DEVELOPMENT & TEST STATUS OF THE THALES HIGH EFFICIENCY MULTISTAGE PLASMA (HEMP) THRUSTER FAMILY

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Abstract: New, magnetically confined plasma thrusters have been developed with unique performance results: a cylindrical HEMP3050 thruster with a nominal specific impulse thrust and input power of 3000s, 50mN and 1.5kW has demonstrated to operate over wide power and thrust range from 5W to 6kW and from 200µN to 150mN, respectively. Aside throttle-ability, low thrusters mass, minimal thermal dissipation and stable and erosion free operation are unique features promising long life and high reliability. A 250h test allowed worst case life time projection >18000h at a thrust level of 57mN. A coaxial HEMP30250 thruster (nominal thrust and specific impulse 3000s and 250mN) operated in March 2005 confirmed the cylindrical to coaxial scaling of the HEMP thruster concept.

I. Introduction

SINCE year 2000, THALES Electron Devices (TED) has been developing ion thrusters based on the HEMP (High Efficiency Multistage Plasma) thruster concept first patented by TED in 1998[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. The specific magnetic field topology provided by periodical arrangement of magnetic cells efficiently confines the plasma electrons und prevents from plasma-wall contact. On the other hand, electron movement towards the thruster anode is strongly impeded 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.

During development the HEMP thruster concept has clearly proven its feasibility and reached a NASA defined technology readiness level (TRL) of 5. The latest HEMP thruster models have demonstrated and confirmed the following features:

(i.) Wide stable operational range in anode voltage and power, propellant mass flow and voltage resulting in a broad range of thrust values of up to 150mN and specific impulses of up to 3700s.
(ii.) Minimum heat dissipation to the thruster of only 10% to 15% of the anode power input.
(iii.) Erosion free operation yielding a high life-time.
(iv.) Compact size and robust design due to the high thrust density of up to $12mN/cm^2$ at the discharge channel exit surface.
(v.) Minimal discharge current oscillations below 3% of the anode current.
(vi.) Minimum complexity with respect to the electric propulsion (EP) system architecture, since only an anode power supply and a mass flow control unit for the propellant inlet is needed.

The current development line is focused on thruster breadboard models of the cylindrical HEMP3050 type, which provide, when operated with Xe, a nominal specific impulse and thrust of 2500s to 3000s and 50mN to

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70mN, respectively. These performance specifications have been chosen to fit the needs of North-South station keeping of state-of-the-art geo-stationary telecommunication satellites. In addition, a first demonstrator model of a coaxial HEMP30250 model has been set up as a basis for a high power thruster aimed towards higher thrust levels ranging from 100 to 375mN.

This paper is organized in four sections: the physical HEMP thruster concept is reviewed in section II. Performance characteristics and the development status of recent HEMP3050 thruster models as well as first efforts towards an up-scaled coaxial HEMP30250 thruster are reported in section III. Finally, a summary and an outlook to future activities are given in section IV.

II. HEMP Thruster Concept

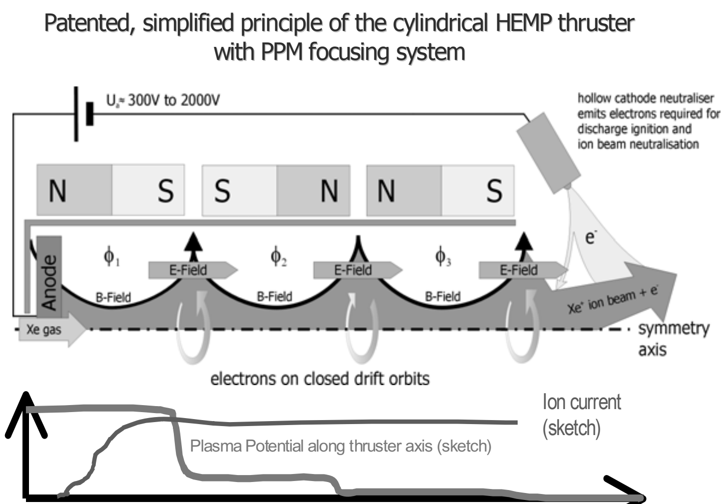

Figure 1: Schematic view of the HEMP thruster concept. Above, the physical arrangement of the thruster components is shown and below the axial distribution of the plasma potential and the ion current is given.

A scheme of the cylindrical HEMP thruster concept is given in figure 1. A dielectric discharge channel is surrounded by a system of periodically arranged permanent magnets (PPM). At the upstream end of the discharge channel the anode and the propellant gas inlet are mounted, and at the downstream end the neutralizer cathode is placed. The PPM system forms magnetic cells in which electrons are efficiently trapped. 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 thrusters are free from wall erosion in contrast to Hall Effect thrusters (HETs) or grid ion thrusters (GITs), which show pronounced erosion at the discharge channel or at the grid system, respectively. In addition, in grounded configuration, HEMP thrusters can be operated without a specific, electron emitting cathode to sustain the discharge. Due to the highly impeded electron flow from cathode to anode, there are no measurable losses due to such currents. In case of HETs, this loss mechanism amounts up to 30% of the anode power.

