Kinetic simulation of the stationary HEMP thruster including the near–field plume region

IEPC-2009-110

Presented at the 31st International Electric Propulsion Conference,
University of Michigan • Ann Arbor, Michigan • USA
September 20 – 24, 2009

K. Matyash [1], O. Kalentev [2], R. Schneider [3],
Max-Planck-Institut für Plasmaphysik, EURATOM Association, Greifswald, D-1749, Germany

F. Taccogna[4]
Istituto di Metodologie Inorganiche e dei Plasmi-CNR, Via Amendola 122/D, 70126 Bari, Italy

N. Koch[5], M. Schirra[6]
THALES Electron Devices GmbH, D-89077 Ulm, Germany

Abstract: The Particle-in-Cell (PIC) method was used to study the High Efficiency Multistage Plasma Thrusters (HEMP), in particular the plasma properties in the discharge chamber. PIC proved itself as a powerful tool, delivering important insight into the underlying physics of the thruster. The simulations demonstrated that the new HEMP thruster concept allows for a high thermal efficiency due to both minimal energy dissipation and high acceleration efficiency. In the HEMP thruster the plasma contact to the wall is limited only to very small areas of the magnetic field cusps.

Nomenclature

B	=	magnetic field
E	=	electric field
R	=	radial coordinate
T_e	=	electron temperature
U_a	=	anode voltage
Z	=	axial coordinate
Δt	=	time step
ε_0	=	permittivity of free space
σ	=	surface charge density

[1] Researcher, Max-Planck-Institute for Plasma Physics, konstantin.matyash@ipp.mpg.de.
[2] Researcher, Max-Planck-Institute for Plasma Physics, okalenty@ipp.mpg.de.
[3] Head of the Helmholtz-Assoc. Junior Res. Group “Computational Material Science”, ralf.schneider@ipp.mpg.de.
[4] Researcher, Istituto di Metodologie Inorganiche e dei Plasmi, Consiglio Nazionale delle Ricerche, francesco.taccogna@ba.imip.cnr.it.
[5] Head of Plasma Devices, Thales Deutschland - Components and Subsystems, Norbert.Koch@thalesgroup.com.
[6] Researcher, Plasma Devices R&D, Thales Deutschland – Components and Subsystems, Martin.Schirra@thalesgroup.com.

I. Introduction

HEMP (High Efficiency Multistage Plasma) thrusters represent a new type of grid less ion thrusters with a particular magnetic confinement of the plasma electrons. The HEMP thruster concept has been patented by Thales Electron Devices with an initial patent filed in 1998 [1]. A schematic view of the HEMP thruster concept is shown in Fig. 1. HEMP thrusters are based on a magnetically confined plasma in which the propellant atoms are ionized and the ions are accelerated to form a propulsive ion beam. In the HEMP thrusters the specific magnetic field topology provided by a sequential arrangement of magnetic stages with cusps efficiently confines the plasma electrons and minimizes plasma-wall contact. Electron movement towards the thruster anode is strongly impeded by this magnetic field topology to form steep electrical field gradients for effective ion acceleration. As a consequence, the HEMP thruster concept allows for a high thermal efficiency due to both minimal heat dissipation and high acceleration efficiency, and for a wide range of operational parameters. The latest HEMP thruster models have confirmed the following important features: broad and stable operational range in anode voltage and propellant mass flow and small heat dissipation to the thrusters, small erosion operation resulting in a long life-time [2].

Optimization process of ion thrusters is necessary to improve e.g. the ionization probability for a higher efficiency. For this, form and size of the thrusters, neutral gas control through valve position and baffles, geometry and form of the electrodes and magnetic field topology can be changed. Here, the computer simulations can help to understand the basic principles of thruster operation to minimize the numbers of prototypes. In this work a newly developed Particle-in-Cell code with Monte Carlo Collisions (PIC MCC) is used to simulate the stationary operation regime of the HEMP thruster prototype DM3a. DM3a has been developed and tested in an early stage of HEMP thruster development in 2002 [3] and has demonstrated the feasibility of this new thruster concept. The PIC simulation delivers a full self-consistent microscopic description. Therefore, any plasma parameter of interest (both macroscopic and microscopic) can be calculated: potential and field, particle density, flux and temperature profiles, particle velocity distribution functions, etc. Thus, PIC simulations give us an important insight into the physics of the thruster, providing information which is difficult or impossible to get in experiments.

