Becker *et al. Journal of Electric Propulsion* (2023) 2:16
https://doi.org/10.1007/s44205-023-00052-z

Journal of Electric Propulsion

RESEARCH **Open Access**

Plasma parameter measurement on a RIT-10 using empirical correlations between non-invasive optical emission spectroscopy and Langmuir diagnostics

Felix Becker[1*†], Benny Nauschütt[1†], Limei Chen[1], Kristof Holste[1] and Peter J. Klar[1]

[†]Felix Becker and Benny Nauschütt contributed equally to this work.

*Correspondence: felix.becker@exp1.physik.uni-giessen.de

[1] Institute of Experimental Physics I, Justus-Liebig-University, Heinrich-Buff-Ring 16, Giessen 35392, Hesse, Germany

Abstract

Characterising and understanding the plasma properties of a rf-coupled electric propulsion device is crucial during testing, qualification and development. Therefore, the optimization of existing diagnostic systems as well as the development of new ones is an important area of electric propulsion research. Here, we present an approach to non-invasively determine the plasma parameters of an operating radio-frequency ion-thruster. For this purpose, a correlation between non-invasive optical emission (OE) spectroscopy and intrusive Langmuir probe diagnostics measurements is established for a reference system. Both types of measurements are performed simultaneously for a wide range of operation points yielding a large reference data set. Based on a principal component analysis (PCA), a correlation between plasma parameters and corresponding OE spectra at different operational points is established. This correlation can then be applied to OE spectra of the plasma of an operating thruster to obtain non-invasively the corresponding plasma parameters, i.e., without having to employ intrusive Langmuir probes. This approach for evaluating optical spectroscopic data in terms of plasma parameters has no need for a theoretical microscopic modeling of the plasma. This makes this approach very versatile and easily transferable to cases where other propellants are used, since no knowledge of excitation cross sections or transition matrix elements and other microscopic parameters of the species of the plasma is required. Such an approach enables continuous monitoring of a thruster's behavior during the qualification process.

Keywords: Optical emission (OE) spectroscopy, Principal component analysis (PCA), Langmuir diagnostics, Electric propulsion

Introduction

Space electric propulsion (EP) systems are on the verge of becoming mass products [1–6]. This commercialization process makes the corresponding space market segment even more competitive, enforcing faster development cycles and cost reduction for qualification and operation of the thrusters on the spacecraft. In this context, the propellant used becomes an issue. The price for xenon, which is the most widely used propellant for plasma-based electric propulsion systems, increases dramatically [7]. Thus, krypton, xenon/krypton gas mixtures or even iodine are currently investigated as alternative propellants for EP systems. As a consequence, reliable, fast and widely applicable diagnostic methods for EP systems need to be established and standardized to unify and speed up the qualification process. This also holds for operando plasma diagnostics applied for characterising the plasma parameters of thruster prototypes during the qualification at high TRL. The standard approach for determining plasma parameters is the use of Langmuir probes. However, this approach is intrusive, i.e., the measurement itself may alter the performance of the thruster at a given operational point [8]. Furthermore, it requires access to the plasma inside the thruster. In particular, in case of gridded ion thrusters, additional dedicated ports on the plasma vessel will be required, which are no use during operation in space, and, therefore, not desired from an engineering point of view. It is well established from microscopic physics that optical emission (OE) spectra of a plasma reflect the fractions of its ionic, atomic and molecular species as well as the occupation of their electronic, and in case of molecular species, vibrational states. Therefore, a correlation between the OE spectra of the plasma and the corresponding plasma parameters exists and, in principle, the plasma parameters can be extracted from the spectra. The conventional approach comprises a microscopic theoretical modelling of the optical emission spectra and a comparison between simulated and experimental spectra (e.g. [9] or [10]). Such a microscopic modelling requires an accurate description of the electronic and vibrational states of the species involved. In addition, the microscopic interaction between the different species as well the radiative and non-radiative recombination processes between the electronic states, which determine the absolute intensities of the optical transitions of the individual species in the OE spectrum, must be described accurately based on microscopic parameters such as scattering cross sections, transition matrix elements, etc. Comparisons even for "simple" plasmas consisting of neutral and charged species of one chemical element, e.g., a noble gas, need to account for hundreds of electronic states and a large set of microscopic parameters to yield an accurate prediction of its OE spectra. The approach is difficult to adopt for more complex plasmas comprising more species, e.g., molecular iodine or mixtures of noble gases. In many cases, the necessary microscopic parameters are not available and not easily accessible by experiments. Therefore, also in the light of the drive towards alternative propellants, ways to employ OE spectroscopy for determining the plasma parameters without having to rely on microscopic modelling need to be sought. We have introduced such an approach in Refs. [11] and [12]. An empirical correlation between plasma parameters and measured spectra is established on the basis of a reference data set by correlating the results of simultaneously conducted OE spectroscopic measurements and Langmuir probe measurements of the same plasma. We employ the so called principal component analysis, a multivariate data analysis approach, for deriving and parameterizing the correlation between the OE spectra of the plasma and the corresponding electron density and electron temperature extracted from the data of the simultaneously conducted Langmuir probe measurements. Based on this correlation, OE spectroscopy can be used to extract plasma parameters from a plasma inside a thruster provided the plasma is excited in the same fashion as that which was used for establishing the correlation. In this fashion, microscopic modelling is circumvented. Furthermore, the approach is easily transferable to other types of plasma, e.g., to plasmas of alternative propellants used in thrusters. Here, we show, as a proof of principle, results where the approach is used to non-invasively extract plasma parameters from an operating RIT-10 thruster with active beam extraction, which is operated with xenon.

