# Status of the THALES High Efficiency Multi Stage Plasma Thruster Development for HEMP-T 3050 and HEMP-T 30250

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**Abstract: High Efficiency Multi Stage Plasma Thrusters (HEMP-Ts) developed by THALES Electron Devices GmbH represent a new concept for ion thrusters with unique operational and performance characteristics. The particular magnetic field topology of HEMP-Ts provides stable and erosion-free operation up to high specific impulses with a low amount of thermal losses and allows for a compact and robust design. The instant-on properties and the absence of discharge instabilities strongly facilitate the propulsion system layout. Therefore HEMP-Ts are an ideal basis for cost-effective, reliable and long-life electric propulsion systems. In the past three years, THALES has addressed two main development axes directed towards HEMP thrusters with nominal specific impulses of 3000 s: the medium power HEMP-T 3050 and the high power HEMP-T 30250 with nominal thrust and input powers of 50 mN and 1500 W and 250 mN and 7.5 kW, respectively. The activities have been performed under support form German and European Space Agency DLR and ESA. Product development is focused on the HEMP-T 3050 capable for position and orbit control of small, mid and large-size telecom satellites. Currently, a radiation cooled HEMP-T 3050 engineering model is being developed, which represents the basic design for the HEMP-T 3050 qualification and flight models. The HEMP-T 30250 has been developed to breadboard level and demonstrates the scalability of the HEMP thruster concept towards high power and thrust levels. This paper reviews the development status, operational and performance characteristics of both HEMP-T 3050 and HEMP-T 30250 thrusters and outlines further activities towards space-qualification.**

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# I. Introduction

IN the recent years, an increasing interest has developed for using ion propulsion systems on board of both scientific and commercial satellites. Particularly in Western Europe, Hall Effect thruster (HET) systems have shown to perform well on Astrium's geo-stationary Eurostar 3000 telecommunication satellite platform[1] and on ESA's Smart-1 mission[2], respectively. Despite the good performance, especially commercial satellite manufacturers still hesitate to equip their space crafts with ion propulsion systems[3]. This is because the benefits arising from the high specific impulse compared to conventional chemical propulsion systems are foiled by the high system costs and complexity of the ion propulsion systems existing so far.

Since the year 2000, THALES Electron Devices TED has started the development of a completely new ion thruster concept, the so-called High Efficiency Multistage Plasma Thruster HEMP-T. This development has been performed in course of diversification activities for satellite applications, where TED is world market leading supplier of traveling wave tubes (TWTs) for telecommunication satellites[4]. The basic HEMP-T concept was derived from TWT physics and technology with respect to electron beam focusing and multi-stage electrostatic potentials in the collector stage[5]. Since then, due to continuous improvements in theoretical understanding of the thruster physics, in testing and diagnostics infrastructure and in manufacturing technologies, the HEMP-T performance could be steadily improved and adapted to the market needs in particular for commercial geo-stationary telecommunication satellites[6,7,8,9,10]. The main features of recently developed HEMP-Ts are a broad operational regime with respect to power, thrust and specific impulse, a high thermal efficiency resulting in a minimum of thermal losses, absence of discharge channel erosion, calm and stable discharge behavior with absence of current fluctuations and only regular discharge current oscillations and instant turning on characteristics. This specific performance and operational characteristics allow for HEMP-T based electric propulsion systems with uniquely low complexity and high cost-effectiveness[3].