An example of the axial evolution of plasma potential and ion current is shown in figure 1, as deduced from energy selective mass spectroscopy and simulation data. Most of the propellant flow is ionized close to the anode, and the first magnetic cusp induces a strong voltage drop, which accelerates the produced ions towards the thruster exit. The following magnetic cells contribute only weakly to the ion current and serve for discharge stabilization and beam formation, respectively.

In order to achieve higher thrust levels, besides the possibility of scaling up the cylindrical configuration, a coaxial version of the HEMP thruster concept has been introduced and first patented in 2001(e.g., [2]). A scheme of a coaxial HEMP thruster is shown in figure 2. Compared to the cylindrical concept, the magnetic field topology is transferred from the axis to the median of a coaxial discharge chamber, and the anode and the propellant gas inlet are ring-shaped. The magnetic circuit is made of an inner and outer magnet system in PPM manner. The operational principle is essentially the same as for the cylindrical thruster, however in case of the coaxial HEMP thruster the magnetic confinement leads to a plasma shape of a thin-walled cylinder. As an interesting feature of the coaxial concept, the fraction of the ion beam emitted from the inner diameter of the plasma cylinder is focused to the thruster axis, which might lead to an improved beam formation due to space-charge effects.

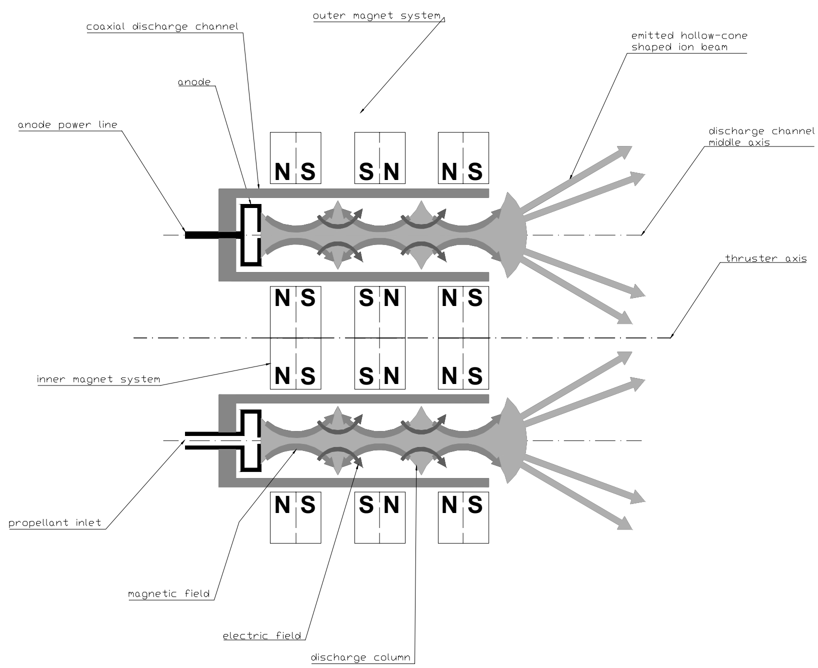

Figure 2: Schematic cross view of the coaxial HEMP thruster concept.

III. Performance Characteristics and Status of Development

A. Test Facilities and Diagnostics

Different test facilities and diagnostics have been employed to measure the operational and performance characteristics of recent HEMP thruster models:

- Direct thrust measurements have been performed by means of a thrust balance installed at the JUMBO test facility at the University of Giessen (in the following referred to as TB/GU). The JUMBO facility consists of a 2.6m diameter × 5m length vacuum tank with an effective pumping speed of up to 100,000l/s for Xenon propellant, provided by cryogenic and turbo molecular pumps. From the measured thrust T at a given propellant mass flow dm/dt, anode voltage U_A and current I_A, the anode specific impulse I_{sp} and total efficiency η_{tot} can be determined as

  $I_{sp} = T/(g \cdot (dm/dt))$, where g is the gravitational constant (1)

  and $\eta_{tot} = T^2/(2 \cdot P_A \cdot (dm/dt))$, where $P_A = U_A \cdot I_A$ is the anode power. (2)

