Particle-in-Cell Simulation of a HEMP Thruster Digital Prototype Optimized for Future Satellite Applications

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Abstract: Simulation results of a High Efficiency Multistage Plasma Thruster Digital Prototype HEMPT-DP1 as well as the design concept of the respective hardware prototype are presented. The HEMPT-DP1 targets in particular to near future low Earth orbit satellite mega constellations, which require cost-effective ion propulsion systems that can be produced in short times. DP1 implements a cylindrical shape of both discharge channel and permanent magnets to allow for simplified design and construction. The discharge channel geometry and the magnetic field topology follow state-of-the-art design criteria for HEMPTs. Results of Particle-In-Cell PIC based numerical studies show plasma properties that exhibit typical features of a HEMPT: plasma wall contact is minimized which results in a low amount of thermal losses and a high acceleration efficiency at the required thruster operational points. A first mechanical design of a hardware prototype derived from the DP1, the HP1, results in a compact and robust thruster with low complexity, which allows for short production times and low costs.

Nomenclature

AOCS = Altitude and Orbit Control System
DSMC = Direct Simulation Monte Carlo method/code
EPS = Electric Propulsion Subsystem
HEMPT = High Efficiency Multistage Plasma Thruster
(V)LEO = (Very) Low Earth Orbit
PIC-MCC = Particle-In-Cell method/code with Monte-Carlo-Collisions
PTTR = Power-to-thrust-ratio

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I. Introduction

LEO mega constellations with few hundreds to thousands of satellites to cover all types of communication tasks are proposed by, e.g., SpaceX [1] or OneWeb [2], respectively. Since a large number of few tens of these satellites are foreseen to be transported into orbit per launch, the satellites need to be very mass efficient. This can only be achieved by using electric propulsion for the altitude and orbit control system AOCS with specific impulses typically in excess of about 1000 s. Despite a limited power budget of less than a few hundred Watts, thrust levels of up to a few tens of Millinewtons are needed with good controllability down to a few tenths of a Millinewton in case of very low earth orbit VLEO operation to allow for atmospheric drag compensation. In addition to the challenging technical demands, there are very ambitious targets in price and delivery time, which both are crucial regarding the economic success of mega constellations.

In this context it is believed that electric propulsion subsystems EPSs based on the High Efficiency Multistage Plasma Thruster HEMPT technology are very well suited. HEMPT-EPSs exhibit a very low complexity, as firstly reviewed in detail by Harmann, Koch and Kornfeld [3]. Also, the basic thruster design itself as described by Kornfeld, Koch and Harmann [4], or earlier by Kornfeld, Koch and Coustou [5], appears to allow for cost effective production.

Therefore, in course of the here presented work, efforts have been made towards the design of a HEMPT to satisfy specifically the needs of mega constellations. As a first step, an appropriate physics design layout with respect to the physics boundary conditions for high efficient and long life operation has been created, already having in mind the constraints in terms of low complexity and robustness in the later hardware design. From this, a first digital prototype, HEMPT-DP1 has been derived. As a next step, numerical studies on DP1 have been performed by means of a fully kinetic particle in cell PIC code. After promising results already in an early stage of the simulations, the mechanical design of a first hardware prototype HP1 has been initiated.

This paper is organized in 5 chapters. Chapter 2 describes and motivates the physics design layout of the digital prototype. In chapter 3 the numerical studies are reviewed in terms of simulation concept and results for the DP1. Chapter 4 outlines the mechanical design of the hardware prototype. Finally, in chapter 5 a summary and outlook to next steps is given.

II. Physics Design Layout of the Digital Prototype HEMPT-DP1

The physics design layout follows basic considerations regarding the HEMPT operational concept. Regarding the HEMPT-DP1, the concept is adapted such to provide mission specific operational and performance characteristics of the thruster. This is achieved by means of a proper choice of discharge vessel geometry and magnetic field topology.

