ENPULSION NANO: A FULLY INTEGRATED ELECTRIC PROPULSION SYSTEM FOR SMALL SATELLITES

17 – 18 – 19 MARCH 2021

David Krejci [(1)], Alexander Reissner [(2)], Tony Schönherr [(3)], Bryan Little [(4)], Quirin Koch [(5)], Bernhard Seifert [(6)]

[(1)] ENPULSION, Wiener Neustadt, 2700, Austria, Email: krejci@enpulsion.com
[(2)] ENPULSION, Wiener Neustadt, 2700, Austria, Email: reissnner@enpulsion.com
[(3)] ENPULSION, Wiener Neustadt, 2700, Austria, Email: tony. schoenherr@enpulsion.com
[(4)] ENPULSION, Wiener Neustadt, 2700, Austria, Email: bryan.little@enpulsion.com
[(5)] ENPULSION, Wiener Neustadt, 2700, Austria, Email: quirin.koch@enpulsion.com
[(6)] FOTEC, Wiener Neustadt, 2700, Austria, Email: seifert@fotec.at

RKEYWORDS: electric propulsion, FEEP propulsion, IFM Nano Thruster

ABSTRACT:

The ENPULSION NANO thruster (formerly: IFM Nano Thruster) is a FEEP propulsion system, providing unmatched total impulse in a volume of just under 10x10x10 cm, including propellant tank, power electronics and all auxiliaries. At time of writing, 62 IFM Nano Thruster have been launched on spacecraft ranging from several kilograms to over 150 kilograms. The IFM technology is based on liquid metal Field Emission Electric Propulsion (FEEP) principle, producing thrust by electrostatically accelerating previously extracted and ionized propellant to high exhaust velocity. The IFM Nano Thruster can be operated between 10 and 40 W input power including neutralizer, resulting in thrust of up to 0.35 mN. By varying extraction potentials, the thruster can be operated at specific impulse levels between 2000 s and 6000 s, adapting to mission needs as well as power availability. Due to the high specific impulse and high propellant density, the thruster can produce total impulses of 5000 Ns when operated at specific impulses at 2000 s and 5000 s respectively. Since the first In-Orbit-Demonstration of the IFM Nano Thruster in early 2018, ENPULSION has built up a high-rate series production facility, which has been producing 2 flight thrusters per week since June 2018. Over 100 flight thrusters have been delivered to customers at time of writing.

This work provides an overview of the current status of FEEP propulsion system, including in-orbit data of IFM Nano Thrusters. It discusses new characterization efforts undertaken, including neutralization measurements over the full performance envelope, and discusses ongoing product updates and testing.

1. ENPULSION NANO thruster and FEEP technology

The ENPULSION NANO thruster (formerly: IFM Nano Thruster), shown in Figure 1, is based on FFEP ion emission, which generates thrust by extraction and acceleration of ions by an electrostatic field from the liquified propellant by means of a Taylor cone. This principle allows a passive (non-pressurized, no active components) propellant feed from the propellant reservoir to the emission sites by capillary forces. The ion emitter has been developed at FOTEC (former Austrian Institute of Technology) for decades and is based on the development of Indium Liquid Metal Ion Sources (LMIS) with exhaustive flight heritage [1-5].

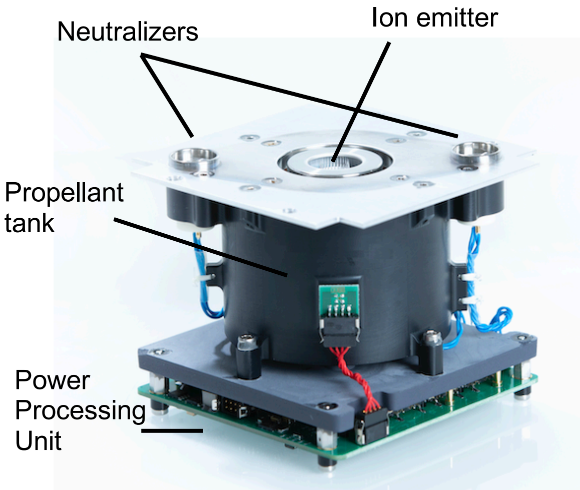

Figure 1. ENPULSION NANO thruster (formerly: IFM Nano Thruster) with key components identified

