Low Complexity and Low Cost Electric Propulsion System for Telecom Satellites Based on HEMP Thruster Assembly

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Abstract: Electric propulsion is often considered as too complex and too costly for wide spread application on telecom satellites. The new Thales HEMP thruster has the ability to overcome this drawback by reducing the electric propulsion system complexity and cutting the cost of a state-of-the-art EP system by 50%. The general layout of a HEMP thruster assembly (HTA) and its building blocks are shown. It consists of a cluster of thrusters with the ability to control the thrust vector without orientation mechanism. As a specific feature, a cluster of HEMP thrusters is operated on one common high voltage line, reducing power supply design complexity and avoiding the use of high voltage relays. The impact onto the system is shown and discussed to identify and present the main drivers of cost reduction. Concept studies of the integration of a HEMP thruster assembly into telecom satellites are outlined and the status of the HTA EP subsystem development at Thales is reported.

I. Introduction

Several electric propulsion (EP) technologies have been developed in the recent years. Some of them, namely resistojet, arcjects, gridded ion thrusters (Kaufman-type) and Hall-effect thrusters, have been used onboard of commercial spacecrafts for North-South Station Keeping (NS/SK). Comparing the number of those electrically propelled spacecrafts with the amount of satellites that might benefit from EP, one has to admit that this new class of thrusters has not been accepted by the market as state-of-the-art technology yet. Only the low specific impulse electro-thermal thrusters (resistojet and arcjet) have been able to enter their niche at a considerable level. They are installed on more than 75% of today’s EP satellite fleet. The main barriers for diffusion of high specific impulse thrusters are the high cost and the additional system complexity those propulsion systems exhibit. The benefit of cost reduction on mission level, by decreasing the wet mass of the spacecraft, is often rendered negligible due to dropping launch costs.

Considering large satellites, a chemical propulsion system would spend in the order of 700kg of propellant for the NS/SK task. Using high specific impulse thrusters like gridded ion engines or Hall-effect thrusters, the propellant needs could be reduced to between 80kg and 150kg of xenon. If it is possible to transfer those mass savings to a second payload in a dual launch option, the mass reduction corresponds to less than 8 Mio. Euro in launch cost cut. More advantage can be gained, if a change to a smaller launcher is possible by reducing the total launch mass of the satellite below launcher specific limits.

It is obvious, that an electric propulsion system at a price exceeding 8 Mio. Euro is economically unviable. Considering the additional risks, the target price must even stay below. Referring to satellite manufacturers the actual price limit is in the order of 6 Mio. Euro, when the trade-off between risk, cost and benefits is balanced. Even at this target price, that seems to be realized with Hall-effect thrusters, the market potential is limited to huge satellites.

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To open the market also with respect to the EP usage on small to medium sized satellites and to give a clear economic advantage compared to chemical propulsion, the total system price for an EP subsystem should be even 50% less. This price target in mind, a HEMP-T EP subsystem has been developed since 2005, based on component developments starting in the year 2000.

II. High Efficiency Multistage Plasma Thruster (HEMP-T)

The core component of the new developed EP system is Thales' patented High Efficiency Multistage Plasma Thruster (HEMP-T). The HEMP thruster consists of a cylindrical periodic permanent magnet stack forming the HEMP-T style magnetic field topology. This field topology separates the discharge into several magnetic cells and confines the plasma on the center axis of the thruster. Therefore the plasma has almost no interaction with the dielectric walls surrounding the discharge volume.

The separation of the discharge column into cells with magnetic mirrors structure between each cell and in radial direction towards the walls, provides a high impedance for electrons. Electrons are not able to cross the separating mirror between cells without collisions, either with the discharge channel walls or with gas atoms or ion inside the volume. The probability to reach the walls and to have collision there is very low due to the mentioned radial mirror[1], so the volume collisions are the only way to allow current flow. The current is therefore proportional to the probability of those collisions that is controlled by the gas density inside the device. Without gas flow no collision can take place and the HEMP thruster shows no leakage current even if the anode is still on high voltage potential and the neutralizer supplies electrons to the exit region of the thruster. This allows the operator to control a HEMP thruster from switching on and off to linear control of the thrust simply by adjusting the gas flow.

