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Force probes for development and testing of different electric propulsion systems

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Abstract

Diagnostics with force probes in plumes of electric propulsion systems for spacecraft (thrusters) are presented. This contribution focuses on showing example measurements with force probes for the most common gridless ion thruster types. The gridless thrusters are investigated at typical operation modes with a force probe at fixed or variable positions in the plume. The probe measures the force on a tiny plate that is attached to a sensitive cantilever in the plume. The elastic deflection of the cantilever is measured interferometrically and translated into a proportional force. Several variants of the instrument have been developed. A HEMP thruster is investigated with a variant of the force probe that simultaneously measures two components of the force vector. With this vectorial probe, it is possible to determine the force vector acting on the probe target while moving the probe through the thruster plume. A Hall thruster is investigated with a simplified variant of the probe, which measures the force along one axis and is equipped with an additional shutter in front of the target. This allows monitoring over long periods of operation. Finally, a force probe is used as an indirect thrust balance for a FEEP thruster. In this case, the force probe can collect the entire plume.

Keywords: Electric spacecraft propulsion; Beam diagnostic; Force measurement; Momentum transfer

1 Introduction

In case of measurements in the plume of electric thrusters, commonly electrostatic probes, like Faraday cups and retarding potential analyzers, are used [1]. The measurements of flux densities with Faraday cups are affected by charge-exchange collisions because neutral beam particles created by charge-exchange collisions cannot be detected [2, 3]. The thrust of an electric engine is commonly measured by thrust balances [4]. These measurements account for neutral particles but they are not plume diagnostics. The force probe enables to perform spatially resolved plume measurements that do not discriminate between ionic and neutral plume particles [3, 5]. Therefore, one could say that force probes combine the non-discriminating aspect of thrust balances with the spatial resolution of Faraday cups.

In this contribution, force probe measurements are presented that are performed in the plumes of HEMP [6], Hall [7], and FEEP [8] thrusters. HEMP and also Hall thrusters

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are gridless plasma thrusters operated with direct current. A plasma is generated and the thrust is produced by extraction and acceleration of the ionic particles, usually xenon ions. Direct current thrusters might require a specific starting procedure involving higher gas fluxes and enhanced voltages. However, the force probe measurement procedure involves alternating measurements with and without beam [5]. Therefore, an iris aperture in front of the force probe target can be used, so that the thruster does not have to be switched on and off for the measurements. The FEEP thruster extracts and accelerates the ions from a liquid metal. In this case, the force probe can absorb the entire plume of the thruster and is used as an indirect thrust balance.

2 Methods and variants of the force probe design

2.1 Two-axes force probe

The two-axes force probe (see Fig. 1) uses a thin circular Cu target (diameter 20 mm) that receives the forces to be measured. A cantilever is fixed at one end, and the target is mounted at the free end. The applied method is a measurement of the deformation of the cantilever ceramic under the action of the force. The cantilever is a ceramic tube with a free length of 175 mm and an outer diameter of 1 mm. The target is grounded by a wire that is fed through the ceramic tube and enables current measurements. Between the ends of the tube, a holder with two small mutually orthogonal mirrors is mounted. Two displacement sensors are fixed at the frame and point perpendicularly onto the mirrors. This construction allows to detect both degrees of freedom of the target displacement.

Because of the undesired oscillations at the natural frequencies of the cantilever, an eddy current damping unit with permanent magnets is applied.

