PERFORMANCE PREDICTION OF NEW FEEP THRUSTER DESIGN VERIFIED WITH DIRECT AND INDIRECT THRUST MEASUREMENTS

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ABSTRACT:

Direct and indirect thrust measurements were carried out simultaneously at a FEEP thruster. The direct thrust measurements were performed using FOTEC's novel mN-thrust balance, which was specially developed for high-voltage electric propulsion systems. The indirect thrust measurements are based on beam properties, analysed with a diagnostics system consisting of 23 Faraday cups and a retarding potential analyser. It has been shown that the simultaneously performed direct and indirect thrust measurements match perfectly and thus verify mutually. Furthermore, a verified ion trajectory simulation model was used to compute the beam distribution of the FEEP thruster. Due to the good agreement with the experimental thrust, the simulation model can be used to predict the thrust of an arbitrary FEEP thruster geometry. This is particularly useful when designing a new thruster to match specific thrust or beam requirements.

1. INTRODUCTION

An important value for characterising an electric propulsion thruster is its thrust range. Firstly, this can be determined directly with a thrust balance [1]–[9]. The second possibility is the indirect determination by measuring the beam via plasma diagnostics [9]. Thereby, the conversion of the beam properties into thrust is done by determining the spatial ion current density distribution of the entire beam and the energy distribution of the ions. The ion beam of a FEEP thruster consists mainly of singly charged ions whose kinetic energy corresponds to the emitter voltage. The ion energy scatters only slightly around the emitter voltage, independent of the angular position [10], [11]. Therefore, a FEEP Thruster is particularly suitable for being characterised with indirect thrust measurement. In this paper, simultaneously performed direct and indirect thrust measurements are shown on the basis of an Indium FEEP

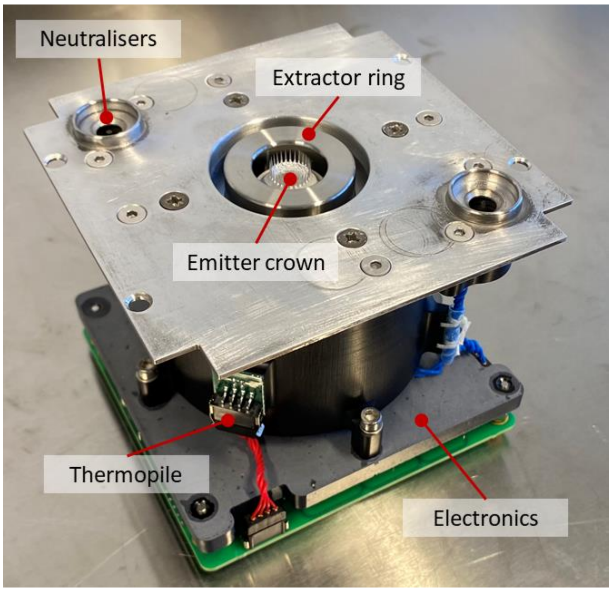

Figure 1. Picture of an IFM Nano Thruster with indicated main components.

Multiemitter (IFM) Nano Thruster, shown in Figure 1. The comparison results are presented for different thruster operation points. Furthermore, the results will be compared with a verified ion trajectory simulation model [10], [12], [13]. Based on the agreement with the experimental results, this model can be used to predict the performance of any arbitrary geometry.

2. THEORY INDIRECT THRUST

The thrust produced by an ion thruster can be calculated indirectly from its beam properties:

$$T = I_{em} \cdot \sqrt{\frac{2m \cdot \eta_v \cdot V_{em}}{e}} \cdot \alpha \cdot \gamma, \quad \text{Eq.1}$$

