVT and Endurance test

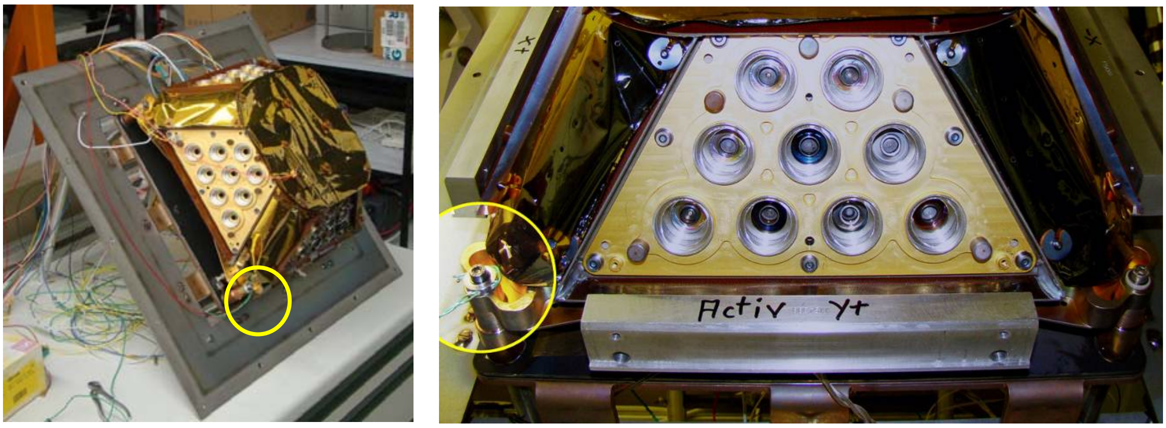

Figure 4: FCA mounted on the temperature controlled plate and conditioning plate shroud (left). Right photo shows front view of the active TCA. Yellow circles indicates position of the temperature reference point (TRP)

4.TVT tests results

The test was started with the Thermal Vacuum Test (TVT). The test procedure foresaw seven thermal cycles with temperatures at the reference point between -1°C and 110°C. After two cycles, a new delivery of LN2 for the cooling did not arrive on time and the test had to be kept on hold for nearly 2 days (between hour 40 and 90 in Figure 5). After resuming the test it turned out to be impossible to stabilize the set-up at the maximum temperature level of 110°C (post-test assessment showed damaged Peltier elements as well as a partially melted contact in the electrical line connecting the resistive loads). In order to proceed with the test, ESA relaxed the test conditions such that the maximum required temperature was only 80°C. Under those conditions the TVT was successfully finished. In order to investigate if the different thermal conditions have any impact on thruster performance, a series of characterization at five distinct temperature levels have been conducted (indicated on the left side in Figure 5 by squares and numbered from 1 to 5). The results are shown on the right side of Figure 5 and clearly indicate no impact from the thermal environment on the performance at all. As a matter of fact, the variation in the I/V characteristics are much less then seen in the needle type emitters (see also Figure 8). Following the last characterization test (no. 5), the set-up was allowed to drift to ambient temperature and the test proceeded without interruption to the endurance testing.

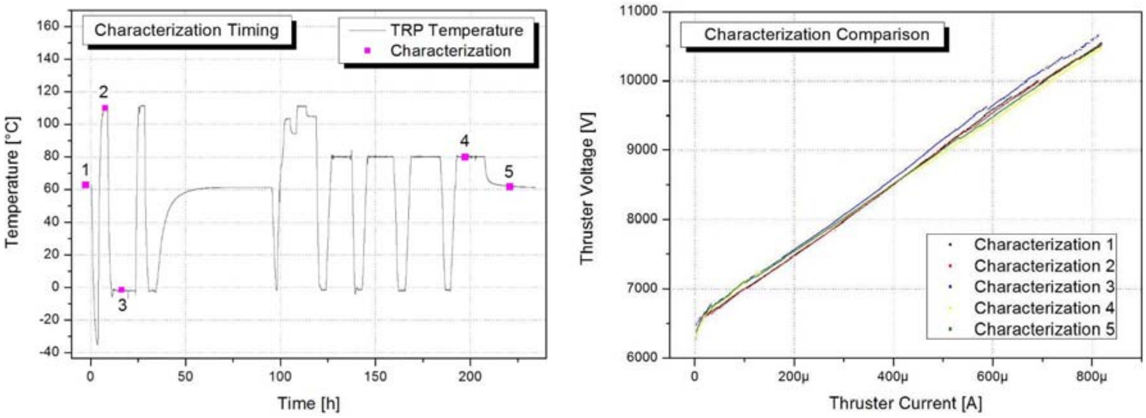

Figure 5: TRP temperature history for the full duration of the TVT (left side). Results of the characterization 1 to 5 (right side)