A. Basic Considerations

Operational principle and technical evolution of HEMPTs are described in detail in e.g., [4], and by Koch and co-workers in [6]. These earlier findings have also experienced recent confirmation in course detailed theoretical and experimental studies on multi-cusped field thrusters by Zhao and co-workers in [7], and by Hu and co-workers in [8] and in [9], respectively:

The key of the HEMPT concept is a magnetic multi cusp arrangement by subsequent axially magnetized permanent magnet rings in opposite polarization. This yields a magnetic field pattern with alternating predominant axial and radial zones with large radial gradients. The magnet system envelopes the dielectric discharge vessel. The anode, typically also serving as propellant inlet, is placed at the upstream end of the discharge vessel. At the downstream exit an electron source, which represents the cathode and serves also as neutralizer of the emitted ion beam, is mounted.

The magnitude of the magnetic field strength is such, that on the one hand the typical Larmor radii of the electrons are much smaller than the discharge vessel diameter, and that on the other hand ion trajectories are hardly influenced. The electrons oscillate in the cusp mirrors generated by the transition from axial to radial magnetic field, where in addition, depending on the strength of the self-consistently built up electric fields, Hall currents induced by the crossed electric and magnetic fields enhance the electron confinement. This results in efficient ionization of the propellant gas and minimized electron wall contact. Typically, ionization occurs mainly in the inner cusp mirrors of the HEMPT, whilst the potential drop is generated at the exit cusp. Therefore well designed HEMPTs practically exhibit a separation of ion generation and acceleration alike gridded ion thrusters with a similarly sharply peaked ion energy distribution around the acceleration voltage. Following this finding, HEMPTs are similar to gridded thrusters, however, with plasma electrons replacing a physical grid. This feature allows for space charge compensated ion extraction, which provides high thrust densities and therefore a compact thruster design. The compactness of the thruster is also supported by the low thermal losses due to the minimized plasma-wall contact. However, the tapering options of the ion optical lens at the thruster exit, which is represented by electrons being confined by the magnetic cusp mirror, are limited. Therefore, HEMPTs typically show a hollow-conical shape of the ion beam with considerable beam divergence compared to the low divergent ion beams emitted by gridded thrusters.

B. Anticipated Operational and Performance Characteristics

The first digital prototype of the here presented work targets to the following operational and performance characteristics:

i. Nominal discharge current range from 0.5 A to 1.5 A with stable operation down to 10 mA.
ii. Nominal discharge voltage range from 200 V to 600 V with possibility of operating at 800 V in case sufficient power is available for operation at high specific impulses.
iii. i. and ii. shall result in thrust levels up to 25 mN at low specific impulses around 1200 s, and maximum specific impulses in excess of 2700 s, respectively. In case additional drag compensation is required the good discharge controllability shall allow for continuous thrust levels down to 0.1 mN
iv. Minimized electron and hence plasma wall contact at the inner cusp surfaces, as expected for a properly designed HEMPT.
v. Minimum interference of the exit cusp plasma with the discharge channel to avoid ion sputtering at the thruster exit and thus to allow for a high operational lifetime.
vi. Robust mechanical design with minimum complexity involving stable manufacturing processes and high cost efficiency

The operational and performance characteristics i. to v. result from appropriate design of discharge channel and magnetic circuit as described in the following, item vi. is addressed by the mechanical design outlined below in chapter IV.