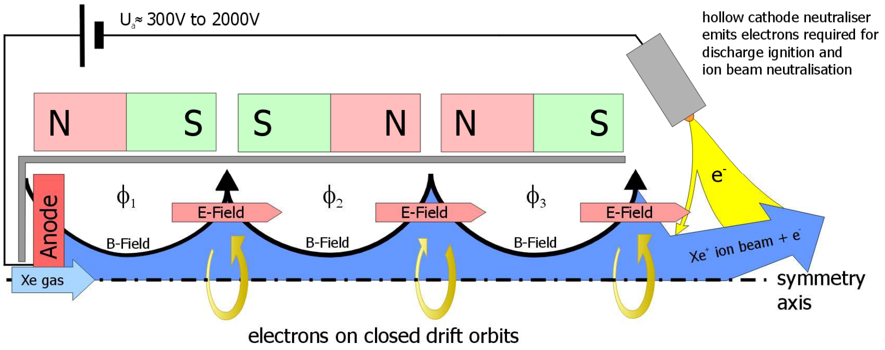

Figure 1: Schematic view of the HEMP thruster's principle of operation

The HEMP thruster is supplied by a single xenon gas feed (other gases like krypton possible) and a single DC high voltage power line to the anode. Due to the high impedance that is solely controlled by the gas flow, HEMP thrusters show no disturbing cross coupling during simultaneous operation of several thrusters on one common anode line. This unique feature reduces system complexity on power supply level especially for a thruster cluster with multiple thrusters running at the same time as it is needed for gimbal free thrust vectoring concepts.

As any electrostatic thruster, the HEMP-T needs a neutralizer to close the current loop and to keep the spacecraft uncharged during thruster operation. In contrast to other gridless thrusters like Hall-effect thrusters, the HEMP-T does not need high electron currents from the neutralizer to sustain the discharge. Few percent of the neutralizer's electron current reaches the anode that is located at the inner end of the discharge channel. There are no surfaces on high voltage potential at the outside surface of a HEMP-T system. The only biased surface is the keeper tip of the neutralizer at a maximum voltage of less then 40V compared to satellite ground..

The HEMP thruster together with its neutralizer is mounted on top of a mechanical mounting structure (MMS). Inside the MMS the flow control unit for the thruster and the neutralizer is integrated. The fully equipped MMS also revered to as HEMP thruster module (HTM), interfaces the module to the satellite structure as well as to the harness and pipework. The geometry of the MMS is platform dependent as it also defines the cant-angle of the thruster with respect to the mounting plane.

The dissipated power during thruster operation is radiated into space using a directional radiator in the infrared, originally developed and used for traveling wave tubes. The HTM is thermally insulated from the satellite structure to restrict the conducted heat load to less than 10W.

