Influence of different anode voltages on the HEMPT

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The High Efficiency Multistage Plasma Thruster (HEMPT) is studied by 2d3v Particle-in-Cell plasma simulations with Monte Carlo collisions coupled with Direct Simulation Monte Carlo for neutrals. Simulations at different anode voltages are used to derive and analyze the scaling of different quantities, e.g. thrust, with the applied anode voltage, and to identify the underlying physics.

Nomenclature

E_n	= electric field
Xe	= Xenon
Xe^+	= single charged Xenon ions
Xe^{++}	= double charged Xenon ions
U_a	= anode voltage
r	= radial position
z	= axial position
$n_{ionization}$	= number of ionization collisions
T	= thrust

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I. Introduction

One big advantage of the HEMP-thruster is its ability to operate at different anode voltages and thereby generating different levels of thrust[1] in a stable and efficient way. In this work the High Efficiency Multistage Plasma Thruster (HEMPT) is studied by Particle-in-Cell (PIC)[2] plasma simulations coupled with Direct Simulation Monte Carlo for neutrals. A kinetic model is needed, because the mena free path of electrons are comparable or larger than the system size allowing non-Maxwellian steady-state distribution functions. Therefore, a fluid approach has too strong limits and a fully kinetic description, like PIC, is necessary. The advantage of the microscopic kinetic treatment of the particles is the immediate access to the important physical properties[3]. From the simulations at different anode voltages a fully kinetic analysis of the different scenarios is possible, such that particle distribution functions, but also fluid moments like densities, velocities and fluxes, are diagnosed[4]. This allows a detailed understanding of the underlying physics which is used to derive and analyze the scaling law of the thrust with the applied anode voltage.

In the paper, after introducing shortly the method the results of PIC simulations for different anode voltages are presented and discussed. Finally, the conclusions are presented.

II. Method

Particle-in-Cell (PIC) methods simulate the motion of each particle in continuous phase space while macro quantities are computed on stationary mesh points. The method follows the trajectories of charged (or neutral) particles in self-consistent electromagnetic (in this case electrostatic) fields computed on a fixed mesh. The macro force is then calculated from the field equations. Due to the symmetry of the HEMP thruster a cylindrical geometry is applied. In the Particle-in-Cell code with Monte Carlo Collisions (PIC-MCC) so-called Super Particles are used (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, charge exchange and neutral-neutral collisions.

