Overview, Qualification and Delivery Status of the HEMPT based Ion Propulsion System for SmallGEO

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Abstract: Thales Electronic Systems has developed and is currently qualifying a novel type of ion propulsion system based on High Efficiency Multistage Plasma Thrusters HEMPTs. The so called HEMPT Assembly is being developed under the HEMP-TIS DLR contract. It shall be used in the frame of the ESA SGEO program, the platform developed by OHB System AG for the Hispasat AG1. The HEMPT Assembly consists of four HEMPT Modules and one Power Supply and Control Unit PSCU which supplies the HEMPT Modules with electric power and controls their operation. The so-called HEMPTIS program (HEMP Thruster In orbit verification on SmallGEO) initiated by the German Space Agency DLR includes all associated component development, system engineering, testing and qualification activities, and the delivery of the respective flight units.

This paper provides the updated status of the qualification activities and refers to the production and delivery status of the flight units.

For instance all flight units of the flow control units have been received. A set of flight units of the thruster modules (HTMs) have been build and are being acceptance tested. The flight power supply and control unit (PSCU) has been manufactured and acceptance tested.

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I. Nomenclature

FCU	=	Xenon propellant Flow Control Unit
HEMPT	=	High Efficiency Multistage Plasma Thruster
HEMPTIS	=	HEMP Thruster In-orbit-verification on SmallGEO
MMS	=	Mechanical Mounting Structure
OHB	=	OHB System AG
PSCU	=	Power Supply and Control Unit
THR	=	Thruster
NTR	=	Neutralizer

II. Introduction

THALES Electronic Systems is developing and qualifying a novel type of ion propulsion system based on the High Efficiency Multistage Plasma Thrusters HEMPTs in course of DLR’s HEMP-TIS project (HEMP-Thruster In Orbit Verification on SmallGEO). This so-called HEMPT Assembly is intended for being integrated on OHB’s SmallGEO geo-stationary satellite platform to perform attitude and orbit control manoeuvres [1].
The benefits of the HEMPT Assembly ion propulsion system are due to its high propellant exhaust velocity which allows for a significant reduction in propellant consumption. As a result the satellite starting mass can be reduced by several 100 kilograms compared to a conventional chemical propulsion system. As a consequence the satellite payload mass is increased and launching costs are reduced at the same time.

The HEMPT Assembly consists of four HEMPT Modules (HTM) and one Power Supply and Control Unit (PSCU) which supplies the HEMPT Modules with electric power and controls their operation. Each of the HEMPT Modules integrates a HEMPT 3050 ion thruster, an HCN 5000 Hollow Cathode Neutralizer and a Flow Control Unit (FCU) which doses the Xenon propellant into the thruster. The particular positioning of the four HEMPT Modules on SmallGEO allows for all necessary position correction manoeuvres in the geo-stationary orbit and for momentum wheel off-loading, respectively.

