Plume characterization of NanoFEEP thrusters with a plasma diagnostics facility using carbon-velvet probes

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Abstract: TU Dresden is currently developing a highly miniaturized Field Emission Electric Propulsion system, named NanoFEEP, with the aim to enable attitude and orbit control of small satellites, especially CubeSats. The development of this propulsion system is currently in the qualification phase of two demonstration missions on the CubeSats UWE-4 and SNUSAT-2. To characterize the plume of the NanoFEEP thrusters and thus to analyze the beam divergence and the thrust vector, TU Dresden has developed a plasma diagnostics facility. In order to measure the spatial distribution of the current density of positively charged gallium particles in the plume of a NanoFEEP-Thruster, 10 mm x10 mm carbon fiber velvet probes are moved on a circular trajectory around the thruster while measuring the probe current with a precise ampere meter. By using the carbon-velvet material with it's extremely high sputtering resistance which strongly suppresses the ion-induced and electron-induced secondary electron emission[1], we are able to measure the local ion current directly without the use of bias potentials. We will present the results of two measurement setups. The first setup with only one carbon velvet probe and two reference wire probes should show prove of concept and was used to learn from the results. In the second setup nine vertically arranged carbon velvet probes are used to also investigate the vertical current distributions of the plume. We will present and analyze the results of the two measurement setups.

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I.Introduction

TU Dresden currently develops a highly miniaturized Field Emission Electric Propulsion system, named NanoFEEP [2], with the aim to enable attitude and orbit control of small satellites, especially CubeSats. The development of this propulsion system is currently in the characterization and qualification phase and two demonstration missions of this electric propulsion system are planned so far. In the first planned mission (see Fig.1) four NanoFEEP thrusters, one carbon nano tube (CNT) neutralizer and the dedicated high voltage electronics will be integrated in the UWE (University Würzburg Experiment) CubeSat platform to demonstrate orbit and two axis attitude control of a one unit (1U)- CubeSat with our electric propulsion system[3]. The second planed mission will be on the South Korean 3U-CubeSat SNUSAT-2, which will use our NanoFEEP propulsion system for deorbiting purposes.

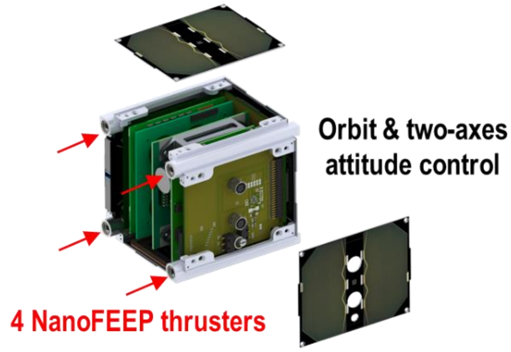

Figure 1. NanoFEEP propulsion system for attitude and orbit control of a 1U CubeSat, using the example of the UWE-4 CubeSat platform. [3]

To characterize the plume of the NanoFEEP thrusters and thus to analyze the beam divergence and the thrust vector, TU Dresden has developed a novel plasma diagnostics facility. In the following, we will introduce the NanoFEEP propulsion system and the plasma diagnostic facility. Moreover, we will present the results of two different test setups. In the first setup, we will compare the results of two different ion current measuring probes (wire probes and a carbon fiber velvet probe). Subsequently, the results of the second test setup with nine vertically aligned carbon fiber velvet probes will be presented and discussed.

II.NanoFEEP Propulsion System

One unit of our NanoFEEP propulsion system consists of two of the actual NanoFEEP thrusters, one field emission neutralizer (silicon chip design) and one dedicated high voltage electronics board in CubeSat dimensions.

A. NanoFEEP Thruster

Our NanoFEEP thrusters are based on the concept of field emission electric propulsion (FEEP) thrusters and are designed with every aspect to be used in a propulsion system capable of being operated on CubeSats. Propulsion systems for CubeSats have to face the strong restraints in volume, mass, and power available on a CubeSat. Our approach to realize that is the very small, light-weight and highly efficient NanoFEEP thruster, as depicted in Fig. 2.