C. Discharge Channel and Magnetic field Topology

HEMPT-DP1 exhibits a cylindrical shape of both applied magnets and discharge vessel to provide minimum mechanical complexity. The discharge channel width is derived from a detailed description of HEMPT-DM3a in [4]. This is because DM3a exhibits a similar operational range as anticipated for DP1 (see [5]). However, in case of DP1 the discharge channel width is enlarged by a factor of about two compared to DM3a. Since this reduces the neutral gas densities at a given propellant throughput, it would presumably result in reduced ionization efficiency. To compensate for this effect, the magnetic field strength on axis has been adapted accordingly towards lower values (in case of DM3a, at the given magnet geometry shown in [4], and assuming a residual induction of 1 T of the permanent magnet material, about 0.2 T to 0.3 T of magnetic induction are expected). As a result, the DP1 design is expected to provide a better filling of the discharge vessel at lower plasma densities and thus sufficiently high ionization yields of the propellant. These considerations are qualitatively confirmed by detailed studies given in [8]. Nonetheless, the radial fields and the radial gradients in the cusp zones in vicinity to the discharge vessel inner radius are kept as high as possible to grossly avoid plasma wall contact. Special care has been taken regarding the magnetic field design at the thruster exit. The magnetic field lines' separatrix is bent slightly outside, such that the filed lines enter the exit sided magnet with minimal interference to the discharge vessel. It is believed, that this will grossly reduce the plasma wall contact at the thruster exit, thus enhance acceleration efficiency and prevent from erosion effects to assure a high operational lifetime. As a drawback, a slightly higher ion beam divergence is expected compared to a magnetic field topology with a more inwardly bent separatrix. The influence of magnetic shaping on beam divergence is described by Koch, Harmann and Kornfeld in a patent filed by Thales Electron Devices GmbH in 2006 [10].

The spatial distribution of the magnetic induction with respect to discharge vessel and anode location is shown in figure 1. Field calculations have been performed by means of an FEM code [11].

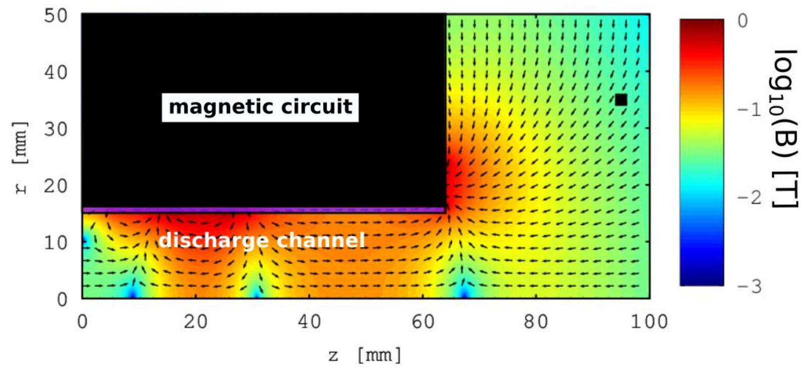

Figure 1: Spatial distribution of the magnetic induction of HEMPT-DP1 according to an FEM simulation. The radial and axial position are denoted as r and z, respectively. The anode is placed at z = 0, and discharge channel (pink) extends from the anode to z = 64 mm. The shown r-z-range also represents the domain of the plasma simulations described in capter III.

The HEMPT-DP1 magnetic circuit essentially consists of three magnet rings with different lengths each. The magnetic material used is available off the shelf from the supplier, withstands space environment and is rated for maximum operational temperatures of 360 °C, the latter allowing for a radiation cooled thruster design. Due to the magnetic field topology, electrons injected from an external cathode will experience four cusp mirrors impeding their movement towards the anode. From the above mentioned considerations, the main potential drop is expected to occur at the exit sided cusp, and the main ionization zones at the inner cusps at z-positions of about 30 and 15 mm, respectively. Despite relatively efficient thruster operation is reported with a two-cusp design in [8], which would reduce thruster production costs and thruster mass, the here presented design is believed to yield improved discharge stability and enhanced efficiency, in particular at low anode voltage operation.

III. Numerical Studies

The numerical studies include a finite element FEM code [11] to simulate the magnetic field distribution and a direct simulation Monte Carlo DSMC code [12] to calculate the neutral gas distribution. Both codes have been used to iteratively optimize the physics design layout described in chapter II from above.