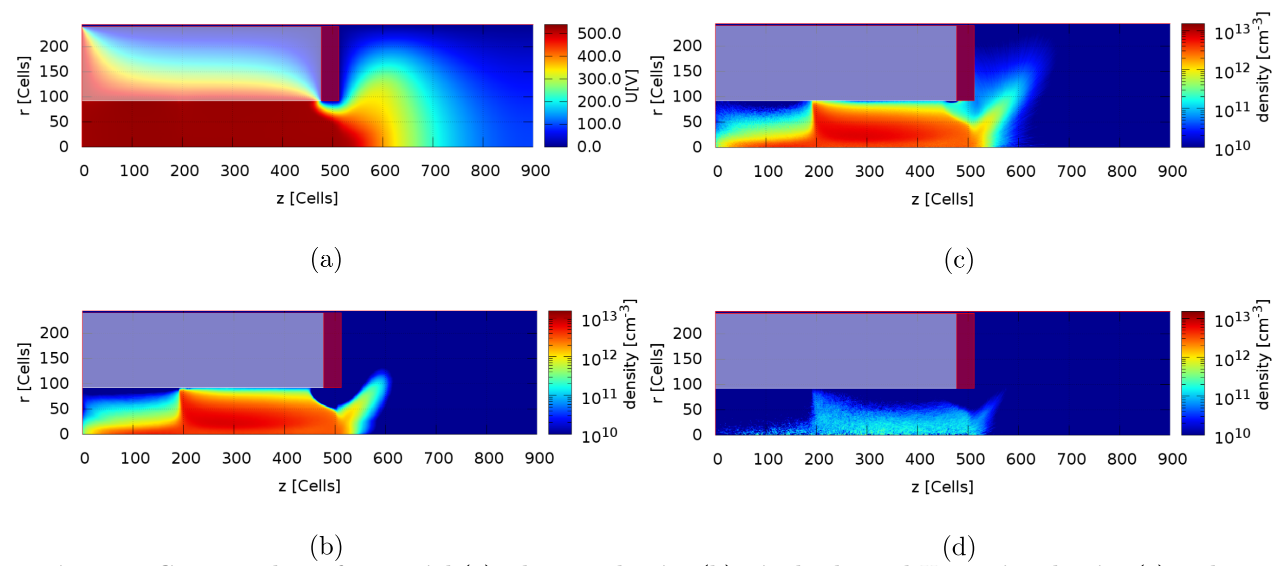

Figure 1. Contour plots of potential (a), electron density (b), single charged Xenon ion density (c) and double charged Xenon ion density (d) for an anode voltage of 520V

In order to self-consistently resolve anomalous electron transport due to near wall conductivity (NWC), a secondary electron emission (SEE) model for the thruster channel dielectric walls is included in the simulation. In our model we resolve 2 spatial (radial and axial) and 3 velocity components (2d3v).

At the anode surface a constant anode voltage is applied. At the dielectric surfaces the floating potential is calculated self-consistently. The net surface charge n_{sc} of the absorbed electrons and ions is calculated at every grid cell and the electric field E_n is used as von-Neumann boundary condition in the Poisson solver.

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 900x244 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 [2]. A total of about 2000000 computational particles were used in the simulation. The cell size 1×10^{-3} mm in the simulation was chosen to ensure that it is smaller than the Debye length in the system. The time step was set to 1.12×10^{-12} s in order to resolve the electron plasma frequency. In total about 3×10^{7} time steps were done before steady-state was reached. One "Super Particle" in this simulation represents 10461 real particles. To solve the Poisson equation the package "SuperLU"[5] is used. Since the discretization of the Laplace operator in matrix form depends only on metric coefficients and only the right hand side of the Poisson equation changes during the simulation, it is sufficient to invert the Poisson equation only once (which is rather time-consuming), and do only the very fast backsolve with the new charge density in every timestep.
The HEMP is operated at different anode voltages with Xenon as process gas. In this simulation electrons, neutral Xe, Xe^{+} and Xe^{++} ions are treated as individual species of particles.
The simulation shows that a plasma builds up inside the channel and the ions get accelerated at the potential drop at the exit. A simulation is assumed to be stationary if the total particle numbers reach a steady state and the total current on all boundaries equals zero. A stationary state is shown in Fig. (1) for an anode voltage of $U_a = 520V$.

The calculation domain in Fig. (1) consists of the thruster and the near-plume region. The thruster itself is build of an anode, a dielectric channel with magnets and a grounded metallic cover at the exit. The region outside the thruster exit: (512, 900) represents the near-field plume zone. The radial and boundary of the near-field region is assumed to be metallic. All metallic surfaces in the simulation, except for the anode are at the ground potential. The axial boundary is of the near-field region is set to a constant potential gradient of E=0.

Secondary electron emission and recycling of ions is applied at the surface of the dielectric. The recycling ions contribute as thermalized background to the neutral distribution. The low-energy secondary electrons from the dielectrics reduce the radial electron losses and increase by this the ionization effectivity. The neutral gas source of $12sccm$ is located at the center of the anode.

Electrons with a Maxwellian distribution and a temperature 1 eV are introduced into the system in the source regions at r=20mm and z=70mm. This source represents the experimental neutralizer and supplies the small amount of primary electrons to initiate the plasma generation in the thruster. In the simulation the electrons from the source, accelerated in the thrusters electric field, are ionizing the neutral gas, creating the plasma in the thruster channel.