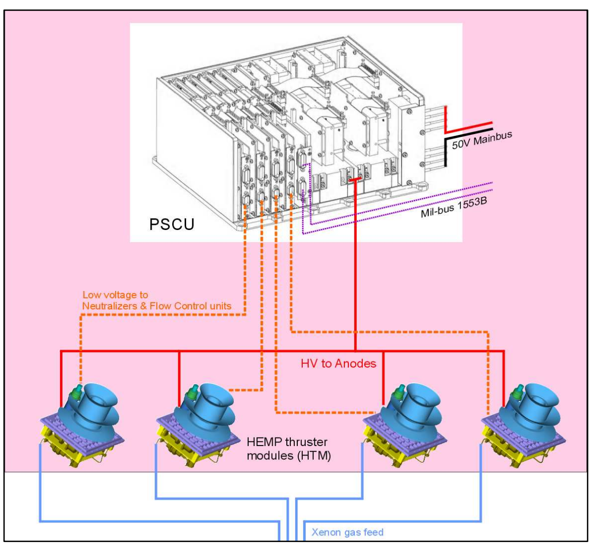

Figure 1 HTA system architecture

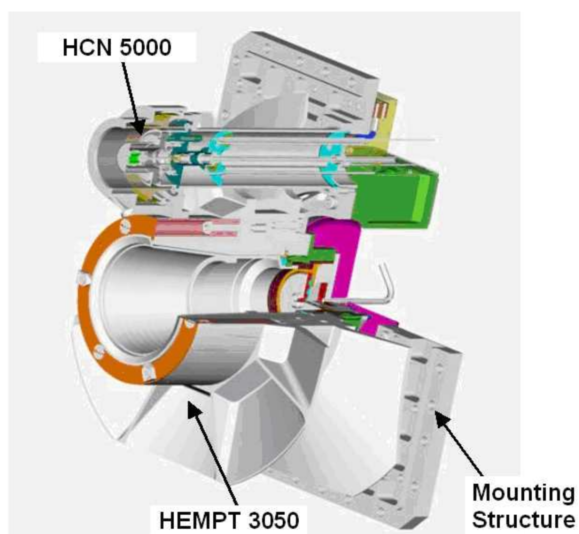

Figure 2 3D-View of Hemp Thruster Module

The core technology of the ion propulsion system is represented by the HEMPT ion thruster, which has been developed by Thales Electron Devices for about 15 years (from concept feasibility [2]) exclusively based on own technologies and patents.

The HEMPT is based on a particular magnetic confinement of the Xenon propellant discharge which at the same time allows for efficient propellant ionisation and ion acceleration. Besides its performance the HEMPT exhibits the unique feature of negligible thruster erosion and therefore shows excellent long-life capabilities [7], [9]. In addition, the HEMPT design concept and operational characteristics enable ion propulsion system architecture with minimum complexity and thus high reliability and cost efficiency [11].

Key Parameters and a general description of the HTA are provided in [10] and in [11].

Further Development activities and Performance Prediction for future applications are elaborated in [16]

III. Verification Status

A Performance and Environmental Verification of the HEMPT Module

As far as possible, performance requirements were verified on component level; after successful verification component integration into the HEMPT Module was performed followed by verification on Module level. For the first qualification test this was done on an Engineering Qualification Model (EQM) of the HEMPT Module which has successfully undergone performance, mechanical and thermal vacuum testing. Meanwhile HTM QM1 was tested for Full Performance and Thermal Performance within a so called Functional Reference Test. HTM QM2 has been manufactured and is now subjected to qualification testing.