Experimental details and theory

Experimental setup

A schematic image of the experimental setup used in this study is shown in Fig. 1. The thruster is a laboratory prototype of a RIT-10 with a cylindrical discharge chamber with a diameter of 10 cm and an extraction system consisting of three grids. It is operated with xenon. The Xe plasma is generated by a radio-frequency generator (RFG) [13, 14] operating at a frequency of approximately 1.1MHz. The thruster is operated in grounded mode without a neutralizer. A Langmuir double probe is inserted into the thruster through the gas inlet to measure the plasma parameters during operation without extraction. The optical emission (OE) spectroscopy measurements are performed from the outside of the vacuum chamber via a window yielding optical access. The light emission from the plasma exiting the grid system is focused onto an optical fiber, which is connected to a Czerny-Turner spectrometer with an optical length of 0.5m and an intensified charge coupled device (ICCD) for detection. The spectral resolution of the detection system is 0.5nm. The distance between the thruster and the detection system is about 3.15m with an angle of approximately 33° to the beam direction. The optical spectra are collected in the spectral range between 815nm and 843nm which exhibits seven distinct emission lines of Xe.

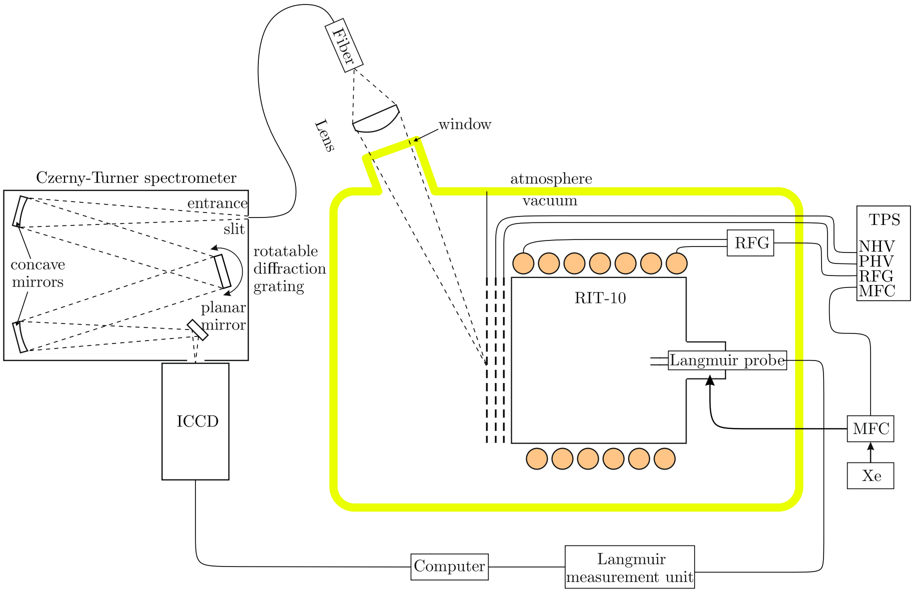

Fig. 1 Schematic image of the used experimental setup. A RIT-10 is operated in a vacuum chamber. A Langmuir double probe is inserted in the gas inlet of the thruster. The OE spectroscopy measurement is carried out through an optical window with focus on the plasma emission from the grid system of the thruster

The test power supply (TPS) consists of the individual power supplies for accelerator grid providing a negative high voltage (NHV) with respect to ground, the screen grid providing a positive high voltage (PHV) with respect to ground (PHV), the RFG for driving the inductive coil and exciting the plasma, and the mass flow controller (MFC) for the propellant supply. The grid voltages PHV and NHV are set to +1700V and −100V, respectively, for extracting the ion beam (active mode) and are both set to zero when the plasma inside the thruster is operated and no beam is extracted (idle mode).

These PHV and NHV settings define the ion optics and yield a focused ion beam for beam currents in the range from 40mA to 80mA with the values given above. The Langmuir probe measurement unit can only be biased with 250V with respect to ground. Therefore, we cannot perform Langmuir probe measurements with active beam extraction, as in this operating mode the plasma and the probe will be biased by the PHV.

Therefore, the reference data set of simultaneously conducted Langmuir probe and OE spectroscopic measurements is acquired without beam extraction in idle mode. The reference data was acquired for 130 different points of operation of the plasma. Each operating point corresponds to a different setting of the propellant gas flow (ranging from 0.8 to 4sccm) and the RF power (ranging from 10 to 90W) for exciting the plasma. All other settings such as PHV and NHV are kept constant. At each operation point, a data pair consisting of a OE spectrum and a corresponding Langmuir probe measurement was acquired using the same acquisition settings for the entire set of reference measurements. The reference data set is analyzed, as described below, to derive the correlation between OE spectra and plasma parameters. This correlation can then be applied to the OE spectrum of the plasma of a thruster operating in active mode for extracting the plasma parameters during beam extraction (for which no direct measurement of the plasma parameters can be performed).

