Test results of the qualification tests for the In-FEEP technology for LISA PF

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The Laser Interferometer Space Antenna project (LISA) is a co-operative program between ESA and NASA to detect gravitational waves by measuring distortions in the space-time fabric. LISA Pathfinder is the precursor mission to LISA designed to validate the core technologies intended for LISA. One of the enabling technologies is the micro-propulsion system necessary to achieve the uniquely stringent propulsion requirements. Two competing systems, a cesium slit emitter (Alta, Italy) and the indium needle emitter technology (AIT, Austria) have been commissioned to develop this micro-propulsion system. At this point, the cesium slit emitter was chosen by ESA as baseline. The indium needle emitter technology was chosen as back-up solution and its development and test are still proceeding and the obtained results are documented in the present publication.

Two major activities are discussed in the present paper. A subcomponent of the thruster, a so-called TCA, was tested in an endurance test for 3650 hours, collecting a total of 586 Ns. The test consisted of three phases. In the first phase the thruster's performance was investigated with a standard laboratory power supply and EGSE. In the second phase the compatibility of the thruster with a flight representative PCU provided by Galileo Avionica S.p.A was tested. Finally, in the third phase a long duration assessment of the thruster was conducted. During this phase (roughly 3200 hrs) the thruster was operated in a mode similar to the one foreseen for operation in space. Additionally, frequent performance and health checks were conducted.

In parallel a flight representative thruster unit is prepared for its qualification test series. In a preparatory step the STM thruster cluster successfully passed a vibration test and an acoustic noise test. All three test series showed successfully the compliance to all requirements. The present paper discusses the test conditions and provides details of the test results.

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 2011, and LISA itself, scheduled to launch in 2014. LISA will consist of three spacecrafts flying in a triangular formation with a side length of several million kilometers. The position of

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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 the same challenging propulsion requirements of LISA are also required 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 Galileo Avionica S.p.A, Astrium, and the Space Propulsion & Advanced Concepts Business Division of the Austrian Institute of Technology-AIT (formerly 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 AIT over the last three decades and its technological maturity and lifetime capability of the LMIS technology has been shown in the past decade[1,2,3,4].

The AIT 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 (mass-spectrometry, space-charge compensation)[5].

II. In-FEEP Cluster Assembly

LISA and its precursor mission, LISA Pathfinder, 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 basically 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 HV 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 such a failure of up to 6 emitter would have no significant effect in terms of required thrust.

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°

In order to transfer the AIT FEEP technology into a flight model, AIT joined forces with Astrium GmbH as industrial partner covering the experience from electric propulsion flight programs to optimized mechanical/thermal design and space qualified high voltage experience[6]. 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.

Verification of the performance of the In-FEEP technology and the TCA/FCA design is to be shown in a series of tests. This includes performance evaluations on LMIS level but also on TCA and FCA level. Environmental test will establish the ability of the thruster to operate in the harsh space environment as well as the capability to survive the launch phase.

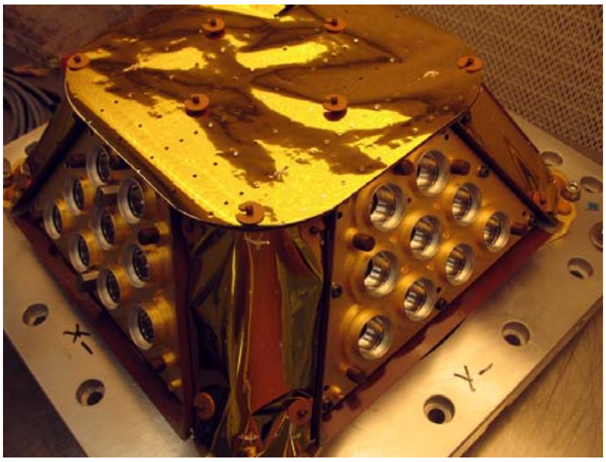

Figure 1: Complete FCA showing two TCAs with each 9 emitter (2 further TCAs on the backside)

III. DM1: Environmental test: Part 1

In order to be compliant to the mass requirements and to stay within the allocated volume envelope, the FCA was designed for mass savings to the extent possible. As a result of this, the structural analysis for a few internal components showed a low safety margin with respect to the required vibration qualification levels. This required a notching during vibration qualification test. A special analysis performed at ESTEC calculated the response on these components resulting from the acoustic noise inputs. In order to verify that even during the notched input levels result the excitations on these components envelope the load expected during acoustic noise, a qualification level test on a specially equipped Structural Test Model (STM) was performed. The components with low safety margin within this STM were equipped with small vibration sensors to measure the loads in-situ. During this test one TCA was equipped flight like with the exception that no active emitters but special mass simulators (EAS) were installed.

The location of the vibration sensors is shown in Figure 2. Furthermore, the individual TCAs have been equipped with a special miniaturized 3-axis vibration sensor in the center emitter position as shown in one of the fotos in Figure 2. The vibration qualification test was performed at IABG in Ottobrunn, Germany. Figure 5 shows the STM mounted on the IABG shaker.