Currently, HEMP-Ts are developed for two power classes and thrust regimes, both optimized for specific impulse operation at about 3000s: HEMP-T 3050 with a nominal thrust of 50 mN (thrust range 15mN to 70mN) at a nominal input power of 1500W and HEMP-T 30250 with 250mN (range 50mN to 330mN) at 7.5kW, respectively. In this operational ranges, anode efficiencies of up to 46% for HEMP-T 3050 and 51% for HEMP-T 30250 are achieved. HEMP-T 3050 is on breadboard level, and a radiatively cooled engineering model is being developed at the moment. Qualification model level of a complete HEMP-T based propulsion system shall be achieved by mid 2008 followed by qualification and life testing. This so-called HEMP Thruster Assembly HTA also includes the own developed HKN 5000 neutralizers[11] and will be entirely integrated and tested by TED. In orbit demonstration shall occur from 2010 onwards on board of OHB's Small Geo-stationary satellite platform SGEO developed in course of the ESA ARTES-11 program[12]. HEMP-T 3050 will be the basis for a modular, reliable and cost-effective commercial propulsion system for state-of-the art small to large communication satellites with typically available input powers for the propulsion system of up to 4kW. The high power HEMP-T 30250 is on breadboard level. It represents scaling-up efforts in cylindrical configuration towards higher thrust and power levels while maintaining the unique features of the HEMP-T concept.

This paper is organized in five sections: the HEMP-T concept and operational features are given in chapter 2. Chapter 3 and 4 review the status of the HEMP-T 3050 and 30250 development, respectively. Chapter 5 gives a summary and outlook to the next development steps.

## II. Thruster Concept and Operational Features

A scheme of the cylindrical HEMP-T concept is given in figure 1. A dielectric discharge channel is surrounded by a system of periodically arranged permanent magnets (PPM system). At the upstream end of the discharge channel the anode and the propellant gas inlet are mounted, and at the downstream end a neutralizer cathode is placed. The PPM system forms magnetic cells in which electrons are efficiently trapped in a cusp-mirror configuration. As a consequence, the plasma electrons are prevented from contacting the discharge channel walls and their flow to the anode is strongly impeded in the zones of high radial magnetic field. Due to the efficient electron confinement starter electrons from the cathode are strongly amplified by an ionization avalanche and the plasma is sustained with a minimum electrical power input. Since electron diffusion to the discharge channel wall is minimized, the sheath potential becomes minimal, and only a minimum ion current at energies below the sputter threshold reaches the wall. Therefore, HEMP-Ts show no erosion phenomena at the inner discharge channel wall. The minimized electron losses to the wall and the high impedance towards the anode allow thruster operation without an external cathode to sustain the discharge. As a consequence, there is no electron loss current flowing from the cathode to the anode. This, together with the negligible power losses to the discharge channel, provides a high thruster thermal efficiency.

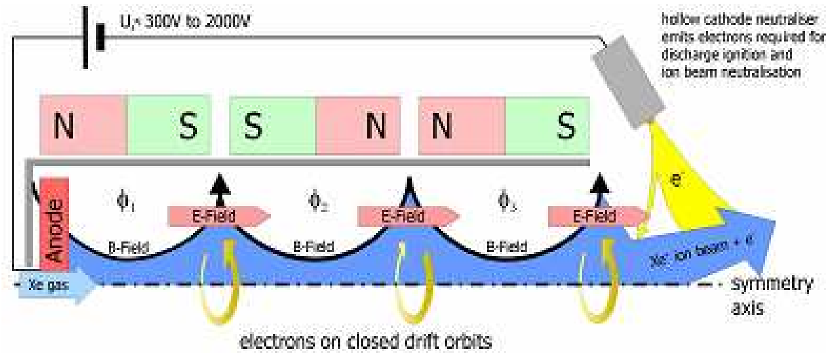


**Figure 1: Schematic view of the HEMP thruster concept. As an example, an arrangement with a cylindrical discharge channel and 3 magnet rings is shown, such that 3 cusp zones with high radial field are formed in the discharge channel.**

