Near-field Beam Diagnostics for Radio-Frequency Ion Thrusters RIT

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Nina S. Mühlich,* Kristof Holste† and Peter J. Klar‡
Justus-Liebig-Universität Giessen, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

and

Hans J. Leiter§
Ariane Group, Im Langen Grund, 74239 Lampoldshausen, Germany
and Justus-Liebig-Universität Giessen, Heinrich-Buff-Ring 16, D-35392 Giessen, Germany

A near-field beam diagnostics system is developed. It is based on a Faraday cup combined with an interchangeable collimator. This diagnostics system is used to measure the ion-current density beam-profile in the near-field of a radio-frequency ion thruster "RIT". Hereby, the extracted current density and the divergence of each channel can be analysed individually. One-dimensional beam profiles for the middle row of holes of the grid system are shown for two different lengths of the collimator leading to different acceptance angles of the probe. The beam profiles reveal that the current density and the divergence of the extracted ions are inhomogeneous. By changing the beam-current of the thruster, it is shown that the magnitude of resulting changes of the beam profile varies spatially. Furthermore, a performance mapping is carried out and is correlated with corresponding beam profiles. All beam profiles reveal that the current density and the divergence of the extracted ions are spatially inhomogeneous. Since these measured values depend on the plasma density and the electron temperature, a non-intrusive access to these plasma parameters is obtained.

Nomenclature

RIT	= Radio-frequency ion thruster
RFG	= Radio-frequency generator
$\dot{m}_n$	= Neutral gas flow
$\dot{m}_0$	= Total mass flow
$\dot{m}_i$	= Ion mass flow

I. Introduction

Up to now beam profile measurements with Faraday probes were mostly carried out at larger distances from the grid system in order to examine the beam profile as a whole. Typical objectives of such beam profile measurements are the determination of thrust vector and beam divergence[1,2] which are important for assessing the interactions of the thruster with the spacecraft.

The scope of this paper is the near-field beam diagnostics. The objective is the determination of the beam-current density directly downstream of the grid system similar to the measurements performed previously

*Master student, I. Physikalisches Institut, Nina.S.Muehlich@physik.uni-giessen.de
†Post-Doc, I. Physikalisches Institut, Kristof.Holste@exp1.physik.uni-giessen.de
‡Professor, I. Physikalisches Institut, Peter.J.Klar@exp1.physik.uni-giessen.de
§Professor, Ariane Group, Team Leader Electric Propulsion, Hans.Leiter@airbusafran-launchers.com

by IOM[3]. In contrast to IOM, the ion optics of each extraction channel of the grid system was individually examined. Thus, the ion-current density and the divergence (ion optics) of each individual channel can be analysed and spatial variations between channels can be revealed. Both quantities depend on the plasma density and the electron temperature in front of the extraction channel inside the thruster. In this way an access to a spatially resolved plasma density and electron temperature is provided. The great advantage is that this diagnostic method is non-intrusive.

Goebel[4] predicts that the plasma density and the electron density is inhomogeneous inside the thruster. Therefore, the ion optic will vary even if the geometry of the extraction channels is equal. The near-field ion beam measurements deliver a direct access to the ion optics of each extraction channel and it will be shown in this paper that the ion optics will differ from extraction channel to extraction channel. Hence, these findings can be used to improve the design of grid system for ion thrusters to extend the life time.

The investigations are carried out for a radio-frequency ion thruster "RIT" with an discharge chamber diameter of 10 cm [5]. A RIT is an electrostatic thruster, where the ionization is achieved by inductively coupling and the ions are accelerated by an electrostatic field of a grid system[6].

A Faraday probe combined with a changeable collimator is used as the detector. The probe moves exactly along the middle row of extraction channels of the thruster grid system and detects the ion-current density distribution of the thruster beam. The entry opening of the Faraday probe collimator is smaller than the extraction channels of the grid system so that the ion-current density distribution of the individual extraction channels can be examined. Different collimator lengths are used for a different angle resolution of the ion trajectories. Beam profiles for different beam-currents and mass flows are measured.

