In-plume thrust measurement of NanoFEEP thruster with a force measuring probe using laser interferometry

IEPC-2017-391

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: To validate TU Dresden's analytical thrust model, the thrust of one NanoFEEP thruster is measured with a force-measuring probe developed by the University of Kiel. The probe uses a laser interferometer to determine the deflection of a carbon fiber velvet target which is placed in the plume of the NanoFEEP thruster. Eddy current damping is used to decrease the cantilever oscillation. By using a carbon fiber velvet target with its extremely high sputtering resistance and low ion-induced and electron-induced secondary electron emission, we are able to measure the thrust directly in the thruster's plume without contaminating the field emission site due to sputtering and without distorting the current measurements. The results of the calculated thrust show good agreement with the measured thrust of the force probe.

Nomenclature

α = ion beam half-angle
δ = angular offset of ion beam center
e = elementary charge
F = analytically calculated thrust
F_{tar} = calculated thrust on target
I_{em} = emitted current
I_{ex} = intercepted current of extractor electrode
I_{tar} = target current
η_d = beam divergence factor
V_{em} = emitter voltage

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I.Introduction

With the emerging interest in CubeSats and other small satellites, not only for research and educational purposes, but also for commercial use, pico- and nano-satellites and their subsystems are rapidly evolving and render new mission scenarios and applications possible. One of the novel upcoming CubeSat mission concepts are multi satellite constellations and even formation flying of CubeSats. To enable such multi satellite missions, an accurate and highly efficient propulsion system is needed facing the strong restraints of CubeSats in space, weight and power. TU Dresden's approach for such a propulsion system is a highly miniaturized Field Emission Electric Propulsion (FEEP) system, named NanoFEEP. One unit of the NanoFEEP propulsion system consists of two NanoFEEP thruster heads, one cold field emission neutralizer silicon chip using Carbon Nano Tubes (CNTs) and the dedicated high voltage power supply board. For a more detailed description of the NanoFEEP propulsion system see Ref. 1.

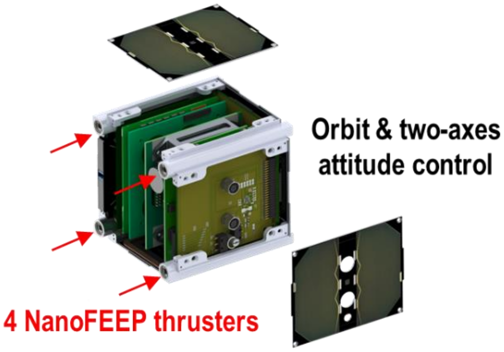

Figure 1. NanoFEEP propulsion system for attitude and orbit control of a 1U CubeSat, using the example of the UWE-4 CubeSat platform. $^{\mathbf{LIT02}}$

So far, two CubeSat missions are planned to demonstrate the performance of the NanoFEEP propulsion system in 2018. On the first mission two propulsion units (four NanoFEEP thrusters integrated in the CubeSat rails, two Neutralizer silicon chips and two electronics boards) will be used on the one unit (1U)-CubeSat platform UWE-4 to demonstrate two-axes attitude and orbit control of a 1U CubeSat with our electric propulsion system, illustrated in Fig. 1. The second mission will demonstrate the deorbiting capabilities of the NanoFEEP propulsion system on the 3U-CubeSat SNUSAT-2 of the Seoul National University.

TU Dresden's highly miniaturized NanoFEEP thrusters have a volume of less than 3 cm^3 and a total weight of less than 6 grams, each. By using gallium as metal propellant, a very low heating power demand of only 50 to 150 mW is needed (depending on the satellites structure temperature) to liquefy the metal propellant. One thruster head is able to generate a continuously controllable thrust over the whole thrust range. Our analytical thrust model estimates the generated thrust to be between 0-8 µN in long-term operation and up to 22µN for short-term operation.[2]

To verify our analytical thrust model, a thrust measurement campaign was performed at TU Dresden using the force probe of the University of Kiel. In this contribution, we will introduce TU Dresden's NanoFEEP thrusters and University of Kiel's force probe which uses laser interferometry and a carbon fiber velvet target. We will also describe the used measurement setup and will present and discuss the results of the thrust measurement campaign.

