# An Interferometric Force Probe for Thruster Plume Diagnostics

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Thomas Trottenberg*, Alexander Spethmann†, and Holger Kersten‡
*Institute of Experimental and Applied Physics, University of Kiel, 24098 Kiel, Germany*

**Abstract: In this article, we present a novel probe for the measurement of forces exerted by a beam of ions and neutral atoms on a small test surface. The probe is intended for thruster plume diagnostics, in particular for the determination of the spatial distribution of the momentum in an exhaust beam. The instrument makes use of a cantilever whose deflection is measured interferometrically along two axes, which enables a simultaneous measurement of two independent components of the force vector. This contribution focuses on setup and calibration of the probe. An example measurement in an ion beam is presented together with a comparison measurement done with an earlier developed force probe based on a different functional principle.**

## Nomenclature

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| $\vec{F}$ | = force acting on the test surface |
| $F_1, F_2$ | = components of the force measured by the first and the second displacement sensor |
| $\vec{d}$ | = displacement of the mirrors mounted on the cantilever |
| $d_1, d_2$ | = components of the displacement measured by the first and the second sensor |
| $D$ | = calibration constant |
| $m_{\mathrm{w}}$ | = mass of a calibration weight |
| $L$ | = length of a wire piece that serves as a calibration weight |
| $\vec{F_g}$ | = weight, e.g., of a calibration mass |
| $\vec{n}$ | = surface normal to the target plane |
| $\alpha$ | = angle of the force to the surface normal; also rotation angle of the tilted setup |
| $\vartheta$ | = tilt angle in case of the tilted setup |
| $z$ | = distance from the ion beam source |

*Research Associate, Plasma Technology, trottenberg@physik.uni-kiel.de
†PhD student, Plasma Technology, spethmann@physik.uni-kiel.de
‡Professor, Plasma Technology, kersten@physik.uni-kiel.de

## I. Introduction

DIAGNOSTICS of thruster plumes are often based on electric probes like Faraday cups and retarding field analyzers, or spectroscopic techniques like emission spectroscopy, laser absorption spectroscopy and laser-induced fluorescence, and sometimes calorimetric techniques are applied. In this contribution, we present a novel technique for the measurement of forces exerted by a thruster plume on a small test surface.

In comparison with our earlier reported force measurements which used electromagnetically compensated pendula[1,2] or falling microparticles,[3,4] this probe is based on a cantilever beam whose deflection is measured interferometrically along two axes.

Scanning a cross section of the plume yields vectorial information about the momentum distribution in the beam. To draw a comparison with a thrust balance, integration over the entire cross section yields the *thrust vector*, and not only the thrust component defined by the orientation of the thrust balance. On the other hand, the measured "differential thrust" at a specific point in the plume, i.e. the spatially resolved momentum flux density, is valuable information for improvements of the *efficiency* of the thruster.

There are advantages over Faraday cup measurements: Firstly, the measured forces are vectors with two components, typically the axial and radial component in the cylindrical coordinate system of a thruster, while a Faraday cup with commonly high acceptance angle does not distinguish the directions of the plume particles. Secondly, the force measurements are not affected by charge-exchange collisions due to remaining gas in the test chamber or inherent neutral gas in the plume, because the probe does not discriminate between charged and neutral beam particles.[1,2,5]

Another application of force probes is the experimental study of the momentum transfer from energetic ions and atoms to solid targets. For example, air molecules interact with surfaces of space vehicles, especially of satellites and small objects in low Earth orbits. A force probe with test surfaces of different materials mounted on a satellite could provide a direct measurement of material specific drag data, when the angle of approach of the test surface is varied. From such experimental data, drag coefficients of satellites could be calculated with high accuracy.[6] At higher energies, particle–surface interaction will include sputtering, and the force probe can provide data for the validation and improvement of sputter models.[7,8] The experimental study of sputtering with the here presented force probe is subject of a companion paper in this conference proceedings.[7]

## II. Description of the probe

The force probe uses a thin ceramic tube as a cantilever beam with one fixed end, as shown in Fig. 1. A small circular test surface with a diameter of 20 mm is mounted at the free end of the ceramic tube. When a force acts on the test surface, the cantilever beam is elastically bent, so that each point on the cantilever beam is displaced from its initial position. The displacement of a specific point on the ceramic beam is the quantity to be measured; it is mainly oriented in the plane perpendicular to the cantilever. In order to determine this two-dimensional deflection, two orthogonally oriented interferometric displacement sensors are used, which measure the displacement of two small mirrors attached to the ceramic beam.