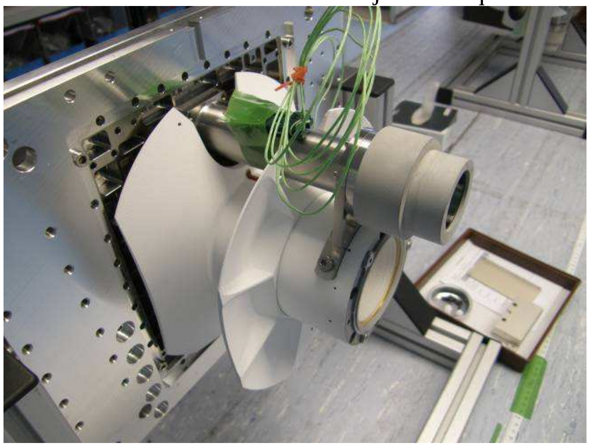

Figure 3 HTM-QM1 during MIP

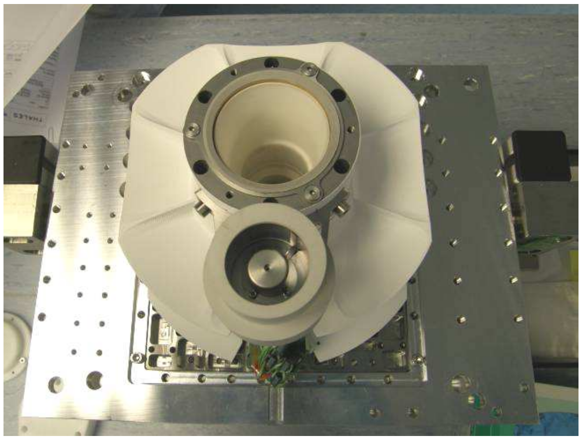

Figure 4 HTM-QM2 during MIP

III.A.1 <u>Endurance test partially with PSCU</u>

As a first test to demonstrate the lifetime a HEMPT Module Engineering Model EM has been subjected to a 4900h endurance test and 3100h extension [7] which covers the required mission life time of 4800h.
In order to identify possible life time limiting effects prior to start of life time qualification and flight hardware production, the 4900h endurance test called Endurance Test ET1 has been performed with a HEMPT Module EM. The components of this module had the same design as those of the EQM, only the harness routing was different and not EMI representative. ET1 has revealed excellent long-term behaviour and unique reliability. As an example no single HEMPT Module induced firing interruption has been observed. This test was prolonged in ULAN facility to increase the total accumulated firing time up to 8000h. During the extension a PSCU-EM was coupled to the HTM and the HTM was operated for several months with this PSCU, demonstrating excellent robustness and interoperability over long term operation.
It was identified in course of this campaign, that thruster performance degradation induced by a conductive graphite layer from chamber material redeposition could be avoided by chamber wall material with a sufficiently high vapour pressure. Subsequently the life time test facility has been refurbished meanwhile to exclude performance degradation due chamber effects for the formal lifetime qualification test.

III.A.2 <u>Launch fairing environment and maintenance free time</u>

Qualification activities of the neutralizer cathode versus the fairing environment of the launcher have been successfully completed, demonstrating a compatibility of the cathode to a total exposure of 60 days to ambient conditions without additional protective means.

Four cathodes have been subjected to the following sequence:

- Plasma operation in vacuum
- 3 days - Exposure to 30°C, 70% rel. humidity
- 60 days – Exposure to 30°C, 60% rel. humidity
- Restart and operation in vaccum
- >100 operational cycles

This enables to have the module maintenance free three months before launch besides removal of red tagged items. Details of this qualification are being presented within this conference [14].

III.A.3 Results on EQM level

Results of performance and environmental qualification tests of the HEMPT Module EQM are given in the Table below.

Parameter	**Req.**	**Test value**	**Compliance**
Thrust	44mN	44.9mN	**Y**
Thruster power	1380W	1370W	**Y**
HTM specific Impulse (=v/g)	2300s	2474s	**Y**
Mechanical load sine vibration	20g	20g	**Y**
Mechanical Load Random	11.6g_{RMS}	11.6g_{RMS}	**Y**
Mechanical Load shock	2000g	up to 3000g	**Y**
HTM lifetime	7200h (qual)	4900+3100h	**Y**

Table 1. Qualification results on HTM-EM/EQM level.

The table indicates that all major performance characteristics are met. In addition the HEMPT Module has shown unchanged characteristics after both mechanical (i.e., vibration and shock) and thermal vacuum testing to qualification levels.

III.A.4 Results on QM level

As a precursor of the flight model acceptance sequence and as first dominant element of the HTM qualification sequence, HTM-QM1 was subjected to a functional reference test, that comprises a full performance test and a performance mapping at the thermal vacuum interface temperatures. This kind of test was introduced to have the performance data produced during thermal vacuum testing already available prior to mechanical and full TV testing with relatively low time impact and for comparison with the thermal vacuum test. Prior to this test as part of the nominal qualification and acceptance tests, the unit was subjected to bonding isolation test, leak test and purifier health test without anomalies. Details of the purifier health test is given in this conference in [13].
Results of performance and functional reference tests of the HEMPT Module QM and qualification tests of NTR QMs are given in the Table below. The provided parameters thrust, power and specific Impulse where tested at the qualification temperature extremes and at ambient temperature. Deviations over temperature remained within measurement uncertainties.

Parameter	**Req.**	**Test value**	**Compliance**
Thrust (over Temperature)	44mN	>44.2mN	**Y**
Thruster power (over Temperature)	1380W	1380W	**Y**
HTM specific Impulse (=v/g) (over Temperature)	2300s	typ. 2400s	**Y**

Parameter	**Req.**	**Test value**	**Compliance**
HTM Minimal Interface Temperature	-15°C	-15°C	**Y**
HTM maximum Interface Temperature at TRP	65°C	65°C (operating) 80°C (non operating)	**Y**
launch fairing environment	40+20 days	60days	**Y**
maintainance free time	3 month	3 month (analysis)	**Y**

Table 2. Qualification results on QM level.