III. Results

For a detailed study of the influence of the variation of the anode voltage simulation runs with the same set-up as discussed before are done varying the anode potential between 340 and 520 V.

A. Reduced anode voltage

The major characteristics, namely a very pronounced potential drop close to the exit very similar to grid thrusters and a rather flat potential profile inside the acceleration channel remains for all the operational points. As a consequence, the plasma wall interaction does not lead to significant sputtering of the dielectric walls in the thruster channel[1].

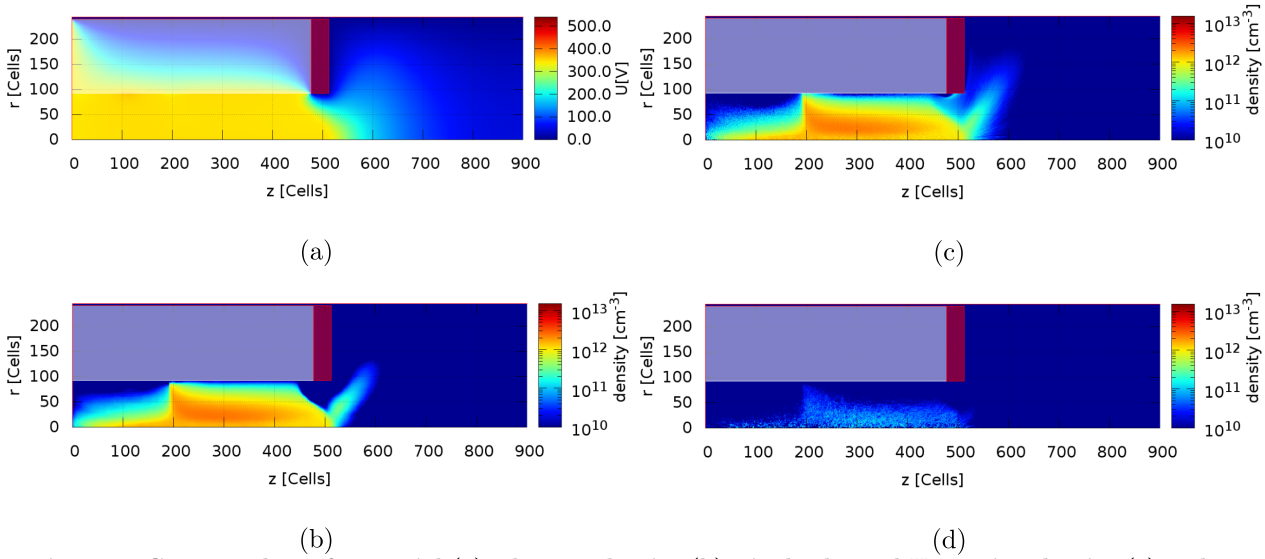

Figure 2. Contour plots of potential (a), electron density (b), single charged Xenon ion density (c) and double charged Xenon ion density (d) for an anode voltage of 340V

Applying a lower anode voltage (see Fig. (2) for the case with 340 V anode voltage) results in a lower energy of the electrons when entering the thruster. As a consequence the ionization rate drops and the particle densities decrease.

B. Anode voltage variation

Another consequence of the increased ionization with higher anode voltage is a drop of the neutral density close to the exit. By this the potential drop moves further into the channel Fig. (3), because the position of the first ionization zone shifts into the channel due to the reduced neutral density at the exit. The potential

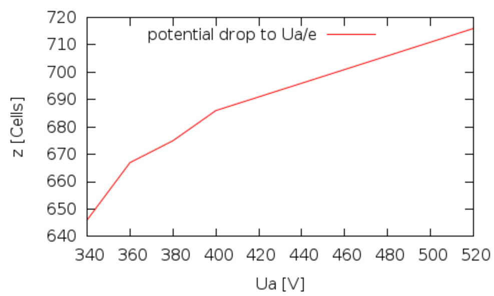

Figure 3. Z position of the potential drop depending on the applied anode voltage U_a

drop location is defined by the position of the potential where it reaches 1/e of of the anode voltage.