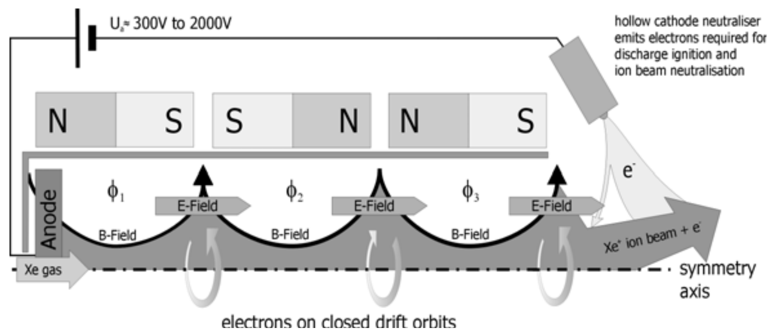


Figure 1. Schematic view of the HEMP thruster concept. As an example, an arrangement with a cylindrical discharge channel and 3 magnet rings is shown, such that 3 cusp zones with high radial field are formed in the discharge channel.

In Chapter II the PIC MCC model and the simulation results for HEMP DM3a thruster are presented. Chapter III summarizes the paper, giving outlook for the future work.

II. PIC MCC simulation of HEMP thruster

We apply a newly developed Particle-in-Cell code with Monte Carlo Collisions (PIC-MCC) to simulate the stationary operation regime of the HEMP thruster prototype DM3a.

The detailed description of the PIC MCC method can be found in dedicated reviews [4, 5]. Here we just outline the main features of our model. In PIC MCC simulations we follow the kinetics of so-called “Super Particles” (each of them representing many real particles), moving in the self consistent electric field calculated on a spatial grid from the Poisson equation. The particle collisions are handled by Monte-Carlo collision (MCC) routines, which randomly change particle velocities according to the actual collision dynamics. All relevant collisional processes are included in the model: electron-neutral elastic, ionization and excitation collisions, ion neutral momentum- transfer and charge exchange collisions. In our model we resolve 2 spatial (radial and axial) and 3 velocity components (2d3v). The computational domain in the present simulations is extended beyond the discharge channel and includes the near-field region of the thrusters.

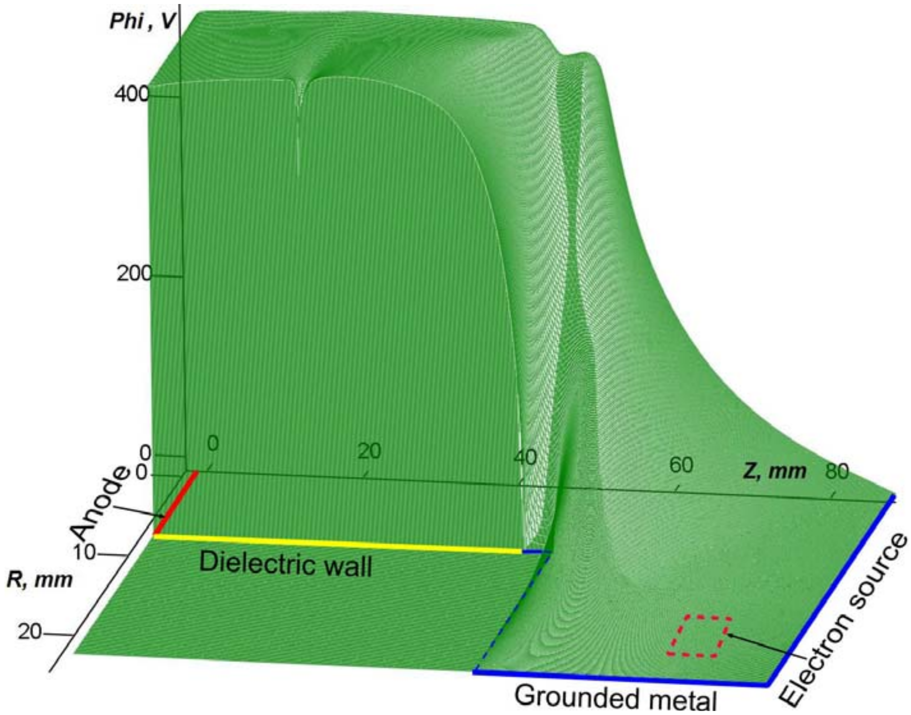


Figure 2. Computational domain for the simulation of the HEMP DM3a thruster with a calculated potential profile.