where I_{em} is the emitter current, m/e the mass to charge ratio of the expelled ions and V_{em} the emitter voltage. The thrust correction factors are the acceleration efficiency η_v, the multipin-charge species term α and the divergence efficiency γ [14]. The η_v factor includes the ion acceleration efficiency, which was analysed for the beam of an IFM Nano Thruster using a retarding potential analyser (RPA) [10], [11]. Thereby, it was observed that the energy of the ions corresponds to the emitter voltage, independent of the spatial angle. The α term considers the fraction of multiple charged ions, which are commonly observed for electric thrusters [14]. Previous analyses of a needle type FEEP thruster have shown that singly charged ions make up 98 % of the total emitted current [15]. The divergence efficiency coefficient γ includes the cosine loss effects on the thrust due to the divergence of the beam. For its calculation the spatial ion current density distribution over the entire beam has to be integrated:

$$\gamma = \frac{1}{I_{em}} \cdot \sum_{ij} I_{ij} \cdot \cos\theta_i \cdot \cos\varphi_j, \qquad \text{Eq.2}$$

where θ and φ are the spherical coordinates of a detector hemisphere in front of the thruster, on which the ion current density I is measured.

It can be summarised that the IFM Nano Thruster can be described very well by a mono-energetic ($\eta_v = 1$) singly-ionised ($\alpha = 1$), beam. Therefore, only the divergence efficiency γ needs to be considered for the indirect thrust computation. These assumptions are also considered for the indirect thrust calculation of the ion trajectory simulation model described in section 3.3.

3. TEST SETUP

In order to be able to compare direct and indirect thrust at the same time, two measurement systems are installed in combination. A picture of the test setup is shown in Figure 2, where the mN-thrust balance is used for direct and the beam diagnostics system consisting of 23 Faraday cups for indirect thrust measurements. The IFM Nano Thruster laboratory model is located on the balance, exactly centred in the semi-circle of the diagnostics system.

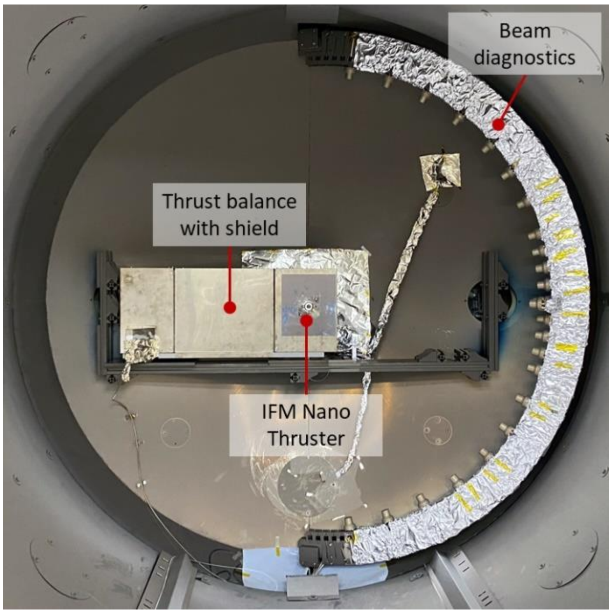

Figure 2. Combined test setup with IFM Nano Thruster, mN-thrust balance and beam diagnostics.

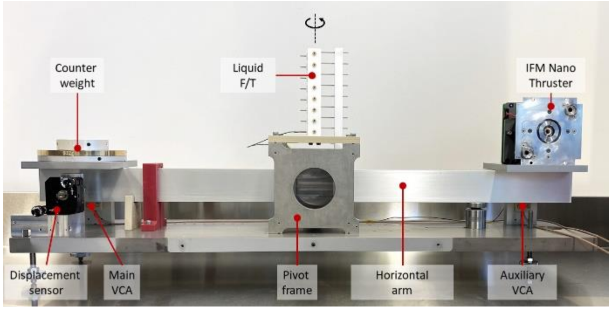

Figure 3. Picture of FOTEC's mN-thrust balance.

