Application of Force Measuring Probes for the Investigation of Sputtering and as Diagnostic for HEMP and Hall Thrusters

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The first application is the experimental study of sputtering by means of vectorial measurements of the forces that occur during the sputtering process. The second application demonstrates profile measurements of a thruster plume using the example of a HEMP thruster. While these two investigations are performed with vectorially measuring probes, a simplified version is used for parameter studies (discharge voltage and gas flow variations) on a Hall thruster. For this third application, a beam shutter is applied which allows a performance monitoring over longer periods of operation.

Nomenclature

E, m	= kinetic energy and mass of a beam particle
e	= elementary charge
$d_1, d_2, \vec{d}$	= measured components and vector of the force probe cantilever displacement
$F_1, F_2, \vec{F}$	= measured components and vector of the force acting on the target surface
$F_{\text{normal}}, F_{\text{in-plane}}$	= components of the force in normal and in-plane coordinates
α	= angle of incidence
β	= angle between the force vector $\vec{F}$ and the target normal $\vec{n}$
$\vec{n}$	= target normal (inwards directed)

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I. Introduction

A. Measurement of Forces due to Sputtering of Solid Surfaces

Sputtering leads to erosion of thrusters and modification of spacecraft surfaces. For instance, beam optics can be changed due to sputtering of the thruster grid system. Also sputtered particles may be deposited on solar cell arrays and change their efficiency. Therefore, sputtering data is a valuable contribution for optimizing a spacecraft design regarding lifetime and efficiency. The sputtering effect is commonly quantified by the sputtering yield, i.e. sputtered particles per incident particles. The experimental determination of sputtering yields is done by measurements of mass changes, thickness changes, detection of sputtered particles with spectroscopic techniques and the accumulation of sputtered materials on collectors. Arrangements of a few collectors in the plume of the sputter target enable angle-dependent measurements. However, all these techniques do not allow angle-dependent measurements of energies in the sputter target plumes. Energy resolved mass spectrometry (plasma monitoring) may allow for energy dependent measurements. However, angle-dependent measurements (for the outgoing particles) are very challenging [1,2]. In this investigation, forces acting on small plane sputter targets exposed to an ion beam at different angles of incidence are investigated. The sputter target is part of a turnable force measuring probe [3]. This setup enables to vary the angle of incidence. The force probe measures interferometrically a two-dimensional vector of the forces acting on target. In this contribution, different target materials consisting of copper and carbon fiber velvet are presented [4]. Copper and carbon fiber velvet are used for the measurements in thruster plumes.

B. Force measurements in the Plume of HEMP and Hall Thrusters

In case of measurements in the plume of electric propulsion thrusters, commonly electrostatic probes, e.g. Faraday cups, are used [5]. The measurements with Faraday cups are affected by charge-exchange collisions, because neutral beam particles cannot be detected. The thrust of an electric engine is commonly measured by thrust balances. These measurements are not spatially resolved and therefore are not suitable for thruster plume diagnostics. The force probe enables to perform local measurements that do not discriminate between ionic and neutral plume particles. In this contribution, force probe measurements that are performed in the plumes of HEMP and Hall thrusters are presented. Dc thrusters might require a specific starting procedure involving higher gas fluxes and enhanced voltages. To allow the measurement procedure of the force probe, i.e. a zero measurement (when the thruster plume is off) and a force measurement (when the thruster plume is on), an iris shutter in front of the force probe target was used in our case.

II. Force probe

The two-axis force probe uses a thin circular sputter target (radius = 10 mm) that receives the forces to be measured. The applied method is a measurement of a deformation of a rigid cantilever under the action of the force (see Fig. 1). 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 grounded by a wire that is fed through the ceramic and enables current measurements. Between the ends of the tube, a holder with two small orthogonal mirrors is mounted. Two displacement sensor optics are perpendicularly directed onto the two mirrors, respectively. This construction enables to detect both degrees of freedom of the target displacement. For details of the two-axes interferometric displacement measurement and the calibration method, see Ref. [4].