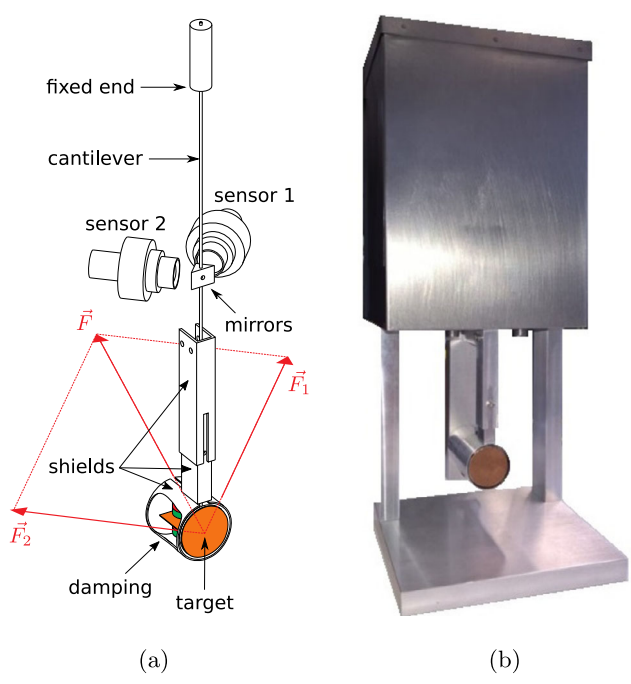


Figure 1 Two-axes force probe. (**a**) View of the essential components with the force acting on the probe target. Note that the force **F** is in general not perpendicular to the target. (**b**) Photo of the capsulated probe

The optical parts and the upper part of the cantilever are shielded from impinging particles with a box-shaped encapsulation [see Fig. 1(b)]. Additional shields protect the lower part of the cantilever, the backside of the target, and the damping unit.

In Fig. 1(a), the illustrated force **F** acting at the target leads to a displacement of the orthogonally arranged mirrors. The sensors 1 and 2 detect the respective displacements, so that the two force components $\mathbf{F_1}$ and $\mathbf{F_2}$ can be determined. The magnitude of the force vector is

$$|\mathbf{F}| = \sqrt{F_1^2 + F_2^2} \ . \tag{1}$$

Before the measurements, a calibration with milligram weights has to be performed. For this purpose, the cantilever is temporarily turned horizontally and the milligram weights are put on the target.

This variant of the force probe was used for the measurements in the plume of a HEMP thruster (see Sect. 3.1). For more details of the two-axes interferometric displacement measurement and the calibration method see Ref. [5] in this journal and Ref. [9].

2.2 One-axis force probe with a shutter

Figure 2(a) shows the one-axis force probe. It is equipped with an iris aperture (diameter 36 mm) as a shutter for either exposing or not exposing the target (diameter 20 mm) to the beam. In this variant of the probe, only one interferometric sensor is used that measures displacements along the target normal. The target consists of "carbon fiber velvet", an artificial microstructured material with low sputtering yield (produced by Energy Science Laboratories, Inc.) [5]. The calibration is again done with milligram weights.

This variant of the force probe was used for the measurements in the plume of a Hall thruster (see Sect. 3.2).

2.3 One-axis force probe as an indirect thrust balance

Figure 2(b) shows the one-axis force probe with a larger measurement target (diameter 40 mm) that captures the entire plume of a FEEP thruster. For this purpose, the target

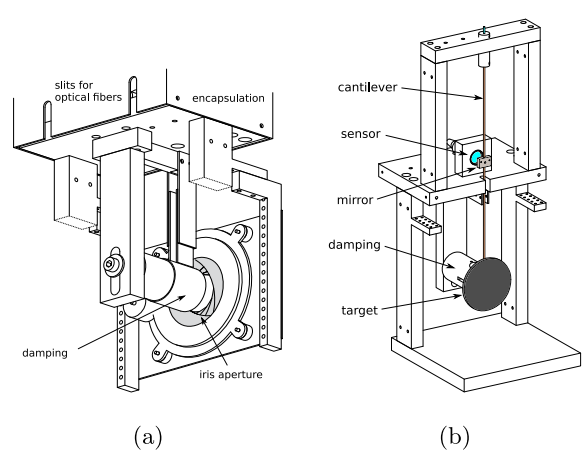


Figure 2 One-axis force probe (**a**) with an iris aperture shutter (view from behind) and (**b**) as an indirect thrust balance (without housing)

consists of the carbon fiber velvet mentioned before (see Sect. 2.2). When the plume particles deeply penetrate into the material, it is very likely that the long fibers stop them and absorb their entire momentum. Due to the low sputtering yield of carbon and the structure of the material, it is improbable that beam or carbon particles leave the target with significant momentum. Therefore, the overall sputtering yield of the target is small. If the size of the target is big enough to capture the entire plume of a thruster, such a force probe can be used as an indirect thrust balance. The calibration is again done with milligram weights.

This variant of the force probe was used for the measurements with the plume of a FEEP thruster (see Sect. 3.3).

