3000 Hour Lifetime Test of an Indium FEEP Cluster for the LISA Pathfinder Mission

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The Space Propulsion & Advanced Concepts Business Division of the Austrian Research Centers (ARC), Austria has been commissioned by the European Space Agency to develop a Micropropulsion Subsystem for the LISA Pathfinder (LISA PF) mission. In preparation for this project, ARC initiated a lifetime test with a LISA PF representative thruster. During this test, 8 Liquid Metal Ion Sources (LMIS) were continuously operated for the planned 2000 hrs at a mean thrust of 50 µN. The test was performed in a flight-representative cluster unit. Assessment of the cluster performance included amongst others the thrust range, thrust resolution and thrust accuracy. It was found that the cluster matched and even exceeded the rigid LISA PF requirements. It was shown that even 8 LMIS (LISA PF configuration has 9 LMIS) can cover the whole thrust range up to 100 µN. The thrust resolution was found to be 0.1 µN, allowing extremely sensitive satellite orbit control. A total impulse of 370 Ns was collected during this test with an average specific impulse of 4500 s. Lifetime limiting effects such as sputtering and internal indium contamination were found to be negligible.

To obtain more data the test was restarted after four months and continued to run for another 1000 hrs with 6 LMIS (two LMIS were kept on hold for analysis purposes). The results of these two tests, which collected a cumulative total impulse of 490 Ns, confirm that the ARC Micropropulsion system can fulfill all the stringent LISA PF requirements and even exceeds the required performance.

I. Introduction

The LISA (Laser Interferometer Space Antenna) 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, to be launched in 2009, and LISA itself, scheduled to launch in 2013. LISA will 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

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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 the same challenging propulsion requirements of LISA are also required for LISA PF (see table 1).

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	0.3 μN
Specific Impulse	> 4000 s
Beam Divergence	< 35°

The micro-propulsion system is one of the enabling technologies for LISA as well as for LISA Pathfinder. In 2006 the Space Propulsion & Advanced Concepts Business Division of the Austrian Research Centers (ARC) was commissioned by the European Space Agency 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 at ARC over the last three decades. The ARC LMIS technology is already used in different space application (mass-spectrometry, space-charge compensation) and has logged more than 12,000 hrs of in-space operation.

Since the late 1990s the LMIS technology was used at ARC to develop a Field Emission Electric Propulsion system (FEEP). The ARC FEEP system uses Indium as propellant. Indium has a variety of advantageous properties such as a relative high atomic mass and low 1st ionization energy. Furthermore, Indium has a low toxicity and can be handled under atmosphere without special precautions. This allows a fast, flexible, and relative low cost development and tests of such systems.

Several breadboard tests[1,2] already demonstrated key performance parameters such as sufficient propellant reservoir size, clusterability to achieve thrusts beyond 100 μN, extremely low thrust noise and controllability. With several tests, reaching durations up to 5000 hrs, ARC was the first to show that In-FEEP technology has also a sufficient lifetime for missions such as Microscope, LISA and similar missions[3,4].

In a recently concluded long duration test (3000 hrs), a LISA PF flight representative cluster unit has been tested and its performance was assessed. In this test it was found that the ARC In-FEEP matches and even exceeds the rigid LISA PF requirements. This paper gives some details of the conducted 3000 hrs test and its results.

II. 3000 hrs Lifetime Test

Separated from the LISA PF project, ARC conducted recently an endurance test with LISA representative emitters and test unit. The emitters which have been chosen for this test were manufactured in the same fashion as the emitters for LISA PF. However, they do not fulfill all the specifications as established for the emitters manufactured for LISA PF and the quality control points they had to pass were much less and more relaxed. Although the test unit used for this test (see **Figure 1**) can be equipped with 16 emitters instead of 9 (as planned for LISA PF), this unit is very representative to the LISA PF flight model design (see **Figure 2**). In particular:

- the reservoirs of the 8 ion emitters contain each 15 grams of Indium per emitter
- LISA PF representative ion beam focusing system
- cover-plate electrode biased to -1 kV, in order to repel secondary electrons
- cluster operated in thrust stabilization mode with a single laboratory HV power supply

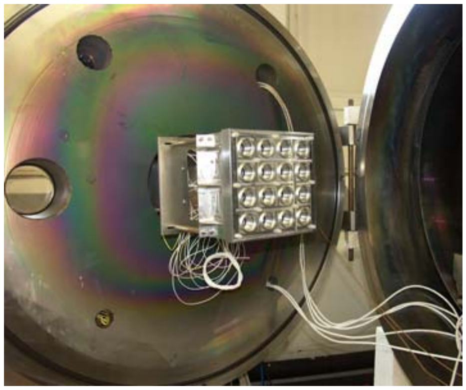


Figure 1. 4x4 Cluster Breadboard mounted in the vacuum chamber.

