Particle-in-Cell simulation of the plasma properties and ion acceleration of a down-scaled HEMP-Thruster

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***Abstract* — First results of computer modeling the characteristics of a down-scaled High Effciency Multistage Plasma Thruster (HEMPT) are presented. The aim of the micro- HEMPT development is to meet the requirements in very precise attitude control of upcoming formation flight satellites and probes. Computer modeling can help reach the performance goals and save experimental time. In this presentation, a Particle in Cell code based simulation is used to investigate a section of the thrusters discharge chamber and how its plasma characteristics react to the change of an input parameter.**

Introduction

Formation flight satellites and probes like LISA (Light Interferometer Space Antenna) require very precise attitude and also position control, typically for continuous operation over several years. Currently efforts are underway to scale electric thrusters down into the thrust and noise levels in the µN and sub- µN regime, respectively. Due to its inherent simplicity and robustness, the High Effciency Multistage Plasma Thruster (HEMPT), appears as a promising candidate. The effort of downscaling this thruster type is undertaken by Astrium Satellites at Friedrichshafen in cooperation with the Center of Applied Space technology and microgravity (ZARM) and the German Aerospace Center (DLR). Currently, stable and reliable thrust levels down to 70 µN have been demonstrated [1], but further downscaling to the 10 µN range still represents a considerable challenge. This paper describes first results from computer models with the aim to a better understanding of a downscaled HEMP Thrusters inner working. Such improved understanding is supposed to help reach the performance goals. In the first part of this paper, the basics of this model are described, starting with a quick overview of this thruster concept, patented by Thales, Ulm [2]. This is followed by a description of the theory and setup characteristics for the used model type. The HEMPT has a unique magnetic field topology. Due to the non-Maxwellian distribution and adiabatic invariant motion of the electrons at the near zero field points [3], Particle-in-Cell is the simulation method of choice. Then the setup of the mod-

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els specifically used in this work is described. The so called magnetic bi-conic cusps are characteristic features for a micro- HEMPTs discharge chamber. These are the zones, where key thruster parameters like ion acceleration and thrust efficiency are determined under the influence of the potential drops of the electrical field. Two almost identical models of the cups - zones are created, with only one parameter changed.

In the second part of this paper, the results of both models are compared. Finally conclusions for possible improvements are taken.

Model basics

HEMP Thruster overview

Like a Hall effect thruster, a HEMPT ionizes and accelerates propellant atoms by the same electric field. The discharge chamber consists of a hollow ceramic tube with an anode at one side and an open end on the other, where magnetically trapped neutralizer- electrons act as a virtual cathode. A schematic view of a HEMP thruster is shown in Fig. 1. The typical feature of the HEMPT is the periodic arrangement of opposing permanent magnets. These create so-called magnetic cusps with a radial magnetic field. In between the cusps the field is mostly axial. Electrons can reach the discharge chamber wall only near the cusps. The magnetic mirror effect reduces the electron loss to the wall according to their loss- cone. Axial movement towards the anode is hindered at the cusp, although not completely prohibited [4]. Both effects result in an effective Plasma confinement.

Plasma model theory

The presented simulations use the VORPAL Engine, a versatile Particle-in-Cell (PIC) code with integrated Monte Carlo Algorithm [5]. A PIC type of simulation follows the kinetic movements of so-called macro particles, who each

