Qualification Test results of HEMP Thruster Modules

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A. Lazurenko[1], A. Genovese.[2], R. Heidemann[3], J. Haderspeck[4], B. van Reijen[5], S. Weis[6], and P. Holtmann[7]
Thales Deutschland GmbH, Business Unit Electron Devices, Germany

K. Ruf[8] and N. Püttmann[9]
Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR) - Raumfahrt-Agentur, Germany

Abstract: Thales Electronic Systems GmbH develops and qualifies an electric propulsion system based on the High Efficiency Multistage Plasma Thruster (HEMPT). The HEMPT Assembly is being developed under the HEMPTIS 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 mission. Two HTM Qualification Models (QM) successfully completed qualification sequence consisting of performance characterization, mechanical testing and thermal vacuum testing. These tests included HTM-QM operation at nominal operation point (@1000V, 1.38A) in a wide range of interface temperatures and in a wide range of environmental (shroud) temperatures, as well as prolonged operation at higher power. HTM-QMs complied with major SGEO mission requirements. HTM-QMs ignited and operated stable in the whole range of temperatures, showing minimal variation of performance, with the thrust ≥44 mN and the total specific impulse >2400s. Beam characterization confirmed the compliance to the requirements on the plasma beam sputtering ability.

Nomenclature

FCU	=	Flow Control Unit
HTA	=	HEMP Thruster Assembly
HTM	=	HEMP Thruster Module
I/F	=	Interface
NTR	=	Neutralizer
PSCU	=	Power Supply and Control Unit
QM	=	Qualification Model
THR	=	Thruster

[1] Testing Manager, Plasma Devices, alexey.lazurenko@thalesgroup.com.
[2] Testing Engineer, Plasma Devices, angelo.genovese@thalesgroup.com.
[3] Components Developer, Plasma Devices, ralf.heidemann@thalesgroup.com.
[4] System Engineer, Plasma Devices, jens.haderspeck@thalesgroup.com.
[5] Components R&D Manager, Plasma Devices, benjamin.reijen@thalesgroup.com.
[6] System Engineering Manager, Plasma Devices, stefan.weis@thalesgroup.com.
[7] Project Manager and Head of Plasma Devices, peter.holtmann@thalesgroup.com
[8] Member of Research Staff, klaus.ruf@dlr.de
[9] Head OOV (On Orbit Verification) and Project Manager HEMP-TIS, norbert.puettmann@dlr.de

I. Introduction

The Business Unit Electron Devices of Thales Deutschland qualifies an electric propulsion system based on the High Efficiency Multistage Plasma Thruster (HEMPT).[1] HEMP Thruster Module (HTM) consists of the HEMPT, the cathode-neutralizer and the flow-control unit (FCU), all these components mounted onto the mounting structure (MMS).[2] FCU distributes Xe between the cathode, at constant flow rate, and the thruster, through the proportional valve which operates in closed loop with the anode current measured at the power supply and control unit (PSCU). The HEMPT assembly (HTA) is intended for integration on board of geostationary communication satellites to perform attitude and orbit control manoeuvres. Each HTA consists of two to four HTMs, electrical harness and one PSCU. Each HTM provides the total specific impulse of >2300s and the thrust of 44mN, under the operating voltage of 1000V and nominal anode current of 1.38A, which is a nominal operation point for SGEO mission.

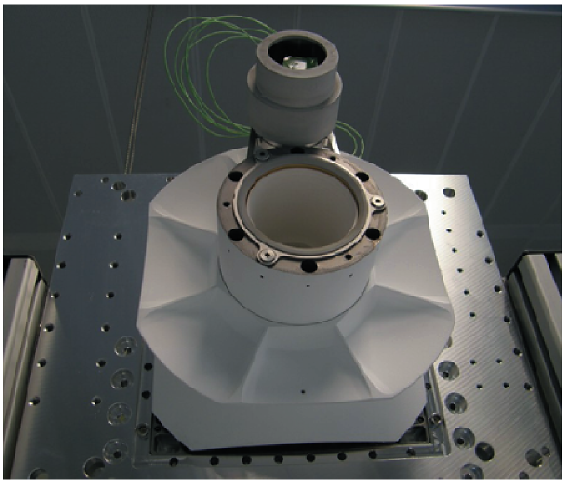

Figure 1. HTM-QM1.