A damping technique for the oscillations at the natural frequencies of the cantilever is applied that makes use of eddy currents. The cylindrical shield around the damping unit extends to the plane of the target surface in order to protect the back side of the target from impinging particles [Fig. 1(a)]. Another shield protects the cantilever; the optical parts as well as the remaining length of the cantilever up to the fixed end are covered by a hood (not shown in the figure). This version of the force probe was used for the following investigation of the sputter effect and the measurements in the plume of a HEMP thruster.

Figure 1(b) illustrates a force $\vec{F}$ acting at the target and the resulting displacement $\vec{d}$ of the mirrors. The two orthogonal components d_1 and d_2 of the displacement are detected by the two sensors 1 and 2, respectively. The calibration enables a determination of the force components $\vec{F_1}$ and $\vec{F_2}$ from $\vec{d_1}$ and $\vec{d_2}$, respectively. The calibration has been performed with certified milligram weights that were put on the target while the cantilever was temporarily turned horizontally. The calibration constant is $23.41\,\mu\text{N}\,\mu\text{m}^{-1}$. The

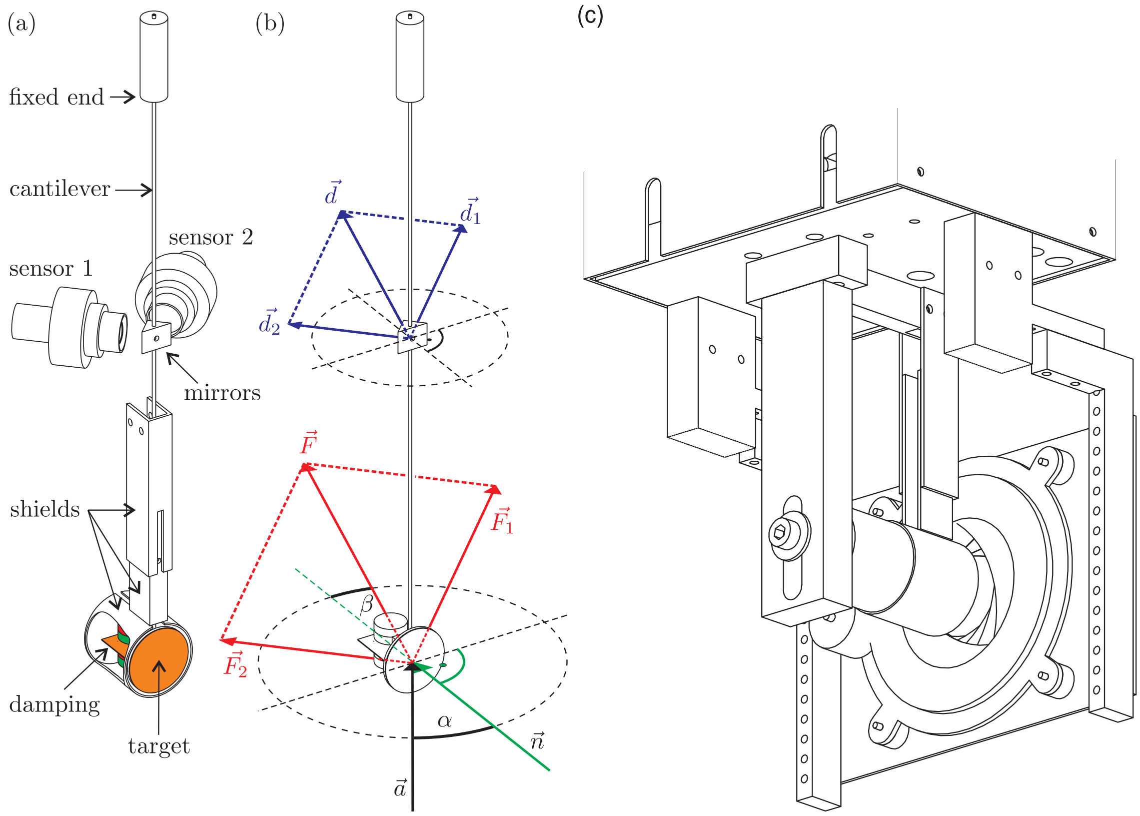

Figure 1. The interferometric force probe. (a) Essential parts of the two-axis version, (b) relevant vectors and angles. (c) One-axis version with iris shutter (view from behind.)

magnitude of the force vector is

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

In Figure 1(c), the force probe is equipped with an iris shutter for hiding the target from and exposing the target to the beam particles. In this case, only one interferometric sensor was used for measuring displacements along the target normal. This version of the force probe was used for the following measurements in the plume of a Hall thruster.