The FCA structure withstood the applied dynamic loads successfully. No visual damaging was detected and the pre and post low level sine sweeps of each excitation direction showed a close match and demonstrate the success of the test. The FCA structure fulfilled the stiffness criteria of first fundamental mode greater than 140Hz. The stiffness of the structure for the Out-Of-Plane (perpendicular to the mounting panel) excitation corresponds to the analysis results as shown in Figure 3. Only the first mode is about 16Hz stiffer than predicted. The stiffness of the structure for the In-Plane (parallel to the mounting panned) excitation is about 50Hz higher than predicted. The stiffness is sensitive concerning the mounting leashes of the base frame and the iso-static mounts, though the conservative approach of the simulation model led to the occurring stiffness discrepancy, which resulted in increased margin of safety. The symmetry of the structure in X and Y direction could be confirmed.

The specified sine input levels were verified during the vibration test (see Figure 4). Due to the higher damping and the higher stiffness of the first modes the sine input levels are non-critical. The specified random input levels have been verified during the vibration test. An adapted notch assessment with only one notch for the Out-Of-Plane excitation has been performed. For the In-Plane excitation no notch was necessary (see Figure 4).

In conclusion it can be said, that the first modes (up to 400Hz) have a higher damping than assumed. For the higher frequencies a lower damping factor is assessed. The notch level verification vibration test program was completed successfully.

Furthermore, the STM FCA participated successfully in a S/C system level acoustic noise test in the ESA/ESTEC facility (see Figure 6). The results of this test will be presented in a future paper.

