LISA Pathfinder Field Emission Thruster System Development Program

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Abstract: The paper presents the design and development logic of the field emission thruster system (or FEEP system) development program for the LISA Pathfinder spacecraft. LISA Pathfinder is the first demonstration spacecraft of the joint ESA/NASA LISA (Laser Interferometer Space Antenna) mission. LISA Pathfinder is built by ESA and will fly as a payload the NASA Disturbance Reduction System. The core technologies under development at ESA and to be verified in orbit are the inertial sensor and the field emission thrusters.

I. Introduction

LISA Pathfinder is an experiment to demonstrate Einstein's geodesic motion in space more than two orders of magnitude better than any past, present, or planned experiment, except for LISA.

The concept that a particle falling under the influence of gravity alone follows a geodesic in spacetime is at the foundation of General Relativity, our best model of gravitation, yet.

Within General Relativity, gravity is not a force acting on material particles, but instead is identified with curvature in spacetime geometry. Particles, in the absence of forces, travel in the straightest possible way in curved spacetime: this path is called a geodesic. In absence of gravity, spacetime is flat and geodesics are simply straight lines traveled at constant velocity.

Achieving high purity geodesic motion is made difficult by non-gravitational forces acting on masses, accelerating them away from the geodesic lines. LISA Pathfinder's experiment concept is to prove geodesic motion by tracking two test-masses nominally in free-fall through laser interferometry with picometre distance resolution. LISA Pathfinder will show that the relative parasitic acceleration between the masses, at frequencies around 1 mHz, is at least two orders of magnitudes smaller than the value demonstrated so far or to be demonstrated by any planned mission.

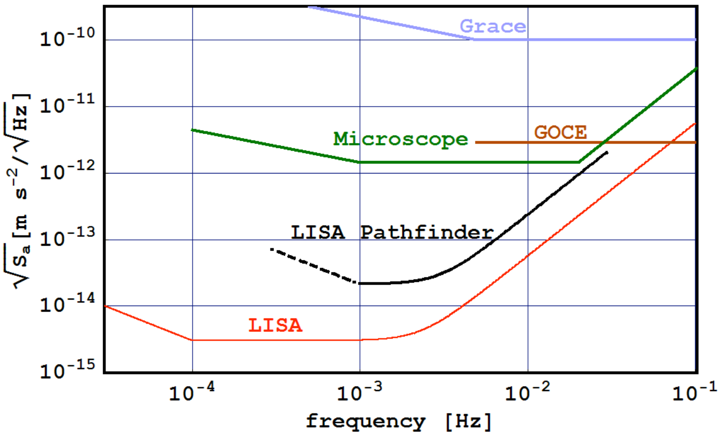

Figure 1. Comparison of required performance of various missions for relative geodesic deviation of test mass pairs. *For LISA Pathfinder the mission requirement are reported as the solid line. The dashed tail is a design goal.*

The basic elements to achieve and prove geodesic motion are the following:

- free floating test masses equipped with motion sensors in all degrees of freedom and free of dynamical disturbances ($< 3\times10^{-14}\ \mathrm{m/s^2}\sqrt{\mathrm{Hz}}\ \mathrm{at\ 1\ mHz}$),
- low-thrust (~10 µN), low-noise

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($\leq 0.1\, \mu N / \sqrt{Hz}$) proportional thrusters to push the spacecraft to follow the test masses,

- a high resolution laser interferometer to measure test mass relative displacement,
- 18-degree of freedom dynamical control laws,
- gravitationally "flat" ($< 5\times10^{-11}$g) and gravitationally stable spacecraft to host the test masses.

Three enabling technologies needed new advances to make this realization possible: low-noise test-mass charge control, a precision test-mass release device, and micro-Newton thrusters.

By using the geodesically moving test masses as reference for a drag-free control system, also the spurious acceleration of the spacecraft will be suppressed more than three orders of magnitude better than for any other existing or planned mission. In combination with its high stability and low self-gravity design, LISA Pathfinder spacecraft will then demonstrate the most perfect inertial laboratory available for Fundamental Physics experiments.

LISA Pathfinder will also realize a high precision differential dynamometer of unprecedented resolution, paving the way for a new generation of force experiments, like searches for 1/r2 law violations, spin-spin interactions, and spin-mass interactions, aimed at searching for new long range interactions beyond the Standard Model.

The high resolution test-mass to test-mass tracking demonstrated by LISA Pathfinder is an essential step for enabling a similar tracking of test masses even when they are located in different spacecraft, at large distance, and in interplanetary space, like in LISA, but also at short distance in low Earth orbit, like in future geodesy missions.

LISA Pathfinder hardware has been designed to be transferred directly to LISA. However, it is obvious that many other possibilities are opened by the results of LISA Pathfinder. LISA Pathfinder is indeed at once a mission in General Relativity and in Precision Metrology and will open the ground for an entirely new generation of missions not just in General Relativity, but in Fundamental Physics at large and in Earth Observation.

II. The LISA Pathfinder Spacecraft

The LISA Pathfinder spacecraft comprises two modules, namely:

- the Science Spacecraft (SCM),
- the Propulsion Module (PRM).

The science spacecraft contains the two main sensor packages, the LTP and DRS, the micro-propulsion systems and the drag free control system. The science spacecraft also accommodates the spacecraft equipment required to provide support functions to the payloads over the mission lifetime.

The inertial sensor core assemblies are each mounted in a dedicated compartment within the central cylinder. The payload electronics and spacecraft equipments are accommodated on shear panels as far away as possible from the sensors to minimize gravitational, thermal and magnetic disturbance. The FEEP and cold-gas micro-propulsion assemblies are arranged symmetrically on the outer panels to provide full control in all axes. The Colloid thrusters are mounted on opposing outer panels.

The target orbit is at the Earth-Sun L1 Lagrange point. This orbit provides a benign gravitational environment at Earth ranges of 1.2 to 1.8 million km, with stable solar illumination and freedom from eclipses. The spacecraft can stay in such an orbit for the operational lifetime 11 or 17 months, with the application of periodic station keeping maneuvers of 1-2 m/s per year.

