Testing and Modelling of the mN-FEEP Start-Up Performance

IEPC-2015-123／ISTS-2015-b-123

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

Alexander Reissner[1], Nembo Buldrini[2], Bernhard Seifert[3], Thomas Hörbe[4], Florin Plesescu[5]
FOTEC Forschungs- und Technologietransfer GmbH

Jose Gonzalez del Amo[6], Luca Massotti[7]
European Space Agency

Abstract: Within the ongoing development of the mN-FEEP thruster under ESA Funding, the Start-Up Performance of the thruster has been evaluated. Tests have been performed with a large number of emitter and critical parameters like the starting voltage and the initial firing homogeneity have been conducted. Furthermore, the initial priming of the emitter after the Start-Up has been investigated. The test results have been collected in a database and correlated to geometrical parameters of the emitter. This correlation has then been used to assess the possibility to model and predict the Start-Up behaviour of the thruster prior to testing.

I. Introduction

For several years, FOTEC is developing the mN-FEEP thruster [1], [2]. The thruster utilizes a liquid metal ion source (LMIS) [3] in order to achieve very high specific impulses and an extreme thrust accuracy. Different from previous developments where a LMIS was utilized as propulsion device [4]–[7], the new thruster type uses a so called porous tungsten crown emitter, shown in Figure 1.

[1] Head of Department, Aerospace Engineering, reissner@fotec.at
[2] Senior Scientist, Aerospace Engineering
[3] Senior Scientist, Aerospace Engineering
[4] Scientist, Aerospace Engineering
[5] Lead Technician, Aerospace Engineering
[6] Head of Electric Propulsion Section
[7] System Engineer, EO Future Mission Division projects (EOP-SF)

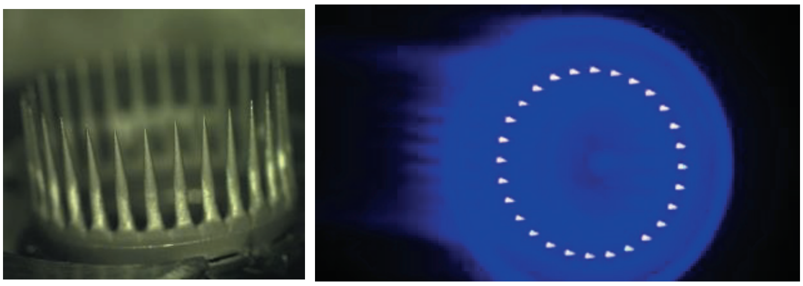


Figure 1 Porous tungsten crown emitter, capable of generating thrust from µN to mN. The crown has a diameter of 10mm.

This emitter is manufactured by a µPIM process as a single piece of porous tungsten with 28 emission sites [8], [9]. The emission sites are then sharpened by electrochemical etching to achieve tip radii of a few µm. The new manufacturing process has the advantage, that batches of about 100 emitter can be manufactured at once. Therefore it was for the first time possible to gather statistically relevant data on the characteristics of the emitter as manufactured, as well as the performance when used in a thruster.

II. Characteristics of the Porous Tungsten Crown Emitter

The porous tungsten crown emitter is manufactured in several steps. These include: Powder injection moulding, sintering, electrochemical etching and wetting. An accurate control of all process parameter in all of these steps is necessary to arrive at a final geometry that has 28 needles with the desired porosity and sharpness. Nevertheless, the desired feature size is so small (tip radii of about 1µm), that stochastic processes in the manufacturing chain start to play an important role. For example the slightest inhomogeneity in the initial feedstock can cause the electrochemical etching to produce a blunter needle. As such small deviations in the manufacturing processes are not completely avoidable, it becomes clear, that the sharpness of the 28 emitter will not be uniform. It will rather be an array of needles with tip radii of 1 to 5 µm in a random distribution. Figure 3 shows the distribution of the sharpness of the emission sites for two different crowns. One can see, that most of the needles have a tip radius between 0.5 and 2 µm. Nevertheless, it is very common that up to three needles are blunter than 5µm. Figure 4 shown the distribution of the needle sharpness over 10 emitter. It can be seen, that 33% of the needles are sharper than 1µm, and another 63% sharper than 3µm.