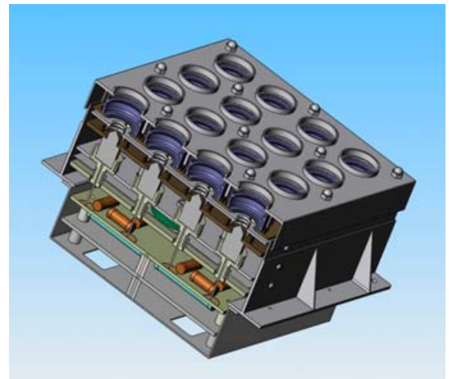


Figure 2. LISA PF representative electrode configuration.

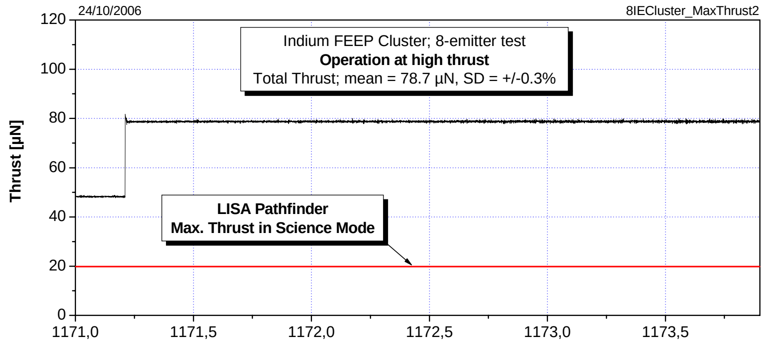
The test was conducted in two segments: the first segment lasted 2000 hrs. During this time the performance was assessed in frequent intervals and their compliance with the LISA PF requirements was assessed. The test was conducted with 8 emitters (amount of emitters which were available at test initiation) and thruster performance was assessed in great detail. As planned, the test was stopped after 2000 hrs. To obtain more data the test was restarted after four months and continued to run for another 1000 hrs with 6 emitters (two emitters were kept on hold for analysis purposes). After 200 hrs into the second segment, an error in the test software led to a failure of the emitter heaters during high thrust operation. In the process of this failure, one emitter was lost and one increased its impedance but recovered later. However unfortunate the loss of one emitter was, it shows the extreme reliability of the In-FEEP emitters. A loss of the heater power only, but with continuing extraction of indium from the needle is considered the absolute worst-case scenario for FEEPs. It potentially can lead to a de-wetting of the needle and a total loss of the emitter. The "worst-case" scenario for LISA PF is the total failure of the power which would lead to a loss of heater power and extraction voltage. Since this is a much less severe case than the experienced loss of only the heater power, it can be concluded that the system is fail-safe with regard to the LISA PF "worst-case" scenario. The five other emitters operated after the failure with the same constant performance as before until the test was concluded after 1000 hrs.

Both test segments were conducted in one of the three large vacuum chambers in the main test laboratory of ARC. The tests were conducted in a vacuum of roughly $5x10^{-7}$mbar. Other than in previous tests[4] the collector on the far-side of the vacuum chamber was covered with indium foil. This prevents sputtering and subsequent deposition of aluminum on the thruster which caused a partial failure in the 5000 hrs test.

