

Architecture, Functional Features and Operational Characteristics of the HEMPT based Ion Propulsion System for SmallGEO

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Stefan Weis¹, Norbert Koch², Martin Schirra³, Alexey Lazurenko⁴, Benjamin van Reijen⁵, Jens Haderspeck⁶, Angelo Genovese⁷, Peter Holtmann⁸
Thales Electron Devices GmbH, Soeflinger Str. 100, 89077 Ulm

Klaus Ruf⁹, Norbert Püttmann¹⁰
*Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR) - Raumfahrt-Agentur, Koenigswinterer Strasse 522-524,
53227 Bonn, Germany*

and

Hendrik Luebberstedt¹¹
OHB System AG, Bremen, 28359, Germany

Abstract: Thales Electron Devices GmbH has developed and is currently qualifying a novel electric propulsion System, the so called HEMP Thruster Assembly (HTA). The HTA uses a lean topology and design, providing a cost effective solution for commercial geostationary satellites. This is achieved by a modularized design of each propulsion unit (HTM) that results also in complete interchangeability. A set of HTMs can be operated from one power supply module without any switching matrix, since HTMs are designed to support a clustered operation. Thrust control can be achieved by control of the propellant throughput only including switch off. This has been utilized for the HTA to reduce the amount of needed power supplies for the thrusters to one high voltage supply for all thrusters, with a second supply in cold redundancy. Also no additional sensors are required for the flow control unit, as the thruster itself is used for the feedback signal to control thrust by propellant flow. In addition the HTM units are designed to be integrated without dedicated pointing mechanisms. In this paper the architecture and the operational and performance characteristics of the HEMPT Assembly ion propulsion system will be presented.

¹ Electric Propulsion System Manager, Plasma Devices, stefan.weis@thalesgroup.com; corresponding author

² Head of Plasma Devices, Plasma Devices, norbert.koch@thalesgroup.com

³ Manager Electric Propulsion Component Development, Plasma Devices, martin.schirra@thalesgroup.com

⁴ Manager Electric Propulsion Testing, Plasma Devices, alexey.lazurenko@thalesgroup.com

⁵ Electric Propulsion Development Engineer, Plasma Devices, benjamin.reijen@thalesgroup.com

⁶ Electric Propulsion System Engineer, Plasma Devices, jens.haderspeck@thalesgroup.com

⁷ Electric Propulsion Testing Engineer, Plasma Devices, angelo.genovese@thalesgroup.com

⁸ Project Manager, Project Office, peter.holtmann@thalesgroup.com

⁹ Project Manager, Robotic Systems, klaus.ruf@dlr.de

¹⁰ Project Manager, Robotic Systems, norbert.puettmann@dlr.de

¹¹ Manager Propulsion Sub-System, hendrik.luebberstedt@ohb-system.de

Nomenclature

ACMU	=	Anode Current Measuring Unit	IV	=	Isolation Valve
ASM	=	Anode Supply Module	MMS	=	Mechanical Mounting Structure
FCU	=	Xenon propellant Flow Control Unit	NHKS	=	Neutralizer Heater Keeper Supply
FCV	=	Flow Control Valve	OHB	=	OHB System AG
HCN	=	Hollow Cathode Neutralizer	PSCU	=	Power Supply and Control Unit
HEMPT	=	High Efficiency Multistage Plasma Thruster	TEDG	=	Thales Electron Devices GmbH
HEMPTIS	=	HEMP Thruster In-orbit-verification on SmallGEO			

I. Introduction

THALES Electron Devices is developing and qualifying a novel type of ion propulsion system based on 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 will be integrated on OHB's SmallGEO geo-stationary to perform attitude and orbit control manoeuvres¹.

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.

The core technology of the ion propulsion system is represented by the HEMPT ion thruster, which has been developed by Thales Electron Devices since about 10 years (from concept feasibility²) 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. In addition, the HEMPT design concept and operational characteristics enable ion propulsion system architecture with minimum complexity and thus high reliability and cost efficiency³.

II. Architecture

A. Overview

Figure 1 shows the layout of the HEMP-Thruster Assembly (HTA). It consists of a PSCU, developed, manufactured and delivered by Astrium ASG in Friedrichshafen and 4 HEMP-Thruster Modules (HTMs), developed, manufactured and delivered by TEDG in Ulm. The Xenon tank, the pressure regulator and the on board computer (OBC) are provided by OHB-Systems under their responsibility for the SmallGEO satellite (see also ¹). TEDG acts as prime contractor for the HTA and is leading responsible for development, qualification and flight model production and verification (described in ⁴).