The table indicates that all major performance characteristics are met. In addition the HEMPT Module shows consistent performance without noticeable performance variation over the interface temperatures.

B HEMPT Assembly Verification and Compatibility with the SmallGEO platform

III.B.1 *HTM – PSCU interoperability on EM level*

After performing a series of so-called coupling tests with different development models of both the PSCU and the HEMPT Module, final verification of the interoperability on Engineering model level has been performed with the PSCU Elegant Bread Board EBB Model and the HEMPT Module EQM. The PSCU EBB could be fully commanded with the underlying telemetry and telecommanding specification and the HEMPT Module has shown full functionality and performance. This interoperability Verification has finally been reconfirmed by the coupling of the PSCU EM with HTM-EM during extension of the endurance testing.

III.B.2 *PSCU – s/c interface interoperability*

In addition the PSCU-EM was tested with a dynamic load simulator and s/c power electronics, confirming the compatibility of the PSCU with the spacecraft power bus and MIL-1553 interface.

III.B.3 *Thruster – s/c sputtering compatibility*

Compatibility verification included analysis of the thruster ion beam impingement effects on the space craft's solar panels. Ion beam impingement analysis has shown that less than 3% of the silver strings connecting the solar cells on the panel will have an erosion depth beyond the requirement.

III.B.4 *Transmission interference and correlation with adjacent thruster*

Electromagnetic compatibility has been verified in course of ESA's EPCOMSIM program performed at Alta Centrospazio, Pisa, Italy. Here the ion beam of a HEMPT Module EM has been fired cross to the antenna beam using the representative EM antennas and reflectors implemented in Alta's large vacuum testing facility. As a result neither attenuation nor phase shift of the antenna signal has been found. In addition possible effects on HET performance in particular EMC wise induced by the HEMPT magnetic stray field have been investigated with the same result, that neither attenuation nor phase shift of the antenna signal could be detected.

III.B.5 *Magnetic stray field effect on adjacent thruster*

In course of a dedicated test campaign at Aerospazio, Siena, Italy, operation and performance of the SPT- 100 have been investigated in presence of the magnetic stray field of the HEMPT 3050. No degradation or change of characteristics has been found.

III.B.6 *Electro magnetic compatibility qualification*

An additional EMI qualification campaign has been performed and accomplished at Aerospace Corp., Los Angeles, U.S. The RE102/103 and RS test data are being published in another paper of this conference submitted by aerospace corporation [12].

III.B.7 *HTM – PSCU inter-operability on QM level*

The final qualification test confirming the compatibility of the HTM with the PSCU has been conducted with the PSCU-EQM and HTM-QM1 comprising the following activities:

- General functional testing
- Testing of operational sequences as defined in telemetry and telecommand specification
- Limited performance of HTA (thrust, ISP, power)
- Test of behavior of anode current control involving FCU flow control valve in particular at start up.
- Limited CE tests
- Testing of GSE for End to End test

The above activities where performed with the PSCU located outside vacuum chamber and the respective HTM located inside the vacuum chamber on a thrust balance. Hence it was possible to determine the thrust, ISP and needed power in a configuration representative for the flight units on the highest level, namely on HTA level. Note, that this is already the configuration intended for the qualification life test, as the HTM-QM1 will be permanently operated by the PSCU-EQM during the life test.
The key performance data and behaviour of the anode loop has been determined at the HTM interface temperatures -15°C, ambient and 65°C in correspondence to the demanded qualification temperature range.