The validation data set consists of OE spectroscopic measurements of the thruster operating in active mode. The Langmuir probe was removed prior to these measurements, otherwise the experimental setting was not altered. We recorded OE spectra along so called performance curves of the thruster each corresponding to a preset ion beam current, here, 40, 50, 60, 70, and 80mA. Each performance curve is acquired by varying the mass flow and simultaneously adjusting the RF power in order to keep the preset ion beam current constant.

OE spectroscopy measurements and principal component analysis

Each OE spectrum $S(\lambda)$ consists of intensity values recorded at 1024 wavelength sampling points. This means that each spectrum can be interpreted as a single point in a 1024-dimensional coordinate space spanned by the wavelength sampling points. Thus, the reference data set forms a cloud of points in this 1024-dimensional data space. As some of the optical transition lines are related, e.g, some of the electronic states involved are the same, or the width of recorded optical transition line covers several wavelength sampling points, the intensity values yielding the single point representing a OE spectrum in the 1024-dimensional coordinate space are not independent of each other. Therefore, it should be possible to reduce the dimensionality of the representation of the data and to preserve as much differences between the data as possible, i.e., to still be able to discriminate between the spectra characteristic for different operational points. To do so, we proceed as follows.

In step 1, the dimensionality of the representation of the line spectra is reduced. The background is subtracted, Furthermore, the entire spectral range outside the seven Xe emission lines is discarded and a single intensity value for each line is derived by adding the strongly related intensity values at all wavelength sampling points within the full width of the emission line. This leaves a single spectrum as a data point in a 7-dimensional coordinate system, the reduced spectrum is a vector with 7 components denoted as $\overrightarrow{S}$. To further reduce the dimensions, the OE spectroscopy data is evaluated in step 2 by a principal component analysis (PCA). A general description of PCA is given in Ref. 13, a specific detailed description of how we apply PCA of the OE spectroscopic data and how we correlate the PCA results with the plasma parameters from the corresponding Langmuir probe data is given in Ref. [11]. In brief, PCA rotates the 7-dimensional coordinate system about the center-of-mass of the data cloud representing the reference spectra such that the new coordinate axes correspond to the axes with the highest variance in the data set. The center of mass of the data cloud is given by the average processed spectrum $\langle \overrightarrow{S} \rangle_{\mathrm{ref}}$ of the reference set. The new coordinate axes are given by the eigenvectors $\overrightarrow{PC}_i$ of the covariance matrix of the data points representing the spectra in the seven dimensions. All seven eigenvalues λ_i of the covariance matrix have positive values as they are variances. The labelling of the axis follows the weight of the variance on the new coordinate axes. The eigenvalues are ordered such that $\lambda_1 < \lambda_2 < \cdots < \lambda_7$. Thus, the first eigenvector $\overrightarrow{PC}_1$ corresponding to the first new coordinate axis accounts for the highest variance eigenvalue, the second eigenvector $\overrightarrow{PC}_2$ corresponding to the second new coordinate axis for the second highest variance eigenvalue, and so on. In case of our data, the first two coordinate axes cover 99% of the total variance within the reference data set. Therefore, we restrict ourselves to the two new coordinate values (scores) PC_1 and PC_2 with respect to the axes $\overrightarrow{PC}_1$ and $\overrightarrow{PC}_2$ for further analysis. Although the seven dimensions of the data points still yield seven dimensions after the PCA, the scores along the first two axes are already sufficient for almost fully grabbing the differences between the spectra, i.e. to separate the data points of all spectra in a two-dimensional plot PC_1 vs PC_2 (see Fig. 2(a)). Thus, the pairs of (PC_1, PC_2) of the reference spectra, yield a sound basis for establishing a correlation between input parameters and optical spectra as well as between optical spectra and corresponding plasma parameters. However, it cannot be predicted in general which number of $\overrightarrow{PC}_i$ is necessary to achieve a full separation of the data points representing the OE spectra or whether a full separation is possible at all. This has to be assessed by trial and error. A high fraction of variance on the $\overrightarrow{PC}_i$ used for separating the data is only an indicator towards a satisfactory result, but neither a necessary nor sufficient condition.

Langmuir probe measurements and plasma parameters

In a Langmuir double probe measurement, a sweeping voltage is applied between two probe wires which are inserted into the plasma. The evaluation of the resulting voltage-current-characteristics provides values for the characteristic parameters of the plasma, the electron temperature T_{e} and electron density n_{e} [8, 15–17]. The evaluation procedure used here is a modified approach on the basis of the standard procedure [8, 15–17]. This modified approach is described in more detail in our previous publications [11, 12].