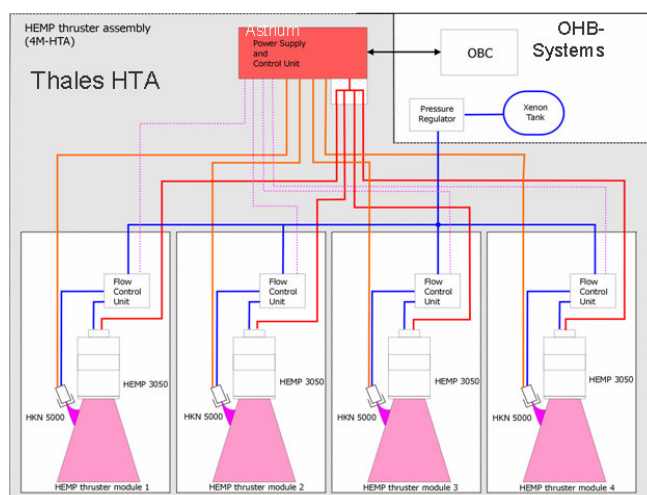


Figure 1. Functional Blocks of the HEMP Thruster Assembly Electric Propulsion System

B. PSCU

The PSCU consists of the following Modules:

- One ICAU module
- One ACMU module
- Two ASM modules
- Four NHKS modules

The ICAU Module provides the logic control interface to the spacecraft. The other modules are controlled from this module. It collects all telemetry from the other modules and autonomously executes predefined sequences upon command. The ICAU also supervises on the telemetry and shuts down sub modules in case of failure events without the necessity of spacecraft involvement.

The ASM module provides the necessary high voltage for thruster operation. For reliability reasons two of them are allocated within the PSCU in cold redundancy. The ASMs can be operated simultaneous, to increase the power and thrust capability of the system.

The high voltage is routed through the ACMU which measures the current supplying the thruster. This current signal is used by the ICAU for the regulation of the thruster current. As the ACMU provides a sensing channel for each HTM, multiple thrusters can be operated simultaneous. For parallel thruster firing, both ASMs are configured "ON", to have sufficient power available. In case of SmallGEO, no simultaneous but subsequent firing is intended.

The NHKS modules provide the driver and control functions for the operation of the HTM modules. In particular the flow control unit, the cathode and the temperature sensors are controlled and supplied by this module. It comprises a heater supply for the cathode as well as a keeper supply. Three temperature sensor channels for thruster, cathode and flow control unit are employed. In addition, three valve drivers and one heater channel are included.

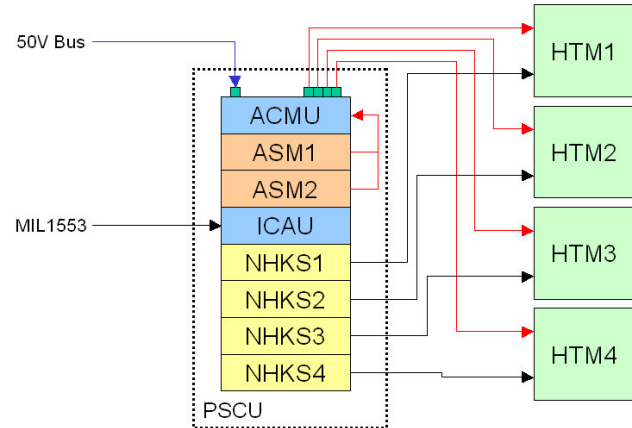


Figure 2. Functional Blocks of the PSCU
HV-Lines in red

C. HTM

Each HTM comprises a HEMP3050 Thruster (THR), a HCN 5000 Cathode (NTR) and a flow control unit (FCU). All these devices are mounted to a mechanical mounting structure (MMS). The FCU comprises one inlet isolation valve (IV1), an isolation valve to distribute flow to the cathode (IV2) a proportional flow control valve (FCV) and a heater for thermal control.

Special attention has been given to the thermal design of the HTM, as the HTM conducts less than 25W of all dissipated power to the spacecraft; in particular the thruster radiates more than 95% of its thermal dissipation to space and conducts less than 15W back to the space craft.

A brief description of the module can be found in ⁴. Details on the HEMPT concept and on general operational and performance characteristics of the HEMPT are reviewed, e.g., in ^{5,6} or ⁷.

Details on the HCN concept and on general operational and performance characteristics of the HCN can be found in ^{8,9,10} or ¹¹.

