Emittance measurement setup facilitating plasma diagnostic of ion thrusters

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Abstract: An experimental setup is presented which facilitates the measurement of ion beam emittances of radiofrequency ion thrusters (RIT) based on the slit-wire method. For the present study, the RIT was equipped with a single orifice three-electrode extraction system. First experimental results and comparisons with simulations are shown. Partial agreement between experiment and simulations could be achieved by assuming negligible space charge. This finding is attributed to space charge neutralization due to the single orifice system which produces an unusually high residual gas density between the RIT electrodes. The correspondingly high rate of collisions between the primary ion beam and the residual gas particles produces sufficiently many electrons for space charge compensation.

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I. Introduction

The concept of beam phase space and the associated beam emittance is widely used in accelerator physics for describing the behavior of an ion beam.\textsuperscript{1} The beam emittance is a valuable quantity characterizing the quality of a beam. It facilitates the calculation of the interdependence of beam parameters with geometrical dimensions of the accelerator. Therefore, large efforts have been undertaken to measure emittances of ion beams from different types of ion sources. In such studies, it is particularly important to map out the dependence of the ion-beam emittance on the ion-source parameters in order to be able to chose the most appropriate set of parameters for optimal ion-beam transport.

The investigation of the quality of the extracted ion beam is particularly important for electric propulsion devices due to the fact that the generated thrust stems from the ejected ions. Commonly the ion beam intensity is measured with an array of movable Faraday cups, which provides insight into the spatial charge distribution. If such measurements are performed at different distances from the thruster the spatial development of the ion beam intensity can be mapped and the divergence angle of the plume can be obtained. To get a deeper insight into the ion-beam properties the measurement of the beam emittance can be useful. As explained later, the emittance can be treated as a conserved quantity if only conservative forces act on the ions. Hence, measuring ion current distributions at different distances from the thruster would potentially be obsolete if a reliable emittance measurement were available. If the ions are generated in a plasma and extracted with help of a multi-grid-system the emittance of the ion beam depends not only on the dimension of the grid-system but also on plasma parameters.\textsuperscript{2} This feature can be exploited to gain access to plasma parameters such as ion temperature by measuring emittances.\textsuperscript{3}

The present paper is organized as follows. In Section II the concept of ion-beam emittance is briefly reviewed. Our newly built experimental setup is described in Section III. First experimental results and corresponding plasma simulations are presented and discussed in Sections IV and V, respectively. Finally, short conclusions are given in Section VI.

II. Ion Beam Emittance

In six-dimensional phase space every particle is described by its position \((x, y, z)\) and momentum \((p_x, p_y, p_z)\).\textsuperscript{4} Assuming that the net-motion of all particles is in \(z\)-direction and further that \(p_z \gg p_{x,y}\) it is convenient to replace the transverse momenta \(p_x\) and \(p_y\) with their angles relative to \(p_z\) according to

\[
x' = \frac{p_x}{p_z}, \quad y' = \frac{p_y}{p_z}
\]  

(1)
The emittance $\varepsilon$ is defined as the phase space volume (see Fig.1) that is occupied by all particles. If the particles are not accelerated after extraction the longitudinal subspace spanned by $\{z, p_z\}$ can be separated from the remaining four-dimensional subvolume. The latter is denoted as the transverse emittance. Further, if the transverse motions are not coupled, the two-dimensional $x$ and $y$ subspaces can be treated independently. Accordingly, the transverse emittances in the so-called trace-spaces $\{x, x\prime\}$ and $\{y, y\prime\}$ are defined as

$$
\varepsilon_x = \frac{1}{\pi} \iint_{\text{area}} dx \times dx', \quad \varepsilon_y = \frac{1}{\pi} \iint_{\text{area}} dy \times dy'.
$$

Assuming that only conservative forces are acting on the particles the Liouville theorem predicts that the phase-space volume is a conserved quantity. In case of decomposed subspaces, the theorem is valid in all three subspaces and therefore, the emittances given by Eq.(2) are constant values. For high-perveant ion sources the influence of space-charge effects cannot be neglected. Forces due to space-charge are non-conservative. Accordingly, the validity of the Liouville theorem has to be considered carefully. The following discussions refer exemplarily to the $\{x, x\prime\}$ trace-space. The results are the same for the orthogonal space $\{y, y\prime\}$.