Figure 2. Highly miniaturized NanoFEEP thruster, dimensions: diameter 13 mm, length 21 mm

Our thruster uses the metal gallium with its very low melting temperature of approx. 30° C as propellant. Combined with a thermally optimized design, this keeps down the heating power demand for liquefying the solid stored metal propellant during operation. Depending on the satellites structure temperature, only 50 to 90 mW of heating power is needed to keep the thruster's operating temperature (for an assumed structure temperature between -10° C and +20° C)[4]. Due to the use of capillary action for propellant feeding, no valves or any active feeding device are necessary to provide the propellant flow towards the needle tip. The simple thruster concept results in a thruster design with a diameter of only 13 mm and a length of 21 mm. With the small dimensions of the thrusters, the integration in any CubeSat structure is very easy and the thrusters can even be placed in the CubeSat rails, as shown in Ref. 3.

Due to the high density of our solid stored metal propellant gallium and due to the high specific impulse (up to 6000 s) and high ionization efficiency, the total weight of the NanoFEEP thruster is only 6 g with a propellant mass of only 0.25 g. This propellant mass is sufficient to operate the thruster up to 1800 hours (at low thrusts up to 2-3 µN). The size of the reservoir can be enlarged without any problems, if longer operation times are required. The maximum generated thrust of one thruster is 20 µN (limited by the high voltage electronics). However, to avoid needle erosion, we recommend a maximum thrust for long-term operation of around 8 µN.

B. Neutralizer and High Voltage Electronics Board

Additional to the mentioned thruster also the necessary neutralizer and the electronics need to face the strong restraints of CubeSats w.r.t. volume, mass and power. Therefore, TU Dresden has developed a highly efficient cold electron source based on the field emission effect as a neutralizer and a high voltage electronics board for the control and the supply of two NanoFEEP thrusters and one neutralizer. The neutralizer uses vertical aligned carbon nano tubes (CNTs) deposited on a silicon chip for electrical field enhancement. With our neutralizer design, we are able to generate electron emission currents of up to 250 µA with an emitter voltage between 900 V and 1500 V.

The developed high voltage electronics board (dimensions: 90 mm x 87 mm x 10 mm, weight: 50g) provides two positive high voltage power supplies (+12 kV and 250 µA max.) for operating two thrusters and one negative high voltage power supply (-3kV and 250 µA max.) for operating the neutralizer silicon chip. See Ref. 2 for more details about the neutralizer silicon chip and about the high voltage electronics board.

III. Plasma Diagnostics Facility

A. Design of Plasma Diagnostics Facility

The centerpiece of our plasma diagnostics facility (illustrated in Fig. 4) being reasonable for the precise and continuous pivoting of ion current measurement probes is a Phytron stepper motor. The vacuum-compatible motor has a full step of 1.8° with the option of a 1/256 micro-stepped rotation. The initial positioning (zero position) of the up to 400 mm long cantilever is realized with two photoelectric sensors symmetrically arranged around the zero position to set the maximum rotation angles. All of the described elements are shielded in a housing as shown in Fig. 4 to avoid liquid metal coating during operation of liquid metal ion sources (such as NanoFEEP). Three staggered arranged stainless-steel wire probes with a length of 500mm are mounted orthogonal to the horizontal cantilever and are properly electrically isolated to enable the current measurement of the of the charged particle beam in different distances to their source (without overlapping each other). The plasma source itself can be easily exchanged and is mounted to a flange above the motor shaft. All components are attached to an aluminum rack, which retains the simple design and a high adaptability to various experimental setups as well as different vacuum chambers.