Two HTM qualification models, HTM-QM1 (see Fig. 1) and HTM-QM2, have successfully completed the qualification testing according to SmallGEO (SGEO) mission requirements and will soon undergo the Lifetime test. The paper presents an overview of test results of HTM-QMs.

II. HTM qualification program

Qualification program includes a comprehensive testing of two qualification HTMs:

- performance characterization,
- mechanical tests,
- thermal vacuum tests.

Prior, during and after these tests the HTMs were subjected to the bonding isolation test, leak test.

A. Test facility and test set-up

All vacuum tests of HTMs are performed at Thales' ULAN test facility in Ulm, Germany[3]. The facility has a vacuum chamber of 4 m length and 2.4 m diameter. The facility is equipped with a cryopump system, and additionally with two turbo pumps. The HTM is installed on top of the thrust balance (see Fig. 2). The facility is equipped with the retarding potential analyzer (RPA) and the energy-selective mass-spectrometer for plasma beam diagnostics. The thrust balance is installed onto a rotational table, thus allowing a scanning of ion beam with the unmovable RPA.

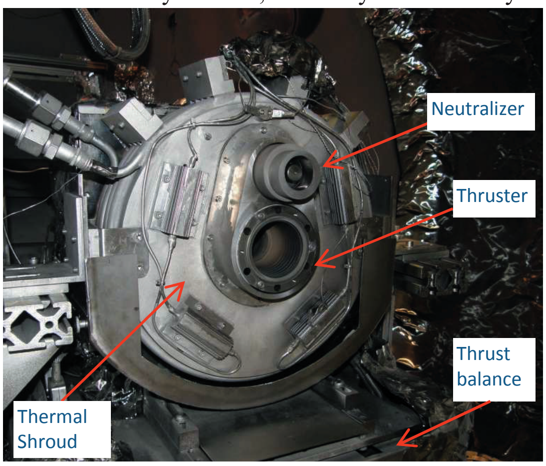

Figure 2. HTM-QM2 at thermal vacuum set-up.

For testing purposes the HTMs are mounted onto the testing frame, which allows for thermal control of the HTM mounting interface (I/F). The FCU is covered with MLI foil during the testing. The THR and NTR are surrounded with a thermal shroud during all in-vacuum tests. The thermal shroud provides a definite radiation environment: shroud can be cooled down by liquid nitrogen, maintained at ambient temperature or heated up; it also protects the optical properties of the THR radiator.

The HTMs are provided with several temperature sensors during all in-vacuum tests.

The HTMs are powered with laboratory power supplies: the anode high-voltage (HV, 1000V) power supply, the NTR keeper power supply (0..50V dc) and the NTR heater power supply (0..15V ac). The HTM FCU is controlled by the FCU Driver, which simulates the FCU controlling function of the PSCU. Xe gas is fed by the facility gas supply system at a constant pressure. Xe of purity 4.0 is used.
The HTMs are operated in the floating cathode configuration throughout the tests.

III. HTM-QM Performance characterization

HTM performance characterization included:

- HTM operation over 4 hours at the nominal SGEO operational point U_a = 1000 V, I_a = 1.38 A, at ambient shroud temperature and ambient I/F temperature (+22°C);
- HTM operation in the extended range of parameters: U_a = 850 .. 1050 V, I_a = 0.3 .. 1.45 A, at ambient shroud temperature and ambient I/F temperature;
- HTM beam characterization at the nominal operational point;
- HTM thrust pulses of 40 min THR firing duration, at the nominal operational point U_a = 1000 V, I_a = 1.38 A, at ambient shroud temperature and ambient I/F temperature.

Thrust measurements were performed during the 40 min thrust pulses.

HTM continuous firing over 4 hours at the nominal operational point demonstrates the capabilities of each HTM-QM for long-duration thrust pulses, which are far outside the nominal thrust pulse duration. HTMs attained a thermal equilibrium state at the end of 4 hours firing with the THR TRP change rate ~1 K/h. All HTM temperatures were within their expected limits.

Each HTM-QM was operated under eight extended operational modes, 5 min for each operational mode. Each of the extended modes was obtained by combining a value of anode voltage from the range 850 .. 1050 V and a value of anode current from the range 0.3 .. 1.45 A, with the maximum anode power limited to 1.45 kW. The HTMs performed stable without anomalies during all eight extended operational modes. Thus, all HTM-QMs have demonstrated the capability to operate continuously under non-nominal anode voltages and non-nominal anode currents without degradation. It is worth to mention here that the prolonged operation (4h) at the most severe extended mode with 1.45 kW anode power is verified at the thermal-vacuum test (see later).