II. Setup of the near-field beam diagnostic system

The new developed near-field diagnostic system is based on a Faraday probe. In Figure 1 the Faraday probe is shown. It consists of a Faraday cup (red), a collimator and a repeller (blue). The repeller is designed as a ring electrode and is negatively biased against the probe system to prevent electrons from entering and to prevent the secondary electrons from leaving the system, which would lead to a fault current.

Using a collimator only allows ions to enter the Faraday cup whose velocity vector is within a certain acceptance angle. With the Faraday cup the collimated ion-current of the beam is measured. The acceptance angle depends on the length and the opening diameter of the collimator. Furthermore, the diameter of the collimator is significantly smaller in relation to the Faraday cup to reduce the high temperature and sputtering effects in the near-field of the thruster beam. In addition, the collimator has a small entrance opening (ø 0.5 mm) to examine the ion-current density distribution of the individual extraction channels (ø 1.2 mm). To reduce sputtering effects, a graphite film is attached to the collimator.

The measuring setup as shown in Figure 2 is installed in the vacuum chamber *Big-Mac*[7]. The Faraday probe (4) is located on a table which moves along a horizontal rail by a stepping motor (5) and a threaded rod. The Faraday probe moves continuously through the beam of the thruster RIT-10 (3) in a distance of approx. 30 mm. The measuring cables are protected by a cable guide (7). Limit switches (6) are mounted on both sides of the moving system.

III. Experimental beam investigations in the near-field

A. Test Description

All near-field measurements in this paper were performed with the thruster RIT-10, which was provided by Ariane Group. The discharge chamber as well as the grid of the RIT-10 have a diameter of approximately 10 cm. The grid system consists of 1583 extraction channels with a diameter of 1.2 mm. The operational parameters of the thruster were fixed at a mass flow of 4.5 sccm, an extraction voltage of 1000 V and an acceleration voltage of -350 V.

The Faraday probe described in Section II is mounted at a distance of 30 mm in front of the grid system. The detector travels exactly along the horizontal middle row of holes of the thruster grid system keeping the distance between grid and detector constant. For the above thruster parameters, a voltage of -80 V is applied to the repeller so that no electrons can enter the detector. This value was evaluated experimentally and confirmed by simulations using the program *SIMION*[8].

Figure 3 shows the Faraday probe in its starting position on the right side. During the measurement

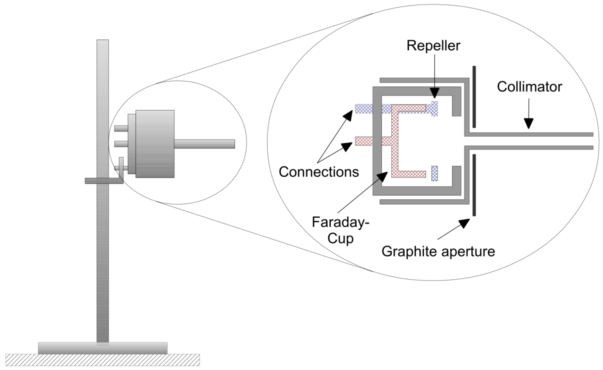

Figure 1. Structure of the Faraday probe consisting of Faraday cup, repeller, collimator and graphite aperture in cross-section.