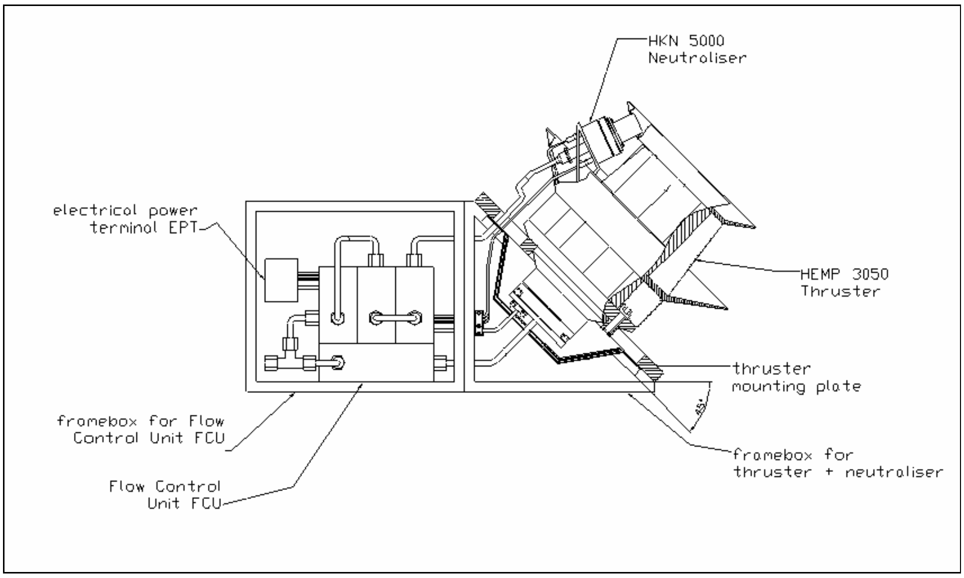

Figure 2. HEMP thruster module

III. Generic HEMP-T electric propulsion system

A multiplicity of HEMP thruster modules is combined with a power supply and control unit (PSCU) to a HEMP thruster assembly (HTA). The number of modules depends on the mission and the spacecraft architecture. The PSCU incorporates a high voltage converter to drive the anode line of the HTMs, low voltage converters to supply the neutralizers and valve drivers for the FCUs. Beside the power conditioning the PSCU also includes a controller and interfaces to communicate with the on board computer, to execute telecommands and to deliver telemetry data.

The number of high voltage converters as well as the control logics and the interfaces is independent of the multiplicity of HTMs. The number of installed supplies and drivers for the neutralizer and the flow control unit (FCU) depend on the HTMs, one for each module. To be flexible in the system architecture, a modular PSCU design representing these requirements has been chosen.

For simplicity and to provide an U.S. export restriction free solution, a bang-bang type of flow control unit has been designed that is able to control the total impulse transferred to spacecraft and the maximum deviation of the real thrust to the commanded average thrust level by a special control algorithm realized inside the PSCU's flow control driver logic. The algorithm uses the excellent proportionality between current and thrust, valid for HEMP thrusters over a wide field of operation.

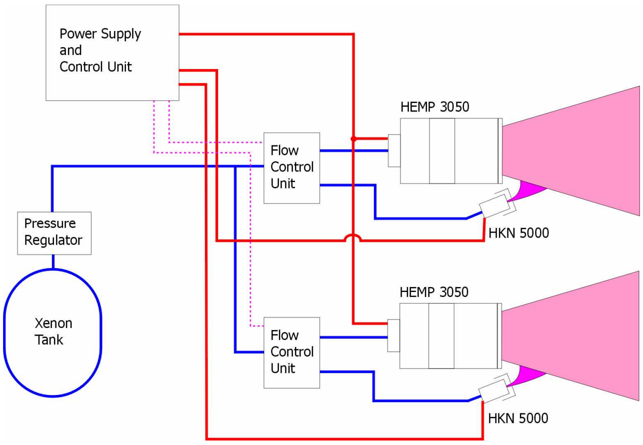

Figure 3. Basic electric propulsion system of a two module HEMP-T cluster

For missions like earth observation with fine pointing requirements when not only a high accuracy total impulse transfer but also a good agreement of real thrust and commanded thrust throughout the whole propulsive maneuver is needed , the bang-bang flow control unit can be exchanged by a FCU with proportional valve.

Single failure tolerance is realized by doubling the complete HEMP thruster assembly with its HTMs, the PSCU, harness and pipework. This complete separation of the both branches ensures that failure crosslink risks are minimized. The only shared component will be the xenon tank structure. Depending on the overall mission strategy the independent branch structure can also be used to operate all thrusters at the same time (without redundancy) for a part of the mission, e.g. to provide maximum thrust during orbit raise or repositioning.

Table 1. Baseline HEMP-T system for a small to medium sized satellite

Total dry mass of EP system	82 kg
Input power from main bus	1500 W
Nominal thrust / specific impulse (incl. neutraliser)	46 mN @ 2500s
Number of thruster modules (thruster, neutralizer, flow control unit, mounting structure and interface)	8 (two redundant branches, four thruster modules each)
Operational tasks	NS/SK, EW/SK, wheel offloading, orbit raise, position acquisition, repositioning

IV. HTA design approach

One of the most expensive and mass contributing components of a today's electric propulsion system is the thruster pointing mechanism. As mechanical device it is also subject to several limitations and risks. A basic strategy to reduce complexity, cost and risk is to abandon this gimbal device. In this case the thrusters will be fix-mounted on the satellite structure. As a result, the thrust vector of a single thruster is no longer in line with the center of gravity of the satellite. During the mission further changes in the mass distribution occur by consuming propellant from the tank. To compensate for the resulting momentum in the case of misalignment, a second thruster has to deliver a compensation momentum. Typically this leads to a configuration where the thrust is split between at least two thrusters located on opposite sides of the center of gravity.