Typically, HEMP-T's exhibit 3 magnetic stages provided by means of 3 oppositely polarized ring magnets. The zones with maximum radial magnetic field denoted as cusps are close to the anode between the 1st and 2nd magnet downstream ("anode cusp"), in the middle of the thruster between the 2nd and the 3rd magnet ("middle" or "main cusp") and at the thruster exit after the 3rd magnet ("exit cusp"). Electrostatic potentials in the plasma are formed self-consistently due to the respective magnetic field configuration, neutral gas density and discharge channel geometry. Current HEMP-T models are designed such that the main potential drop occurs at the exit cusp with minimum potential drops at the other cusps. High reflection of electrons in the cusp-mirror situation is achieved for a high ratio of the (predominantly radial) magnetic field strength at the inner discharge tube radius at the cusp middle plane to the (predominantly axial) magnetic field strength downstream the cusp. In addition, the curvature of the magnetic field at the exit cusp is mainly affecting ion beam formation. Since electrons are kept off the dielectric channel wall, this charges up positively due to some ions reaching the wall and therefore the discharge channel serves as additional focusing element for the ion beam. The main cusp typically carries the higher portion of electronic wall losses and, together with the anode cusp, serves for discharge stabilization. Beam divergence is mainly caused by ionization and charge-exchange on low potential in the plume region downstream the thruster exit cusp and is therefore influenced by electronic impedance of the exit cusp radial magnetic field and by the neutral gas density at the thruster exit. Development efforts are directed towards optimization of magnetic field topology and discharge channel geometry and an optimum adaptation of the neutral gas density distribution to achieve minimum electronic losses on anode and discharge channel wall, a low ion beam angle, a high ionization efficiency inside the discharge channel and a minimum plume potential. A detailed overview on HEMP-T physics and on theoretical modeling is given in reference[13].

## III. Status of HEMP-T 3050

### A. HEMP-T 3050 Breadboard Models

Current HEMP-T 3050 models are the so-called demonstrator models DM9-1 and 9-2, which have been developed under DLR contract 50JR0341. DM9-1 and 9-2 are conductively cooled thruster models on breadboard level and form the basis for further development towards engineering and qualification models. Thruster characterization has been performed in the ULAN test facility by means of a thrust balance, and angular ion beam characteristics have been investigated with a bolometer and a retarding field potential analyser[10]. Despite having a broad operational range in applicable anode voltages and power levels, DM9-1 and 9-2 were optimized for operating at high specific impulses of about 2500 to 3000s at anode voltages between 800 and 1000V with thrust values from 15mN to 70mN corresponding to power levels from 400 to 2000W. In this range, the anode efficiency ranges from 36% at the low power point to 46% at high power operation. Nominal operation is at about 1650W, 3000s and 50mN with an anode efficiency of about 45%. The corresponding power-to-thrust ratio is about 33W/mN and the divergence is about 50° for the 90% total ion current solid angle integral (a detailed discussion on the evaluation of the beam divergence is given in ref.[10]).

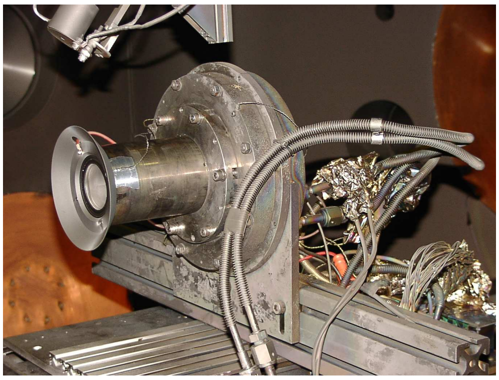

**Figure 2: HEMP-T 3050 DM9-1 mounted on the thrust balance of TED's ULAN testing facility.**

A photograph of DM9-1 mounted on the thrust balance of TED's ULAN facility is given in figure 2. In this case the thruster is already equipped with a radiation shield mounted on the exit to get first experience with radiation cooling for the engineering model and to verify thermal calculations. The radiation shield is thermally decoupled from the exit magnet and is in addition electrically isolated. It mainly serves to dissipate the power coming from ion backflow from the plume. The isolated configuration allows for measuring the floating plume potential at the location of the shield and effectively reduces the energy of ions impinging the shield by this floating potential. As a result, the temperature at the thruster exit magnet could be reduced by 40K at a thruster input power of 1400W compared to the original DM9-1 set-up without the radiation shield.