In order to access this sharpness of the individual needles, a software tool has been developed allowing to derive the base radius of the taylor cone from SEM pictures of the needles, as seen in Figure 2.

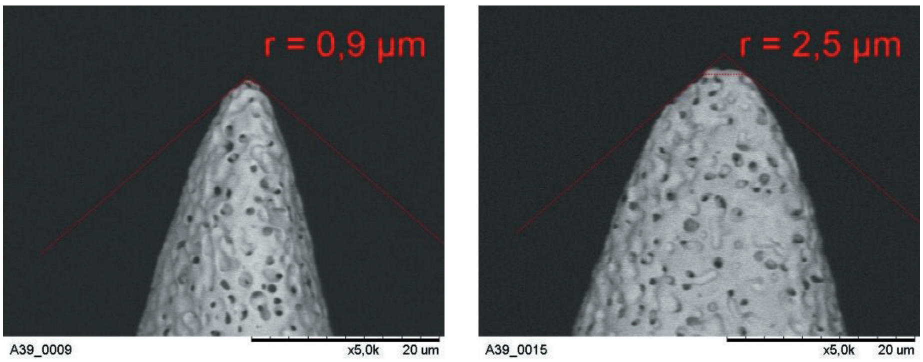


Figure 2 Analysis of the needle sharpness using SEM pictures

This inherent characteristic of the crown emitter is in fact an advantage. A theoretical crown that has only very sharp needles of 0.5µm would have a low starting Voltage, but a high impedance. A theoretical crown with only blunt needles of 3µm on the other hand would have a low impedance, but a high starting voltage. A real crown with distribution of the sharpness as shown in Figure 4 can combine a low starting voltage (which is defined by the sharpest needles) with a low impedance (which is due to the blunter needles). Figure 5 shows this comparison between the theoretically uniform needles and the real distribution of the tip sharpness of crown A39. The calculation of the current/voltage characteristics used for this figure will be described in detail in section V.