Main part of the numerical studies concerns the self-consistent description of the plasma parameters by a fully kinetic Particle-In-Cell code with Monte Carlo collisions PIC-MCC from which the thruster characteristics are derived. First successful application of this code has been demonstrated already in 2009 by Matyash and co-workers [13], [14]. The concept of PICC-MCC and the results obtained for HEMPT-DP1 are reviewed in the following.

A. PIC-MCC Simulation Concept

The mean free paths inside a HEMPT are equal or longer than the system size, which allows non-Maxwellian electron distribution functions and requires a kinetic simulation method. Due to the rotational symmetry of the system, the spatial domain was reduced to r-z, and an electrostatic 2d3v PIC-MCC was used [15], [16]. In the PIC-MCC simulation so-called Super Particles (each of them representing many real particles) move in the self-consistent electric field calculated on a spatial grid by solving Poisson's equation. The magnetic induction of the magnetic circuit is included in the Lorentz force, but the plasma currents are considered negligible to modify the magnetic fields. All relevant collisions are included in the model: electron-electron Coulomb, electron-neutral elastic, ionization and excitation collisions, ion-neutral momentum transfer and charge exchange collisions. To produce double ionized ions both processes of direct ionization of neutral atoms and of ionization of single ionized ions are considered. The dynamics of the background neutral gas is self-consistently resolved by DSMC. Plasma surface interactions like ion recycling, thermal re-emission and secondary electron emission are provided by a Monte Carlo erosion module. For electrons an anomalous transport model according to Bohm diffusion is applied.

For time and spatial resolution of the simulation, $\Delta t = 0.05 / \omega_{\mathrm{pe}} = 0.3$ ps and $\Delta r = 0.5\ \lambda_{\mathrm{D,e}} = 0.004$ mm is taken, with ω_{pe} and $\lambda_{\mathrm{D,e}}$ being the plasma frequency and the Debye length, respectively. In figure 1 from above, the simulation domain and the thruster geometry are given. In order to reduce the computational time, the size of the system is scaled down by a factor 30. In order to preserve the ratio of the particles mean free paths and the gyroradii to the system length, the collisions cross-sections and the magnetic field are increased by the same factor 30. This results for the calculational domain in a grid of 247 x 449 cells, containing the thruster channel and the near field plume. Xenon has is used as propellant gas, and at the anode a potential of 500 V is applied. The discharge vessel is dielectric, which is included in the Poisson solver. All other boundary conditions are set to ground potential. An electron source which provides thermal electrons of 1 eV with a source current of 14 mA, is placed in the plume region to represent the cathode.

B. Simulation results of the HEMPT-DP1

For the plasma simulation, HEMPT-DP1 has been operated at an anode voltage of 500 V with Xenon (Xe) being used as propellant. The simulation results on the main plasma characteristics obtained for HEMPT-DP1 are shown in figure 2. Here, the density of electrons and singly ionized Xenon propellant ions as well as the plasma potential are given.