Also, ions leaving the thruster get higher energies, resulting in an increased thrust. Within the voltage range studied, a linear dependence of the thrust as a function of anode voltage is observed, as seen in Fig. (4). In the experiment the thrust T is proportional to the square root of the anode voltage U_a $\left(T \propto \sqrt{U_a}\right)$, due to a feedback driven electron source (neutralizer) regulated by the current at the anode, resulting in a constant anode current for different anode voltages. This is not covered in this simulation. But the impact on the qualitative trends of the plasma characteristics inside the thruster is low.

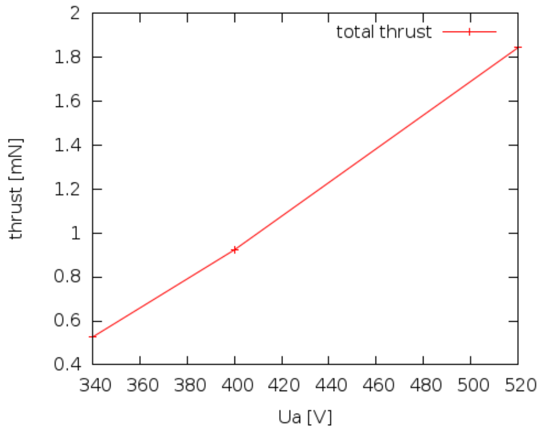

Figure 4. Total thrust of the HEMP for different anode voltages

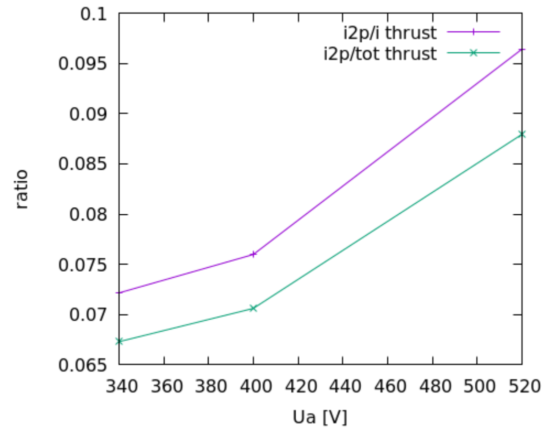

Figure 5. Contribution of double charged ions to the thrust of the HEMP for different anode voltages

The contribution of double charged ions to the thrust increases with anode voltage. The energy of single charged ions leaving the thruster scales linear with the applied anode potential. For the double charged ions one gets twice the energy compared to the single charged ions (see Fig. (5)). Interestingly, the ratio of double charged to single charged ions drop with increased anode voltage. The ionization zone of single charged ions gets radially broader with increased anode voltage, because the electron energy gets larger and by this ionization increases.

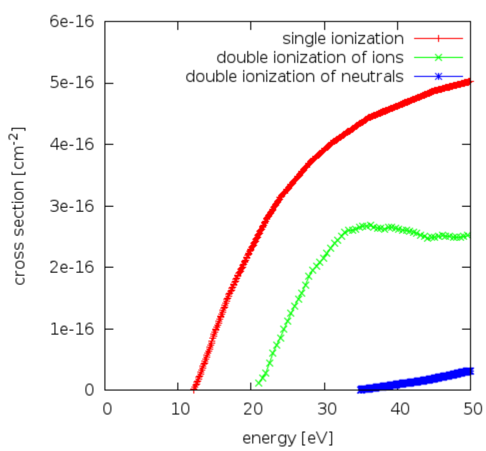

Figure 6. Cross sections for the ionization collisions

The threshold of the single ionization process (12eV) is lower than for both channels of the double ionization process (20eV for double ionization of single charged ions and 35eV for direct double ionization of neutrals).