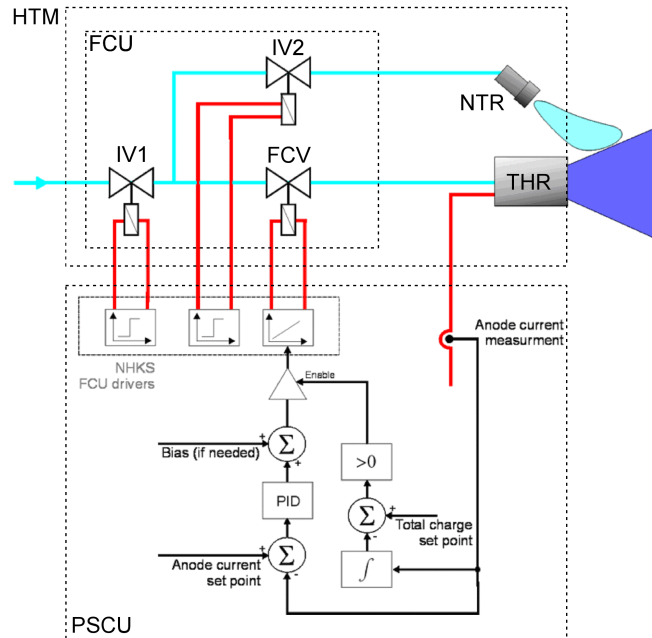


Figure 3. Functional Diagram of the HTM and the thrust control loop

III. Functional Features

D. Thrust control

The propellant supplied to the thruster is controlled by the FCV that is followed by a flow restrictor. The FCV provides the capability to adjust the flow by adjusting the control current through the valve. By use of the flow resistor, the flow remains limited for fully open conditions, what is important for controller stability and to limit gas consumption in failure. As the thruster current is solely dependent on the Xenon flow through the, the thruster current is measured and used for a closed loop regulation; this eliminates the need for any flow or pressure measuring provisions. The measuring is performed within the PCSU in the ACMU. To eliminate ripple on the feedback signal it is low pass filtered directly on the ACMU. The control loop is closed in the PCSU through the ICAU, where the PID regulator is located, and finally within the NHKS, that provides the Valve drivers (see also figure 3). The control loop eliminates any thermal dependence of the flow control valve offsets. The closed loop controller is build as analogue regulator to achieve low ripple behaviour. In addition, there is an open loop operation feature included, to operate the FCV prior ignition of the thruster (what implies the absence of a valid feedback signal) and shortly after the ignition. The ICAU detects the ignition of the thruster and transients automatically from open loop to closed loop operation.

This concept enables for very fast thruster switch on, once the cathode is already operating and reaching of the desired thrust level. Typically 30 seconds after the Thrust on Command, the nominal thrust level is reached to 5% precision, after one minute to 1%.

E. Control of Impulse

The HTA integrates the impulse equivalent of each thruster firing cycle by integrating the thruster current over time, and stops thruster operation upon completion of a previously chosen impulse. Therefore there is no need for accurate thruster firing time control. As a consequence variations in thrust have only minimal impact on the actual manoeuvre as fluctuations and deviations are automatically compensated.

This functionality is build into the PCSU of the HTA. The PCSU executes predefined sequences stored in the PCSU. With a small set of commands these sequences are started. During the sequences, each HTM is initialized and the thruster is started. The thruster is autonomously stopped upon completion of the required impulse.

F. Performance Figures

1. Mass

Parameter	Typical (without margin)	applicable margin	remark
Mass of HTM	6.44 kg	+9%	Margin decreases with successful qualification
Mass of PCSU	14 kg	+10%	Margin decreases with successful qualification
Mass of Harness	3.9kg	+10%	Margin decreases with successful qualification
Mass of one HTA	43,6kg	+9.5%	Margin decreases with successful qualification

Table 1. Mass figures of the HTA

The mass of one total system comprises four HTMs, one set of Harness and the PCSU. This totals to a projected mass of 43,6kg for one HTA. For reliability reasons two HTAs should be integrated on the spacecraft, resulting in a mass of 87,2kg. Note, that the tubing for the Xenon supply is attributed to the spacecraft side and therefore excluded from the mass budget.