III. Measurements of Sputter effects on a target in an ecr ion source

The investigation of the sputter effect was previously discussed in Ref. [4]. In this paper, the main results are summarized. The knowledge of sputtering is important for the interpretation of the measured forces. The materials copper and carbon fiber velvet are used for the following force probe measurements in thruster plumes. It is found that carbon fiber velvet is a promising material for force probe measurements.

The ion beam is generated by a microwave broad beam ion source [6] (see Fig. 2). The grid system for ion extraction and acceleration consists of three spherically curved graphite grids with a curvature radius of 300 mm and a diameter of 125 mm. An antenna emits approximately 360 W of 2.4 GHz microwaves into the source chamber. The vacuum chamber is basically a stainless steel cylinder with an inner diameter of 65 cm and a length of 160 cm. The argon gas pressure in the target chamber is 2×10^{-2} Pa.

For the measurements, the force probe is mounted on a rotatable platform driven by a step motor (see Fig. 2). The cantilever is aligned with the vertical rotational axis of the platform. The target is positioned at the symmetry axis of the ion beam source at a distance of 880 mm. As indicated in Fig. 1(b), the angle of rotation $\alpha = 0°$ means perpendicular incidence, and in general, α is the angle enclosed by the inwards directed target normal $\vec{n}$ and the ion beam direction $\vec{a}$, i.e. the angle of incidence. The step motor allows steps of $\Delta\alpha = 1.8°$.

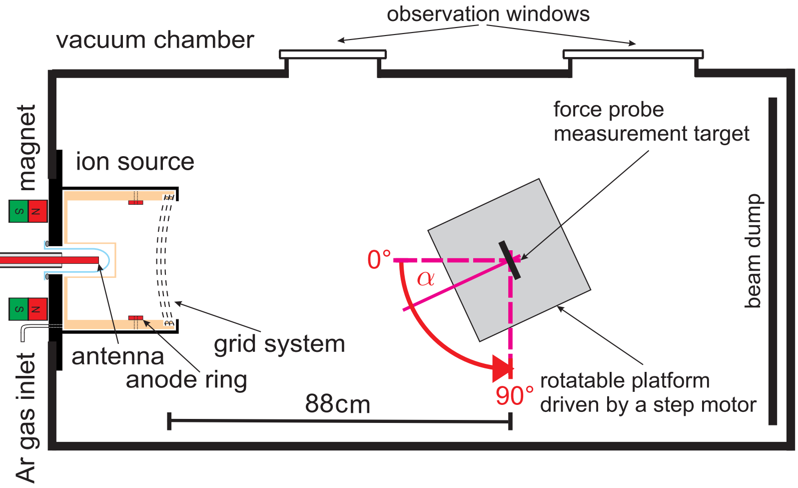

Figure 2. Schematic plan view of the cylindrical vacuum chamber with the broad beam ion source. The rotatable measurement platform is positioned at a distance of 880 mm to the ion source. The force probe target is sketched in the center of the platform. (For better visibility, the parts are not true to scale.)

