Validation and Extension of the PlasmaPIC Code for Plasma Modelling in Radio-Frequency Ion Thrusters

Final Report

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I. Objectives

I.1 Overall Project Objective

Radio-frequency ion thrusters (RITs) have been investigated at Justus Liebig University Giessen for many years. Alongside experimental research, plasma simulation has become a central pillar of this work. The project aimed to systematically validate and extend the PlasmaPIC simulation code developed in Giessen, enabling a realistic description of the physical processes occurring in RITs.

Simulating the plasma in an RIT is particularly challenging: low plasma densities require a kinetic, particle-based description, while the extraction grids must be represented in three dimensions. Reliable validation against experimental measurements is essential before such simulations can be used confidently in academic and industrial research. Comprehensive plasma simulations can then serve as a reference for assessing simplified engineering models and identifying their ranges of validity.

In addition to modelling the discharge plasma, realistic simulation of ion extraction through the grids was a key objective. The three-dimensional structure must be represented accurately because the arrangement and geometry of the grid apertures strongly influence the extracted beam.

Approximate methods were also needed for larger RITs. Because the computational cost of fully three-dimensional simulations increases substantially with thruster size, a two-dimensional description was pursued as a practical alternative. This approach captures the main physical processes in larger thrusters while treating extraction separately in a three-dimensional model.

The overall objectives can be summarized in three main points:

- Validation of the PlasmaPIC simulation code developed in Giessen

  Detailed characterization of ion extraction and beam properties

  Development of a two-dimensional modelling method for large RITs

I.2 Relevance to DLR Funding Objectives

Electric propulsion is a key technology for future satellite missions. With RIT (ArianeGroup) and HEMPT (Thales), Germany already holds a strong position in international competition. Simulation can make a major contribution by improving physical understanding and reducing the need for extensive experimental campaigns, particularly long-duration tests.

The validation and extension of PlasmaPIC undertaken in this project established a basis for more efficient development of innovative technologies, shorter development cycles and reduced costs. The project therefore directly supports DLR objectives of strengthening the competitiveness of German industry and advancing scientific and technical excellence in electric propulsion.

The project also provided an excellent platform for training students and early-career researchers in numerical plasma physics and electric space propulsion, helping to strengthen long-term expertise in this strategically important field.

I.3 Scientific and Technical Objectives

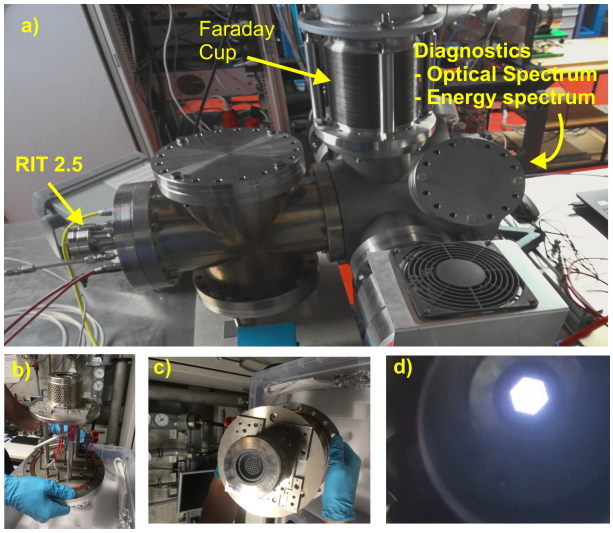
The main scientific and technical objectives were:

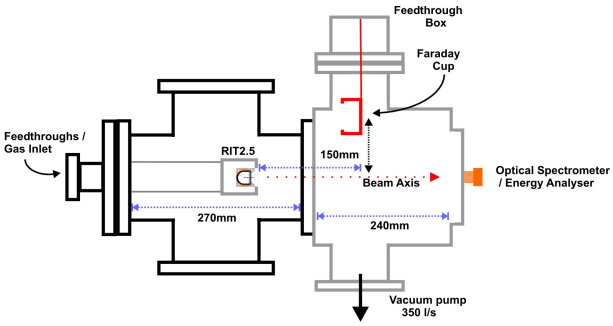
1. Validate PlasmaPIC against experimental measurements from RITs and established engineering models.

2. Develop and implement an ion-extraction module to describe the ion beam immediately downstream of the grids with quantitative and geometric accuracy.
3. Develop a two-dimensional modelling approach for large RITs that combines realistic physics with reduced computational cost.
4. Optimize algorithms and reduce runtimes to make PlasmaPIC practical for complex geometries and extended simulation times.