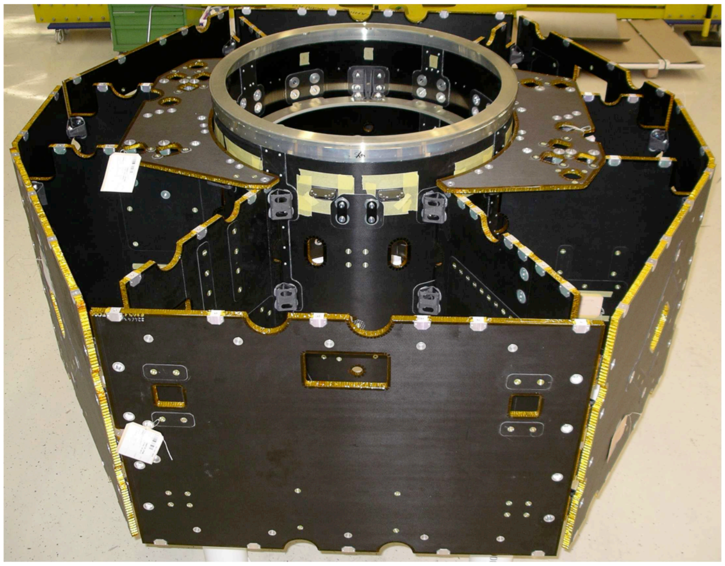

Figure 2. LISA Pathfinder Science Spacecraft structure.

The propulsion module (PRM) separates from the science spacecraft (SCM) prior to drag free operations to prevent disturbances which would be generated by the residual propellants acting on the inertial sensors.

III. The FEEP Subsystem

The Micro-Propulsion Subsystem (MPS) is based on Field Emission Electric Propulsion (FEEP) technology. The main features of the propulsion system are:

- It is able to produce stable thrust levels ranging from 0.1 μN to 150 μN.

- It is able to produce thrust with a resolution capability better than 0.1 μN and time response better than 190 ms for any specified thrust step in the required thrust range.
- Thrust noise, as measured indirectly through electrical parameters and through direct beam sampling, is compatible with the requirement for proper DFACS operation.
- Once deployed and initialized in orbit, it has no moving parts, nor gas leaks that could result in spacecraft disturbance.
- The thruster does not need ferromagnetic materials, and the magnetic disturbance on the test mass can be prevented by adequate design rule.

The proposed Micro-propulsion Subsystem is divided in three main parts (called Micro Propulsion Assembly - MPA): each one consisting of one FEEP Cluster Assembly, one Power Control Unit, one Neutralizer Assembly as shown in Figure 3.

The FEEP Cluster Assembly (FCA) consists of a self-contained unit of 4 FEEP Thrusters Assembly, which include propellant reservoir, mounted on a support structure with any necessary interfaces and support bracket (mechanical, thermal and electrical). The four thrusters are devoted to provide thrust to the required vector directions and they are commanded individually and work in hot redundancy.

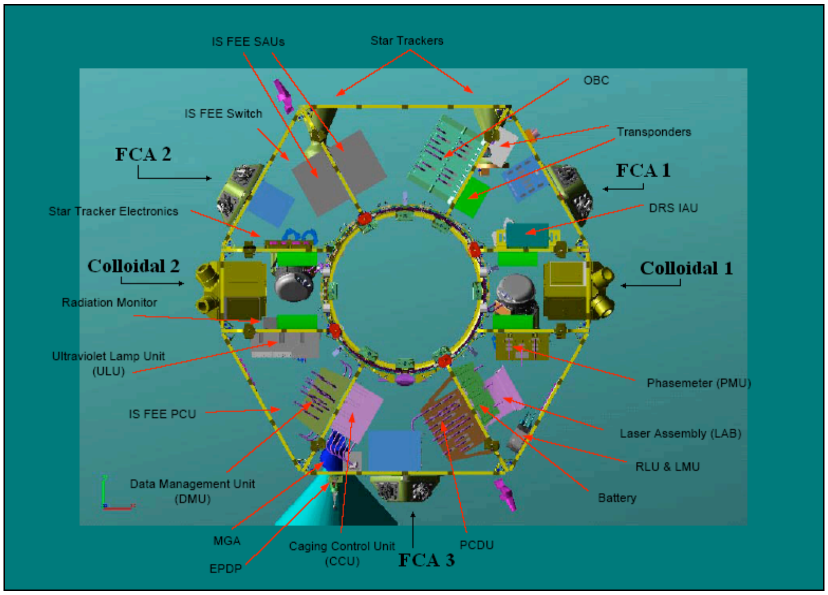

Figure 3. Spacecraft and MPS layout.

The Neutralizer Assembly (NA) consists of a self-contained unit of two Neutralizer unit mounted on a support structure with any necessary interfaces and support bracket (mechanical, thermal and electrical). The neutralizer is necessary to nullify the spacecraft unbalance due to ion thruster operation. The neutralization function is implemented by means of cold redundant hardware.

The Power Control Unit (PCU) consists of a self-contained electronic unit mounted on a support structure with any necessary interfaces and support bracket (mechanical, thermal and electrical). The PCU interfaces the spacecraft (Power and TC/TM tasks) and provide power and control to both FEEP Cluster and Neutralizer assemblies. The HV interconnection box and relevant harness is part of this equipment.

According to the above architecture, each MPA will be mounted at 120 degrees with respect to the others. The PCU will be allocated inside the spacecraft while the FCA and NA will be mounted externally.

Neutralization is necessary to nullify the spacecraft unbalance due to FEEP thruster operation (thrust is generated by means of emission of positive ions). For LISA PF the neutralization function has been implemented by means of:

- Self-adjustment concept (the electrons are emitted according to the S/C unbalance caused by FEEP operation).
- Cold redundant hardware (in order to protect the propulsion system from Single Point Failure due to neutralizer fault).

Moreover, to reduce any possible risk associated to the Thrusters/Neutralizer compatibility issue (e.g. propellant contamination, dimensions, temperature and so on) and to increase flexibility, the neutralizer has been configured as a self-standing unit (dedicated mechanical box) where two neutralizers (main and redundant) have been allocated. The so formed Neutralizer Assembly is allocated on the external wall of the satellite and not on the same panel where the FCA is located. As a consequence of this choice and taking into account of the LISA PF space environment (L1 with very low plasma density), neutralization function is assured by means of additional bias voltage (200V max) to enhance electron emission. Consequently being allocated far from FCA has reduced effects of propellant contamination and electric field caused by the FEEP operation.

