Overview of RIT Simulation Areas in Giessen with Focus on Plasma Simulation

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Designing and optimizing radio frequency ion thrusters (RITs) for applications in space are challenging and ongoing processes. Hereby, the simulation is an essential and well established tool. Thus, we model the ion optics of the gridded extraction system and the thermodynamic behaviour of the RIT. Furthermore, we apply the transformer model for the self-consistent numerical 1D/3D hybrid modeling of radio-frequency ion thrusters. All these descriptions have in common the necessity of knowing the plasma parameters inside the discharge vessel. Especially for the μN-RITs, these values are tediously to measure without influencing the discharge due to the small size of discharge chamber. As a result of this we have developed our fully three dimensional particle in cell (PIC) code "PlasmaPIC" from scratch. Using this tool we are now able to predict plasma parameters inside the discharge chamber. We will give an overview of the mentioned simulation activities in Giessen and show simulation results as well as comparisons with the experiment.

Nomenclature

RIT	= radio frequency ion thruster
$PIC - MCC$	= particle in cell — monte carlo collision
RF	= radio frequency
$ECRIS$	= electron-cyclotron resonance ion source

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I. Introduction

The focus of the project "RITSAT" funded by the state of Hesse lies on the understanding and optimization of μN-RITs. Building different μN-RITs and testing of them are time consuming and in part expensive, so that an alternative strategy is of great interest. Modelling the whole thruster can resolve these issues and in addition it is a non intrusive method for determining parameters in contrast to most measurements by experiments. Therefore, one part of this project is to describe the whole thruster by simulations. We apply a self-consistent numerical 1D/3D hybrid modeling of radio-frequency ion thrusters to determine the coupling efficiency of the RF generator and the plasma. The thermal modelling is performed using "Comsol" and the ion optics are simulated with the simulation tool "Kobra". For all these simulations precise knowledge of the plasma parameters inside the inductively coupled plasma discharge is required. To obtain these parameters a three dimensional PIC code "PlasmaPIC" was developed from scratch. Using this tool plasma parameters can be calculated with a high spatial and temporal resolution. In the following we will present the single simulation areas briefly. We will show some interesting aspects of each area. For detailed information we will refer to the corresponding IEPC proceedings.

II. Self-Consistent Numerical 1D/3D Hybrid Modelling of Radio-Frequency Ion Thrusters

In this paper, we show a numerical model of gridded radio-frequency (RF) ion thrusters. The model is based on a set of self-consistently coupled conservation equations for charge, energy, and mass inside the system. The charge conservation is realized by implementation of the Uniform Density Discharge Model introduced by Lieberman et al.[1] and Lee et al.[2]. The 1D models are coupled to a 3D quasi-stationary electromagnetic field solver which offers the opportunity of evaluating arbitrary induction coil and discharge chamber geometries in fairly reasonable simulation time. Several input parameter sets can be computed in parallel due to multi-core implementation. Therefore, the presented model can be regarded as a toolbox for ion thruster engineering purposes and rapid virtual prototyping.

The model predicts electrical parameters such as thruster and plasma impedance as well as propulsive performance data. It is thus possible to use it for finding optimized coil and chamber geometries together with optimized input parameters (coil current, volumetric propellant flow rate, and extraction grid voltages) in order to obtain improved mass and electrical efficiency, as shown in figure 1.

To prove the validity of the model, performance mappings experimentally performed on a RIT 4 ion thruster assembled at the University of Giessen are used to verify the computed data, as can be seen in figure 2.

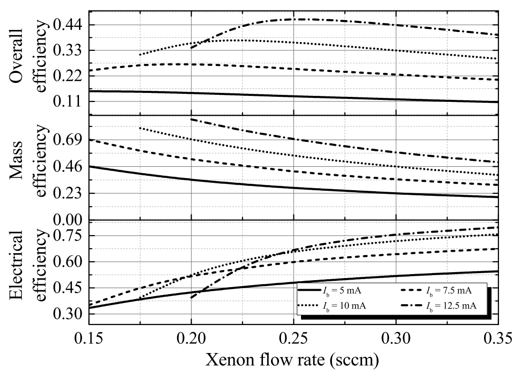


Figure 1. Electrical, mass and overall efficiency as a function of the mass flow rate.

