Self-consistent Simulation of the Coupling Between Plasma and Neutral Gas in μN-RIT

IEPC-2011-323

Presented at the 32^{nd} International Electric Propulsion Conference,
Wiesbaden, Germany
September 11–15, 2011

R. Henrich[*], D. Feili[†] and C. Heiliger[‡]
I. Physikalisches Institut, Justus Liebig University, 35392 Giessen, Germany

This paper deals with the up to now rf plasma simulation using PIC-MCC method for μN-RITs. Beside the RF generator and coil parameters a main input parameter for the plasma discharge modeling is the neutral gas density profile inside the thruster. At first, we investigated these profiles depending on the gas inlet position, grid configuration, and amount of gas flow. To handle this task we used the software Flowsim which had been developed at the *I. Physikalisches Institut* of the University of Giessen. We will present results for a simplified μN-RIT with a cylindrical discharge chamber. Further, we will show the dependence of plasma and neutral gas distributions within the ionization chamber. As a consequence a self-consistent combination of the plasma and neutral gas modeling is not necessary.

Nomenclature

$\mu N - RIT$	= μNewton Radio-frequency Ion Thruster
PIC	= Particle In Cell
$PIC - MCC$	= Particle In Cell - Monte Carlo Collisions
$DSMC$	= Direct Simulation Monte Carlo
$sccm$	= standard cubic centimeter per minute
RF	= Radio-Frequency

[*]PhD student, Justus Liebig University, Robert.Henrich@physik.uni-giessen.de.
[†]Dr., Justus Liebig University, Davar.Feili@physik.uni-giessen.de.
[‡]Prof. Dr., Justus Liebig University, Christian.Heiliger@physik.uni-giessen.de.

I. Introduction

Ion propulsion systems with small thrusts and high accurate controllability while possessing low power and propellant consumption are a need for many of upcoming space missions. A very promising thruster concept is a radio frequency ion thruster with μN thrusts (μN-RIT)[1]. However, further optimizations of μN-RIT have to be carried out to fit the high requirements of space missions especially power demand. The optimization of the system can only be done in an interactive exchange between experiment and simulation. The state-of-the-art μN-RIT 2.5 (fig. 1) is the object of investigation in this paper. The 2.5 indicates the diameter of the discharge vessel, working in 10^{-3} mbar region, the low neutral gas density 10^{19} to 10^{20} particles/m^3 and plasma density 10^{16} to 10^{17} particles/m^3 requires the use of a particle in cell (PIC) algorithm[2] to resolve the moderate particle interactions correctly. In this paper we give an overview of the up to now used plasma simulation tool. Furthermore we discuss the influence of various parameters on the neutral gas density profile which is an important input parameter for the plasma simulation.

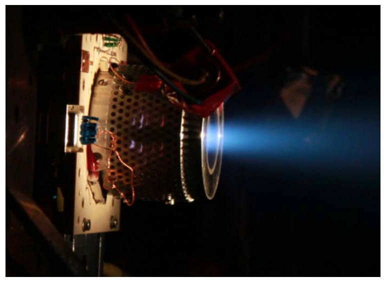


Figure 1. μN-RIT 2.5

II. Model for μN-RIT Simulation

The main parts of the plasma simulation program rely on xoopic[3] which is a 2D rotationally symmetric PIC tool with a 3D velocity treatment. In such a simulation only one plane of a cylinder with the edges radius and length is considered. Every movement in ϕ-direction will be projected in this plane. The field calculations in r-z-direction are done by solving the Poisson's equation every time iteration step. Taking into account the discharge chamber surrounding coil, we implemented an additional algorithm calculating the upcoming E-M field[4,5]. At this the complex amplitude of the azimuthal induced electric field is derived in cylindric coordinates by equation (1). The magnetic field components in r and z direction can be calculated by solving $\frac{\partial \tilde{\vec{B}}}{\partial t} = -(\nabla \times \tilde{\vec{E}})$ for $\tilde{E}_\phi$ (eqautions. (2) and (3)).