A. PCU

The FEEP Micro Propulsion System foreseen for LISA Pathfinder is composed of three propulsion sections, each one consisting of 4 FEEP thruster assemblies and 2 neutralizers allocated outside the spacecraft and aimed to perform ultra-high precision pointing capability. In order to perform the control and power management of the above propulsion equipments, inside the spacecraft and in proximity of each pod a dedicated Power Control Unit (PCU) is foreseen. According to this architecture, the PCU has to fulfill the following main tasks:

- Control and power management of four independent field emission thrusters for both FEEP technology in order to provide a thrust level ranging from 0.1 µN to 150 µN with high resolution and low noise. To this purpose, the PCU allocates 8 High Voltage generators with voltage/current control and on-board calibration capability (Baseline voltages: +12kV for emitter electrode and –1Kv for accelerator/cover plate electrode). These high voltages require voltage regulation range varying from 3.5kV to 13kV at very low currents (from 0.5KA to few mA). The PCU also allocate 8 low voltage generators for propellant heating and the supply for release of the cover lid mechanism (slit FEEP technology only).

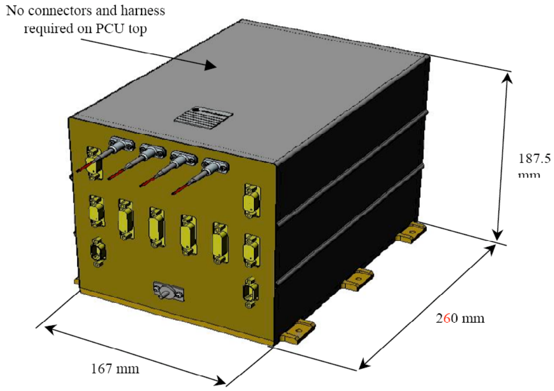

Figure 4. PCU layout. *For LISA Pathfinder a single PCU drives four thrusters and two neutralizers.*

- Control and Power management of two thermionic neutralizers (one main and one in cold redundancy) necessary to nullify the charge spacecraft unbalance due to FEEP operation. To this purpose, the PCU allocate four voltage generators with voltage/current control and on-board calibration capability.
- Single point failure tolerant architecture to allow the operation of three thrusters and one neutralizer in case of single failure at FEEP Subsystem level. This configuration will be also applied to the spacecraft interfaces (Main Bus and command/telemetry interface lines are available in cold redundancy).

Finally, despite the high number of functions and supplies necessary for proper operation, the PCU need to be light and efficient.

B. Neutralizer

Neutralizer units are required for the FEEP in space operation to provide electrons for charge compensation upon ejection of positive ions from the FEEP thrusters. In this way the build up of electrostatic charge on the spacecraft surfaces can be avoided. The neutralizer produces a nominal electron current of 6 mA, suitable to counterbalance the electrical charge of up to four identical FEEP thrusters delivering each one an ion beam current of 1.5 mA (equivalent to more than 150 µN of thrust). The thrusters are operated independently, and can be all active at the same time. The two neutralizers in the Neutralizer Assembly (NA) are normally operated one at a time: one is active and the other is cold redundant. In some cases, both neutralizers could be operated simultaneously.

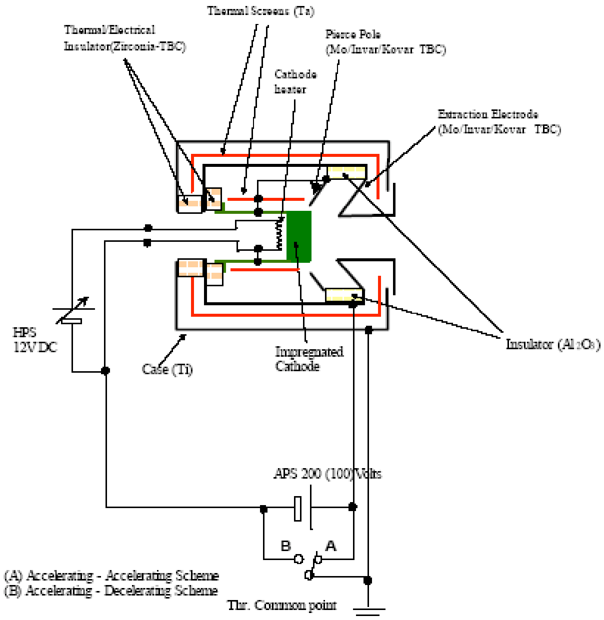

Figure 5. Neutralizer schematic. *For LISA Pathfinder a cathode bias up to 200V is applied to overcome the expected large sheath in L1.*

The neutralizer design is based on a moderately high perveance Electron Gun (EGUN). The EGUN is realized by integrating the thermionic cathode and the beam conditioning electrode structure into a suitable mechanical support that is also be in charge of handling thermal issues. For a small electron gun as the one designed, the gun perveance defined as the ratio between the cathode current and the cathode-to-anode voltage powered by a 1.5 factor - is considered low-moderate if assumes values up to 1 μPerv, whereas it is considered high if the values are above 1 μPerv. In general, with a low perveance e-gun design, the advantages are:

- Allows the adoption of low cathode-to-anode voltages limiting the risk of arising discharges between electrodes.
- Less criticalities for cathode damage due to back sputtering erosion from ion bombardment is also an advantage (expected from neutrals diffused from the FEEP outlet and ionized in the neutralizer anode region). The erosion phenomenon strongly affects the cathode lifetime: in fact at energies greater than 200-300 Volts, for typical cathode materials (including Tungsten matrix used in most of cathodes), the sputtering yeld increases fastly, rising up to 1 and more for energies around 1000 Volts (depending also from the bombarding ion mass).
- A more compact anode-to-cathode region allowing to save volume and mass and, consequently, to minimize the externally radiating surface areas. This, in principle, is expected to provide benefits in terms of power demands for cathode heating at steady operation, as well as in shortening the heating time.

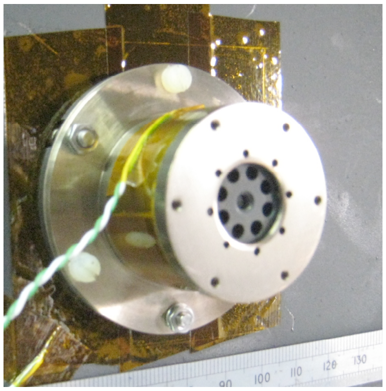

Figure 6. Neutralizer during plasma chamber testing.

On the other side, a low perveance design which uses high cathode-to-anode voltages guarantees a better penetration of the emitted electrons into the FEEP generated plasma (ambient plasma and charge-exchange ions), thus overcoming space charge issues impacting the neutralization process effectiveness. This is achieved anyway in this design by biasing negatively the cathode in the range from several tens of Volts up to two hundred Volts.