II. NanoFEEP Thrusters

A. Working Principle of FEEP

Field Emission Electric Propulsion (FEEP) thrusters in general are based on the field emission effect. The working principle of such a FEEP thruster using very sharp needles is shown in Fig. 2. By applying a high electric potential of several kilovolts between a sharp needle tip, wetted with the liquid metal propellant, and a ring shaped extractor electrode, an ion beam is generated. Due to the interplay of the surface tension of the metal propellant and the applied electrostatic force, the liquid metal film forms a so-called Taylor Cone and a corresponding jet on top of the needle tip. If the electric field strength on top of the Taylor Cone jet reaches the field evaporation strength of the metal propellant (in the order of 10^{10} V/m), the metal propellant is evaporated, ionized, and accelerated in the very same electric field. The metal ions are emitted with velocities of up to 100 km/s. This high velocity and the high ionization rates, especially at lower emitting currents, make it possible to reach a very high specific impulse of 6000 s [3].

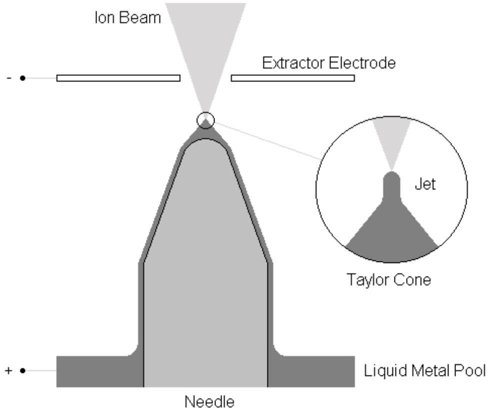

Figure 2. Basic principle of a Field Emission Electric Propulsion (FEEP) system, needle type. [4]

B. Thruster Design

To achieve a highly efficient and stable ionization of the metal propellant, the NanoFEEP thrusters use our novel porous Liquid Metal Ion Sources (LMIS)[5]. This LMIS consists of a very sharp porous tungsten needle with an open porosity. The metal propellant wets the porous needle (see Fig. 3) and the needle's open porosity provides a self-feeding propellant flow from the reservoir to the needle tip due to capillary action. With this passive propellant feeding no valves or propellant feeding devices are necessary.

In order to reduce the power demand for liquefying the metal propellant, we are using gallium as metal propellant with its low melting temperature of approximately 30° C. Other metal propellants, like e.g. indium with a melting temperature of 157° C, would lead to a much higher heating power demand and would consequently not be feasible for a FEEP propulsion system on a 1U CubeSat with its strong power limitations. Besides the choice of the propellant material, the design of the NanoFEEP thruster itself is optimized w.r.t thermal losses to reduce the heating power demand. The design of the NanoFEEP thrusters results in a highly miniaturized and compact module with a diameter of only 13mm (including housing), a length of 21 mm and a total wet weight of less than 6 grams. Fig. 4 shows one manufactured NanoFEEP thruster compared to a 1-Euro-coin to illustrate the small size of the thruster heads.

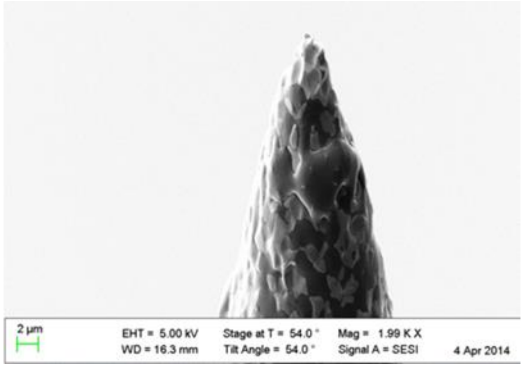

Figure 3. SEM image of a porous tungsten needle wetted with the metal propellant gallium. [3]

The estimated lifetime of one NanoFEEP thruster of about 1800 hours for continuous operation at thrusts between 1 to 2 µN is only limited by the reservoir size, which can be easily increased to extend the thruster's lifetime.

