Three-Dimensional In-FEEP Plasmadiagnostics

M. Tajmar*, K. Marhold†, and S. Kropatschek‡

Space Propulsion
ARC Seibersdorf research, A-2444 Seibersdorf, Austria

Abstract

Indium Field-Emission-Electric-Propulsion (FEEP) thrusters can produce forces in the μN range with ultra precision and very low thrust noises. Recently, this thruster was selected for the advanced phase C/D of ESA's GOCE satellite mission. As part of the qualification phase, extensive beam diagnostics need to be performed to investigate the thruster's main operational characteristics like beam divergence losses and thrust vector stability. For this purpose, a new facility is under construction at ARC Seibersdorf research which shall be able to measure accurate 3D ion beam densities of the In-FEEP thruster. This paper presents the first measurements of 1D profiles and preliminary calculations on the total beam divergence and thrust coefficient factors along the full thrust range.

1.0 Introduction

Indium Field-Emission-Electric-Propulsion (FEEP) is an high-specific impulse electrostatic propulsion concept[1,2] developed at ARC Seibersdorf research (ARCS). The ion source consists either of a needle covered with Indium or a capillary with Indium inside, which is heated above the Indium melting point (156.6 ºC). Then a sufficiently high electric potential is applied between the emitter and an extractor electrode until a field strength of 10^9 V/m is reached at the tip. A so-called Taylor cone is formed as an equilibrium between the surface tension and the electric field strength with a jet protruding due to space charge. Atoms are then ionised at the tip of the jet and accelerated out by the same field that created them. The expelled ions are replenished by the hydrodynamical flow of the liquid metal.

This Indium Liquid-Metal-Ion-Source is used on several satellites to provide potential control of satellites (e.g. CLUSTER-II) or as the core of a mass spectrometer (instrument COSIMA to be used on ROSETTA). Since 1995, this ion source is being developed as a dedicated low-thrust propulsion system for ultraprecise attitude and orbit control. Presently, the In-FEEP thruster is prepared for its first application, being selected for the advanced phase C/D on ESA's GOCE (Gravity Field and Steady-State Ocean Circulation Mission) satellite[3], to be launched in early 2006. Hence, present activities are focused on a successful qualification phase to be carried out along this year. This also includes beam diagnostics to accurately calculate the thruster's performance, extending previous measurements on an old breadboard configuration[4]. The GOCE thrust requirements range from 2-650 μN. In the selected design, twelve individual ion emitters (one being redundant) will form one so-called MTA (Microthruster Assembly), each having a reservoir size of 30 g and providing thrusts between 0.18 and 60 μN.

One thruster element is shown in **Fig. 1** in a breadboard configuration, similar to the one used for ongoing endurance tests[2]. The extractor electrode consists of a ring on ground potential, which can be heated in order to evaporate any Indium contamination to ensure a required thruster lifetime of 14,000 hours continued firing. A plume shield above the extractor limits the ion beam to a maximum half-angle divergence of 60°. This plume shield is biased at –1 kV to repel electrons from the ambient plasma. This is necessary due to GOCE's LEO orbit of only 250 km altitude, which translates in ambient pressures as high as 3×10^{-6} mbar. The electrical connections are shown in **Fig. 2**.

* Staff Member, also Lecturer, Aerospace Engineering Department, Vienna University of Technology, A-1040 Vienna, Austria, Email: martin.tajmar@arcs.ac.at
† Undergraduate Student, Email: klaus.marhold@arcs.ac.at
‡ Undergraduate Student, Email: sebastian.kropatschek@arcs.ac.at

The present paper will describe the set-up of a new beam diagnostics facility and first test results of the GOCE breadboard single-thruster element. This data is used to calculate the main thruster performance parameters.

2.0 Beam Diagnostics Facility

In-FEEP thrusters require a very careful diagnostics facility design because nearly all surfaces get covered with Indium after some time of testing. Therefore, all mechanical parts need to be shielded. Since low currents in the µA range are emitted, the probe needs to move close to the thruster exit for good measurements. Hence, the probe has to be small in order not to disturb the beam too much.