Emphasis was laid on the investigation of the thruster discharge stability. It is observed that there are no irregular current fluctuations for the entire operational envelope and there is only a regular nearly sinusoidal current oscillation with a frequency of about 80 to 100kHz depending on operational regime. The amplitude of the current oscillation is about 25 to 30% of the DC current value at the nominal operational point. As a consequence of the calm and stable discharge behavior, no additional filtering network with capacitive and inductive loads is needed. Operation with space-type power processing units (PPUs) originally designed for supplying the grid voltage for grid thrusters from Astrium and ETCA demonstrated absolutely stable thruster operation and full PPU efficiency[3,14].

First technology tests have been performed with respect to vibration loads as expected during satellite launch. It was observed, that the 1$^{st}$ Eigen frequency of the thruster was at about 800Hz. A load of 20g RMS provided by the TED vibration test bench has been applied for 3 minutes. After disassembling the thruster components, no damage or wear mechanisms could be identified.

A further main focus was to investigate the performance stability in course of long term thruster operation. For this purpose, two 400h endurance runs have been performed. The thruster has been operated at an anode voltage of 1000V, a Xenon flow of 16.25sccm and an anode power of 1.4kW corresponding to the nominal working point on OHB's SGEO satellite[11]. During both runs the thruster kept steadily running and there was no single flame out. The thruster was only switched off when the cryo pumping system of the vacuum system had to be regenerated. It has been observed, that once thermal equilibrium has been reached, the thruster temperatures and the discharge current stayed constant with running time. Measurements of the thrust, which could not be performed continuously but were taken typically once or twice between 2 cryo system regeneration cycles, also showed a constant thruster performance. As an example, the evolution of discharge current and relevant thruster temperatures vs. running time is given in figure 3 for a 3 days run between 2 cryo system regeneration cycles.

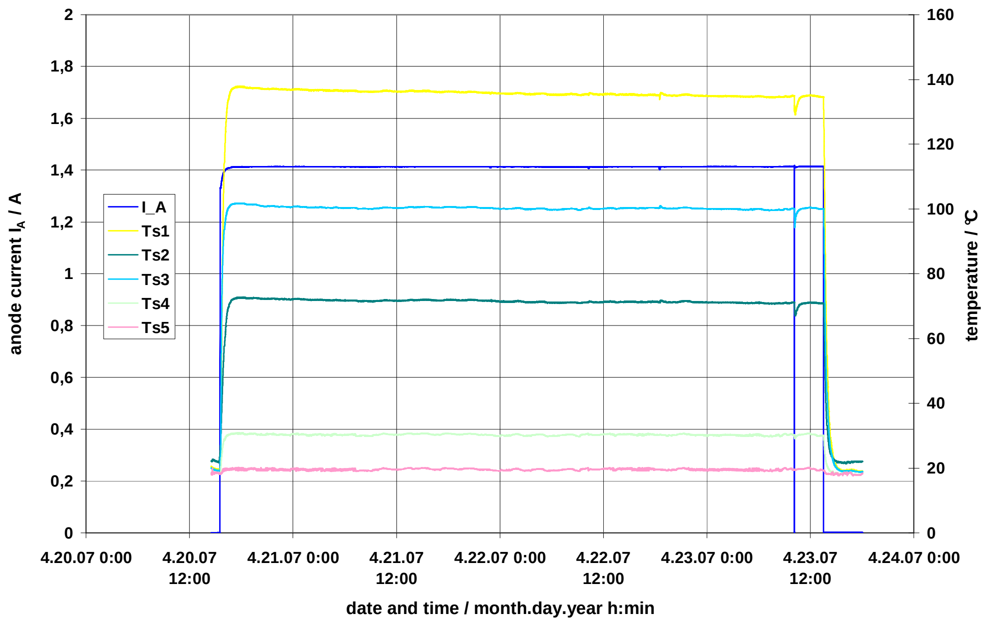


**Figure 3: Thruster anode current $I_A$ and relevant thruster temperatures Ts1…5 vs. running time for a 3 days run of HEMP-T 3050 DM9-1 in course of a 400h endurance test.**

It is observed, that after a warming up time of about 1.5h, the anode current stays constant within 15mA. Also all relevant thruster temperatures remain nearly unchanged with a maximum variation of 4°C. The difference in current immediately after thruster start-up and steady-state operation is about 70mA. This variation will be compensated in case of operation on a satellite, since the thruster will not be operated with a constant Xenon mass flow as in case of the endurance runs, but the mass flow will be in closed-loop regulation with the anode current[3]. As pointed out above, no single flame out has occurred. The thruster was only switched off once the end of the run (on 4.23.07, 10:00h) to zero the thrust balance and measure the thrust.