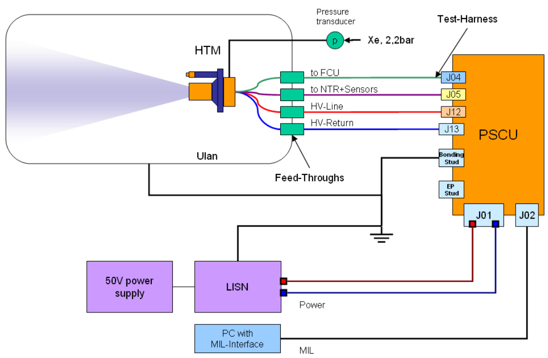

Figure 5 General Testsetup of Interoperability Test using HTM-QM1 with PSCU-EQM

III.B.8 *Compatibility with inlet pressure ripple*

A dedicated test with the pressure supply assembly providing the xenon to the HTM is planned within the upcoming qualification sequence.

III.B.9 *Summary*

. In summary most relevant compatibility aspects of the HEMPT Assembly with the SmallGEO platform have already been successfully verified on HTM EM/EQM level, as indicated in table 3.

Parameter	**Req.**	**Test value**	**Comp-liance**
EMC-Qualifica-tion (Aerospace)	Accomplished		
EMI-Test (Alta)	no bit errors,	no bit errors, attenuation nor phase shift	**Y**
Interoperability with PSCU	Compa-tible	>1000h	**Y**
Compatibility with adjacent thruster	No per-formance deg.	No per-formance deg.	**Y**
PSCU interopera-bility with s/c bus	Compa-tible	Compatible	**Y**

Table 3. Qualification results on HTM-EM/EQM level.

In addition to the previous, the status of the compatibility aspects of the HEMPT Assembly with the SmallGEO platform demonstrated on HTM-QM level is indicated in the table 4.

Parameter	Req./Task	Test value	Comp-liance
PSCU-EMC Qualification	Accomplished on PSCU-EQM		
Interoperability HTM-QM1 with PSCU EQM	Operational sequences	Fully functional	Y
	Regulation loop	flawlessly	Y
	Thrust function	>44mN	Y
	Power demand	typ. 1506W	Y
Interoperability with s/c gas supply	Pressure ripple tollerance	open	open

Table 4. Qualification results on HTM-QM level using PSCU-EQM.

IV. Flight Hardware Status

Manufacturing of HTM FM1..4 has been accomplished. This involved the following steps: First the HTMs are readily assembled from the components Thruster, Neutralizer and Mechanical mounting structure. Then they are mated with their FCU and the joints welded. Subsequently each module will see acceptance / qualification test sequence as demonstrated on the HTM-EM/EQMs namely leak test, performance or functional reference test, mechanical environment testing, thermal vacuum testing.

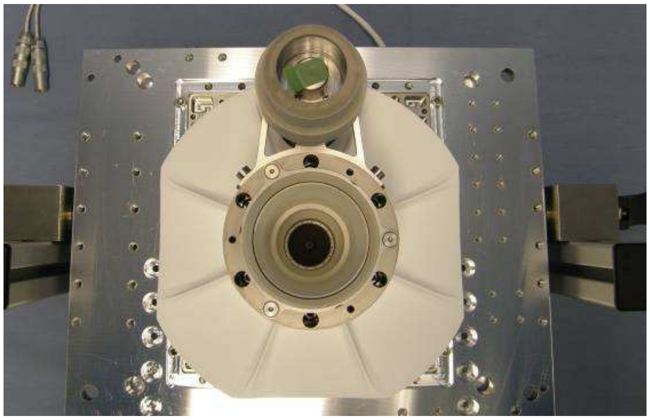

Figure 6 HTM-FM1 during MIP

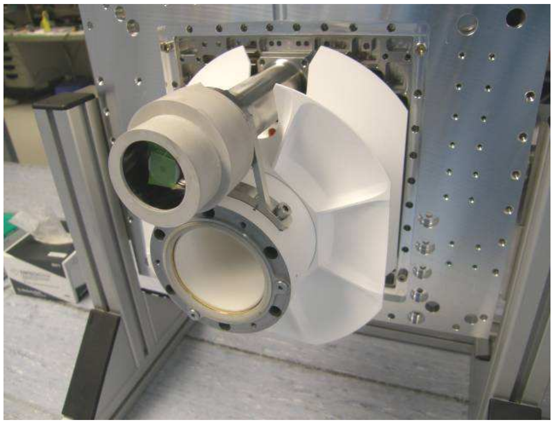

Figure 7 HTM-FM2 during MIP

FM1 and FM2 have been tested with the functional reference test, that besides full functional performance comprises thermal performance at the thermal vacuum test plateaus. This has been decided to have the performance at different temperatures available prior to the full environmental acceptance testing sequence.