3 Measurements in electric propulsion thruster plumes

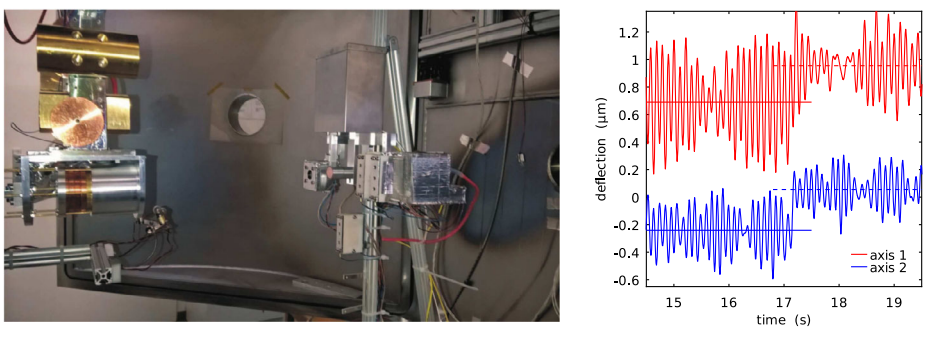
3.1 HEMP thruster

The measurements in the plume of a HEMP (High Efficiency Multistage Plasma) thruster were carried out in a test chamber of the Laboratory for Enabling Technologies, Airbus (Friedrichshafen, Germany).

HEMP thrusters [6] generate a plasma by magnetic and electric fields. An elongated cylindrical discharge chamber is enclosed by ring magnets providing a magnetic cusp field. Mainly the potential drop at the thruster exit is responsible for the acceleration of the ions generated in the magnetized direct current plasma.

The two-axes force probe (see Sect. 2.1) was mounted together with a Faraday cup and a retarding potential analyzer on a swivel arm [see Fig. 3(a)]. This enabled scans around the HEMP thruster, which was mounted on a thrust balance, at a distance of 37 cm. The force probe was always directed to the HEMP thruster (center of rotation) independently from its position. Figure 3(b) shows data of a measurement. One can clearly see the abrupt change in the equilibrium position of the force probe cantilever when the thruster is switched off. The equilibrium positions are time averaged over 2 seconds starting or ending 0.2 s after or before the switching, respectively.

We want to point out that for the HEMP thruster measurements it was not necessary to use the two-axes force probe; a one-axis force probe would be sufficient. The only reason we used the two-axes force probe was its availability at the time when the opportunity for



(a) (b)

Figure 3 (**a**) View into the HEMP thruster test chamber. The swivel arm with force probe, Faraday cup, and retarding potential analyzer can be seen on the right side. On the left side one sees the thruster together with a dummy of the same mass mounted on the thrust balance. The dummy that is required for this kind of thrust balance hides the thruster behind it. (**b**) Detected sudden change of the two equilibrium positions (solid and dashed horizontal lines) for the firing ($t < 17.2$ s) and the switched off ($t > 17.2$ s) thruster, respectively

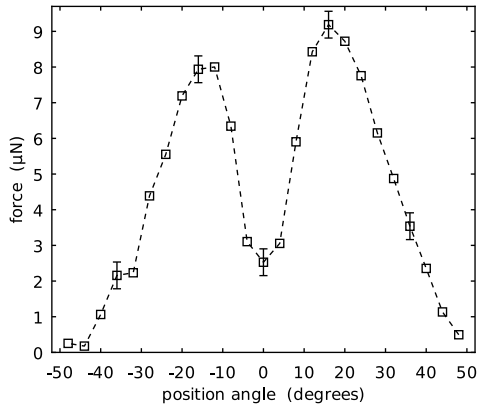


Figure 4 Force profile of the HEMP thruster operated in the "High I_{sp} Mode" (700 V discharge voltage, 145 mA discharge current, 2.5 sccm Xe gas flow)