The ion beam of HTM-QMs was characterized in terms of ion current density and ion energy (potential) at approx. 1 m from the thruster exit at the nominal operational point. Ion charge state was characterized as well with the help of energy-selective mass-spectrometer. These characterizations were performed in the horizontal plane of THR. Ion current, ion energy and ion charge state were input data for an ion sputtering analysis with the SGEO satellite configuration. Each HTM was found to comply with the SGEO sputtering requirements.

The HTMs performed a fully representative thrust pulse - operational sequence as applied to the SGEO mission, including a HTM start-up, operation and a shut-down. This sequence was carried-out under I/F and shroud ambient temperatures (+22°C). The HTMs were operated at the extended I/F temperature range during the thermal vacuum testing later on. The HTM-QMs performed the start-up sequences without anomalies. NTR and THR ignited reliably. NTR and THR ignition times were in the expected limits; they are highly reproducible within 4 s between different thrust pulses and from one HTM to another. THR operated stable at U_a = 1000 V, I_a = 1.38 A, with a low cathode-to-ground voltage < $|-15\text{V}|$.
All HTM QMs have very close values of thrust ≥44 mN, providing more than 2400 s of total specific impulse (with the requirement >2300 s) at 1.4 kW electrical power (THR+NTR).

HTM-QMs have successfully passed the bonding, isolation tests and the leak tests before and after the performance characterization.

IV. HTM-QM Thermal vacuum testing

HTM-QM thermal vacuum characterization included:

- HTM I/F temperature cycling between -15°C ("cold") and +65°C (operational "hot") /+80°C (non-operational) with the help of testing I/F fluidic thermal stabilization system; several cycles were performed with the imposed temperature gradient over the I/F;
- HTM environmental (shroud) temperature cycling between -160°C ("cold") and +41°C ("hot") with the help of thermal shroud;
- HTM representative pulses including start-up, operation for 20 min, 40 min, 4h at nominal operation point and shut-down under extreme combinations of I/F and environmental (shroud) temperatures: I/F "cold" – environment "cold", I/F "cold" – environment "hot", I/F "hot" – environment "cold", I/F "hot" – environment "hot".

- HTM beam characterization at the nominal operational point under ambient, cold and hot I/F and environmental conditions;

During the thermal vacuum testing each HTM-QM has accumulated more than 10 “cold” starts and more than 10 “hot” starts. HTM-QMs ignited confidently and operated stable (Fig. 3) in the whole range of temperatures, meeting all performance requirements.

In particular, HTM-QMs have shown stable, reproducible ignition and operation under the “worst case” thermal conditions:

1) Start-up and operation at “high power” mode with the anode power of 1.45 kW, and under “hot” I/F and “hot” environment. This operation mode is achieved by setting the anode current to 1.45A and keeping the nominal anode voltage of 1000V. HTM-QMs have operated 4h without anomalies, with the thruster at thermal equilibrium at the end of operation (THR TRP change rate ~1 K/h) and all temperatures within their expected limits. This operation is considered as a “stress-test” for permanent magnets of the thruster, because they perform under the “worst case” thermal loads. To detect possible changes due to these heavy thermal loads, the HTM performance was characterized under the ambient conditions before and after this “high power” operation: no any variation in performance was noticed for both HTM-QMs (see also Fig.4).

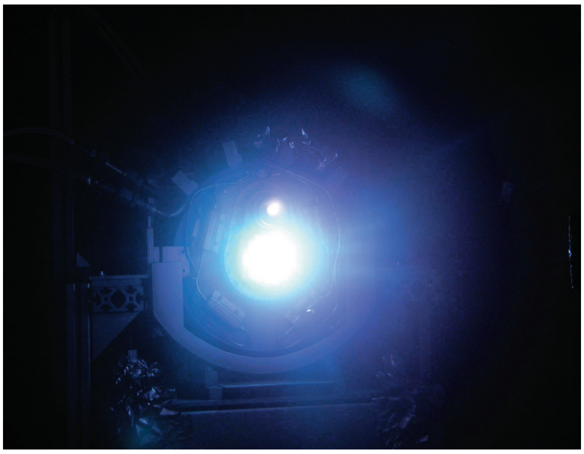

Figure 3. HTM-QM1 firing at thermal vacuum testing.