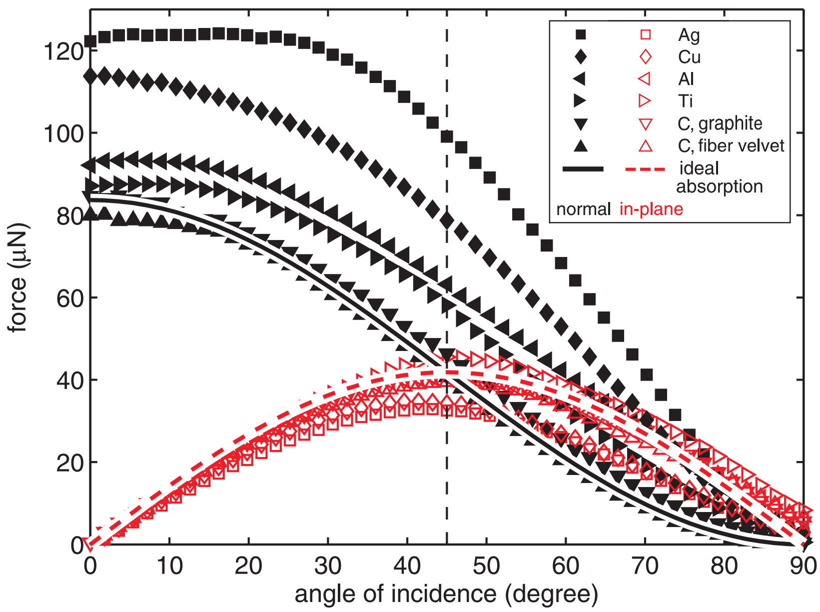

Figure 3. Measurement of the normal force F_{normal} and the in-plane force $F_{\text{in-plane}}$ versus the angle of incidence α for different target materials and an argon beam energy of $E_{\text{in}} = 1220\,\text{eV}$.

In Figure 3 the normal and the in-plane component of the measured magnitude of the force vector $|\vec{F}|$ with its angle β to the target normal , i.e. the projections on the target normal,

$$F_{\text{normal}} = |\vec{F}| \cos\beta \tag{2}$$

and on its plane

$$F_{\text{in-plane}} = |\vec{F}| \sin\beta \ , \tag{3}$$

are plotted over the angle of incidence for different target materials. The black solid curve and the red dashed curve represent the ideal absorption of the beam particles in normal and in-plane direction, respectively. The deviations of the measured forces from the ideal absorption are attributable to sputtering, for which reason the contribution of sputtered target atoms and reflected beam particles can be neglected in the case of carbon fiber velvet[2]. As one result of Fig. 3, carbon fiber velvet is the best sputter resistent material of all investigated materials for force meter applications in test chambers for electric space propulsion. In the beginning of the development of the force probe we used copper as target material. This is the reason why copper was used for measurements in the plume of a HEMP thruster (see Sec. IV) and the carbon fiber velvet for the more recent measurements in the plume of a Hall thruster (see Sec. V). Today, we use only carbon fiber velvet for thruster plume diagnostics.

IV. Profile force measurements in the plume of a HEMP thruster

The measurements in the plume of a HEMP thruster were performed in a test facility [7,8] of Airbus in Friedrichshafen (Germany). In the test chamber (see Fig. 4) the HEMP thruster was mounted on a thrust balance (see left). A swivel arm (see right) was equipped with the two-axis force probe, Faraday cups and a retarding-field analyzer.

Figure 4. View into the test chamber: the swivel arm (on the right) equipped with the force probe, Faraday cups and a retarding-field analyzer in front of the HEMP thruster (on the left).

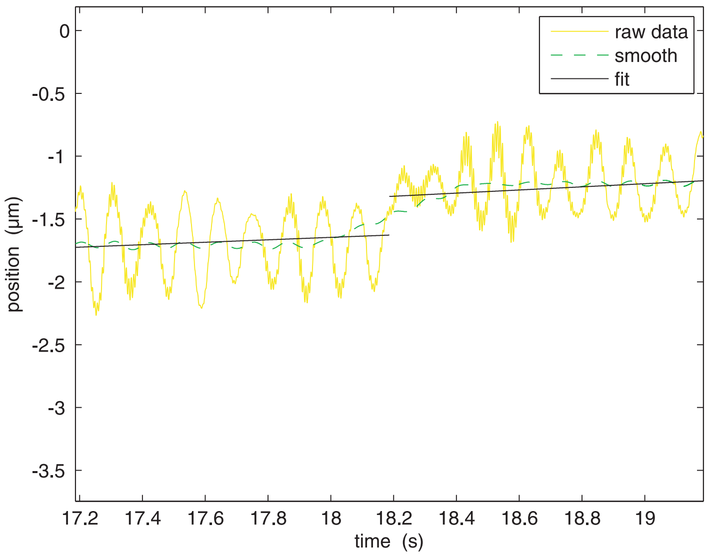

Figure 5. Single force measurement.