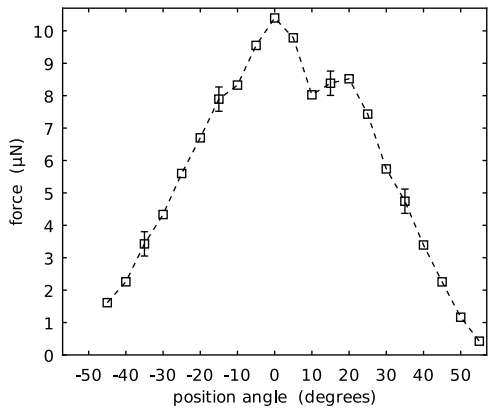


Figure 5 Force profile of the HEMP thruster operated in the "Low I_{sp} Mode" (350 V discharge voltage, 245 mA discharge current, 4 sccm Xe gas flow)

measurements with a HEMP thruster opened up. The two-axes force probe was originally developed for the study of sputtering [9].

By rotating the swivel arm around the thruster, forces can be measured at different angular positions. The resulting beam profile is shown in Fig. 4. In this example, the HEMP thruster was operated in the "High I_{sp} Mode" (700 V discharge voltage, 145 mA discharge current, 2.5 sccm Xe gas flow), where I_{sp} means specific impulse indicating exhaust velocity. Figure 5 shows an example of the "Low I_{sp} Mode" (350 V discharge voltage, 245 mA discharge current, 4 sccm Xe gas flow). The gas pressure in the chamber was 3×10^{-3} Pa.

Note the qualitatively different shapes of the plumes. HEMP thrusters are known for the hollow cone-shaped plumes to which Fig. 4 corresponds. For lower acceleration voltages, as in Fig. 5, the apex angle of the cone becomes smaller and the minimum at the axis raises, i.e. the cone is filled.

The thrust can be estimated from the beam profile, i.e. the N forces F_i measured at the angular positions α_i ($i = 1, \ldots, N$). To this end, the force components parallel to the thruster axis, $F_{\parallel,i} = (F_i/c)\cos(\alpha_i)$, are calculated. The energy-dependent coefficient $c > 1$ is calculated with the TRIM code, which takes the additional momentum transfer by sput-

tered Cu target particles into account [10]. The factor is c = 1.0595 for 700 eV Xe ions and c = 1.0356 for 350 eV Xe ions impinging on Cu. The thrust can be estimated by numerical integration of the forces over a half sphere surface behind the HEMP thruster under the assumption of a plume with rotational symmetry about the thruster axis.

Obviously, this assumption is not fully met since the data shown in Figs. 4 and 5 show an asymmetry. For this reason, we weighted the forces for the corresponding angles α and $-\alpha$ equally.

The estimated thrust based on the rotationally symmetrical force distribution for the "High I_{sp} Mode" is 2.9 mN and for the "Low I_{sp} Mode" 3.6 mN. The thrust balance measured 3236 μN and 3200 μN [11].

3.2 Hall thruster

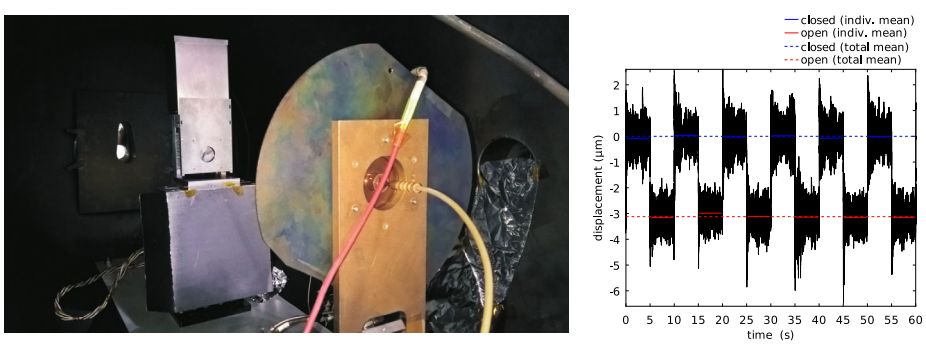
The measurements in the plume of a Hall thruster were carried out in the test chamber NExET (New Experiment on Electric Thrusters) of the ICARE (Institut de Combustion, Aérothermique, Réactivité et Environnement) laboratory of the French National Center for Scientific Research CNRS in Orléans, France.

