Overview of Indium LMIS for the NASA-MMS Mission and its Suitability for an In-FEEP Thruster on LISA

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Abstract: Manufacturing in large numbers and qualification of Liquid-Metal-Ion-Sources as the core element for FEEP thrusters has been the biggest challenge in all FEEP-missions so far including the GOCE, µSCOPE and LISA Pathfinder programs. FOTEC (previously the Austrian Institute of Technology) is developing indium ion emitters for the ASPOC instrument on the NASA MMS satellite formation to actively control the satellite’s floating potential. A total of 36 flight-model (FM) ion emitters for four spacecraft have been produced and qualified in addition to qualification and breadboard models which were also lifetime tested. With a launch date in 2014, the emitter manufacturing and the main emitter qualification program has been successfully completed. This paper will review the overall ion emitter program for MMS and the statistics and lessons learned from the successful manufacturing program. The same qualified ion emitters may be also used directly for the Indium FEEP thruster that was developed for LISA Pathfinder. A short analysis will be presented predicting the overall thruster capabilities for such a FEEP thruster using the available MMS ion emitters. It would fulfil all requirements even for the LISA mission.

Nomenclature

\[ \eta = \text{mass efficiency} \]
\[ I = \text{emitter current} \]

I. Introduction

FOTEC, the research company from the University of Applied Sciences Wiener Neustadt (previously Austrian Institute of Technology) has a long history in developing liquid-metal ion sources for space applications including instruments for active spacecraft charging compensation, secondary-ion mass spectrometers and field emission (FEEP) thrusters\(^1\). Presently, we are developing ion emitter modules for the ASPOC (Active Spacecraft Potential Control) instrument onboard the NASA MMS (Magnetospheric Multiscale) Mission, which consists of a formation of four satellites exploring fundamental plasma processes in the Earth’s magnetosphere to be launched in 2014. This mission requires 8 instruments plus one flight-spares with two modules each where each module houses two individual ion emitters making a total of 36 ion emitters. In addition, two qualification (QM) and one breadboard module (BM) with again two emitters each had to be built, qualified and tested. A rigorous quality management system was setup to control the entire manufacturing and testing process. Presently, all ion emitters (including flight models) were manufactured and the qualification process successfully concluded including extensive lifetime, thermal cycle and vibration testing. The flight modules (FM) are presently assembled, tested and prepared for shipment.
Although the ion emitter module has a similar mechanical interface compared to the previous ASPOC instrument on Double-Star, it was significantly improved with respect to our old designs. Most importantly, a new extremely stable and reliable ion source based on capillaries was developed in addition to a new thermal design and improved electronics with a high-voltage pre-resistor and spark protection diodes. Our testing program revealed ion sources with very similar characteristics and stable behavior during thermal cycles (more than 20 tested without any influence on current-voltage characteristics) based on strict manufacturing tolerances and efficient manufacturing.

The ion source was developed for a target current range between 20-40 µA with peaks up to 100 µA, which is similar to the ion source requirements for our LISA Pathfinder/LISA FEEP thruster. The development of FEEP thrusters for missions like µSCOPE, GOCE and LISA Pathfinder in the past revealed two main problem areas:

- Performance degradation during long operation, in particular during thermal cycles (between liquid and solid state of propellant), with a tendency to higher operating voltages
- Low manufacturing output, requiring many manufacturing loops to produce stable ion emitters

Both shortcomings are presently addressed in the development of porous tungsten multi-emitters that enable much larger currents and thruster compared to single emitters and are manufactured in large quantities using micro-powder injection molding. However, special activation procedures (initial high current operation) is presently required to homogenize performance after thermal cycles and during long-term operation which is presently under assessment. The MMS ion source could be used “as-is” with a larger propellant tank in the present LISA Pathfinder thruster unit which was jointly developed with Astrium. This paper will give an overview of our MMS ion emitter module and source characteristics as well as an outlook of its performance in a LISA-type thruster configuration.