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r}\epsilon_0\mu_0\omega^2 - \frac{1}{r^2} + \frac{\partial^2}{\partial z^2} \right) \tilde{E}_\phi = i\omega\mu_0(\tilde{J}_c + \tilde{J}_p) \tag{1}$$

$$\tilde{B}_z = -\frac{i}{\omega r}\frac{\partial}{\partial z}(r\tilde{E}_\phi) \tag{2}$$

$$\tilde{B}_r = \frac{i}{\omega}\frac{\partial}{\partial z}\tilde{E}_\phi \tag{3}$$

ω : frequency of the coil
$\tilde{J}_c$: complex current density amplitude in coil
$\tilde{J}_p$: complex current density amplitude of plasma

Finally, the power deposition P into the plasma is given by equation (4).

$$P = \frac{1}{2}Re(\tilde{J}_p^* \tilde{E}_\phi) \tag{4}$$

II.A. Plasma - Neutral Gas Interaction

Xoopic is a so called particle in cell monte carlo collision (PIC-MCC)[6] simulation including the collision reactions between the charged particles and the neutral gas. Here the neutral gas distribution is a required constant input parameter. Elastic, inelastic and ionizing collisions are also considered. During the collision evaluation a neutral gas particle is created to calculate the post collision velocity of the incident particle by solving the energy and momentum equations. Afterwards the created neutral particle will be removed from the system without affecting the neutral gas temperature and density.

II.B. Neutral Gas Density Distribution

Measuring the neutral gas density distribution is not practicable for the small dimensions of the μN-RITs. Thus the neutral gas distribution is simulated by a direct simulation monte carlo (DSMC)[7,8] procedure which is based up on the tracking of superparticles. By discretizing in space and time the particle interactions are also considered. The 3D simulation of the DSMC is the main baseline of Flowsim developed at the University of Giessen. This code assumes a diffuse particle interaction at the model boundaries where the reflected velocity vector of the particle is independent of the incident angle and distributed by a sine-cosine function. The main feature of Flowsim is the possibility of simulating arbitrary 3D geometries.

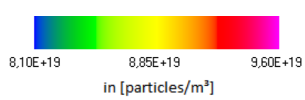
III. Flowsim Simulation of a μN-RIT

Calculations for the discharge vessel of a μN-RIT regards various gas inlet positions, grid configurations as well as different mass flows are already realized. This includes two different neutral gas inlets at top and bottom and a grid with 13, respectively 37 apertures. The first grid configuration had been evaluated for mass flows in the range of 0.17 to 0.21 sccm and the second one in the range of 0.06 to 0.08 sccm to meet the operation pressures. The temperature of the boundaries and the exiting neutral gas particles is set to 300 K for all simulations. The results of the above mentioned simulations are shown in table 1. The following 2D

Table 1. Average densities for different system parameters [10^{19}m^{-3}]

mass flows [sccm]	0.06	0.07	0.08	0.17	0.19	0.21
13 apertures; top inlet	6.94	8.04	9.18	-	-	-
13 apertures; bottom inlet	6.96	8.11	9.24	-	-	-
37 apertures; top inlet	-	-	-	6.99	7.82	8.65
37 apertures; bottom inlet	-	-	-	6.93	7.75	8.60

density profiles are cut planes of a 3D simulation. They are perpendicular and centered to the circular base of the vessel. As expected the average density is rising with the mass flow. The gas inlet position has no noticeable effect for the emerging average density. Nevertheless the inlet position is of greatest interest for the neutral gas density distribution (fig. 2 and fig. 3).



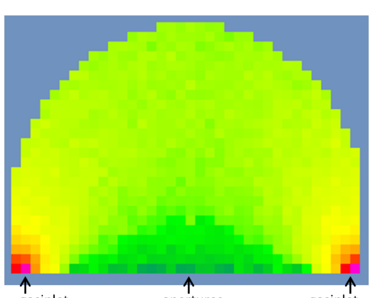


Figure 2. 2D density profile: bottom gasinlet, 37 apertures, 0.21 sccm massflow.

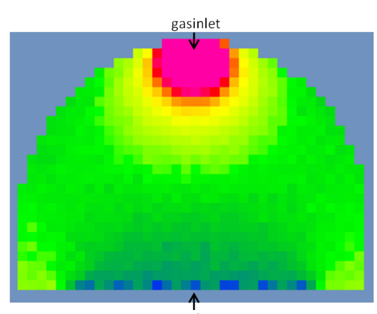
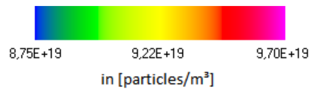


Figure 3. 2D density profile: top gasinlet, 37 apertures, 0.21 sccm massflow.