Hall thrusters [7] make use of crossed magnetic and electric fields. An annular discharge chamber, called channel, is filled with a radial magnetic field. The electric field lines start from the anode ring at the bottom of the discharge chamber and end at the cathode (neutralizer) somewhere laterally next to the thruster. The gyrating electrons drift along the channel and perform impact ionization, while the unmagnetized ions are extracted and accelerated out of the plasma by the electric field.

In the following, we show measurements in the plume of the 200 W class magnetically shielded ISCT200-MS Hall thruster. The thruster uses permanent magnets instead of magnetic coils to create the radial magnetic field [12–14].

The one-axis force probe with an iris aperture (see Sect. 2.2) is positioned at a distance of 71 cm to the Hall thruster [see Fig. 6(a)] and grounded like the chamber. The Hall thruster system consisting of anode, cathode (neutralizer), and the energy supply is electrically floating against the grounded vacuum chamber.

Figure 6(b) shows an example of a periodic opening-closing sequence of measurements with the help of the iris aperture. The iris is periodically opened and closed for 5 s, re-



(a) (b)

Figure 6 (**a**) View into the test chamber NExET at the force probe (left) with closed iris aperture and the Hall thruster (right, view from behind on the thruster cooling plate). (**b**) Example measurement with a periodic opening-closing sequence of the iris aperture. For better visibility, only a part of the sequence is shown

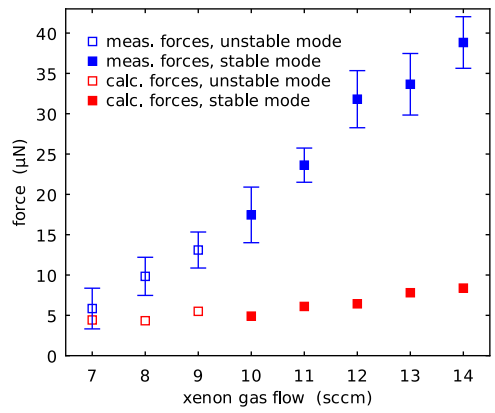


Figure 7 Flow-dependent measurement of forces at a fixed Hall thruster acceleration voltage of 200 V. Note the two operating modes depending on the gas flow. The calculated forces are based on the measured currents onto the probe target

spectively, while the thruster is continuously operating. The chamber pressure during the measurements is approximately 10^{-4} Pa.

Figure 7 shows the measured forces at U = 200 V anode voltage with respect to the cathode (acceleration voltage of the thruster) plotted against the xenon gas flow rate (7 sccm to 14 sccm). The measured forces (blue symbols) show an almost linear increase with increasing gas flow, even though the operating mode changes from "unstable mode" with strong oscillations of the discharge current in the 10–20 kHz range (unfilled symbols) to "stable mode" with small oscillations of the discharge current (filled symbols). The oscillations in both cases correspond to an ionization instability known as "breathing mode" [15].

The electric currents I are simultaneously measured with the measurement target and converted with Eq. (2) into forces (red symbols):

$$F_{\mathrm{Xe}} = \frac{I}{e}\sqrt{2\,e\,U\,m_{\mathrm{Xe}}}\ , \tag{2}$$

where m_{Xe} is the atomic mass of xenon and e is the elementary charge.

It turns out that the forces calculated from the currents are much smaller than the measured forces. The other way around, the measured forces require significantly higher ion currents. We attribute most of the current reduction to the electrons from the neutralizer. Note that the Hall thruster system is electrically floating, so that all ions are compensated by electrons somewhere in the chamber. The probe surface is part of all current collecting surfaces. (Although the currents may not be balanced at a specific surface element in the chamber, the sum for all surfaces must be zero.) Charge-exchange collisions with background gas in the thruster and in the vacuum chamber also reduce the ion current because they convert a part of the ion beam into a neutral beam. Makrinich and Fruchtman describe the effect of charge-exchange collisions in the thruster and its contribution to the thrust [16, 17].