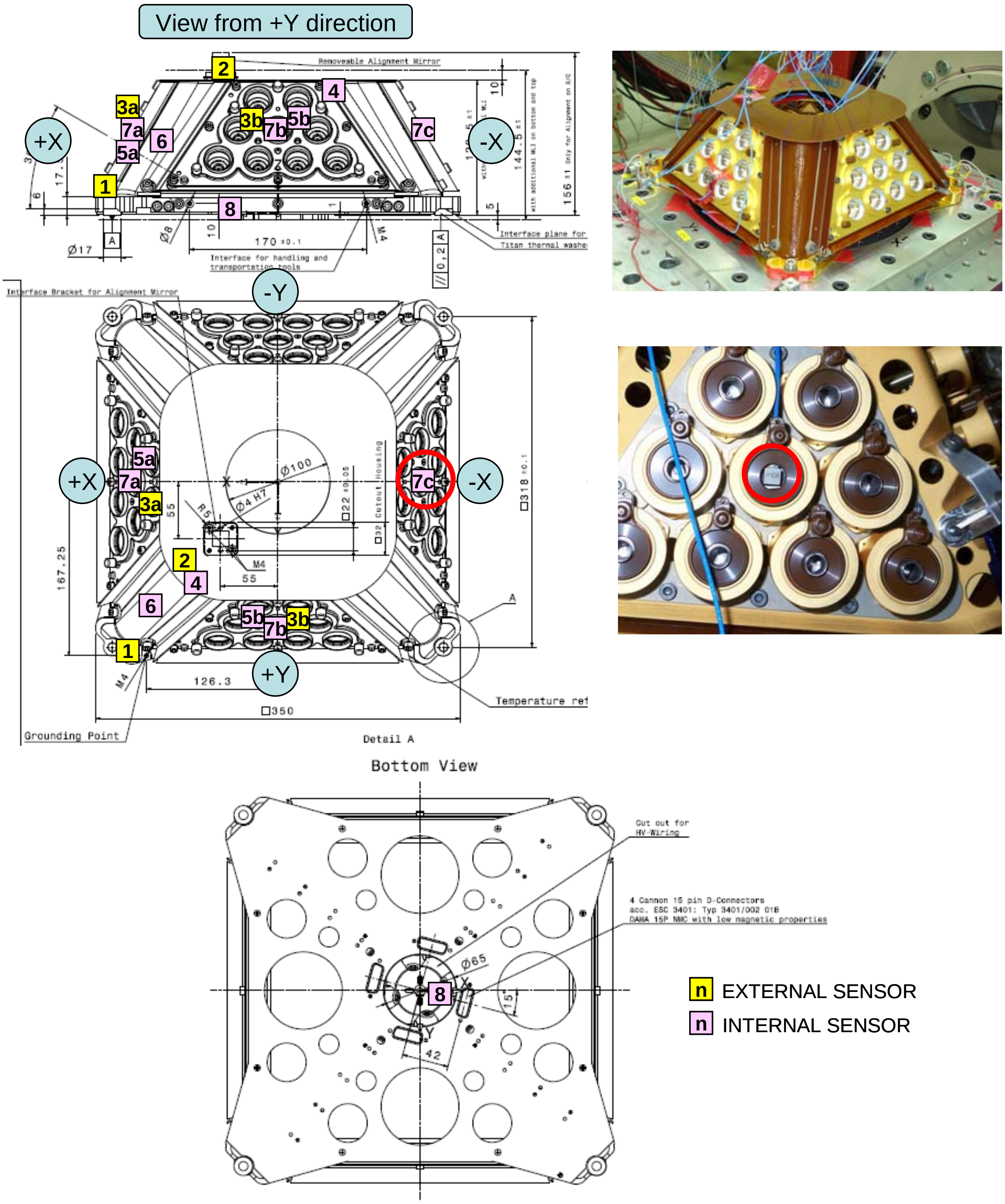

Figure 2: Locations of the vibration sensors in the FCA

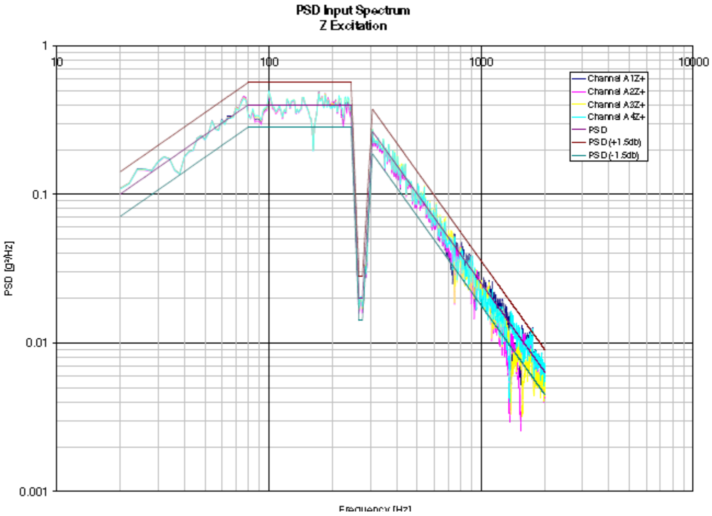

Figure 3: Random vibration excitation Out-Off Plane

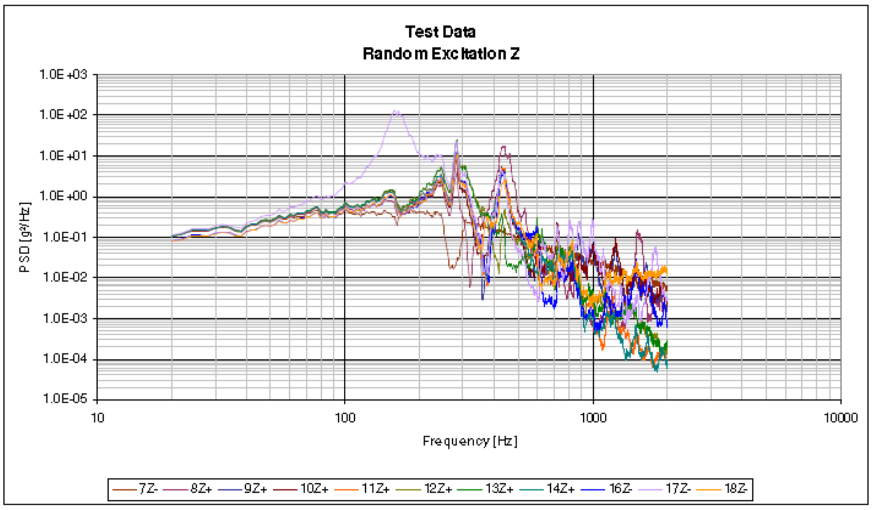

Figure 4: Random response z-Axis

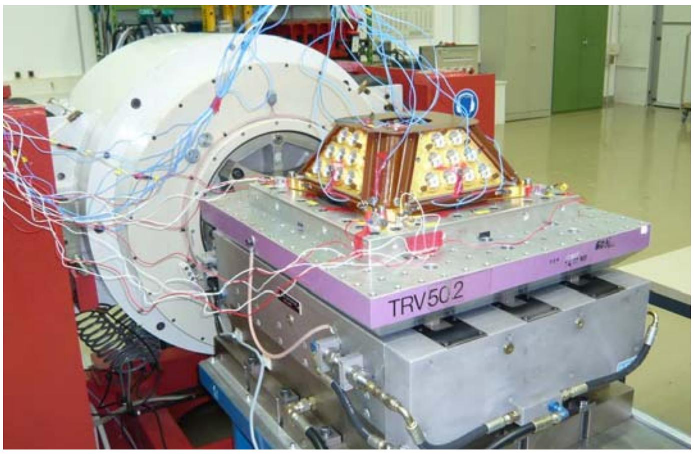

Figure 5: DM1 STM on the shaker at IABG.

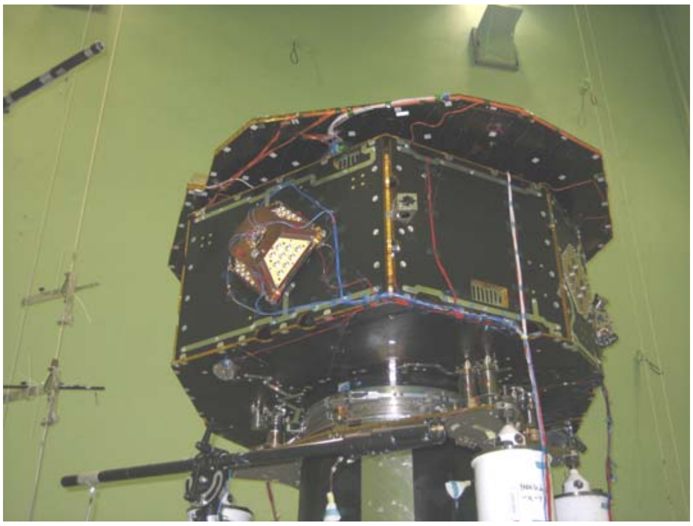

Figure 6: FCA STM on LISA Pathfinder Spacecraft Structure during Acoustic Noise Test

IV. TCA qualification tests

The subject of one of the first scheduled qualification tests was a flight representative TCA equipped with 9 LMIS. For a standard test, only emitters manufactured and selected according to the stringent manufacturing and selection process would have been chosen. However, for this test emitters were chosen which have either been rejected (due to non-compliances with some of the selection criteria) or have not even passed the full manufacturing and selection process. The reason for choosing non-selected emitters was due to, at that point of time, unresolved questions with regard to the impact of outgassing effects of the TCA structure on the emitters. In spite of the fact that those emitters are not fully selectable, they were considered to have fair chance to perform sufficiently for the purpose of this test.