The interferometric displacement sensor is a commercial product (attoFPS 3010) from the attocube systems AG, Germany,[9,10] which applies the frequency-modulation continuous wave (FMCW) interferometer method.[11] It uses the path between a plane fiber end and a mirror as resonator cavity, where a focusing lens is placed between fiber and mirror. A few percent of the 1550 nm laser light (150 $\mu$W) are reflected backwards at the plane end of the fiber, when the light leaves the wave guide, and serve as the reference wave, while most of the light leaves the fiber and reaches the mirror. The light reflected by the mirror re-enters the fiber through the same plane end and finally interferes with the reference wave at the detector outside the vacuum chamber at the other end of the wave guide. The detector signals of both sensors are processed in the electronics unit.

In order to overcome the typical drawbacks of a conventional Fabry-Pérot interferometer, i.e. low sensitivity sensing spots at the interference maxima and the ambiguity of the displacement direction, this setup modulates the laser wavelength sinusoidally with a frequency of 12.5 MHz.[11,12] The use of optical fibers and vacuum feedthroughs allows to keep the resonator length short and to have the electronic parts outside the vacuum chamber.

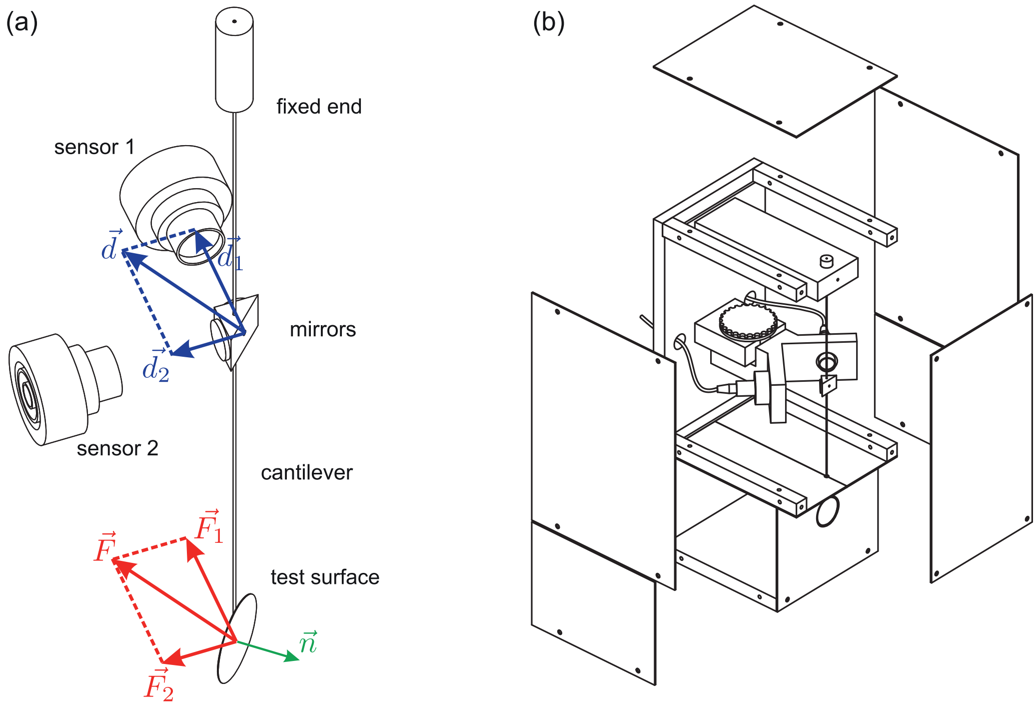


**Figure 1. Force probe. (a) The drawing of the essential parts shows that a force $\vec{F}$ acting the test surface is related to a displacement $\vec{d}$ of the mirrors. The indexed components of the displacement are measured through the two sensor optics and correspond to the two indexed force components. (b) Exploded view of the force probe with its casing and the optical fibers connected to the sensor heads.**

## III. Calibration and linearity test

For the calibration, the instrument is laid on its rear side as shown in Fig. 2(a). The forces used for the calibration are generated by fifteen weights put on the center of the test surface. The weights are $(1.6 \ldots 14.6)$ mm $\pm 0.2$ mm long pieces of 350 $\mu$m uncoated copper wire; the mass per unit length was previously weighed with a precision balance ($10.00 \pm 0.01$ g have a length of $11.71 \pm 0.01$ m). The lengths of the wire pieces were measured with a microscope, where the error of $\pm 0.2$ mm is mainly due to the irregular cutting edges. The masses $m_\mathrm{w} = (1.37 \ldots 12.43)$ mg $\pm 0.17$ mg were put, one at a time, on the test surface.