Summary of the Experimental Investigations

A dedicated test facility was designed and constructed to investigate the RIT-2.5 radio-frequency ion thruster. It enabled targeted measurements of key plasma parameters, particularly electron temperature, and of the extracted ion beam. The RIT-2.5 was operated in a vacuum chamber connected to a diagnostics chamber, allowing flexible deployment of different instruments.





The ion beam was initially characterized using a Faraday cup to determine the extracted current as a function of operating parameters, including mass flow rate, input power and extraction voltage. An optical spectrometer was used to estimate the plasma electron temperature by a line-ratio method based on xenon emission lines. This non-invasive approach is particularly suitable for sensitive discharge plasmas where intrusive diagnostics, such as Langmuir probes, may be impractical.

The energy distribution of the extracted ions was also measured using a retarding-field energy analyser (RFEA). In combination with simulations, the shape of the measured energy spectrum provides information on the plasma density and electron temperature inside the discharge chamber. This enabled indirect assessment of parameters that are difficult to measure experimentally.

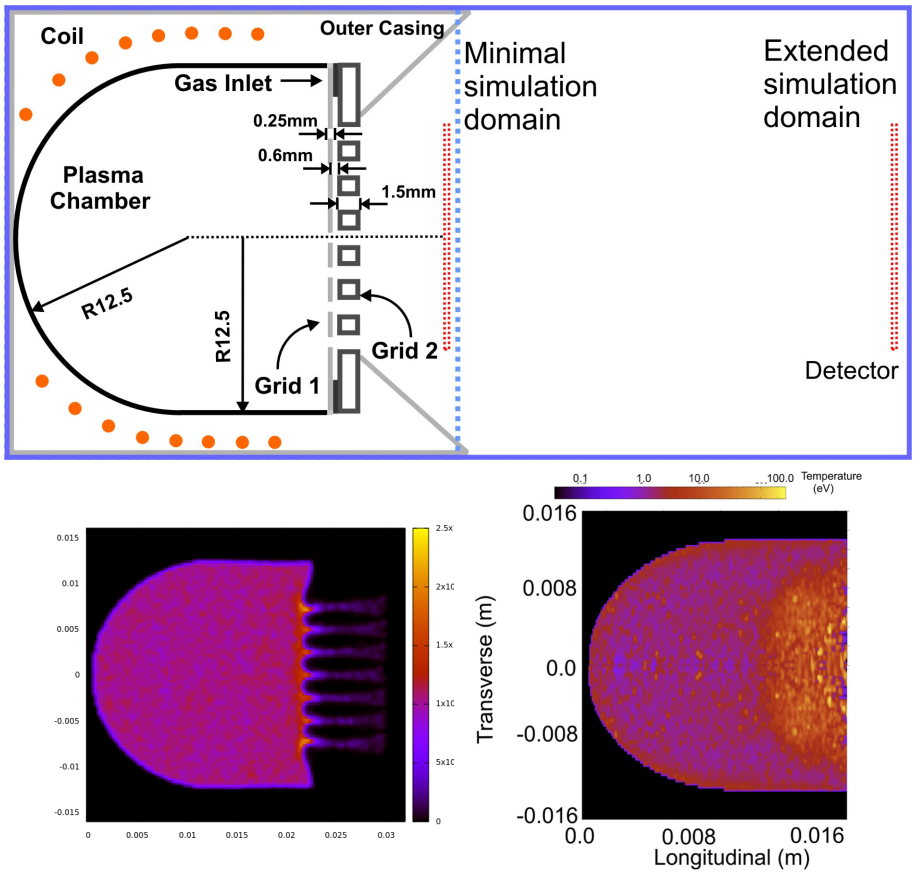
These measurements provided a central experimental basis for validating the PlasmaPIC numerical models. Direct comparisons between simulations and experiments allowed relevant parameter ranges to be tested and the simulation model to be refined. In particular, agreement between measured and simulated energy

distributions supports the reliability of the code and enables studies of operating regimes that are difficult to access experimentally.

The experimental programme thus served both to characterize the RIT-2.5 and to establish a reference for further development and validation of the simulation methods. The resulting framework can support future optimization of the RIT-2.5 as well as investigations of grid erosion, ion-beam deflection and alternative propulsion concepts.