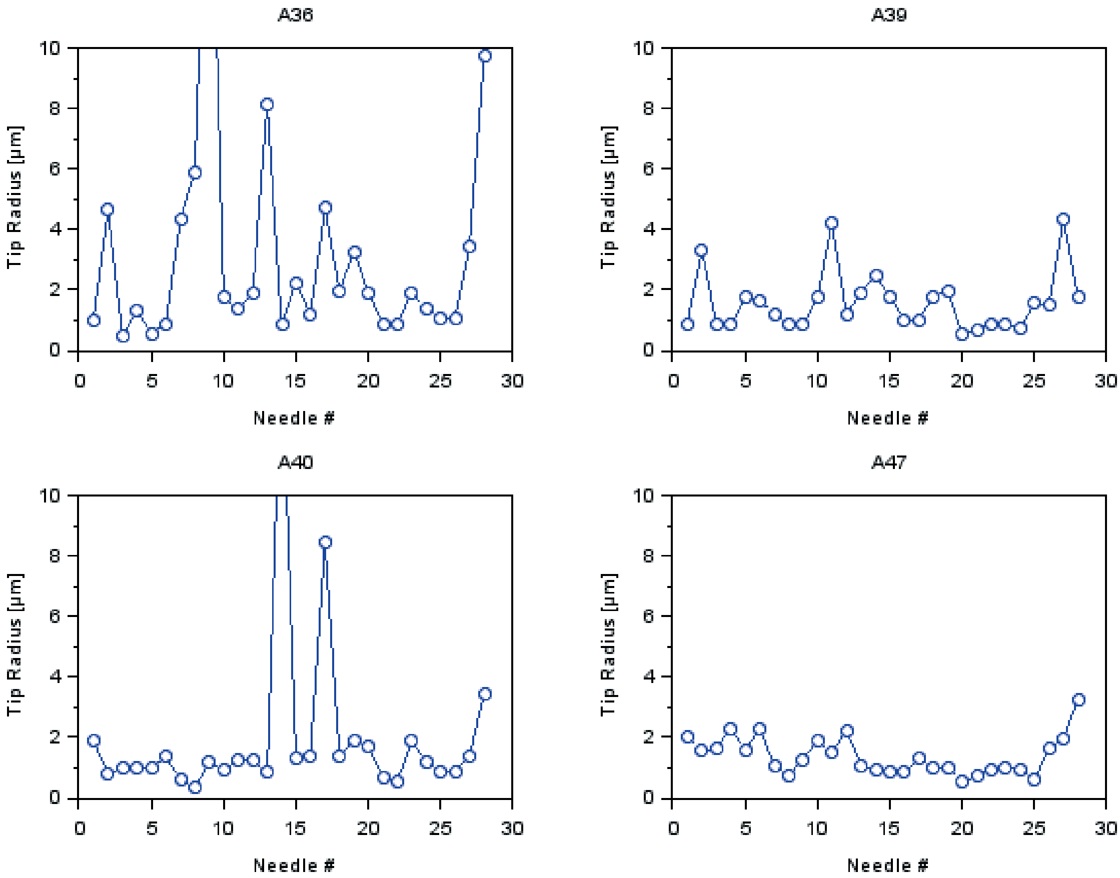


Figure 3 Sharpness of the 28 Emission Sites of four crown-Emitter

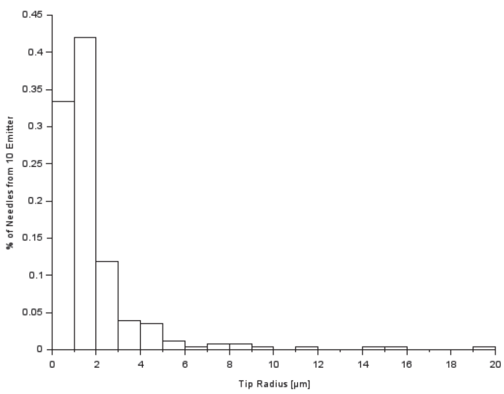


Figure 4 Distribution of the Needle Sharpness from 10 Emitter

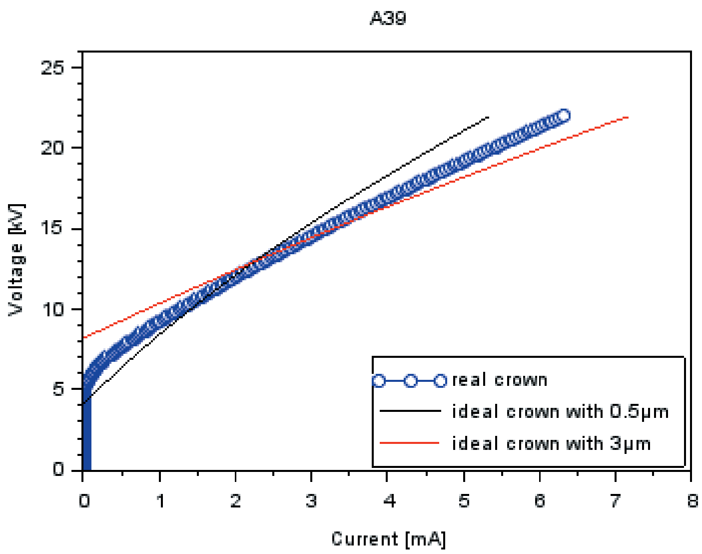


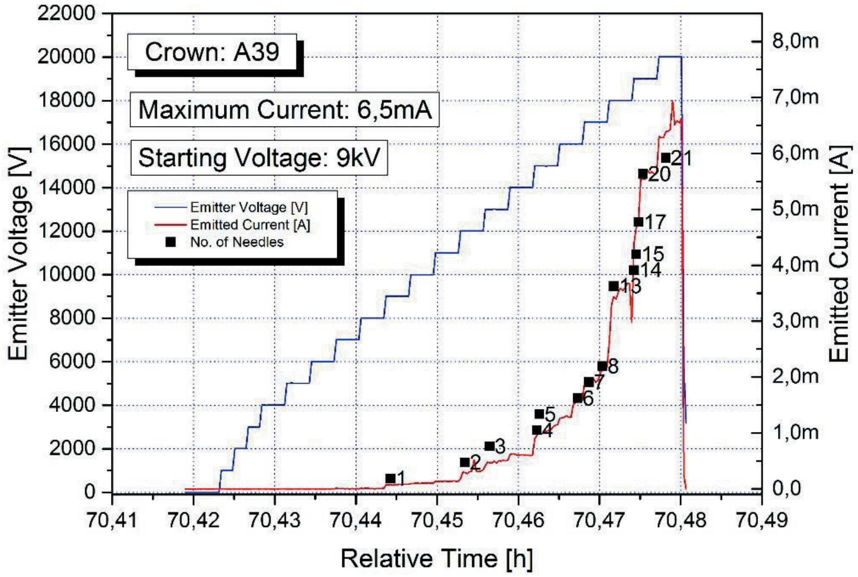
Figure 5 Comparison of the current/voltage characteristics for one crown with identical needles of 0.5µm sharpness, one with identical needles of 3µm sharpness and one with the real measured radius profile

III. Definition of the Emitter Start-Up Performance

A crucial step in the manufacturing of a Liquid Metal Ion Source is the wetting of the propellant metal onto the emitter. In the case of Indium as a propellant, this is achieved by heating the tungsten emitter to above 800°C under high vacuum (1e-6 mbar) in a dedicated facility. After successful wetting, the emitter is being mounted in the thruster and has only to be heated above the melting point of Indium (156°C). Each emitter then undergoes a so called priming sequence, in order to ensure stable operation. The start-up of the emitter can therefore be divided into two main characteristic: first, the very first initial starting of the emitter after the wetting and second the effectiveness of the priming procedure. Those two have been investigated in an extensive testing campaign testing more than 30 emitter in a thruster module.

IV. Testing