The thruster utilizes Indium, a metal propellant, that is in solidified stated during ground handling, integration, and launch. The thruster features two neutralizers in cold redundancy, and a digital PPU which provides power and control for all necessary subsections to operate the thruster and provides telemetry back to the spacecraft onboard computer using standard communication protocols. By controlling voltages of both the emitter and the extractor, the emission current, and thus the resulting thrust, can be decoupled from the acceleration potential, and hence the specific impulse. This allows to operate the thruster in an envelope of specific impulse and thrust.

To increase thrust, multiple emission sites, allocated in a crown shaped emitter, are operated in parallel. An active emitter is shown in Figure 2.

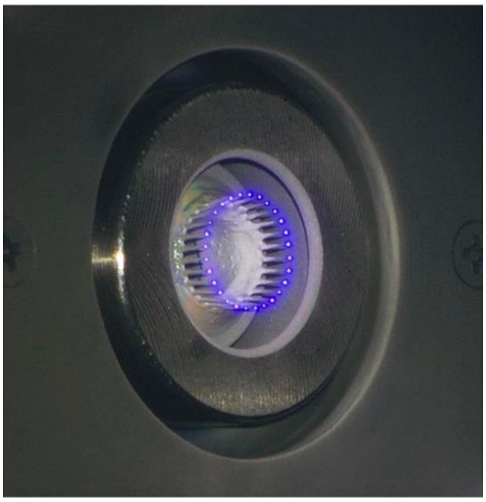

Figure 2. Ion emission from the porous crown ion emitter

2. PREVIOUSLY REPORTED IN ORBIT DATA

At time of writing, 50 ENPULSION NANO thrusters have been launched into orbit on 21 different spacecraft. In orbit data of 5 thrusters has been previously reported, including the IOD mission onboard a 3U Cubesat that verified the thrust generated by comparison to expected change in orbital parameters [6-8]. An excerpt of the thruster telemetry showing the key parameters are shown in Figs. 3 and 4. Figure 3 shows the propellant liquification, as well as the hot standby phase, in which the propellant is maintained at operational temperature, interrupted from active firing sequences.

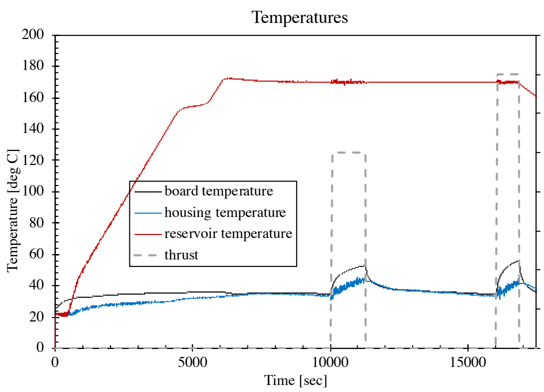

Figure 3. In-orbit temperature telemetry [8]

Figure 4 shows selected thrust telemetry parameters during thrust execution from hot-standby mode. During this firing, the thruster was operated in a thrust controlled mode, in which the thruster controls the indirectly measured (red line) thrust to the commanded (dashed black line).

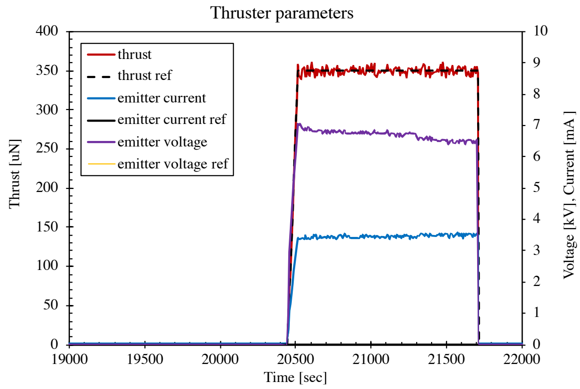

Figure 4. In-orbit thrust telemetry [8]

The ability of controlling emitter current and emitter voltage independently by having the active extractor voltage control, allows to operate the thruster within an envelope of thrust and specific impulse as shown in Figure 5. Variations in the microscopical characteristics of emitters lead to certain variability of emitter properties, allowing for certain selection of emitters for specific mission needs. Figure 5 shows an exemplified envelope, indicating the region that is accessible for all emitters on a statistical basis.
In addition, the plot indicates samples of firing parameters that were conducted with 5 different ENPULSION NANO thrusters.