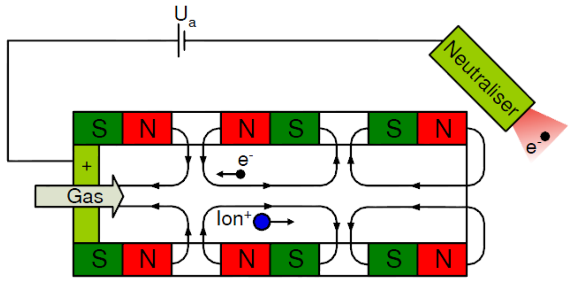


Fig. 1: HEMP-Thruster principle [1]

represent several real particles. These particles with charge q and velocity vector $\boldsymbol{v}$ are moved according to the Lorentz force $\boldsymbol{F} = q(\boldsymbol{E}+\boldsymbol{v}\times\boldsymbol{B})$ in a leapfrog scheme by a Boris pusher. While magnetic field generated by plasma currents is considered to be negligible at expected plasma densities, the field $\boldsymbol{B}$ generated by the permanent magnets is an essential part of this simulation. For large scale interactions the electric field $\boldsymbol{E}$ is solved on a grid. Short scale interactions are treated as collisions by the Monte Carlo Algorithm. The in regards to the ionization process most important collisions are included in this model: electron- neutral elastic, excitation and ionization. For the collisions, cross sections from the evaluated electron data library are used [6]. This thruster is cylinder symmetric, therefore a cylindrical coordinate system is chosen and due to this symmetry the model can be limited to a 2 dimensional R - Z - plane (with arbitrary Phi). All three velocity vector components v_R, v_Z and v_{Phi} are calculated, in order to realistically account for the electron gyration motion in the magnetic field.

Model setup HEMP Thrusters magnetic cusps area

The aim of this model setup is to study in particular the plasma properties in the discharge channel near the cusps, and how they react to changes in the electron source. The simulation domain represents an R - Z - cut plane through a cylinder with radius $R = 2.5$ mm and length Z = 7.5 mm. Those values are due to the geometric parameters of the micro HEMPT variant this simulation is oriented on. The simulations max

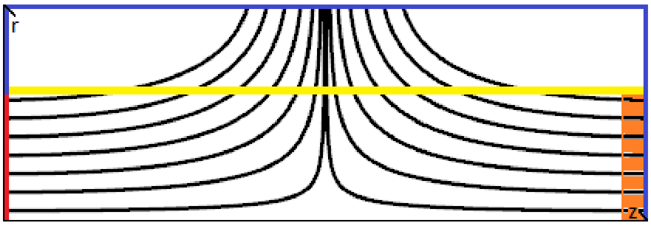


Fig. 2: Computational domain for the cusps area: Anode (red), grounded metal boundary (blue), dielectric surface (charge accumulation) (yellow), electron source (orange), magnetic field (black).

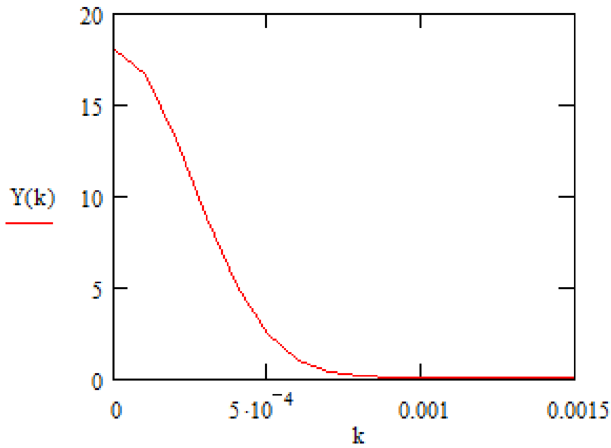
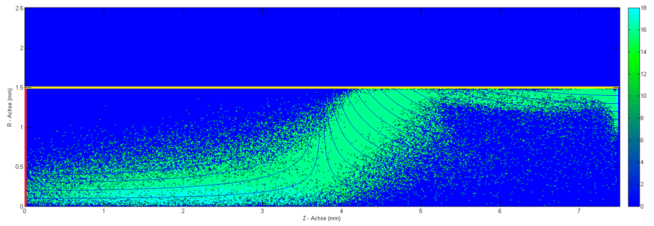