3.1. Thrust Balance

For the direct thrust measurements of the IFM Nano Thruster laboratory model, FOTEC's horizontal mN torsion balance is used, which is an advancement of the µN balance developed in 2013 [1]. The balance is suitable for high voltage (< 20 kV) and high current (< 3 A) electric propulsion systems. Since 2013, it has received several upgrades, to be able to cover a thrust range over six orders of magnitude (10 µN – 1 N) with high accuracy (<2 % of corresponding magnitude range) [16].

A picture of the mN-thrust balance is shown in Figure 3. It consists of a horizontal arm suspended by two spring bearings in the centre, which ensure frictionless deflection of the arm. The IFM Nano Thruster test module is located on the right balance table and the counterweight on the left table. Since the balance is based on a force-feedback mode, the arm is kept in its centre position by using a voice coil actuator (VCA), which is located underneath the counterweight table. The VCA uses Lorentz forces to compensate the force generated by the thruster. For compensation, the VCA requires a certain current, which can be converted into thrust. An optical displacement sensor is used to verify the balance arm position. A software-based control loop controls the VCA based on the sensor measurements. A second auxiliary VCA allows a direct verification and calibration of the thrust balance, by applying a test force. Electric liquid metal feed-throughs (F/T) are used for the lead wire connections for supply or for reading out of the thruster parameters. Detailed information on the thrust balance can be found in [16].

3.2. Beam Diagnostics

In 2021 FOTEC developed an upgraded beam diagnostics system to analyse the properties of an ion beam [16], [17]. The beam diagnostics system, shown in Figure 2, is located in FOTEC's large vacuum facility with a length of 3 m and 2.2 m diameter. The system consists of a rotatable semi-circular diagnostics arm equipped with 23 digital Faraday cups (DFCs). The diagnostic system measures the ion current density distribution of the entire beam from -80° to +80° in 1° steps. From the ion current density distribution, the main beam properties can be calculated, such as thrust vector and the divergence half-cone angle. Furthermore, the generated thrust can be computed from the beam profile with

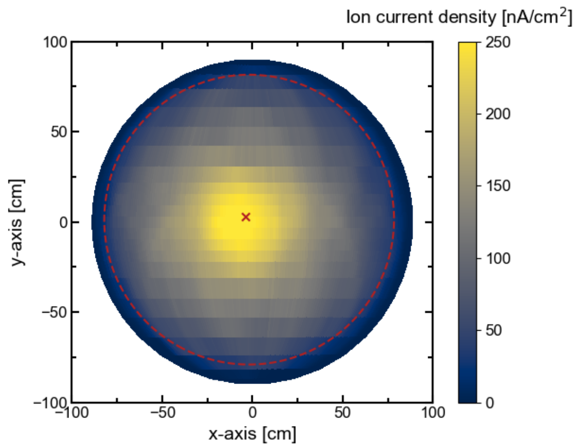

Figure 4. Beam profile measured with FOTEC's beam diagnostics system.

high accuracy using Eq. 1 [16]. Figure 4 shows a projected beam profile from the spherically recorded measurement data. It was measured at nominal emitter current of 3.5 mA of the IFM Nano Thruster test module. The computed thrust vector is indicated with a cross and the divergence angle with a dashed circle. Detailed information about the beam diagnostics system can be found in [16].

3.3. Ion Trajectory Simulation Model

An ion trajectory simulation model was set up in COMSOL Multiphysics using the AC/DC and the particle tracing modules [10], [12], [13]. The newest update of the model is based on experimental beam measurements of several IFM Nano Thruster test modules [12]. Therefore, the geometry of an IFM Nano Thruster is implemented in the model. Ions are initialised at a so-called Taylor cone tip and their trajectories are computed. The movement of the particles through the system creates a space charge that is assigned to the mesh elements. As in the experiment, the ions also reach a virtual detector hemisphere in order to be able to measure the beam profile. The hemisphere viewed in cross section is shown smaller in Figure 5 than in reality. From the computed ion current density distribution at the hemisphere the thrust can also be calculated using Eq. 1.