Figure 3. Design of TU Dresden's plasma diagnostics facility (CAD model)

The ion beam measurement is performed while continuous rotation of the cantilever between the maximum angular

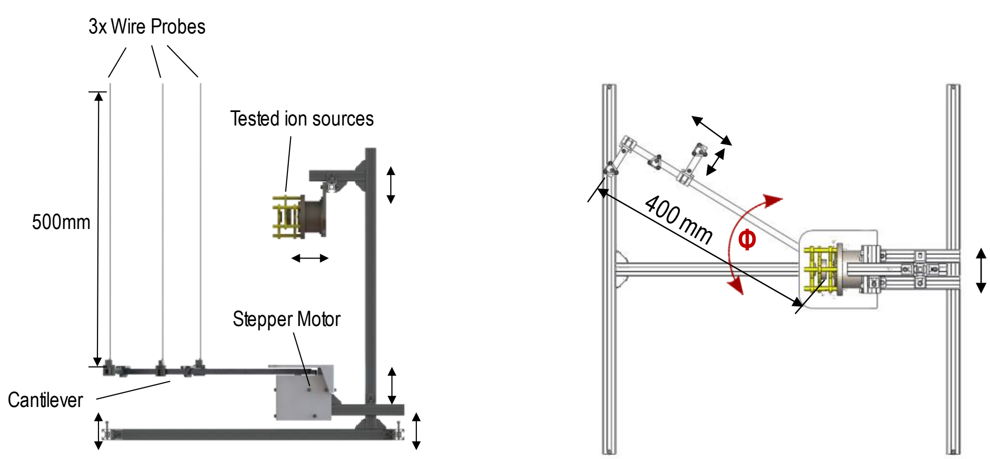

Figure 4. Side view (left) and top view (right) of TU Dresden's plasma diagnostics facility

positions of the stepper motor. The electrical current at the wire probes is measured with a Keithley pico ampere meter. The measured currents together with the corresponding motor position is logged with our LabView data acquisition software. Depending on the configured motor speed, the duration of one cantilever oscillation is approximately 90 s.

B. Setup with a Single Carbon Fiber Velvet Probe

This experiment setup is seen as a first attempt and as a proof-of-concept experiment in order to learn from the results and to build up a more precise setup, described later. The plume measurements of the NanoFEEP thrusters of this first test setup are performed with the plasma diagnostics facility using two of the three wire probes (front and middle position) and one carbon fiber velvet[5] target as shown in Fig 5. The third wire probe has not been used for the measurements, because the ion current profile of the plume would have exceeded the maximum pivot angles of the plasma diagnostics facility. The used carbon fiber velvet probe has a surface area of approx. 10 mm x 10 mm and is mounted on the front wire probe. It is as well as the wire probes electrically connected with a Keithley pico ampere meter to measure the impinged ion current on the probes while they pivot horizontal through the thruster's plume. However, the measurement with the three probes could only be performed subsequently, because only a single channel ampere meter was available during the tests and each probe had to be switched separately to the ampere meter.