Each of the emitter that has been tested has been initiated first by increasing the voltage in steps of 1kV and measuring the emitted current as well as the number of needles firing. In the top of Figure 6, one can see that Crown A39 started to fire with one needle at 9kV. Then at 12 kV, a second needle started to fire and finally at 20kV, 21 needles were firing with a current of 6.5mA.



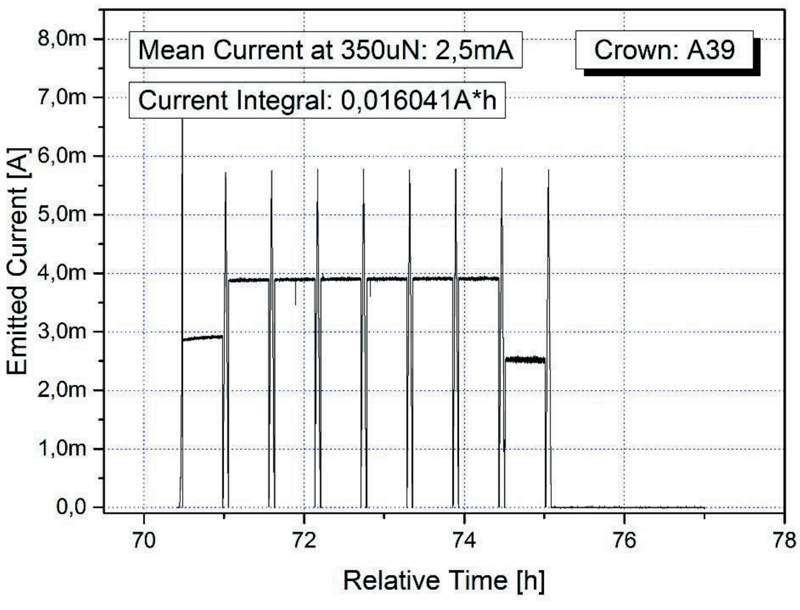


Figure 6 Automated test procedure to assess the startup performance. Top: Initial start-up, Bottom: Complete sequence

After this initial starting, the emitter was firing at nominal thrust of 350µN for 30 minutes, followed by a priming sequence, where it was firing at higher currents of 4mA for three hours. After the priming, another half hour at nominal thrust concluded the test program. During the priming, the current-voltage characteristics of the emitter was measured every 30 minutes, in order to assess an evolution over time. The complete sequence can be seen in the bottom of Figure 6. The peeks in the bottom of Figure 6 are characterizations of the current voltage characteristics of the emitter. Figure 7 shows the evolution of these characteristics during the priming. It can be seen, that for this specific crown, the final performance has already been reached in the second characterization. After that, the performance stays constant during the remainder of the priming sequence.