V. Tests results

The test was initiated on the 9th of September, 2008 and in spite of using emitters which do not fully comply with the selection criteria, 8 of the 9 emitters ignited without difficulties. The performance of 7 of the 8 operating emitters was according to specification. The one emitter operating outside of the specification was already prior to test initiation marked as a high risk emitter due to its electric characteristics and its low performance was expected. While this emitter ceased to operate after ~800 hours, the remaining 7 emitters operated without problems and with constant behavior over the full duration of the test (3650 hours).

Figure 7: Installment of the TCA test unit in the AIT test facility

The test itself consisted of three phases; an initial, so-called, acceptance test was designed to identify the begin-of-life performance of the thruster. This test was conducted with the standard AIT laboratory power supplies and the AIT thruster control system, including a dedicated “Switch-box” which allows individual emitter voltages and currents to be measured. The thruster was operated at constant thrust level of 50µN, interrupted by frequent thruster characterizations and beam diagnostic measurements[5]. The total runtime of this test was 340 hours.

In the following the interface test phase was initiated. This test used the elegant bread-board of the flight power control unit (PCU) and electrical ground support equipment (EGSE), both provided by Galileo Avionica S.p.A, Italy. This test was designed to investigate the interactions between the thruster itself and its electrical interface (PCU, EGSE). The compliance to a set of requirements was investigated including the thrust range capability, thrust resolution, thrust noise, thrust controllability and linearity, sparking, beam divergence and many others. Compliance for all requirements, subject to this test, has been shown in spite of the fact that only 7 of the 9 emitters have been nominally operating. The interface test had a total run time of 140 hours.

Only the acceptance and the interface test were originally planned to be conducted for this test unit. However, after finalization of the interface test it was together with ESA decided to let the thruster run as long as the schedule allows. This period was called endurance test. It was again conducted with the AIT laboratory power supplies and the AIT thruster control system and ran for another 3170 hours bringing the total run time to 3650 hours.

Depending on the test set-up, each test phase investigated a particular set of requirements and its compliance to those respectively. The thrust resolution was e.g. investigated during the acceptance test. Figure 8 shows the thrust as calculated based on the individual emitter voltages and currents. The commanded thrust step was 0.3 µN and Figure 8 shows that the produced thrust steps correspond well with the commanded thrust steps. As an independent verification of this, Figure 8 shows also the collector current which follows roughly the same shape (not the same since thrust is proportional to the product of the emitted current and the square root of the acceleration voltage).The same accuracy as shown in Figure 8 for a thrust between 14 and 16 µN was obtained over the complete thrust range. Figure 9 shows that in the very challenging low thrust regime (<0.9µN), the thrust resolution has the same accuracy as for higher thrust. After roughly 3600 hours this thrust resolution assessment was successfully repeated and as shown in Figure 16 the thruster was capable of providing a even higher resolution of 0.1µN.

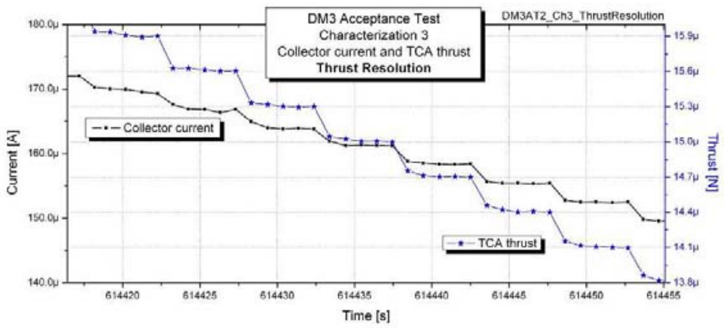

Figure 8: TCA thrust resolution in the science mode

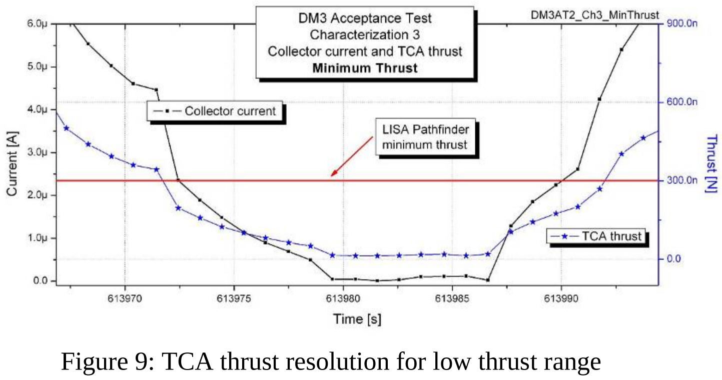

Figure 9: TCA thrust resolution for low thrust range

Thrust origin:
Due to the spatial distribution of the 9 emitters the thrust vector origin is potentially subject to variations over time and over thrust range. For LISA PF the thrust foot point has to be within a region defined by a circle with a radius of 25 mm around the theoretical TCA thrust center. Since every emitter has an individual characteristic, the allocation of the 9 emitter in a TCA has a significant impact on the thrust foot point. AIT developed an allocation model to evaluate the position of each individual emitter (of a set of 9 emitters) such that the foot point is always within the requirement. From the theoretical possible number of permutations (362,880) the best one is chosen.