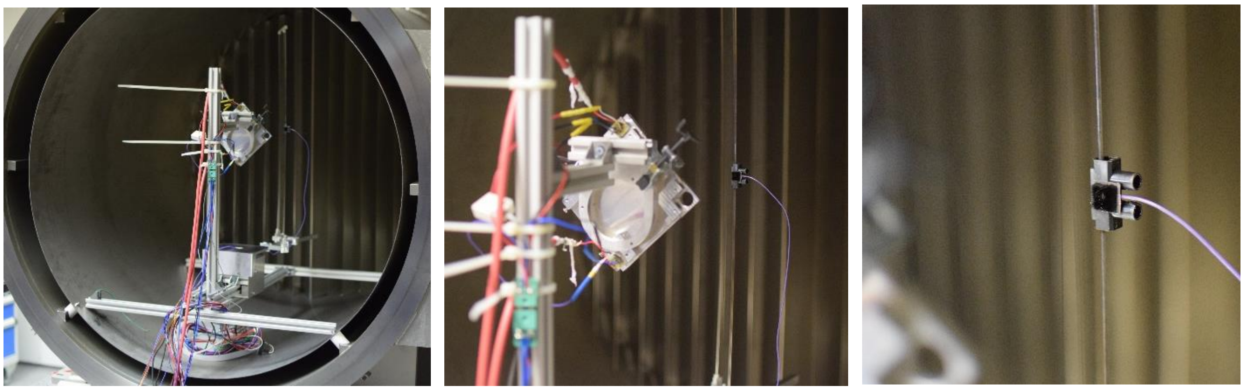

Figure 5 Test setup of the plasma diagnostics facility with a single carbon velvet probe mounted on the front wire probe. Current measurements with two of the three wire probes (front and middle position) are used as reference for the carbon velvet probe measurement.

The carbon fiber velvet material has an extremely high sputtering resistance and strongly suppresses the ion-induced and electron-induced secondary electron emission 1. Therefore, it promises very good results of the ion current measurements without being distorted by secondary electron effects and consequently without the need of a probe bias potential. As opposed to that, the two used wire probes are biased during the measurements with a negative potential of -30 V to suppress the measurement of secondary electrons of the environment (e.g. of the collector).

The measurement results of the two wire probes are used as reference and are compared to the carbon velvet probe measurements in section IV to analyze and discuss the different probes behavior.

C. Modified Setup with Multiple Carbon Velvet Probes

Based on the results and learnings of the first measurement setup, an improved and modified second setup is tested. Major change of this setup is that not only one but nine carbon velvet probes are used and mounted vertically aligned on the middle wire probe as shown in Fig. 6. Again, each carbon velvet probe as well as the used front wire probe (for reference measurement) are separately switched to the Keithley pico ampere meter of the first setup and therefore the measurements are performed again subsequently at constant thruster emission currents.

As we detected charging effects of the anodized aluminum structure in the first setup of the plasma diagnostics facility, electrically conductive aluminum foil is used in the modified setup (see Fig. 6) to cover the front structured parts of the ion beam facility, which eliminate the observed charging effects. Moreover, the measurement results of the first setup show right-shifted plume profiles (see section IV). This was caused by an axial misalignment of the thruster with respect to the rotation axis of the cantilever in the first setup, what is corrected in the modified setup. The results of the first setup also show a slight shift of the falling edges of the beam

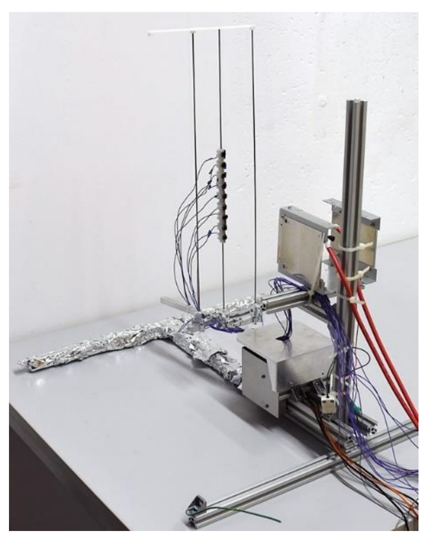

Figure 6. TU Dresden's plasma diagnostics facility, equipped with nine carbon-velvet probes mounted on the middle wire probe. The front wire probe is used for reference measurements.

profiles depending on the rotation direction of the cantilever. This was traced to a time delay in the data acquisition software between the probe current measurement and the measurement of the cantilever position. This is eliminated in the modified setup by performed modifications of the data acquisition software.

IV. Test Results of the NanoFEEP Thruster Plume

In the following we present and discuss the results of the two measurement setups described before. We analyze the thruster's plume with the measured angular probe current distributions for different thruster emission currents and compare the results of the two different probe types (wire probes and carbon velvet fiber probes).