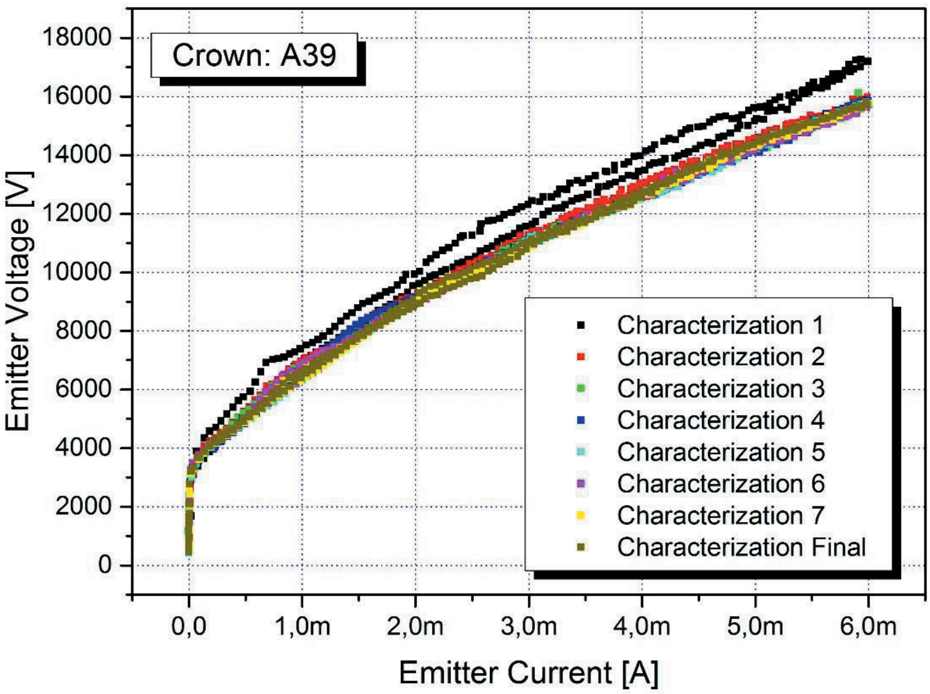


Figure 7 Evolution of the Emitter Performance during the Priming sequence

V. Modelling

The goal of the presented activity was to establish analytical models to predict the emitter performance from the distribution of the needle sharpness. Such predictive models would allow the selection of well performing emitter without the need of an expensive wetting, priming and testing campaign. Such modelling requires an in-debth analysis of the physical effects contributing to the formation of the Taylor cone and the extraction of Ions. This has been assessed in detail in ref [10].

For a parabolic needle shape, with a counter-electrode placed at a distance h from the needle-tip of radius r, the electric field E_0 as function of the applied voltage V_0 is given by [11]

$$E_0 = \frac{2V_0}{r \ln\left(\frac{2h}{r}\right)}$$

The pressure difference Δp between the internal p_{int} and external pressure p_{ext} of a conducting liquid surface [12] with principal radii of curvature r_1 and r_2 can be described by [13]

$$\Delta p = p_{int} - p_{ext} = \gamma\left(\frac{1}{r_1} + \frac{1}{r_2}\right) - \frac{1}{2}\epsilon_0 E^2$$

Combining those two equations yields the critical voltage at which the electric stress exceeds the contribution from the surface tension and ions start to be extracted [14]

$$V_{0C} = \sqrt{\frac{\gamma r}{\epsilon_0}} \ln\left(\frac{2h}{r}\right)$$

Because it requires a higher voltage to actually shape the liquid cone than is necessary to maintain it once it has been established, the extinction voltage V_{0X} (the voltage at which the ion source ceases emitting ions) is lower than the onset voltage [10]. The difference in onset and extinction voltage gives rise to a hysteresis on the voltage-current graph. Typical values of the extinction voltage for needles lie up to 10% below the onset voltage[11].