Figure 8 shows energy-dependent measurements at thruster voltages from 125 V to 300 V and a gas flow of 10 sccm. The measured forces (blue symbols) show a general increase with the discharge voltage and an additional jump to higher forces when the opera-

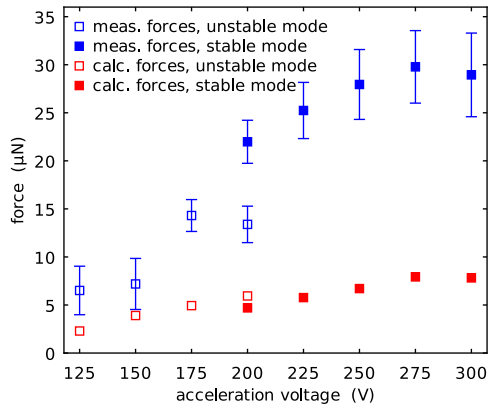


Figure 8 Energy-dependent measurement of forces at a gas flow of 10 sccm through the Hall thruster. Note the two operating modes depending on the acceleration voltage. The calculated forces are based on the measured current onto the probe target

tion mode switches at an acceleration voltage of 200 V from the "unstable mode" (unfilled symbols) to the "stable mode" (filled symbols). The forces calculated from the measured currents (red symbols) are again much smaller than the measured forces.

3.3 FEEP thruster

The measurements with a FEEP (Field Emission Electric Propulsion) thruster were carried out in a test chamber of the Technical University of Dresden, Institute of Aerospace Engineering, in Germany.

FEEP thrusters [8] use molten metals or ionic liquids as propellant and are based on field evaporation. By an electric field between a liquid conductor on a sharp needle or in a capillary and an extractor electrode with opening, single atoms can be evaporated, ionized, and accelerated. The liquid forms a Taylor cone on top of the needle or capillary tip. At the apex of the Taylor cone, the electric field strength reaches the required strength for field evaporation.

In the following experiment, a highly miniaturized FEEP thruster, a so called NanoFEEP thruster with porous emitter, is used [18], see Fig. 9(a). Liquid gallium, which needs to be heated to temperatures above the melting point of approximately 30°C, serves as propellant. The porous tungsten needle transports the propellant by capillary action from the reservoir to its tip, similar to a fountain pen.

The 40 mm target of the force probe was larger than in case of the above shown measurements with the other thrusters with the intention to absorb the entire FEEP thruster plume. The force probe target was positioned at a distance of only 15.5 mm from the thruster, so that the thruster axis pointed perpendicularly to the target center. A neutralizer was not used in this setup. The measurements were carried out with the one-axis interferometric force probe with carbon fiber velvet target (see Sect. 2.3).

Figure 9(b) shows typical raw data obtained by the force probe. The abrupt changes of the equilibrium position can be detected clearly (red lines). For this measurement, the force probe can be regarded as an indirect thrust balance.

Figure 10 shows the target current measured with the force probe and the current lost to the chamber plotted against the net ion current emitted by the FEEP thruster, i.e. the

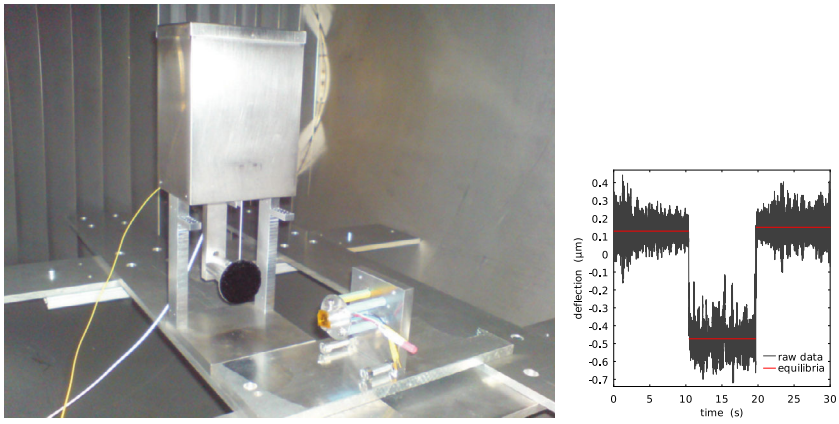


Figure 9 (**a**) View into the test chamber at the force probe (left) with the carbon fiber velvet measurement target (diameter 40 mm) and the FEEP thruster (right). Unlike the measurement configuration, the thruster was rotated by 90 degrees for better visibility. (**b**) Example measurement of the displacement. The thruster is firing for 10 s starting at $t \approx 10$ s