The procedure of a single force measurement consists of an initial reference measurement when the HEMP thruster is off and a following measurement in the plume (see Fig. 5). The jump between the two fitted polynomial functions of first degree is due to this procedure. With the calibration of the force probe, the jump can be translated to the force acting on the force probe target.

By turning the swivel arm circularly around the thruster forces for different position angles could be determined. This scan is shown in Fig. 6 for the high Isp mode (700 V, 145 mA, 2.5 sccm, xenon) and in Fig. 7 for the low Isp mode (350 V, 245 mA, 4 sccm, xenon) at a gas pressure in the chamber of 3...6 $\times 10^{-3}$ Pa.

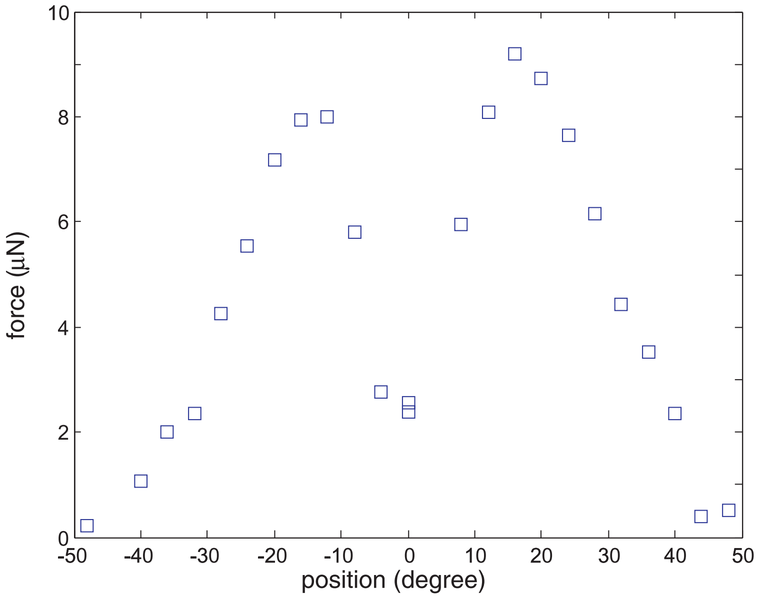

Figure 6. Force scan in the plume at high Isp mode (700 V, 145 mA, 2.5 sccm, xenon).

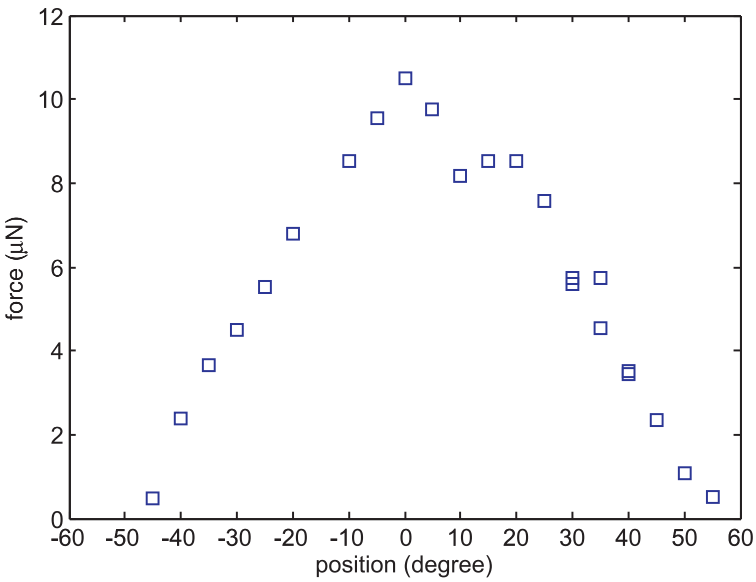

Figure 7. Force scan in the plume at low Isp mode (350 V, 245 mA, 4 sccm, xenon).

The thrust can be estimated with the beam axis components of the measured forces. These components are integrated over the hemisphere in front of the thruster where the measured forces are assumed to represent the force density on spherical zones. We calculated a total force of 3.1 mN for the high Isp mode and 3.7 mN for the low Isp mode. From this force value, the thrust can be calculated when the enhancement due to sputtering is known. The enhancement factor can be calculated with the help of the sputter code SRIM [9] as we did in [4]. The measured forces are enhanced by the factors 1.0595 for 700 eV Xe ions, and 1.0356 for

350 eV Xe ions impinging at a Cu target. The thrusts are therefore 2.9 mN and 3.6 mN and in accordance with those measured with the thrust balance of the test facility [7,8].