The relation between the emission current of a single needle with the applied voltage can further be described as

$$I = \frac{3\pi\sqrt{\frac{2e}{m}}\gamma r cos\phi}{2\sqrt{V}}\left(\left(\frac{V}{V_{0X}}\right)^2 - 1\right)$$

As the Voltage applied to a crown of 28 needles is the same for every needle, the total ion current emitted by the crown is the sum of all individual currents

$$I_{Crown}(U) = \sum_{28} I_i(U)$$

Figure 8 shows the results of the analytical model and a comparison with different crown emitter tests. It can be seen that the model predicts the starting voltage and the impedance of the emitter very well.

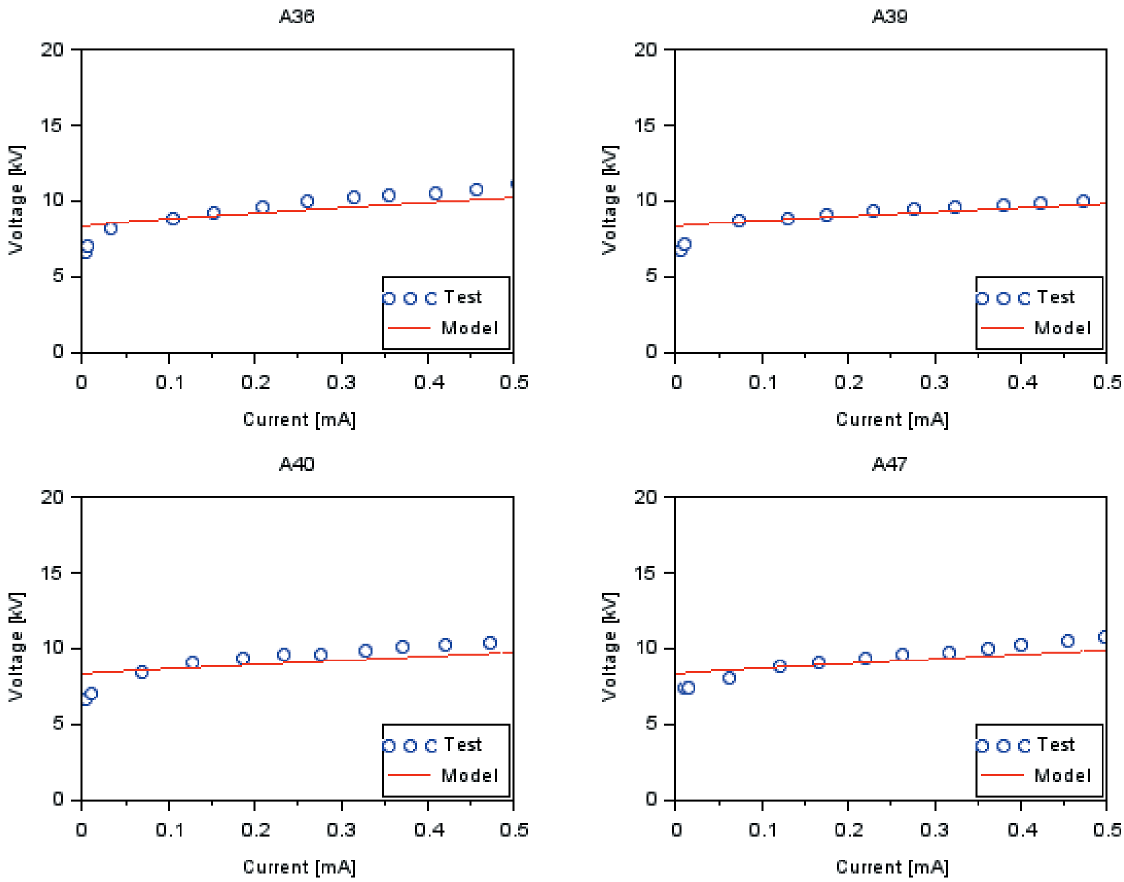


Figure 8 Comparison of the analytical model with test results.

