

# Status of the Indium FEEP Micropropulsion Subsystem Development for LISA Pathfinder

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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.**

**ARC together with Astrium GmbH is jointly developing a flight design for an Indium FEEP Microthruster-Cluster suitable for LISA Pathfinder. The paper reviews some of the basic design elements and performance parameters which are compliant with the LISA PF requirements for ultra-precise attitude and orbit control.**

**The present paper details some of the test conducted during the manufacturing of the Indium needle emitters. Furthermore, it presents the series of qualification tests conducted with the flight representative units. Final verification of the present design and the needle FEEP technology will be obtained by an extended lifetime tests.**

## 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 2015. 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 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.

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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).

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

Table 1. LISA PF Key Thruster Requirements.

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 (see table 2).

Experiment	Function	Spacecraft	Nr. of LMIS	Operation Time
LOGION	Test of LMIS in $\mu$ -Gravity	MIR	1	24 h (1991)
MIGMAS/A	Mass Spectrometer	MIR	1	120 h (1991-94)
EFE-IE	S/C Potential Control	GEOTAIL	8	600 h (1992 -)
PCD	S/C Potential Control	EQUATOR-S	8	250 h (1998)
ASPOC	S/C Potential Control	CLUSTER	32	Ariane 5 Launch Failure 1996 Still operational after Crash
ASPOC-II	S/C Potential Control	CLUSTER-II	32	6515 (2000 -)
COSIMA	Mass Spectrometer	ROSETTA	2	Launched 2004 (tested in space)
ASPOC/DSP	S/C Potential Control	DoubleStar	4	4456 h (2004 -)

Table 2. Space Experience of ARC Indium LMIS (as of 2005).

Since the late 1990s the LMIS technology was used at ARC to develop a Field Emission Electric Propulsion system (FEED). The ARC FEED system uses Indium as propellant. Indium has a variety of advantageous properties such as a relative high atomic mass and low 1<sup>st</sup> 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<sup>1,2</sup> already demonstrated key performance parameters such as sufficient propellant reservoir size, clusterability to achieve thrusts beyond 100  $\mu\text{N}$ , extremely low thrust noise and controllability. With several tests, reaching test durations up to 5000 hrs, ARC was the first to show that In-FEED technology has also a sufficient lifetime for missions such as Microscope, LISA and similar missions<sup>3,4</sup>.

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-FEED matches and even exceeds the rigid LISA PF requirements. This paper gives some details of the conducted 3000 hrs test and its results.

In order to transfer the breadboard into a flight model, ARC 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<sup>5</sup>. This paper describes the In-FEED thruster technology in general, the particular propulsion system developed for LISA PF and presents the most pertinent results of a recent 3000 hrs test with LISA PF representative technology.

## II. Liquid Metal Ion Source (LMIS)

A LMIS produces an energetic Indium ion beam by extracting ions directly out of the liquid Indium propellant. It consists of a needle covered with Indium which is heated above the Indium melting point (156 °C). Then a sufficiently high electric potential is applied between the emitter and an extractor electrode until a field strength of about  $10^9$  V/m is reached at the tip. The equilibrium between the surface tension and the electric field strength forms a so-called Taylor cone on the surface with a jet protruding due to space charge (see Figure 1). Atoms are then ionized at the tip of the jet and accelerated out by the same field that created them. The expelled ions are replenished by the hydrodynamical flow of the liquid metal. Contrary to other electric propulsion systems, ionization and acceleration takes place in one step using the same electric field. This avoids complications well known from volumetric ionization processes and leads to a very high electric efficiency of  $> 95\%$ . Indium ions are 98% singly charged along the complete thrust range<sup>6</sup>. Typical emitter voltages range from  $U_E=3.5-10$  kV for currents of  $I_E=1-150$   $\mu$ A of a single LMIS. This corresponds roughly to a thrust of 0.1-15  $\mu$ N.

Depending on the total impulse that the thruster has to deliver, several different tank reservoirs were developed ranging from 0.22 g up to 30 g of Indium capacity (see Figure 2).