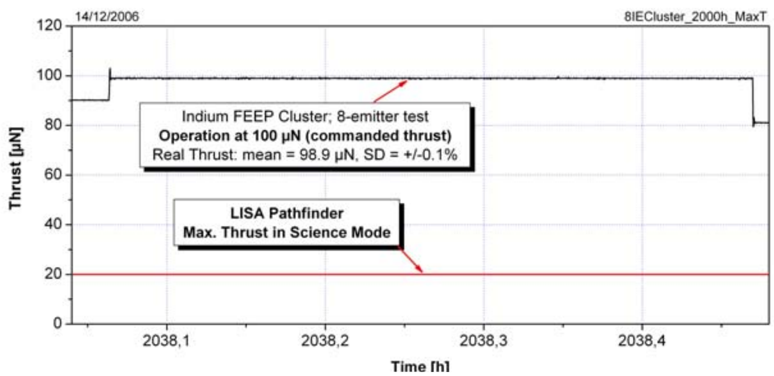
Major goal of this test was the assessment of all the pertinent LISA PF requirements such as thrust range, minimum thrust capability and thrust accuracy etc. Furthermore, any potential changes in performance over time and potential lifetime limiting factors have to be assessed (sparking, deposition, sputtering effects).

The following graphs show the result of the 3000 hrs test. Figure 3 shows the thrust stability and accuracy at three different times during the test. Comparing graph a) and b) one can see that the thrust accuracy (difference between commanded thrust and real thrust) is actually improving over time even at maximum thrust. It has to be noted that the maximum thrust can be reached with only 8 emitters instead of the 9 foreseen in the LISA PF flight model (see also Fig. 4). The fact that 8 emitters can cover the same thrust range as the planned 9 emitters shows the redundancy capability of the system. Furthermore, even 5 emitters (graph c) can fulfill the thrust requirement in the science mode which is the mode the propulsion system mainly operates in during the mission.

a)



b)



c)

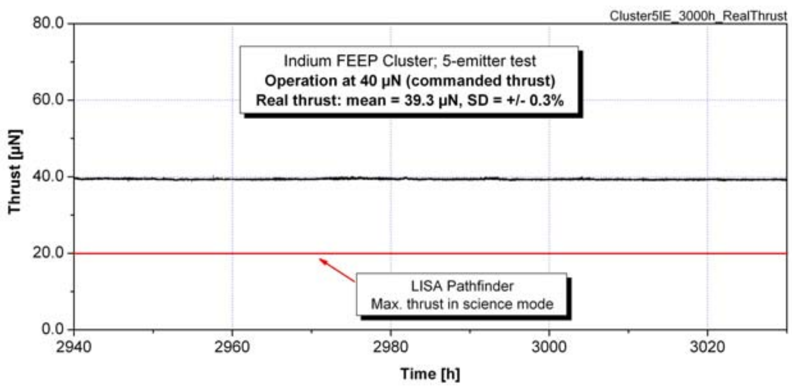


Figure 3: Thrust stability and accuracy over 3000 hrs (top two graphs are obtained with 8 emitters while the lower one only with 5 emitters).

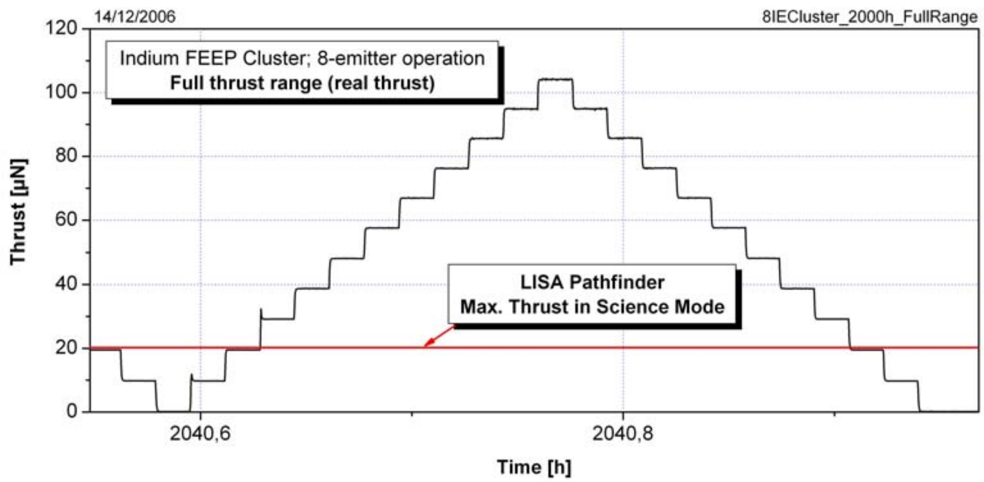


Figure 4. LISA PF thrust range demonstrated with 8 LMIS, after 2000 hrs of continuous operation.