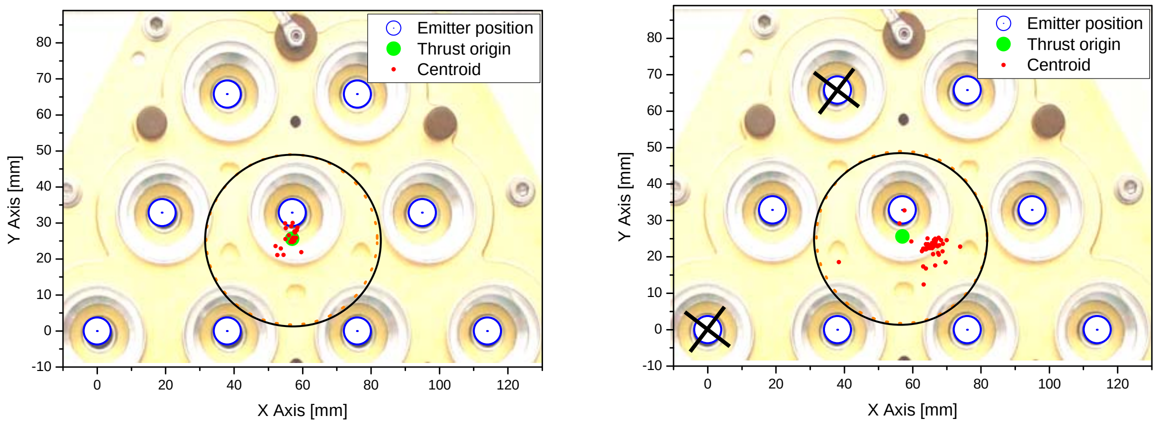

Figure 10: Thrust foot point prediction prior to the test (left) and thrust foot pointed obtained in the test (right). “X” indicates the two non operative emitters

The left side of Figure 10 shows the result of such an allocation superimposed with a picture of a TCA to show the position of all 9 emitters. The black circle visualizes the limit of the requirement. The green dot symbolizes the theoretical thrust center and the small red points indicate the thrust foot point as a function of the thrust level (0-100µN). While the left side of Figure 10 shows the prediction made prior to the test initiation (based on the I/V characteristics of each individual emitter) the right side of Figure 10 shows the thrust foot point calculation based on the test results (measured I/V characteristic of each emitter as a function of the thrust). As discussed above, 2 of the 9 emitters did not operate (indicated by a X in the right side of Figure 10). This is causing a slight shift of the thrust foot points but as shown in Figure 10, all the thrust foot points are still well within the requirement.

Beam shape and divergence:
In addition to the very low vapor pressure of indium (9 magnitudes lower than cesium at their respective melting points) the needle configuration has the advantage that the surface area from which indium can evaporate is extremely small (in the 10^{-9} m^2 range). The risk of evaporating indium which might contaminate the spacecraft can therefore be considered negligible. However, if the beam divergence is above a certain limit the extracted ions might be deposited on the spacecraft structure. Consequently, the maximum allowable beam divergence for LISA PF is 25° (containing 99% of the beam current). AIT is verifying the compliance with this requirement with a beam diagnostic device[7]. The beam diagnostic can measure the general shape of the beam as well as the beam divergence by comparing measurements at different downstream location. The beam divergence assessment was conducted for each individual emitter as well as for the complete TCA. The individual measurement has shown that the beam divergence of all operative emitters is well within the requirement. The average beam divergence of the individual emitters is 21.1° (±1.1°) with a maximum measured divergence of 21.7° (more details are reported in reference 5).

Comparison of the beam shape obtained at different times during the test allows furthermore assessment of the health of the TCA. Figure 11 compares the beam shape as measured at the beginning of the test (140 hours) with the one measured shortly before finalizing the test (3600 hours). The plots are superimposed with a picture of the TCA to visualize the correlation between location of the emitters and the measured beam profile. The one emitter which failed to ignite is marked with a cross (solid lines). The other emitter which worked initially but deteriorated and failed to work after ~800 hours is marked with a cross (dotted lines). Within the measurement accuracy of the beam diagnostic, a comparison of the two measurements show that in spite of nearly 3500 hours of operation, extended high thrust periods, thermal cycling and exposure to air the beam shape has hardly changed. This again indicates that not only the individual emitter performance is constant over the observed test period. The only region in which significant variations can be seen, is in the very left part of the beam profile shown in Figure 11. The main reason for this is assumed to be the one emitter which operated initially and failed to operate after ~800 hours (see discussion above).