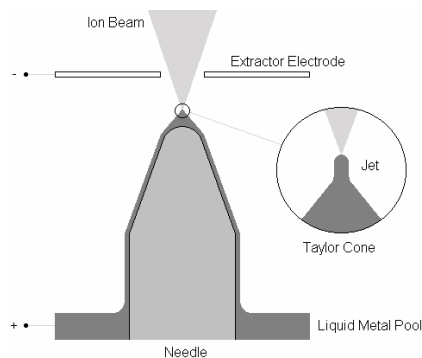


Figure 1. Concept of a Needle Liquid Metal Ion Source.

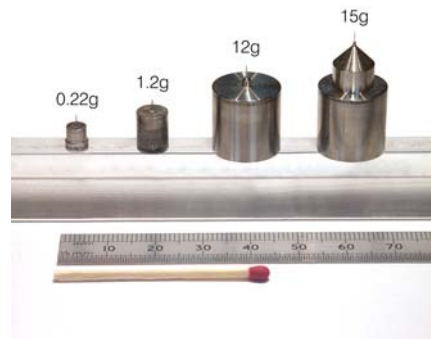


Figure 2. Indium Reservoirs.

Indium was chosen as a propellant due its high atomic mass, low ionization potential and good wetting properties. Moreover, it can be handled in atmosphere with no risk, greatly simplifying thereby the development and testing and reducing the associated R&D costs. Compared to other propellants used for FEEPs<sup>7</sup>, Indium also has a very low vapor pressure and a high melting temperature (156°C). Both properties are significant system advantages. The low vapor pressure ensures that a possible contamination of the spacecraft by the propellant in orbit is minimized and also relaxes complex sealing procedures prior to launch. The high melting temperature of 156°C ensures that the propellant is solid during launch and the LMIS can therefore easily withstand the high vibration loads. During the CLUSTER-II qualification, the ARC emitters successfully withstand vibration loads of 30 g RMS tested along 20-2000 Hz which is very representative for LISA PF. The solid state of the propellant during launch also simplifies the system since no valves or other devices (blast-disks) are required to avoid propellant spilling (open tank methodology).

Developed more than 20 years ago, Indium LMISs were first successfully tested onboard of the Russian MIR space station in 1991 and have since then flown on a number of satellites as part of a spacecraft potential controls or mass spectrometer devices (see Table 2). This makes it the only space-proven LMIS and up to this point the various LMIS from ARC have logged more than 12,000 hours of combined operation in space on 8 different spacecraft. They have also demonstrated excellent robustness surviving an ARIANE 5 launch failure onboard the CLUSTER satellite. After the crash from an altitude of several kilometers, the LMIS was recovered and sent back to ARC and tested. The test results showed that the LMIS had about the same good operational characteristics after the crash as at the point of its delivery.

The performance values for a single In-FEEP emitter baselined for cluster operation is summarized in Table 3.

Table 3. Single LMIS Characteristics.

Parameter	Values
Thrust	0.1 – 15 $\mu\text{N}$ / Emitter *
Thrust Resolution	< 0.1 $\mu\text{N}$
Thrust Noise	< 0.1 $\mu\text{N}/\sqrt{\text{Hz}}$ **
Minimum Impulse Bit	< 5 nNs
Total Impulse	490 -1000 Ns / Emitter ***
Specific Impulse	4000 - 8,000 s
Singly Charged Fraction	98%
Electrical Efficiency	95% ****

\* peaks up to 30  $\mu\text{N}$  are possible.  
 \*\* from 10 Hz to  $10^{-4}$  Hz  
 \*\*\* Using the present reservoir size of 15 g, larger sizes are possible, depending on actual thrust profiles  
 \*\*\*\* Comparing the current to the emitter with the current in the ion beam (minus extractor and plume shield current losses)

The LMIS technology was the starting point of the FEEP thruster developments at ARC. After an initial ESA contract to develop a 25  $\mu\text{N}$  thruster prototype in early 1996, significant R&D was devoted to endurance testing and the development of a microthruster assembly in a pre-phase C/D program for ESA's GOCE satellite<sup>3</sup>. Since then, significant progress was made with regard to characterization of FEEPs<sup>2,8</sup> as well as with regard to the development of advanced cluster concepts<sup>9</sup>. Standard 2x2 cluster units (4 emitters) are used for emitter characterizations but also units capable to integrate up to a total of 16 emitters were built and tested at ARC. Beside of the LISA PF effort, recent developments include the development of microstructured FEEP thrusters<sup>10</sup> with the goal to achieve thrust levels up to 1mN.