In a classic electric propulsion system each operating thruster needs a dedicated power supply and control unit (PSCU). If the thrusters have to be throttleable for thrust vectoring, each PSCU must be able to deliver the power of the maximum throttle level even if the thruster operates at lower thrust level. Typically the power available for the EP system is limited by the mission design and shared by the operating thrusters with the needed ratio to obtain momentum compensation. Therefore the power converting capability of the supply units installed on the satellite is oversized by the throttle ratio. Redundant or non operating thrusters can be connected to the same PSCU but must be switched off by high voltage relay switching matrices while one thruster is running.

Designing a HEMP-T EP system follows a different approach. Since all thrusters can be operated on the same anode line, only one PSCU is needed. This PSCU must only be capable to process the power defined by the mission for the EP task. The power is split between the thrusters by adjusting the gas flows to the needed ratio. Therefore no additional power reserve has to be installed for throttling.

Besides the momentum compensation to abandon the gimbal, the scalability of a modular cluster is also an advantage. The HEMP-T cluster is based on medium sized thrusters with a nominal thrust level of 50 mN. The EP system for missions with higher thrust requirements is easy to design and to set-up by delta-qualifying a tailored cluster using the same 50 mN modules.

V. Cost Reduction

To open up the market potential for EP on small and medium sized satellites, it has been claimed as development goal for an electric propulsion system that the cost of a complete system has to drop significantly. To reach this goal, Thales Electron Devices has consulted with experts from component suppliers and satellite manufactures to evaluate the potential of a HEMP-T based EP system. As baseline for this analysis a propulsion system for station keeping and wheel offloading with one failure tolerance has been investigated. For cost comparison, a SPT-100 system with thruster pointing mechanism was considered as representative for today’s low cost, high specific impulse EP. As result of the investigation, all partners agreed that a HEMP-T system has the potential to reduce the costs by nearly 50%.

Table 2. Comparison between a HEMP-T system and a SPT based system as used on large telecommunication satellites (single failure tolerant).

	Total Dry System		Thruster/ HKN/ Harness		FCUs/ Valves		PSCUs + FUs if required		Gimbal + add. AIT		Pipework		Dry Tank/ Pressure regulator	
Configuration	% cost	dry kg	% cost	kg	% cost	kg	% cost	kg	% cost	kg	% cost	kg	% cost	kg
GEO 8 HEMP Satcoms	multiplicity		8T+8N		8		$2^{*)}$		0		8		1	
	50.6%	**100.0**	20%	26.4	8%	12.0	15%	20.0	-	-	2.6%	2.1	5%	39.5
GEO 4 SPT, gimbaled	multiplicity		4T+8N		4		2		2		4		1	
	100%	**106.1**	23%	18.9	4%	6.6	33%	20.8	33%	19.0	2%	1.3	5%	39.5

VI. Target Mission and Status

Thales Electron Devices GmbH is open for cooperation for future HEMP-T systems. In a first step, a collaboration with EADS Astrium Satellites GmbH (Friedrichshafen) for the HEMP-T PSCU[2] has been started to make available a qualified HEMP-T reference system and to push forward for a first mission. Following the idea of a reference system, the design is kept flexible to allow modifications towards different platforms. For the first mission it is dedicated to do station keeping, station acquisitioning, repositioning and wheel offloading tasks on a small geostationary satellite with the ESA ARTES-11 funded Small GEO platform developed by OHB Bremen as baseline and target mission. The proposed concept was evaluated in an ESA concurrent design facility (CDF) session and found to be well suited.