Figure 2(b) displays the two orthogonal components of the displacements measured by the two sensors and the absolute value of their vectorial sum versus the force exerted by the weights. We obtain a calibration constant of $D = 2.24 \pm 0.13\,\mu$N/$\mu$m.

We performed a test under typical beam conditions that shows the proportionality of the displacement to the exerted force. The probe was placed in our HIBEX (*horizontal ion beam experiment*) chamber, 38 cm in front of the broad beam ion source. The beam was pulse-width modulated at a frequency of 1 kHz with variable duty cycles, in order to fine control the force on a relative scale, while the exact absolute values were of subordinate relevance for this test.

Each force measurement consists of a previous reference measurement when the beam is off and a following main measurement in the beam. Thereafter, the beam is switched off, and the displacement is measured again. The deviation of this last measurement from the initial displacement is a measure for the precision of the individual measurement, and is taken in the following as the error. The error due to the calibration is small in comparison to the latter.

Figure 2(c) shows the absolute value of the measured force plotted versus the duty cycle. The expected proportional behavior is maintained over the full range.

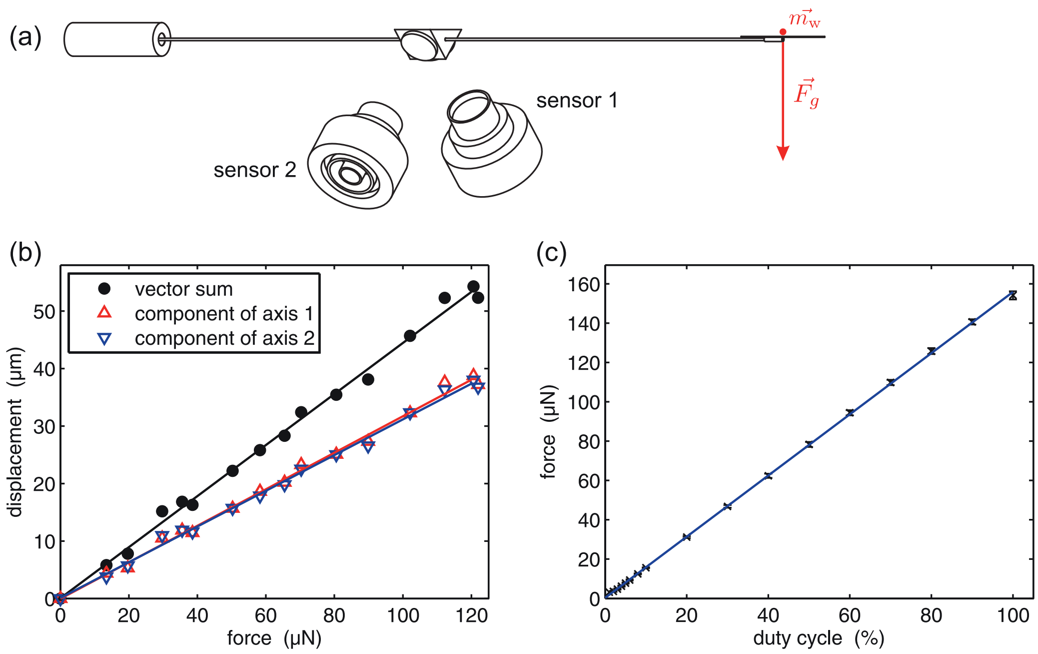


**Figure 2. Calibration. (a) Orientation of the setup for the calibration with weights of mass $m_\mathrm{w}$. (b) Measurement of the displacements caused by the calibration weights. (c) Linearity test by means of a pulse-width modulated ion beam.**

## IV. Demonstration of a vectorial force measurement

In this section, we describe a demonstration of a vectorial measurement of a test force. For this purpose, the (undeflected) cantilever axis is tilted by an angle of $\vartheta = 0.72°$ to the vertical [see Fig. 3(a)], so that the fraction $\tan\vartheta = 1.25\%$ of the weight of the target plate itself (and a corresponding effective part of the weight of the ceramic) simulate the force to be measured. For a variation of the direction of this force, the instrument is rotated about the cantilever axis, causing a deflection in different directions from this axis [see Fig. 3(b)].