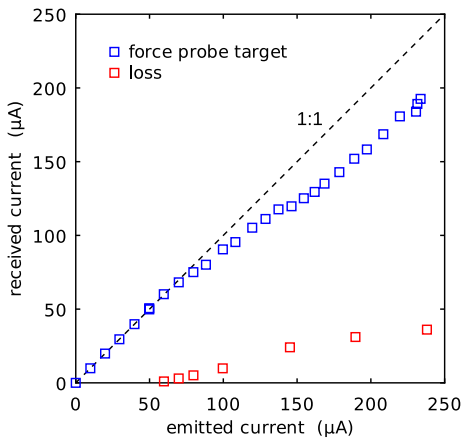


Figure 10 FEEP emitter current, force probe target current, and the current measured at the beam dump and the chamber walls. The latter obviously stem from ions that missed the target

current through the emitter minus the loss current at the FEEP extractor electrode, where already some of the ions get lost. The intention of the setup was that the entire plume be collected by the force probe target. Up to approximately 60 μA, the emitted current equals the current collected by the force probe target, and no current is lost. For higher currents, a part of the emitted ion current did not reach the force probe target. This indicates that a part of the plume misses the target.

Figure 11 shows the measured forces plotted over the net emitted current. The force is roughly proportional to the ion current. There seems to be a negative parallel offset at higher currents that could be explained with the ions that miss the target. For a simple estimate, we corrected the measured forces by the relative proportion that corresponds to

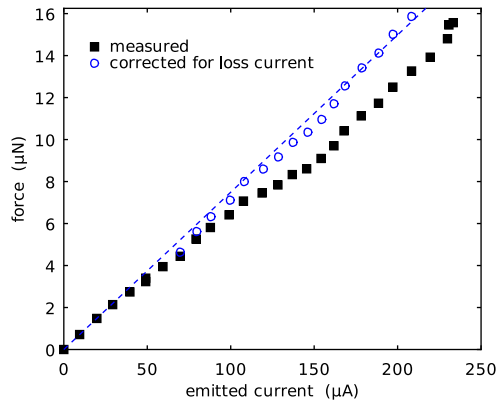


Figure 11 Indirect thrust measurement of a FEEP thruster with the force probe. Note the negative parallel offset at the higher currents due to ions missing the target. The correction for the loss current significantly reduces the offset

the loss current relative to the target current. The blue markers and the linear fit indicate that the correction indeed makes the offset disappear.

It is not easy to estimate the force at the target from the measured currents and respective emitter voltages for several reasons. A gallium stain is found on the measurement target that indicates that the beam does not hit the target exactly in the center. The spot is about 6 mm away from the center of the target, which corresponds to an angular offset of $\delta = 21$ degrees. Moreover, it was known in advance that the plume divergence is a function of the emitted current [19]. The divergence half angle increases with the current up to angles of 50 degrees. The oblique thrust vector and the beam divergence have a reducing effect on the measured force. An estimate requires a careful characterization of the plume or additional assumptions and are beyond the scope of this article, but such a calculation can be found in Ref. [19].

4 Conclusion

In this contribution, various electric propulsion systems were tested with customized force measuring probes. The probes measure by an interferometric technique the forces generated at the measurement target by the impacting energetic plume particles.

The plume of a HEMP thruster was investigated with a two-axes force probe. The probe was moved on a circular path around the thruster. Beam profiles of forces for the two typical operation modes could be measured. For the measurements in the plume of a Hall thruster, a one-axis force probe was equipped with a shutter. The periodically switched iris shutter allowed measurements without switching the thruster continuously on and off, and it was possible to expose the probe to the plume over a long time span. The measurements showed the typical operation modes with different discharge current oscillation levels. Both in case of the HEMP and the Hall thruster, the measured forces were higher than the forces derived from the current measurements, which can be attributed to the sensitivity of the force probe to neutral beam particles that, in contrast, the electrostatic probes are blind for. In case of a FEEP thruster, a one-axis force probe with enhanced target size was successfully used as an indirect thrust balance.

The force probe proved to be a suitable instrument for development and testing of electric propulsion systems.

