Plasmadiagnostics in the Plume of a Radiofrequency Ion Thruster

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Christoph Eichhorn,* Frank Scholze,† Carsten Bundesmann,‡ and Horst Neumann§
Leibniz-Institute of Surface Modification (IOM), Permoserstrasse 15, D-04318 Leipzig, Germany

Within recent research activities, we have developed and tested an Advanced Electric Propulsion Diagnostics (AEPD) platform which allows for simultaneous in-situ measurements of various properties characterizing electric propulsion systems, such as ion beam current densities, ion energy distribution and ion beam composition, grid temperature, curvature and erosion. Currently, an extension of the diagnostic instrumentation by means of a measurement probe based on emission spectroscopy is built up and tested. Progress in developing the emission spectrocopic set-up and first measurements in the plume of the radiofrequency ion thruster ISQ40RF, which has been designed and built at the institute, are reported.

I. Introduction

With respect to the characterization of both plasma parameters and thermal or mechanical properties of electric propulsion (EP) devices, a large variety of experimental methods has been developed and applied within the EP community in order to achieve a better understanding of relevant physical processes in the discharge and in the plume of EP systems, as well as to judge thruster performance with respect to mission requirements, such as the lifetime of critical thruster components. Ideally, measurements of several parameters should be carried out *in situ* and, furthermore, as simultaneous as practicable, to study possible corellations between properties, while ensuring their comparability at fixed plasma conditions to circumvent uncertainties introduced with respect to a break of the vacuum or interim inspection and re-adjustment of the thruster system.

For this purpose, the Advanced Electric Propulsion Diagnostics- (AEPD-) complex has been developed at the Leibniz-Institute of Surface Modification (IOM).[1] This platform consists of a five-axis positioning system, including three high-precision, ultra high vacuum specified linear and two rotary tables, as well as several defined mounting locations for the thruster test object and the respective diagnostic instrumentation. Thereby, the system allows to study a wide range of geometric orientations of interest between thruster and detectors. The standard instrumentation involves a telemicroscopy head for optical imaging of the thruster parts of interest, a triangular laser head to trace distortions of surface geometries, e.g. the curvature of an accelerator grid, and a pyrometer to measure thermal properties of thruster components. With respect to the characterization of the plume plasma, a Faraday probe to map the local beam current density, and an energy-selective mass spectrometer to analyze the composition, the energy and the mass distribution of the ion beam are installed. The system has been sucessfully tested in several measurement campaigns, including the characterization of a radiofrequency RIT-22 and a SPT-100 Hall effect thruster.[2–5]

In addition to the already implemented plasmadiagnostic instrumentation, further measurement techniques are currently under review to extend the capability of the platform. Optical emission spectroscopy

*Research Scientist, Department of Ion Beam Technology, christoph.eichhorn@iom-leipzig.de
†Senior Research Scientist, Department of Ion Beam Technology, frank.scholze@iom-leipzig.de
‡Senior Research Scientist, Department of Ion Beam Technology, carsten.bundesmann@iom-leipzig.de
§Senior Research Scientist and Group Leader, Department of Ion Beam Technology, horst.neumann@iom-leipzig.de

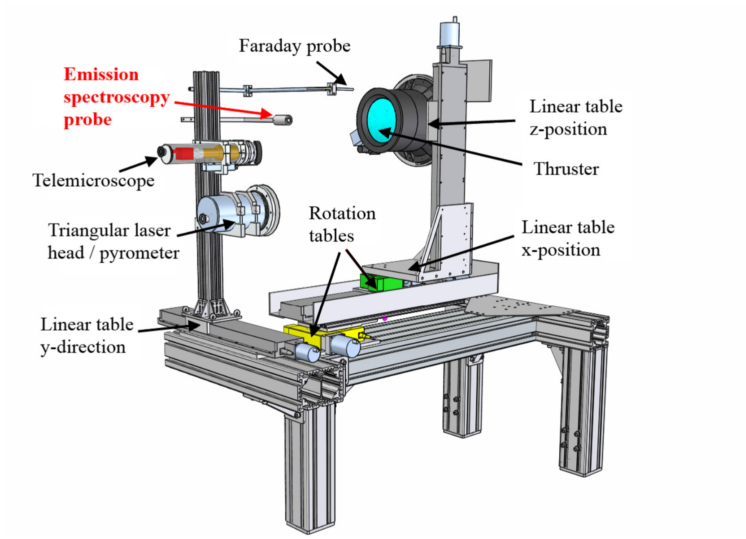

Figure 1. Left: Diagnostic instrumentation including the emission spectroscopy probe on the 5-axis positioning system of the AEPD complex.[4] Right: The ISQ40RF ion source.