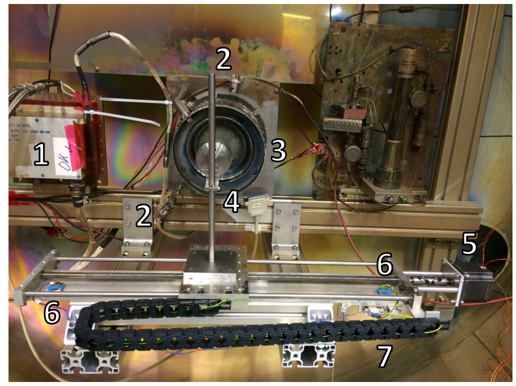

Figure 2. Measurement setup in the vacuum chamber *Big-Mac*. 1: RFG, 2: Filaments, 3: RIT-10, 4: Faraday probe, 5: Stepping motor, 6: End switch, 7: Cable duct.

the probe moves with a adjustable step width to the left. In the following measurements, two collimators were used with an entrance opening of 0.5 mm. The length of the two collimators were 60 mm and 100 mm, respectively, in order to obtain the beam profiles with different spatial resolutions.

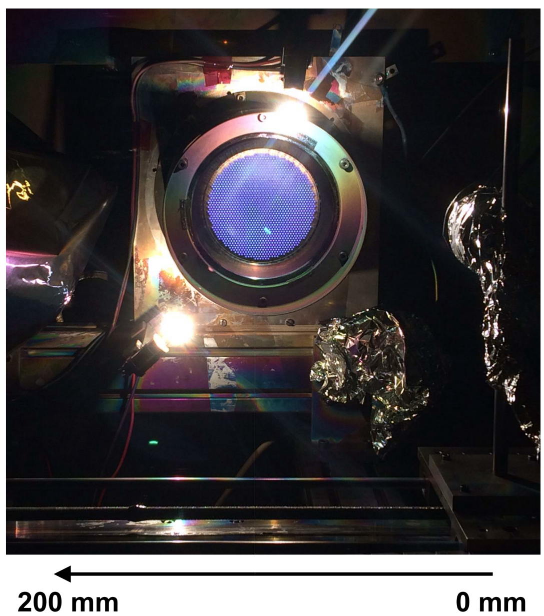

Figure 3. Measurement setup with the RIT-10 as well as both filaments powered up. The direction of the arrow represents the measuring direction of the Faraday probe.

B. Influence of the thruster beam-current variation on the plasma

In order to understand the following near-field measurements of the thruster beam, it is important to know that the measured current not only depends on the extracted current itself but also on the beam divergence. Both quantities depend on the plasma density as well as on the electron temperature inside the thruster. Accordingly, the measured current reflects the plasma density and the electron temperature.

In Figure 4 the beam profiles for different beam-currents between 100 mA and 235 mA are shown. The profiles were obtained using the collimator with a length of 60 mm. Therefore, only ions up to a maximum exit angle of 4,5 degree were detected. The observed wave structure of the profiles shows clearly that individual holes of the grid system can be resolved. In every beam profile, it can be seen that the current density varies spatially. This indicates that the plasma parameters inside the thruster are not homogeneously distributed.

A comparison of the beam profiles for 100 mA to 150 mA shows that the increase in the center is higher than at the edge. Furthermore, the overall increase of the current density is higher than the expected 50 % due to the increased beam-current. This reveals that the beam divergence for 150 mA is less than for 100 mA. Further increasing of the beam-current up to 235 mA, a saddle structure occurs which becomes more pronounced with increasing beam current. In the extreme case, the ion-current density at the center of the beam profile drops for a beam-current of 235 mA even down to that of a beam-current of 100 mA. In addition to the influence of beam divergence, an explanation for the saddle structure is the change in the plasma density for the different beam-currents. According to Schäfer's[9] measurements the plasma density inside a RIT thruster shows a similar behaviour for the decrease of the neutral gas pressure. This decrease corresponds to the increase of the beam-current. Because, if I_b increases, the ion mass flow from the thruster will also increase. As a result of this increase, the neutral particle flow from the thruster $\dot{m}_n = \dot{m}_0 - \dot{m}_i$ will decrease, consequently the pressure in the ionisation chamber of the thruster also will decrease.