II. Ion Emitters for MMS-ASPOC Instrument

The ASPOC instrument for MMS is jointly developed by the Austrian Academy of Sciences (Instrument Lead, Controller and Software), FOTEC/University of Applied Sciences Wiener Neustadt (Ion Emitter Modules), RUAG Space Austria (Electronics) and ESA/ESTEC (Modeling). The overall instrument is shown in Figure 1 including the electronics box at the bottom and two ion emitter modules with two emitters each on the top. Only the Multi-Layer-Isolation (MLI) wrapped around the ion emitters is missing in the picture. A purge connector is mounted on the lower left side for providing a continuous flow of nitrogen during storage. The picture on the left indicates that the modules on top are protected by a Teflon cover cap that has to be removed prior to launch (red-tag item).

A detailed cross section of the module as well as the emitter-heater assembly is shown in Figure 2. The ion emitter is welded on a heater assembly that houses a PT-100 resistor used for both heating and temperature sensing inside a ceramic tube. This protects the low-voltage heater from the emitter high-voltage. The emitter is mounted inside a stiff structure made out of glass fiber-reinforced PEEK that gives mechanical stability and provides a good thermal isolation to minimize heater power. On top, the extractor electrode is connected to ground and includes a plume shield that limits the field-of-view to a half-divergence angle of 45°. At the bottom, the printed-circuit-board (PCB) contains a pre-resistor in the high-voltage emitter line as well as spark protection diodes on all low-voltage lines. Both emitters in a module are connected together to a single high-voltage line. The active ion emitter is chosen by heating up a specific emitter. The specifications and characteristics of the ion emitters are summarized in Table 1.

The main improvements with respect to our previous designs can be summarized as follows:

- Improved ion emitter design: The emitters are made entirely of tantalum (capillary and reservoir) which does not dissolve into indium and therefore provides clean indium without contamination. The emitter structure is a sharpened micro-capillary that provides exceptionally stable performance, low operating voltage and is insensitive to thermal cycles. In addition, the reservoir size was increased from 0.5 g (used for the DoubleStar ASPOC instrument) to 1.2 g for additional lifetime margin.
- New thermal isolator (glass fiber-reinforced PEEK) for higher vibration resistance and the possibility to change emitters (screw fixation).
- No spring cap on the top of the module. Extensive testing showed that purging only is sufficient for the ion emitters. This simplifies the design and eliminates a potential risk of failure.
- No high-voltage connectors but flying leads.
- A larger emitter-extractor distance (4 mm extractor diameter) for a longer lifetime and implementation of 45° half-angle plume shield.
- Increased high-voltage capability of 12 kV to ensure emitter operation even at higher voltages that can develop due to backspattering contamination from the extractor electrode.

Figure 1. Ion Emitter Modules on ASPOC Instrument (Left ... Qualification Model with Electronics Box, Right ... Schematic of Modules on Interface with Transparent Cover).

Figure 2. Cross Section of Ion Emitter Module (Left) and Emitter-Heater Assembly (Right).

Table 1. Requirements and Characteristics of the MMS Ion Emitters.

<table>
<thead>
<tr>
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<th>Mission Requirement</th>
<th>Indium Liquid-Metal Ion Source with Tantalum Capillary</th>
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<tbody>
<tr>
<td>Ion Beam Performance</td>
<td>5-100 µA (20 µA Typical)</td>
<td>Very good stability along the whole ion current range</td>
</tr>
<tr>
<td>Field-of-View</td>
<td>&lt; 45°</td>
<td>&lt; 45° per design</td>
</tr>
<tr>
<td>Nominal Voltage</td>
<td>4-10 kV, ignition &lt; 8kV,</td>
<td>Ignition is typically &lt; 7 kV, operating voltage is around 6 kV</td>
</tr>
<tr>
<td></td>
<td>operating voltage &lt; 7kV</td>
<td></td>
</tr>
<tr>
<td>HV Power Consumption</td>
<td>&lt; 0.65 W</td>
<td>0.34 W @ 20 µA</td>
</tr>
<tr>
<td>Heater Power Consumption</td>
<td>&lt; 1 W</td>
<td>0.75 W (typical)</td>
</tr>
<tr>
<td>Lifetime</td>
<td>5300 h</td>
<td>&gt; 9100 h @ 20 µA</td>
</tr>
</tbody>
</table>
A. Ion Emitter Manufacturing and Characteristics

Capillary emitter usually have a high starting and operating voltage due to the rather large outer diameter of around 160 µm (smallest commercially available size) compared to the micron-size tips of needle emitters. In order to achieve the low voltages required for MMS, the capillary needed to be sharpened (see Figure 3, Left). Tight manufacturing tolerances were applied in order to achieve a good homogeneity of the emitters.