(OES) represents a non-intrusive method to measure plasma properties, such as the electron temperature, if an appropriate collision-radiative model can be constructed. Based on the experimental determination of emission excitation cross sections for electron-atom and atom-atom collisions,[6] Karabadzhak et al.[7] have developed such a collision-radiative model that, in particular, includes terms for electron-induced collisional excitaion out of metastable states besides ground state excitation processes, and tested the model in the discharge and the plume of a TSNIIMASH D-55 anode layer Hall effect thruster. Since then, the Karabadzhak model has been applied in varoius investigations of Hall effect thrusters.[8–11] Meanwhile, Sommerville et al.[12] measured ion-collision emission cross sections for an extended range of the ion energy which coincide with selected ion thruster operation conditions. Moreover, results from the comparison of experimental data obtained in the plume of a Hall effect thruster with simulated spectra based on a model including electron-induced excitation and de-excitation, and de-exciation by spontaneous emission involving 173 levels in (neutral) xenon have been published recently by Yang et al.[13]

In this paper, an emission spectroscopy set-up, which has been designed as an extension of the standard diagnostic instrumentation of the AEPD system, is described. The set-up involves an emission spectroscopy probe, which can easily be implemented on a free slot of the AEPD detector test bench. In addition, first OES measurements in the plume of the radiofrequency ion source ISQ40RF are reported.

II. Experimental

A. Current experimental set-up

The measurements presented here shall demonstrate the capability of the emission spectroscopic extension of the AEPD system, and are part of a new comprehensive test campaign with respect to discharge and plume characterization of the test article, involving Faraday probe measurements, mass spectrometry and emission spectroscopy. Both Faraday probing and mass spectrometry represent maesurement techniques that are standardly integrated on the AEPD system (Figure 1, left). The Faraday probe consists of a 1.9 mm in-diameter graphite collector, which is mounted in a small-sized tube of 101 mm in length to ensure a sufficient distance between the electrical contacts within the probe and the thruster with respect to investigations in the near-field region at the thruster exit plane; the energy-selective mass spectrometer (Hiden EQP 300) allows for scans in the mass range between 1 and 300 amu, and ion energies up to a maximum of 5000 eV, similar to previous set-ups.[1]

For the emission spectroscopy measurements, a probe has been prepared that can be located, like all other AEPD components, in the vacuum chamber. The probe consists of a tubus, equipped with a lens of 25.4 mm in diameter and a focal length of 75 mm, following a design used in related research fields.[14] The collected light is imaged onto the 200 μm aperture of an optic fibre and guided via a vacuum feedthrough on the entrance slit of a 500 mm spectograph in Czerny-Turner configuration (Chromex 500IS). Spectra are obtained applying a 300 grooves/mm grating and recorded with a 750×242 pixel thermoelectric cooled CCD detector (ST-6, Santa Barbara Instrument Group). In the present configuration, the wavelength range between ~ 785 nm and 925 nm can be covered in three successive measurements. The FWHM of the spectral linewidth of the detected emission lines is 1.1 nm, which is narrow enough to resolve all NIR emission lines of interest. The contribution of emission lines of higher orders can be minimized by inserting appropriate edge-pass filters positioned near the collecting optics located in the probe.

Within the test campaign of the emission spectroscopy set-up, the in-house developed ISQ40RF radiofrequency ion source[15] is used as test article (Figure 1, right). This ion source has been used extensively for material research in the field of electric propulsion related to the measurement of sputter yields for xenon impingement on selected materials, and accelerator grid lifetime prediction.[16–18] The thruster is operated in a two-grid configuration, beam neutralization by temporary electron extraction from the discharge chamber is supported applying a pulse width modulation to the potential of the screen grid. The potential is modulated between -150 V (with the accelerator grid potential being modulated appropriately) and the respective positive screen grid voltage at a duty cycle of 0.5 with a frequency of 1 kHz in the present measurements. Positive screen grid voltages are applied between 300 V and 900 V, with xenon gas flow rates at 1 sccm and 1.5 sccm. The input power of the radiofrequency generator is varied between 40 W and 90 W.