The cathode technology uses Barium oxides (Barium Alluminium and Calcium oxides). The most advanced and preferred one is the 6:1:2, as it is considered by manufacturers, to be able to provide similar performances as the 4:1:1 but with enhanced resistance to poisoning and humidity. Enhancement is implemented by the use of a small quantity of Scandium oxide in the impregnate mix (6:1:2X). These enhancements and in particular the use of Scandium mix technology further lowers the cathode work function (from 2.1eV for standard 6:1:2 down to ≈1.8eV with 6:1:2X). Furthermore these cathodes have experimentally demonstrated smooth variation of the current density with temperature at low emission, allowing the control of the emission by temperature limitation to be an effective mode of operation. In our case the advantage of using a 6:1:2X is its potentiality in reducing the heating power to meet the requirements on the max power from the bus.

C. Needle FEEP

The Needle FEEP technology is based on liquid metal ion source technology, where ions are generated by field emission from a sharp needle (micron). It was adapted to space use intended for spacecraft potential control and the use in space borne mass spectrometers. Here fast ions were produce to determine strength of the magnetic field in the solar system by measuring the gyration radii. Several such Liquid Metal Íon Sources (LMIS) were and are being used on different space missions. The LMIS is the core part of each functional chain of the FEEP emitter element. For the Indium Needle FEEP technology it consists of a Tantalum reservoir (tank), filled with Indium (propellant). For operation the reservoir is heated above the Indium melting temperature and the Indium by capillary forces is transported to the tip on a Tungsten needle. Here due to the high field strength Indium ions are extracted and accelerated by the extractor electrode.

1. Indium Needle Emitter

The ion source consists of a needle covered with Indium, which is heated above the Indium melting point (156.6 °C). Then a sufficiently high electric potential is applied between the emitter and an extractor electrode until a field strength of about 109 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. 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 hydro dynamical 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 leads to a very high electric efficiency of > 95. Indium ions are 98% singly charged along the complete thrust range. In addition to ions, also slightly charged

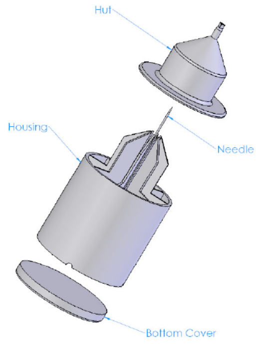

Figure 7. Needle emitter with its reservoir.

micro droplets are emitted due to instabilities of the Taylor cone at higher currents. This reduces the amount of propellant available for producing thrust, hence the ratio of mass emitted as ions compared to the total mass emitted by a LMIS is termed mass efficiency.

The needle protrudes about 1mm out of the capillary, which is sufficient to have a high electric field from the tip-effect, and on the other hand it is close enough to ensure easy Indium re-supply to the tip from the capillary and the reservoir. During heating and cooling of the LMIS, stresses in the Indium film appear during the phase change from liquid to solid. As the Indium on the tip is very small compared to the mass stored in the reservoir, risk of de-wetting can occur as the reservoir Indium tries to suck the Indium from the tip. In order to protect the Indium on the tip from de-wetting, a thin Tungsten film is deposited after the initial tip wetting. This skin holds the Indium always on the tip and protects it from de-wetting. Tungsten has the lowest solubility in Indium and a very high melting point so that this skin is no lifetime concern.

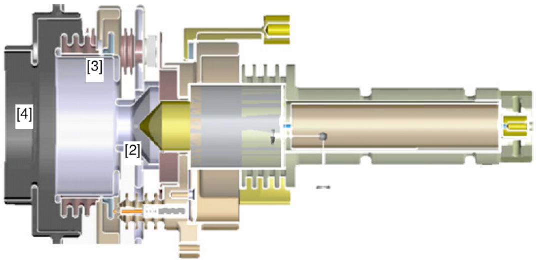

Figure 8. FEEP Thruster Element. *On the left side the extractor electrode [2], the focusing electrode [3] and the cover-plate [4]. On the right side the FEE.*

The reservoir is designed to hold 15g of Indium. Although the preferable reservoir shape is only conical to maximize the capillary forces towards the emission site, the main body of the reservoir is cylindrical. This is necessary, as the LMIS needs to be mounted and dismounted from the front side of the thruster. The conical structure is only necessary at the end as a transition from the cylinder to the needle. On the inside of the reservoir fins have been implemented in order to facilitate the indium flow towards the needle.

2. *Thruster and Cluster Assembly*

The LMIS forms the basis of a FEEP Thruster Element (called FTE), the smallest thrust-producing element of an FCA. The basic thrust producing components of a FTE are the Emitter (LMIS) and the Extractor Electrode. While the emitter is at a potential of + 12kV the potential difference needed to accelerate the ion is provided by an annular extractor electrode which is in ground potential. As this basic Indium FEEP element produces a beam having a divergence angle of about 65° a 3rd electrode LMIS was to be added to narrow this divergence angle to 35°. This focusing electrode is on the same potential as the LMIS. The 4th and final electrode is the cover electrode, supplied with -1kV to prohibit electron back flow. The LMIS and the Pre-resistor form the FEEP emitter element (FEE).

The FEE to produce thrust has to be brought to a temperature of 170 °C. The heat is produced by means of an Aluminum heater plate. Conductive heat transfer through the ceramic isolator and the Aluminum emitter holder heats the LMIS. To isolate the FCA structure from the LMIS potential an emitter isolator is used. This is an integral piece that as well isolates the contact pin. This part of emitter isolator was a labyrinth type surface to provide increased isolation length and sputter shadowing to minimize the risk of short circuits by conductive coating that may build up during long life missions. The thruster cluster assembly (TCA), in other words the thruster, is made of 9 FTE and are powered and controlled in parallel. During ground testing each FTE is monitored individually to assess cross-talk effects and identify failed units, though in orbit the FTE is controlled and monitored as a single thruster.

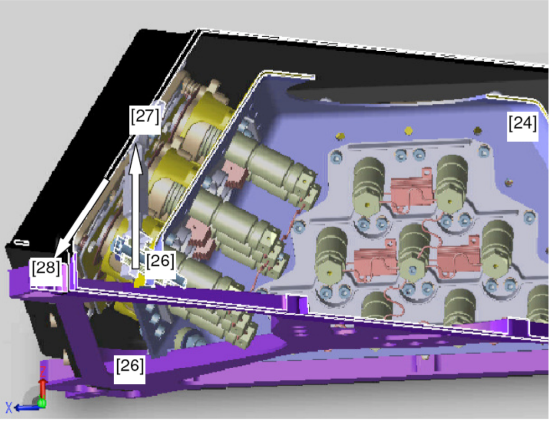

Figure 9. Needle FEEP Cluster Assembly section. *Cold assembly [27], hot assembly [24] and S/C interface [26]*

The FEEP Cluster Assembly (FCA), made of four TCA, is a structurally self-standing unit that will be mounted on the spacecraft's outer wall. It has to provide the structure to mount the four TCA, allow aligning the FCA on the S/C, provide electrical interfaces, provide the thermal shielding to minimize heat losses, and provide isolating between the high voltage of the electrodes and the structure /spacecraft. The thermal design of the FCA is such that the hot assemblies of all 4 TCA are mounted on one frame. By this it is assured that all LMIS are on a uniform temperature even in case of a heater failure. The structural design is based on an isostatic connection of the central truncated pyramid structure of the hot assembly to the based frame in all four corners by triangular connection brackets. The hot assembly is fixed to each of these four brackets by one thermally isolated screws. On the other side each bracket is fixed to the base frame by 2 screws. By this the loads a directly transferred to the 4 bolts that hold the base frame to the spacecraft panel.