Figure 5 shows the same measurement series as in Figure 4 but recorded with a collimator of length 10 cm. This collimator has an acceptance angle of 2,7 degree, so a smaller number of ions can enter and consequently the ion-current densities are lower than these in Figure 4. Using this collimator, only the ions which leave the grid system along the normal direction should be detected. Thus, ions from adjacent extraction channels should not be detected. Contrary to Figure 4 the saddle structure is only formed above 200 mA. This shows that ions with a smaller exit angle are less affected by the spatial variation of the plasma parameters.

Both Figures show that a near-field beam measurement reveals that, first, the plasma parameters are not homogenous and, second, that their dependence on beam-current varies spatially.

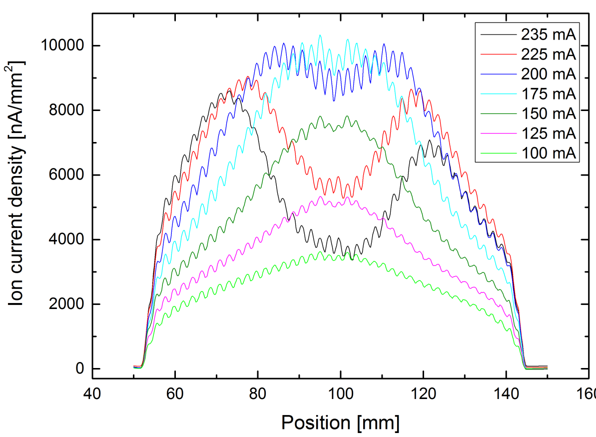

Figure 4. Ion-current density profiles for different beam-currents, recorded with a collimator length of 6 cm resulting in an acceptance angle of 4,5 degrees.

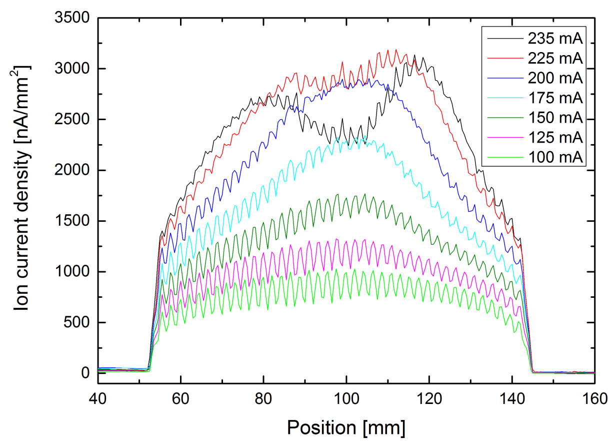

Figure 5. Ion-current density profiles for different beam-currents, recorded with a collimator length of 10 cm resulting in an acceptance angle of 2,7 degrees.

C. Influence of the neutral gas density on the plasma

As described in the previous subsection, the plasma parameters of the thruster are reflected in the measurements by the Faraday probe. A performance mapping of the thruster was carried out to further investigate this relationship. In a performance mapping the high-frequency power required for keeping up a set beam-current is plotted against the mass flow for different beam currents.

Figure 6 shows a performance mapping for the beam-currents 100 mA, 150 mA, 200 mA, 225 mA and 235 mA. As expected, the recorded curves have a hyperbola-like shape.

In Figure 7 ion-current density profiles with mass flows of 4 sccm and 6 sccm for three different beam-currents (100 mA, 200 mA and 235 mA) were measured with the collimator length of 60 mm. For a low beam-current of 100 mA, there is almost no change of the beam profiles comparing 4 sccm and 6 sccm. It is noticeable that at higher beam-currents (200 mA and 235 mA) the overall ion-current density profile is lower for 6 sccm compared to 4 sccm.

The performance mapping curves in Figure 6 reveal that the RFG power required for a beam-current of 100 mA for mass flows of 4 sccm to 6 sccm is almost constant. In contrast, the performance mapping curves for the beam-currents 200 mA and 235 mA show a strong drop in RFG power with increasing mass flow in this range. Unfortunately, the limitation of the DC input current provided by the RFG to a maximum value of 3 A, restricts the recording of the performance data at low mass flows. As the RFG power decreases, the electron temperature will also decreases and thus the beam divergence will be changed. This change is clearly visible in the ion-current beam profiles.