Recently, we manufactured and tested a second-generation design of the NanoFEEP thrusters. The new design keeps the same dimensions and the performance of the thrusters, but has a more modular structure and the thrusters are easier to access. This makes it more comfortable to exchange any part of the thruster during testing, and the manufacturing process could be simplified as well. Moreover, we could improve the electrical interface and the ability of integration in a CubeSat in the new version. The here presented thrust measurement results were obtained with the first-generation design of the NanoFEEP thruster, because the new thruster version has not been manufactured before the thrust measurement campaign started. As later tests of the new thruster design showed the same performance as the first-generation design and because no changes of emission relevant parts were made, we assume that the here presented thrust measurements are valid also for the new thruster design.

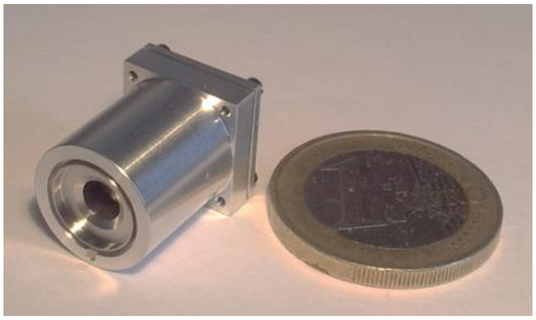

Figure 4. Manufactured NanoFEEP thruster compared to a 1-Euro-coin. [3]

C. Performance of NanoFEEP Thrusters

Several operation and performance tests of different NanoFEEP thrusters have been performed so far, like shown in Fig. 5. In these tests, the current-voltage characteristics and the ionization mass efficiency of the LMIS were measured. The mass efficiency was determined by comparing the measured weight difference of the LMIS at constant current levels with the emitted amount of charges determined by the measured emitter current. This method of determining the mass efficiency represents the direct proportion of ionized metal atoms emitted during the tests[3].

By using our analytical thrust model, (described in the next section) we are able to calculate the generated thrust in consideration of ion beam divergence. With this analytical model we are able to determine and are consequently able to actively control the total generated thrust by controlling the emission current continuously over the full thrust range with our high voltage CubeSat electronics.

Figure 5. Operating NanoFEEP thruster.

Fig. 6 shows an exemplary current-voltage characteristic (begin of life) of one of the tested NanoFEEP thruster prototypes with an almost linear progression and a typical starting voltage between 3.3 and 5.5 kV. With advancing operation time, the starting voltage increases while the impedance (the slope of the characteristic) decreases. This typical behavior of FEEP thrusters is considered in the system design and can be compensated by the generous margin of the maximum output voltage of 12 kV of our high voltage power supply board. In addition, Fig. 6 gives a thrust equivalent of the emitter current on the secondary horizontal axis, calculated with our analytical thrust model. The NanoFEEP thrusters can be operated continuously over the whole thrust range from 0 to 20 µN (equivalent to a 0 to 250 µA emitter current). Though, a maximum emitting current of only 100 µA (equivalent to a thrust of approximately 8 µN) is recommended for safety reasons at long-term operation (more than several hundred hours) to avoid needle erosion. Moreover, we have to take into account the strong power restraints of CubeSats. If we for example assume that on a 1U-CubeSat a maximum power of 1 W is available for the propulsion system we are able to generate 8µN of thrust including all power conversion efficiencies, heating and neutralizer operation with one NanoFEP thruster.