### B. HEMP-T 3050 DM10

HEMP-T 3050 DM10 is a further conductively cooled breadboard model, some aspects of which have been developed in the framework of the ESA TRP program 20019/06/NL/SFe. DM10 is currently being set-up and thruster characterization will be performed by end of September 2007. The goal of DM10 development is an improvement in anode efficiency towards 50% and a reduction in ion beam divergence to below 45°. In addition, DM10 incorporates technology features designed for the HEMP-T 3050 engineering model.

In order to increase the anode efficiency, the magnetic circuit has been modified to further reduce electron wall losses by improving the electron confinement in the cusp-mirror configuration. Therefore the magnetic field topology has been changed as to increase the ratio ζ between radial field in the cusp plane and axial field downstream the respective cusp. The magnetic field circuit has also been modified to minimize the magnetic stray field and the magnetic dipole moment of the thruster, both issues being important for satellite integration. In addition, the discharge channel diameter has been increased. This reduces the power density at the inner discharge tube radius in the cusp planes and it reduces the neutral gas pressure at the thruster exit for a given ionization efficiency. Therefore a reduction in plume divergence is expected due to a reduced charge exchange rate and due to a reduced plume potential, respectively. A comparison between DM9-1 and DM10 of the changes in ζ at the anode, main and exit cusp ("(AC/MC/EC)"), in the discharge channel diameter ∅ at the main cusp and at the thruster exit ("(MC/exit)"), in the magnetic dipole moment D in $Am^2$ and in the magnetic stray field B in $10^{-5}$T in 25cm distance to the thruster middle axis is given in table 1. It can be seen, that for DM10 ζ could be significantly increased for all cusps by a factor of 2.66 to 3.44. The increase in diameter will reduce the neutral gas density at the exit by a factor of about 2 and enhance the Hall parameter also for the inner cusps. It will also reduce the power density dissipated to the wall at the anode and main cusp middle plane by a factor of 1.6 and of 1.06 at the exit cusp assuming the same amount of power losses as in case of DM9-1. The clear reduction of the magnetic dipole moment by a factor of 16 and of the stray field close to the thruster by a factor of 14 will strongly facilitate thruster integration on the satellite, in particular when the ion propulsion system is foreseen to be placed close to magnetic field sensitive payload elements such as TWTs.

| | **ζ (AC/MC/EC)** | **∅ / mm (MC/exit)** | **D / Am2** | **B / 10-5 T (r=25cm)** |
|---|---|---|---|---|
| **DM 9-1** | **1.53 / 1.70 / 3.07** | **22.5 / 45** | **95.5** | **55** |
| **DM 10** | **4.07 / 4.2 / 10.57** | **37 / 48** | **5.79** | **4.0 (=EMF)** |

**Table 1: Comparison between DM 9-1 and DM 10 of the cusp-mirror ratio ζ for anode, main and exit cusp, of the inner diameter ∅ of the discharge channel at main cusp middle plane and thruster exit, of the dipole moment D and of the magnetic stray field induction B in a radial distance of 25cm to the thruster middle axis. EMF denotes the Earth residual magnetic induction of 4Gauss.**

### C. HEMP-T 3050 EM Engineering Model

The HEMP-T 3050 EM engineering model is a completely radiatively cooled thruster and forms the basis for the later HEMP-T 3050 QM qualification model for the propulsion system on board of OHB's SGEO satellite[12].

HEMP-T 3050 EM incorporates the magnetic circuit topology and discharge channel geometry developed for HEMP-T 3050 DM10. Therefore it is expected that HEMP-T 3050 EM will provide anode efficiencies of about 50% and a beam divergence of ≤ 45°. The technologies applied for material processing, surface treatment and for soldering and brazing processes are mainly derived from space qualified TWT technologies. Additional effort has been made to qualify specific ceramic-to-metal joints and surface coatings with respect to thermal cycling, thermally and conductive properties and robustness against vibration loads.