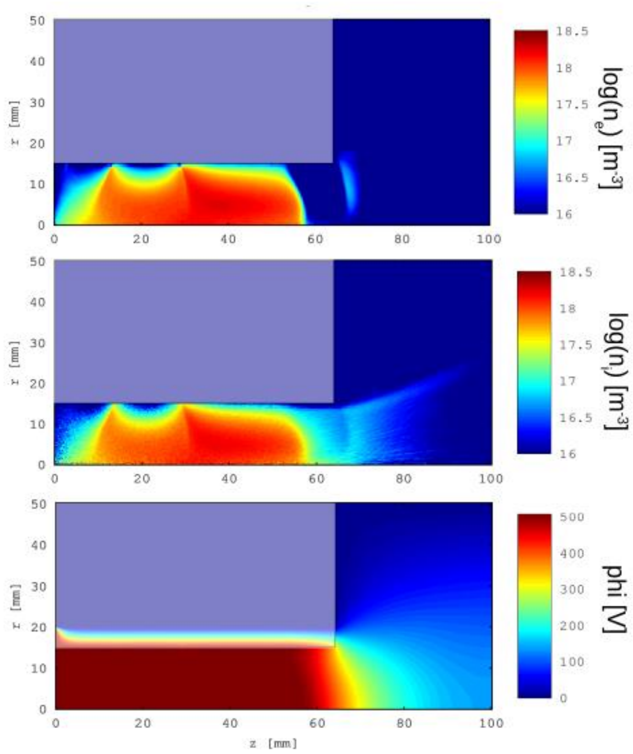

Figure 2: Simulation results of the spatial distribution of the main plasma characteristics of HEMPT-DP1. Above: electron density in logarithmic scale. Middle: density of singly ionized Xenon propellant ions given in logarithmic scale. Below: plasma potential.

It is found, that the amount of double charged ions corresponds to 6 % of single charged ions with a similar density distribution as the single charged ions. The density distributions demonstrate the well-known characteristic of an HEMPT, namely minimized plasma-wall contact inside the thruster channel limited to the cusp locations.

The resulting plasma potential shows the characteristic flat potential evolution inside the thruster channel and the sharp potential drop at the exit. This leads to an efficient acceleration of the emitted ions.

As a result, in the inner region of the discharge channel ions are only lost at the cusp locations wall due to quasi-neutrality. The erosion here is minimized, because the energies of the impinging ions are well below the sputter threshold. Outside the acceleration channel, the magnetized plume electrons in the exit cusp follow the magnetic field lines and hit the exit magnet. In this region, the potential drop generates an electric field pointing out of the thruster exit. Since electrons are grossly prevented from impinging the discharge vessel inner surface, practically no ion impingement is observed, which confirms the design concept of HEMPT-DP1 towards a maximum operational lifetime.

In order to allow for comparison of the visible appearance of a HEMPT in operation, the spatial distribution of the excited Xenon neutrals has been extracted from the simulation results. This corresponds to the experimentally observed light emission The distribution is shown in figure 3. It can be seen, that the plasma appears well confined close to the thruster axis, as typical for HEMPTs and as shown, e.g., in the photographs given in [8].

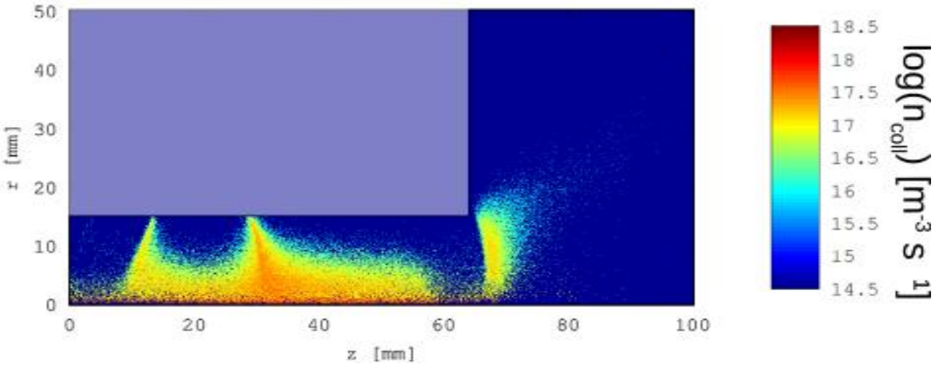

Figure 3: Simulation results of the spatial distribution of the neutral Xenon excitation rate density in logarithmic scale corresponding to the visible light emission of HEMPT-DP1.

In a further step, the angular distribution of the emitted Xenon ions in both single and double ionized state in terms of relative particle currents has been derived from the simulation results. This is shown in figure 4.