The definition of the emittance as the area that the particles occupy in the phase-space raises the question how the (usually only few) particles with outlying phase-space coordinates should be accounted for. For instance, if one assumes a Gaussian distribution of particles the emittance as defined above would be infinitely large. Hence, it is common practise to define the emittance as the area that contains a fraction of the beam. A recipe for dealing quantitatively with this issue was introduced by Lapostolle.\textsuperscript{5} It is based on particle statistics. The particles inside the two-dimensional trace-space $\{x, x\prime\}$ can be treated as a statistical distribution with mean values $<x>$ and $<x\prime>$. Hence, it is obvious to define the emittance as the area that is determined by the standard deviations from these mean values. As a consequence the root-mean-square (rms) emittance $\varepsilon_{\text{rms}}$ of an ion beam is defined as

$$
\varepsilon_{\text{rms}} = \sqrt{\langle x^2 \rangle <x^2> - <xx\prime>^2}
$$

with $\langle x^2 \rangle$, $\langle x'\prime^2 \rangle$, and $\langle xx\prime \rangle$ as central second-order moments of the particle distribution. A detailed analysis of this formalism with respect to data evaluation is given by Zhang.\textsuperscript{6} All experimental emittances shown in this paper are rms-emittances calculated with this formalism (see Fig.2).

### III. The Experimental Setup

#### A. Emittance Measurement

Measurements of emittances are routinely performed with different experimental methods like Allison scanner, pepper-pots and slit scanner.\textsuperscript{7-9} All of these methods have in common that a small fraction of the ion beam is cut out at a well-known position. In an adequate distance downstream the delimiter the position of the beam fraction is scanned. With this information a mapping of the angular distribution of the fraction can be performed. The general tendency is the utilization of the pepper-pot method, which uses an array of small holes (\textmu m-range) arranged on a plate for the fragmentation and a scintillator crystal to observe the ion intensity. The crucial part of this realization is the crystal. Due to interaction with ions, the surface of the scintillator gets destroyed. The damage increases with lower ion velocity and higher mass, therefore this method seems to be unsuitable for ion thrusters.
In this work the slit-wire method is used (see Figs. 3 and 4). The incident beam is decomposed by an array of 25 slit (width: 0.4 mm, distance slit-to-slit: 2 mm) into a bunch of beamlets. The beamlet distribution behind the slits is scanned with a thin wire. The position of the wire is recorded with a sensitive potentiometer, which allows to convert values into a length scale. The distance between slits and wire has to be adjusted to ensure that the beamlets can be separated in the analysis. The beamlet with the highest intensity is selected with no loss of generality as the center reference. This means, that the center of the reference peak is in line with one of the slits from the array, therefore, it is not affected by angular deviation. From this point of view, all other beamlets can be associated with one particular slit of the array. This facilitates the calculation of the angular distribution for every slit. Since the geometry of the slit array is well known, the phase-space profile weighted with the ion current can be calculated. The slit plate is equipped with two perpendicular slit arrays to measure the complete four-dimensional transverse phase-space distribution of the ions.

The experiment can be controlled through a computer program. The measurement procedure is as follows:
Figure 5. Schematic of the radiofrequency ion thruster (RIT) used in this work. A high-frequency electromagnetic field is inductively coupled in a discharge chamber by a surrounding coil. Electrons in the plasma are accelerated by the induced field and ionize xenon atoms, thereby sustaining the plasma. Xenon gas is fed steadily into the plasma by a mass-flow controller. A pressure-shock is used to ignite the plasma. Ions are exhausted from the plasma by a single orifice three-electrode ion optic. The optical behaviour and the dimension of the extraction system are given in the text.