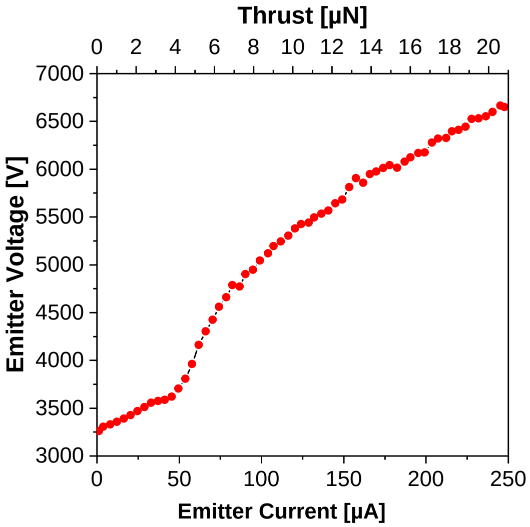

Figure 6. Current-voltage characteristic of a NanoFEEP thruster with calculated thrust equivalent.

Besides the here presented thrust measurement campaign, various other tests are planned in the next months to further investigate the thruster's performance. The planned tests include long-term operation tests (2000 h), further beam diagnostic tests, qualification tests and the direct measurement of the generate thrust with TU Dresden' thrust balance to validate and compare the thrust measurements of the here used force probe.

D. Analytical Thrust Model

TU Dresden's analytical thrust model for the NanoFEEP thrusters uses the difference between the emitted current I_{em} and the intercepted current of the extractor electrode I_{ex} representing the total net emission ion current, and the voltage potential of the emitter V_{Em} to calculate the generated force of the NanoFEEP thrusters along the thruster axis. The thrust is calculated in our model as follows:

$$F = \eta_d \cdot (I_{em} - I_{ex}) \cdot \sqrt{\frac{2 \cdot m_{Ga} \cdot V_{Em}}{e}} \tag{1}$$

Where m_{Ga} is the atomic mass of the metal propellant gallium, e is the elementary charge and η_d is the ion beam divergence factor. To determine the divergence factor η_d, we use Malina's formula[6], where α is the ion beam half-angle:

$$\eta_d = f(\alpha) = \frac{1 - \cos(2\alpha)}{4(1 - \cos(\alpha))} \tag{2}$$

Malina assumes cone-shaped streamlines originated from a point source for rocket engines with his formula, but it can also be used for FEEP thrusters as it depicts the conical ion beam shape very well. With this approach, we assume a constant ion beam density over the ion beam half-angle, but this is in good agreement with recently performed ion beam measurements of the NanoFEEP thrusters in Ref. 7.

The needed ion beam half-angle for determining the divergence factor is again a function of the emitted current I_{em}, and was measured before for the tested thruster with our ion beam diagnostic facility[7]. The current dependent ion beam half-angle measurements were performed with the same NanoFEEP thruster used for the here presented thrust measurements and the results are fitted with the following logarithmic fitting function:

$$\alpha[^\circ] = f(I_{em}) \approx 12.283^\circ \cdot \ln(I_{em}[\mu A]) - 15.191^\circ \quad (3)$$

This fitting function for angles in degrees is used for the thrust calculations to determine the current dependent ion beam divergence factor in Eq. (1) and (2) for the tested thruster.

III.Force Probe

The force probe[8,9] is designed to measure forces on a measurement target inside the plume of ion sources, especially electric propulsion thrusters. The force probe has recently been used for spatially resolved measurements in thruster plumes[10] as well as for the study of sputter effects [9].

In this contribution, the force probe (see Fig. 7) is used, with the intention to absorb the entire plume of a NanoFEEP thruster. For this purpose, the force probe uses a circular measurement target. The target is especially large (radius = 40 mm) compared to the usually used ones and is made of carbon fiber velvet. Previous investigations showed that carbon fiber velvet is a nearly perfect absorber [9].

The applied method is a measurement of a deformation of an elastic cantilever under the action of a force. The cantilever is fixed at one end, and the target is mounted at the free end. The cantilever is a ceramic tube with a free length of 175 mm and an outer diameter of 1 mm. The target is electrically grounded by a wire fed through the ceramic tube to enable current measurements. An interferometric displacement sensor optic is directed perpendicularly to a mirror that is fixed on the ceramic tube. A damping technique for the cantilever oscillations at the natural frequencies is applied that makes use of eddy currents.