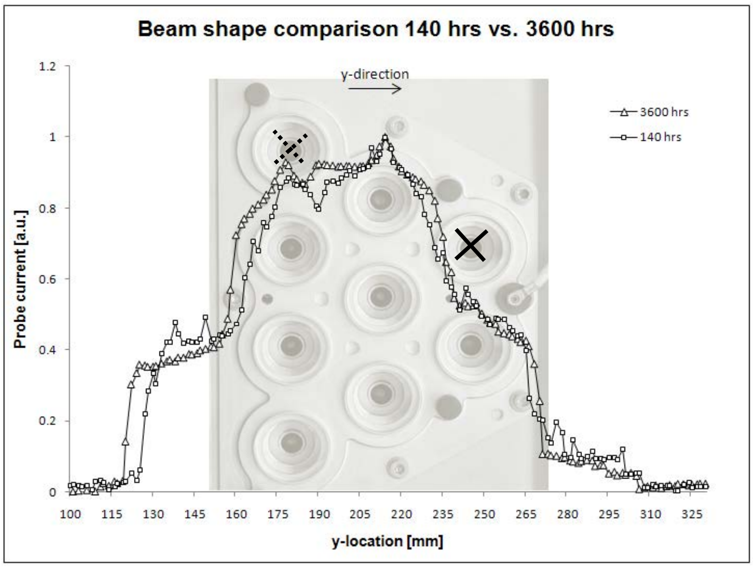

Figure 11: Comparison of the TCA beam shape for two different times during the test.

<u>Sparks</u>:
The occurrence of sparks within the thruster is for LISA PF dangerous in two ways. Firstly, sparks might cause thrust noise and therefore endanger the accuracy of the scientific experiment on LISA PF and secondly sparks might cause erosion of the needle FEEP and have detrimental effects on the thruster lifetime. The monitoring of sparks within the thruster was therefore required for all the tests. During all test phases the spark rate was measured with an AIT spark counter. In addition, during the interface test the Galileo Avionica S.p.A hardware monitored the spark rate on its own. After an initial period of relative high spark rate at the beginning of the acceptance test, the spark rate went nearly to zero. For example, during a constant thrust (50µN) period of nearly 80 hours only 1 spark was measured (LISA PF requirement is less than 2 sparks per 1000s). During a high thrust (75µN) period in the endurance test only 5 sparks were measure in 8 days. This measured spark rate might even overstating the real spark rate due to the excessive sensitivity of the AIT spark counter. During the interface test, the AIT spark counter worked simultaneously with the flight representative spark counter integrated into the PCU/EGSE of Galileo Avionica S.p.A. While the latter measured at no point any sparks, the AIT spark counter detected in a time period of 16 hours 2 sparks occurring at a thrust level of 100 µN.

<u>Noise measurements:</u>
The maximum allowable noise of the micropropulsion system is one of the most stringent requirement of LISA and LISA PF and in general impossible for most propulsion systems to be compliant with. For LISA the thrust noise is required to be smaller than 0.1 $\mu N/Hz^{1/2}$ for the frequency range between 0.01 and 1 Hz. The needle FEEP is well known for its low noise in the frequency range relevant for LISA which is one reason why this particular system is considered for the LISA mission. The noise range of needle FEEPS was investigated in the past and it was found that the noise contribution of the power supply is much higher than the one originating from the FEEPs. During the interface test, the noise was therefore measured while using the flight representative power supply and EGSE. It was found that the needle FEEP thruster is compliant with the LISA noise requirement in the full thrust range with a noise roughly one magnitude below the requirement. Representative for this investigation, two results are shown in Figure 12 and Figure 13 (kindly provided by Galileo Avionica S.p.A).