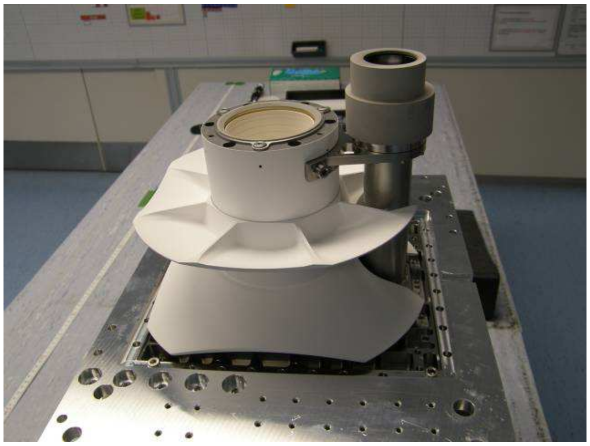

Figure 8 HTM-FM3 during MIP

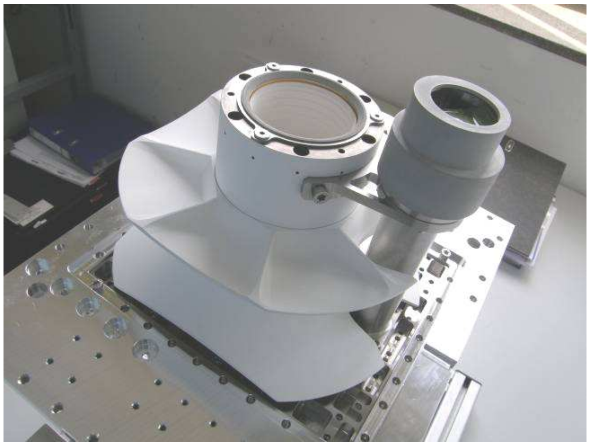

Figure 9 HTM-FM4 during MIP

FM3 and FM4 have been tested for Full Performance already. All the modules FM1..FM4 have prior to their functional testing been tested for the normal workmanship tests such as bonding isolation test, leak test, purifier health test [13]. Next steps will be further acceptance testing and End-to-End testing with the associated power-supply PSCU.

Figure 10 PSCU PFM at incoming inspection

PSCU Manufacturing has also been completed. The PSCU was manufactured and acceptance tested involving full performance, mechanical environment as PFM and thermal vacuum testing as PFM by Astrium Friedrichshafen. A Conducted Emission EMC testing was done in addition. Subsequently this unit was delivered to Thales and is currently in preparation for end-to-end testing. Shipment to OHB will be endorsed after completion of End-to-End test.

The flight harness sets have also been delivered by OHB and Astrium. The necessary manufacturing activities on the high voltage terminals are done and the flight harness set is ready for the End-to-End test.

V. Conclusions

TESG has further developed its HEMPT technology to set up a reliable and cost effect ion propulsion system.

Supported by German Space Administration DLR through the HEMPTIS project, a HEMPT Assembly has been set up for OHB's SmallGEO platform. So far essential operational, performance, environmental and life time requirements could be verified on EM and EQM level. In addition the first QM and all designated flight units FM1..4 have been tested for full performance. QM1 is ready to be subjected to the formal environmental qualification sequence including life test together with its adjacent module QM2.

FM1..4 are continuing being subjected to further acceptance testing and the End-to-End test together with the harness and PSCU PFM.

Next steps are the start of the HEMPT Module life time qualification and finally the delivery of the HEMPT Assembly Flight Unit to OHB.

VI. Acknowledgments

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OHB qualification temperature data is provided as courtesy of OHB Systems AG.

VII. References

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