### III. FEEP Cluster Assembly

In order to produce the maximum thrust level of 100  $\mu\text{N}$  as required for LISA Pathfinder (see Table 1) nine LMIS are operated in parallel to operate as one FEEP Thruster Cluster Assembly (TCA) operated by one single HV power supply. The number of 9 is the result of a trade-off between life capability and available mass and 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 0.1  $\mu\text{N}$  and about 30 $\mu\text{N}$  such a failure of one or two LMIS would have no significant effect on the expected lifetime of the other LMISs in the cluster.

Moreover for LISA PF a set of 12 TCA grouped in 3 FEEP Cluster Assemblies (FCA) each containing 4 TCA is required. The key development tasks with respect to the FCA are:

- Minimize mass and envelope for the FCA
- Provide sufficient heater energy to maintain the temperature required to operate the Indium LMIS with a minimum power
- Survive the harsh launch environment
- Ensure a safe operation of the FCA under the HV conditions of up to 15 kV potential difference.

The FEEP Cluster assembly (FCA) is roughly spoken the fixation for the core elements of the FEEP thruster, the Liquid Metal Ion Sources (LMIS). The propellant of the 36 LMIS integrated in the FCA has to be heated above the Indium melting point of 156.6 C and the high electrical potentials between -1kV (cover plate) and +12kV (emitter maximum voltage) have to be provided to the LMIS by the FCA. The demands for the high voltage design are to isolate the electrical high voltage insulation of each FEEP Cluster and to provide the distribution of the high voltage potential within the FCA.

The structural development approach focuses on the design which is adapted to the high mechanical launch loads and stiffness requirements together to cope with minimum heater power requirement. The design drivers for the

development are highest thermal insulation combined with maximum stiffness (eigenfrequency), strength and HV-constraints.

The FCA exists basically of 2 main assemblies, a hot inner frame and a cold outer housing main assembly. The hot and cold main assembly exists again of 2 identical, four times built-in, hot and cold, subassemblies, mounted to the inner frame (hot) and to the outer housing (cold). The completely integrated, hot internal frame is fastened with thermally isolated isostatic mounts to the outer housing. This hot and cold System design was chosen to get an optimized, stiff structure with a high eigenfrequency. The second reason is that this arrangement allows minimizing the number of hot structure supports and also minimizing the number of heat transfer connection to the outer cold housing and the satellite.

The following figures depict the complete FCA and the various subassemblies.

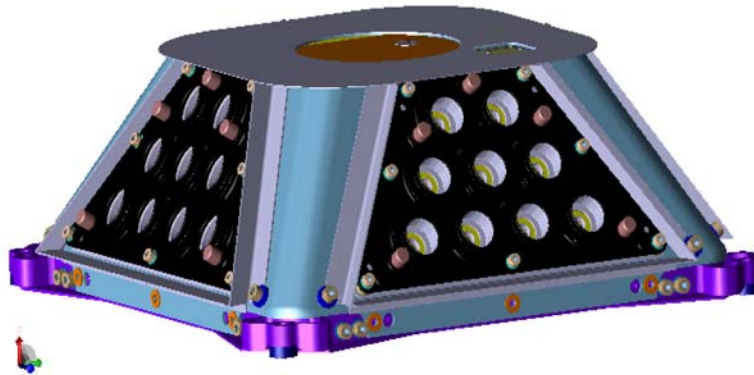


Figure 3. Complete FCA.