Large parts of the electron distribution functions have higher energies than the threshold energy for single ionization, whereas mostly energetic tail electrons allow double charging of the ions (see Fig. (6)). This leads to the stronger increase of single charged ion density with respect to double charged ions, which can be also seen in the particle densities comparing Fig. (1) and Fig. (2).

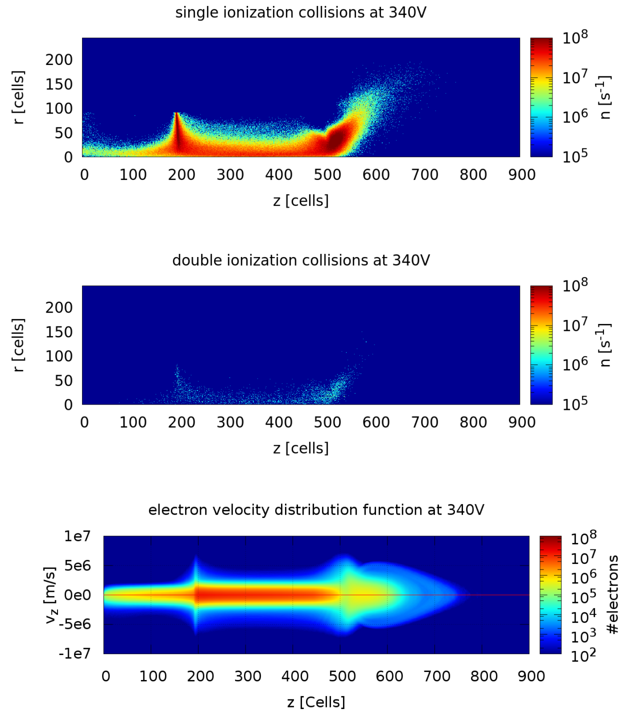

Figure 7. Ionization rates and line integrated v_z electron velocity distribution function at 340V anode voltage

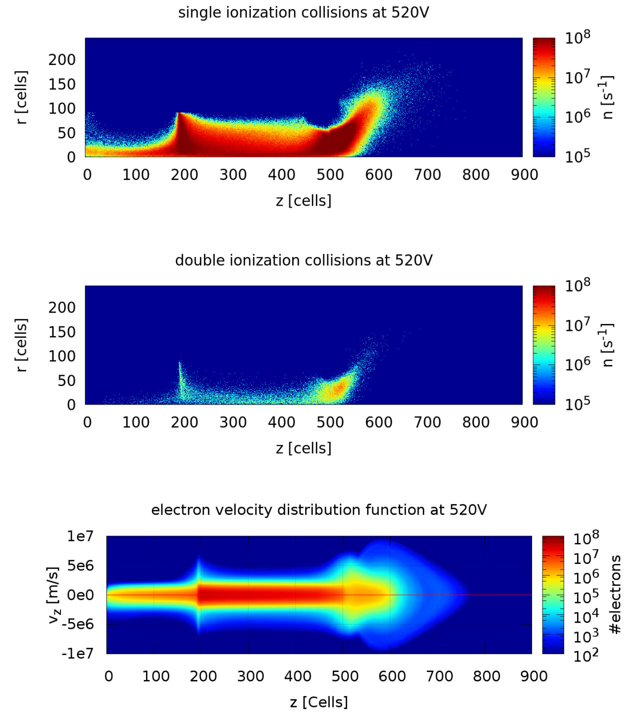

Figure 8. Ionization rates and line integrated v_z electron velocity distribution function at 520V anode voltage