V. Long-term force measurements in the plume of a Hall thruster

The measurements in the plume of a Hall thruster [10] (ISCT200-MS) were performed in a test bench (NExET) of the Institut de Combustion Aérothermique Réactivité et Environnement in Orléans (France).

A. NExET test bench

All experiments related to the testing of the force probe have been performed in the cryogenically-pumped NExET (New Experiments on Electric Thrusters) vacuum chamber. NExET is based on a 1.8 m in length and 0.8 m in diameter stainless steel tank. Primary pumping is ensured by a dry pump that evacuates 400 m^3/h. A 350 l/s turbomolecular pump is capable of further evacuating the chamber down to 10^{-4} Pa (N_2), by absorbing light gases such as N_2, O_2, H_2O and H_2. The cryogenic pump absorbs gases such as Xe and Kr. The pumping speed is around 8,000 l/s when the 0.5 m^2 cold plate is sustained at 35 K. The overall pump stack warrants a background pressure as low as 2×10^{-3} Pa (Xe) during operation of a 200 W input power plasma source. The heavy particle momentum exchange mean free path in the chamber is therefore in the order of the chamber length. The interaction of the plume with residual gas is therefore neglected. A large water-cooled screen covered with graphite tiles is mounted at the back of the chamber. It absorbs a part of the ion beam energy, which reduces the thermal load onto the cryogenic surface. The chamber is equipped with several observation windows, access ports, and vacuum feed-through connectors for power lines, gas lines and diagnostic tools. A large front door enables easy access to the interior of the vessel.

B. ISCT200-MS Hall thruster

ISCT is an acronym for ICARE Small Customizable Thruster. The ISCT200 is a versatile 200 W-class Hall thruster using permanent magnets for generating the magnetic field instead of helical magnetizing coils [10,11]. In this work, a magnetically shielded version of the ISCT200 is used [11,12]. The main characteristics of the ISCT200-MS Hall thruster are the following:

- The annular channel outer diameter is about 50 mm.
- The channel geometry is in the so-called 2S0 configuration, that means the channel widthto- mean diameter ratio is twice the standard one, where this standard ratio is defined as that of the well-known Russian SPT100 thruster. As demonstrated in a preceding study, a broad channel improves the performance level of a Hall thruster in terms of thrust, mass utilization, ion production cost, ion velocity, thermal load, and operation envelope [5].
- The inner and outer channel walls are made of BN-SiO_2 ceramic.
- A set of SmCo permanent magnets combined with a soft iron magnetic circuit generate the magnetic field topology (magnetic shielding type).
- The propellant gas is injected at the back of the dielectric channel using a metal injector placed behind the ceramic through a circular iris shutter.
- The anode is a 5 mm in width and 1 mm in thickness steel ring placed at the back end of the channel in contact with the surface of the outer dielectric wall.
- Heat pipes made of copper conduct the heat towards a large radiator installed at the back of the thruster body.
- During operation, the thruster body is floating.

A heated hollow cathode with a disk-shaped LaB_6 emitter was used to generate the electron current needed for discharge balance and ion beam neutralization. The cathode is located outside the channel. The thruster as an electrical subsystem with anode, cathode, and power supply is floating with respect to the vacuum chamber at laboratory ground potential. High-purity xenon (Xe) was used as the propellant gas for both the thruster discharge and the cathode discharge. The cathode has been operated with a constant Xe mass flow rate of 0.2 mg/s. Typically, about 150 W electrical power is applied to the cathode to sufficiently heat-up the emitting element.

C. Force measurement experiment

The force probe was positioned at a distance of 71 cm to the Hall thruster ISCT200-MS (see Fig. 8). The used design of the force probe with one-dimensional interferometric detection was additionally equipped with an iris shutter in front of the measurement target. The operation of the thruster depends on the xenon gas flow (7 sccm...14 sccm) at a chamber pressure of about 10^{-4} Pa and the thruster voltage (125 V...300 V).