During the present measurements, all measurement sensors are installed in the vacuum facility at IOM (length 3 m, diameter 1.1 m), equipped with two turbo molecular pumps (pumping speed 2200 l/s each), and a cryogenic pump (pumping speed 6000 l/s). With respect to the measurement assembly, the thruster position and alignment can be varied by means of one rotation and three linear tables.

B. Extension of the AEPD system

The AEPD complex is a diagnostic platform including maesurement sensors, a five-axis positioning system and the suspension arrangement of the thruster. The platform is shown in Figure 1, left. The three linear tables offer a maximum travel range of 700 mm at a maximum travel speed of 50 mm per second and a positioning reproducibility better than 0.1 mm, the rotary tables can rotate 360° at a maximum of 3° per second with a reproducibility better than 0.5°, see Bundesmann et al.[1] Thereby, nearly every geometric alignment of interest between the measuremnt sensors and the thruster can be achieved. The emission spectroscopy probe will be mounted on the sensor rack of the system, with line-of-sight rectangular to the central thruster axis, as shown in Figure 1, left. The installation will allow for radial scanning of the the respective thruster system. Data acquisition within the AEPD software package is intended.

III. Measurements and Discussion

Figure 2 exemplarily shows an emission spectrum obtained in the plume on the central thruster axis. In the investigated wavelength range, the sprectrum is dominated by emission lines of neutral xenon. Axial distances at 25, 50, 75 and 115 mm downstream the exit plane have been investigated for several screen grid voltages.

Two important line ratios, as considered in the Karabadzhak model, are displayed in Figure 3. In the regular operation mode (i.e. with neutralization by pulse width modulation), line ratios I_{823}/I_{828} between 1.8 and 2.5 and I_{834}/I_{828} between 0.29 and 0.37 have been found. Both line ratios increase significantly, when beam neutralization is turned off, reaching values for I_{823}/I_{828} in the range of 4.8 and 7.1 and for I_{834}/I_{828} in the range of 0.50 and 0.72. Following the Karabadzhak model, lower values for both line ratios applying beam neutralization by pulse width modulation would indicate a larger electron temperature. This fact is not surprising since neutralizing electrons recieve energies up to 150 eV. However, this means that the validity of the Karabadzhak model under these experimental conditions does not hold, and the electrons in the beam divide into several "species": A high energetic component resulting from the accelerating mechanism, electrons that occur due to ionizing collsions of neutrals with high energetic electrons, external electrons that are involved in the neutralization process due to the plume potential, including a thermal or non-thermal velocity distribution subsuming each component.

When the neutralizer is turned off, neutralization of the beam is provided by electrons that are captured by the potential developed within the plume. With the absence of high-energetic electrons, lower collision

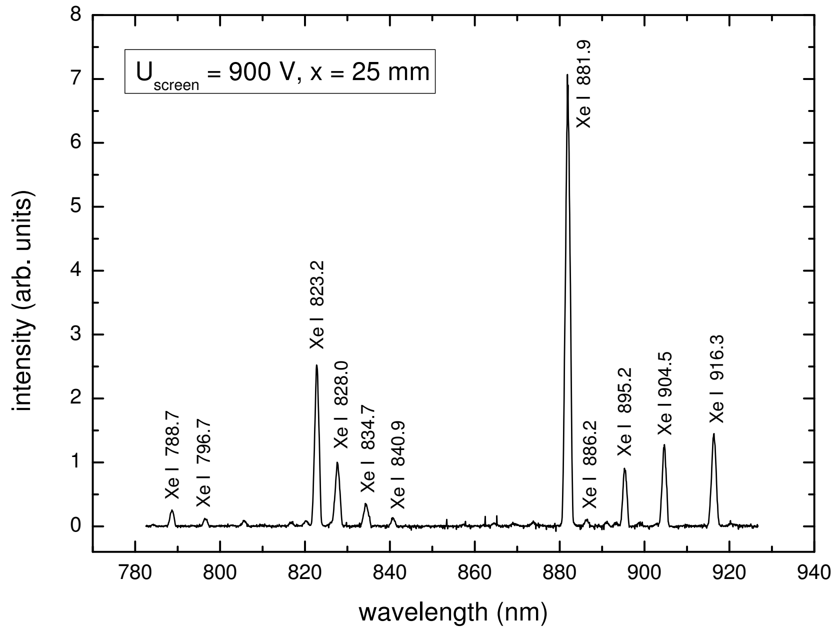

Figure 2. NIR spectrum in the plume of the ISQ40RF ion source at an axial distance 25 mm downstream the exit plane, with U_{screen}=900 V, P_{RF}=45 W. All indicated emission lines are associated to neutral xenon.