Figure 5 shows the individual thrusts in the 4x4 Cluster Breadboard after more than 1000 hours of continuous operation; at 100 µN, they are ranging between 11 and 13.5 µN, which is a relatively small spread, considering that these LMIS have not been pre-selected according to the strict LISA PF emitter requirements. Furthermore, this thrust spread got even smaller with time; in Fig. 6, after 2000 hours, the individual thrusts range from 11 to 13 µN.

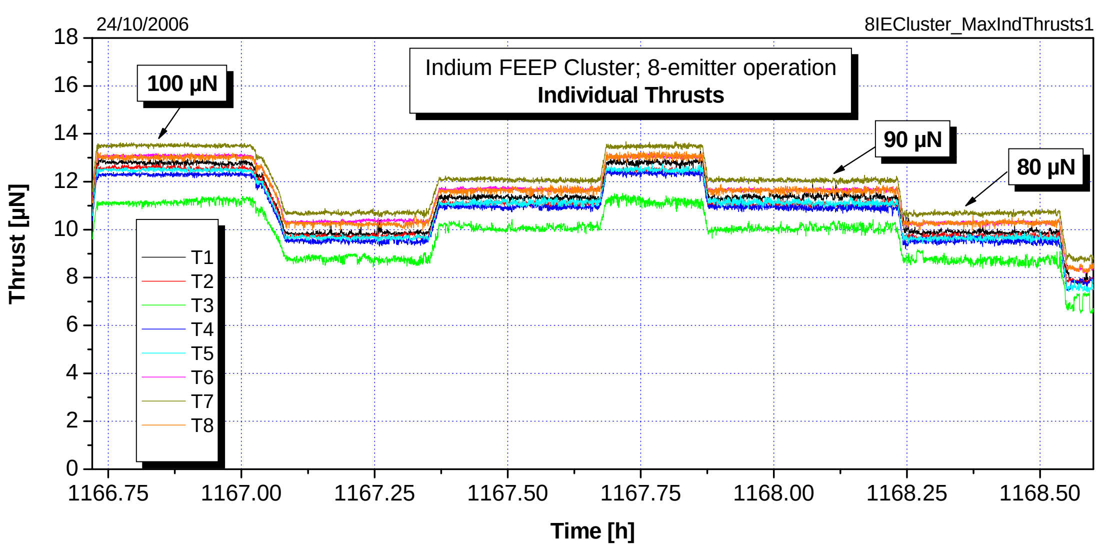


Figure 5. Individual thrusts in the 4x4 Cluster Breadboard after 1000 hours of continuous operation.