5.Endurance test results

During the endurance test the thruster was thrust controlled and, with the exception of the last part of the test, set to a required constant thrust of 25µN. At such low thrust levels (< 3µN per emitter) hardly any self-cleaning of the emission zone occurs which is therefore a much more challenging mode of operation than medium thrust and even high thrust operation. This effect can be seen in Figure 6, showing the thruster voltage during the endurance testing. Between each of the characterizations the voltage shows a slight tendancy to increase. Following a characterization (vertical line), during which the thrust is shortly increased to 100 µN, a self-cleaning occurs and the voltage settles back to a lower voltage. This trend is in general week but seems to be stronger in the first several characterizations until the increase get weaker and weaker each time. During the last 100 hours of testing the thrust was increased to 50 µN, corresponding to a thruster voltage of roughly 9 kV. A total of 9 characterizations have been conducted during the endurance test. The results of two characterizations were lost since the same file names were used and the data of a previous test was overwritten by the one of the preceding test. However, from the date of the seven other characterization test (see Figure 6) one can see that no real information were lost. The remaining seven data sets show nearly the same data with very little variation.

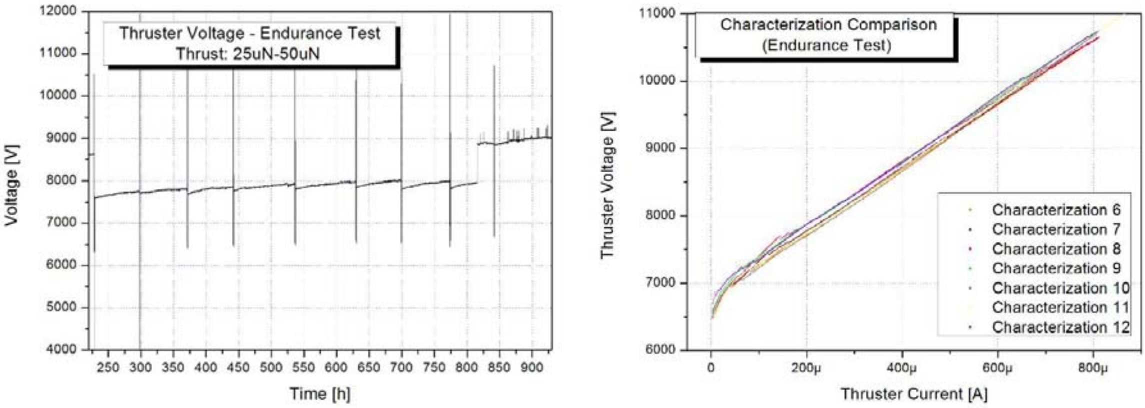

Figure 6: Thruster voltage for 25µN and 50µN (left) and characterization results (right) over the duration of the endurance test

As a matter of fact, the stability of the thruster equipped with capillary emitters was significantly better than a comparable test with the FCA equipped with needle emitters (see Figure 8). The voltage at 100µN (most left point of each curve) is on average lower for the capillaries than for the needles. On the other hand, in Figure 8 one can observe that the on-set voltage of capillary emitters is more than 2 kV higher for the capillaries than for the needle emitters (due to the enlarged base of the Taylor cone). This is a clear disadvantage (fewer margins) but in view of the great stability of the performance considered acceptable. Furthermore, due to the higher emission homogeneity of the capillary emitters, one can reduce the pre-resistor within the thruster (30 MOhm) and therefore increase again the margin in voltage.

Beside of a stable performance over time, one can assess the health of a FEEP thruster by monitoring the leak currents onto the thruster electrodes, i.e. the extractor and cover plate. A high current on either of those electrodes indicates a poorly aligned Taylor cone which can be an early indication of an emitter failure. Furthermore, high leak currents on either electrode mean high sputtering rates which can lead to a contamination of the emission zone reducing the lifetime of an emitter significantly. Figure 7 depicts the current leaks on extractor and cover plate electrode over more than 500 hours of testing. The stable, low level of current indicates the exceptional health of the thruster. It could be also interpreted as a sign of a low beam divergence. However such a statement needs verification by dedicated beam measurements.

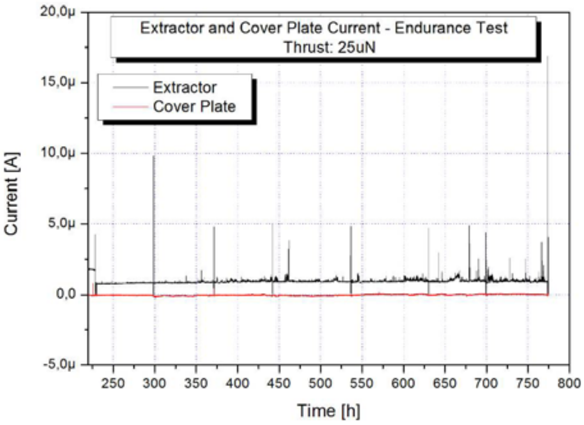

Figure 7: Leak currents at 25 µN during the endurance test

At the very end of the test and upon request from ESA, the maximum thrust capability of the present set-up was assessed. At a voltage slightly lower than 12kV, the thruster emitted 1100µA.and produced a thrust of 138µN.