The procedure of a single force measurement consists of an initial reference measurement when the beam is off, a following measurement in the beam, and a final reference measurement when the beam is off again (see Fig. 8). After calibration the jump between the reference measurements and the measurement in the beam is taken as the force acting on the target. For details of the displacement measurement and the calibration method, see Ref. 8.

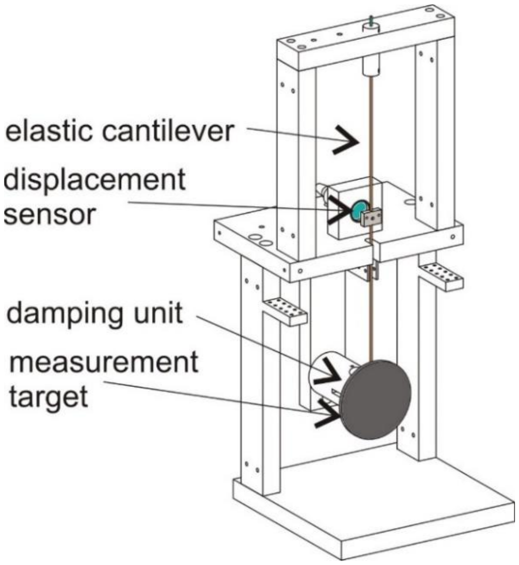

Figure 7. The interferometric force probe (CAD model).

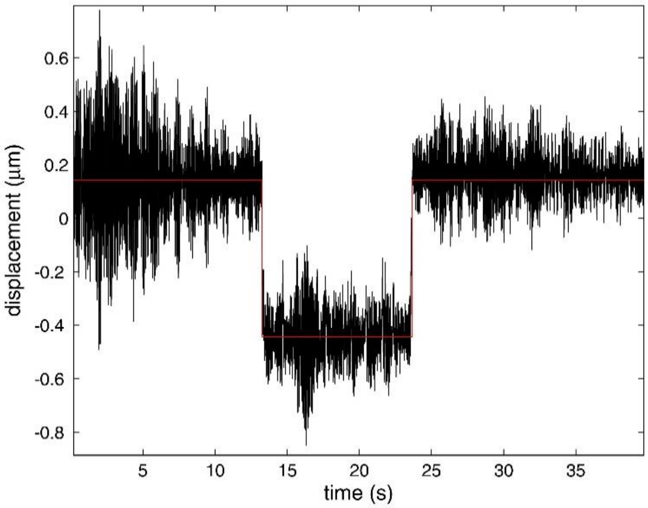

Figure 8. Displacement signals of the cantilever beam due to beam forces acting on the target.

IV. Thrust Measurement Setup

The force probe and the NanoFEEP thruster are placed inside of a large Faraday cup (named collector), as show in Fig. 9. Ion currents on the collector are measured with an electrically grounded shunt resistor to detect possible ion currents beyond the carbon fiber velvet target. The NanoFEEP thruster is directly placed in front of the circular target of the force-measuring probe (see Fig. 10) at a distance of approximately 15.5 mm, and the ion current is also measured through a grounded shunt resistor.

For each thrust measurement, the NanoFEEP thruster is turned on for approximately 10 s at a constant emission current and turned off again. Meanwhile, the resulting cantilever deflection of the force probe is measured with the laser interferometric displacement sensor. To determine a possible electrostatic influence of the high voltage potential of the NanoFEEP thruster, a zero reference measurement with an emitter voltage of 4000 V is performed. As this emitter voltage lies under the starting voltage of the tested NanoFEEP thruster (approx. 5000 V) no ion emission takes place in this reference measurement. The non-emission is also confirmed by the measured absence of target and collector current. As this zero reference measurement showed no detectable deflection of the cantilever, we conclude that the emitter potential has no influence on the thrust measurement results in our measurement setup.