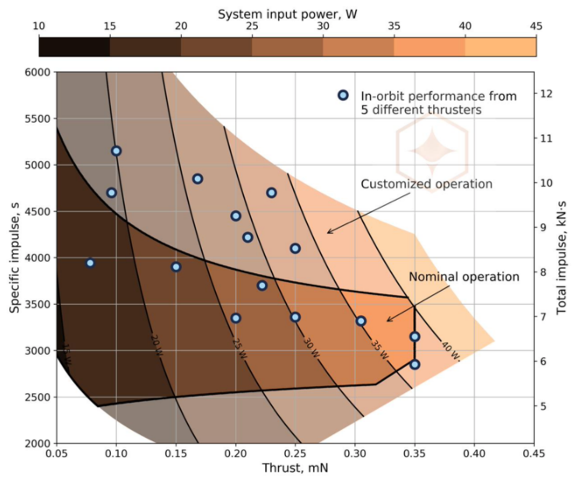

Figure 5. Performance envelope with on-orbit data points

3. THRUSTER TESTING

The thrust model used in the ENPULSION NANO, which is reported by the thruster as part of the telemetry provided, has been compared to measured thrust in a test campaign at the ESA propulsion laboratory on two flight-like thrusters over different operation points of the performance envelope [9]. Thrust reported hereafter refers to the telemetry output based on this thrust model.

In this section, results from exemplary performance mapping tests are presented. The performance envelope test, which reflects the plot shown in Figure 6, shows the relationship between thrust and specific impulse and is accomplished by varying emitter and extractor voltage independently (Figure 7). The total bus power is also plotted. By increasing the emitter voltage with high extractor voltage, a high-thrust range is achieved. Then, decreasing the extractor voltage while maintaining high emitter current and voltage produces a region of high specific impulse and lower thrust. Throughout the envelope, the neutralization is measured to ensure compensation of the positive ion beam by the neutralizer.

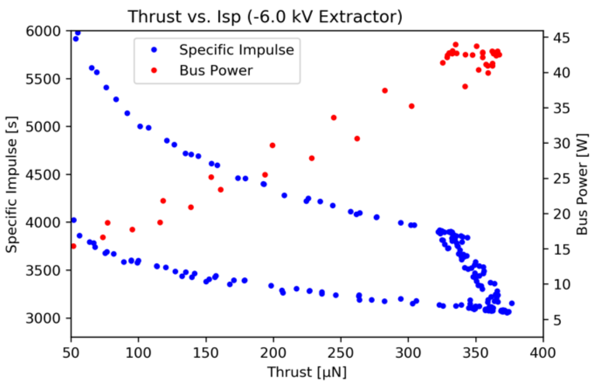

Figure 6. Test results showing the performance envelope of a thruster

Another important characteristic of the FEEP emitter is the impedance. Impedance is the relationship between emitter voltage and current – a higher impedance means that higher discharge voltages are needed to achieve required thrust. In Figure 7, the impedance is measured using voltage-current (V-I) curves with the extractor biased to 3 levels of negative polarity. $(-4\,kV, -6\,kV, and -8\,kV)$. The mean slope of these lines is taken to be the emitter impedance.