Typical Startup HTM

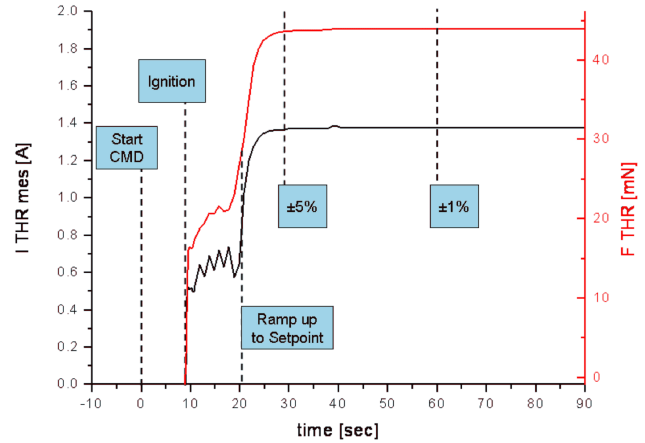


Figure 4. Typical startup of HTM

2. Thermal / Power

ID	Parameter	Condition / State	typical	Worst case*	remark
A	HTA input power	PSCU idle (directly after power on)	10W	16W	
B	HTA input power	Preheating of a HTM	58W	70W	
C	HTA input power	during thruster firing @44mN	1491W	1528W	
D	HTA input power	during thruster firing@44mN with parallel preheating of a second HTM	1539W	1580W [#]	
C	HTM dissipation conducted to spacecraft	during thruster firing@44mN (hot interface)	N/A	18W	
C	PSCU dissipation	during thruster firing@44mN	77W	98W	
D	PSCU dissipation	during thruster firing@44mN with parallel preheating of a second HTM	93,3W	120W	
D	Harness Dissipation	during thruster firing@44mN with parallel preheating of a second HTM	2,8W	3,2W	

Table 2. Power figures and thermal dissipations of HTA

The power figures given in table 2 are for typical operational conditions such as 50V bus voltage, ambient interface temperatures, steady operation (no transients). The worst case values given also consider effects such as bus voltage variations, drift over temperature, aging and attribute to shortly increased power demand due to sequence demands. See also chapter IV for a description of the referenced operational modes (ID).

3. ISP

Parameter	typical	Worst case	remark
ISP of Thruster	>2800s		
ISP of HTA	2450s	2310s	Includes sequences, non operational losses and some failure cases

Table 3. Specific impulse of HTA

Although the specific impulse of a single thruster is in excess of 2800s, the supply for the neutralizer cathode, the dynamics of the flow control unit together with internal leakage of valves and reliability/failure considerations result in a typical ISP of 2450s and a worst case ISP of about 2310s for the total HTA.

4. Thrust

Parameter	min	nominal	max	remark
Thrust	<20mN	44mN	45mN	Nominal equals SGEO configuration

Table 4. Thrust range of one single HTM

The nominal operational point on SGEO is 44mN. The HTA is currently being qualified for this operational point. Never the less, the thruster can be throttled down to ~20mN. Short term operation testing demonstrates the capability to increase the thrust with the current design up to 60mN and even more with small modifications to the design. The HEMPT technology demonstrated the capability to extend up to 7.5kW thruster input power for a single thruster¹² which enables thrust levels up to the 250mN class.

5. Further parameter

Parameter	Demonstrated (ET) ¹³	RQM for flight	RQM for qualification	remark
Total Impulse	0.8 x 10 ⁶ Ns	0.76 x 10 ⁶ Ns	1.14 x 10 ⁶ Ns	
Restarts cycles	>200	6500	9800	
Operational duration	>4000h	4800h	7200h	
Discharge voltage	1000V	-	-	Thruster can accept 500V..1100V
HTA Xenon mass flow rate	≤1.89mg/s	1.95mg/s	1.95mg/s	One HTM operating, see also ISP RQM refers to worst case.

Table 5. Key parameters of HTA / HTM

* includes variation of bus voltage, aging, temperature, initial tolerances.

[#] includes variation of bus voltage, temperature, initial tolerances, excludes aging (is compensated by commanding).

Table 5 comprises key parameters of the HTM. These parameters have been investigated in an endurance testing of one HTM engineering model¹³. Note, that the Xenon mass flow requirement is merely derived from the ISP. The indicated mass flow of 1.95mg/s corresponds to an ISP of 2300s at 44mN thrust.

IV. Operational Characteristics

G. Operational Modes

The PCSU provides predefined macro sequences (see figure 5) and is strictly speaking not using operational modes. Instead the spacecraft software uses the macro-sequences and implements the operational modes on a higher level. In this way all time critical sequences are capsulated and fully controlled in the PCSU. This relieves the spacecraft from time critical supervision and timing tasks. When the software has to change the operational state, it invokes the respective sequence and waits for completion of it. In this way the following operational Modes are formed:

- 0: Off
- A: PCSU standby
- B: HTM heating/NTR operation
- C: HTM firing
- D: (B+C) on 2 HTMs

A typical manoeuvre sequence on SGEO is the firing around one orbital node, that involves the subsequent activation of two thruster modules with the overlapping heating up of the modules (see figure 6). This is a compromise to optimise power demand and time between the firings. To perform such a sequence, the spacecraft software turns on the PCSU and uploads the desired parameters for the manoeuvre. Then the first HTM is preheated. Shortly before the desired start of the thruster the respective neutralizer is activated with a command. Then there is the possibility to start the thruster with the desired thrust level and impulse bit (see above).. After this the Thrust_off Command is invoked for the first HTM; this stops the thruster and the neutralizer discharge and prepares the HTM for shut down. Finally all devices on the respective HTM are shut off. For the second HTM the same sequence is executed, but timely shifted. The last thing is to shut off the PCSU.