The two components $F_1(\alpha)$ and $F_2(\alpha)$ of the force are shown for the rotation angles $\alpha = (0° \ldots 360°)$ in Fig. 3(c); they alter like a sine–cosine pair. Correspondingly, in the force plane spanned by the axes, the force vector $\vec{F} = (F_1, F_2)$ plotted in Fig. 3(d) describes a circle with small errors.

## V. Example of use

Finally, we demonstrate an application of the probe for a measurement of an axial beam profile. The probe is mounted on a laterally and axially movable translational stage with the test surface at the beam axis and always directly facing the beam source. For comparison with the earlier developed galvanometric force probe,[2] that probe is mounted beside the interferometric force probe and can be moved to the same position at the beam axis by a lateral movement of the stage. By this means, quasi-simultaneous measurements with both probes are possible. The forces are measured at the distances $z = (38 \ldots 118)$ cm from the ion source in 2.5 cm steps.

Figure 4 shows the force profiles along the beam axis measured with both force probes. The errors of the interferometric force probe are significantly smaller than the errors of the galvanometric probe, but both are in good agreement.

## VI. Conclusion

This paper presented an instrument for the measurement of forces exerted on a small test surface by a particle beam. The functional principle is based on a cantilever with one fixed end and the test surface

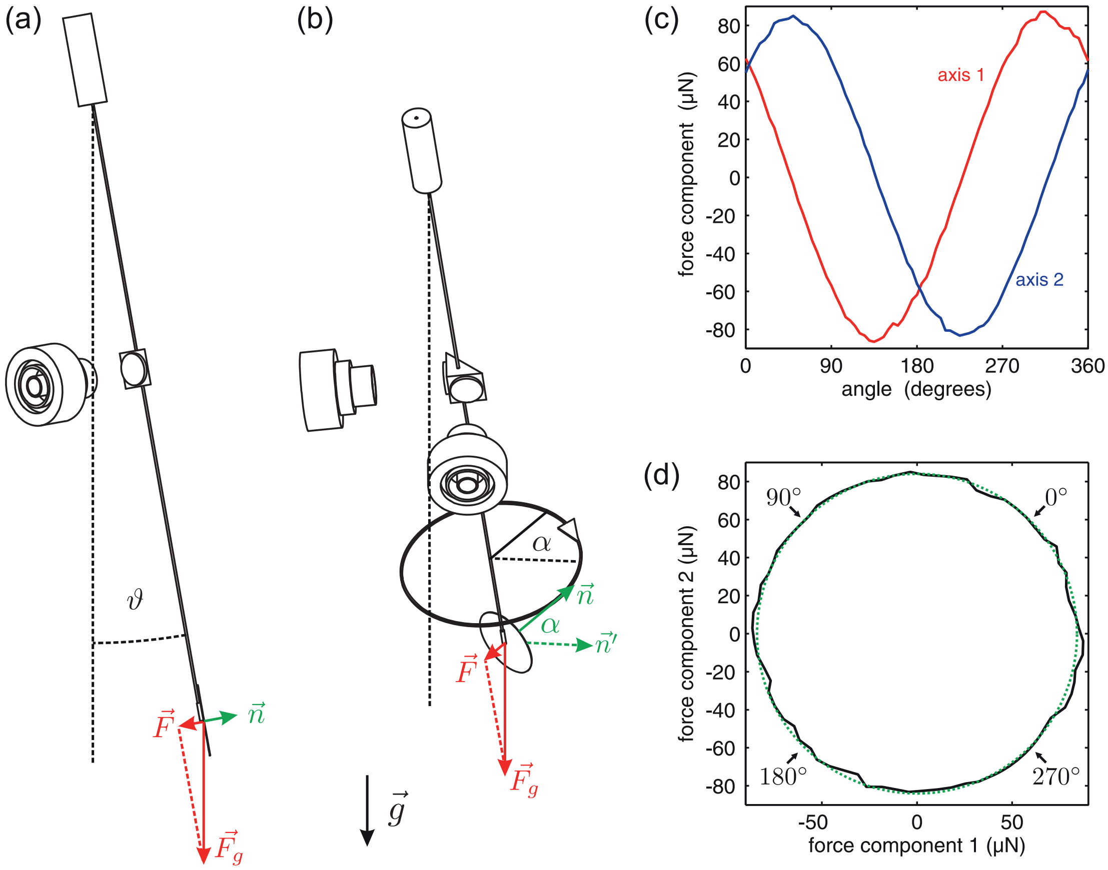


**Figure 3. Demonstration of a vectorial force measurement. (a) Due to the tilt angle $\vartheta$, a small fraction of the weight $\vec{F}_g$ acts as an effective force $\vec{F}$. (b) Rotation of the probe about the cantilever axis by an angle $\alpha$ makes the force vector $\vec{F}$ oblique to the test surface's normal $\vec{n}'$. (c) The two force components vary as the probe is rotated. (d) Vectorial force in the plane perpendicular to the cantilever axis.**

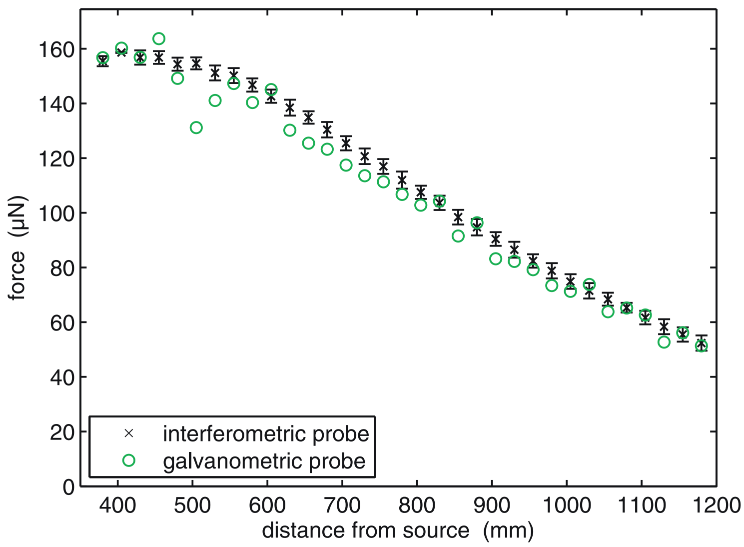


**Figure 4. Measurements of the force exerted by the beam of an ion source at different distances. For comparison, simultaneous measurements with an electromagnetically compensated force probe are shown.**

mounted at the free end, where the deflection of the cantilever is measured interferometrically. Between the free and the fixed ends, two mirrors are attached which reflect the laser light from two interferometer optics. By means of this arrangement, the displacement of the test surface can be recorded in two dimensions, i.e. in the plane perpendicular to the cantilever beam.