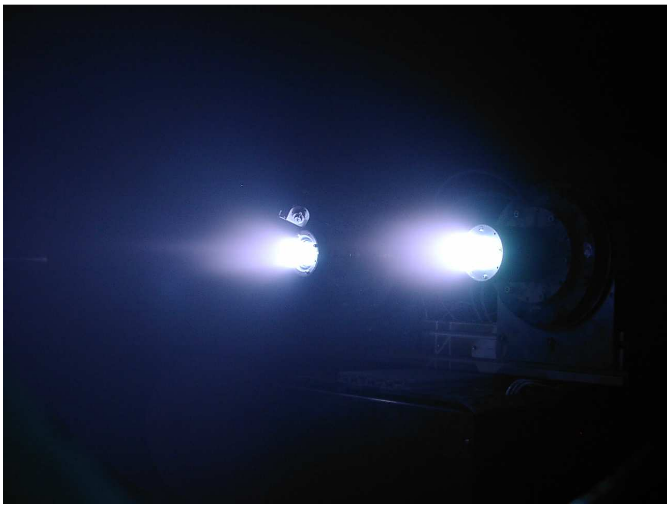

Figure 4. Two module HEMP-T cluster during test firings. The cluster is operated on one common anode line of a single PSCU. A hollow cathode neutralizer is mounted above the left thruster.

The electric propulsion system of the Small GEO[3] is designed to have two branches. One equipped with HEMP thrusters, the second equipped with thrusters of a different, space proven type. The HEMP thruster assembly will consist of four modules and one power supply and control unit. Both branches are connected to one common xenon storage and supply system[2]. The xenon supply contains a pressure regulation that keeps the inlet pressure at a constant level suitable for both systems (~2 bar) and a latch valve selecting one of the two branches as operational.

The HEMP system is planned to be operated as primary branch while the other technology is a redundant system.

The EP system will be controlled by a control unit integrated into the power supply. It is commanded via a 1553-MILBUS interface to the onboard computer system. The integrated controller will be realized in hardware using a FPGA.

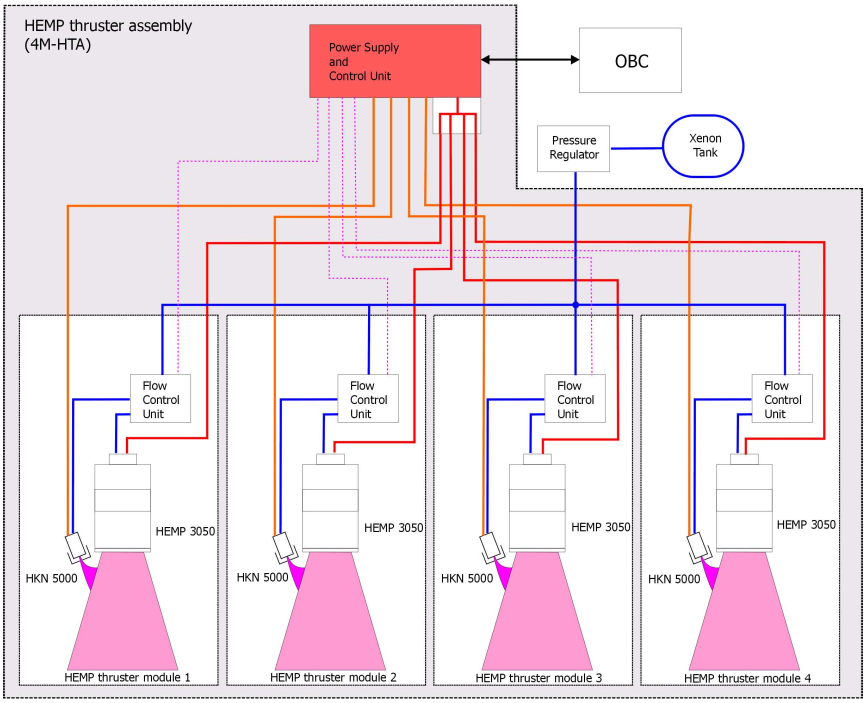

Figure 5. Schematic overview of the HEMP-T EP system for SGEO

In figure 5 the basic layout of the HEMP-T assembly for the Small GEO (SGEO) platform is shown. Four thruster modules (4M-HTA) are directly connected to the PSCU. Each connection line is formed by a shielded high voltage cable connected to the thruster's anode and a return line connected to the neutralizer's cathode. A second cable distributes the three low voltage lines for heater, keeper and common return to the neutralizer. The xenon feed lines are split behind the latch valve (not shown) into four medium pressure lines to the flow control units. Each flow control unit supplies the flow to the thruster and the neutralizer of its module.