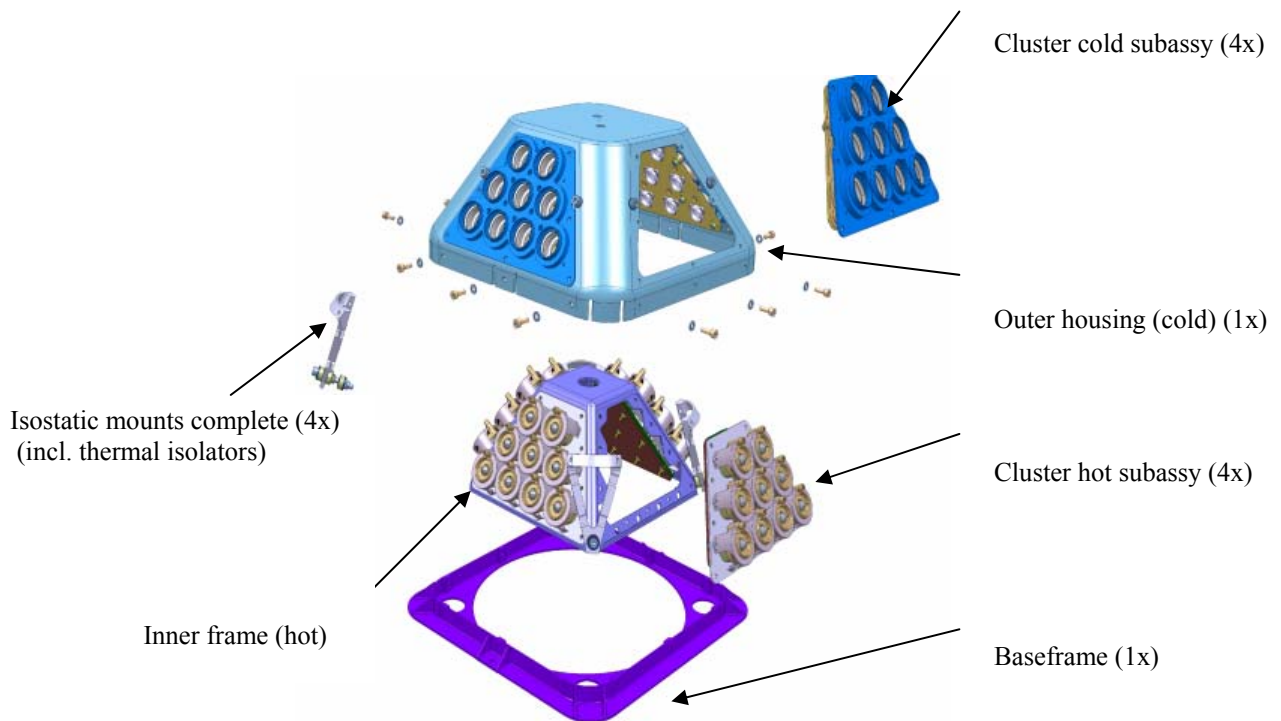


Figure 4. FCA main and subassemblies with hot and cold assembly.

Each of the 4 Cluster hot subassemblies consists basically of the 9 pre installed single LMIS, an aluminium hot plate, heated with two redundant heaters, a radiation shield as well as a pre resistor HV-distribution board. The Cluster hot subassembly is the one with highest mass contribution. Thus very stiff single suspensions for the HV supplied emitters electrodes (LMIS) are foreseen. The following figure depicts a section of this hot assembly.

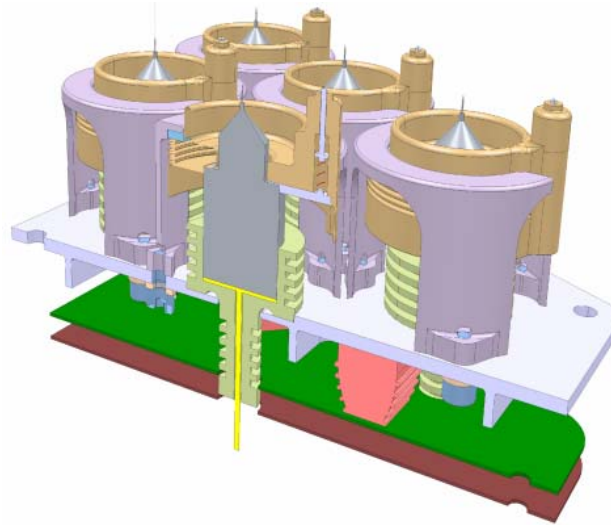


Figure 5. Cluster hot assembly

The Cluster cold subassembly consists of an aluminum cover plate and two mounted subassemblies. These are the insulation plate with 9 integrated aluminum focusing electrode rings and the extractor mounting plate with the extractor rings. For IR radiation protection the lower side is gold plated with respect to a minimum distance to the – 1kV extractor rings. The whole assembly is a very stiff construction and can be compared with a sandwich part. The extractor mounting plate is connected to PCU with 2 redundant HV-wires, the focusing electrodes are individually connected to the emitter by the spring loaded connector pin of the LMIS through a 9 holes in the printed circuit board. The following figure shows roughly the setup of the cold assembly.