Typical deflections are in the order of magnitude of one micrometer per micronewton, and it has been shown that the force probe is able to measure forces down to the order of magnitude of micronewtons. The Fabry-Pérot type interferometer setup uses fiber optics, one for each of the two axes, which allow that only the small resonator parts have to be integrated in the probe, while the laser and the value acquisition electronics are operated outside the vacuum chamber.

The calibration was performed by putting small weights directly on the test surface. For this purpose, the cantilever and the test surface were oriented horizontally, so that the weight acted in direction of the surface normal. The proportionality between displacement and force was demonstrated with a pulse-width modulated ion beam.

An example of use was presented that measured the force in an ion beam at different distances from the ion source. The obtained profile was compared with a profile that was simultaneously measured with a formerly developed, differently working galvanometric force probe. Lateral shifting of the platform allowed to measure with both diagnostics alternately at the same positions, and good agreement was found.

We plan to use the here for the first time presented interferometric force probe for different applications, ranging from thruster plume diagnostics as presented in this proceedings article, the experimental study of sputtering, which will also be presented at this conference,[7] to experiments aiming at a better understanding of plasma–wall interactions. Recently, our group reported on an experiment where the force exerted by a low-pressure rf plasma on a limiting test surface was measured.[13] There, a similar test surface was mounted on a pendulum whose deviations were recorded with a camera. Such kind of experiments could be performed more conveniently and with higher accuracy with an interferometric setup similar to the here presented.

## Acknowledgments

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