By varying the bias potential of the carbon velvet probe at constant thruster currents, we found in contrast to the measurements with the wire probes that the ion current measurements are unaffected by the probe bias potential. Therefore, all carbon velvet probes measurements are performed without a probe bias potential. In contrast to that, all wire probes are biased with a Voltage of -30 V throughout all presented measurements to suppress falsified measurements of secondary electrons.

The probe positions due to the staggered arrangement of the wire probes are already considered in the presented results by a corresponding angular offset.

A. Results of Single Carbon Velvet Probe Tests

The results of the probe current measurements (see Fig. 7 to Fig. 8) were performed at different constant thruster emission currents between 15 and 100 µA and show an increasing plume divergence half-angle between 25° and 48°.

Comparing the first test setup probe (=target) current angular distributions of the two used wire probes (shown in Fig. 7 and 8) with the results of the single carbon velvet probe measurements (shown in Fig. 9), we can find some common features and differences which are analyzed ad discussed the following.

All measurements of the first setup have in common that the maxima of the probe current distributions are not located at the target zero position (offset of approx. 12°) and that the distributions seem to be increasingly right-shifted and negatively skewed for higher emission currents. The assumed reason for the shifted zero position is that the thruster did not emit on a parallel axis to the cantilever's angular zero position. This may either be caused by a not straight emission of the tested thruster or by an angular misalignment of the thruster. For the increasingly right-shifted and negatively skewed current distributions we assume that this is caused by a later detected relative horizontal position offset between the thruster's emission point (needle) and the motor axis (rotation axis) which result in a not constant over time distance between the probes and thruster and yields to a right-shifted and negatively skewed distribution.

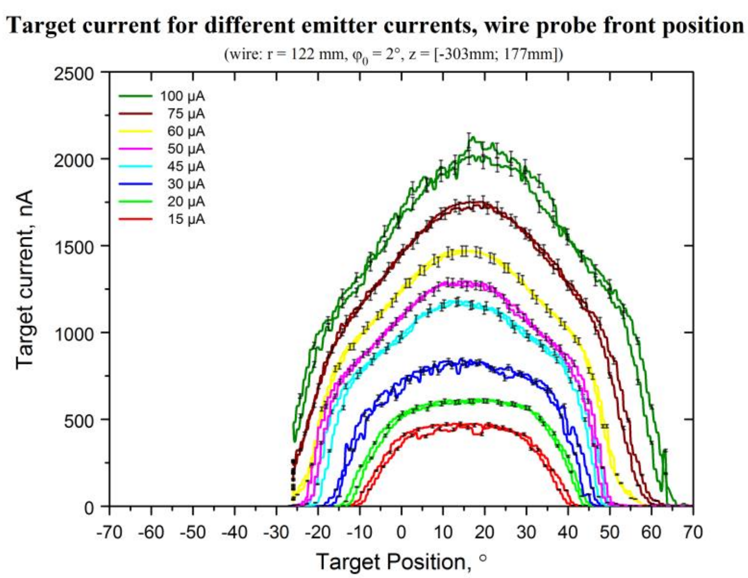

Figure 7. Angular target current distribution of the NanoFEEP thruster plume for different constant emission currents between 15 and 100 µA, measured with wire probe 1 (front position).

The major difference between the results of the wire probes and the carbon velvet probe is the different shape of the current distributions. The wire probe measurements show a parabolic shape with their maximum in the middle of the ion beam. This is due to the fact that the impinged surface of the wire probes grows with the beam divergence and consequently with the proximity to the plume center. But this also makes it not possible to measure directly the ion beam current density because the probe measuring surface varies throughout the measurement.

In contrast to that, the carbon velvet probes have a small and normally constant measuring surface area. Therefore, the slope of the carbon velvet distributions (see Fig. 12) is higher and a plateau develops if the carbon velvet probe fully enters the thruster plume. This plateau indicates a nearly constant ion current density in the plume center.