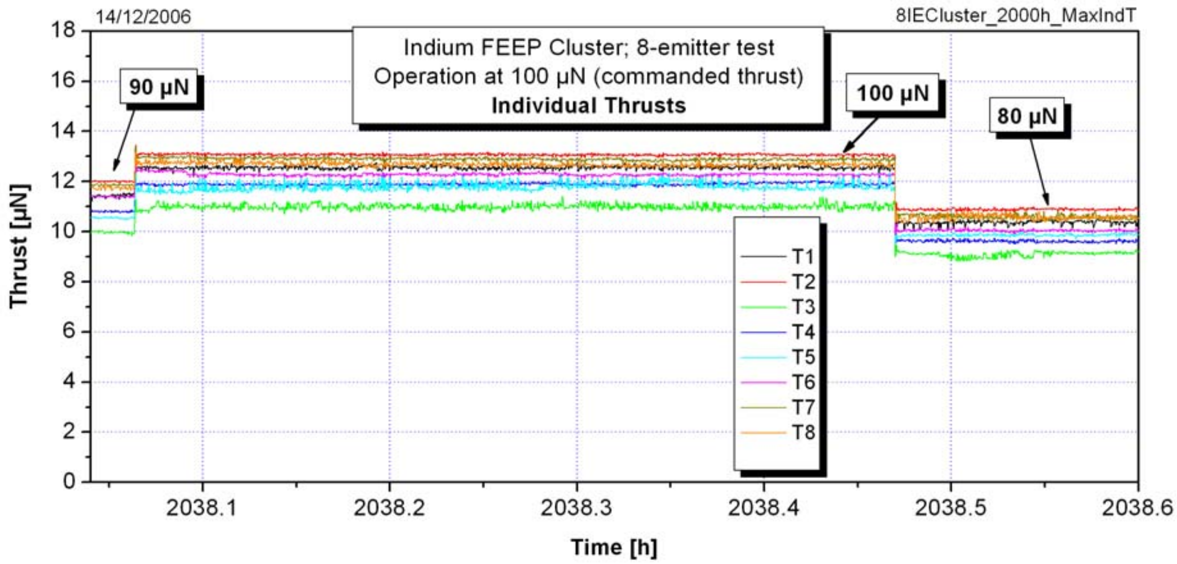
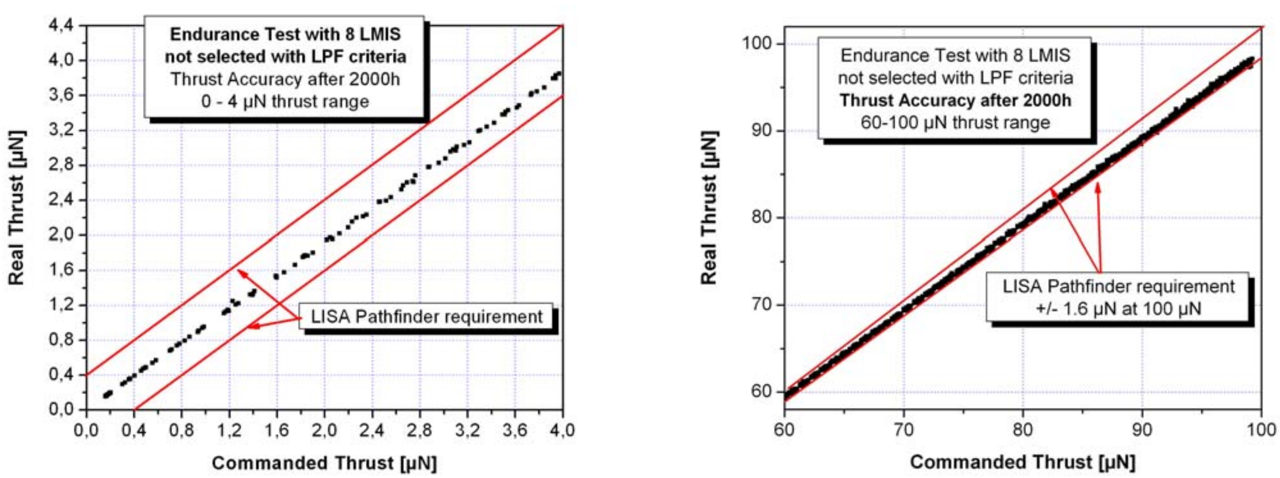


Figure 6. Individual thrusts in the 4x4 Cluster Breadboard after 2000 hours of continuous operation.

Thrust accuracy (commanded thrust vs. real thrust) is of highest importance in the science mode due to the high sensitivity of the science instruments (detection of gravitational waves). Figure 7 shows a comparison between the commanded and measured thrust over the complete thrust range; as can be seen the Indium FEEP cluster is fully compliant with the LISA PF accuracy requirements both in science mode and at high thrust.



a) **b)**

Figure 7. Thrust accuracy after 2000 hrs; a) in science mode, b) at high thrust.

To be compliant with the controllability requirements the propulsion system must be capable to cover the whole thrust range (0.3 – 100µN), but in particular has to ensure a thrust resolution of >0.3µN in particular in the science mode (up to 20µN). The data shown in Figure 8 were obtained at the 2000 hrs milestone and show that the Indium FEEP cluster even exceeds this requirement, being capable to provide a thrust resolution of less than 0.1µN.