One main difference of HEMP-T 3050 EM compared to breadboard level models is the change from conduction to radiation cooling. Therefore, a thermal design has been developed to cool the thruster by means of a radiator in analogy to the collector cooling scheme of some types of TED's traveling wave tubes[15]. The thermal design has to assure that even under maximum heat dissipation to the thruster, i.e., at 1400W thruster input power and radiator orientation directly towards the sun, the temperature of the permanent magnet system does not exceed 250°C. This provides a safety margin of 50°C, since the magnet material used is capable to withstand 300°C without irreversible losses in magnetization. In addition, the temperature at the connection of the anode power line is to be kept below 180°C which represents the maximum qualification temperature of space-qualified PTFE insulated cable technology. One main input for the thermal design was a detailed thermal analysis performed on HEMP-T 3050 DM8. In course of a 250h endurance test[7], DM8 was equipped with 10 temperature sensors, 3 of which were placed inside the permanent magnet stack to measure the temperature at the inner magnet radius close to the cusp middle planes. The temperature distribution at thermal equilibrium of the thruster allowed determining the total amount of dissipated power losses and the heat flux distribution impinging on the different thruster components. It has been calculated, that at a thruster input power of 1800W the total amount of dissipated losses is 270W, which is about 15% of the input power. This result has been confirmed experimentally, where a power loss of 260W was determined by applying heating elements at the thruster to simulate the temperatures measured in thermal equilibrium. The heat flux distribution calculated by means of the thermal model is given schematically in figure 3. The main locations where power losses are dissipated are the anode (120W), the anode cusp (20W), the main cusp (80W) and the exit cusp and thruster exit plane (20W).

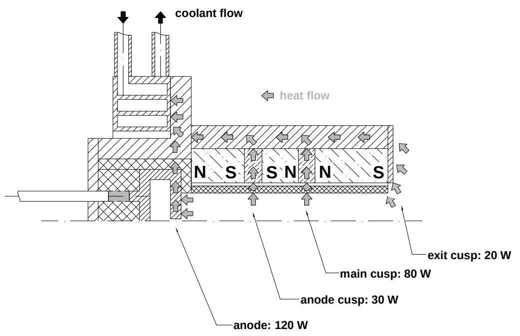


**Figure 3: Schematic view of the heat flux distribution calculated from the thermal model based on measurements with HEMP-T 3050 DM8 at 1800W input power.**

For the radiator design for HEMP-T 3050 EM, as a conservative assumption 280W were assumed as thermal losses, which corresponds to 20% of the nominal input power of 1400W. The same relative heat flux distribution as observed for DM8 was assumed. For the thruster design possibly low temperature gradients are anticipated, which is provided by the appropriate choice of materials and geometries. In order to reduce the temperature at the anode and, in particular, to the anode cable, a radiator is placed on the anode with a double radiation shield. This allows for radiating anode losses towards the temperature relatively insensitive discharge channel and towards the thruster exit. Special care has been taken to guide the heat flux dissipated onto the inner discharge channel wall at the cusp middle planes via the magnetic circuit assembly towards the radiator cones to keep the magnets on a sufficiently low temperature level. The thermal model for HEMP-T 3050 EM is given in figure 4. The radiator