- Measurements of the angular distribution of the ion beam power by means of a thermal target have been performed in our test facility at TED Ulm, which consists of a 1m diameter × 1m length thermal vacuum chamber with an effective Xenon pumping speed of up to 8,000l/s provided by cryogenic and turbo molecular pumps. Thermal target measurements (in the following referred to as TT/TED) yield the ion beam power per solid angle thus allow for determination of the total ion beam power P_B, the effective ion beam angle α_{eff} and thus of the thermal efficiency $\eta_{th} = P_B / P_A$ and the beam angle efficiency $\eta_{angle} = cos^2 \alpha_{eff}$. The thermal losses dissipated in the thruster are then given by $P_{loss} = (1 - \eta_{th}) \cdot P_A$. It is important to note, that the thermal target measures the sum of kinetic and potential energy of the impinging ions. In order to obtain the kinetic beam power efficiency η_{bp}, the thermal efficiency has to be corrected for the so-called frozen losses due to (multiple) ionization, production of excited states and light emission. The total anode efficiency from equation *(2)* can also be written as

$\eta_{tot} = \eta_{BP} \cdot \eta_{angle} \cdot \eta_{ion}$, where η_{ion} is the ionization efficiency, which denotes the fraction of emitted ion flow to the input atomic propellant flow, *(3)*

and $\eta_T = \eta_{BP} \cdot \eta_{angle}$ is called the electrical thrust efficiency. *(4)*

B. Performance Data of HEMP3050 Breadboard Model DM7 (Status May 2004)

The envelope of operational and performance data of DM7 has been determined via TB/GU measurements and is given in figure 3. A wide range in thrust from 5mN up to 152mN and specific impulse values from 500s to 3620s

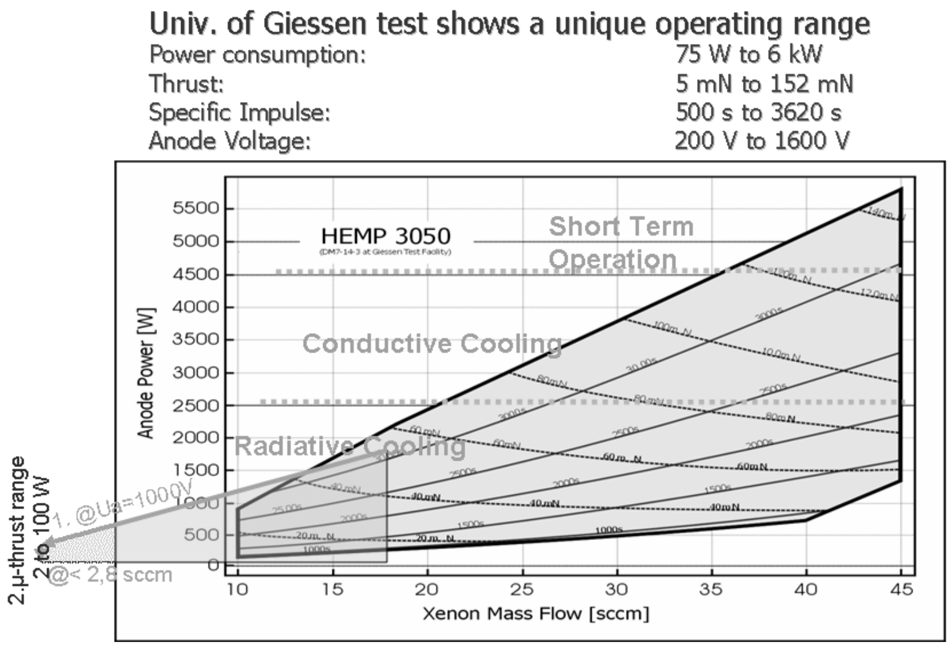

Figure 3: Envelope of performance and operational data of DM7 as measured by TB/UG.

could be achieved at anode voltage and power levels ranging from 200V to1600V and from 75W up to 6kW, and a Xenon propellant mass flow from about 1mg/s to 4.5mg/s, respectively. For all mass flows investigated, the anode current was nearly constant for anode voltages above 300V. By employing a more sensitive power supply, DM7 can be operated at anode power levels down to 2W, i.e., the anode power can be throttled by a factor of as high as 3,000. Additionally, thruster operation at a few Watts indicates the possibility to achieve thrust levels in the µN range.

In the entire range of anode powers investigated, HEMP3050 DM7 showed stable operation. Although the power dissipated in the thruster due to thermal losses is less than 15% of the anode input power, different cooling schemes are foreseen to provide stable operation on the spacecraft. For input powers below 2.5kW, the thruster can be cooled by means of an appropriate radiator, whereas for power levels between 2.5kW up to 4.5kW, conductive cooling is needed. Power levels between 4.5kW and 6kW can only be applied for short thrust periods. The total anode efficiency of HEMP thruster DM7 has shown to increase with anode voltage and has been above 40% for a wide range of operational parameters with peak values of 47% at a Xenon mass flow of 2.2mg/s and voltages above 1200V (for more details see ref. [3]).