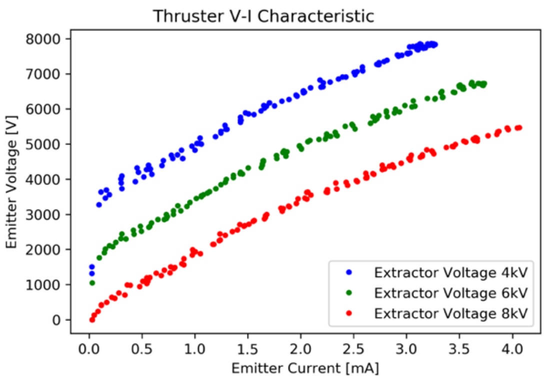

Figure 7. V-I curves of the FEEP emitter

Figure 8 shows a 10-hour continuous firing test verifying the thrust control over extended duration. In this operational mode, internal control loops of the thruster adjust ion emission current and emitter voltage to maintain the commanded thrust. The evolution of the resulting emitter voltage shows the initially decreasing of the emitter impedance to achieve the commanded thrust, as the emitter is burnt in after exposure to air.

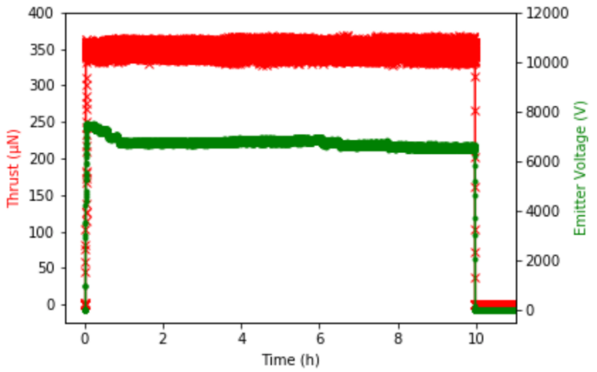

Figure 8. 10-hr firing of the ENPULSION NANO

4. NEUTRALIZATION VERIFICATION

Since the thruster emits positively charged ions, a neutralizer is used to avoid charging of the spacecraft by means of electron emission. A test setup was developed to verify this neutralization capability, both in development and during acceptance testing of each ENPULSION NANO thruster flight unit.

4.1. Neutralization Test Setup

The ENPULSION NANO is assembled inside a test housing that is mounted to a cooling plate in a $1.5\,m^3$ vacuum chamber. It is electrically isolated from the cooling plate. Three measurements are required to verify full ion beam neutralization with redundancy: the collector current, the housing (thruster casing) current, and the power processing unit (PPU) current as schematized in Figure 9.

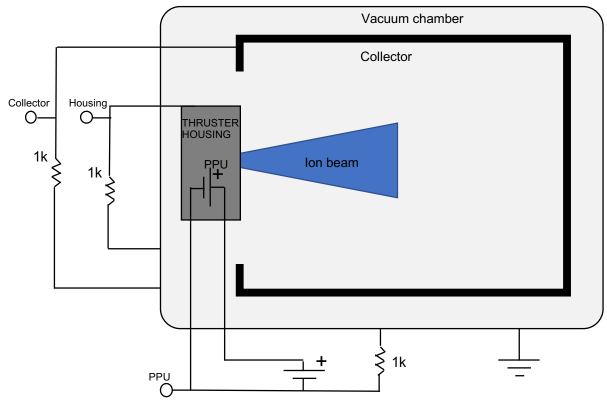

Figure 9. Neutralization set-up schematic

Each is electrically connected via feedthrough to a shunt resistor, and the voltage across each resistor is transmitted from a voltage measurement device to the PC. The PPU communications and power are isolated from earth to enable measurement of ions and electrons leaving the electrical system. With ions and electrons impinging on the collector, this measurement alone is sufficient to determine full neutralization of the ion beam. To supplement this evaluation, the PPU measurement is used by subtracting the ion and electron current impacting the thruster casing. This will be described further in Section 4.2.

4.2. Test results

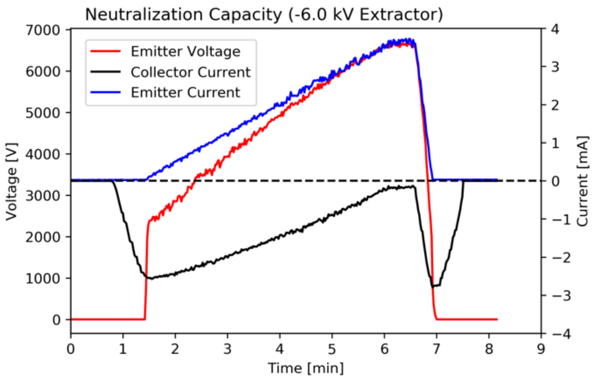

Figure 10. Emitter sweep

To verify the neutralization capacity of the thruster, an emitter sweep is done. The extractor voltage is held at a fixed polarity, and the emitter voltage is increased to a maximum while maintaining charge neutralization. As seen in Figure 10, the collector current starts at a high negative level when only the neutralizer is engaged. Then, the emitter current is increased, bringing the beam close to neutralization. With the collector current staying below zero, the ion beam is shown to be over-compensated.