Due to these constraints, we decided to measure the beam's ion density using two 1.6 mm diameter tungsten wire probes that can move in the X- and Y-direction (see **Fig. 3**), similar to a beam diagnostics facility at ESTEC[5]. One wire only can be used to gather fast 1D profiles. If both wires are used, then the wire which is closer to the thruster shields part of the ion beam on the second wire probe. By first measuring the current on the second wire and then moving the shielding wire, one can derive the current density on the shielded area by simply subtracting the shielded wire current from the unshielded wire current (see **Fig. 4**). Both probes are mounted on Teflon isolators, the measurement wires from the isolators are shielded from external disturbances using co-axial wires up to the chamber's flange. In order to repel secondary electrons from the probe itself or the facility, the wire probes are biased at –28 V.

The probes are moved using Phytron stepper motors (VSS-HV 42.200.2.5), which are high-vacuum compatible. The whole probe assembly can be moved in thrust direction on a ground plate using a larger Phytron VSS-HV 52.200.5.0 stepper motor. All stepper motors are controlled using a custom LabView program, a National Instruments PCI-7334 stepper motion controller and Phytron ZSO 42-40 and ZSO 72-70 power stages. The current measurements are done using Keithley 485 Pico Amperemeters, the output is connected again to the LabView program using a National Instruments PCI-6036E data acquisition card and an AI-03 isolation amplifier.

The plasma diagnostics facility is mounted on the collector inside the ARCS LIFET#2 vacuum chamber (see **Fig. 5**). This electrically connects the grounding plate and housing with the collector in order not to loose collector current and to ground the beam diagnostic facility.

2.1 Reconstruction of 2D Beam Density Profiles from 1D Data

In a first step, only one wire probe was used to test and verify the whole set-up and LabView program. However, also the 1D data can be used for a good thruster characterization. Since we use only rotationally symmetric electrodes, also the ion beam must be rotationally symmetric. This is also indicated by the low extractor currents (usually around 1% of the emitter current). Using this symmetry, we can calculate the real beam ion density using a reconstruction algorithm used for example in medical computer tomography.

This algorithm is illustrated in **Fig. 6**. Imagine the rotationally symmetric ion beam is subdivided into radial zones of constant current densities. If the wire probe moves into the beam from the outside, it first receives a current I_0 only from the outermost radial shell. By calculating the area A_0, one can then calculate the current density j_0 of this outer shell. By moving further to position 1, we can then calculate the area on which current density j_0 is contributing to the wire's current I_1. After subtracting the current contribution from shell 0 we can then continue to derive the current density j_1 from shell 1.

$$j_0 = \frac{I_0}{\text{Area}(0,0)}$$
$$j_1 = \frac{I_1 - j_0 \cdot [\text{Area}(0,1) - \text{Area}(0,0)]}{\text{Area}(1,1)}$$
$$j_2 = \frac{I_2 - j_0 \cdot [\text{Area}(0,2) - \text{Area}(0,1)] - j_1 \cdot [\text{Area}(1,2) - \text{Area}(1,1)]}{\text{Area}(2,2)} \quad \ldots \tag{1}$$

Area(x,y) calculates the area of the shell from position x to y.

In order to verify the algorithm and computer program, we assume an In-FEEP thruster firing at a distance of 3 cm in an area of 5026 mm^2 (radius of 40 mm). The ion density is homogeneous, the emission current is 100 µA. Therefore, we expect a constant beam density of 0.02 µA/mm^2. This constant beam density was re-calculated into a wire probe profile (see **Fig. 7**, left). The right side of **Fig. 7** shows the output from the algorithm program. Despite a numerical artefact at the edge, the program accurately calculated the beam density of 0.02 µA/mm^2. Hence, we can use 1D profiles and this algorithm to calculate accurate ion beam density distributions, which can be used to calculate how much thrust is actually produced in the thruster direction (thrust coefficient factor). This allows us to compute a precise thrust from electrical measurements only.

2.2 Beam Profiles

Figs. 8-12 shows the beam profiles from the Y-wire probe at a distance of 30 mm from the thruster's needle tip at beam currents from 10-600 µA. The initial half-angle beam divergence at 10 µA is about 28°. Up to 400 µA, the ion beam is well within the 60° half-angle limit from the plume shield. Then the geometrical limit influences significantly the beam shape. At currents below 400 µA, the beam shape resembles a Gaussian bell-shape, after 400 µA the geometrical limits reshapes the beam more closely to a cosine distribution. Even at maximum current, the ion beam does not go beyond 60° (the slightly larger value in the plots is due to the diameter of the probe).