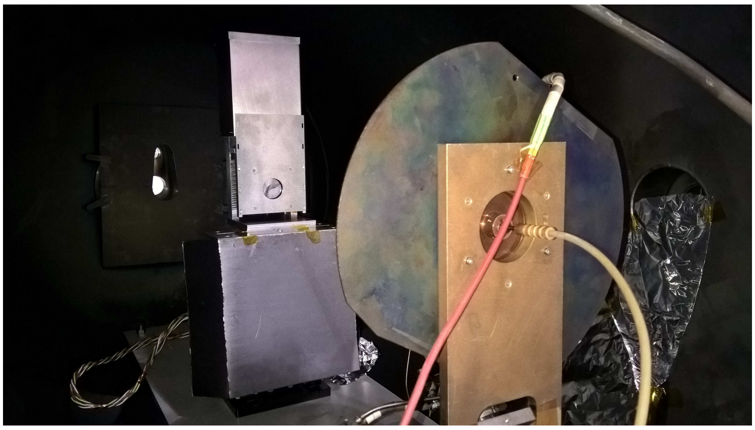

Figure 8. View into the test chamber: the force probe (left) is covered by the closed iris shutter and is positioned in front of the Hall thruster (right). The big circular radiator hides the thruster.

Figure 9 shows a measurement with the help of the continuosly switching iris shutter in front of the force probe target. The iris shutter was used with a periodic opening-closing time. This allows to perform long-term measurements without the nesessity to turn the thruster on and off. This way, the starting and ending time of one single measurement is fully controllable by the shutter electronics.

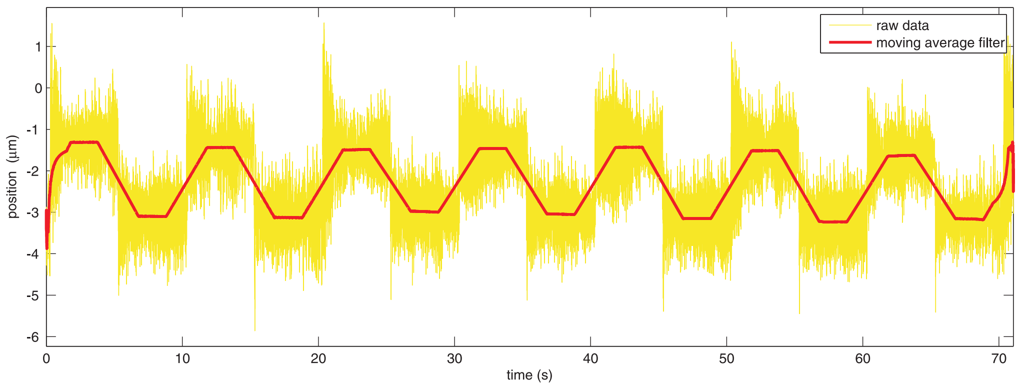

Figure 9. Example of long-term recording by the force probe with an iris shutter (periodic opening-closing time), measured in the plume of a Hall thruster.

Figure 10 shows flow-dependent measurements at 200 V anode potential. The measured forces (blue markers) show a linear increase with a change from high discharge current oscillation level (unfilled markers) to low discharge current oscillation level (filled markers). The error bars are due to the repeated measurements. The simultaneously measured currents on the target are converted into forces by

$$F_{\mathrm{Xe}} = I/e\,\sqrt{2\,e\,U\,m_{\mathrm{Xe}}} \quad . \tag{4}$$

However, these calculated forces are much smaller than the measured ones. The reason could be understood from the from the neutralization of the plume by the hollow cathode neutralizer. Another reason can be searched in an effect described by Makrinich and Fruchtman [13,14]. Ion-neutral collision in the thruster could effectively enhance the residence time of the ions in the accelerating field, and thus cause additional thrust.