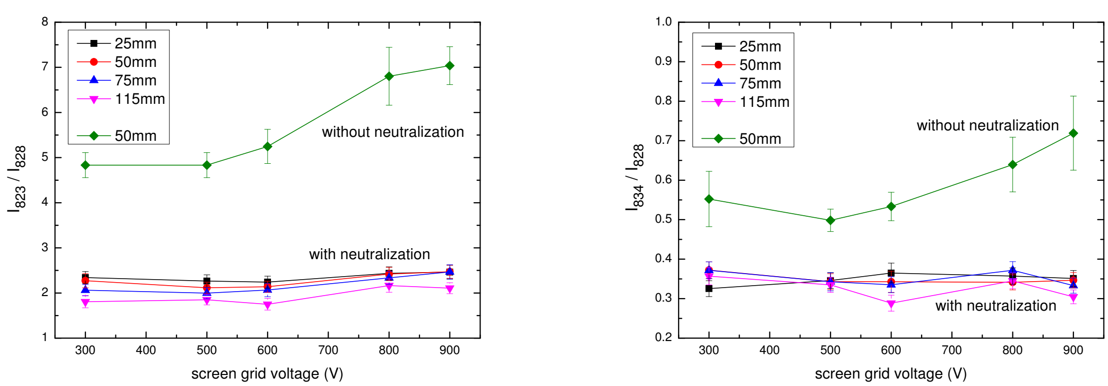

Figure 3. Emission line ratios measured at several axial distances, in dependence of the screen grid voltage. All measurements are integrated emissions over the line-of-sight. The measurements at axial distance of 50 mm are shown with and without beam neutralization.

energies give the impression of a lower "electron temperature". In this case, the beam divergence remains small, as investigated in Faraday probe measurements, which is exemplarily shown in Figure 4 for one operation condition, $U_{screen} = 600$ V. Faraday probe measurements have been carried out at axial distances between 115 and 415 mm downstream the thruster exit plane. The ion energy distribution, as shown in Figure 5 for the corresponding operation condition, is nearly monoenergetic while, relative to the beam voltage, shifted by the plasma potential.

The complicated situation in interpreting the emission spectroscopy data, and the need for a detailed investigation of the electron energy distribution function for the corresponding operation conditions, is no