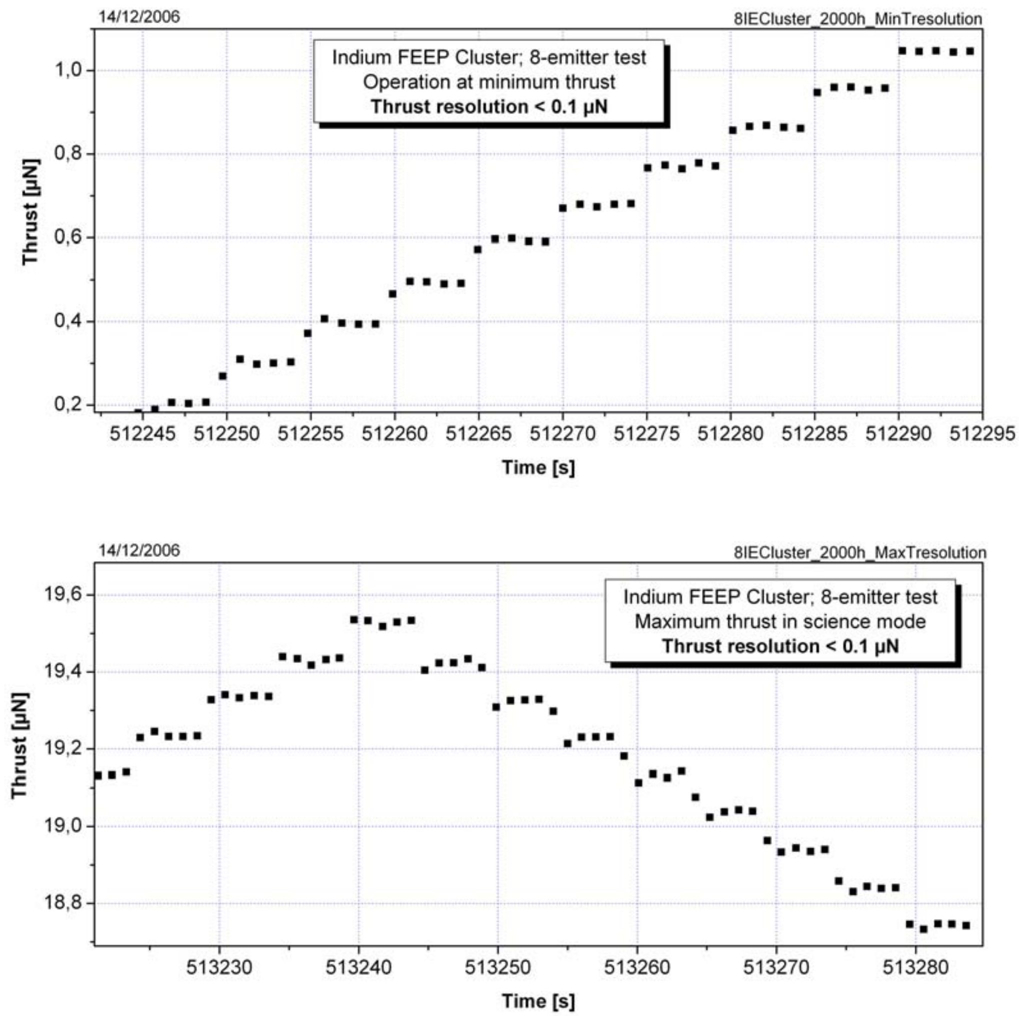


Figure 8. Thrust resolution and dynamic response at 2000 hrs.

The extreme sensitivity of the science experiment results in very challenging requirements also on the thrust noise. The thrust noise is a function not only of the thruster itself but also of the stability of the power supply. Although the data shown in Figure 9 are obtained with a commercially available laboratory power supply, they indicate that the LISA PF requirement with regard to the thrust noise can be easily fulfilled. The thrust noise is expected to significantly decrease further with a flight representative power control unit.

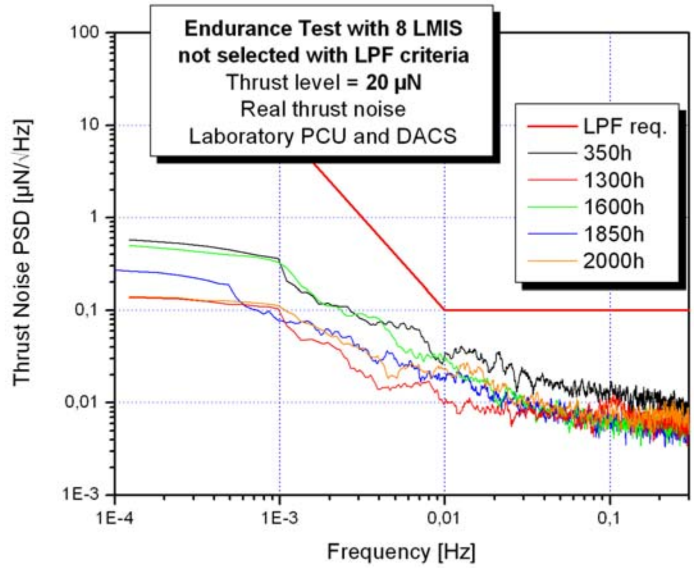


Figure 9. Thrust noise in the science mode at different times during the test.