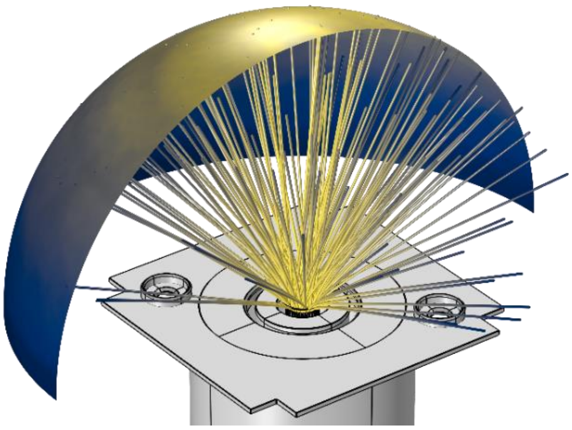

Figure 5. Simulated ion trajectories of an IFM Nano Thruster with beam profile on detector sphere.

4. RESULTS

4.1. Direct vs Indirect Thrust Measurements

Direct and indirect thrust measurements of an IFM Nano Thruster test module are performed simultaneously with the mN-thrust balance and the beam diagnostics system. Thereby, the thruster is operated at different operation points by varying the emitter voltage V_{em} at nominal emitter current I_{em}. At every operation point direct thrust measurements were performed for 5 minutes and an average value was built. Afterwards, a 20 min beam diagnostics scan was carried out. In addition, the results are compared with the ion trajectory simulation model. Both, the experimental beam diagnostics measurements and the simulation results are computed into thrust using Eq. 1.

The results of the two experimental thrust measurement systems and the simulation results are shown in Figure 6. The thruster emitter current is constant at 3.5 mA and the emitter voltage is varied from 5 to 10 kV. All three data series show a thrust increase with increased emitter voltage. This can be explained with Eq. 1, where the thrust is proportional to the square root of the emitter voltage V_{em}.

The directly measured thrust is ~8.5 µN higher than the experimental indirect thrust. An explanation is the vertical inaccuracy of the beam diagnostics system, due to the position of the Faraday cups, shown in Figure 2. However, the deviation is within the accuracy of the used thrust balance magnitude range, which is <20 µN (2 % of 1000 µN).

The computed thrust from the simulation model is even lower than the indirect thrust calculated from the experiment. This can be explained by the fact that every emitter has slightly different properties and only an average value was covered in the simulation model [12].

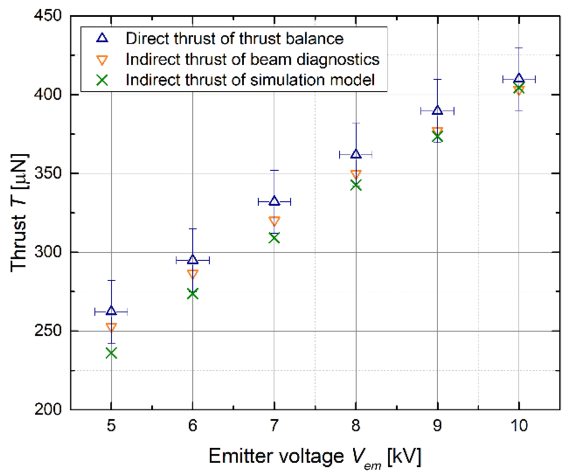

Figure 6. Comparison of direct (red) and experimental (blue) and simulated (green) indirect thrust measurements at constant emitter current of 3.5 mA at different emitter voltages.