The total ion beam divergence for each beam current is shown in **Fig. 13** (left). The steep increase in beam divergence at low currents shows that beam divergence is initially dominated by the ion beam's space charge. Starting at 100 µA, the geometrical limitation from the plume shield takes over as the dominant factor. This curve is similar to the one derived from old measurements[4].

Due to present limitations in the mechanical set-up and stepper motor speed, one profile lasts about 5 minutes. All profiles were done operating the thruster in current-control mode. Hence, the voltage was able to vary. Those variations can be as large as ± 1 kV at high currents (> 300 µA). Therefore, the profile at higher currents appears not as smooth as the ones recorded for lower currents due to the long time required to finish the profile and the possible voltage variations. In the future, the profile speed shall be optimised to last < 1 minute.

2.3 Thruster Performance

All profiles were evaluated using the 2D re-construction algorithm to calculate the thrust coefficient factor $c(I_E)$ to account for beam divergence losses in the theoretical thrust equation:

$$F = 1.54 \times 10^{-3} \times (I_E - I_{Extr} - I_{PS}) \times \sqrt{U_E} \times c(I_E), \tag{2}$$

where I_E is the emitter current, I_{Extr} the extractor current, I_{PS} the plume shield current and U_E the emitter potential. The beam current leaving the thruster is the emitter current subtracted by the losses on the extractor and plume shield.

Fig. 13 (right) shows the thrust coefficient factor *c* along the beam current ranging from 0.91 at low currents to 0.76 at 600 µA. The values are slightly higher than the ones derived from an earlier configuration[4], because the plume shield focused the ion beam within the 60° half-angle cone. Moreover, the –1 kV bias potential on the plume shield reflects secondary electrons from the collector inside the chamber. Hence, the emitter current measurement is not influenced by those secondary electrons. It is estimated that those secondary electrons contributed up to a few percent to previous measurements. Direct thrust measurements at JPL indicated a nearly constant thrust coefficient of 0.77 along the thrust range. Accounting for the secondary electrons and the new plume shield configuration, the new measurements seem to be well in line to those direct thrust measurements.

The extractor and plume shield current losses are plotted in **Fig. 14**. This shows that the electrical efficiency of the thruster is always > 95%. Using the current losses and the thrust coefficient value, **Fig. 15** (left) shows the calculated thrust performance and the current-voltage characteristic, ranging from 1-65 µN as required for the GOCE MTA thruster assembly. We can then compute the specific impulse by:

$$I_{sp} = \frac{F}{\dot{m} \cdot g} = 132.36 \times \sqrt{U_E} \times c(I_E) \times \eta \, , \tag{3}$$

where η is the mass efficiency or propellant utilization efficiency. Typical values are described in Tajmar and Genovese (2003)[6] (e.g. at 100 µA a typical mass efficiency is 40%). Using these values **Fig. 15** (right) shows the specific impulse and the power-to-thrust ratio. I_{sp} ranges from 8000 – 1700 s and *P/F* from 48 – 86 W/mN along the emitter current range.

Conclusion

A beam diagnostics facility was design to measure the three-dimensional ion beam density distribution. As a first test, 1D ion beam profiles were measured for an In-FEEP thruster operating between 1-65 µN. A 2D reconstruction algorithm was applied to the profiles to compute the accurate thrust coefficient factors and the thruster's main performance parameters. This is an important step towards the successful qualification of the In-FEEP thruster.

Acknowledgement

This work has been carried out under PATP with MTA-Prequalification Activities Ref. GOCE-AFG-0161/2002.

References

[1]Genovese, A., Steiger, W., and Tajmar, M., "Indium FEEP Microthruster: Experimental Characterization in the 1-100 µN Range", *AIAA Joint Propulsion Conference*, AIAA 2001-3788, 2001

[2]Genovese, A., Tajmar, M., Buldrini, N., and Steiger, W., "Extended Endurance Test of the Indium FEEP Microthruster", *AIAA Joint Propulsion Conference*, AIAA 2002-3688, 2002

[3]Johannessen, J.A., and Aguirre-Martinez, M., "Gravity Field and Steady-State Ocean Circulation Mission", *Reports for Mission Selection*, ESA SP-1233, 1999

[4]Tajmar, M., Steiger, W., and Genovese, A., "Indium FEEP Thruster Beam Diagnostics, Analysis and Simulation", *AIAA Joint Propulsion Conference*, AIAA 2001-3790, 2001