Furthermore an inhomogeneous density profile is revealed. An additional outcome is the dependence of the number of apertures and the resulting density distribution. A lower number of apertures leads to a more homogeneous density profile (fig. 4 and fig. 5). Note the different scale range for figure 2 and 3 and figure 4 and 5.



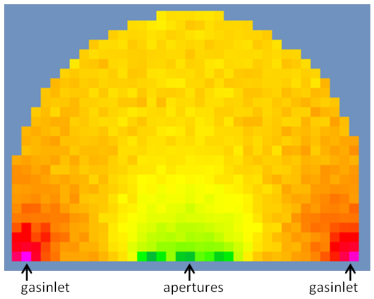


Figure 4. 2D density profile: bottom gasinlet, 13 apertures, 0.08 sccm massflow.

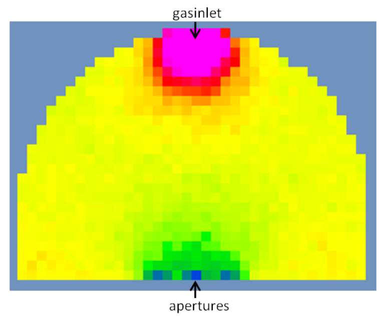


Figure 5. 2D density profile: top gasinlet, 13 apertures, 0.08 sccm massflow.

IV. Plasma Simulation Results

The initial simulations are done for a cylindrical μN-RIT with a diameter of 2.5 cm and a length of 1 cm. The results are based up on a frequency of 3 MHz, a current of 4 A and an average neutral gas density of $8 \cdot 10^{19}$ Particles/m^3. As expected the simulation confirms a substantial decrease of the electric field (fig. 6) from the outer boundaries to the center of the discharge vessel. This is due to the azimuthal RF eddy field and the plasma screening. Despite the decreasing plasma density (fig. 7), the deposit power (fig. 9) into the plasma is located at the outer regions of the vessel. As shown in figure 8 the ionization rate is dominant at