A linear motor facilitates the movement of the wire-scanner. The relative precision of the wire position is 0.15%. The scanning distance between two data points can be adjusted. At each position several measurements of potentiometer value and ion current are performed. Mean values and standard deviations are protocolled. The ion current is measured with a picoammeter (Keithley model 6485). This unit can measure ion currents as low as a fraction of a picoampère with a minimum resolution of 10 fA. The ion current that is impinging on the slit aperture is measured with an analog electrometer (Keithley model 610C). Due to the partial transparency of the slit array, this value is just a rough estimate of the total ion current. The slit plate is covered with a thin graphit layer to reduce secondary particle emission from the surface. The plate can be biased with a positive repelling voltage to keep secondary electrons on the plate. No visible influence of secondaries on the beamlet distribution was observed, therefore, this feature has not been used to avoid distortion of the ion beam movement by stray electrical fields.

The slit-wire method is mechanically robust. The slit-plate is relatively thick (2mm) and can withstand ion bombardment for a long time. The scanning-wires are thin and may break faster, but can be exchanged easily. The disadvantage of this method is its slowness as compared for instance with the pepper-pot method, which requires only a few seconds for a complete measurement of the complete transversal phase-space. In contrast the time for a one slit-wire scan with high resolution is about 20 minutes. For the measurement of both trace-spaces this value has to be doubled. The usage of multi-wire systems for increasing the speed of measuring is being tested.

The entire setup is installed in a cubic vacuum chamber with a side length of 38 cm. Two oil-diffusion pumps with a pumping speed of 760 l/s for nitrogen are installed to produce a vacuum with background pressures around $3 \times 10^{-7}$ mbar, when the thruster is off. During operation time of the thruster the pressure is around $6 \times 10^{-6}$ mbar. Theses values already include the conversion factor for the used xenon propellant. The oil-diffusion pumps share a fore-vacuum pump with a pumping speed of 14 m³/h.

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B. Ion Thruster

In this work the investigated ion beam was generated in a radiofrequency (rf) ion thruster (RIT). The rf-principle was invented at Justus-Liebig-University Giessen in the 1960s. Since then, different sizes of RITs have been developed and characterized. The thruster used in this work is a RIT-4, which means that the diameter of the ceramic discharge chamber is 4 cm. The rf-thruster and the relevant physical processes are extensively described in literature, therefore only a short explanation of the working principle is given. Ions are produced by electron-impact ionization in a discharge chamber (see Fig. 5). In order to achieve efficient ionization the plasma is heated by a rf frequency electromagnetic field which is inductively coupled into the plasma by a surrounding coil. The propellant (xenon) is funneled continuously into the plasma. The gas-flow is controlled by a mass-flow controller (Bronkhorst), which allows to adjust the flow between 0.02 sccm (standard cubic centimeter per minute) and 1.5 sccm. The electromagnetic rf-field is generated by a radiofrequency generator (RFG, APCON RFG40 NTR #003). This unit has a working frequency of 2.6 MHz and delivers a power up to 70 W. The RIT and the RFG are both installed inside the vacuum chamber. The RFG is attached to a water cooled plate since it requires cooling during operation.

The ion extraction is performed with a single orifice three-electrode system. The first electrode is in contact with the plasma. Therefore, the adjusted voltage on this electrode biases the potential of the plasma due to the consistency of the electric potential. By using a multi-aperture system, which is the common choice for this thruster type, the overlap of the different initial ion beams would prevent a feasible analysis. To find suitable working conditions of the thruster a performance map has been measured (see Fig.6). Radiofrequency-power and gas-flow are adjusted to obtain the iso-current curves (related to the extracted current from the plasma) for 200 µA, 300 µA, and 400 µA. Therefore, three operating points have been selected for the emittance measurements (15 W, 0.02 sccm; 20 W, 0.04 sccm, 23 W, 0.06 sccm). However, the latter point was disregarded in the data analysis because of problems with the stability of the thruster at this condition. The gas-flow of 0.06 sccm is too high to warrant stable operation of the thruster if there is only one aperture on each electrode. It turned out that voltage breakdowns prohibited reasonable measurements. A typical measurement result of the beamlet distribution is shown in Fig.7. The distance from the slit aperture to the wire was 36.5 mm. The thruster had been placed a few centimeters in front of the slits. This distance was appropriate to image the whole beam on the slits. Normally the extracted ion beam from a thruster is neutralized with electrons. Here, this procedure was not applied since the ion currents extracted from the thruster were comparatively small. However, a simple neutralizer has recently installed in the setup and will be used in future experiments. Due to time restrictions most measurements were performed only for one transverse trace-space.