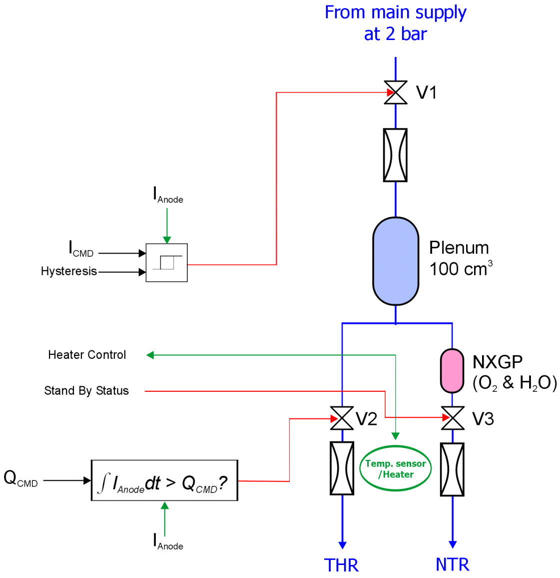

Figure 6. Schematic view of the bang-bang flow control unit and algorithm

The flow control unit for the Small GEO platform will be a bang-bang type controller with an inlet valve connected to the supply line from the latch valve, flow restrictors, a plenum and two outlet valves – one to the thruster, the second to the neutralizer. The flow restrictors define the time constants of the FCU and the fixed flow split between neutralizer and thruster. The operation of the FCU is controlled by a two point controller for the inlet valve and an integrating comparator circuit for the outlet valve to the thruster (s. figure 6). The valve to the neutralizer is switch by telecommands.

For HEMP thrusters the anode current is directly proportional to the thrust over a wide range of operation. Therefore, the total impulse the EP system shall deliver at constant anode voltage, can be commanded and controlled by translating the commanded total impulse transfer into a total charge transfer. The anode current of the running thruster is integrated and compared with the requested charge transfer. As long as the integrated current is below the request charge transfer, the outlet valve to the thruster stays open. Reaching the requested charge transfer the valve closes and the thruster ceases operation immediately. This control loop guarantees a precise control of the total impulse transfer. A second controller compares the anode current with a commanded current level that represent the average thrust level the EP system shall deliver during the propulsive maneuver. This two point controller opens the inlet valve to repressurize the plenum if the current drops below the commanded value reduced by given threshold. The valve stays open until the anode current reaches an upper limit defined by the commanded value plus the threshold. The threshold is sized in a way that the deviation of the real thrust from the commanded average thrust stays within a specified range and that the total number of valve cycles stays within the specification.

Detailed descriptions of the hollow cathode neutralizer[4], the HEMP 3050 thruster[5] and the baseline power supply[2] from EADS Astrium Satellites Friedrichshafen as well as the status of the components development can be found in the referenced papers.

During the development of the HEMP-T EP system for Small GEO, the selected components have been developed to elegant breadboard level. To ensure the compatibility functional and coupling tests are requested on a regular time schedule. Therefore the involved components are joined to a system to confirm crucial functions and elements of the requirements by test as early as possible.

One of the most important milestones during 2007 was the operation of HEMP thrusters together with high voltage power supplies developed for gridded ion engines by EADS Astrium Friedrichshafen and Thales Alenia Space ETCA. Both breadboard PSCUs worked very well and comparable. The Astrium model (HVPS) yielded a higher efficiency (97% compared to 95%) due to their new innovative converter concept[1]. The Astrium HVPS resided already inside the vacuum chamber to demonstrate the validity of the thermal design.