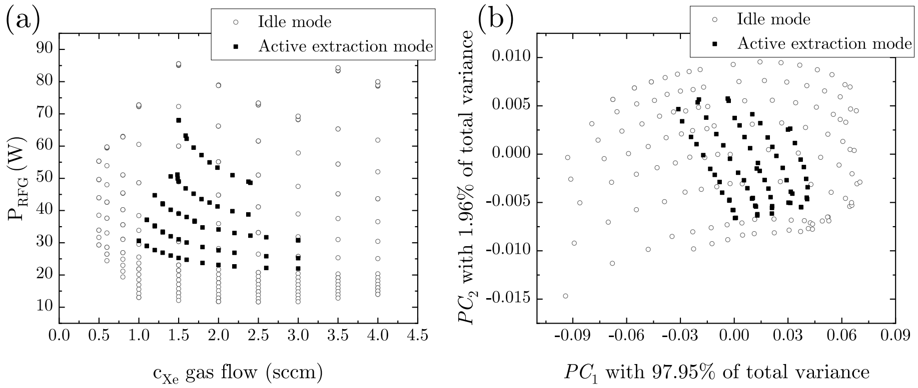

Fig. 2 Mass flow c_{Xe} of the propellant Xe and power setting P_{RFG} of the RFG are the only parameter settings varied in the operation of the thruster apart from switching on and off the extraction. The circular, open data points correspond to the reference data set (thruster in idle mode) and the square shaped, full data points to the validation data set (thruster in active extraction mode). **a** All pairs of settings $(c_{\mathrm{Xe}}, P_{\mathrm{RFG}})$ for which OE spectra are acquired. **b** Pairs of scores (PC_1, PC_2) derived directly by the PCA in case of the reference data and resulting from the expansion of corresponding processed OE spectra in terms of the principal components of the reference set in case of the validation data

Briefly summarized, the saturation regions of the typical Langmuir double-probe characteristics are fitted with a linear dependence. The measured curve is corrected using the slope of the fit and normalized by the intercept. Now, the electron temperature can be calculated from the maximum slope at a voltage of approximately zero, which is determined using a third order polynomial fit in this region.

Correlation between PCA scores and plasma parameters, analysis of OE spectra of unknown plasma parameters

The values of the electron temperature and the electron density of the reference data set plotted versus the corresponding PC_1 and PC_2 scores yields two 2D-surfaces, $T_e(PC_1, PC_2)$ and $n_e(PC_1, PC_2)$. The 2D surfaces are parameterized by curve fitting to a two-dimensional polynomial fitting function of the form

$$f(PC_1, PC_2) = \sum_{i=0}^{n} \sum_{j=0}^{i+j \leq n} a_{i,j} \cdot PC_1^i \cdot PC_2^j \tag{1}$$

where we chose $n = 3$. The fitted functions $T_e(PC_1, PC_2)$ and $n_e(PC_1, PC_2)$ represent the correlation between the OE spectra and the corresponding plasma parameters. Another OE spectrum $\overrightarrow{S}$ taken of the same thruster under operation (even with extraction of an ion beam) can then be analyzed in terms of its plasma parameters as follows. It needs to be processed according to step 1 and can then be expanded in terms of the eigenvectors $\overrightarrow{PC}_i$ of the reference data set derived in step 2:

$$\overrightarrow{S} = \langle \overrightarrow{S} \rangle_{\mathrm{ref}} + \sum_{i=1}^{7} PC_i\left(\overrightarrow{S}\right)\overrightarrow{PC}_i \tag{2}$$

The corresponding expansion coefficients are the scores PC_i of this spectrum and can be derived according to

$$PC_i\left(\overrightarrow{S}\right) = \left(\overrightarrow{S} - \langle\overrightarrow{S}\rangle_{\text{ref}}\right) \cdot \overrightarrow{PC}_i \tag{3}$$

making use of the orthogonality of the principal components. The values of $PC_1\left(\overrightarrow{S}\right)$ and $PC_2\left(\overrightarrow{S}\right)$ obtained in this fashion can be inserted into $T_e(PC_1, PC_2)$ and $n_e(PC_1, PC_2)$ to derive the two plasma parameters corresponding to the spectrum.