IV. Experimental Results

Useful measurements were performed at two data points of the performance map (0.02 sccm, 15 W and 0.04 sccm, 20 W). The voltage on the first electrode, which has contact to the plasma, was adjusted to the values 250 V, 500 V, 750 V, 1000 V, 1250 V, and 1500 V. For every screen voltage the acceleration electrode voltage was adjusted to 5%, 10%, 20%, and 50% of relative to the screen electrode voltage. For screen voltages below 1000 V additional fractions of 100% and 150% were adjusted. A typical measurement result of the beamlet distribution is shown in Fig.7. The distance from the slit aperture to the wire was 36.5 mm. The thruster had been placed a few centimeters in front of the slits. This distance was appropriate to image the whole beam on the slits. Normally the extracted ion beam from a thruster is neutralized with electrons. Here, this procedure was not applied since the ion currents extracted from the thruster were comparatively small. However, a simple neutralizer has recently installed in the setup and will be used in future experiments. Due to time restrictions most measurements were performed only for one transverse trace-space.

Figure 6. Performance mapping of the RIT. Operating points (15 W, 0.02 sccm; 20 W, 0.04 sccm, 23 W, 0.06 sccm; 23 W, 0.06 sccm) are emphasised by a surrounding ellipse. As discussed in the text, the latter mapping point has been omitted from evaluation due to instabilities of the thruster during experiments.

As discussed later, even the minimal gas-flow of 0.02 sccm seems to be too high to bring the thruster into normal operating conditions. Therefore, the present measurements have to be interpreted with due care.
Experimental data were evaluated with the Emittance Analysis System (EAS) software written by R. F. Welton and M. P. Stockli.\textsuperscript{14} Rms-emittances were calculated with an ion current threshold of 10\%, which is a commonly used value in emittance measurements.\textsuperscript{15} The experimental rms-emittance values for the two operation points of the thruster are presented in Fig.8. The estimated error due to geometrical inaccuracies is estimated to be around 5\%, statistical errors are similar in size. The shown errors bars only account for statistical uncertainties in order to facilitate a better comparison between the measurements at different plasma parameters. The geometrical inaccuracies are of systematic nature and bias all experimental emittance values in the same way. The obtained emittance values are all of the same order of magnitude. A slight trend towards higher values at higher RFG-power and gasflow is visible except for a screen voltage of 1500 V. In case of higher screen voltages a tendency for a minimal emittance can be observed at acceleration grid voltages around 10\% of the screen voltage. This suggests optimal extraction parameters for the used thruster under the adjusted working parameters. Nevertheless, more data points are needed to validate this assumption.

As mentioned earlier, the emittance can be affected by space charge. In case of intense low-energy beams this effect should be relatively high. Therefore, in the data analysis particular attention has been given to this issue. A possible way is the normalization of the emittance value to the extracted current. Experimentally, there are several options for normalization. For every measurement the current on the slit plate was recorded but this value does not seem to be very precise because of the only partial transparency of the plate and the missing repelling voltage. Therefore, secondary electrons are lost for the current measurement and the measured value is just a rough estimate. The current on the screen electrode is measured more precisely by a voltage drop across a 100 k\(\Omega\) resistor, but it is not clear if this value adequately represents the exhausted ion current. The acceleration electrode current was also recorded, thus, the difference between 1st and 2nd electrode is also a possible normalization value. Results from the different normalization options are shown in Fig.9. Normalizations on the screen current and on the slit plate current deliver similar results and have, thus, been preferentially used in the data analysis.