The following main system building aspects have been successfully addressed:

- High impedance test. Without gas the current to a thruster with applied high voltage is below 1 mA (measurement limit)
- Two thrusters directly connected to one shared common anode line
- Control of the thrusters only by gas flow adjustment (powered by common anode line)
- Independent throttling of both thrusters
- Coupling test of one single HEMP 3050 thruster with HVPS from Astrium. HVPS inside vacuum chamber
- Coupling test of one single HEMP 3050 with thruster with ETCA PSCU. PSCU resided outside the vacuum chamber
- Fast thrust on/off by chopping the outlet valve of the FCU
- Thruster - thruster interference test by placing the thrusters at minimum distance showed no negative influence
- Thruster - traveling wave tube interference test by placing a thruster magnet stack close to a TWT in operation
- Integration of the HEMP-T system into the Small GEO satellite design during ESA CDF session
- Beam profile measurements
- Transient behavior during start-up and shut down, conducted EMI investigation

The next steps of the HEMP-T system development will concentrate on technology aspects to reach EM/EQM level. Within the Small GEO framework the qualification of the system is planned within 2008 while the life test will take at least two years. The results of a first 5000h endurance test will become available by mid 2009. First in orbit test results are expected in 2011. For the future Thales Electron Devices GmbH is looking forward to deliver a qualified, space proven and low cost propulsion system that can easily be adopted to satellite platforms ranging from small size with approx. 1000kg of dry mass up to large ones with several tons.

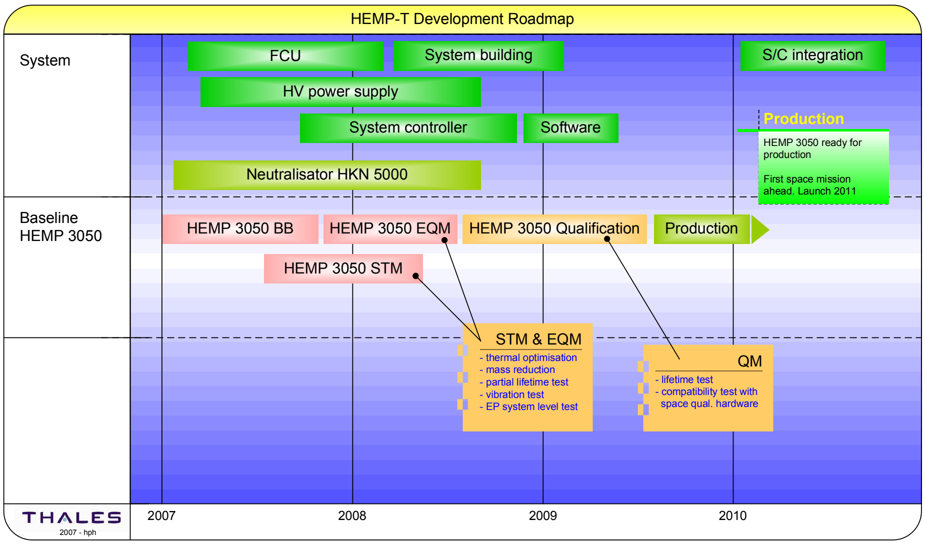

Figure 7. **HEMP-T development roadmap**

VII. Summary and Conclusion

HEMP-T electric propulsion systems have the potential to open up the market of EP for small to large size satellite platforms. Designing a propulsion system using the low complexity of a HTA can cut cost by up to 50%. The development of the HEMP-T EP system has shown a remarkable progress during the last two years. The feasibility on system level has been demonstrated and further steps towards EM level have been carried out. The qualification and life test is expected during the next two years. A first mission in orbit is planned for 2011.

VIII. Acknowledgment

A significant part of the HEMP 3050 thruster and neutralizer development has been supported by the German Space Agency DLR (FKZ 50JR0341 and FKZ 50JR0342). Detailed investigations of the HEMP-T cluster have been carried out in the framework of an ESA-TRP project (ESTEC Contract No.20019/06/NL/SFe). The authors thank EADS Astrium Satellites GmbH and Thales Alenia Space ETCA for the opportunity to perform PSCU coupling tests. We also thank OHB System AG and EADS Astrium Toulouse for their contributions and support for the system layout and cost calculation aspects.

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