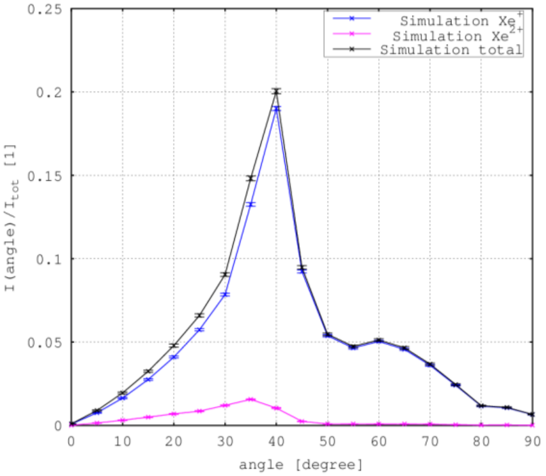

Figure 4: Simulation results of the angular distribution of the emitted Xenon ions for HEMPT-DP1in both ionization states.

As a result of the shape of ion optical lens at the thruster exit represented by the magnetically confined electrons – see also electron density distribution in figure 2 – the main ion current for both ionization states is emitted at an angle of about 40 °. This represents a very good compromise with respect to beam divergence and minimized plasma contact at the thruster exit, moreover, since the latter aspect is focus of the presented development.

Analysis of typical thruster operational and performance parameters show a produced thrust level of 2.5 mN, an ionic specific impulse of 1840 s, and a power-to-thrust-ration PTTR of 17.9 W/mN. The acceleration efficiency, which at the given operational point is about equal to the thermal efficiency, is found to be as high as 98 %. This means that thermal dissipation to anode and discharge channel walls amounts only 2 % of the discharge anode power. Those data are considered very encouraging and confirm the presented design objectives. However, it has also been found that the ionization yield is much lower compared to typical values of around 80 % obtained for efficiently operating

HEMPTs. Also the thermal efficiency is believed to be over-estimated in our simulation, and is expected to be well below 90 %.

Both underestimation of ionization yield and thermal losses point to additional electron transport paths, which have not been adequately considered in our simulation studies. It is believed, that additional electron transport is induced by micro turbulences. In general, existence of turbulent structures are observed practically for all magnetically confined plasma systems, as investigated, e. g., in early studies from 1966 by Janes and Lowder [17]. The inclusion of additional radial transport with realistic eddy sizes and correlation lengths is possible by adding a random walk model in real space with empirical diffusion coefficients, which are for such systems in the order of 1 m²/s. This broadens the profiles, increases by this strongly the ionization and the plasma plugging of the neutral gas in the acceleration channel. Such additional turbulent transport also reduces strongly the density structure outside the exit cusp in the plume and improves by this the ion angular distribution. Here, further studies are needed.

IV. Mechanical Design

The design of the HEMPT hardware prototype HP1 exhibits mechanical robustness and high modularity at significantly reduced costs. It follows a strictly modular concept, which allows for minimum modification efforts in case of changes in working point requirements. Already at an early stage of the hardware prototype development, attention is paid to the cost effective production of all piece parts, sub-assemblies and components. In addition, all necessary production tools are considered. As one result, hardware production involves only well-established and stable manufacturing processes. Thus, merely turning, milling, drilling, and eroding are applied, and only a very limited number of thermal treatments are necessary. The presented design approach therefore allows for later mass production with excellent process controllability to satisfy the needs of up-coming mega LEO constellations.

An overview drawing of the HEMPT-HP1 based on the physics design layout outlined above for the HEMPT-DP1 is shown in Figure 5.