[5]Nicolini, D., Marcuccio, S., and Andrenucci, M., "3-D Plume Characterization of a FEEP Thruster", *AIAA Joint Propulsion Conference*, AIAA 2000-3269, 2000

[6]Tajmar, M., and Genovese, A., "Experimental Validation of a Mass Efficiency Model for an Indium Liquid Metal Ion Source", Applied Physics A, in Press (2003)

Figure 1 In-FEEP with Extractor Heater Configuration and Plume Shield

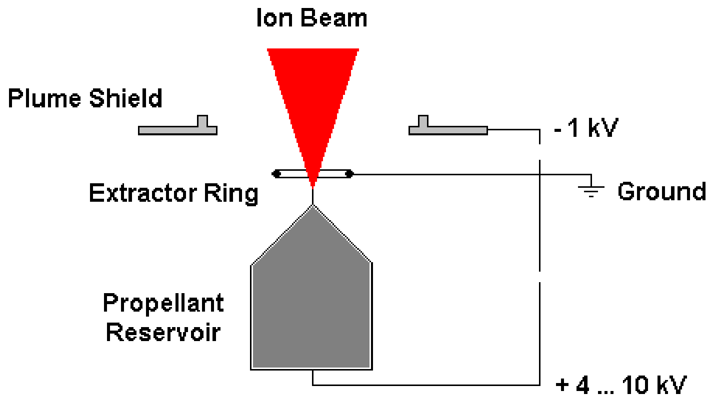


Figure 2 In-FEEP Electrical Connections

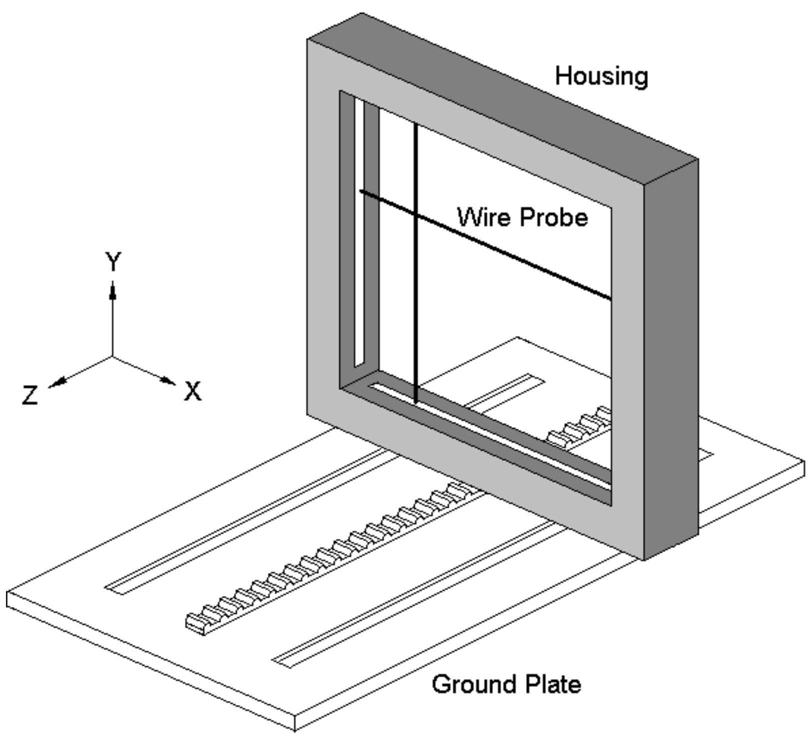


Figure 3 Plasma Diagnostic Schematic