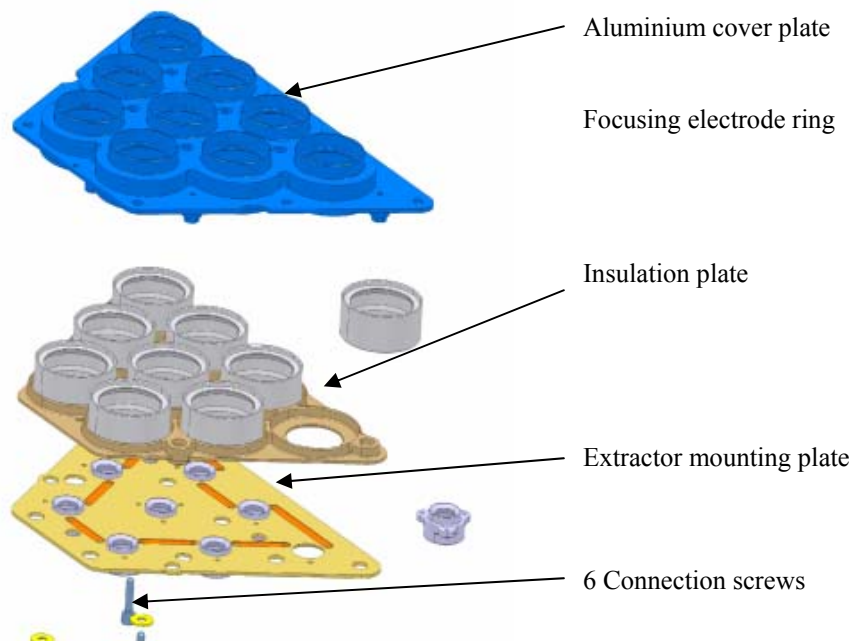


Figure 6. Cluster cold assembly.

The above described design has passed the Preliminary Design Review (PDR) in the framework of the LISA PF project and the LMIS will be soon integrated. Following integration, the cluster will pass through a series of tests including electrical and environmental tests, followed by a lifetime test over several thousand hours for qualification.

#### IV. LMIS Manufacturing

The manufacturing process of the Liquid Metal Ion Sources (LMIS) was defined and fixed at the beginning of the project. The highly complex process of the LMIS manufacturing consists of roughly 45 major steps. At each step the manufacturing is accompanied by a tight cleanliness and contamination control. This includes, metallurgical control of the utilized indium propellant at several stages of the LMIS manufacturing process, dedicated tools, and various cleaning processes for the propellant reservoirs, needles etc. Due to this process it is ensured that no particles larger than  $40\mu\text{m}$  can enter the propellant reservoir. At several points during the manufacturing process the quality of the LMIS is monitored and documented by a Secondary Electron Microscope (SEM) and other means. In addition, each manufacturing step is documented in production sheets providing therefore a gapless monitoring of the production history of each individual LMIS.

Furthermore, the quality and performance of each LMIS is evaluated and monitored by two major tests which are considered part of the manufacturing process. Each test has duration of 100 hrs. The first test, the so-called "burn-in" test is the first test after the assembly and filling of the LMIS. It is conducted in a dedicated test unit providing space for 4 LMIS. During this test, several thermal cycles are conducted and the LMIS performance is evaluated several times during the 100 hrs test. Test conditions (thrust etc.) are chosen such this test simulates closely the conditions during operations on LISA PF. These tests allow a first evaluation of the LMIS performance and provide therefore a quality filter under real operational conditions.

The second test is conducted in a so-called 4x4 test unit (see Figure 7). This unit provides space for up to 16 emitters. Beside of the larger number of emitter locations (compared to the 9 locations of a TCA) the unit is nearly identical to a TCA (see Figure 4) and provides not only more extensive performance data basis but also provides data of the cluster behavior of the LMIS.