Fig. 3: Model 2: Electron source intensity over radial distance

R is to include the grounded potential (0 V) of the inner surface of the magnetic and placeholder rings. The length $Z = 7.5$ mm equals the midpoint to midpoint distance of two magnetic rings. Since it is focused solely on simulating the cusp region, the simulation model includes only two of the opposite poled magnetic rings. The magnetic field is imported from a stationary finite element simulation. At $Z = 0$ mm, for 0 mm $\leq$ R $\leq$ 1.5 mm an anode potential is set, while 1.5 mm $\leq$ R $\leq$ 2.5 mm is grounded. The opposing side, $Z = 7.5$ mm, 0 mm $\leq$ R $\leq$ 2.5 mm is grounded and serves as a cathode that creates the potential drop which drives the plasma discharge (Fig. 2). In this particular model the side opposing the anode is a closed boundary, other than the open end of the real thruster, which is not scope of this investigation. At $R = 1.5$ mm particles are absorbed and charge accumulation is simulated by replacing each absorbed particle with an unmovable one of the same charge. This boundary represents the dielectric surface of the thrusters discharge chamber wall. Both anode and cathode are absorbing for all particles, with the exception of the cathode being reflecting for source electrons, as to not have a back-flow of those. An electron source lies at the surface of the cathode (7.49 mm $\leq$ Z $\leq$ 7.5 mm, 0 mm $\leq$ R $\leq$ 1.5 mm). At this thruster variant, at 400 V anode potential, an anode current of 7 mA was measured, resulting in a power consumption of 2.8 W. In order to preserve the power to volume ratio of the 17.5 mm long discharge chamber for the 7.5 mm long model, the anode potential is reduced to 171 V. Only electron and Ion movement is traced as macro particles in this simulation. Neutral gas is treated as a static background, whose density is used as an input parameter for the Monte Carlo code. Neutral gas distribution is constant at $4 \cdot 10^{21}$ particles per cubic meter, taken as average value of a neutral gas simulation performed on a model of the thruster and its near exit region. The cell size is $\Delta R = \Delta R = 1 \cdot 10^{-2}$ mm, resulting in a computational grid of $750 \cdot 250$. This size was chosen to resolve the smallest Debye length resulting from the plasma density and temperature expected for this type of thruster. The time step size was set to $5 \cdot 10^{-12}$ s in order to resolve the electron gyration motion at the strongest magnetic field strength. For the two models investigated the electron source varies in its radial distribution. For the first model the current density stays the same from $R = 0$ mm to $R = 1.5$ mm. For the second model, an R- dependent Gaussian distribution is applied, which concentrates most of the current at low R- values (Fig. 3). The absolute current stays the same for both models.

Results

The results of both models are presented in parallel. We begin with the final distribution of the source electrons shown in Fig. 4, being overlaid with magnetic field lines. Due to neutral collisions the electrons do have a certain mo-



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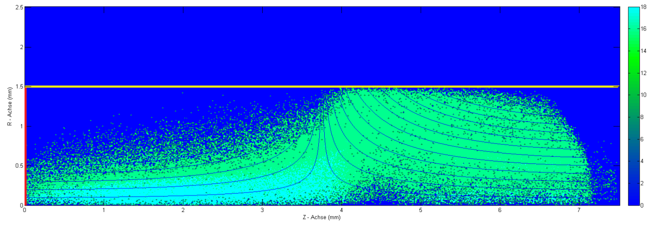
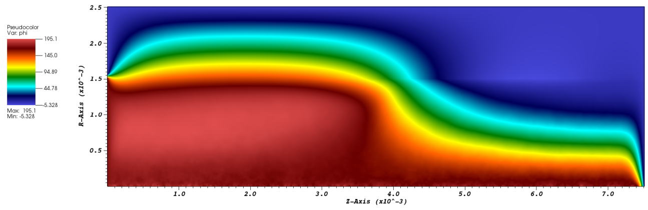
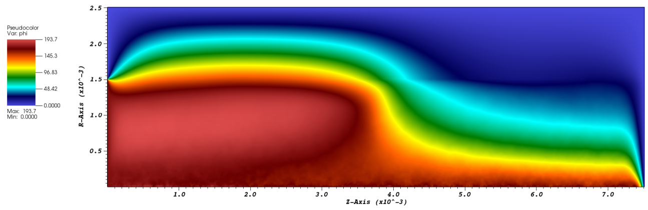