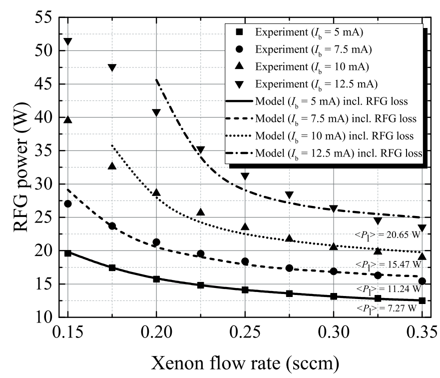
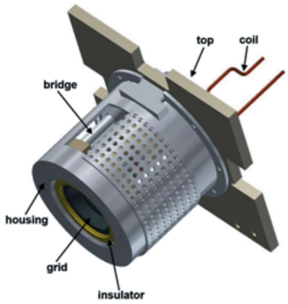


Figure 2. Comparison of the simulation with the experiment for a RIT 4 ion thruster.

III. Thermal Modelling

For the thermal design of the satellite it is important to know the thermal behavior of the thruster, which is one of the hottest components. Some parts of the satellite, especially the electronics are thermally sensitive and have to be protected against excessive heat. In addition to the thermal distribution, the thermal simulation contains information about power losses in the thruster and thus about its efficiency, because the thruster is not only heated by the plasma, but also by direct ohmic losses and eddy current losses. At the University of Giessen we have developed a thermal model[3,4] of the thruster using the program "Comsol"[5]. The model combines an electromagnetic and a thermal simulation. With the help of the electromagnetic simulation we analyze the heat sources due to power losses in the thruster. To determine the power deposition into the plasma, we use plasma simulation programs that are presented in this proceeding. We also have the ability to calculate the plasma conductivity analytically and are thus able to determine the power deposition into the plasma using the electromagnetic simulation. For this purpose we need knowledge of the neutral particle density, the plasma density and the electron temperature. Another way to determine the power deposition into the plasma is the analysis of the power consumption of the RF generator. To check the results of our model we have built up an extended experiment. In this experiment we have measured the coil current by a current monitor and the temperatures with the PT-100 sensors. The results of the simulation and the values experimentally determined are shown in figure 3.

	measured	simulated	deviation
T_{coil}	133.2 °C	136.6 °C	2.6%
$T_{chamber}$	143.2 °C	142.9 °C	0.2%
T_{top}	79.8 °C	77.3 °C	3.1%
$T_{housing}$	83.1 °C	78.0 °C	6.1%
$T_{insulator}$	85.1 °C	81.5 °C	4.2%
T_{bridge}	89.3 °C	82.8 °C	7.3%
T_{grid}	91.6 °C	91.0 °C	0.7%
$T_{contact\ surface}$	15.6 °C		



	heat sources
plasma:	1.85 W
induction coil:	2.45 W
grid system:	0.52 W
housing:	0.08 W
residual parts:	0.19 W

control parameter of the thruster:

coil current : $I_{\mathrm{coil}} = 5.66\,\mathrm{A}$

mass flow : $\dot{m} = 0.15\,\mathrm{sccm}$

positive voltage : $U_p = 1200\,\mathrm{V}$

negative voltage : $U_n = 150\,\mathrm{V}$

extractions current : $I = 3.1\,\mathrm{mA}$

Figure 3. Comparison of the thermal simulation with the experiment of a working thruster.

IV. Modelling of the Ion Thruster Optics

Ion-optical simulations can be performed with the "KOBRA3-INP" code[6,7]. "KOBRA" has been used for a few decades to simulate different kinds of ion sources like electron-cyclotron resonance ion sources (ECRIS). It solves the Vlasov equation in three dimensions by using the finite difference method to simulate extraction from a plasma and models particle trajectories without any restriction in symmetry. With this it is possible for instance to study misalignment effects in multiple grid extraction system. A space charge map is created during the ion-ray-tracing. Hence, the actual space charge map always belongs to the previous potential map. A self consistent charge distribution is found by an iterative process. The code is equipped with an sputtering model to calculate the grid erosion of the extraction system of a gridded ion source. The figures 4 - 6 show a comparison of the "KOBRA" code with a particle in cell calculation by Lingwei et al.[8]