Results and discussion

The reference data set consisting of OE spectra and simultaneously conducted Langmuir probe measurements was acquired with the thruster operating in idle mode, i.e., the high voltages of the extraction grid system were turned off. The validation data set consists of OE spectra only, as the thruster was operated in active mode, i.e., with the high voltages of the extraction grid system switched on to generate the ion beam. In this active operational mode Langmuir probe measurements cannot be conducted. The only other operational settings which were varied during acquisition of the two data sets were the propellant mass flow c_{Xe} and the power P_{RFG} of the RFG driving the plasma. Figure 2 (a) depicts all the pairs of settings $(c_{\text{Xe}}, P_{\text{RFG}})$ used when acquiring both data sets. The circular, open data points denoting the reference data set cover a wider parameter space than the square, full data points denoting the validation data set. In particular, the validation data lies fully within the reference data range. This is an essential requirement for two prerequisites which need to be fulfilled. First, it is the basis for a reliable expansion of processed OE spectra of the validation set in terms of the principal components of the reference data set and, second, it can be anticipated that the unknown plasma parameters of the validation data set lie within the range of the known plasma parameters of the reference data set. The latter is important as the unknown plasma parameters shall be determined on the basis of the polynomials used for describing the 2D-surfaces $n_e(PC_1, PC_2)$ and $T_e(PC_1, PC_2)$. The plots of the corresponding (PC_1, PC_2) pairs obtained for the two data sets suggest that all these prerequisites are fulfilled. There are essentially no overlapping data points in each set. Furthermore, the trends in terms of mass flow variation, RFG power variation are preserved for all pairs of scores (PC_1, PC_2) derived directly by the PCA in case of the reference data and resulting from the expansion of corresponding processed OE spectra in terms of the principal components of the reference set in case of the validation data. The preservation of the trends in terms of mass flow and RFG power for the reference data set and the different performance curves measured for different beam currents in the validation data is highlighted in Fig. 2 (b). The plot of the scores (PC_1, PC_2) of PCA of the reference OES data set is shown again in in Fig. 3 (a). The series of data points where the RFG power is varied for constant propellant mass flow are highlighted by different symbols. The individual measurement series for different constant gas flows are arranged in curved lines, which reflect the changes in the RFG input power. In this case, the scores PC_1 of the first principal component account for 97.95 % of the data variance, which mainly corresponds to changes in the

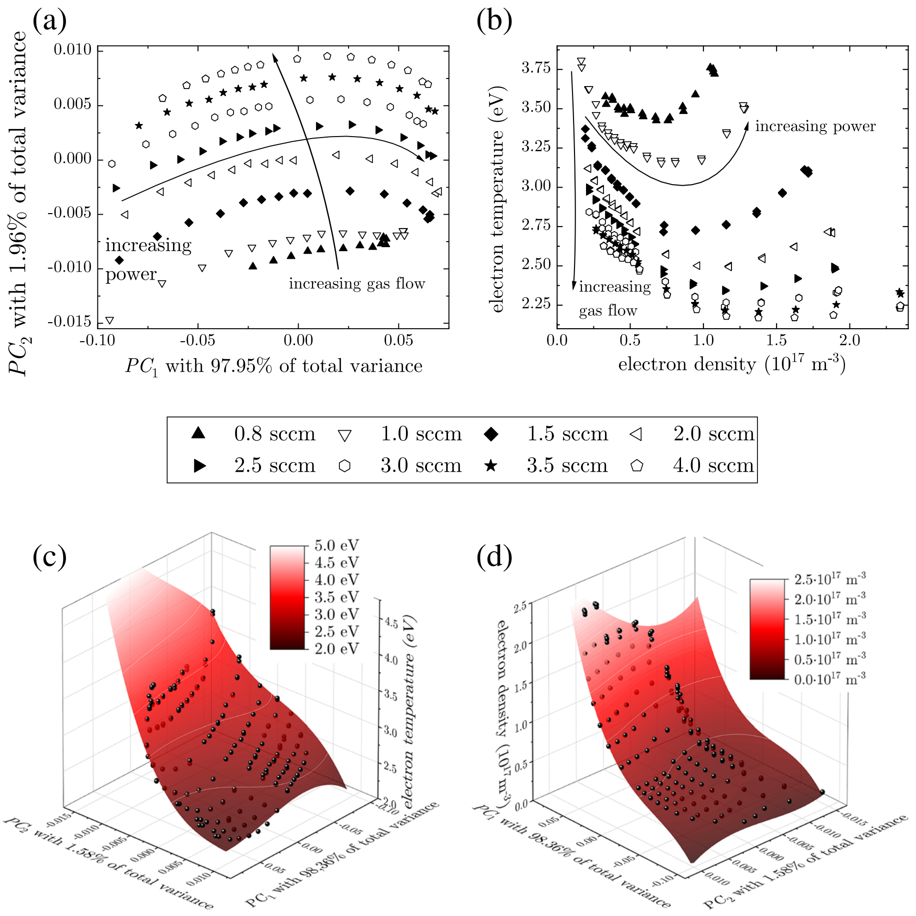

Fig. 3 **a** Plot of the scores (PC_1, PC_2) of PCA of the reference OES data set. **b** Corresponding plasma parameters extracted from the Langmuir probe measurements. Correlation between the first two PC scores and a corresponding plasma parameter (black symbols) together with the fitted correlation function for **c** the electron temperature T_e and **d** the electron density n_e

RFG input power. The scores PC_2 of the second principal components account for only 1.96 % of the data variance and mainly contains the information about the gas flow.