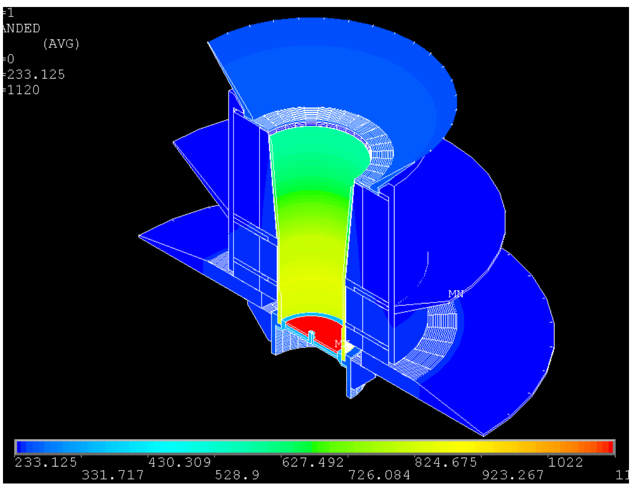


**Figure 4: Thermal model of HEMP-T 3050 EM. Assumed were 280W of thermal power losses dissipated to the thruster and a background temperature of 100°C corresponding to thruster operation with the radiator pointing directly towards the sun. The geometry shown is not to scale.**

essentially consists of three radiator cones, one close to the anode, one at the main cups middle plane and one on the exit, respectively. The shape and the surface coating of the radiators is such as to radiate the dissipated power in radial and forward direction to provide a minimum interaction with the satellite surfaces. The temperature distribution along the main thruster elements which are the anode assembly, the magnetic circuit assembly, the radiator assembly and the discharge channel assembly are shown. The calculation is based on the assumption of a dissipated loss power of 280W and a background temperature of 100°C which corresponds to thruster operation with the radiator pointing directly towards the sun. It can be seen, that there are only small temperature gradients along the radiator and the magnetic circuit assembly. The lowest temperature is 233°C at the outer radius of the first radiator cone close to the anode. The maximum temperature on the magnets is 250°C; a detailed view on the temperature distribution along the magnets is given in figure 4. The discharge channel stays below 860°C, which is far away from the critical temperature of about 1200°C of the ceramic material used. The hottest surface is represented by the radiator mounted on the anode, which gets as hot as 1120°C. This allows for a high amount of radiated power and reduces the heat flux to the anode by about 80%.

The main focus of the thermal design of HEMP-T 3050 EM is to keep the magnets on a temperature of 250°C at maximum even under worst case conditions. The detailed temperature distribution along the magnets is given in figure 4. The hottest zone at 250°C is at the inner magnet radius of the first anode sided magnet, whereas the minimum temperature amounts 241°C at the outer radius of the exit sided magnet.

In summary, the model calculations show that the thermal design is sufficient to maintain the temperatures of all components of the HEMP-T 3050 EM engineering model, in particular of the permanent magnets, on a safe level including large margins.

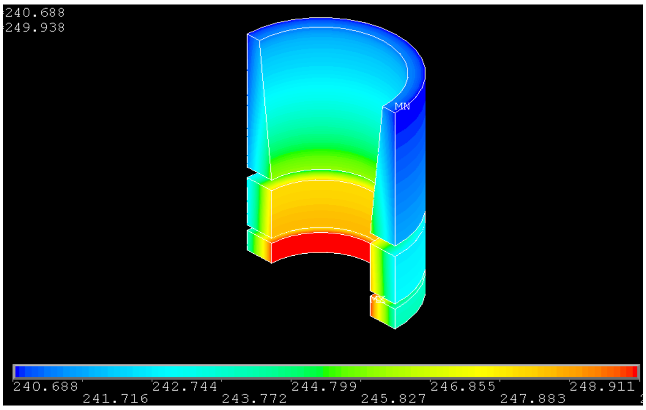


**Figure 5: Thermal model calculations for the temperature distribution along the magnets of the radiatively cooled HEMP-T 3050 EM at a thruster input power of 1400W and a background temperature of 100°C. The geometry shown is not to scale.**

## IV. Status of HEMP-T 30250

HEMP-T 30250 represents an up-scaling of the HEMP-T technology towards higher thrust and power levels while maintaining the typical HEMP-T operational features and characteristics. Nominal thrust and power levels are 250mN and 7kW at a specific impulse of 3000s. The development activities were supported in the framework of DLR contract 50JR0341 and ESA TRP program 20019/06/NL/SFe.