Comparison of Simulation and Experiment

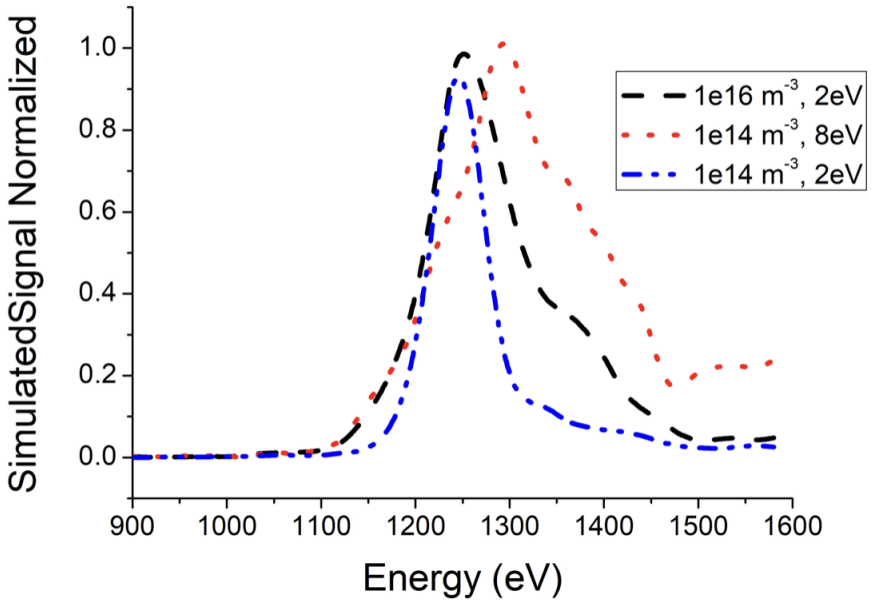
Particle-in-cell (PIC) simulations using the in-house PlasmaPIC code were performed to interpret the measured energy distribution functions (EDFs). The simulation-domain figure shows a two-dimensional region comprising a reduced model for characterizing the discharge plasma and an extended domain for modelling ion outflow and extraction. A virtual detector plane, 1 mm thick, was defined near the outer boundary to record ion trajectories. This enabled reconstruction of longitudinal energy spectra and transverse phase-space distributions of the extracted ions.



Representative results are shown in the simulation-results figure. The plasma-density and electron-temperature distributions reveal the formation of a plasma sheath near the extraction apertures. Accelerated ions form a focused beam in this region. A narrow peak appears in the energy distribution immediately downstream of the extraction boundary, while farther downstream the individual grid apertures become visible in the phase-space representation.

Typical experimental parameters were assumed in the simulations, including a plasma density of $n_e = 1 \times 10^{15}$ m^{-3} and an electron temperature of $T_e = 2$ eV. The resulting average plasma parameters were compared with the experimentally measured EDFs. Particular attention was paid to the EDF width, which is sensitive to changes in density and temperature.

Because direct density measurements inside the discharge chamber were not possible without intrusive diagnostics (e.g. Langmuir probes), an indirect approach was adopted. The EDF width measured with the RFEA was systematically compared with PIC simulations. The corresponding figure illustrates simulated



EDFs for different plasma densities and electron temperatures. Both peak position and spectral width depend on n_e and T_e, with higher densities producing broader distributions.

Detailed comparison of measurements and simulations showed that low densities reproduce the peak position but underestimate the measured width. Very high densities, by contrast, produce excessive peak shifts and unrealistic distributions. The best agreement with the experimental data was obtained for a plasma density of approximately $n_e = 1.2 \times 10^{16}$ m^{-3} at an electron temperature of $T_e = 4.5$ eV.

An additional parameter study supported this relationship, revealing an approximately linear dependence of EDF full width at half maximum (FWHM) on plasma density. This comparison enabled an estimate of the discharge plasma density and provided an important validation of the simulation methodology.

Overall, the comparison demonstrates that combining experimental RFEA diagnostics with kinetic PIC simulations provides a robust approach for investigating ion thrusters. It enables plasma conditions to be quantified even when direct measurements are unavailable and supplies valuable validation data for further numerical-model development.