C. 250h Endurance Test of HEMP3050 Breadboard Model DM8 (Status December 2004)

In order to prove erosion-free operation, a 250h endurance test at the JUMBO facility has been performed on HEMP3050 thruster DM8 at its nominal thrust and specific impulse values of 57mN and 2600s, respectively. The thruster has been operated with a THALES Electron Devices N5000 hollow cathode neutralizer [4], and the test incorporated thrust balance measurements and continuous recording of the electrical parameters and relevant thruster temperatures. DM8 shares the same PPM system and discharge channel as DM7, but employs a new type of gas inlet and anode high voltage connection, which is capable to withstand temperatures as high as 300°C and is high voltage prove up to 10kV.

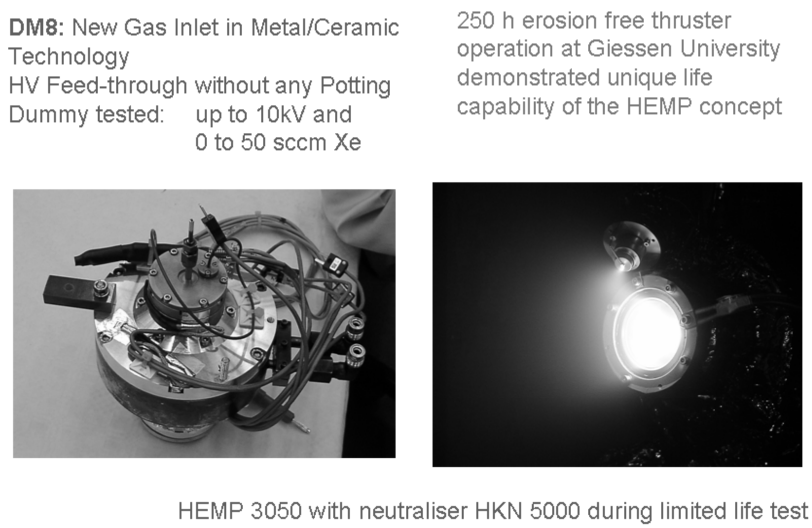

Figure 4: HEMP3050 thruster DM8. Left: view on the new type of gas inlet with HV proved anode supply feed through. Right: During operation with N5000 hollow cathode neutralizer.

In figure 4 photographs of the gas inlet view of DM8 and of DM8 in operation together with the N5000 neutralizer are shown. It is important to mention, that HEMP3050 DM8 showed stable operation during the entire test period with constant performance characteristics. Thruster operation was only stopped in course of regeneration of the cryogenic pumping system.

After the endurance test, the thruster has been disassembled and a destructive physical analysis (DPA) on the discharge channel has been performed. The new type of gas inlet and anode feed through showed no sign of deterioration. In Figure 5 a photograph of the discharge channel cross cut is shown. The discharge channel has been analyzed by means of scanning electron microscopy (SEM) in combination with energy resolved X-ray diffraction (EDX). It has been shown, that the dark deposit on the discharge channel surface exclusively consists of materials from the vacuum chamber walls (mainly iron and nickel), which where sputter-eroded due to ion beam impingement. Zones A, B and C denote the areas of maximum radial magnetic fields, where the thermal load is highest. Here changes in color are visible. A detailed analysis of the 3 zones is shown in the SEM pictures from figure 6.

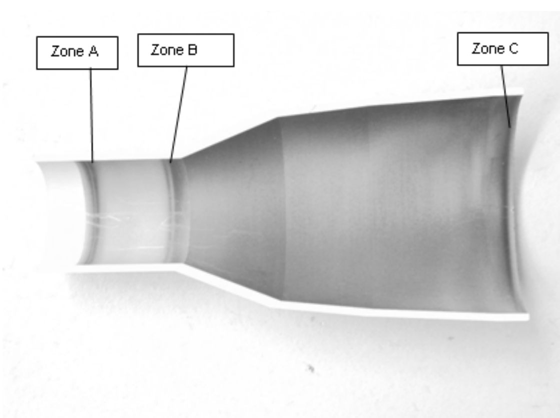

Figure 5: Photograph of the discharge channel cross cut after 250h of operation. Zones A, B and C show the areas of maximum radial magnetic field.

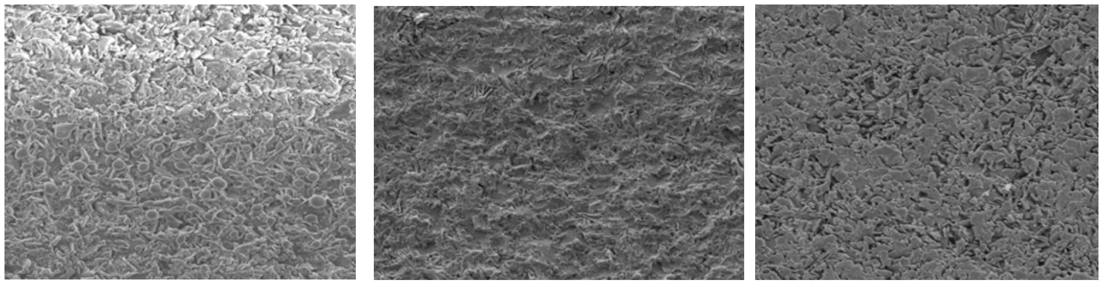

Figure 6: SEM pictures of Zones A (left), B (middle) and C (right) indicated in figure 5, respectively.