Each emitter has to pass a burn-in test of 150 h which includes 3 thermal cycles at every 40 hours and a full current-voltage characterization at the beginning and the end. The nominal current is 20 µA with 50 µA peaks between the thermal cycles. This test is done in a test module that allows easy changing of emitters and is fully automated with a LabView program. In addition, SEM pictures are taken after manufacturing, wetting and testing. All manufacturing and testing procedures were computer controlled as much as possible in order to arrive as standardized processes. Especially the wetting process was optimized in the beginning to achieve really optimum wetting results and exceptional stability throughout thermal cycles and long term operation. Our manufacturing efficiency is shown in Figure 3 (Right) and illustrates our learning-curve and continuous improvement. We now arrived at an efficiency rate of nearly 100% requiring only one manufacturing cycle for fulfilling all tolerances and operation requirements.

Since burn-in testing (7 days per emitter) and emitter manufacturing (around 2 days per emitter) run in parallel and we could produce nearly two compliant emitters per week with two test chambers and individual test modules. Further parallelization is possible, for instance 4-emitter burn-in test modules exist for our larger vacuum chambers which could increase our production rate to nearly 6 emitters per week if running in parallel.

![Figure 3. Tantalum Capillary Unfilled (Left), Filled with Indium (Middle) and Manufacturing Efficiency (Right).](image)

![Figure 4. Current-Voltage Characteristic (Left) and 150 h Burn-In Test with Three Thermal Cycles (Right).](image)
Figure 4 shows a typical current-voltage characteristic and burn-in performance evolution. As it can be seen, the operational stability is excellent also during thermal cycles (turning the heater off and on again, seen at 40, 80 and 120 h). We specifically tested the stability during thermal cycles in the following test. The heater was switch and an off periodically for 20 times and the emitter was fired for 1000 s during each hot condition. Also the current-voltage characteristic was measured at the beginning and at the end of the test as shown in Figure 5. This proves that our capillary emitter is insensitive to thermal cycles which is a very important quality criterion.

Figure 5. Thermal Cycles (Left) and Operationg Voltage Evolution (Right).

Mass Efficiency was tested over the most important current range as shown in Figure 6. Below a critical current $I_c$ of 9.5 µA, no droplets are produced. We can then identify the Rayleigh (between 10-30 µA) and Faraday (> 30 µA) droplet regime that gradually reduces mass efficiency. Capillary emitters are a good choice is the typical long-term operation current is below 30 µA. For ASPOC applications, this is the case and hence capillary-type emitters with their stability are an excellent choice. Higher current operations should be limited in time in order not to consume too much propellant. Mass efficiency may be calculate with the following expressions:

$$
\eta = \begin{cases} 
100\% & I < 9.5\mu A \\
2.94 \times 10^2 \cdot I^{-0.48} & 9.5 < I < 30\mu A \\
1.21 \times 10^5 \cdot I^{-2.218} & 30 < I < 50\mu A \\
18 & I > 50\mu A
\end{cases}
$$

(1)

Figure 6. Mass Efficiency Measurement (Left) and Lifetime Extrapolation for 1.2 g Reservoir (Right).
B. Ion Emitter Extensive Testing

After selection from the 150 h burn-in test, the emitters are ready for integration into the BB, QM and FM modules. Then, another 150 h burn-in test is done and all selection criterions have to be fulfilled again. Lifetime tests were done with the Breadboard module (1000 h with one emitter + Burn-In testing) and the two Qualification modules (850 h on all four emitters + Burn-In testing). The breadboard test is shown in Figure 7 and one representative qualification test is shown in Figure 8. All tests were passed with very stable performance.

![Figure 7. 1000 h Breadboard Module Lifetime Testing with BB1/1 Emitter (Left) and Module after Test (Right).](image)

![Figure 8. 850 h Qualification Module Lifetime Testing with QM1/1 Emitter (Left) and Module after Test (Right)](image)
The lifetime test emitter has therefore seen a total of $2 \times 150 \text{ h} + 1000 \text{ h} = 1300 \text{ h}$ testing and 26 thermal cycles without any significant change in performance. This demonstrates the robustness of our capillary ion emitter design. No lifetime limits were found after the post-test inspection (mass efficiency measurements, extractor electrode droplet deposition, visual inspection, etc.).