Conference Contributions and Publications

1. Prospects of kinetic plasma simulation using PlasmaPIC-Cyl code for grid erosion studies, N. Joshi, submitted to J. Electric Prop.
2. Three dimension Particle in Cell simulation of a radio frequency ion thruster (RIT2.5) : model validation with experiments, N. Joshi, O. Meusel, C. Heiliger, J. Electric Prop., preprint on Research Square
3. 3. 2.xD - Particle in Cell simulation of a radio frequency ion thruster RIT2.5 using cylindrical coordinate system: model validation with experiments, N. Joshi, P. Auffarth , C. Heiliger, J. Electric Prop., preprint on Research Square
4. 2.xD - simulation of a radio frequency ion thruster, N. Joshi, P. Auffarth , C. Heiliger, Conf. Proc. IEPC 2024 Toulouse, France
5. Holistic Modelling of erosion processes in Radio- frequency ion thrusters, K. Keil, N. Joshi, K. Holste, C. Heiliger, P. Kar, Conf. Proc. SPACE PROPULSION 2024 Glasgow, Scottland
6. Particle-in-Cell Simulation of radio-frequency ion thruster RIT-1.0, N. Joshi, C. Heiliger, J. Elec. Propuls 3, 2024
7. Fluid-Kinetic-Hybrid Simulation for Ion Thruster using Polymorphic Particles, Ninad Joshi and Christian Heiliger, J. Electric Prop. 2, 2023

8. Particle in Cell simulation for large Radio-frequency ion thrusters using 3D cylindrical coordinate system, N. Joshi, P. Auffarth, C. Heiliger, Conf. Proc. IEPC 2022 Boston, USA
9. Modelling of erosion processes in gridded ion engines in combination with global model for radio-frequency ion thruster, K. Keil, N. Joshi, K. Holste, C. Heiliger, P. Kar, Conf. Proc. IEPC 2022 Boston, USA
10. Ion optic simulation with the Particle in Cell simulation and Calculation of Grid Erosion, K. Keil, N. Joshi, K. Holste, C. Heiliger, P. Kar, Conf. Proc. SPACE PROPULSION 2022 Estoril
11. Ion thrusters for electric propulsion: Scientific issues developing niche technology into a game changer, K. Holste et al, Rev. Sci. Instr. 2020

II. Results Achieved

The project delivered substantial advances in the development and validation of the PlasmaPIC simulation software developed in Giessen. The main results are summarized below:

II.1 Further Development of PlasmaPIC

The existing PlasmaPIC code was substantially extended and optimized, increasing its versatility and computational performance. In particular, runtimes were reduced and numerical stability was improved, enabling more complex scenarios and longer simulations to be calculated efficiently.

II.2 Development of PlasmaPIC-Cyl

A major milestone was the development of PlasmaPIC-Cyl, a new version designed specifically for kinetic plasma simulations in cylindrical or rotationally symmetric geometries. This tool substantially facilitates realistic modelling of radio-frequency ion thrusters and comparable configurations.

II.3 Validation and Comparison with Experiments

Validation studies demonstrated good agreement between results from PlasmaPIC and PlasmaPIC-Cyl, experimental data and established simulation packages. This supports the reliability and predictive value of the methods developed. The resulting validated simulation tools can serve as references in both academic and industrial settings.

II.4 Broad Range of Applications

The developed codes enable a wide range of applications:

- Design and optimization of ion thrusters, including studies of plasma distributions, beam properties and efficiency.

  Studies of grid erosion and interactions between the ion beam and extraction grids.

  Analysis of ion bombardment of sensitive surfaces, such as solar panels, to support investigations of satellite service life.

  Applications to innovative concepts such as atmosphere-breathing electric propulsion (ABEP) and, in the longer term, fusion-based space propulsion concepts.

II.5 Extensibility to New Research Areas

The project also established a foundation for future extensions of PlasmaPIC through additional modules, for example:

- a computational fluid dynamics (CFD) module for detailed flow modelling in hybrid propulsion concepts;

an electromagnetic (EM) module for investigating wave propagation and coupling effects, including applications in ionospheric physics.

Mile-stone	Original timestamp	Task	Renewed timestamp
MS 1	Q4/ 1. Year	Validation of PlasmaPIC with RIT 4.0->2.5	Done
MS 2	Q1/ 2. Year	Implementation of Extraction	Done
MS 3	Q2/ 2. Year	2D model will be finished	Done
MS 4	Q4/ 2. Year	Extraction implemented with domain decomposition	Done
MS 5	Q1/ 3. Year	Optimization of 2d Modell	Done
MS 6	Q1/ 3. Year	2D model validation 4.0 -> 2.5	Dane
MS 7	Q4/ 3. Year	Extraction of RIT4 validation	Done
MS 8	Q4/ 4. Year	Scaling laws	
MS 9	Q2/ 5. Year	Extraction optimization	Done
MS 10	Q2/ 5.Year	Final report	Done

The project thus achieved the main objectives of the funding proposal while establishing a basis for the continued development and long-term use of PlasmaPIC in research and applications.