On the left picture above, the original, relatively porous structure of the discharge channel wall ceramics can be seen. Zone A denotes the dark zone, where the material becomes denser. Zone B is the hottest area of the discharge channel, where the ceramic material undergoes a sort of sintering process leading to an additional densification. In both zones A and B, no signs of ion sputtering can be identified. Zone C at the thruster channel exit essentially shows the original ceramic structure.

Further, zones A, B and C have been investigated by means of a profilometer in order to determine the depth of the grooves caused by the densification or sintering process. Whereas the depth in zone C was negligible, a depth of 3.5µm and 10µm has been measured in zone A and B, respectively. At a given ceramic wall thickness of 1.5mm and under the conservative assumptions of firstly a linear progression of the sintering effect, i.e., linear increase of the depth of the groove with operational time and secondly an end of life at a depth of 0.75mm, i.e., half of the discharge channel width, the total thruster life capability can be determined to an integrated total impulse of 3.8×10^6Ns or an operational life-time of 18,500h, respectively.

D. HEMP3050 Thruster DM8 Operation with Krypton Propellant (Status December 2004)

In addition to the 250h endurance test reported above, a comparison of performance data has been performed operating HEMP3050 thruster DM8 with Krypton propellant in alternative to the normally used Xenon propellant. At a given mass flow and anode voltage, Krypton operation has yielded slightly higher total anode efficiencies and the increase in power-to-thrust ratio was less than the expected square root out of the atomic mass ratios. It is assumed that in case of Krypton operation the ionization efficiency is higher and the fraction of multi-charged ions is reduced compared to Xenon operation, due to the higher energy thresholds for multi-stage ionization levels. The excellent Krypton compatibility of HEMP thrusters offers interesting perspectives with respect to the electric propulsion system, since Krypton is by a factor of 10 less expensive than Xenon. Detailed data on the comparative measurements are given in ref. [5].

E. Latest Development Models of HEMP3050 Thrusters: DM9-1 & 2 (Status September 2005)

Based on the innovative gas inlet design of DM8, the magnetic circuit and discharge channel geometry of HEMP3050 thruster models DM9-1 and DM9-2 have been optimized in order to further increase the thermal and beam power efficiency, to reduce the effective ion beam angle and divergence and to minimize discharge oscillations. Thermal target measurements at TED Ulm have been performed subsequently on DM8, DM9-1 and DM9-2 to allow for direct comparison. All thrusters have been tested for Xenon gas flows ranging from 10sccm to 30sccm (which corresponds to mass flows from 0.98mg/s to 2.93mg/s), anode voltages from 200V to 1400V and power levels up to 3kW, respectively. The beam power efficiency has been derived from the measured thermal efficiency by setting $\eta_{BP} = \eta_{th} \cdot (1 - \kappa / U_A)$, where κ has been set conservatively to an empirical value of 40V to account for the frozen losses. Since, after correction for the residual gas effect[§], all three thruster models show the nearly same anode current for a given input Xenon flow and anode voltage, their ionisation efficiency η_{ion} is assumed to be the same. Comparing the values obtained with DM8 from TB/GU tests with those from TT/TED

[§] In order to correct for the sensitivity to residual gas of an individual thruster, the pressure in the vacuum chamber (determined by a capacitive gauge) is varied at given thruster operational parameters and the variation in discharge current is recorded. Extrapolation to infinite pumping speed represents the values expected in space.

measurements, η_{ion} can be determined using equations *(2)* and *(3)*. Inserting the obtained value of η_{ion} in *(3)* yields the total efficiency based on TT/TED data. As an example, in figure 7, the thermal, beam power, angular, electrical thrust and total efficiency is shown for DM8, DM9-1 and DM9-2 for a Xenon gas flow of 20sccm corresponding to a mass flow of 1.95mg/s. This operational range has been chosen, since between 1000V and 1200V of anode voltage the design values in thrust between 50mN and 65mN and in specific impulse between 2500s and 3000s are achieved.