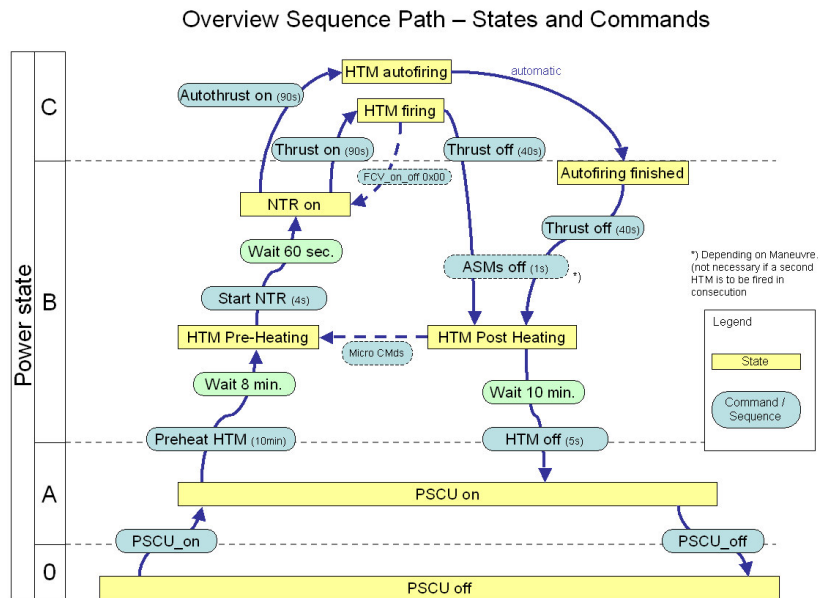


Figure 5. Overview of operational states and commanding sequences

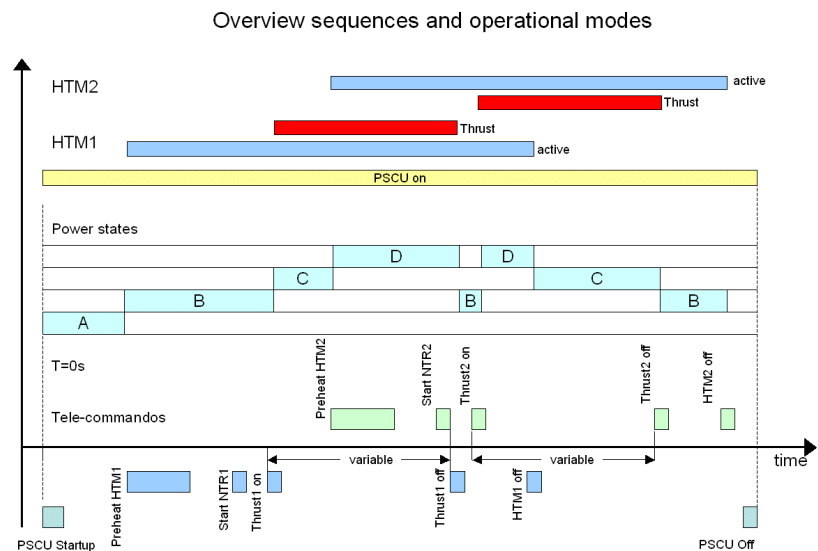


Figure 6. Timeline of operation.

Indicated are the necessary commandos to perform the manoeuvre (bottom), the resulting power states (A – D) and the phases of activity for the individual thruster modules.

V. Conclusion

TEDG has further developed its HEMPT technology to set up a reliable and cost effective ion propulsion system. Supported by German Aerospace Agency DLR through the HEMPTIS project, a HEMPT Assembly has been set up which shall have its first flight on OHB's SmallGEO Platform.

The HEMP Thruster Assembly (HTA) provides unique features such as precise thrust control, fast turn on time, attractive ISP, direct impulse control and low commanding demands. All critical commands and supervision tasks are encapsulated inside the PSCU to relieve the spacecraft software from time critical activities.

With this attributes, it is very well suited for Small GEO and future small geostationary satellite platforms.

Acknowledgments

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