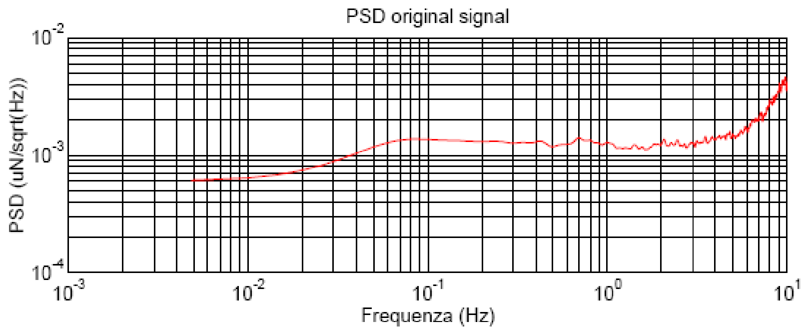

Figure 12: thrust noise at a thrust level of 4µN

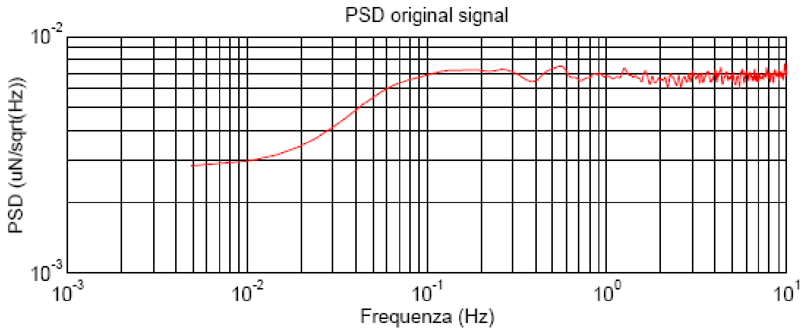

Figure 13: thrust noise at a thrust level of 80 µN

<u>Thermal cycle/exposure to air</u>:
The effect of thermal cycles on the emitter is thoroughly investigated during the emitter manufacturing cycle. During the whole manufacturing process each emitter has to pass at least 9 thermal cycles (a thermal cycle is defined as follows: T<90°C → T>180°C → T<90°C). An emitter is selected as a LISA PF emitter only if it passes all the thermal cycles and its performance afterwards is within the requirement specifications. Nevertheless, another thermal cycle plus a 12 hour exposure to air was required by the costumer as part of the interface test. Performance and characteristic of all the emitters was tested prior to and after the thermal cycle/exposure to air. The test showed no measurable performance change of the emitters by this procedure. Figure 14 shows a comparison of the collector current (total emitted current) as measured prior to the cycle and afterwards. With the same control parameter of the PCU/EGSE the thrust variation is only 0.1% which is smaller than the measurement accuracy. Further indication that the performed thermal cycle had no measurable impact on the performance is the above discussed stable beam shape, and the stable TCA voltage characteristic and the TCA impedance (see next chapter).

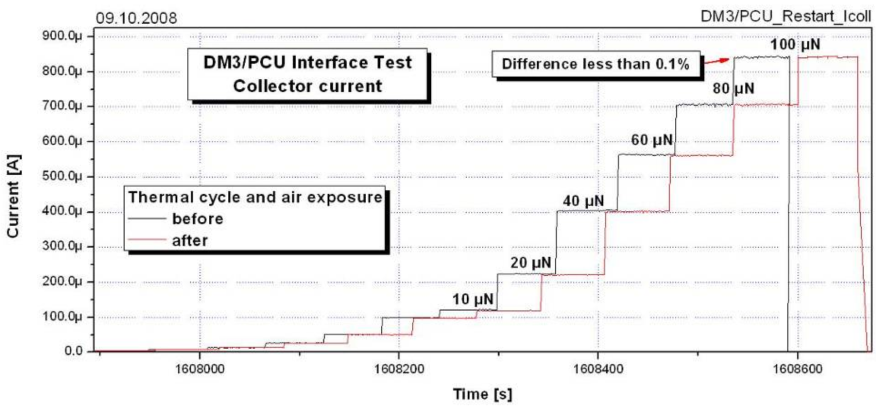

Figure 14: TCA performance before and after the thermal cycle/exposure to air.

Thruster health:

While most of the discussed compliance checks are important, they provide only a snap-shot in time of the thruster performance and health. Most important in such a long test is to verify the effects, if any, of such an extended period of operation on the health of the thruster and its performance respectively. However, even at 3650 hours no red flag showed up indicating any significant problems with the emitters or the TCA.

Current losses on the extractor and the cover plate are good indicators of the health of the emitters and the TCA. Increasing losses indicate problems with the emitter (e.g. Taylor cone shift) or with the TCA (e.g. internal contamination causing a reduction of the electric insulation). Since the sum of the extractor and cover plate leak currents has been measured to be smaller than 5 µA during initiation of the test as well as after 3600 hours of operation, this indicates excellent emitter and TCA health.

The health of the emitters can be assessed furthermore by their individual impedance. Increasing emitter impedance over an extended period of time is a telltale indicator of potential problems. Along this line, the TCA voltage (acceleration voltage) provides similar information but also includes information about the TCA health (e.g. occurrence of leak currents). A constant or decreasing TCA voltage indicates good emitter and good TCA health. Figure 15 depicts the emitter impedance and the TCA voltage as a function of the test duration. The average emitter impedance slowly decreases over the 3650 hours - indicating excellent emitter health. The TCA voltage (@50µN) shows a slight increase at ~800 hours which is related to the above mentioned failure of one emitter. Overall in 3650 hours, the TCA voltage increased only 3.1 % corresponding to 232 V. Although this slight increase is fully within expectations and does not constitutes problem (maximum allowable voltage is 12 kV), based on the decreasing impedance also a decreasing TCA voltage was expected. The only possible explanations are losses in the electric periphery (outside of the vacuum chamber) or current losses to ground (which are not monitored directly) inside the vacuum chamber or the thruster.

Investigating this issue, it was found that indeed certain emitters show an increasing current loss over the last 600 hours of the test. Although the level of the leak currents did not endanger the thruster operation, it is in the long term a potentially lifetime endangering event. Post test assessment after disassembling the thruster components showed indeed that slight indium contamination can be seen in the vicinity of the those emitters. The reason for this was found easily. During assembly of the test unit, a labyrinth which is designed to protect against such events was not included. This particular labyrinth, when assembled in the unit, prevents that the emitters can be removed again without destroying the labyrinth and possibly other thruster hardware. Since for this test unit an exchange of emitters was planned, the labyrinth was not installed causing the contamination and the leak currents. In future test units such labyrinths will be included and additionally a newly designed extractor plate will furthermore reduce any internal contamination risk.