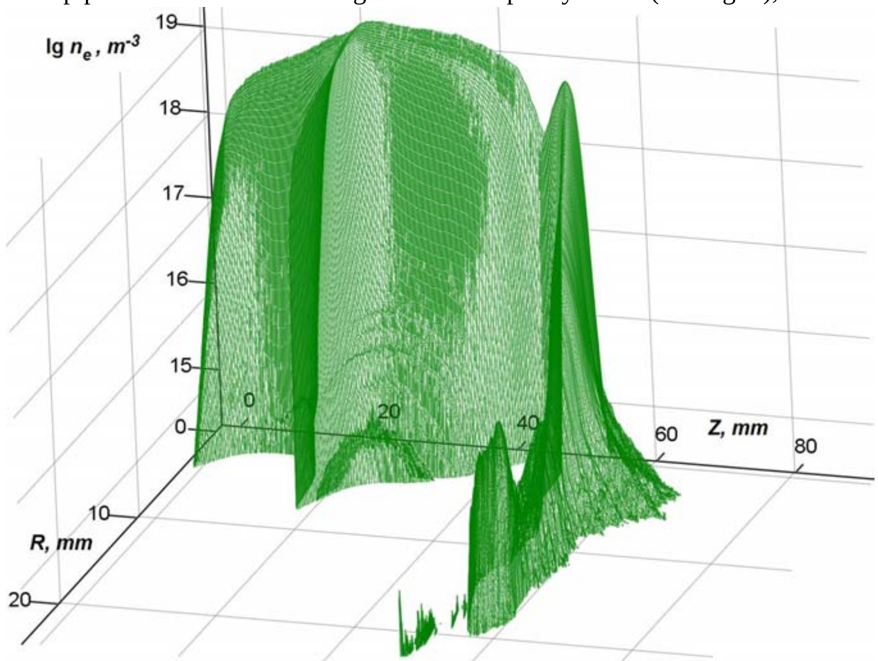
The simulation computational domain together with calculated potential profile is shown in Fig. 2. The computational domain represents a cylinder with length $Z_{\max} = 89\,mm$ and radius $R_{\max} = 24\ mm$. The thruster length is $Z_{thr} = 51\ mm$. The thruster inner radius is $R_{thr} = 9\ mm$. At $Z = 0$ the metal anode is located. The major part of the inner surface of the thruster is dielectric. Only the outer ring at the exit is made of metal. The region outside the thruster exit: $Z_{thr} < Z < Z_{\max}$ and $R < R_{\max}$ represents the near-field plume zone. The radial and axial boundaries of the near-field region are assumed to be metallic. All metallic surfaces, except for the anode are at ground potential. At the anode, a voltage $U_a = 500$ V is applied. At the dielectric surface of the thruster the floating potential was calculated self-consistently. The net surface charge σ of the absorbed electrons and ions was calculated at every grid cell and the electric field $E_{diel} = -\dfrac{\sigma}{2\varepsilon_0}$ was used as von Neumann boundary condition for the Poisson equation. The maximum magnetic field from the permanent magnets in the system is about $B_{\max} \approx 0.4\ T$. All surfaces in the simulations are assumed to be absorbing for particles. The simulation includes the electrons, Xe^+ ions and the neutral Xenon atoms. Only charged particles dynamics was followed in the simulation, whereas the neutral Xenon was treated as fixed background. The electrons with a Maxwellian distribution and a temperature $T_e = 2$ eV are introduced into the system at the source region: $54\,mm < Z < 58\,mm$ mm and $16\,mm < R < 20\,mm$. The electrons from the source, accelerated in the thruster electric field, are ionizing the neutral gas, creating the plasma in the thruster channel. In order to ensure an equilibrium solution, the electron source strength was adjusted during the simulation using feed-back control loop.

To reduce the computational time the size of the system is scaled down by a factor of 10. In order to preserve the ratio of the charged particles mean free paths and the gyroradii to the system length, the neutral Xenon density and the magnetic field are increased by the same factor 10.