As the carbon velvet probe was not mounted at the same height as the thruster, the probe did not move through the plume center. This can be seen in Fig. 11 at low emission currents of 15 to 30 µA where the plume divergence is still small and only a part of the carbon velvet probe surface goes through the plume and consequently no plateau and a similar shape as the wire probe distributions can be observed.

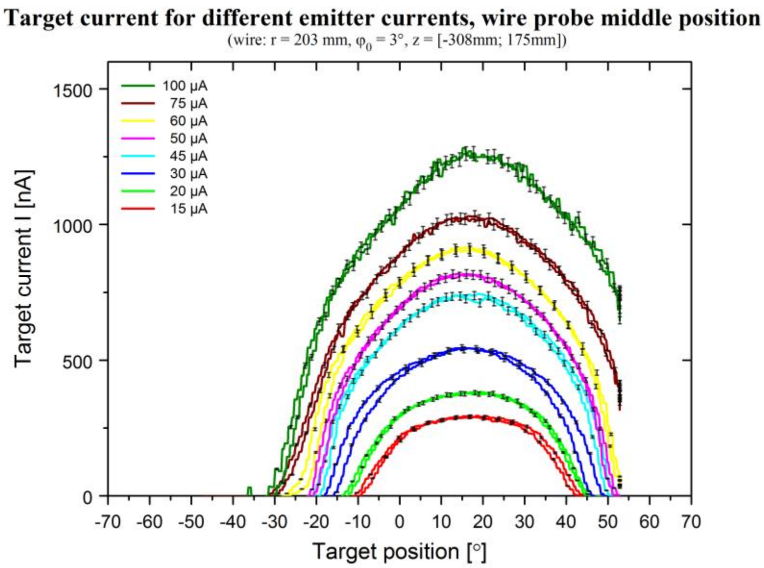

Figure 8. Angular target current distribution of the NanoFEEP thruster plume for different constant emission currents between 15 and 100 µA measured with wire probe 2 (middle position).

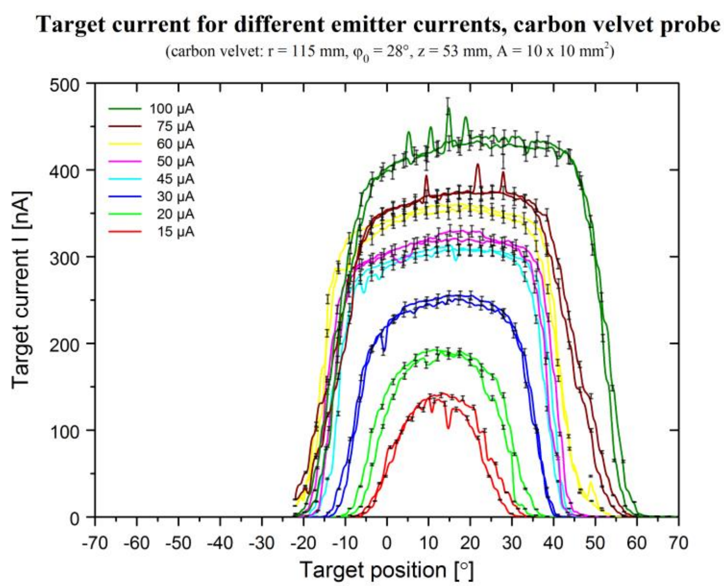

Figure 9. Angular target current distribution of the NanoFEEP thruster plume for different constant emission currents between 15 and 100 µA measured with carbon-velvet probe (front position).

B. Results of Multiple Carbon Velvet Probe Tests

Fig. 10 shows the probe current distributions of the tested NanoFEEP thruster of the second modified test setup with nine carbon velvet probes (A to I) mounted vertically aligned (z position) on the middle wire and the front wire probe (J) as reference. The thruster was operated throughout these measurements at a constant emission current of 30 µA. The results of carbon velvet probe A are not included in Fig. 10, because no current was measured (probe outside of plume).