D. Slit FEEP

The Slit FEEP is a linear field emission ion thruster. Accelerating liquid metal propellant, which is ionized by field emission, generates thrust. Field emission is generated by applying an intense electric field on the liquid metal inside the edge of a sharp hallow blade (emitter slit). To create the required electric field, a voltage difference of up to 13 kV is applied to the electrodes and the emitter is sharpened to a tip radius of 1 micron or less. The height of the emitter slit is below two micron to avoid/limit droplets emission. The propellant feeding from the tank to the emitter relies solely on capillarity. The thruster operates with Cesium liquid metal propellant. Being Cesium an alkali metal, it is absolutely necessary to guarantee during all phases of the AIT and of the mission that oxygen and/or water do not get in contact with propellant. In order to avoid the propellant and the thruster parts to be in contact with air, the tank is bolted and sealed on the thruster unit and the thruster is sealed under argon environment by a container that will be opened once in space. In addition, a rupture disk that is opened also in space by the propellant's thermal expansion seals the propellant tank.

1. *Cesium Slit Emitter*

While there exist different field emitter configurations, such as the needle, the capillary and slit emitter types, the principle of operation is the same in all cases. In the slit capillary forces through a narrow channel feed emitter the liquid metal propellant. The emitter consists of two identical halves made from stainless steel, and clamped or screwed together. A nickel layer, sputter deposited onto one of the emitter halves, outlines the desired channel contour and determines channel height (slit height, typically < 2 μm) and channel width (slit length, a few mm).

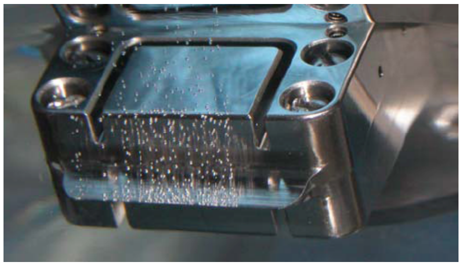

Figure 10. Slit emitter during one of the acceptance tests. *The slit location is visible via the bubbles*

In order to manufacture a slit a couple micron high and long some millimeters, and with blade sharpness in the order of one micron, the emitter unit must be manufactured by complex procedures comparable only to the ones used in optics engineering (polishing, metal deposition, extreme cleanliness control, etc.). The slit, resulting after the interfacing of the two Half-Emitters, is obtained by deposition (magnetron sputtering) of a thin film (pure Nickel is currently used) on one Half-Emitter, with masking of the area in correspondence of the gap. The uniformity of this layer is a key parameter for both emitter performance (slit size and shape) and for sealing aspects. The sharpness of the blade on each half-emitter, its straightness and the flatness of the mating surface in correspondence to the slit, is obtained by sequencing steps of precise machining and polishing (lapping). It is well recognized that the lapping (or "polishing") of the blades surfaces and their sharpening are among the most critical technological issue for the Half Emitter realization. Moreover it has been already demonstrated that their accuracy is strictly correlated with the performance repeatability.

2. *Cesium Tank*

Cesium having a very low vapor pressure, the main design drivers of the device is the vapor locking limitation. The FEEP propellant tank is small (about 80cc). Due to its specific shape, but also to the specific geometry of the tank outlet TSD location (Tank Sealing Device), a specific design of a Propellant Management Device (PMD) has to be performed in order to cope with the issue of:

- System initialization (priming) (TSD opening and thruster cesium feeding);
- System functioning during thruster actuation (draining).

The tank sealing device guaranties a leak tight sealing of the tank during ground operations. This device has to open at a given temperature (or pressure), moreover, its design has to be such that no gas (or particle) contamination could exist. These constraints have also to take into account that the capillary flow path, from tank inlet to emitter has to be

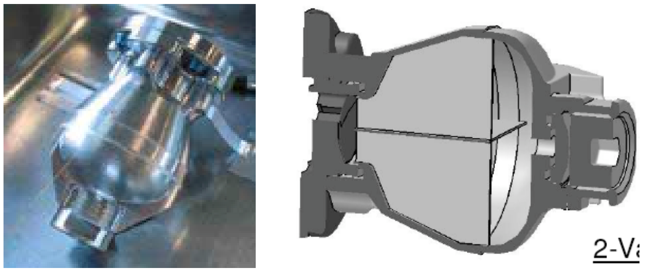

Figure 11. Cs Tank. *Left, picture before filling; right, schematics*

continuously decreasing, in order to avoid vapor lock (vapor should not find any stable zone along the feeding line).

The propellant management device continuously feeds the emitter with liquid cesium. Due to the very low vapor pressure of the fluid, the liquid will flow only by means of capillary gradient (the largest capillary dimension has to be in the tank and the smallest at the emitter level). This gradient is governed by the geometrical dimensions and by the surface tension. Concerning the geometrical dimension, they decrease all along the flow from tank to emitter, concerning the surface tension it is of course mainly dependant of the wetting angle (materials wetting properties with Cs), and also dependant of the temperature. A variation of 20°C of the fluid temperature, induce a variation of about 2% on the fluid surface tension. The capillary potential through the tank is not affected since the design considers such aspect and limits any adverse Marangoni effect.

The reservoir is a container for liquid metal (Caesium) perfectly sealed after filling to prevent propellant contamination and leaks. It is closed at one side by a calibrated rupture disc (called also the Tank Sealing Device or TSD) acting as an irreversible normally closed valve. The burst of the disk is obtained by pressurization of the propellant by thermal expansion. The reservoir is warmed up by two heater units mounted on the tank external surface. Once the TSD is open the PMD shall establish the proper geometrical and material conditions in order to promote the capillary actions pulling the propellant up to the emitter's slit. For manufacturing reasons, the FEEP tank is made of two parts, the tank body and the tank cap welded together after machining. The filling port is machined on the tank cap and the required flat surfaces for heater units mounting are provided as well. The TSD is a separate part mounted on the tank body.