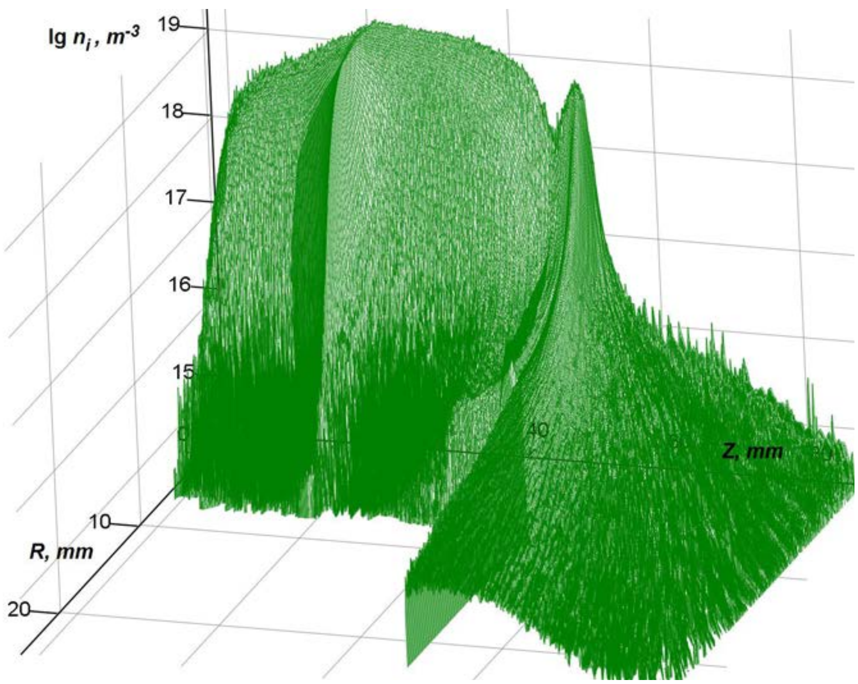
An equidistant computational grid 890x240 was used in the simulation. The Poisson equation is discretized on this grid using a centered 5-point scheme. The particles equations of motion are solved for the discrete time steps with the leap-frog / Boris algorithm [4]. A total of about 1000000 computational particles were used in the simulation. The cell size $\Delta R = \Delta Z = 10^{-2}$ mm in the simulation was chosen to ensure that it is smaller than the smallest Debye length in the system. The time step was set to $\Delta t = 1.12 \cdot 10^{-12}$ s in order to resolve the electron plasma frequency. In total about ~ 10^6 time steps were done before steady-state was reached.

The simulation was carried on a single processor Intel Xeon workstation. The duration of the run until the equilibrium solution was obtained was about 80 hours.

The equilibrium solution for the potential profile is presented in Fig. 2. One can see that the axial potential drops appear at the two cusp positions – where the magnetic field is purely radial (see Fig. 1), so that axial mobility of the



a)



b)

Figure 3. Electron (a) and ion (b) density profiles in the HEMP DM3a thruster.

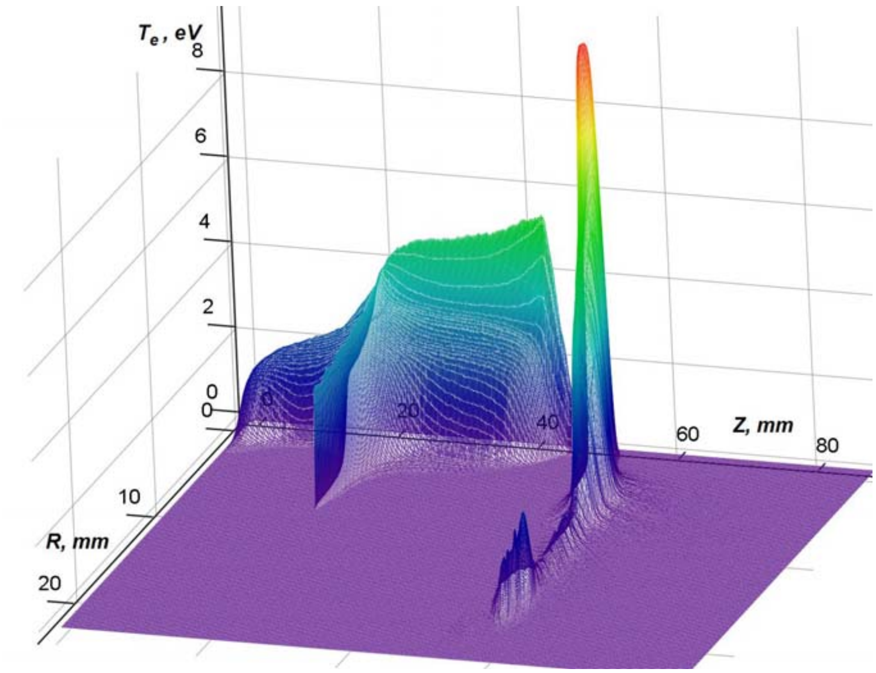


Figure 4. Electron temperature profile in the HEMP DM3a thruster.