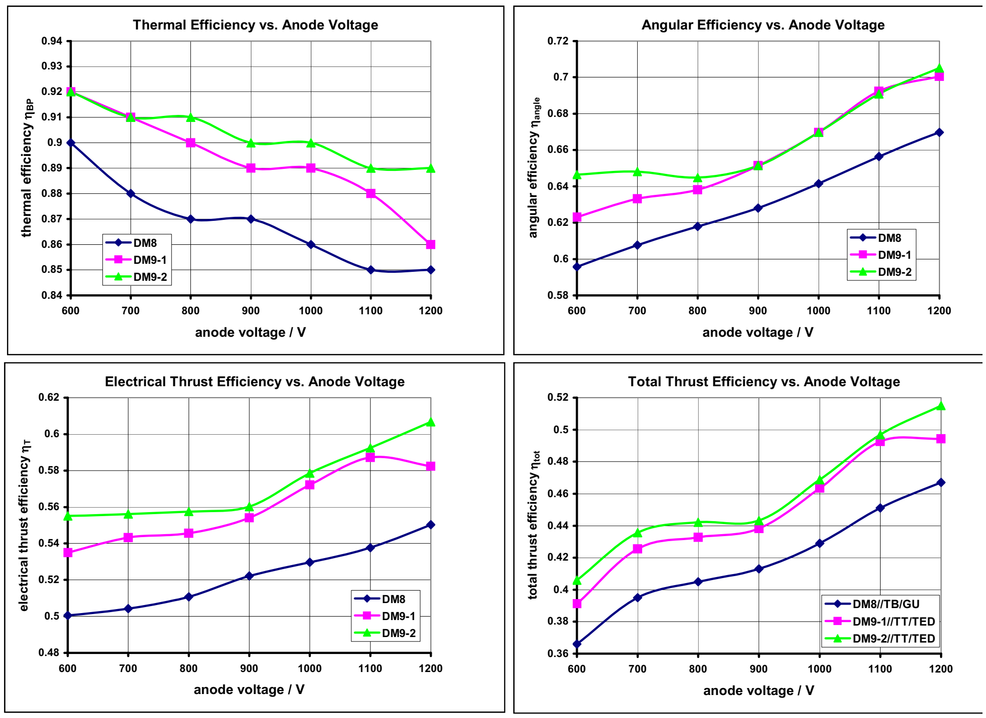

Figure 7: Thermal, angular, electrical thrust and total anode efficiency for HEMP3050 thruster models DM8, DM9-1 and DM9-2 as a function of anode voltage for a Xenon mass flow of 1.95mg/s.

It can be seen that the newly developed models DM9-1 and DM9-2 are clearly superior in both thermal and angular efficiency compared to DM8. As a consequence, the electrical thrust efficiency is a factor of about 1.1 higher and so is the total anode efficiency, which is between 47% and 51% for anode voltages between 1000V and 1200V. Comparing DM9-1 and DM9-2, besides the slightly better efficiency, DM9-2 is nearly free of any discharge oscillations for the entire operational envelope. Whereas DM7 and DM8 thruster models have exhibited oscillation amplitudes, which were up to 20% of the anode current, the corresponding value of DM9-2 is 3% at maximum. This new feature is attributed to an additional improvement in magnetic confinement of the plasma electrons.

F. System Aspects: Compatibility Tests with EADS-Astrium Space Power Supply

An engineering model of a 1.2kW power conditioning unit (PCU) from EADS-Astrium has been purchased to verify electric propulsion system compatibility of HEMP3050 thruster models. The PCU is derived from an EADS-Astrium development for the Qinetic T6 GIT for the GOCE mission from ESA. HEMP3050 thruster models have shown stable operation over the entire PCU range up to voltages of 1.2kV. In case of DM8 and DM9-1 an additional 1.5µF capacitor had to be added to minimize discharge current oscillations. In case of the latest HEMP3050 thruster model DM9-2, the thruster anode line could be directly connected to the PCU due its low level of discharge oscillations. With respect to electric propulsion system aspects this is a clear advantage since, compared to the architecture of a HET based EP system, no additional filter unit is needed to damp discharge current oscillations.

G. First Results with Coaxial HEMP3250 Thruster DM1 (Status March 2005)

A first laboratory model DM1 of a coaxial HEMP30250 thruster has been set up in March 2005. Photographs of the DM1 thruster model during the set up phase and after installation in the TED test vacuum chamber are shown in fig. 8.