3. *Lid Opening Mechanism*

The main purpose of the LOM is to create a closed and protective environment around the emitter. In order to protect it from oxygen and moisture contamination the LOM is filled with ultra pure and dry inert gas. When the thruster is in orbit the LOM will be opened. The following are the main design drivers of the LOM:

- Thruster Unit sealed in closed position: the LOM is designed to withstand the internal overpressure of the inert gas and the thermo-mechanical loads during launch phase;
- Lid release from closed position: a paraffin actuator is used to open the LOM; suitable motorization margins are provided;
- Overpressure release during opening: overpressure is taken into account with respect to the opening energy;
- Rotation to open position: motorization to open the Lid and minimize shock at the end stop.

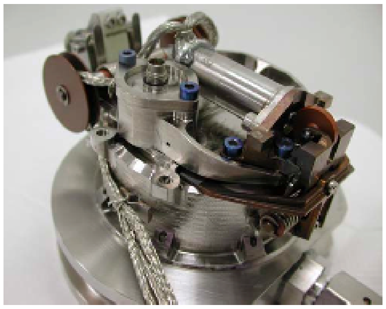

Figure 12. Lid Opening Mechanism (LOM).

The actuator is a paraffin actuator, with main structural material made of stainless steel. The seal between the housing and the lid consists of a rubber o-ring which is held in a dove-tail type groove in the housing. The dove-tail type groove holds the o-ring in its place in the housing when the lid opens. The end stop consists of a GFRP blade which is bolted onto the housing. It stops the lid in an open position of 105°. The elasticity of the blade is driven by the 70 Hz requirement for the lid in open position. The resulting elasticity allows the lid to overshoot the end position by 6° - 8°. Based on the results with the BBM, no additional damping material is needed.

4. *Thruster and Cluster Assembly*

The Thruster Unit (TU) is the core part of the thruster since it comprises the two electrodes (emitter and accelerator) providing both propellant ionization and acceleration, and other critical elements such as the main insulator that provides electrical isolation between the thruster HV components.

The TU is bolted to the tank and covered by the container, which keeps the thruster under clean Argon environment. The gas is in overpressure (~1.2 bar) monitored by a pressure sensor on the lid. The tank is sealed by a rupture disk and during operation is heated to keep the propellant liquid (there is no heater on the thruster unit). Once in orbit the container's lid is opened, the thruster out-gassed and then rupture disk broken by thermal expansion of the propellant. The propellant flows to the thruster by

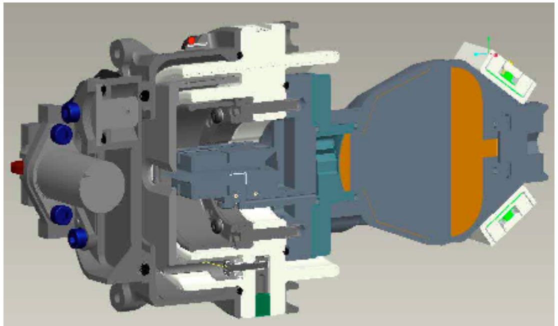

Figure 13. Slit FEEP Thruster Assembly. *LOM, thruster unit incl. emitter, tank and heaters.*

capillarity. Once the Cesium propellant reached the emitter tip the thruster can be operated.

The heater is composed of three ceramic parts (heater insulator, heater cover and sensor cover), an heater and a temperature sensor. All the previous parts are bonded, the assembly is called Heater Assembly (HA). After that the HA group is completed, the HA can be bonded on dedicated surfaces of the tank. Such operation is performed outside in air after the tank has been filled with propellant and joined to the thruster.

The FCA is made up of five major components: four Thruster Assemblies and one Thrusters Cluster Structure; plus the elements required for thermal control (MLI and thermal washers) and the harness which connects the FCA to the PCU. The Thruster Cluster Structure (TCS) is designed in order to guarantee the required thrusters assembly position and alignment, while carrying all the loads deriving from the thermal (on orbit) and mechanical environment (on launch). Moreover, the TCS performs a thermal control function, by providing a closed environment for the propellant tanks and by redistributing peak heat loads between the various FCA equipments. The TCS is completely surrounding the TA tanks, therefore acting as a Faraday cage. Electrostatic isolation of critical parts is indeed one of the main drivers in designing the TCS Structure: the tank of each thruster, in fact, will reach the emitter voltage during operation, and good electrostatic isolation needs to be guaranteed to ensure proper functionality of the thrusters themselves.

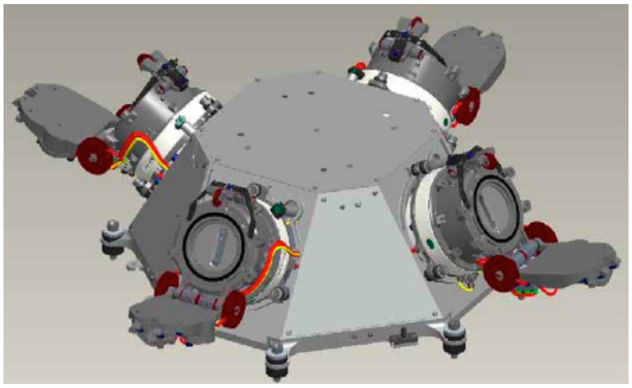

Figure 14. Slit FEEP Cluster Assembly. *With the four thruster lids open.*

IV. The “Nanobalance” Thrust Stand

The Nanobalance (NB) is the complex instrument that ultimately verifies the thruster systems performance during the qualification/verification phase. The thrust stand itself is a dual pendulum balance where the plate deflection is measure by a laser interferometer. Designed to be able to measure accurately the full thrust range required down to a resolution fractions of micronewton, it has recently been upgraded to be able to measure the thrust noise required ($\leq 0.1\,\mu N/\sqrt{Hz}$). The system is based on multi-stage passive/active noise filtering array. A Thrust Stand a Vacuum System, a Laser Metrology System and a Digital Control Unit basically composes the NB. The thrust stand is insulated from the mechanical vibrations environment by the following means:

- The anti-seismic, concrete block of the laboratory on which the vacuum chamber is tested;
- The pneumatic suspensions of the vacuum chamber;
- The silent blocks installed between the vacuum chamber internal rails and the lower plate of the Horizontality Control System;
- The Horizontality Control System.