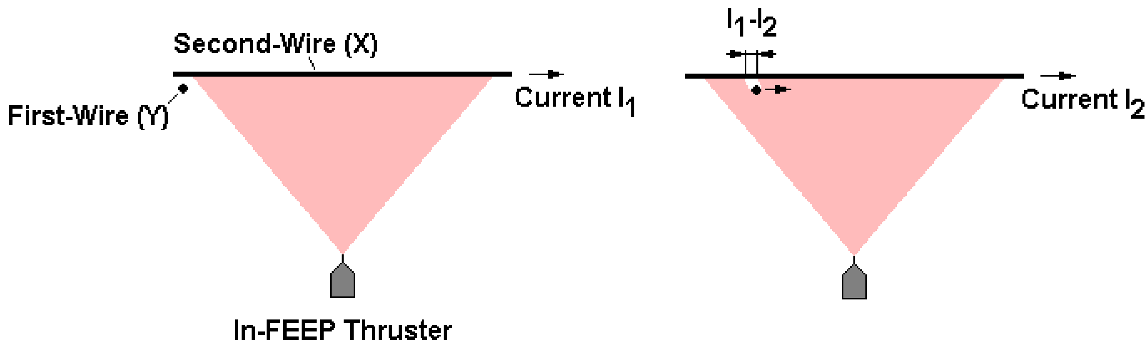


Figure 4 2D Current Density Measurement

Figure 5 Plasma Diagnostic Facility inside Vacuum Chamber

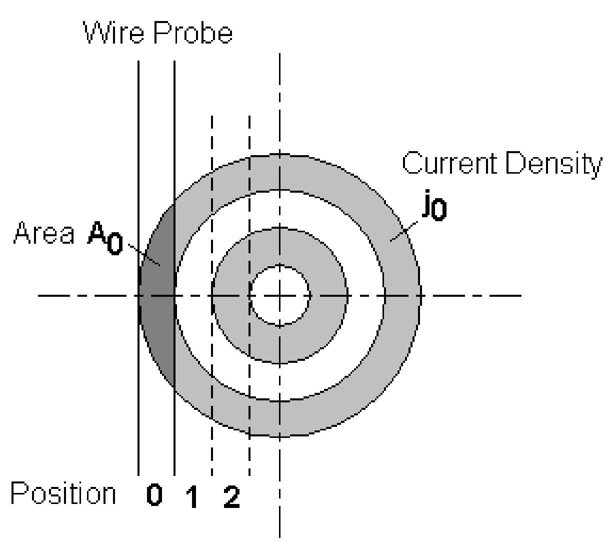


Figure 6 2D Ion Beam Reconstruction

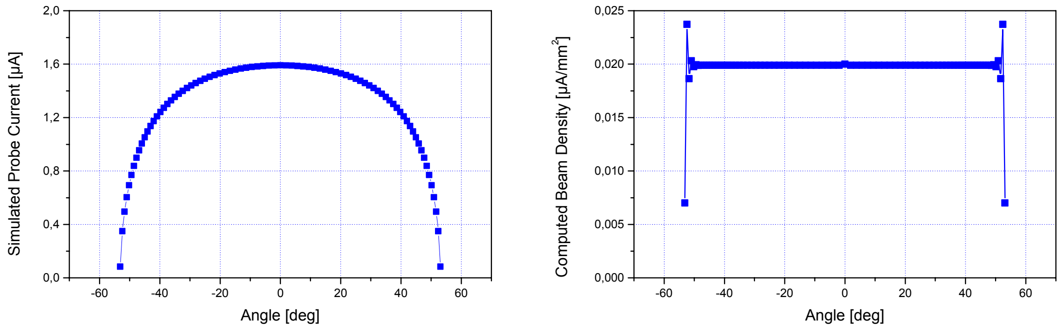


Figure 7 Simulated Probe Current for Constant Beam Current Density and Reconstructed Simulated Beam Density at Z=30 mm

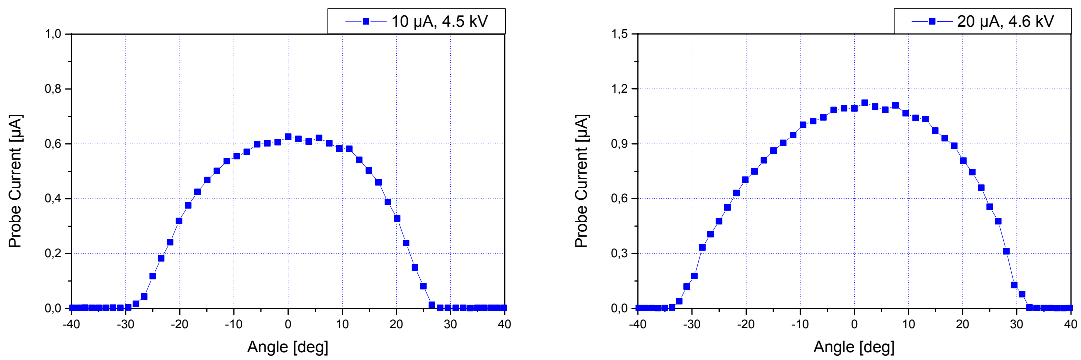


Figure 8 Beam Profile at Beam Current of 10 µA (left) and 20 µA (right), Probe Biased at –28 V, Z=30 mm