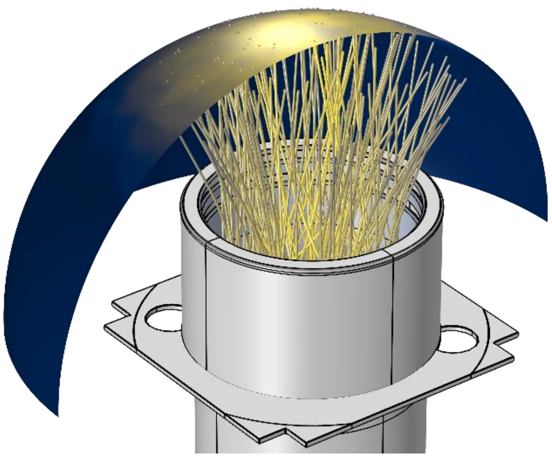

Figure 7. Simulated ion trajectories of a new thruster geometry with focused beam profile on detector sphere.

4.2. Performance Prediction

Section 4.1 has shown that the thrust of an IFM Nano Thruster can be determined indirectly via the ion current density distribution of the beam. Based on the agreement between the ion trajectory simulation model with the experiment, this can be used to predict the thrust for any FEEP thruster geometry. For example, a lens system can be developed to focus the beam. Figure 7 shows such a lens system, which reduces the beam divergence angle and the misalignment of the thrust vector.
Figure 8 shows the indirect thrust computation of the simulation model for the IFM Nano Thruster (Figure 5) and for the optimised geometry (Figure 7). The optimised geometry leads according to the simulation model to a thrust increase of ~30 %. More information about the analysis of the new thruster geometry developed under the use of the simulation model can be found in [12].

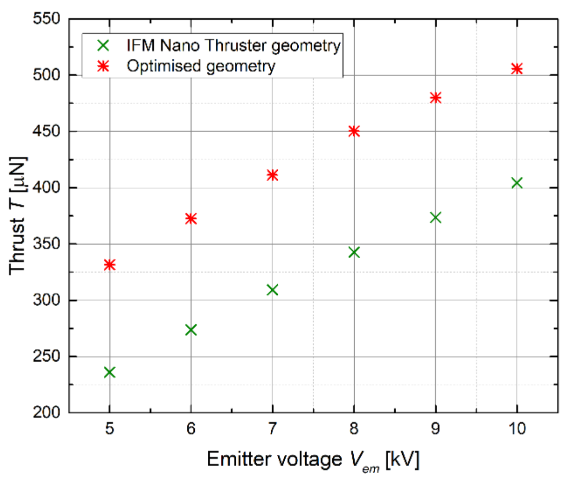

Figure 8. Comparison of simulated indirect thrust of IFM Nano Thruster and optimised geometry at constant emitter current of 3.5 mA at different emitter voltages.

5. CONCLUSION

Experimental direct and indirect thrust measurements were performed simultaneously and show a high degree of agreement. This demonstrates the reliability of indirect thrust measurements for FEEP thrusters. Furthermore, the agreement of the indirect measurement results with the results of a verified ion trajectory simulation model were presented. This implies that any geometry can be simulated in the model and its performance can be predicted. This is particularly important for the development and optimisation of the electrostatic lens system to focus the ion beam.

6. REFERENCES

[1] B. Seifert, A. Reissner, N. Buldrini, F. Plesescu, and C. Scharlemann, 'Development and Verification of a µN Thrust Balance for High Voltage Electric Propulsion Systems', presented at the 33rd International Electric Propulsion Conference, Washington, D.C., Oct. 2013. Accessed: Jul. 16, 2014. [Online]. Available: http://erps.spacegrant.org/uploads/images/images/iepc_articledownload_1988-2007/2013index/vvs6dqil.pdf

[2] D. Rafalskyi *et al.*, 'In-orbit demonstration of an iodine electric propulsion system', *Nature*, vol. 599, no. 7885, pp. 411–415, Nov. 2021, doi: 10.1038/s41586-021-04015-y.

[3] A. Schwertheim, E. Rosati Azevedo, G. Liu, E. Bosch Borràs, L. Bianchi, and A. Knoll, 'Interlaboratory validation of a hanging pendulum thrust balance for electric propulsion testing', *Rev. Sci. Instrum.*, vol. 92, no. 3, p. 034502, Mar. 2021, doi: 10.1063/5.0037100.