The first two elements insulate the thrust stand from the vibrations propagating through the laboratory floor. The second two elements insulate the thrust stand also from the vibrations acting directly on the main body of the vacuum chamber, like those produced by the pumps. Clearly the vibration rejection transfer function of the concrete block cannot be adjusted, while for the other devices this is possible: regulating the air pressure in the pneumatic suspensions, selecting suitable silent blocks and different kinds of constraints of the HCS on these elements, changing the lateral stiffness of the HCS operating on the lateral springs and on the lateral constraints of the vertical supports.

The Thrust Stand is the core of the NB where the thruster to be characterized is installed. The Thrust Stand consists of two tilting plates made in Copper Beryllium alloy, each connected by an elastic joint (machined in the plate itself) to a rigid spacer made of Zerodur. The natural frequency of the tilting plates is 13.44 Hz, without thruster installed. The thruster to be characterized is installed on one of the tilting plates. A second (passive) thruster is installed on the second tilting plate for balancing purposes (the two tilting plates, with the thrusters installed shall be as much identical as possible in terms of natural oscillation frequency). The force produced by the micro-thruster induces a displacement of one tilting plate with respect to the other, which is measured by means of the Laser Metrology System. The force is measured along the direction of the metrology laser beam between the tilting plates. Two voice coil actuators are installed at the bottom of the tilting plates and are utilized as calibration devices.

The Laser Metrology System is composed by a “reference laser” and a “measurement laser” (both frequency doubled Nd:YAG lasers working at the wavelength of 532 nm). The reference laser is frequency stabilized against an Iodine hyperfine transition. The measurement laser feeds a Fabry-Perot interferometer whose spherical mirrors, forming a resonant optical cavity, are mounted on the tilting plates. The error signal of this interferometer, generated by means of the Pound-Drever-Hall technique, is utilized to vary the frequency of the measurement laser (by changing the temperature and the size of the laser crystal) to keep it always in resonance with the optical cavity. In practice the frequency of the measurement laser is varied to chase the relative displacement of the two tilting plates produced by the action of the thruster. The frequency variation of the measurement laser is measured against the stable frequency of the reference laser, by measuring the beat frequency of the two lasers with a frequency-meter. The beat frequency is then converted in force through the NB scale factor.

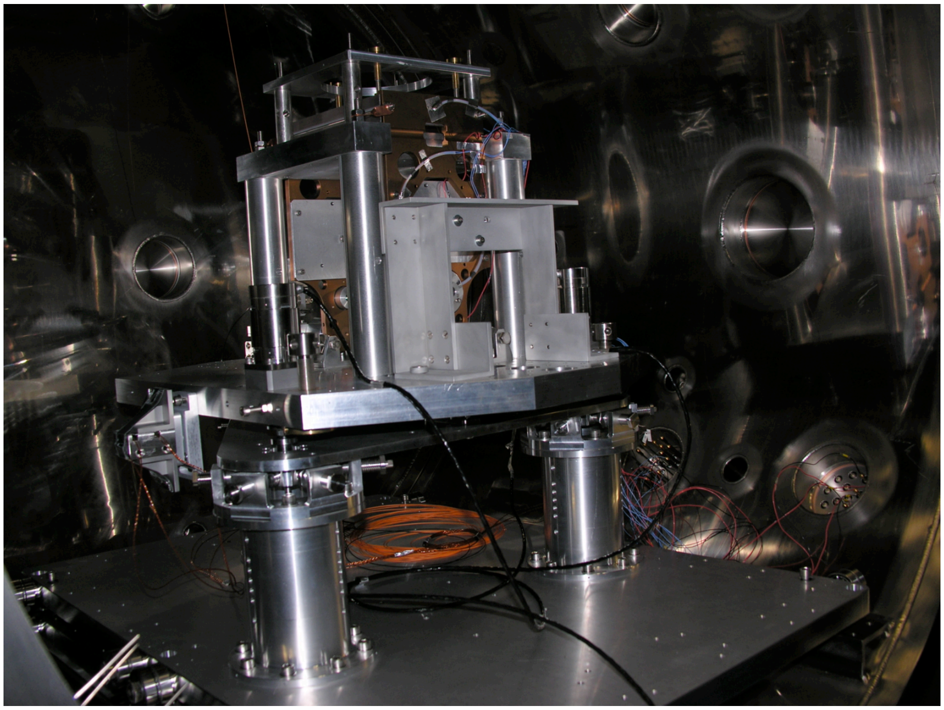

Figure 15. The Nanobalance. *The thrust stand is sitting on the horizontal control system, inside the vacuum facility. All of the vacuum facility is placed on active dampers, and installed on the anti-seismic block.*

A Horizontality Control Stage is interposed between the Thrust Stand base plate and the platform interfaced with the vacuum chamber. The horizontality of the Thrust Stand is maintained by two piezoelectric actuators driven by the measurement of the tilt-meter installed on top of the Zerodur spacer. This required also to measure the effects of the Thrust Stand columns deformation. This stage includes also a mechanical decoupling system for further reducing the level of the horizontal accelerations at the NB Thrust Stand, along the measurement direction.

V. Development and Verification Approach

The LISA Pathfinder project has been divided in two main phases for FEEP technology validation:

- Phase 1: For design, development and technology validation (including preliminary life test)
- Phase 2: For life testing completion, production and delivery of flight models.

Since both FEEP candidates need to demonstrate their capability to meet the LISA Pathfinder requirements, both have been proposed for the MPS and are in competition during Phase 1. During this development phase the elements if the subsystem are designed, built and qualified according to mission requirements, and the thrusters subjected to reduced life testing and other dedicated tests to establish their readiness for flight. It is important to note that the two main objectives of phase 1 are to allow ESA to select the FEEP thrusters on basis of a sound development and qualification process and to secure an in time procurement of reliable MPS subsystem on basis of qualified and stable production and verification processes.

Currently all components of the subsystem (PCU, Neutralizer, Needle FCA, Slit FCA) has passed CDR and is the qualification units are under manufacturing. First qualification test will begin end of this year. After successful completion of phase 1, go-ahead for flight production of one FEEP technology will be provided. Accordingly, the phase 2 will be aimed for production and delivery of flight models and any supporting parts necessary for the LISA Pathfinder spacecraft.