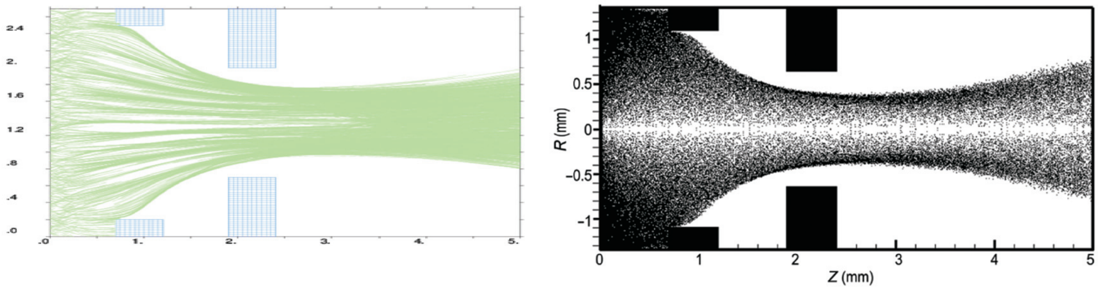


Figure 4. Comparison of the KOBRA code (left) with a particle-in-cell calculation by Lingwei et al[8] (right) using the same grid geometry and plasma conditions as given there. Both simulations reflect the same behaviour of the extracted ions.

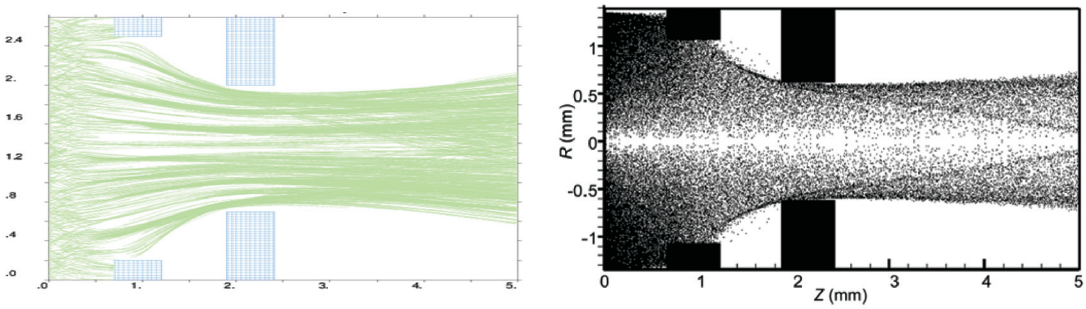


Figure 5. Comparison of the KOBRA code (left) with a particle-in-cell calculation by Lingwei et al[8] (right) with under-focusing conditions of the ions.

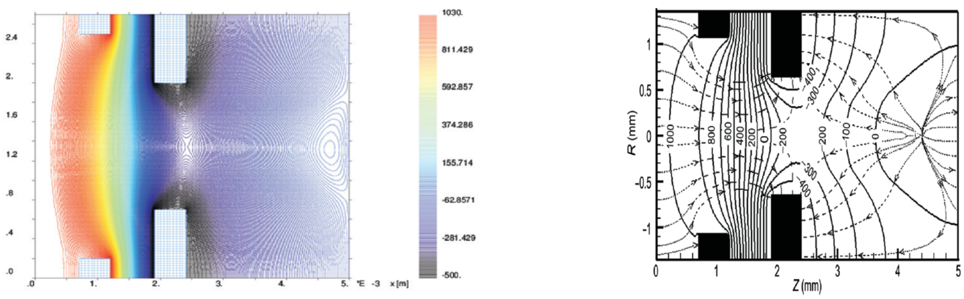


Figure 6. Comparison of the KOBRA code (left) with a particle-in-cell calculation by Lingwei et al[8] (right) for the potential map.