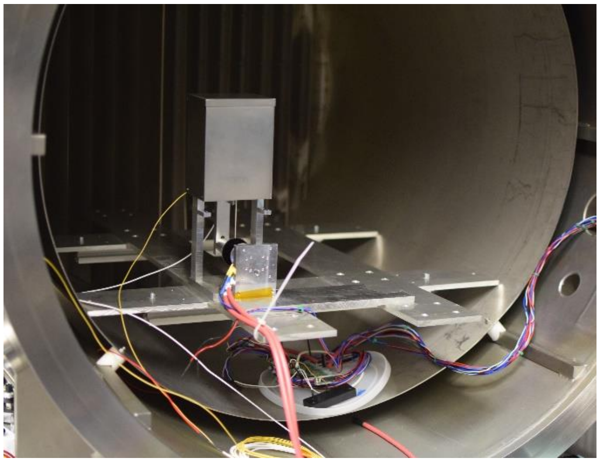

Figure 9. Thrust measurement setup: University of Kiel's force-measuring probe inside of the collector (Faraday cup) of TU Dresden's vacuum chamber.

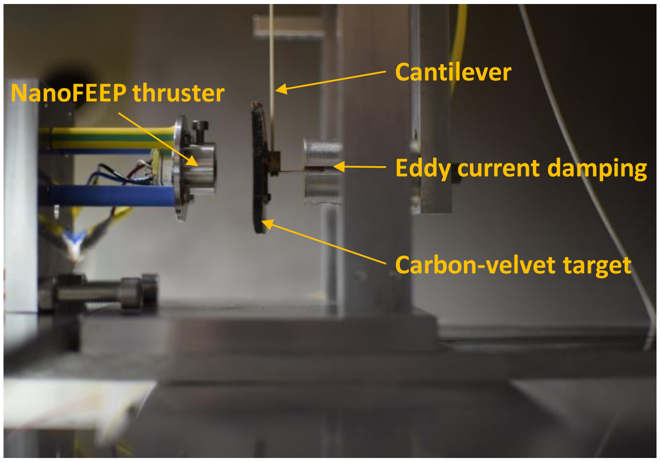

Figure 10. NanoFEEP thruster in front of carbon fiber velvet target of the force-measuring probe.

V.Thrust Measurements

The thrust measurements are performed at constant emission currents between 10 and 250 µA to characterize the full thrust range of the tested NanoFEEP thruster. Fig. 11 shows the measured target current, the collector current and the total emission current (difference between emitted current and extractor current, see Eq. (1)). It can be seen, that at total emission currents between 0 and 50 µA no collector current is measured and the emission current is equal to the target current. This is because the whole ion beam is absorbed from the carbon fiber velvet target. For higher currents though, due to the increase of the beam divergence, the beam reaches the edge of the target and finally goes beyond the target. The measured increasing collector current shows this in Fig. 11. At the same time, also the difference between emission current and target current increases (to the same extent as the collector current). As we only measure a portion of the ion

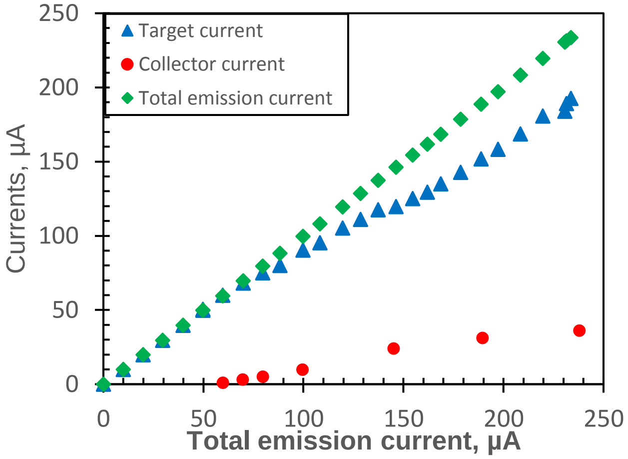

Figure 11. Target and collector current over the total emission current (difference of emitting current and extractor current).

beam on the carbon fiber velvet target at higher emission currents, we have to consider this in the following data analysis of the thrust measurements.