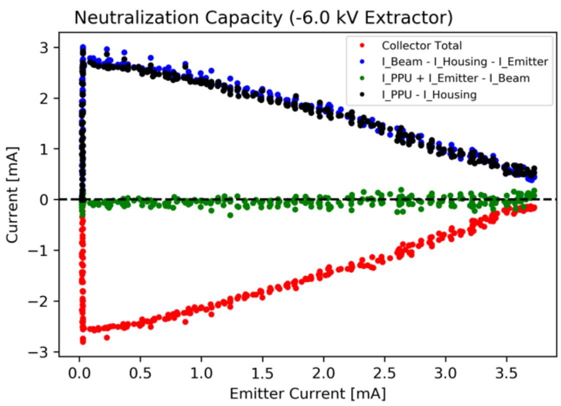

Figure 11. Derived current values from the emitter sweep test

In Figure 11, the collector current is shown to have remained negative throughout the test. The other values of interest are the neutralizer beam current (I_{beam}), emitter current ($I_{emitter}$), housing/casing current ($I_{housing}$), both measured by the PPU, and the PPU current (I_{PPU}). I_{PPU} is the sum of electron and ion current leaving the emitter and neutralizer, while $I_{housing}$ accounts for any charged particles impacting the thruster top plate or neutralizer extractor. The current exiting the PPU should be equivalent to the difference between the electron and ion beam current, which is why $I_{PPU} + I_{emitter} - I_{beam} = 0$ across the operational range. If one subtracts the housing and emitter current from the neutralizer beam current (seen in blue), equal values should be seen by subtracting the housing current from the PPU current. Thus, two independent measurements are successful in verifying beam neutralization.

To demonstrate a sample thrust profile, the firing steps are done as shown in Figure 12. One of the two neutralizer filaments are initiated, followed by a ramp-up of emitter current controlled for thrust with a fixed extractor voltage. The steps are controlled from $100\,\mu N$, $200\,\mu N$, $300\,\mu N$, up to $350\,\mu N$. The neutralizer beam current is varied to ensure the positive beam is over-compensated, represented by the negative collector current in the plot below.

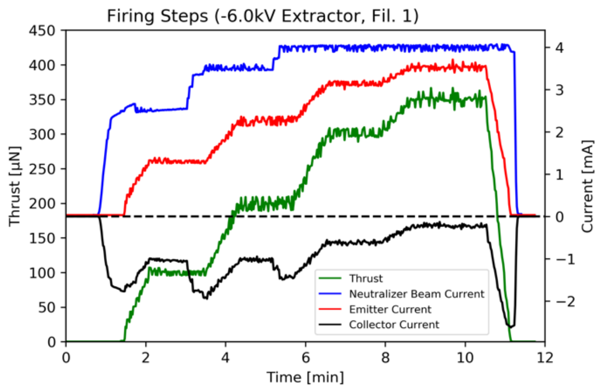

Figure 12. Functional firing steps

Finally, the same data that produced the envelope in Figure 6 may be used to show the extractor and emitter voltage settings required to achieve variable magnitudes of thrust (Figure 13).