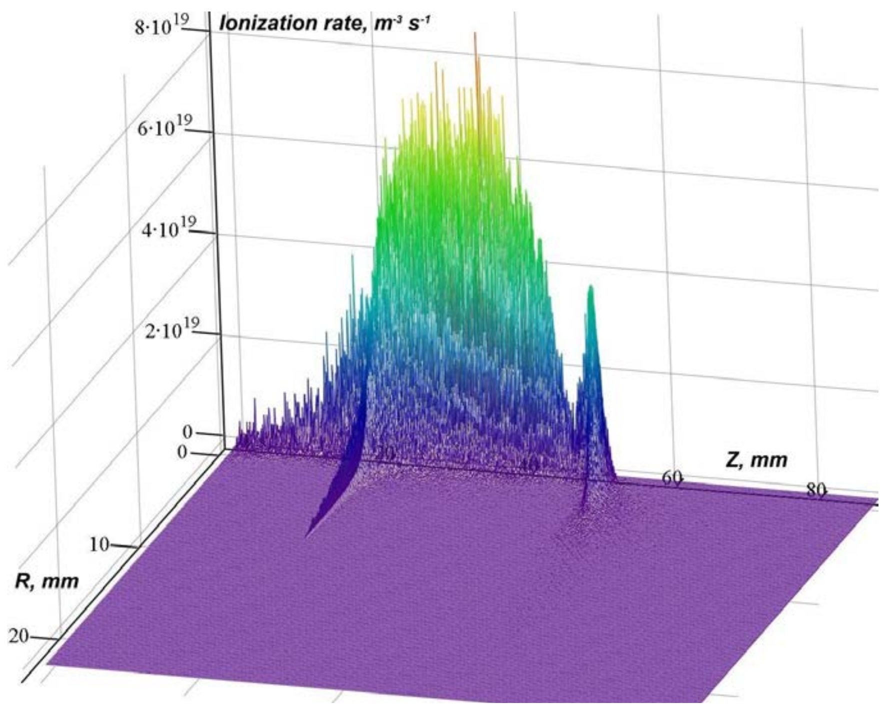


Figure 5. Ionization rate profile in the HEMP DM3a thruster.

electrons is strongly reduced, whereas the ion motion is not affected by the magnetic field. The main potential drop, both axial and radial, appears near the exit cusp at the thruster exit plane. This potential drop is responsible for the acceleration of ions and determines their angular distribution. Therefore, energetic ions in HEMP are generated only at the thruster exit.

The electrons are able to escape to the thruster surface only at the cusps positions, were the radial sheath potential drops are formed as can be seen in Fig. 2. Away from the cusps, where the magnetic field is purely axial, the electron flow to the wall is practically zero. As the ions are not magnetized, they are able to reach the wall, so that the dielectric surface acquires a positive charge, resulting in a radial electric field directed from the wall towards the axis. In Fig. 2 between the cusps one can distinguish the corresponding potential rise towards the wall. This electric field inhibits further ion flow towards the wall. In equilibrium, the ion current to the wall equals the electron current i.e. becomes negligible. Thus, this radial electric field is acting as an ion lens, focusing the ion flow streaming towards the thruster exit.

The profiles of the electron and ion densities are presented in Fig. 3. Here, it is clearly visible that the plasma contacts the thruster inner wall only at the cusps positions, where the electrons are trapped in the azimuthal *ExB* drift motion. One can see, that in the near-field region, after the thruster exit, the ion density is much larger, compared to the electron density, as the electrons are efficiently confined axially at the exit cusp by the radial magnetic field. The uncompensated positive ion space charge outside the thruster is responsible for the steep potential drop at the exit. This result supports the experimental observation that neutralization of the exiting ions space charge is not necessary for HEMP thruster operation, so that it can normally operate even without neutralizer [6].