A. Angular Offset of Ion Beam Center

The inspection of the carbon fiber velvet target after the performed thrust measurements show that the center of the impinged ion beam seem to have an offset with respect to (w.r.t.) the center of the target. This can be seen by the off-centric white gallium spot on the target surface in Fig. 12. The offset of the spot center to the target center is approximately 6 mm, which corresponds to an angular offset δ from the thruster axis of approx. 21°. One reason for this detected angular offset may be the misalignment of the thruster w.r.t. the target's center. Another reason may be an angular emission of the tested thruster. Beam diagnostic tests of the tested thruster performed before[7] showed an angular emission offset of only approx. 12°. This is why we assume that the angular offset of the ion beam center on the target is caused by both mentioned reasons. Nevertheless, the detected angular beam center offset will be considered in the following data analysis of the thrust measurements.

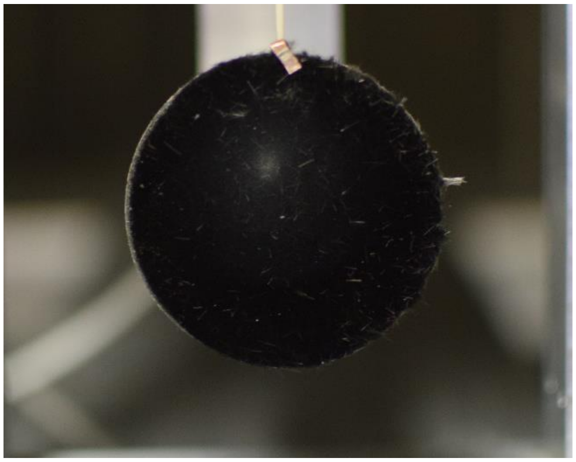

Figure 12. Gallium spot on carbon fiber velvet target representing the angle offset of ion beam.

B. Thrust Measurement Results

As shown in Fig. 11 not the entire ion beam impinges on the target surface at higher emission currents. In order to compare the measured thrust of the force probe with the calculated thrust of our analytical thrust model, we have to substitute the total emitted current $\left(I_{em} - I_{ex}\right)$ in Eq. (1) with the measured current on the target I_{tar}. Moreover, considering the ascertained angular offset of the ion beam center δ (see section V. A.), Eq. (1) is multiplied by the ion beam angular offset factor $\cos(\delta)$. The calculated thrust on the carbon fiber velvet target F_{tar} consequently becomes:

$$F_{tar} = \eta_d \cdot I_{tar} \cdot \sqrt{\frac{2 \cdot m_{Ga} \cdot V_{Em}}{e}} \cdot \cos(\partial) \tag{4}$$

By using Eq. (4) and the current dependent beam divergence factor of Eq. (2) as well as the fitting function for the beam divergence angle α of Eq. (3), we can calculate the resulting thrust on the force probe target as a function of the total emission current. The comparison of the so calculated thrust with the measured thrust of the force probe is shown in Fig. 13. As can be seen, the measured and calculated thrust results are in good agreement and confirm our analytical thrust model for the NanoFEEP thrusters.

Based on the described results of measured and calculated thrust on the target, we can calculate the total generated thrust along the ion beam axis of the tested NanoFEEP thruster. For this, we can use our original analytical thrust model from Eq. (1) - (3) by using the measured total emission current $\left(I_{em} - I_{ex}\right)$ and the current dependent ion beam divergence factor η_d. The resulting total thrust is shown in Fig. 14. It can be seen that the total generated thrust of NanoFEEP increases almost linearly with the emission current up to a maximum thrust of approx. 20 µN.