Two design philosophies have been followed: A coaxial HEMP-T with a coaxial discharge channel and an inner and outer magnetic circuit assembly[16] and a cylindrical HEMP-T where the physics boundary conditions from the HEMP-T 3050 are transferred towards a larger discharge volume[8]. Though it could be shown, that the HEMP-T concept can be transferred to a coaxial geometry, it turned out that cylindrical scaling yields better results and needs less technological effort. 4 HEMP-T 30250 demonstrator models DM1 to DM4 have been developed and set-up, of which DM2, DM3 and DM4 are on breadboard level. DM2 and DM3 differ by small modifications in the magnetic circuit layout and have essentially the same performance characteristics. Peak performance values of HEMP-T 30250 DM3 are a thrust of 330mN, a specific impulse of 3150s and an anode efficiency of 51.5% at an input power of 10kW[8]. DM4 shares the same magnetic field topology and discharge channel geometry but incorporates a radiation cooled anode and a radiator at the thruster exit to improve the thermal stability under high power operation.

In figure 5, a photograph of HEMP-T 30250 DM4 mounted on the thrust balance of TED's ULAN test facility is shown. The thruster discharge channel exit diameter is 92mm and the total thruster length and weight is 250mm and 14.5kg, respectively.

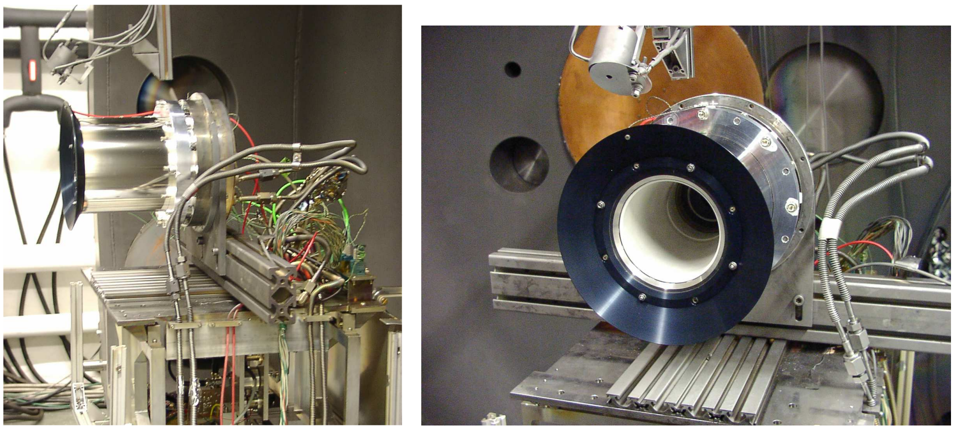

**Figure 5: HEMP-T 30250 DM4 mounted on the thrust balance of the ULAN test facility. Left: side view; right: front view.**

Tests have been performed in grounded configuration with a laboratory type hollow cathode used for discharge ignition. HEMP-T 30250 DM4 has shown the same performance as DM3 as expected due to the same layout in magnetic circuit and discharge channel properties. However, the temperature on the rear side of the anode assembly could be significantly reduced. As a consequence, the thruster could be operated under steady-state conditions at an input power of 6kW without running into the temperature limit of 180°C of the anode power cable, whereas in case of DM3 steady-state operation was limited to 4kW.

## V. Summary and Outlook

In course of TED's diversification activities, HEMP thrusters with a nominal specific impulse of 3000s have been and are being developed in two power and thrust classes: HEMP-T 3050 with a nominal thrust and input power of 50mN and 1500W and HEMP-T 30250 with 250mN and 7.5kW, respectively. At the moment, development is focused on HEMP-T 3050, which forms the basis for a modular, reliable and cost-effective ion propulsion system for commercial small to large geo-stationary telecommunication satellites and for scientific missions. An advanced breadboard model targeting improved anode efficiency and reduced plume divergence, HEMP-T 3050 DM10, is currently being set-up, and the design and technology of a radiation cooled engineering model, HEMP-T 3050 EM, is being developed. Qualification and life tests of a complete HEMP-T based propulsion system for OHB's SGEO satellite is foreseen to start mid 2008, and in-orbit-demonstration onboard of SGEO shall start in 2010.

## Acknowledgements

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