One of the major properties of an LMIS is its impedance. This impedance is basically the hydrodynamic resistance of the indium flow, but expressed as an electric property. The impedance defines the necessary extraction voltage to generate a given current. An LMIS requires a certain time to stabilize its impedance characteristics. Figure 10 shows the change in impedance of the 8 emitters that performed the first 2000 hours of this endurance test. Six LMIS showed a stable impedance since the start, while two emitters started with very high values of impedance; however, after around 500 hours their impedance decreased to similar values as the other LMIS.

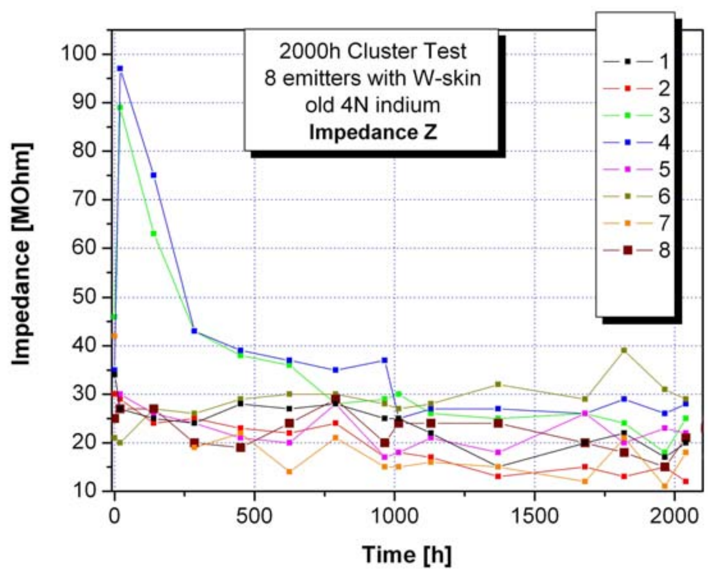


Figure 10. Change of impedance over time.

Investigation of the test unit after 3000 hrs showed no indication of lifetime limiting effects such as excessive indium deposition or electrode sputtering (see Figure 11). Due to the similarity of the utilized test unit to the LISA PF flight model developed by Astrium GmbH, this suggests that the design is suitable for the planned lifetime test and the LISA PF mission itself.

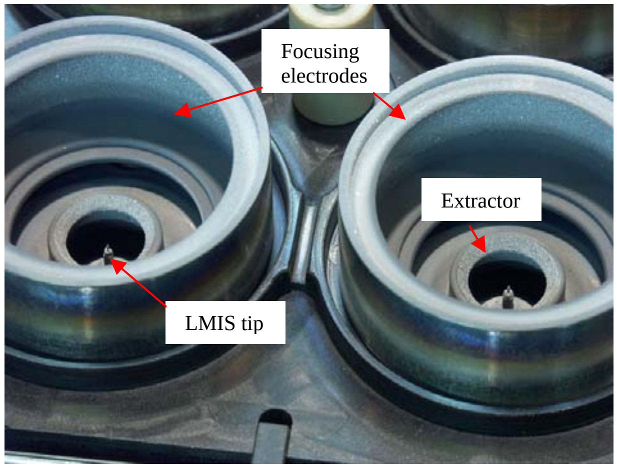


Figure 11. 4x4 Cluster Breadboard electrodes after test.

III. Conclusion

The In-FEEP thruster concept for LISA Pathfinder has been presented. A detailed design and lifetime test campaign is currently under preparation to demonstrate the compatibility with LISA PF and other missions that require ultra precise attitude and orbit control. A 3000 hrs test with LISA PF representative emitters and cluster unit has been conducted collecting a total impulse of 490 Ns at an average specific impulse of roughly 4500 s. Furthermore analysis of the test data shows that the proposed propulsion system can fulfill all the stringent LISA PF requirements and even exceeds the required performance. Furthermore, the test has shown that all the LISA PF requirements can be fulfilled with only 8 emitters (including full thrust range), and has therefore proven the redundancy potential of the proposed In-FEEP propulsion system.

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