### III. Use of MMS Ion Emitters for LISA FEEP Thruster

The MMS capillary ion emitters could be used for FEEP thrusters such as the model that was developed by AIT/FOTEC and Astrium for the LISA Pathfinder mission\(^\ddagger\). This thruster houses nine 15 gram indium Liquid-Metal ion sources (LMIS) that are firing in parallel by a single high-voltage power supply (see Figure 9). The proven manufacturing efficiency, performance stability and insensitivity to thermal cycles would make them an interesting alternative for the presently used tungsten-coated indium needle LMIS that require much longer time for manufacturing and risks of increasing voltage after thermal cycles. Only the low mass efficiency at higher currents makes long term operation in this regime problematic. However, the predicted thrust in science mode is around 25 µN (= 250 µA for the total assembly) which reduces the individual current of the 9-emitter assembly to around 30 µA which is still acceptable. The high thrust period is required around 75 µN for initial constellation orientation and accelerometer calibration which is believed to be less than 2 weeks in total.

We can use the current-voltage as well as the mass efficiency characteristics of our MMS ion source to predict the performance parameters for a LISA-type thruster. We will assume the same 15 g tantalum reservoir size similar to the present LISA Pathfinder emitter tanks. The MMS capillary emitter was already tested with the same larger reservoir size and a propellant expulsion test at higher currents demonstrated\(^3\) that this configuration can empty the propellant tank with an expulsion efficiency of >99.08%. Our analysis assumes an average emitter voltage of 6 kV, a beam divergence efficiency of 95% (as achieved with the focusing electrode in our LISA thruster design), a mass efficiency of 60% in science mode and 6% in high thrust mode according to our measurements.

Our analysis is summarized in Table 2. All requirements – even the LISA lifetime requirement are met with this solution. Of course all other propulsion requirements such as thrust noise, bias, etc. are met as well which has been demonstrated many times in the past.

### Table 2. Performance Characteristic of FOTEC LISA-Thruster (9 LMIS Assembly) with MMS Ion Emitters and 15 g Reservoirs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>LISA Requirements</th>
</tr>
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<tbody>
<tr>
<td>Thrust Range</td>
<td>0.1 – 100 µN</td>
<td>0.3 – 100 µN</td>
</tr>
<tr>
<td>Specific Impulse (at 25 µN Science Mode)</td>
<td>5,841 s</td>
<td>&gt; 4,000 s</td>
</tr>
<tr>
<td>Total Impulse(^3)</td>
<td>6,102 Ns</td>
<td>4,000 Ns</td>
</tr>
</tbody>
</table>

\(^3\) assuming 14 days at 75 µN and the rest at 25 µN average
IV. Conclusion

We developed a highly reliable and stable long-life Liquid-Metal ion source which will be used in the ion emission modules for the ASPOC instrument on the NASA MMS mission. All ion source manufacturing has been finished and detailed statistics, inspection and quality assurance documentation are available that show how our manufacturing process was constantly improved to near perfect efficiency. Although developed for space instrument applications, the same ion source may also be used in our FEEP thruster that we developed for the LISA Pathfinder program. The following advantages could be derived from our MMS program experience:

- Fully qualified ion source – more than 50 ion emitters produced.
- Documented statistics to predict realistic schedules for large batch ion source manufacturing. We achieved a production rate of 2 ion sources per week which can be easily upgraded to 6 ion sources per week with our existing facilities. This would enable to manufacture all ion sources for a LISA-type thruster (9 emitters per panel with 4 thruster panels and 3 thruster clusters on the spacecraft = 108 ion sources) in about 5 months.
- Proven insensitivity to thermal cycles.
- Excellent performance stability and very similar current-voltage characteristics due to tight manufacturing tolerances.
- Fulfills all propulsion requirements – even the LISA total impulse.
- Less vulnerable to contamination and outgassing due to capillary design.
- No change in LISA thruster module or electronics.

The 50 MOhm pre-resistors in our LISA thruster would limit the current-difference between emitters to less than 10 µA (assuming a 500 V maximum spread between emitters which is larger than observed) that would result in excellent homogeneity. At least, the MMS emitters present an interesting alternative for our LISA thruster that is already available and qualified.

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References