6. Post test assessment

Post test assessment included a visual inspection (SEM) of the emitters and a weight measurement of each emitter. The weight measurement clearly showed that 2 of the 9 emitters have not worked at all (none of the emitters went through a selection or pre-testing procedure). A total propellant consumption of 2.77 g was assessed. For an accurate performance calculation, all emitted currents have been integrated, resulting in a total of 975.5 As over the duration of the TVT and endurance test. Based on this the following performance was calculated:

Table 2: Performance during TVT + Endurance testing

Total generated impulse	114.7 Ns
Specific impulse	5018 s
Mass efficiency	42 %

The mass efficiency is very close to the one required by LISA PF. Considering that two of the 9 emitters have not worked at all, the real, averaged, mass efficiency is even higher than shown in Table 2.

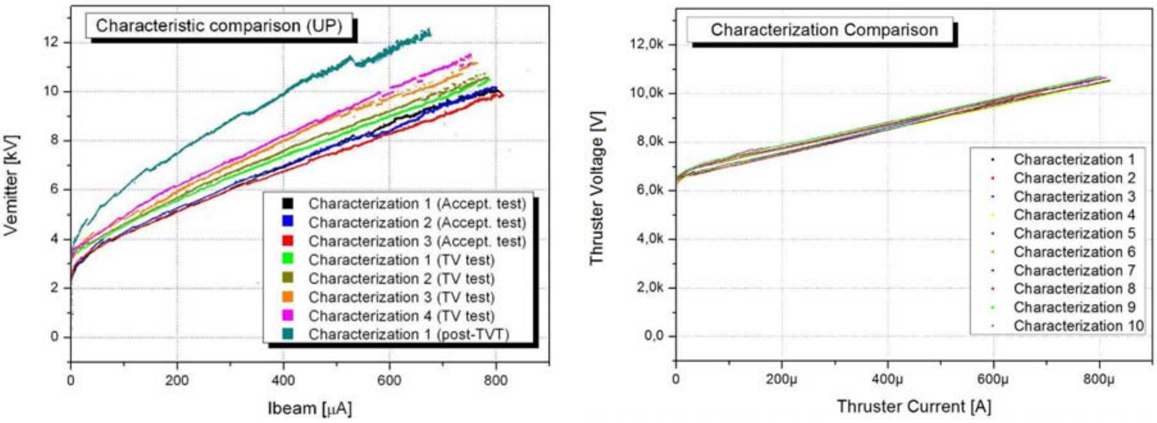

Figure 8: Comparison of characterization results obtained with needle emitters (left) and capillary emitters (right). Both tests were conducted with the same FCA

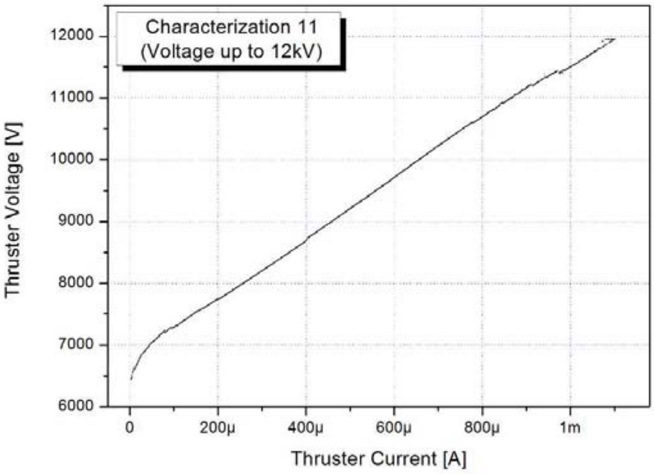

Figure 9: Current emission at maximum voltage (12 kV)

7. Conclusion

In order to investigate the suitability of capillary emitters for a LISA PF type mission, the thruster hardware (FCA) which was developed within the LISA PF project was equipped with nine capillary emitters. The test which was conducted with this hardware was a combination of a TVT and endurance test. In total, the test ran 930 hours with the endurance test lasting 700 hours.

If was found that the capillary emitters show a much stapler performance than the needle emitters. Over the complete duration of the test, marginal voltage variation in the range of ±100 V occurred. This, together with the low leak currents, indicates an exceptional health of the thruster.

The thruster generated 114.7 Ns of total impulse during the test. Average specific impulse was 5018 s and the mass efficiency was 42%.

8. Acknowledgments

The presented work was funded by the European Space Agency in the framework of the LISA PF program. The authors would like to thank the LISA PF team at ESA for their support and the LISA PF opportunity.

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