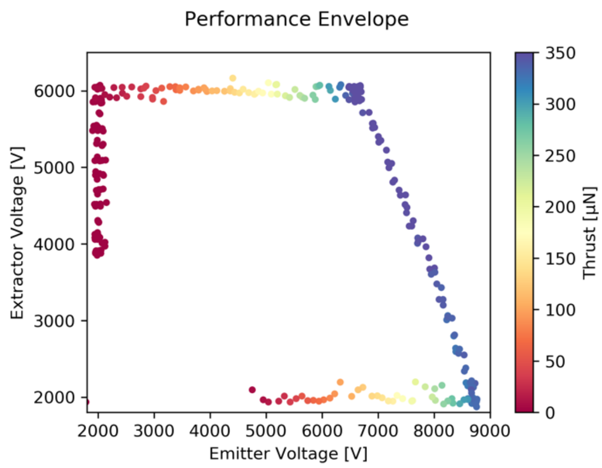

Figure 13. Electrical settings for performance envelope

In the monochromatic sections of the graph, such as the high emitter voltage setting with variable extractor voltage, the specific impulse would be modified.

5. CONCLUSION

The ENPULSION NANO thruster (formerly: IFM Nano Thruster) is a liquid metal FEEP thruster using passive propellant supply based on capillary forces, and generates thrust by electrostatic acceleration of ions from Taylor cone-based emission sites. To prevent spacecraft charging, an electron emitter is used as neutralizer no zero the net emission of charges from the spacecraft. To date, 62 thrusters have been launched on 24 different spacecraft. This work presents verification tests of the neutralization capability, conducted during development. Such direct verification of neutralization is conducted for each flight unit during acceptance testing, showing the ability to achieve thrust while preventing charging of the supply ground.

6. REFERENCES

1. Fehringer, M., Ruedenauer, F., Steiger, W., “Space-proven indium liquid metal field ion emitters for ion microthruster applications,” *33rd Joint Propulsion Conference and Exhibit*, 1997.

2. Tajmar, M., Genovese, A., Steiger, W., “Indium Field Emission Electric Propulsion Microthruster Experimental Characterization,” *Journal of Propulsion and Power*, Vol. 20, No. 2 2004, pp. 211-218.

3. Vasiljevich, I., Tajmar, M., Grienauer, W., Plesescu, F., Buldrini, N., Gonzalez del Amo, J., Carnicero-Dominguez, B., Betto, M., “Development of an Indium mN-FEEP Thruster,” *44th AIAA/SAE/ASEE Joint Propulsion Conference*, AIAA 2008-4534, Hartford, CT, 2008.

4. Vasiljevic, I., Buldrini, N., Plesescu, F., Tajmar, M., Betto, M., Gonzalez del Amo, J., “Consolidation of milli-Newton FEEP Thruster Technology based on Porous Tungsten Multiemitters,” AIAA 2011-5592, 47th AIAA/SAE/ASEE Joint Propulsion Conference, San Diego, CA, 2011.

5. Jelem, D., et al., *Performance Mapping and Qualification of the IFM Nano Thruster FM for in Orbit Demonstration,* 53rd AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA, 2017.

6. Seifert, Bernhard, Buldrini, Nembo, Hörbe, Thomas, Plesescu, Florin, Reissner, Alexander, Krejci, Krejci, David, Friedhoff, Pete, Lai, Steve: In-Orbit Demonstration of the Indium-FEEP IFM Nano Thruster, SPC2018-183, *6th Space Propulsion Conference*, Seville, Spain, May 2018.

7. Krejci, David, Reissner, Alexander, Seifert, Bernhard, Jelem, David, Hörbe, Thomas, Plesescu, Florin, Friedhoff, Pete, Lai, Steve: Demonstration of the IFM Nano FEEP Thruster in Low Earth Orbit, *4S Symposium 2018*, 56, Sorrento, Italy, May-June 2018.

8. Krejci, David, Reissner, Alexander, Schönherr, Tony, Seifert, Bernhard, Saleem, Zainab, Alejos, Ricardo: Recent flight data from IFM Nano Thrusters in a low earth orbit, 36th International Electric Propulsion Conference, IEPC-2019-724, Vienna, Austria, Spt 2019.

9. Krejci, David, Hugonnaud, Valentin, Schönherr, Tony, Little, Bryan, Reissner, Alexander, Seifert, Bernhard, Koch, Quirin, Bosch Borras, Eduard, Gonzalez del Amo, Jose: Full Performance Mapping of the IFM Nano Thruster including Direct Thrust Measurements, Journal of Small Satellites, Vol. 8, No. 2, pp. 881-893.