Examples for normalized data are shown in Fig.10 for the screen voltages 750 V and 1500 V. Additionally the screen currents are included in the inset for a better comparison. The extracted currents are increasing with increasing acceleration electrode voltage. This behavior is expected because the potential difference between the first two electrodes determines the extractable current. The higher rf-power also leads to a higher ion current because more energy is injected into the plasma. Therefore, the electron-impact ionization rate is increasing which is equivalent to a bigger amount of Xe-ions. The higher gas-flow at 20 W increases the target density for the electrons, hence the number of produced ions also increases. For a screen voltage of
1500 V the curves in Fig.10 show a similar behavior, which means that the emittance is not been affected strongly by space charge. The behavior for 750 V is different at lower acceleration grid voltages but levels for 50% and higher. Correspondingly, space charge effects may have been significant at low acceleration voltages. Further investigations are needed to clarify this issue.

From the measured emittances we can obtain beam parameters like diameter and divergence angle. This
Figure 9. Influence of different possible ways of data normalization. The normalization is used for analyzing the influence of space charge effects on the measured emittance values (see text). The presented data are given for a screen voltage of 1500 V (20 W, 0.04 sccm).

will be discussed on another occasion, when the data analysis is fully completed. In the following section we will focus on the comparison of the measured emittance values with results from computer simulations.

V. Plasma and ion optics simulation

For the ion-optical simulations the KOBRA3-INP software is used. KOBRA has been used over few decades to simulate different kind of ion sources like electron-cyclotron resonance ion sources (ECRIS). It is a three-dimensional Vlasov solver which uses the finite difference method to simulate extraction from a plasma and modelling particle trajectories without restrictions in symmetry. This general approach allows in particular to investigate the influence of misalignment and tilting effects of the extraction electrodes to the ion beam. In future experiments we will try to validate the quality of the alignment by emittance measurements. Deviations should be visible especially in comparison of the two transversal phase-spaces. With this method we also hope to get access to the thrust vector, which is sensitively depending on the grid alignment.

The simulation of ion extraction from a plasma is challenging due to the higher complexity of the physical

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<tr>
<td>screen thickness</td>
<td>( t_s )</td>
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<td>distance ( 2^{nd} - 3^{rd} ) grid</td>
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<tr>
<td>deceleration-grid thickness</td>
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Figure 10. Rms-emittances normalized on the screen electrode current for rf-powers of 15 and 20 W and for screen voltages of 750 and 1500 V. In the insets the corresponding screen currents are shown.

processes. In the plasma the space charge has to be compensated. In the plasma sheath region the electron density $n_e$ has to decrease as a function of the potential $\phi$ according to $\left( k = 1.38 \times 10^{-23} \text{ J K}^{-1} \right)$

$$n_e = n_{e,0} \times \exp \left( -\frac{\phi_P - \phi}{kT_e} \right).$$

Thus, the input file for a simulation with KOBRA requires besides the definition of the geometry, the plasma potential $\phi_P$, electron temperature $T_e$, ion temperature $T_i$, ion mass $M$ and ion current $I$. In addition, the boundary conditions of the box have to be set. The standard procedure is to set the left area of the problem box constantly on plasma potential and define the starting coordinates of the ions close to this surface (within one meshsize). The calculation of the plasma meniscus is done in an iterative self-organizing process, performed by creating a space charge map after the trajectory calculation and including this map in the next iteration for solving the Poisson equation until self-consistency is achieved. For a representative simulation the starting conditions of the ions have to be chosen correctly. The thruster electrode parameters used in the simulation are given in Table 1.

For the present simulation a mesh size of $180 \times 65 \times 65$ with 0.05 mm per mesh and 45000 trajectories were chosen. In this section we will discuss exemplary the simulation with 750 V screen grid and -150 V acceleration grid voltage for different plasma parameters. In Fig.11 the result of the simulation with an electron temperature of 7 eV, ion temperature 0.05 eV and 20 V plasma potential is shown. To indicate the shape of the meniscus the potential from 750 V to 770 V is also plotted in the lower panel of the figure. The plasma potential of 20 V was chosen due to measurements with a retarding potential analyzer, which was installed into the experimental setup recently. The result of the measurement with 750 V on the screen electrode is shown in Fig.12. An electron temperature of 7 eV and an electron density of $n_e = 1.66 \times 10^{17} \text{ m}^{-3}$ were measured directly inside the discharge chamber with a triple Langmuir probe. A ion current density $J$ of 3 mA cm$^{-2}$ was calculated using

$$J = \frac{1}{2} n_e e \sqrt{\frac{kT_e}{M}}$$

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Figure 11. Simulation of the ion extraction from the plasma with the single orifice three-electrode geometry of the investigated thruster. Screen voltage is 750 V, acceleration grid voltage -150 V, plasma potential 20 V and electron temperature 7 eV.