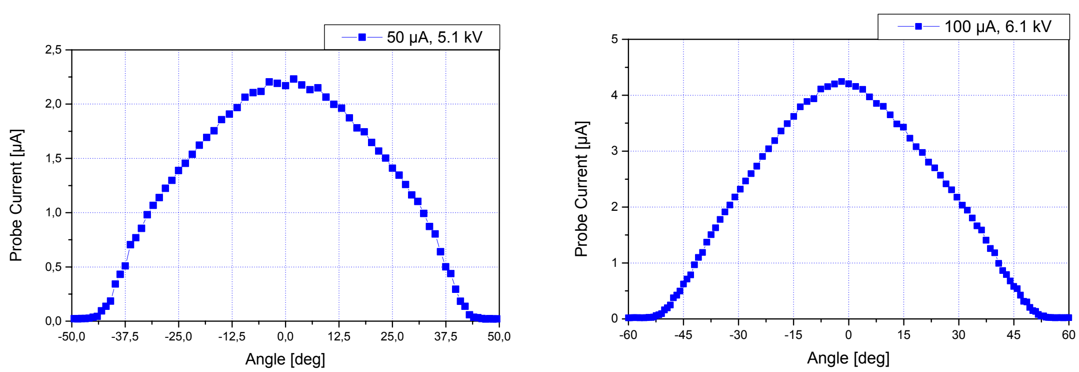
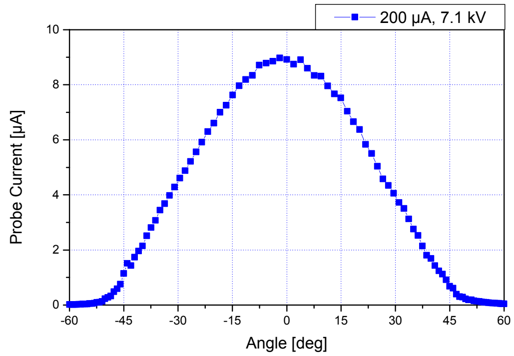


Figure 9 Beam Profile at Beam Current of 50 µA (left) and 100 µA (right), Probe Biased at –28 V, Z=30 mm



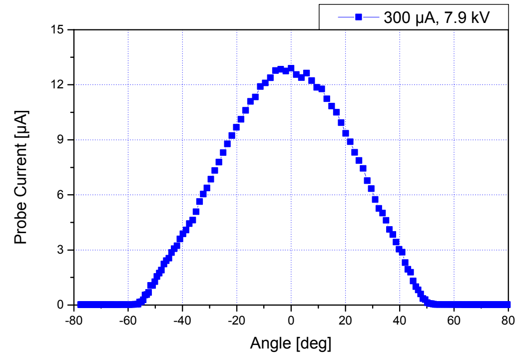
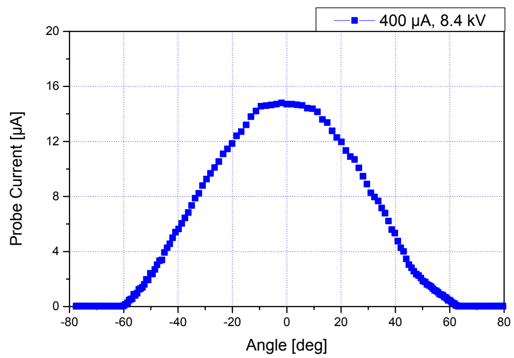


Figure 10 Beam Profile at Beam Current of 200 μA (left) and 300 μA (right), Probe Biased at –28 V, Z=30 mm



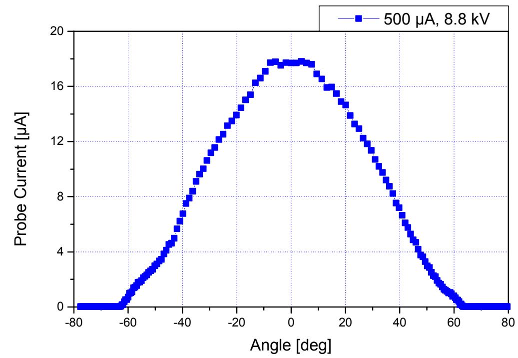


Figure 11 Beam Profile at Beam Current of 400 μA (left) and 500 μA (right), Probe Biased at –28 V, Z=30 mm