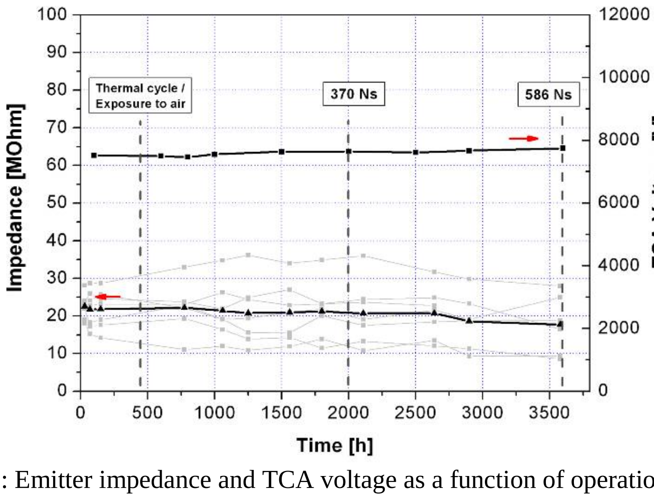

Figure 15: Emitter impedance and TCA voltage as a function of operational time.

Notwithstanding those slowly developing leak currents, the thruster and the emitters performance was excellent. A final thruster characterization included a check of the total thrust range (0.1 – 100µN) and a thrust resolution assessment. Figure 16 depicts the results of this assessment. The test verified the capability to produce the full thrust range after 3600 hours and with only 7 instead of 9 emitters. Furthermore, not only the thrust resolution of 0.3 µN was achieved but also a thrust resolution of ~0.1µN (see left side of Figure 16). The only limitation both in accuracy and size of the possible thrust steps are the laboratory power supply and control software used for this test.

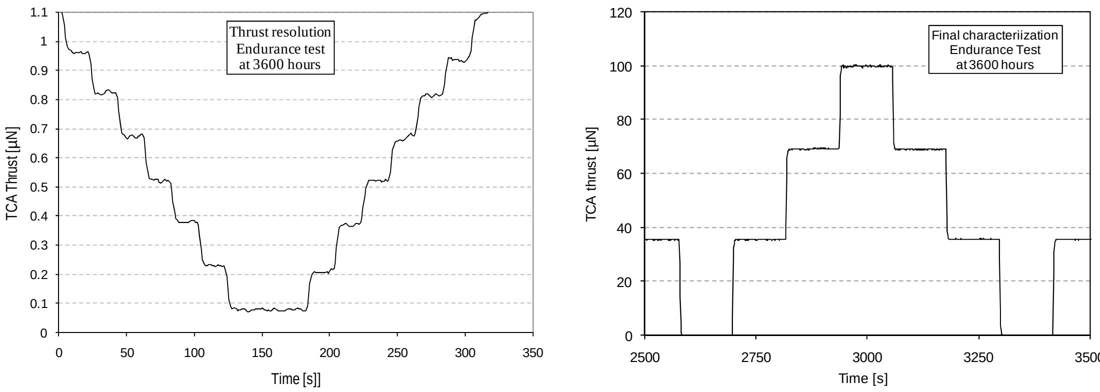

Figure 16: TCA thrust resolution (left) and final characterization (right) at the end of the endurance test (~3600 hours).

Post test assessment:

Beside of the already discussed occurrence of a low level of leak currents, no lifetime limiting effects have been found during the test or in the post test assessment of the emitters and the TCA. Calculation of the mass efficiency of each individual emitter (by measuring its weight) showed that the average mass efficiency of the operative emitters was 59% and the average specific impulse was 4700 s.

VI. Conclusion and Outlook

Within the In-FEEP technology qualification efforts for LISA PF, two test series have been performed in the recent months. One test series was focused on a Structural Test Model (STA) and included vibration and acoustic tests. Both tests successfully confirmed the compliance with all the requirements subject to those tests. Subject of the other test series was the Thruster Cluster Assembly (TCA), i.e. one thruster side of the FCA. Within this test, the TCA has been tested for 3650 hours generating a total impulse of 586 Ns. Even more important than the achieved total impulse bit is the fact that the thruster has shown no sign of lifetime limiting effects. Beside of the occurrence of small leak currents after roughly 3000 hours of operation (due to a missing labyrinth which is designed to exactly prevent the occurrence of leak currents), neither the emitters nor the thruster itself show any lifetime detrimental effects. The test was terminated due to scheduling constrains. However, all measured parameters (impedance, TCA voltage etc.) indicate that the thruster could operate for the full LISA operational time and even longer. Based on the measured mass efficiency during this test, a TCA equipped with 9 operational emitters has a life expectancy of 39,000 hours generating a total impulse bit of 6300 Ns at an average thrust level of 50µN.

During this test, all requirements, subject to the three test phases, have been investigated and compliance plus, in most cases, a comfortable margin has been established. This includes the thrust range capability, thrust resolution, thrust noise, thrust controllability and linearity, thrust response, sparking rate, beam divergence and many others.

Although unplanned, the test has also shown the excellent redundancy of the Needle FEEP concept. In spite of the failure of two emitters, compliance to all the requirements has been shown. The failure of two emitters is again due to the fact that not fully selectable emitters have been used for this test and a high probability of the failure was predicted prior to the test initiation.

Presently the STA is prepared for a series of further tests. An initial functional verification test will be followed by a vibration test. Subsequently, the unit will undergo a thermal test, simulating the condition the unit would see when assembled on the spacecraft and exposed to in-space temperature. Finally, the test unit will be exposed to a lifetime test over at least 2000 hours.

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