VI. Conclusions

Using a newly developed software to analyze the geometrical properties of each emission site from SEM pictures of the porous tungsten crown emitter, it was possible to establish an analytical model that can predict the startup-performance of the emitter. This model has been correlated with a test campaign investigating the startup of more than 30 emitter with a statistical variation in geometrical properties that result from the manufacturing process. In an ongoing effort, the model will be improved to predict the nominal operation of the emitter. This way, a fast screening and selection after the manufacturing will be possible, ensuring that only emitter with high performance will be selected for a thruster application. Together with the fact, that the new manufacturing process is a batch process where 50 to 100 emitter are being manufactured simultaneously, this screening will allow for a highly efficient manufacturing of well performant emitter, mitigating in fact the major drawback of previous FEEP emitter technologies.

VII. References

[1] I. Vasiljevich, M. Tajmar, W. Grienauer, F. Plesescu, N. Buldrini, J. Gonzalez del Amo, B. Carnicero Domunguez, and M. Betto, "Development of an Indium mN-FEEP Thruster," 2008.

[2] A. Reissner, N. Buldrini, B. Seifert, F. Plesescu, C. Scharlemann, and J. G. del Amo, "mN-FEEP Thruster Module Design and Preliminary Performance Testing," presented at the 33rd International Electric Propulsion Conference, Washington, D.C., USA, 2013.

[3] M. Tajmar, C. Scharlemann, A. Genovese, N. Buldrini, W. Steiger, and I. Vasiljevich, "Liquid-metal-ion source development for space propulsion at ARC," *Ultramicroscopy*, vol. 109, no. 5, pp. 442–446, Apr. 2009.

[4] M. Tajmar, "Overview of indium LMIS for the NASA-MMS mission and its suitability for an In-FEEP thruster on LISA," in *Proceedings of the 32nd International Electric Propulsion Conference*, Wiesbaden, Germany, 2011.

[5] C. Scharlemann, A. Genovese, N. Buldrini, R. Schnitzer, M. Tajmar, H. Früholz, and R. Killinger, "Development and Test of an Indium FEEP Micropropulsion Subsystem for LISA Pathfinder," 2007.

[6] C. Scharlemann, A. Genovese, N. Buldrini, R. Schnitzer, M. Tajmar, H. Früholz, and R. Killinger, "Indium FEEP Micropropulsion Qualification Test Program for LISA Pathfinder," presented at the Fifth International Space Propulsion Conference, Heraklion, Greece, 2008.

[7] C. Scharlemann, A. Genovese, R. Schnitzer, N. Buldrini, P. Sattler, and M. Tajmar, "In-FEEP Endurance Test for LISA PF," 2009.

[8] M. Tajmar, I. Vasiljevich, and W. Grienauer, "High current liquid metal ion source using porous tungsten multiemitters," *Ultramicroscopy*, vol. 111, no. 1, pp. 1–4, Dec. 2010.

[9] I. Vasiljevich, N. Buldrini, F. Plesescu, M. Tajmar, M. Betto, and J. Gonzalez del Amo, "Porous tungsten crown multiemitter testing programme using three different grain sizes and sintering procedures," in *Proceeding of the International Electric Propulsion Conference*, Wiesbaden, Germany, 2011.

[10] I. Vasiljevich, "Design, development and testing of a highly integrated and up-scalable feep-multi-emitter using indium as propellant," PhD Thesis, TU Vienna, Vienna, Austria, 2010.

[11] P. D. Prewett and G. L. R. Mair, "Focused ion beams from liquid metal ion sources," *Vacuum*, vol. 43, no. 3, p. 272, Mar. 1992.

[12] R. G. Forbes, G. L. R. Mair, N. N. Ljepojevic, and W. Liu, "New understandings in the theory of liquid-metal ion sources," *Appl. Surf. Sci.*, vol. 87–88, pp. 99–105, Mar. 1995.

[13] R. G. Forbest, "Understanding how the liquid-metal ion source works," *Vacuum*, vol. 48, no. 1, pp. 85–97, Jan. 1997.

[14] G. L. R. Mair, "Current-voltage curves in liquid metal ion sources," *Vacuum*, vol. 36, no. 11–12, pp. 847–850, Nov. 1986.