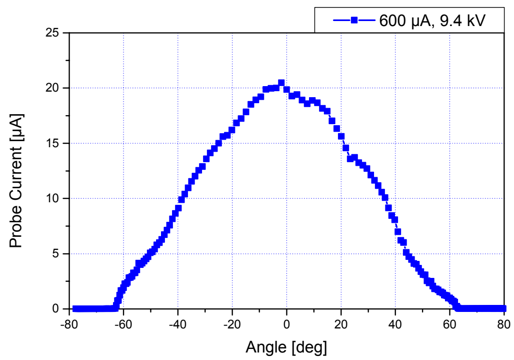


Figure 12 Beam Profile at Beam Current of 600 μA, Probe Biased at –28 V, Z=30 mm

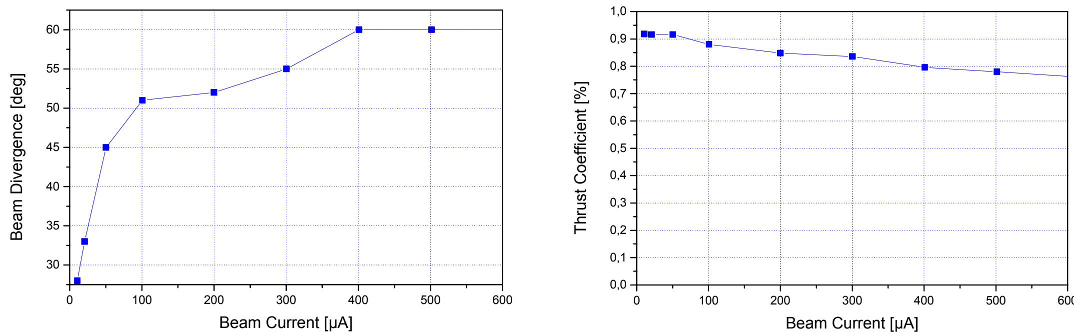


Figure 13 Total Beam Diverence (left) and Computed Thrust Coefficient (right) for Beam Currents from 10 µA – 600 µA

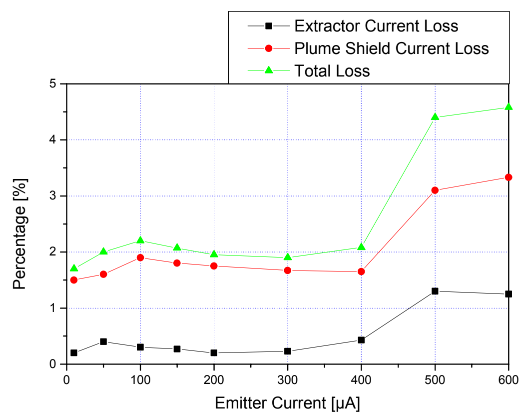


Figure 14 Extractor and Plume Shield Currents Loss for Beam Currents from 10 µA – 600 µA

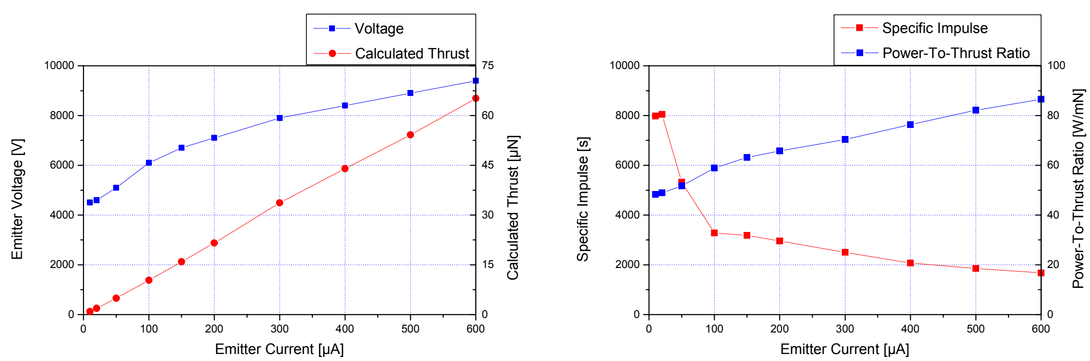


Figure 15 Voltage and Calculated Thrust (left) and Specific Impulse and Power-to-Thrust Ratio (right) for Beam Currents from 10 µA – 600 µA