(b)

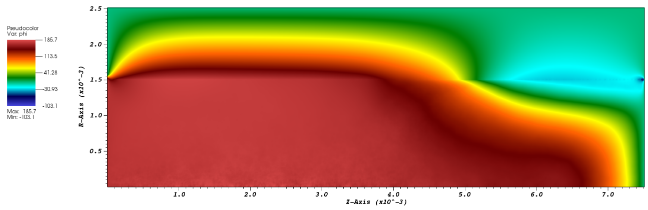
Fig. 4: Source electron density in $1/m^3$, lg 10. (a) model 1; (b) model 2



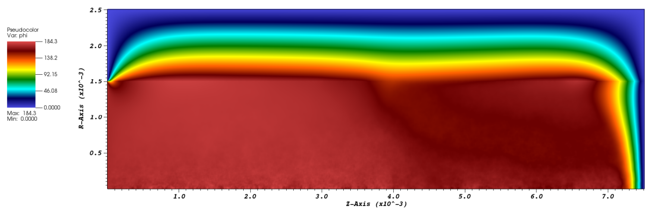
(a) Model 1, potential (V), T $= 5 \cdot 10^{-9}$ s



(b) Model 2, potential (V), T $= 5 \cdot 10^{-9}$ s



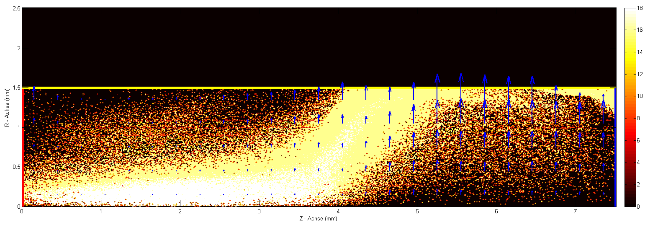
(c) Model 1, potential (V), T $= 1 \cdot 10^{-6}$ s



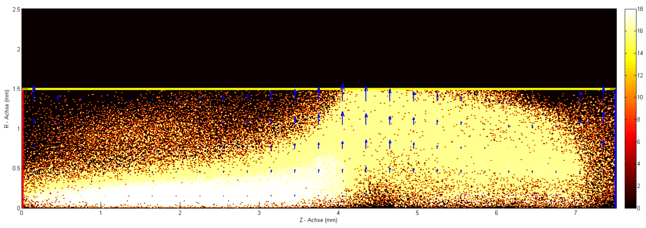
(d) Model 2, potential (V), T $= 1 \cdot 10^{-6}$ s

Fig. 5: Electric potential for different models at different times

bility perpendicular to the magnetic field lines [7]. From now on the cusp will be seen as a separator of two regions. In respect to the expected z- movement of the ions, they will be called upstream and downstream of the cusp, with the former being near the anode and the latter being near the cathode. Downstream of the cusps, in the first model, where the source is not focused on smaller radii, most of the source electrons have migrated to higher radii. The focusing in the second model clearly counteracts this migration and the distribution is more uniform along R. In both models, upstream of the cusp it is clearly visible that the electrons are bundled towards the z- axis by the magnetic field. The migration in the downstream region of the first model causes a significant amount of electrons being absorbed by the dielectric discharge chamber wall. This creates a surface charge that is negative relative to the plasma potential, which can be seen in the upper right corner of Fig. 5 (c). In both models the plasma potential lies a few volts above the anode potential. Early in the simulation, at T $= 5 \cdot 10^{-9}$ s, a potential step has formed due to the hindering of movement of the electrons in Z- direction at the cusps, which causes them being reduced in the upstream region. At later times the potential has even out and shows a rather flat profile. This indicates that the generation of new electrons plays a significant role, compensating for the earlier lack of electrons in the upstream region. Ion density and the radial component of the ion movement are portrait in Fig. 6. The peak values of the ion density is in order of magnitude of $1 \cdot 10^{18}$ to $1 \cdot 10^{19}$ particles per cubic meter. One can see that the ion distribution in both models shows a great similarity with the electron distribution. In the downstream region, by comparison of the second model with the first, it becomes obvious that less surface charge due to less electrons near the ceramic wall reduces the stream of ions towards this boundary. Consequently, less ions are absorbed and their overall ion number is greater than in the first model, as shown in Fig. 7. The distribution of electrons generated by ionization is similar to both the source electrons and the ions, see