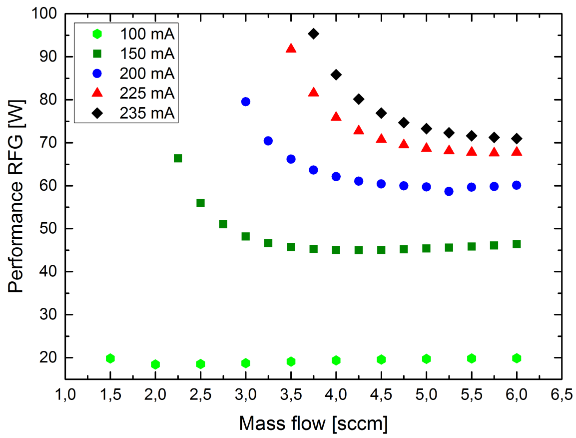

Figure 6. Required power of the RIT-10 as a function of the mass flow for beam-currents set to 100 mA, 150 mA, 200 mA, 225 mA and 235 mA, respectively.

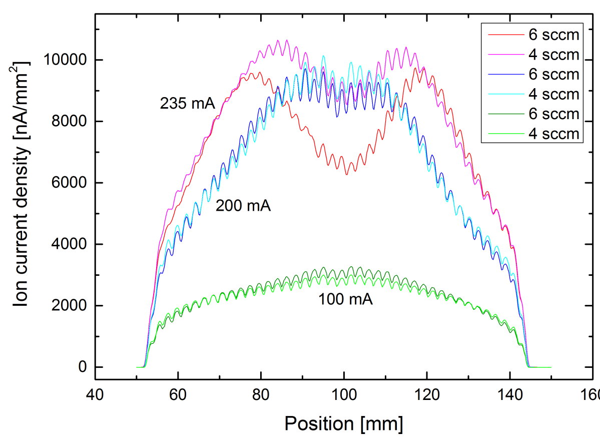

Figure 7. Comparison of the beam profiles for different mass flows for the beam-currents 235 mA, 200 mA and 100 mA, respectively.

IV. Conclusions

The spatial distribution of the ion-current density in the near-field of a radio-frequency ion thruster was measured using a Faraday probe. A combination of a Faraday cup and an interchangeable collimator were used as Faraday probe. The entrance opening of the collimator was that small that the ion-current density of every hole of the grid system could be resolved independently. This is reflected by the wave structure of the beam profiles measured. On the one hand, the experimental investigations were carried out by changing the thruster beam-current and, on the other hand, by changing the mass flow. The beam profiles reveal that the plasma density and the electron temperature are not homogeneous inside the thruster and in addition, that their dependence on beam current varies spatially. The changing mass flow effects the plasma parameters which is also reflected in the beam profiles.

By using the Faraday probe for measurements of the ion-current density distribution in the near-field of a thruster beam, important properties of the plasma and the thruster can be analysed. In particular, the current density distribution of individual extraction channels can be studied. This is extremely useful for verifying the ion optivs design of existing grid systems and provides essential information for life-time simulations. The newly developed measurement methodology yields access to the plasma density distribution in the ionization chamber right in front of the grid system. This is valuable information for optimizing future ion-optics systems. In contrast to intrusive probe measurements, the newly developed probe does not disturb the plasma significantly. Moreover, the near-field diagnostics of the Faraday probe is not limited to one-dimensional measurements and can be easily extended to two-dimensional measurements. By this means it is suitable for all probing kinds of gridded ion thrusters and broad-beam ion sources for surface modifications in industrial applications. The developed Faraday probe and the corresponding measurement methodology, thus, have great potential for in-depth investigations of plasma parameters close to the grids.

A more detailed description of the beam diagnostics system and the measurements can be found in Ref[10].

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