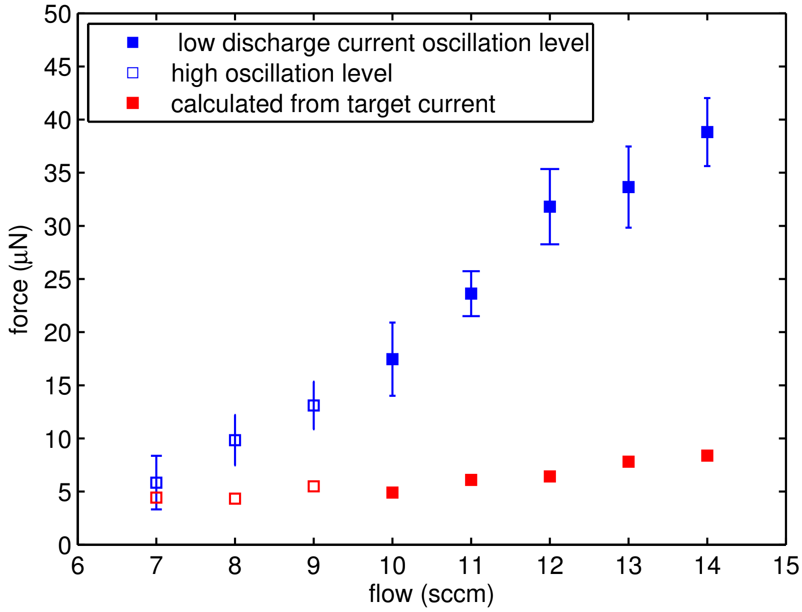

Figure 10. Gas flow-dependent measurements at an axial distance of the force probe to the Hall thruster of 71 cm and an anode potential of 200 V.

Figure 11 shows energy-dependent measurements at 10 sccm gas flow. The measured forces (blue markers) show an increase with a change from high discharge current oscillation level (unfilled markers) to low discharge current oscillation level (filled markers).

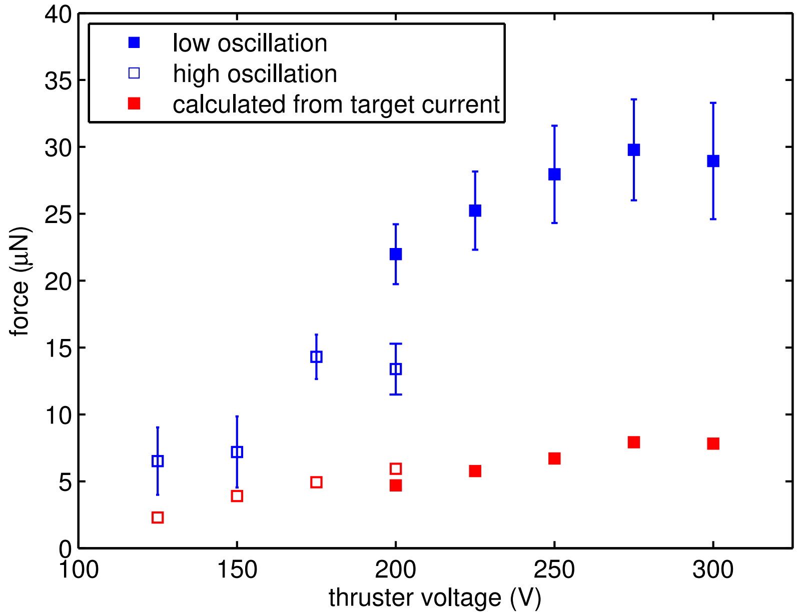

Figure 11. Energy-dependent measurements at an axial distance between force probe and Hall thruster of 71 cm. The gas flow is 10 sccm.

VI. Conclusion

In this contribution, different applications of the interferometric force probe were shown. Accordingly, different designs of the interferometric force probe were used. The material depending measurements showed that carbon fiber velvet is a promising target material for force meter applications in test chambers for electric space propulsion. The scan in the plume of a HEMP thruster yielded the force profile for two different thruster modi. The long-term measurements in the plume of a Hall thruster revealed the forces for two different discharge current oscillation levels. Thus, a force probe version combined with a periodically controllable iris shutter proved to be a suitable instrument for electric populsion diagnostic. In both experiments, the calculated forces based on current measurements are smaller than the real measured ones. This result can be attributted to a neutral (or neutralized) component in the beam, and means that the force probe accounts for both charged and uncharged particles.

Acknowledgments

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