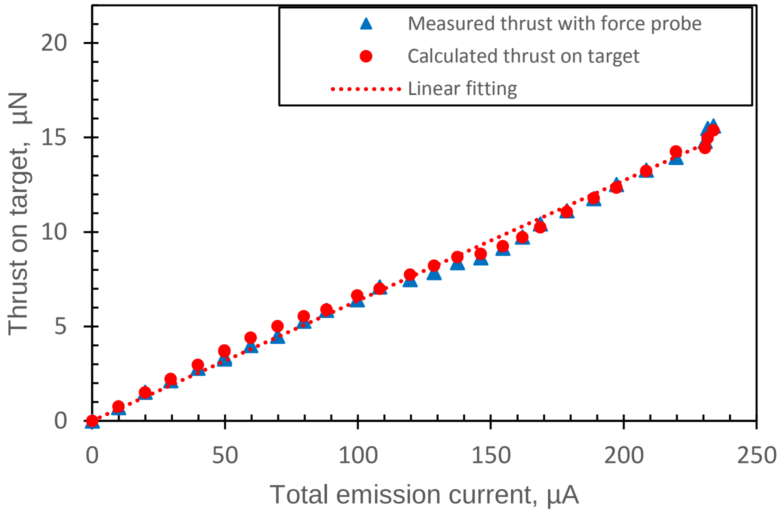

Figure 13. Comparison of measured and calculated thrust acting on the force probe target.

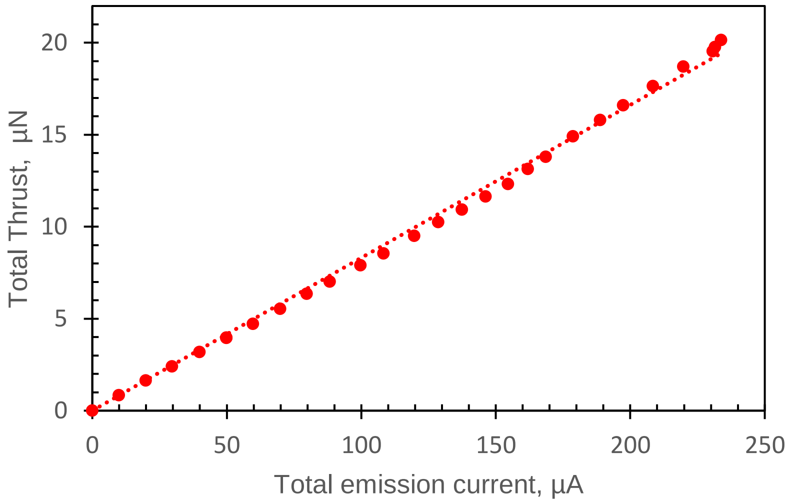

Figure 14. Total generated thrust of tested the NanoFEEP thruster as a function of the total emission current (=difference between emitter and extractor current).

VI.Conclusion and Outlook

We have presented the results of indirect in-plume thrust measurements of a NanoFEEP thruster with a force probe using laser interferometry and a carbon fiber velvet target. The force measurement results are in good agreement with the analytical calculated thrust. The results also showed an almost linear progression of the generated thrust over the total emitted ion current of up to 20 µN. The detected ion beam angular offset will be further investigated with the second generation design of the NanoFEEP thruster. Moreover, thrust measurements with other force probe designs, e.g. TU Dresden's horizontal thrust balance, are planned in future to confirm the measured thrust values and to compare the different thrust measuring probes.

Acknowledgments

We gratefully acknowledge the support for the NanoFEEP propulsion system development by the German national space Agency DLR (Deutsches Zentrum fuer Luft- und Raumfahrttechnik) by funding from the Federal Ministry of Economic Affairs and Energy (BMWi) by approval from German Parliament. Special thanks go to L. Martin-Perez and S. Mewis. Further thanks go to the Wuerzburg University and to the Seoul National University for the great cooperation. Moreover, we want to thank W. Pilz (TUD), T. Wilfinger (RHP-Technologie GmbH), A. Gruner (LH Mittweida), M. Krug (Fraunhofer IKTS), F.-G. Hey (Airbus D&S), J. Brutscher (GBS Elektronik) and M. Siegel (TUD) and the company Teledyne Reynolds for their support.

The development of the force probe has received funding from the German Aerospace Center (DLR) under grant no. 50 RS 1301.

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