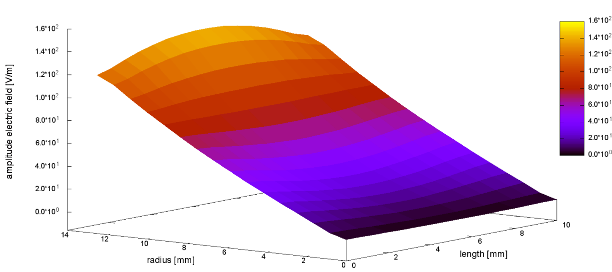


Figure 6. induced electric field amplitude in ϕ-direction

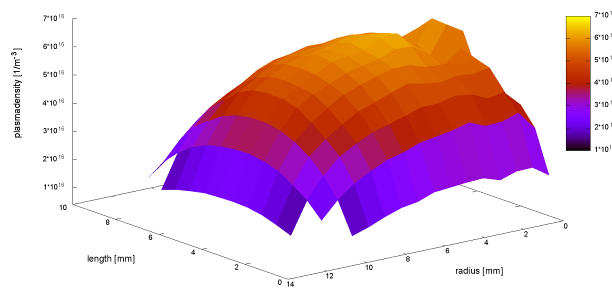


Figure 7. plasma density

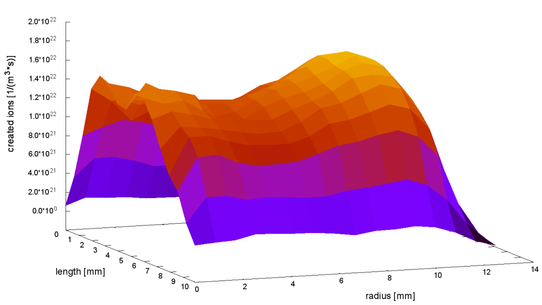


Figure 8. average ion production

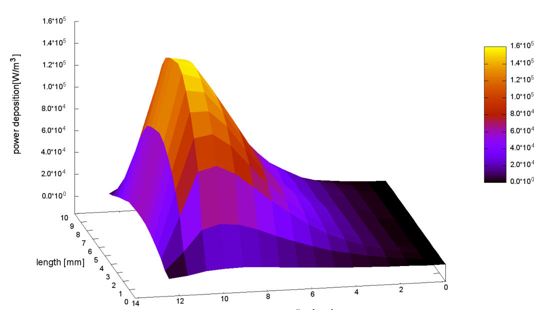


Figure 9. average power deposition to plasma

the outer regions which can be explained by the local high power deposition. The raising of the ionization rate as well as the abrupt jump of the plasma density near the center of the thruster is attributable to the cylindrical grid, because the cell volume drops to zero. It is obvious that a high ion production has a need of a sufficient subsequent local delivery of neutral gas. Assuming a 1D case (fig. 10) the neutral gas is ionized in region I and will recombine at the boundary in region II ($\vec{j}_{created\ ions}$). The quantity of this current depends on the ionization rate (R) as well as the ratio of volume to surface. In the steady state this current has to be equal to the current of the neutral gas ($\vec{j}_{gas}$) resulting from the difference in density (Δn). Postulating the same mean velocity $\bar{v}$ in both regions leads to

$$\frac{1}{2} \cdot R \cdot \frac{Volume}{Surface} = \Delta n \cdot \bar{v} \tag{5}$$

Approximately the density will change in the range of one percent in this simple model for a cube with 1 cm edges and for the up to now calculated ionization rate of $1.8 \cdot 10^{22}$ s^{-1}. Against earlier assumptions of a higher ionization degree a self-consistent plasma neutral gas calculation seems not to be necessary for these values.

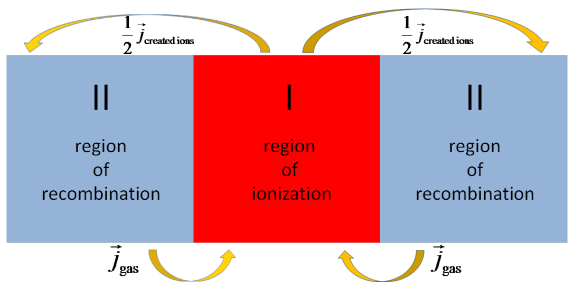


Figure 10. 1D model of the occurring currents

V. Concluding Remarks

The 3D DSMC neutral gas simulation with Flowsim demonstrates the smoothing influence of the bottom gas inlet location on the neutral gas distribution inside the μN-RIT without influencing the average density. Furthermore the bottom gas inlet leads to a better neutral gas supply in the outer ion production regions. We showed that the plasma production areas are located at the outer regions. Although the ionization rates are high compared with other plasma discharges, our results show that there is no necessity for using a self-consistent treatment of plasma and neutral gas at these parameters.

References

[1]Davar Feili, Davina M. Di Cara, Hans J. Leiter, Jose G. Del Amo, Horst W. Loeb, Stefan Weis, Danny Kirmse, Hans Mueller and Bruno K. Meyer, "The μN RIT-4 Ion Engine: a first step towards a European mini-Ion Engine System development," *IEPC-2007-218*, The 30th International Electric Propulsion Conference, Florence, Italy , 2007.

[2]C. K. Birdsall, A. B. Langdon, "Plasma Physics Via Computer Simulation," 1997.

[3]J.P.Verboncoeur, A.B. Langdon, N.T.Gladd, "An object-oriented electromagnetic PIC code," *Comput. Phys. Commun.*, Vol 87, 199-211, 1995.

[4]K.-I.You, N.S.Yoon, "Discharge impedance of solenoidal inductively coupled plasma discharge," *Phys. Rev. E*, 59, 6, 1998.

[5]Yoshinori Takao, Naoki Kusaba, Koji Eriguchi and Kouichi Ono, "Two-dimensional particle-in-cell Monte Carlo simulation of a miniature inductively coupled plasma source," *Journal of Applied Physics 108*, 093309, 2010.

[6]V. Vahedi, M. Surrendra, "A Monte Carlo collision model for the particle-in-cell method: applications to argon and oxygen discharges," *Comput. Phys. Commun.*, Vol. 87, 179-198, 1995.

[7]G.A.Bird, "Molecular Gas Dynamics and the Direct Simulation of Gas Flows," 1994.

[8]Francis J. Alexander and Alejandro L. Garcia, "The Direct Simulation Monte Carlo Method,"' *Computers in Physics*, Vol. 11, 6, 1997.