Figure 3(b) shows a plot of series data pairs (n_e, T_e) extracted from the Langmuir probe measurements and corresponding to the series of data points in Fig. 3(a). The data points (n_e, T_e) are also well separated in the plot and show clear trends. Each operational point has been measured twice with the Langmuir probe yielding similar results. As expected for constant mass flow, the electron temperature T_e rises towards lower gas flows and the electron or ion density n_e increases with higher input power [18–20]. The finding that the data points do not overlap in both plots, i.e., that of PC_1 vs PC_2 derived by OES and that of n_e vs T_e derived from corresponding Langmuir probe measurements, and the clear trends observable suggest that there exists a one-one correspondence between the OE spectra of the plasma inside the thruster and its plasma parameters. As further confirmation, we have plotted the electron temperature T_e and the electron density n_e as a function of the corresponding PC_1 and PC_2. The smooth 2D surfaces of the two plasma parameters are shown in Fig. 3(c) and (d). The red curves show corresponding fitted surfaces described by the polynomial function defined in Eq. 1. The R^2-values of the fitted

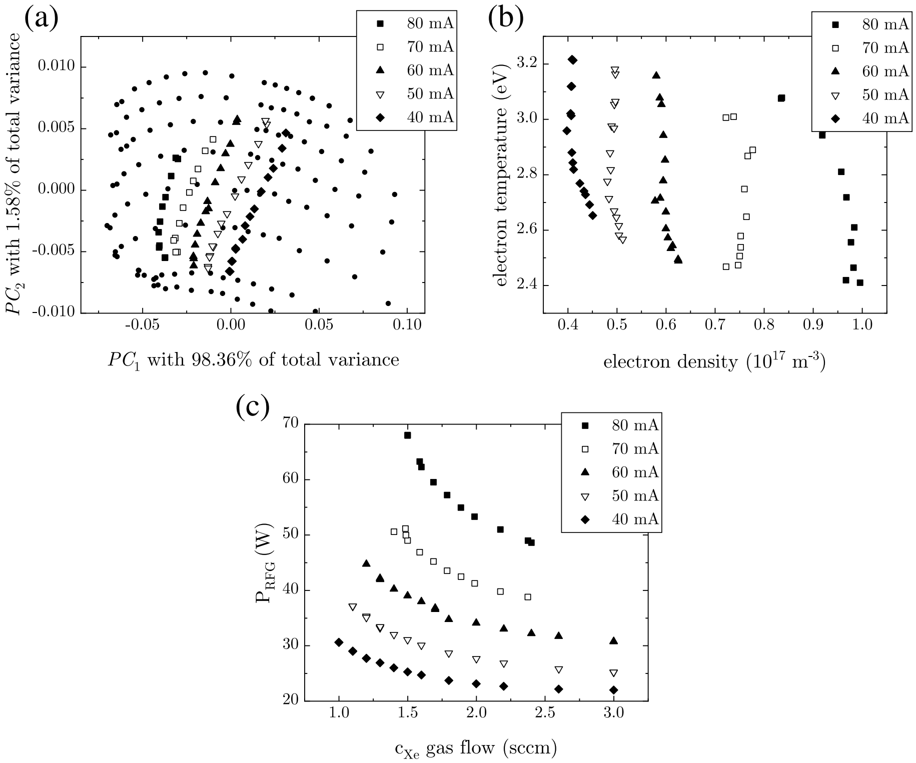

Fig. 4 **a** Plot of the (PC_1, PC_2) data pairs of the validation data set. The corresponding PCA scores of the reference data set are shown as small dots for comparison. **b** Plasma parameters of the validation data set calculated using the correlation functions for the plasma parameters $n_e(PC_1, PC_2)$ and $T_e(PC_1, PC_2)$. **c** Performance curves for five different beam currents which define the operation points where the validation data have been acquired

surfaces are 0.97 and 0.99 for T_e and n_e, respectively. The results are very similar to previous measurements on a different RIT-like setup [11, 12].

The correlation between plasma parameters and optical spectrum established and parameterized by the fitting of the 2D surfaces as correlation functions $n_e(PC_1, PC_2)$ and $T_e(PC_1, PC_2)$ is now applied to OE spectra of the validation data set obtained on the same thruster during active ion beam extraction. The OE spectra of the validation set are processed as described in Section "Experimental details and theory" and their PC_1 and PC_2 scores with respect to the reference data set are derived. Figure 4(a) shows again a plot of the (PC_1, PC_2) data pairs of the validation data set. The data points belonging to the same performance curve are denoted by the same symbols, different performance curves by different symbols. The plasma parameters corresponding to each OE spectrum of the validation set are calculated by inserting its scores PC_1 and PC_2 into the correlation functions $n_e(PC_1, PC_2)$ and $T_e(PC_1, PC_2)$ according to Eq. 3. We have plotted in Fig. 4(b) the corresponding pairs of plasma parameters (n_e, T_e) using the same color scheme as in Fig. 4(a). The plasma parameters belonging to the same performance curve as well as the data sets of the different performance curves show meaningful trends. The performance curves are shown in Fig. 4(c). The electron temperature T_e decreases with increasing gas flow and the electron density n_e increases with increasing beam current. Both effects are expected and in accordance with the literature [18–20]. Furthermore, the electron density is almost independent of the gas flows for a given beam current. This is also anticipated because the extraction of a constant ion beam current requires a constant ion density n_i within the plasma and it holds $n_i = n_e$ because of the neutrality condition of the plasma.