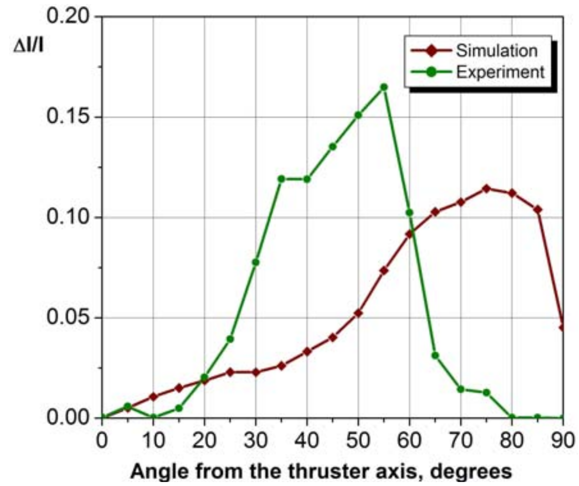


Figure 6. Ion current contribution in 5° wide solid angle sectors scaled to the total ion current.

In the electron temperature profile, shown in Fig. 4, one can see that the most efficient electron heating is taking place at the exit cusp, where the electrons get the energy from the strong axial electrical field as they are gyrating in the radial magnetic field, trapped in the azimuthal *ExB* drift. However, the ionization rate in Fig. 5, shows its maximum at the axis between the cusps, as both the electron and the neutral densities are higher in this region.

In Fig. 6 the angular distribution of the ion current leaving the thruster calculated with PIC MCC and obtained experimentally for HEMP DM3a are shown. The PIC simulation reproduces fairly well the general shape of the experimental current distribution. The average ion beam divergence angle in the simulation is 62^{o}, while in the experiments it is 45^{o}. The higher ion current divergence obtained in the simulation can be attributed to artifacts of the proximity of the radial boundary of the computational domain in the thruster near-field region.

III. Conclusion

The Particle-in-Cell code with Monte Carlo Collisions was used to study the High Efficiency Multistage Plasma Thrusters, in particular the plasma properties in the discharge chamber. PIC MCC proved itself as a powerful tool, delivering important insight into the underlying physics of the thruster.

The simulations demonstrated that the new HEMP thruster concept allows for a high thermal efficiency due to both minimal energy dissipation and high acceleration efficiency. In the HEMP thruster the plasma contact to the wall is limited only to very small areas of the magnetic field cusps.

For an even better understanding of ion thrusters, the numerical models have to be extended to include further parts of the plume. This will reduce the influence of the boundary conditions which can produce artifacts, if the domain boundaries are too close. A complete 3-dimensional model will also be necessary to self-consistently resolve the anomalous electron transport due to *ExB* drift in the azimuthal electric field.

Acknowledgments

The authors want to thank the German Space Agency DLR for funding through Project No. 50 RS 0804. R.S. acknowledges funding of the work by the Initiative and Networking Fund of the Helmholtz Association.

References

[1]G. Kornfeld, H. Seidel, J. Wegener, “Plasma Accelerator Arrangement”, Patent. PCT/DE99/01708 filed 11 June 1999, Priority: Germany No. 198 28 704.6, filed 26 June 1998.

[2]N. Koch, H.-P. Harmann, G. Kornfeld, "Status of the THALES High Efficiency Multi Stage Plasma Thruster Development for HEMP-T 3050 and HEMP-T 30250", Proceedings of the 30th International Electric Propulsion Conference, Florence, Italy, September 17-20, 2007, IEPC-2007-110.

[3]G. Kornfeld, N. Koch, G. Coustou, "First Test Results of the HEMP thruster concept", Proceedings of the 28th International Electric Propulsion Conference, Toulouse, March 2003, IEPC-2003-212.

[4]C. K. Birdsall, A. B. Langdon, Plasma physics via computer simulation, McGraw-Hill, New York, 1985.

[5]D. Tskhakaya, K. Matyash, R. Schneider, F. Taccogna, "The Particle-In-Cell Method", Contrib. Plasma Phys., Vol. 47, No. 8-9, pp. 563–594, 2007.

[6]G. Kornfeld, N. Koch, H.-P. Harmann, "Physics and Evolution of HEMP-Thrusters", Proceedings of the 30th International Electric Propulsion Conference, Florence, Italy, September 17-20, 2007, IEPC-2007-108.