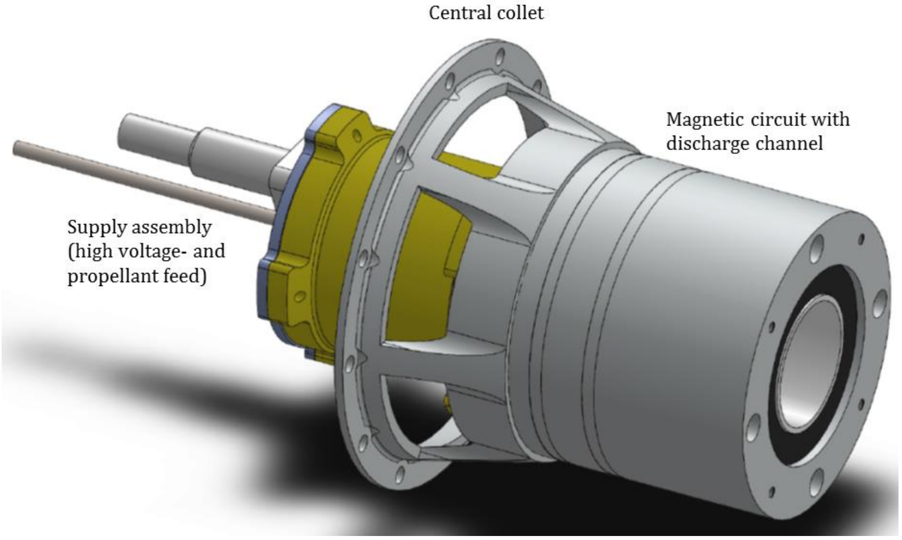

Figure 5: Overview technical drawing of the hardware prototype HEMP-HP1 derived from the digital prototype HEMPT-DP1. The thruster's three main sub-assemblies are indicated.

The HEMPT-HP1 comprises three main sub-assemblies which are described below:

A. Magnetic circuit with discharge channel

The magnetic circuit contains three cylindrical permanent magnet rings fixed in a dedicated mechanical seat. The mechanical seat of the magnets rings is designed to withstand all occurring thermal loads and mechanical stresses caused by thruster operation and spacecraft launch as well as solar panel deployment. This shall assure stable thruster performance over the complete service life. At the inner diameter of the magnet rings, the cylindrical dielectric discharge channel is guided. The cylindrical shape of the magnet system and the discharge channel allows for a simplified and cost-effective manufacturing of the corresponding piece parts. Furthermore, this geometry enables an explicitly easy assembly of the HEMPT-HP1.

B. Supply assembly

The supply assembly contains the anode voltage connection and the propellant feed. For the propellant supply interface to the spacecraft conventional stainless steel tubing is applied. A standard high voltage pin plug serves as anode voltage interface. Electrical insulation of the high voltage parts to the surrounding metal casing is provided by ceramic piece parts with simplified geometries. Conventional sealing technology is applied to avoid propellant losses. Thermal analysis shows that the design allows for significantly reduced thermal loads at the propellant and high voltage interfaces to the spacecraft. At its downstream end, the supply assembly tightens the discharge vessel to cope for discharge shortening to the surrounding magnet system.

C. Central collet

The central collet complies with two duties: Firstly, it accommodates both the magnetic circuit with the discharge channel and the supply assembly. Secondly, it serves as mechanical and thermal interface to the spacecraft.

Depending on the material used and the contour of the central collet, distinct spacecraft requirements can be satisfied. For example, two central collet designs with either dedicated thermal connection to the spacecraft or with thermal decoupling are available. In case of deviating interface requirements to the spacecraft, the central collet can be easily adapted.

V. Conclusion

A high efficiency multistage plasma thruster digital prototype, HEMPT-DP1, has been developed to foster the technical and economical demands of future mega satellite constellations. Discharge vessel geometry and magnetic circuit are optimized towards minimized plasma-wall contact to provide a high acceleration efficiency, low thermal dissipation and negligible erosion. The performed numerical studies essentially confirm the anticipated thruster characteristics. However, the simulation results also show non-realistic behaviors, which presumably are due to an under-estimation of enhanced electron transport induced by micro turbulences, which shall be subject of intense studies in the future.

Encouraged by the numerical results obtained for HEMPT-DP1, the mechanical design of a first hardware prototype, HEMPT-HP1, has been initiated. The design not only copes for thermal characteristics of the thruster in operation, but also for typical spacecraft interface and launch requirements. It is mainly based on standard manufacturing processes, and will allow for well controllable and cost effective production of the thrusters with short delivery times.

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