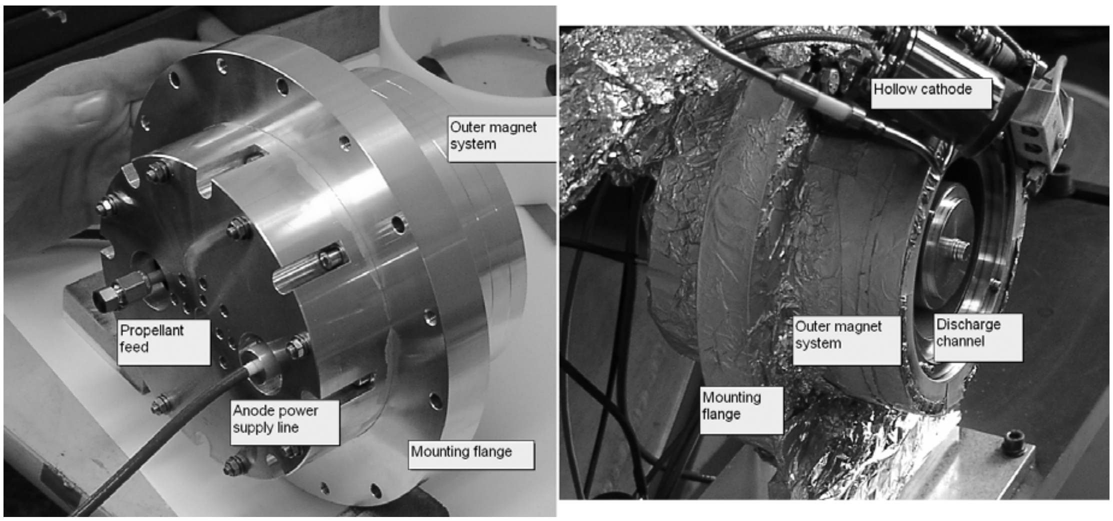

Figure 8: First HEMP3250 laboratory model DM1. Left photograph: rear side of the thruster. Right photograph: side view onto exhaust plane (thruster mounted in vacuum test chamber).

The concept for the thruster gas inlet and connection of the anode power line, which has have been overtaken from HEMP3050 thruster model DM8, has shown to provide high voltage insulation up to 10kV for Xenon gas flows from 1 to 300sccm at a maximum operational temperature of up to 250°C[**].

In order to provide azimuthally symmetric gas distribution in the discharge channel, gas is fed from the anode via multiple holes, and in the anode itself a two-stage flow impedance allows for a azimuthally homogeneous gas pressure already in front of the holes.

Purpose of our first laboratory model DM1 was to demonstrate in how far the thruster operational parameters and discharge behavior are comparable to what is typically observed in cylindrical HEMP thruster models. Therefore we have chosen a very simple magnetic field pattern with only one main magnetic cell. The width of the discharge channel is small in order to provide sufficient ionization yields already at low propellant mass flows[††]. However, from our experience with cylindrical geometries, the small channel width would result in a non-negligible plasma-wall contact. In order to compensate for this effect the magnetic field strengths were increased, but, nevertheless, results from particle-in-cell (PIC) simulations of the thruster plasma have predicted a certain amount of wall losses.

Taking into account, that our first coaxial HEMP thruster model is the basis for a 10kW thruster, its geometry is very compact. The thruster outer diameter is 140mm (the mounting flange with a diameter of 200mm is not taken into account), the length is 150mm and the thruster weight is below 6kg.

In course of first characterization tests, the thruster has been operated at anode voltages between 150 and 1500Vand Xenon mass flows of up to 3mg/s. The maximum anode power applied was 3kW. A photograph of the thruster in operation is shown in fig. 10. In contrast to our advanced cylindrical HEMP thruster models, a cathode current was required to operate the thruster discharge, which was 10% to 15% of the total anode current. At constant thruster mass flow the leakage current increased when the background pressure was increased, or at increased anode voltage, respectively.

[**] The temperature limit is due to the limited operational temperature of the high voltage cable.

[††] Due to the limited pumping speed and chamber size in our current vacuum test facility, a sufficiently low background pressure in vicinity of the thruster exhaust can only be provided for Xenon mass flows below 3mg/s.

A strong dependence of the total anode current on residual chamber pressure has been observed. In addition the anode current tended to increase with anode voltage, whereas in case of cylindrical HEMP thrusters the anode current showed nearly no variations for anode voltages above 300V.

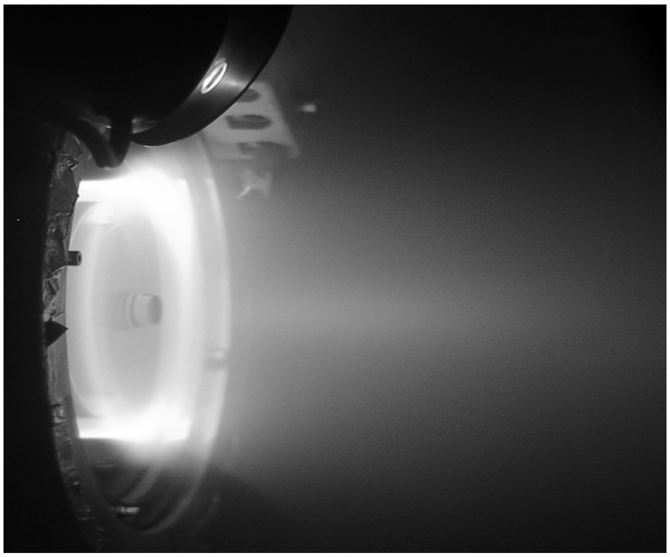

Figure 9: First laboratory model of a coaxial HEMP30250 thruster in operation.