2) Start-up and 40 min operation, start-up and 4h operation at the nominal operation point (1.38A, 1000V) under “hot” I/F and “hot” environment, with the imposed temperature gradient over the I/F. HTM-QMs have operated without anomalies, with the thruster at thermal equilibrium at the end of operation and all temperatures within their limits. Beam characterization has confirmed the compliance with the SGEO sputtering requirement.
3) Start-up and 40 min operation, start-up and 4h operation at the nominal operation point (1.38A, 1000V) under “cold” I/F and “cold” environment. HTM-QMs have operated without anomalies, with the thruster at thermal equilibrium at the end of operation and all temperatures within their limits. Beam characterization has confirmed the compliance with the SGEO sputtering requirement.
4) Start-up and operation after reaching the coldest thruster temperature during the SGEO mission according to the thermal analysis (“no sun”).

Beam characterization was performed at ambient I/F and environmental conditions as well, at the beginning of thermal vacuum testing and at the end. Throughout the testing, including the performance characterization, beam of HTM-QM1 and HTM-QM2 complies with the SGEO requirements.

Stability of HTM performance is illustrated in Fig.4 and Fig.5, where the thrust and the total specific impulse of HTM-QM1 are presented. Total specific impulse is over 2400s throughout the testing.

As at the performance testing, HTM-QMs have successfully passed the bonding, isolation tests and the leak tests before and after the thermal vacuum testing.

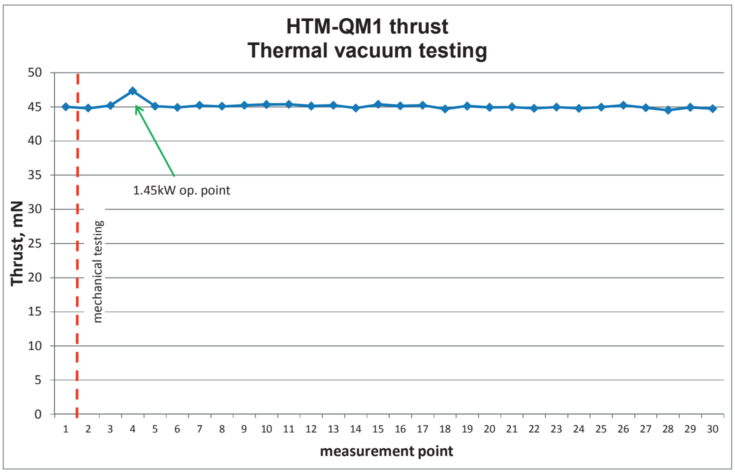

Figure 4. HTM-QM1 thrust over the performance and thermal vacuum testing.

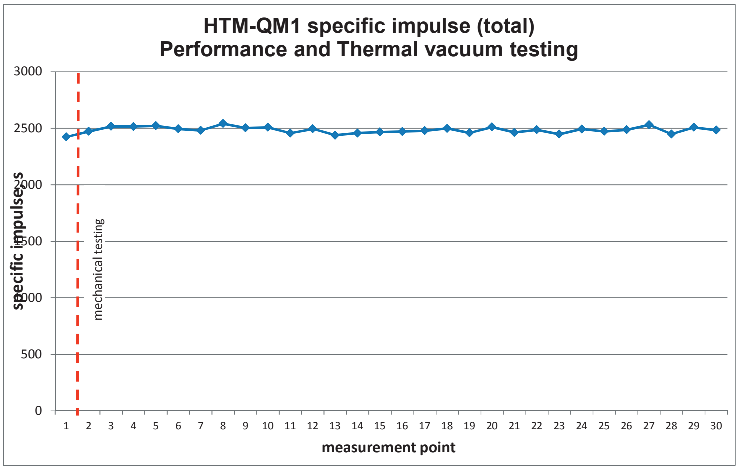

Figure 5. HTM-QM1 specific impulse (total) over the performance and thermal vacuum testing.

V. Conclusion

Qualification results of two HTM QMs have demonstrated the compliance to major SGEO mission requirements, with the thrust of 44mn and specific impulse >2400s. Very low performance variation throughout the performance and thermal vacuum testing demonstrates the robustness of the HEMP technology. The upcoming test activities will include the Lifetime test.

Acknowledgments

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