However, some words of caution are necessary. In the set up used the Langmuir probe was positioned inside the gas inlet and was probing a small volume inside the plasma. In the OE spectroscopy measurement, the emission of the thruster from the grid area was collected by a lens and its demagnified image focused on to the entrance slit of the spectrometer. Thus, the OE spectroscopic measurement reflecting a spatially averaged spectrum of the plasma is correlated with a local measurement of the plasma parameters at the insert. It should be noted that the one-to-one correlation between plasma parameters extracted by Langmuir-probe measurements and OE spectra is the more reliable, the more the probe volumes of the Langmuir probe measurement and OE spectrum overlap and agree. It is best if the two volumes are the same. The uncertainty of the correlation depends on the overlap of the probed volumes, but also on the variation of the plasma parameters inside the plasma volume. Such a variation is definitely present in rf plasmas confined in vessels as it is the case in gridded ion thrusters. This somewhat introduces a degree of uncertainty in the measurement approach as it stands as the plasma is not homogeneous inside the plasma vessel towards the sidewalls of the vessel or across the grid system, i.e., the plasma parameters measured by the Langmuir probe in a small volume are not representative for the entire plasma. However, this issue will be overcome, when optical and Langmuir probe measurement probe the same, preferentially very small volume. One possible concept for refining the measurement approach, is to use a reference set-up consisting of plasma body and a grid system with only one extraction channel and the Langmuir probe placed directly behind this orifice. This way, by solely focusing the plasma emission, which exits this orifice, on to the spectrometer slit, it will be guaranteed that the OE spectrum and the Langmuir probe measurement is characteristic for the same defined volume within the plasma. Spatially resolved OES across the plasma vessel or the grid system of a RIT may then yield spatial maps of the local plasma parameters with a spatial resolution of the characteristic probe volume of the reference measurement set-up. Based on such knowledge, it will be possible to assess how much the locally determined plasma parameters differ from globally averaged plasma parameters. This will provide essential information for optimising global models of the plasma, which often simply assume constant average plasma parameters or empirical spatial plasma profiles [20]. Empirical plasma profiles used in global modelling of thrusters can be verified experimentally which will be a great help in improving such global models.

Conclusion

In this work, we demonstrated that a one-to-one correlation can be established between OE spectra of a rf-plasma inside a thruster and its plasma parameters obtained by simultaneously conducting Langmuir probe measurements. We show that the parameterized correlation based on such a reference set of measurements can be used to derive plasma parameters solely from other OE spectra provided they were recorded under the same conditions as the reference set. Exemplarily, we discuss this approach for a RIT-10 thruster operating with xenon. The reference set consists of more than 100 pairs of simultaneously conducted OE and Langmuir-probe measurements of the plasma inside the thruster in idle mode. This data forms the reference data set. The OE spectra of the reference set were simplified in a two-step process keeping the distinct differences between the spectra. The first step consists of transforming each OE spectrum into a vector whose components represent the integrated intensities of the characteristic optical transitions of the propellant in the spectral range under consideration. In the second step, a PCA was performed on the vectors of the reference set. The scores of the first two principal components show a one-to-one-correlation with both of the plasma parameters, electron temperature and density, derived by analyzing the Langmuir probe data. This correlation can be fitted by polynomial functions of the two scores and thus be parameterized. Furthermore, we validate that the correlation determined from the reference set can indeed be used to analyze additional OE spectra of the thruster in terms of characterizing its plasma state. The validation data set consisted of OE spectra recorded of the same thruster in active mode along performance curves recorded for various beam currents. That the trends in the plasma parameters extracted using the established correlation are realistic. This finding confirms that the proposed approach is viable. Such a non-invasive OE spectroscopic measurement as a means of extracting plasma parameters can be easily performed and employed in the proposed fashion on the majority of plasma-based thrusters independent of the type and size. It will be particularly useful in case of gridded ion thrusters where the plasma is enclosed and difficult to access, e.g., in case of flight models. The approach yields valuable insight into the plasma behavior of an operating ion thruster and, thus, its performance. It provides a novel way of analyzing the characteristics of a plasma of plasma-based ion thrusters during testing and qualification for space. In particular, no microscopic theory of the electronic states and the emission of the plasma is needed for extracting the plasma parameters from the OE spectra. The approach solely relies on experimental data and a representative reference measurement. This may contribute to faster and more reliable development cycles of thruster technology in the future.

Acknowledgements
F. Becker and B. Nauschütt are grateful for funding of their PhD positions by the JLU-Ariane Group Graduate School "Radio frequency ion thrusters". Furthermore, EU regional funding via the EFRE scheme of the State of Hesse is gratefully acknowledged.

Authors' contributions
F.B. and B.N. wrote the manuscript and performed and evaluated the measurements. L.C. assisted in evaluating the OES measurements using PCA. K.H. and P.J.K. supervised the activities and provided the idea for the experiment. All authors contributed to data interpretation and discussion. All authors read and approved the final manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL.

Availability of data and materials
The data sets used and/or analyzed during the current study are available from JLUdata under the link http://dx.doi.org/10.22029/jlupub-4193.