Measurements of the polar angle distribution of the ion beam power density by means of our thermal diagnostics show a peak of ion beam power density on axis but also a relatively wide angular spread. The peaked ion current distribution might be caused by a space-charge effect due to the ion beam fraction focused towards the thruster axis, as indicated in section II. Due to the insufficient testing environment, HEMP30250 thruster model DM1 could only be tested at a few operational points. As a result of the large exhaust surface of the thruster, the small vacuum chamber and the short distance of our thermal diagnostics to the thruster exit of only 450mm, the diagnostics provide rather qualitative than quantitative results. Nevertheless, it could be shown that the cylindrical HEMP thruster concept can be scaled to a coaxial geometry. However, the observations made with our first laboratory model indicate a clear improvement potential with respect to an enhanced magnetic confinement of the plasma electrons. A more detailed report on our activities in coaxial HEMP thruster development is given in [6].

IV. Summary and Outlook

Experimental characterization has demonstrated the unique features of the HEMP thruster concept invented by THALES Electron Devices. HEMP thrusters are compact devices, which exhibit a high thermal efficiency, unique throttle ability, erosion-free operation, high reliability, minimal discharge current oscillations, and allow for a simplified architecture of the electric propulsion system. The performance characteristics of our latest HEMP3050 thruster model DM9-2, which is designed for a nominal thrust and specific impulse of 50mN to 70mN and 2500s to 3000s, and the future development potential are summarized in table 1.

Table 1: Current status and future potential of HEMP3050 thruster models

	Thermal Efficiency	Angular Efficiency	Ionization Efficiency	Total Efficiency	95% Divergence	Relative Amplitude of Discharge Oscillations
Current Status (DM9-2)	0.9	0.7	0.75… 0.85‡‡	0.5	45°… 55°	< 3%
Future Potential	0.9	0.9	0.9	> 0.7	< 45°	< 3%

In order to provide higher power and thrust levels a first coaxial HEMP30250 thruster model has been set up and tested, which shows the feasibility of scaling the cylindrical HEMP thruster concept to a coaxial geometry. Due to an improved understanding of the effects of magnetic field topology on thruster operational behavior and performance, improvements with respect to our high power thruster development are expected soon. It is obvious

‡‡ Currently, the large systematic error in the determination of the potential energy of the emitted ion beam leads to a large uncertainty in the determination of the ionization efficiency.

that any future development directed towards high power applications will strongly depend on thruster concepts exhibiting a high thermal efficiency, as is the case for HEMP thrusters.

Aiming towards improved diagnostic capabilities, THALES Electron Devices has designed and purchased a large thruster test facility for detailed experimental characterization of our thruster models. The ULAN (ULmer ANlage) facility consists of a 2.4m diameter × 4m length vacuum tank with an effective pumping speed for Xenon of 60,000l/s to 120,000l/s[§§] provided by turbo molecular and cryogenic pumps. A photograph of ULAN is shown in figure 10. In order to allow for an entire characterization of ion beam properties and thruster performance, ULAN will be equipped with a complete diagnostic package, which involves a thrust balance, an energy-selective mass spectrometer and various other thermal and electric ion beam sensors [7]. At the time this paper is written, the vacuum control system has been finalized and the cryogenic pumping system is being installed and tested. As a first step, it is planned to install temporarily the thrust balance from Giessen University / EADS Space Transportation for tests on our latest HEMP3050 thruster models DM9-1 and DM9-2 to verify the promising data obtained with our thermal target measurements[***].

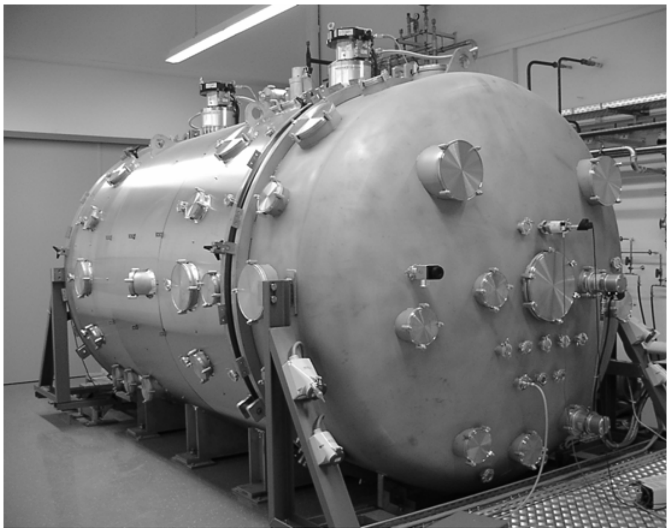

Figure 10: New TED test facility "ULAN" (status September 2005). ULAN will be equipped with a complete diagnostic package for entire characterization of ion beam properties and thruster

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[§§] 120,000l/s is the maximum possible pumping speed for fully equipped facility.

[***] First thrust measurements are planned for mid of October, the results of which shall be presented at this conference