(a)



(b)

Fig. 6: Xenon ion density in $1/m^3$, lg 10. (a) model 1; (b) model 2

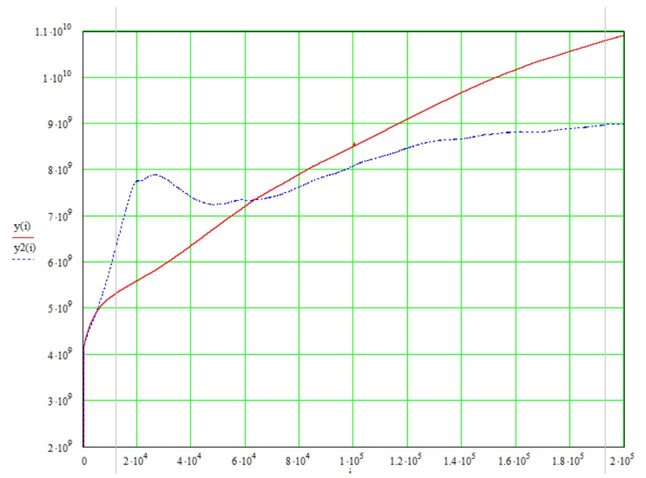
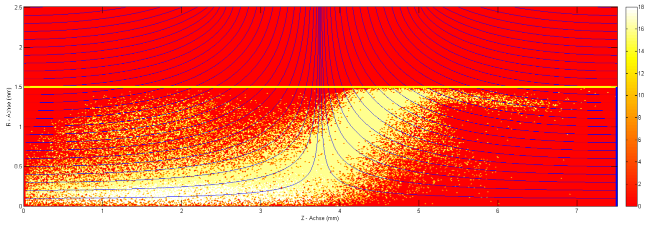


Fig. 7: Comparison of overall xenon ion number over time for model 1 (blue) and model 2 (red)

Fig. 8.

Conclusions

A model of the cusp area of a micro HEMP thruster has been studied for two cases. The radial variation of the source electrons current shows a significant change in the electron distribution and confinement. It becomes further obvious that by the conditions given by the magnetic field, the ion distribution is strongly influenced by the electron distribution. Therefore



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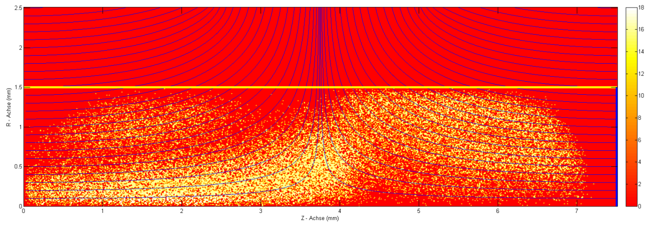

(b)

Fig. 8: Density of electrons generated by ionization in $1/m^3$, lg 10. (a) model 1; (b) model 2

plasma confinement, and finally thruster performance, can be improved by concentrating the source electrons towards the axis. Further investigation is necessary to determine to which degree source electrons are already concentrated in such a way, if further concentration is necessary and if so, how it can be archived.

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