[4] A. Neumann, J. Simon, and J. Schmidt, 'Thrust measurement and thrust balance development at DLR's electric propulsion test facility', *EPJ Tech. Instrum.*, vol. 8, no. 1, p. 17, Dec. 2021, doi: 10.1140/epjti/s40485-021-00074-7.

[5] Z. Zhang *et al.*, 'Design and fabrication of a full elastic sub-micron-Newton scale thrust measurement system for plasma micro thrusters', *Plasma Sci. Technol.*, vol. 23, no. 10, p. 104004, Oct. 2021, doi: 10.1088/2058-6272/ac1ac3.

[6] M. Kößling, M. Monette, M. Weikert, and M. Tajmar, 'The SpaceDrive project - Thrust balance development and new measurements of the Mach-Effect and EMDrive Thrusters', *Acta Astronaut.*, May 2019, doi: 10.1016/j.actaastro.2019.05.020.

[7] S. Xu, Z. Zhang, Z. Zhang, W. Yang, H. Tang, and W. Y. L. Ling, 'Time-frequency-domain method for thrust noise characteristics of electric thrusters', *Acta Astronaut.*, vol. 188, pp. 308–325, Nov. 2021, doi: 10.1016/j.actaastro.2021.07.033.

[8] D. G. Courtney, S. Dandavino, and H. Shea, 'Comparing Direct and Indirect Thrust Measurements from Passively Fed Ionic Electrospray Thrusters', *J. Propuls. Power*, vol. 32, no. 2, pp. 392–407, Mar. 2016, doi: 10.2514/1.B35836.

[9] F. G. Hey, *Micro Newton Thruster Development: Direct Thrust Measurements and*

Thruster Downscaling, 1st ed. 2018. Wiesbaden: Springer Fachmedien Wiesbaden : Imprint: Springer Vieweg, 2018. doi: 10.1007/978-3-658-21209-4.

[10] N. S. Mühlich, B. Seifert, and F. Aumayr, 'IFM Nano Thruster performance studied by experiments and numerical simulations', *J. Phys. Appl. Phys.*, Nov. 2020, doi: 10.1088/1361-6463/abc84c.

[11] N. S. Mühlich, S. Keerl, W. Engel, E. Ceribas, and R.-J. Koopmans, 'Retarding Potential Analyser Development for Low Density FEEP Thruster Beam Diagnostics', presented at the International Electric Propulsion Conference, Vienna, Austria, Sep. 2019.

[12] N. S. Mühlich, J. Gerger, B. Seifert, and F. Aumayr, 'Performance improvements of IFM Nano Thruster with highly focused ion beam generated with a compact electrostatic lens module', *Submitted to Acta Astronaut*.

[13] N. S. Mühlich, B. Seifert, and F. Aumayr, 'Verification of simulation model based on beam diagnostics measurements of the IFM Nano Thruster', presented at the 72nd International Astronautical Congress (IAC), Oct. 2021.

[14] D. M. Goebel and I. Katz, *Fundamentals of electric propulsion: ion and Hall thrusters*. Hoboken, N.J: Wiley, 2008.

[15] M. Fehringer, F. Ruedenauer, and W. Steiger, 'Indium liquid-metal ion sources as micronewton thrusters', 1998, pp. 207–213. doi: 10.1063/1.57413.

[16] N. S. Mühlich, J. Gerger, B. Seifert, and F. Aumayr, 'Simultaneously measured direct and indirect thrust of a FEEP thruster using novel thrust balance and beam diagnostics', *Acta Astronaut.*, vol. 197, pp. 107–114, Aug. 2022, doi: 10.1016/j.actaastro.2022.05.009.

[17] N. S. Mühlich, B. Seifert, E. Ceribas, J. Gerger, and F. Aumayr, 'High-Precision Digital Faraday Cups for FEEP Thrusters', *Submitted to JINST*, 2022.