A quantitative analysis of the ionization distribution for the production of single and double charged ions confirms this picture. One uses the ionization collision distribution (Fig. (7+8)) to calculate as a function of the axial location z its radial mean value for the scenarios with different anode potentials. First the weighted mean value of ionization $r_{mean}(z)$ at each value z is calculated:

$$r_{mean}(z) = \frac{\int r * n_{ionization}(r,z)\mathrm{dr}}{\int n_{ionization}(r,z)\,\mathrm{dr}}\,, \tag{1}$$

$$r_{mean,total} = \frac{\int r_{mean}(z) * \left(\int n_{ionization}(r,z)\mathrm{dr}\right)\mathrm{dz}}{\int\int n_{ionization}(r,z)\mathrm{dr}\,\mathrm{dz}}\,. \tag{2}$$

Integrating the mean values over the axial distance z delivers one integral number for the radial ionization distribution for one anode voltage and the different charge states.

An example for the case of 520 V anode potential is shown in Fig. (9). This can also be done for the ionization collision distribution for the creation of double charged ions. Analyzing this for the different anode voltages one observes a clear difference between single and double charged ions, as expected from the previous discussion. The radial position of ionization processes increases due to the electron energy distribution inside the channel (Fig. (7+8)). Due to the higher threshold of the cross sections the broadening of the ionization area increases slower for double ionization than for single ionization processes.

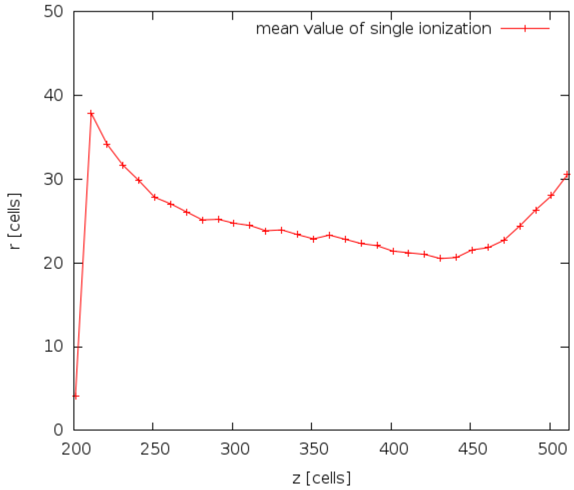

Figure 9. Mean value of the radial distribution of ionization collisions inside the thruster channel at 520V anode voltage as a function of axial location z.

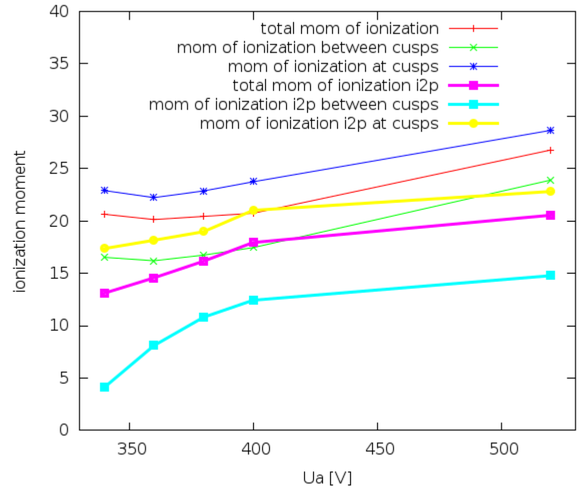

Figure 10. Ionization weighted mean values for different areas inside the channel for single and double ionization processes and different anode voltages.

IV. Conclusion

The Particle-in-Cell method was used to study the effect of varying anode voltage on the High Efficiency Multistage Plasma Thruster. The simulations demonstrated that the new HEMP thruster concept shows a linear dependence of thrust with anode voltage allowing a flexible adjustment to different operational scenarios. The contribution of double charged ions to the thrust increases with anode voltage, whereas the ratio of double charged to single charged ions drop with increased anode voltage. This originates from a stronger radial broadening of the ionization zone of single charged ion with increased anode voltage compared with the ionization zone of double charged ions. This is explained by the change of the electron distribution functions and the difference of cross sections for the production of single and double charged ions.

Acknowledgments

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