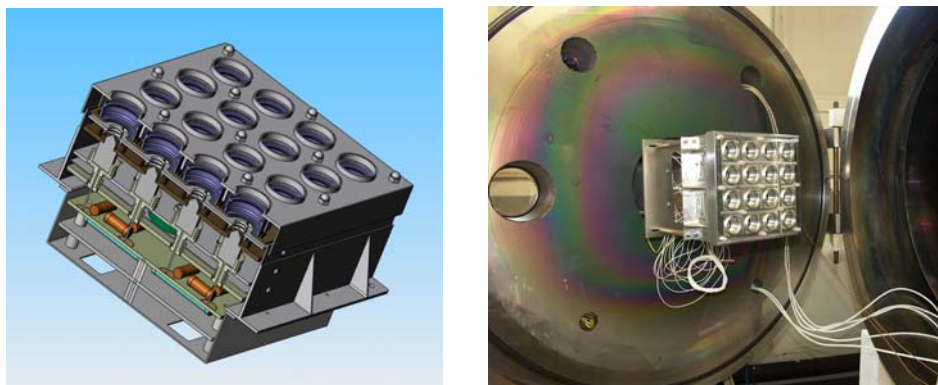


Figure 7: 4x4 Cluster test unit schematic (left) and installed in the vacuum chamber (right)

Together, those two tests with a total of 200 hrs operational hours provide an extensive data basis and manufacturing quality control. Each LMIS delivered subsequently for integration into a FCA has therefore proven several times its operation under realistic conditions and therefore mitigates any failure risk in the subsequent extensive testing as discussed in the following paragraphs.

#### V. TCA/FCA test series

The LISA PF propulsion system qualification includes 3 demonstration units (DM). Each of the units will undergo a dedicated series of test. One DM will be utilized for thrust measurement at Thales Alenia Space, Italy. A

second DM will be utilized for off-nominal test at ARC. In this test series a FCA will be tested at conditions although not foreseen at nominal operation but considered possible. The third DM will undergo the most extensive testing. This includes beside of the standard HV testing a full scale environmental testing consisting of vibration tests and thermal tests. The thermal test will be conducted in the ARC test facility with a dedicated thermal shroud. The DM unit will be attached to an interface plate which will simulate the satellite surface (see Figure 8). The temperature of this interface plate can be actively controlled by means of several Peltier elements. The temperature of the interface plate ranges from  $-50^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ . The shroud itself is cooled by means of liquid Nitrogen, therefore providing ideally a background temperature down to  $-195^{\circ}\text{C}$ . A schematic test assembly and the thermal shroud itself are shown in Figure 8.

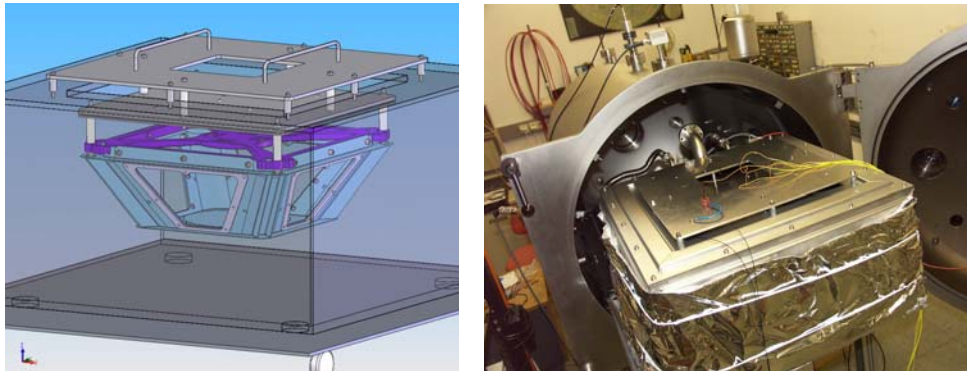


Figure 8: Schematic depiction of the assembled DM in the thermal shroud (left) and the thermal shroud (right)

Furthermore, a dedicated test will be conducted to investigate the beam structure and behavior. This test will be conducted with the ARC beam diagnostic facility<sup>11</sup> (see Figure 9). With the beam diagnostic facility, the beam divergence and thrust vector accuracy can be evaluated for the complete TCA as well as for individual emitters. To facilitate the tests of individual emitters a dedicated control box equipped with HV voltage, vacuum suitable switches was designed. This box allows the controlled switch on and off of individual emitters (a feature which is not possible on LISA PF).