V. Three-dimensional Plasma Discharge Modelling using "PlasmaPIC"

For modelling the inductively coupled plasma discharge we have developed "PlasmaPIC" from scratch[9, 10]. It is a fully three-dimensional explicit particle in cell — monte carlo collisions (PIC-MCC) code[11–13]. To handle the tremendous computational effort we parallelized all elements of the PIC algorithm and paid special attention for the field solver, which has the highest amount of communication. The parallelization efficiency has an excellent behavior up to a few hundred cpu cores[9]. The field solver itself is divided into an electrostatic part for solving the Poisson equitation and an electromagnetic part for calculating the electric and magnetic fields arising from the currents of the coil and the electrons[14, 15]. The applied algorithm for solving both parts is the finite difference method successive over relaxation (SOR). For advancing the charged particles the leap-frog method is used. For the MCC part a constant neutral gas distribution in time is assumed and the collision of the electrons with the neutral gas the elastic scattering, excitation and ionization are included. For the collisions of the ions with the neutral gas the elastic scattering and charge-exchange collisions are incorporated. One of the greatest advantages of "PlasmaPIC" is the ability to create arbitrary three-dimensional geometries with a CAD program and import these. The imported geometry as well as a schematic of an μN-RIT 1.0 is shown in figure 7. It shows the coil (red) spirally surrounding the discharge chamber (light gray) and the two extraction grids (dark gray). The diameter of the discharge vessel is 10 mm and the inner height is 9.2 mm. For this geometry we performed a plasma discharge simulation. The working gas is xenon. The input parameter used for the power deposition is 0.08 watt. The coil consists of five turns and operates at a frequency of 5 MHz. The neutral gas density is at $2 \cdot 10^{20}$ particles per cubic meter. At the first grid 1500 V and at the second grid 150 V are applied. After 30 RF cycles the simulation has reached the steady state. Figure 8 shows the electron density. The slight asymmetry in the electron density is due to the slope of the coil and can only be observed with a three dimensional simulation. Furthermore, first qualitative comparisons with experiment were completed and were in good agreement.[10]

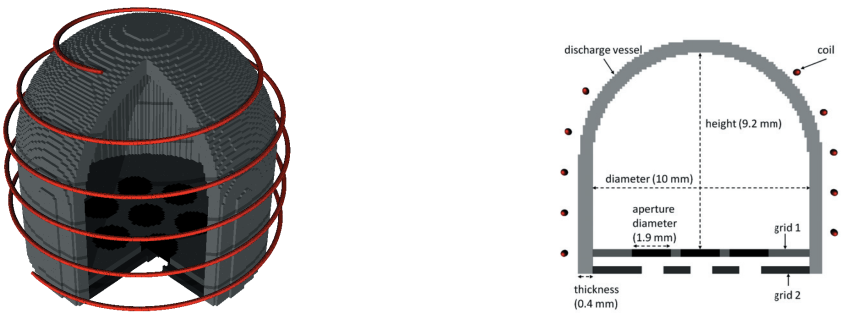


Figure 7. Three dimensional overview (left) and two dimensional schematic (right) of the μN-RIT 1.0 used in "PlasmaPIC"

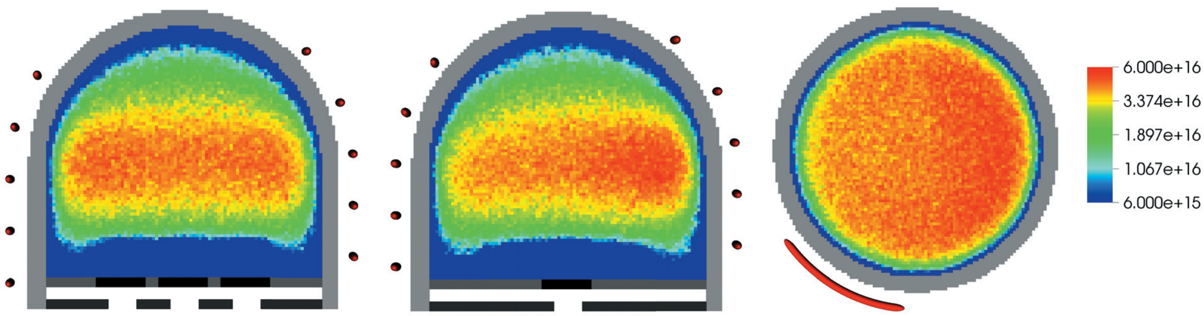


Figure 8. Electron density in 1/m^3 for a μN-RIT 1.0: x-z plane (left), y-z plane (middle) and x-y plane at position 4 mm above grid 1 (right).

VI. Conclusion

At the University of Giessen we have established a wide area of modelling μN-RITs during the last years. The thruster simulation encompass the transformer model for the coupling of the RF generator and the plasma, the three dimensional thermal modelling, the ion optics modelling, and the modelling of inductively coupled plasma discharge using the self-developed “PlasmaPIC” tool. All these areas of simulation are dependent on each other and only by interlocking all areas a complete and precise modelling of the whole thruster is possible. We have shown that the simulation results are in good agreement with the experiments. We are now on the verge of predicting performance parameters for new designs of our thrusters.

Acknowledgments

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