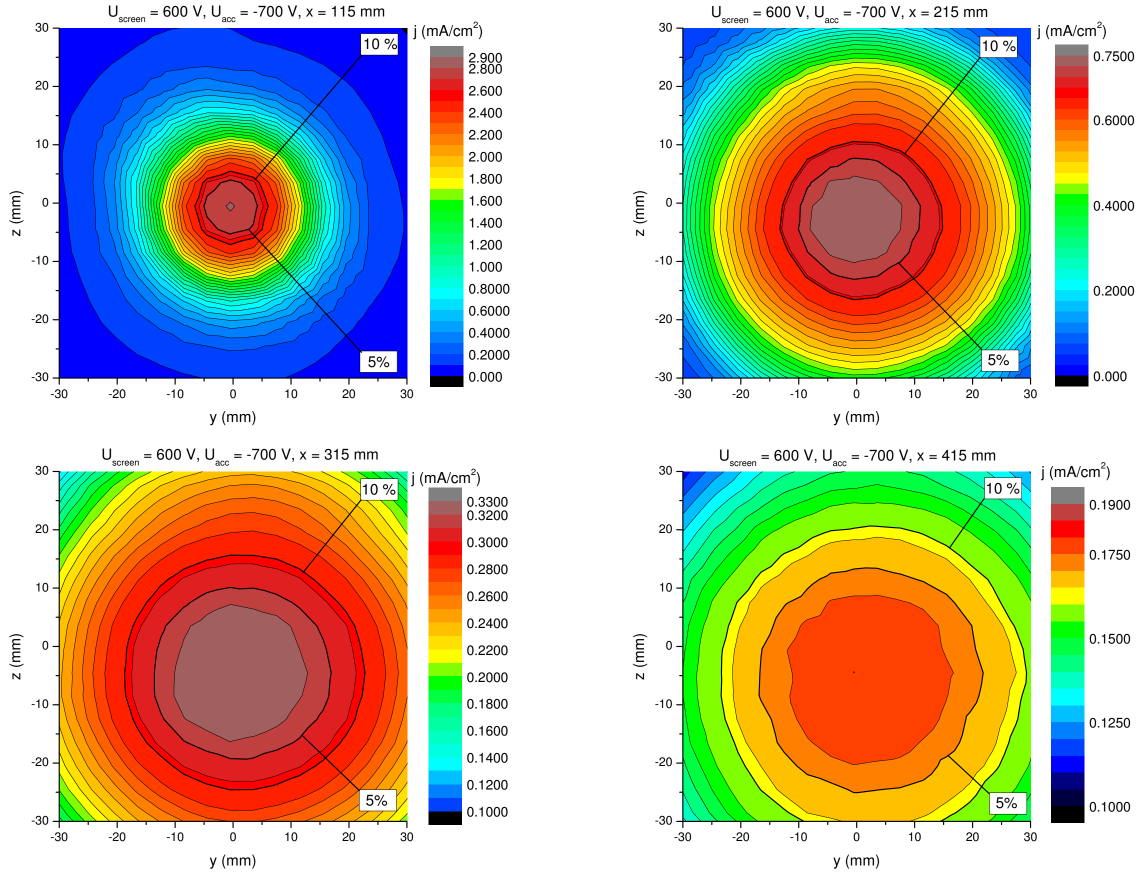

Figure 4. Exemplary Faraday mapping profiles in the plume of the ISQ40RF ion source, without beam neutralization, U_{screen}=600 V, P_{RF}=40 W. Within marked areas, the current density differs less then 5 or 10% with the central value, respectively.

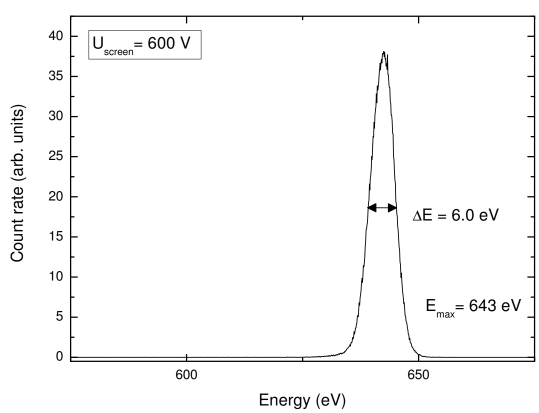

Figure 5. Ion energy distribution at 132 amu measured on the central thruster axis, same operation condition as in Figure 4.

drawback, since present work was focused on the test of the emission spectroscopy set-up as future part of the AEPD system. In this context, also the implementation of Abel inversion techniques is subject of ongoing work at the institute.

IV. Conclusion

An emission spectroscopy set-up as an extension of the Advanced Electric Propulsion Diagnostics platform has been described. OES test measurements in the plume of the radiofrequency ion source ISQ40RF have been presented. Line ratios of the detected intensities at 823 nm, 828 nm and 834 nm have been measured for several operation conditions on the central thruster axis. Relative intensities show markable differences with vs. without neutralization, which has been expected due to the presence of high energetic non-thermal electrons for the applied neutralization mechanism. Since the electron energy distribution function has not yet investigated in detail for our experimental conditions, the Karabadzhak model can not be applied directly to extract electron temperatures. This remains, as well as further improvement of the OES set-up and the technical implementation of the probe on the AEPD system, part of our current activities.

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References

[1] Bundesmann, C., Tartz, M., Scholze, F., Leiter, H. J., Scortecci, F., Gnizdor, R. Y., and Neumann, H., "Note: An advanced in situ diagnostic system for characterization of electric propulsion thrusters and ion beam sources," *Review of Scientific Instruments*, Vol. 81, No. 4, 2010, pp. 046106.

[2] Bundesmann, C., Tartz, M., Scholze, F., Neumann, H., Leiter, H. J., Scortecci, F., Feili, D., Frigot, P.-E., and Gonzalez del Amo, J., "In-situ temperature, grid curvature, erosion, beam and plasma characterization of a gridded ion thruster RIT-22," *Proceedings of the 31st International Electric Propulsion Conference*, Ann Arbor, MI, Paper IEPC-2009-160, Sept. 2009.