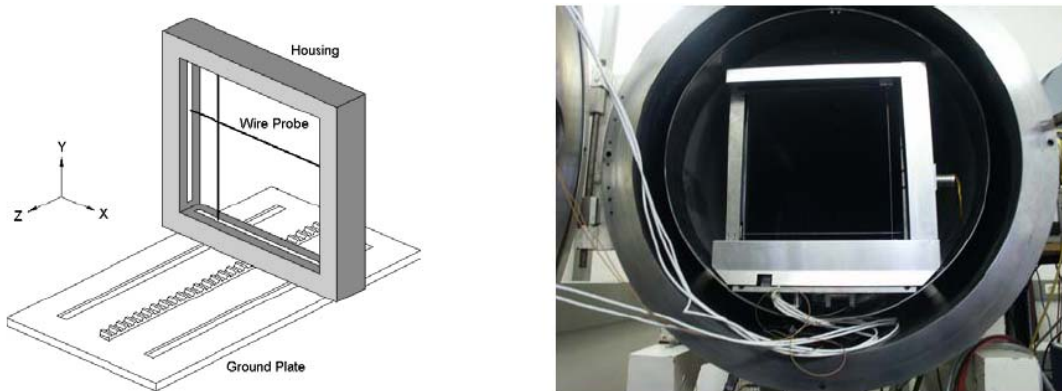


Figure 9: Schematic depiction of the ARC beam diagnostic (left) and its integration into the vacuum chamber (right)

The data obtained with the beam diagnostic (see Figure 10) will then allow to evaluate the compliance to the requirements with regard to thrust vector accuracy and beam divergence.



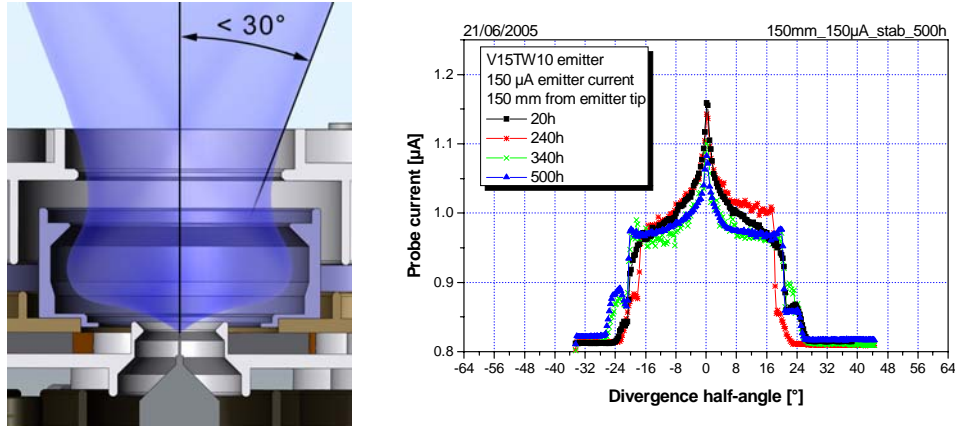


Figure 10: Exemplary set of data obtained with the beam diagnostic facility

Finally, one of the DMs will be tested for several thousand hours. This test will allow investigation of the long term behavior of the LMIS as well as the general design of the FCA. The test will be run at the ARC test facilities in one of the large vacuum chambers. Although based on the experience obtained with the recent 3000 hrs test<sup>12</sup>, no major difficulties in such a long duration test are expected, special precautions are taken to ensure that the test will run without any interruptions. This includes a collector plate covered with indium foil to prevent back-sputtering of collector plate material and subsequent contamination of the FCA, a redundant pump system, and several independent power grids and UPS.

## VI. Bread Board Test

As preparation for the above mentioned tests, a Bread Board unit of a TCA was investigated at Astrium Friedrichshafen with regard to its HV capabilities (see Figure 11). The tests were performed at a temperature level below the Indium melting temperature. The applied voltage ranged up to 18 kV, which is about twice the nominal operation value. The successful tests showed that the HV design of the thruster is suitable for operation.

Following this test, the Bread Board unit will be integrated in the ARC test facility for a short term test with operating Indium FEEP emitters. This test will provide further data about the thruster design and constitutes an important step in its qualification process.