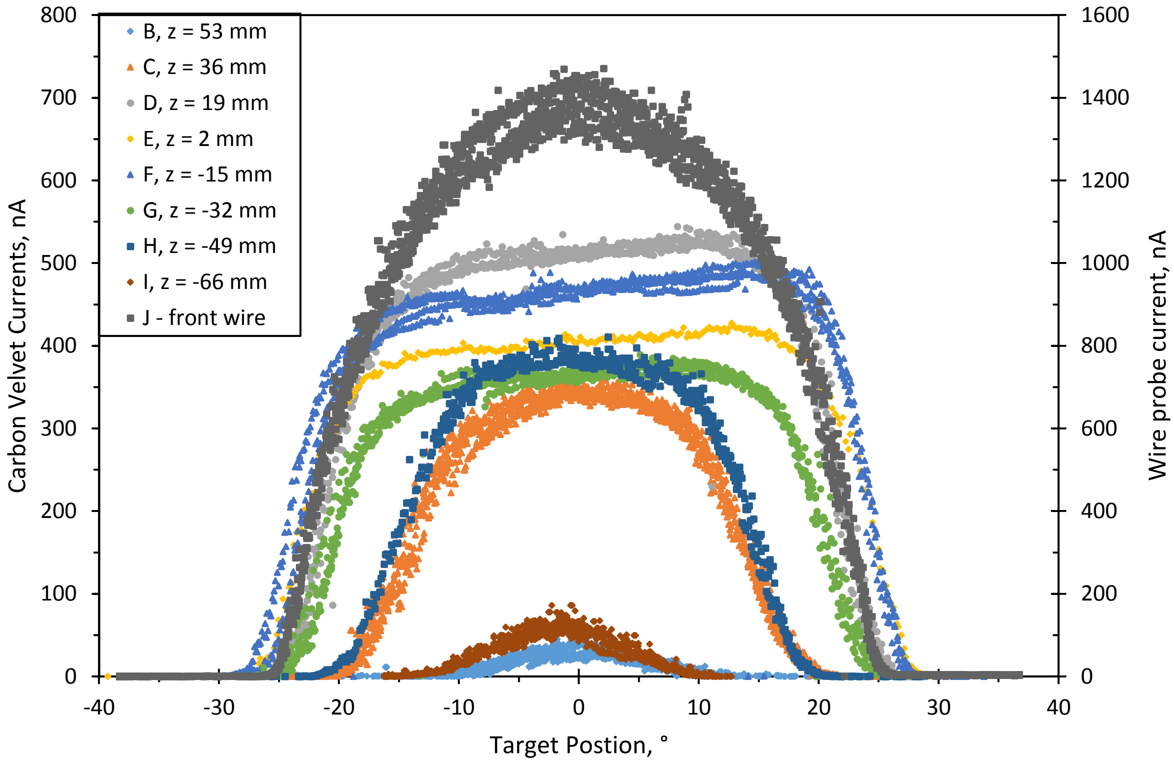

Figure 10. Angular probe current distributions of NanoFEEP thruster plume measured with nine vertically arranged carbon-velvet probes (A to I) and one wire probe as reference. The thruster was operated at a constant emission current of 30 µA throughout all measurements.

V. Outlook

For the future we are planning the following modifications and tests with our plasma diagnostics facility:

- Upgrading of ion beam diagnostic facility with: Multiplexing of Carbon Velvet current measurements, retarding potential analyzer
- Multiple tests of different NanoFEEP thrusters, studies of the influence of different designs on ion beam divergence
- Investigation of the influence of long-term operations on beam profiles and beam divergence
- Ion beam diagnostics of simultaneous operation of multiple NanoFEEP thrusters
- Investigation of other thrusters, e.g. TU Dresden's Hall thruster

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