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Abbreviations
DLR, German Aerospace Center; HEMP, High Efficiency Multistage Plasma; FEEP, Field Emission Electric Propulsion; NExET, New Experiment on Electric Thrusters; ICARE, Institut de Combustion, Aérothermique, Réactivité et Environnement; Isp, specific impulse; TRIM, Transport and Range of Ions in Matter.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
AS wrote the manuscript, AS and TT designed the force probes, performed the probe measurements, and evaluated the data, DB operated the test facility with the FEEP thruster, FGH operated the test facility with the HEMP thruster, LG operated the test facility with the Hall thruster, TT planned the test campaigns, HK, SM, and MT provided oversight. All authors read and approved the manuscript.

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References
1. Brown DL, Walker MLR, Szabo J, Huang W, Foster JE. Recomended practice for use of Faraday probes in electric propulsion testing. J Propuls Power. 2017;33:582–613.
2. Trottenberg T, Spethmann A, Schneider V, Stahl M, Giesenhagen M, Kersten H. Non-electrostatic diagnostics for ion beams. Contrib Plasma Phys. 2012;52:584–92.
3. Spethmann A, Trottenberg T, Kersten H. Instrument for spatially resolved simultaneous measurements of forces and currents in particle beams. Rev Sci Instrum. 2015;86:015107.
4. Polk JE, Pancotti A, Haag T, King S, Walker M, Blakely J, Ziemer J. Recommended practice in thrust measurements. In: 33rd international electric propulsion conference. Washington D.C., USA. 2013. Proceedings paper: IEPC-2013-440.
5. Trottenberg T, Spethmann A, Kersten H. An interferometric force probe for beam diagnostics and the study of sputtering. EPJ Tech Instrum. 2018;5:3.
6. Kornfeld G, Koch N, Harmann H-P. Physics and evolution of HEMP-thrusters. In: 30th international electric propulsion conference. Florence, Italy. 2007. Proceedings paper: IEPC-2007-108.
7. Goebel DM, Katz I. Fundamentals of electric propulsion: ion and Hall thrusters. JPL space science and technology series. Jet Propulsion Laboratory, California Institute of Technology; 2008.
8. Tajmar M, Genovese A, Steiger W. Indium field emission electric propulsion microthruster experimental characterization. J Propuls Power. 2004;20(2):211–8.
9. Spethmann A, Trottenberg T, Kersten H. Measurement and simulation of forces generated when a surface is sputtered. Phys Plasmas. 2017;24:093501.
10. Trottenberg T, Spethmann A, Rutscher J, Kersten H. Non-electrostatic diagnostics for ion beams and sputter effects. Plasma Phys Control Fusion. 2012;54:124005.
11. Hey FG. Micro Newton thruster development, direct thrust measurements and thruster downscaling. Wiesbaden: Springer; 2018.
12. Mazouffre S, Bourgeois G, Dannenmayer K, Lejeune A. Ionization and acceleration processes in a small, variable channel width, permanentmagnet Hall thruster. J Phys D, Appl Phys. 2012;45:185203.
13. Lejeune A, Bourgeois G, Mazouffre S. Kr II and Xe II axial velocity distribution functions in a cross-field ion source. Phys Plasmas. 2012;19:073501.
14. Grimaud L, Mazouffre S. Ion behavior in low-power magnetically shielded and unshielded Hall thrusters. Plasma Sources Sci Technol. 2017;26:055020.
15. Giannetti V, Saravia MM, Andreussi T. Measurement of the breathing mode oscillations in Hall thruster plasmas with a fast-diving triple Langmuir probe. Phys Plasmas. 2020;27:123502.
16. Makrinich G, Fruchtman A. Enhancement of electric force by ion-neutral collisions. Appl Phys Lett. 2009;95:181504.
17. Makrinich G, Fruchtman A. Experimental study of a radial plasma source. Phys Plasmas. 2009;16:043507.

18. Bock D, Tajmar M. Highly miniaturized FEEP propulsion system (NanoFEEP) for attitude and orbit control of CubeSats. Acta Astronaut. 2018;144:422–8.
19. Bock D, Spethmann A, Trottenberg T, Kersten H, Tajmar M. In-plume thrust measurement of NanoFEEP thruster with a force measuring probe using laser interferometry. In: 35th international electric propulsion conference. Atlanta, Georgia, USA. 2017. Proceedings paper: IEPC-2017-391.

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