Code availability
The Code is available from the authors upon reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

Received: 8 August 2022 Accepted: 22 April 2023

References

1. Groh KH, Loeb HW, Velten HW (1984) Performance data comparison of the inert gas RIT 10. J Spacecr Rocket. 21(4):360–365. https://doi.org/10.2514/3.25663
2. Kim V, Popov GA, Kozlov V, Skrylnikov A, Grdlichko D. Investigation of SPT Performance and Particularities of it's Operation with Kr and Kr/Xe Mixtures. In: Proceedings of the 27th International Electric Propulsion Conference, Electric Rocket Propulsion Society, IEPC-01-065, Pasadena, CA. 2001
3. Linnell JA, Gallimore AD (2006) Internal plasma potential measurements of a Hall thruster using xenon and krypton propellant. Phys Plasmas. 13(9):093502. https://doi.org/10.1063/1.2335820
4. Linnell JA, Gallimore AD (2006) Efficiency Analysis of a Hall Thruster Operating with Krypton and Xenon. J Propuls Power. 22(6):1402–1418. https://doi.org/10.2514/1.19613
5. Holste K, Gärtner W, Zschätzsch D, Scharmann S, Köhler P, Dietz P, et al. Performance of an iodine-fueled radio-frequency ion-thruster. Eur Phys J D. 2018;72(1). https://doi.org/10.1140/epjd/e2017-80498-5
6. Dietz P, Gärtner W, Koch Q, Köhler PE, Teng Y, Schreiner PR et al (2019) Molecular propellants for ion thrusters. Plasma Sources Sci Technol. 28(8):084001. https://doi.org/10.1088/1361-6595/ab2c6c
7. Holste K, Dietz P, Scharmann S, Keil K, Henning T, Zschätzsch D et al (2020) Ion thrusters for electric propulsion: Scientific issues developing a niche technology into a game changer. Rev Sci Instrum. 91(6):061101. https://doi.org/10.1063/5.0010134
8. Demidov VI, Ratynskaia SV, Rypdal K (2002) Electric probes for plasmas: The link between theory and instrument. Rev Sci Instrum. 73(10):3409–3439. https://doi.org/10.1063/1.1505099
9. Vlcek J, Pelikan V. A collisional-radiative model applicable to argon discharges over a wide range of conditions. II. Application to low-pressure, hollow-cathode arc and low-pressure glow discharges. J Phys D Appl Phys. 1989;22(5):632–643. https://doi.org/10.1088/0022-3727/22/5/010
10. Boffard JB, Jung RO, Lin CC, Aneskavich LE, Wendt AE. Argon 420.1–419.8 nm emission line ratio for measuring plasma effective electron temperatures. J Phys D Appl Phys. 2012;45(4):045201. https://doi.org/10.1088/0022-3727/45/4/045201
11. Nauschütt BT, Chen L, Holste K, Klar PJ. Non-invasive assessment of plasma parameters inside an ion thruster combining optical emission spectroscopy and principal component analysis. EPJ Tech Instrum. 2021;8(1). https://doi.org/10.1140/epjti/s40485-021-00070-x
12. Nauschütt B, Chen L, Holste K, Klar PJ (2022) Combination of optical emission spectroscopy and multivariate data analysis techniques as a versatile non-invasive tool for characterizing xenon/krypton mixed gas plasma inside operating ion thrusters. J Appl Phys. 131(5):053301. https://doi.org/10.1063/5.0074412
13. Simon J, Probst U, Klar PJ. Development of a Radio-Frequency Generator for RF Ion Thrusters. In: 34th International Electric Propulsion Conference, Hyogo-Kobe, Japan. 2015
14. Junker JE, Probst U, Klar PJ. Development of a full bridge series resonant radio-frequency generator for optimized RIT operation. In: 36th International Electric Propulsion Conference, Vienna, Austria. 2019
15. Benedikt J, Kersten H, Piel A (2021) Foundations of measurement of electrons, ions and species fluxes toward surfaces in low-temperature plasmas. Plasma Sources Sci Technol. 30(3):033001. https://doi.org/10.1088/1361-6595/abe4bf
16. Johnson EO, Malter L (1950) A Floating Double Probe Method for Measurements in Gas Discharges. Phys Rev. 80(1):58–68. https://doi.org/10.1103/physrev.80.58
17. Bhattarai S (2017) Interpretation of Double Langmuir Probe I-V Characteristics at Different Ionospheric Plasma Temperatures. Am J Eng Appl Sci. 10(4):882–889. https://doi.org/10.3844/ajeassp.2017.882.889
18. Goebel DM, Katz I (2008) Fundamentals of Electric Propulsion, 1st edn. John Wiley & Sons, Hoboken
19. Reeh A, Probst U, Klar PJ. Global model of a radio-frequency ion thruster based on a holistic treatment of electron and ion density profiles. Eur Phys J D. 2019;73(11). https://doi.org/10.1140/epjd/e2019-100002-3
20. Dietz P, Reeh A, Keil K, Holste K, Probst U, Klar PJ, et al. Global models for radio-frequency ion thrusters. EPJ Tech Instrum. 2021;8(1)10. https://doi.org/10.1140/epjti/s40485-021-00068-5

Publisher's Note