[3] Bundesmann, C., Tartz, M., Scholze, F., Neumann, H., Scortecci, F., Scaranzin, S., Frigot, P.-E., Gonzalez del Amo, J., and Gnizdor, R., "In-situ temperature, erosion, beam and plasma characterization of a SPT-100D EM1 with an advanced electric propulsion diagnostic system," *Proceedings of the 31st International Electric Propulsion Conference*, Ann Arbor, MI, Paper IEPC-2009-141, Sept. 2009.

[4] Bundesmann, C., Tartz, M., Scholze, F., Leiter, H. J., Scortecci, F., and Neumann, H., "In Situ Characterization of the Accelerator Grid of an Ion Thruster," *Journal of Propulsion and Power*, Vol. 27, No. 3, 2011, pp. 532–537.

[5] Bundesmann, Scholze, and Neumann, H., "Advanced Electric Propulsion Diagnostics," *Electronic Journal of the Moscow Aviation Institute*, Vol. 60, 2012.

[6] Chiu, Y.-H., Austin, B. L., Williams, S., Dressler, R. A., and Karabadzhak, G. F., "Passive optical diagnostic of Xe-propelled Hall thrusters. I. Emission cross sections," *Journal of Applied Physics*, Vol. 99, No. 11, June 2006, pp. 113304.

[7] Karabadzhak, G. F., Chiu, Y.-H., and Dressler, R. A., "Passive optical diagnostic of Xe propelled Hall thrusters. II. Collisional-radiative model," *Journal of Applied Physics*, Vol. 99, No. 11, 2006, pp. 113305.

[8] Sommerville, J. D. and King, L. B., "An optical Diagnostic for Hall Thrusters Including Metastable Contributions," *Proceedings of the 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Sacramento, CA, Paper AIAA-2006-4823, July 2006.

[9] Matlock, T. S., Hargus, W. A., Larson, C. W., and Nakles, M. R., "An Inversion Method for Reconstructing Hall Thruster Plume Parameters from Line Integrated Measurements," *Proceedings of the 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, Cincinnati, OH, Paper AIAA-2007-5303, July 2007.

[10] Spektor, R. and Beiting, E. J., "Non-Invasive Plasma Diagnostic Inside A Hall Thruster Discharge," *Proceedings of the 30th International Electric Propulsion Conference*, Florence, Italy, Paper IEPC-2007-69, Sept. 2007.

[11] Gonzales, A. E., Hargus, L. B., and Nakles, M. R., "Non-Intrusive, Time-Resolved Hall Thruster Near-Field Electron Temperature Measurements," *Proceedings of the 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, San Diego, CA, Paper AIAA-2011-, Aug. 2011.

[12] Sommerville, J. D., King, L. B., Chiu, Y.-H., and Dressler, R. A., "Ion-Collision Emission Excitation Cross Sections for Xenon Electric Thruster Plasmas," *Journal of Propulsion and Power*, Vol. 24, No. 4, 2008, pp. 880–888.

[13] Yang, J., Yokota, S., Kaneko, R., and Komurasaki, K., "Diagnosing on plasma plume from xenon Hall thruster with collisional-radiative model," *Physics of Plasmas*, Vol. 17, No. 10, 2010, pp. 103504.

[14] Löhle, S., Lein, S., Eichhorn, C., Herdrich, G., and Winter, M., "Spectroscopic investigation of an inductively heated CO_2 plasma for Mars entry simulation," *Journal of Technical Physics*, Vol. 50, No. 3, 2009, pp. 233–246.

[15] Zeuner, M., Scholze, F., Dathe, B., and Neumann, H., "Optimisation and characterisation of a TCP type RF broad beam ion source," *Surface and Coatings Technology*, Vol. 142–144, 2001, pp. 39–48.

[16]Deltschew, R., Tartz, M., Plicht, V., Hartmann, E., and Neumann, H., "Sputter characteristics of carbon-carbon compound material," *Proceedings of the 27th International Electric Propulsion Conference*, Pasadena, CA, Paper IEPC-2001-118, Oct. 2001.

[17]Tartz, M., Hartmann, E., and Neumann, H., "Validated simulation of the ion extraction grid lifetime," *Review of Scientific Instruments*, Vol. 79, No. 2, 2008, pp. 02B905.

[18]Tartz, M., Heyn, T., Bundesmann, C., Zimmermann, C., and Neumann, H., "Sputter yields of Mo, Ti, W, Al, Ag under xenon ion incidence," *European Physical Journal D*, Vol. 61, 2011, pp. 587–592.