Figure 12. Retarding potential analyzer measurement (black symbols) for 750 V on the screen electrode. A plasma potential of about 20 V was determined from a Gauss-Fit (red curve) of the first derivative (blue curve).
Figure 13. Increase of the simulated emittance value due to the influence of space charge. The black curve is calculated with full space charge, the red curve uses a strong under-relaxation of space charge.

The simulation shows an acceptable focussing of the ion beam. The rms-emittance at 7 mm (referred to problem box) is 10.19 mm mrad. Due to space charge effects this value will increase as a function of distance from the thruster. The final coordinates and momenta of the particles from the extraction simulation have to be taken as input parameters for an additional simulation of the beam propagation in a bigger problem box. In a distance of 4 cm, which is equivalent to experimental conditions, the rms-emittance has grown to 149.6 mm mrad which is significantly higher than the experimental result of 28.8 mm mrad.

A possible explanation for this discrepancy has been given by Spädtke.\textsuperscript{18} The space charge of the primary beam can be compensated due to collisions of the primary beam with residual gas atoms. In these collisions secondary particles will be produced according to

\[ \text{ion}_{\text{primary}} + \text{residual gas atom} \rightarrow \text{ion}_{\text{primary}} + \text{ion}_{\text{residual gas}} + \text{electron} \]  

\[ (6) \]

The residual gas ions will be repelled out of the beam, the electrons will follow the primary ions due to their higher mobility and compensate the space charge. A similar effect occurs when primary or secondary ions collide with the acceleration electrode surface. Secondary electrons from this reaction will also compensate the space charge of the primary ion beam. It was mentioned that the minimal gas flow of 0.02 sccm seems to be still too high for a single orifice system. This assumption is supported by the uncommonly high currents on the acceleration electrode in all experiments. For instance, for 750 V we measured a current of 136 $\mu$A on the screen electrode, which represents the extracted ion current from the plasma. On the acceleration electrode we measured 23 $\mu$A, which is a loss of 17%. Typically, this value is around few percent of the screen grid current. Hence, the thruster is in an unusual working mode and it is obvious that the space charge is more compensated as expected in the simulation. A reduction of the influence of space charge performed with the method of under-relaxation of the space charge potential gives a rms-emittance of 35 mm mrad (see Fig.13). This value agrees much better with experiment, but there is still a need for improvement. On the theory side, secondary effects like interaction of the primary beam with the residual
A newly-built experimental setup has been presented that facilitates emittance measurements on ion beams extracted from a single orifice radiofrequency thruster. Comparisons with ion beam simulations performed with the KOBRA-3D code shows a rough agreement between experiment and simulation if the influence of space charge is suppressed. This seems to originate from an unusual working mode of the ion thruster due to a too high gas flow into the discharge chamber which leads to a high rate of collisions of primaries with the residual gas between screen and deceleration electrode. By future elimination of these experimental restrictions we hope to get more insight into the plasma and the extraction process by emittance measurements.

VI. Conclusion

A newly-built experimental setup has been presented that facilitates emittance measurements on ion beams extracted from a single orifice radiofrequency thruster. Comparisons with ion beam simulations performed with the KOBRA-3D code shows a rough agreement between experiment and simulation if the influence of space charge is suppressed. This seems to originate from an unusual working mode of the ion thruster due to a too high gas flow into the discharge chamber which leads to a high rate of collisions of primaries with the residual gas between screen and deceleration electrode. By future elimination of these experimental restrictions we hope to get more insight into the plasma and the extraction process by emittance measurements.
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