VI. Spacecraft Contamination and Neutralization Effect Analysis

A. Simulations, models validation and materials compatibility testing

The work concerns the characterization of the FEEP and Colloidal thrusters plume and its effect on the LISA Pathfinder spacecraft. This concerns in particular contamination and charging (neutralization). The analysis uses as input the existing plume models from the thruster manufacturers, existing experimental results, and the SPIS (ESA spacecraft environmental simulation software) work performed within the LISA Pathfinder project. Additional experimental results will be provided in the frame of already running activities (i.e. Cs neutral flux and secondary electron emission to be performed at ONERA using Laser Induced Florescence). If required by the plume-spacecraft interaction analysis or validation, dedicated tests will be performed in ESTEC propulsion laboratory (EPL). The results of the analysis will be used for effect analysis. In particular, the predicted deposition rates to run test campaigns for the effect of propellant deposition on the optical and thermo-optical properties of spacecraft surfaces; the charging results to assess impact on LTP and mission performance.

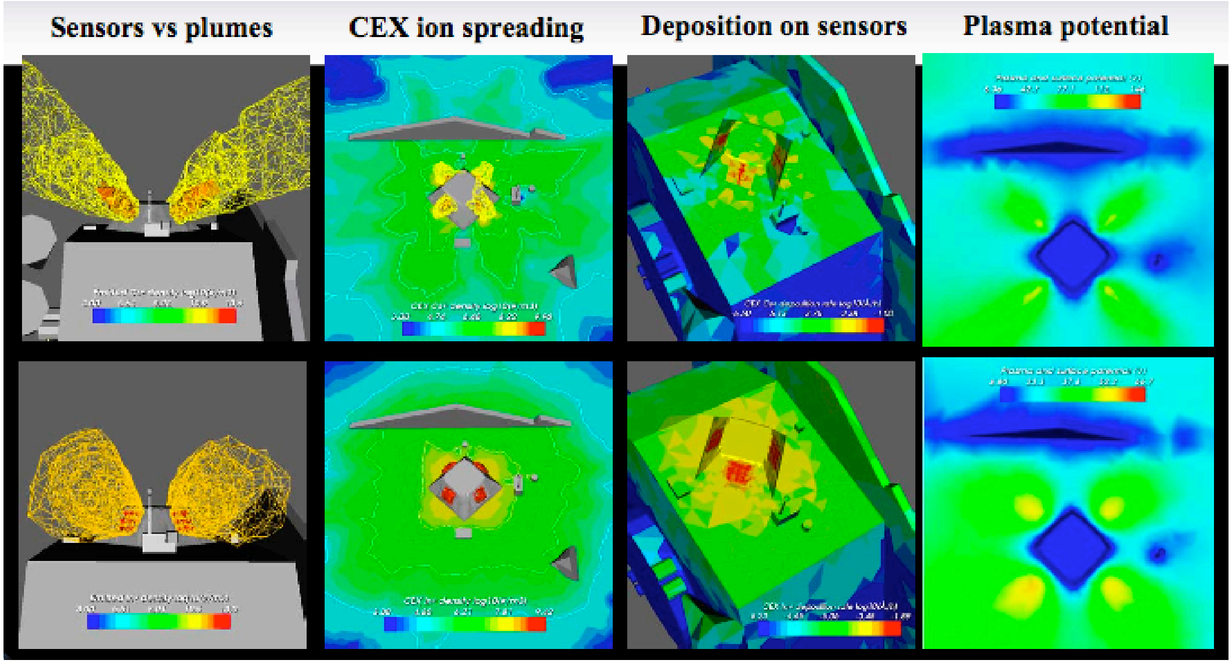

Figure 16. Plume and deposition simulations. *Upper row Cesium Slit FEEP, second row Indium Needle FEEP; third column shows location of EPDP diagnostic package.*

In more detail:

- Understanding of the physics of the FEEP (Cesium and Indium) and the Colloid thrusters and the interaction processes.
- Set up of models for the interaction using modeling software, separate plume models and data given from experiments.
- Perform modeling to determine deposition rates and charging, and to provide data from these simulations.
- Set up and running of tests for effect analysis.
- Prediction of possible problems (contamination, charging and similar issues on or close to important optical and/or thermo-optical parts of the satellite) by using the results from the models and testing, and to propose solutions for these possible problems.

The overall ongoing activity is to set up models for the spacecraft-plume interaction and to supply information and data about how the plume will interact with the spacecraft.

B. In flight measurement: the EPDP diagnostic package

As done for SMART-1, a diagnostic package will be installed to measure the plasma environment and the propellant deposition in the vicinity of the thrusters. The results of the measurements will provide valuable data for LISA and other future missions, and will be used to validate the spacecraft environment simulations.

The EPDP instrument consists in the baseline of 4 items:

- Plasma Diagnostics Assembly (PDA) composed of:
  - Langmuir Probe (LP), for the measurement of plasma parameters
  - Retarding potential Analyzer (RPA), for the characterization of ion energy distribution and current density
  - Heaters for FEEP propellant evaporation
  - LP/RPA front end electronics
- Contamination & Deposition Diagnostics Assembly (CDA), composed of two physical sub-units:
  - Quartz Crystal Microbalance for mass deposition/erosion investigation (QCM)
  - Solar Cell Patch with mechanical support and electrical interconnections (SC)
- EPDP Electronics Unit (PCU), with the following functions:
  - Probes Conditioning
  - Heaters control
  - Power Conversion & Distribution
  - TLC/TM interface with the spacecraft
  - Spacecraft Power Bus Interface

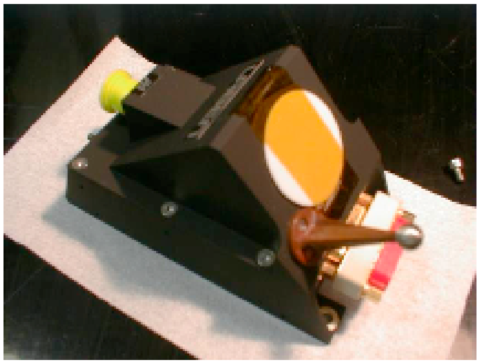

Figure 17. The SMART-1 EPDP flight PDA. *The LISA Pathfinder one is based on this one, adapted for use with FEEP*

VII. Conclusion

The development of the field emission thruster system for LISA Pathfinder is well underway. Both thruster technologies are progressing and will begin within the year qualification testing. After achievement of the mid term lifetime milestone (375 Ns of total impulse), and all other testing is accomplished, the flight manufacturing with one selected thruster technology will begin. In parallel all of the technologies and activities required by the program have been implemented.

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- Slit thruster
  - Alta, Pisa, Italy (thruster, cluster)
  - Galileo Avionica, Florence, Italy (slit emitter)
  - Astrium, Toulouse, France (Cs tank)
  - Oerlikon, Zurich, Switzerland (lid mechanism)
- Needle thruster
  - ARC, Seibersdorf, Austria (In LMIS)
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- Neutralizer and EPDP
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- Thrust stand Nanobalance
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