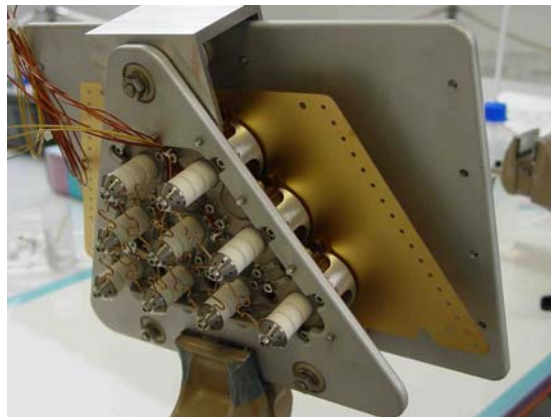


Figure 11: Bread Board test unit

## VII. Conclusion

The In-FEEP thruster concept for ultra precise attitude and orbit control designed for LISA Pathfinder has been presented. A detailed design and lifetime test campaign is currently in preparation to demonstrate its compatibility with the requirements of LISA PF. A recent successful HV test with a bread board unit of the TCA constitutes an important step in the design qualification. Further planned tests include, amongst others, environmental tests (vibration, thermal), beam diagnostic tests and a lifetime test extending over several thousand hours. With this test series it is anticipated that the suitability of the needle FEEP emitter technology and the FCA design will be proven. A successful demonstration would not only allow the utilization of this technology on LISA PF and eventually on LISA but also on other future missions such as Microscope etc.

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## References

- <sup>1</sup>Tajmar, M., Genovese, A., and Steiger, W., "Indium FEEP Microthruster Experimental Characterization", *AIAA Journal of Propulsion and Power*, Vol. 20, No. 2, 2004, pp. 211-218
- <sup>2</sup>Genovese, A., Buldrini, N., Tajmar, M., Tamas, E., Vasiljevich, I., Marhold, K., and Ruedenauer, F., "Indium FEEP Cluster Development", *AIAA Joint Propulsion Conference*, AIAA-2005-4385, 2005
- <sup>3</sup>Genovese, A., Tajmar, M., Buldrini, N., and Steiger, W., "2000h Endurance Test of an Indium FEEP Microthruster Cluster", *AIAA Journal of Propulsion and Power*, Vol. 20, No. 2, 2004, pp. 219-227
- <sup>4</sup>Genovese, A., Buldrini, N., Andres, K., and Tajmar, M., "5000h Endurance Test of an Indium FEEP 2x2 Cluster", *AIAA Joint Propulsion Conference*, AIAA-2006-4827, 2006
- <sup>5</sup>M. Tajmar, C. Scharlemann, A. Genovese, N. Buldrini, M. Boss, R. Killinger, "Indium FEEP Micropropulsion Subsystem for LISA Pathfinder", AIAA-06-4826, Joint Propulsion Conference, Sacramento, CA, 2006
- <sup>6</sup>Tajmar, M., "Influence of Taylor Cone Size on Droplet Generation in an Indium LMIS", *Applied Physics A*, Vol. 81, No. 7, 2005, pp. 1447 – 1450
- <sup>7</sup>M. Andrenucci, L. Biagioni, F. Ceccanti, M. Saviozzi, D. Nicolini, "Endurance Tests of 150  $\mu$ N FEEP Microthrusters", IEPC, 2005-183, International Electric Propulsion Conference, Princeton, 2005
- <sup>8</sup>Tajmar, M., "Development of a Lifetime Prediction Model for Indium FEEP Thrusters", *AIAA Joint Propulsion Conference*, AIAA-2005-4386, 2005
- <sup>9</sup>Vasiljevich, I., and Tajmar, M., "Development of a Focus Electrode for an Indium FEEP Thruster", *AIAA Joint Propulsion Conference*, AIAA-2005-4384, 2005
- <sup>10</sup>Tajmar, M., "MEMS Indium FEEP Thruster: Manufacturing Study and First Prototype Results", *AIAA Joint Propulsion Conference*, AIAA 2004-3619, 2004
- <sup>11</sup>Tajmar, M., Marhold, K., Kropatschek, S., Hense, K., "Advanced 3D Plasmadiagnostic for the Indium FEEP Microthruster", AIAA 2003-4569, *AIAA Joint Propulsion Conference*, Huntsville, AL, 2003
- <sup>12</sup>Scharlemann, C., Genovese, A., Buldrini, N., Schnitzer, R., Tajmar, M., Frühholz, H., Killinger, R., "Development and Test of an Indium FEEP Micropropulsion Subsystem for LISA Pathfinder", AIAA-07-5251, Joint Propulsion Conference, Cincinnati, OH, 2007