High Specific Impulse Solutions for Orbit Raising, Orbit Topping and Station Keeping with the HEMP-T Electric Propulsion System

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Abstract: The recently evolved demand for commercial all-electric telecommunication satellites changes the requirements of current electric propulsion systems (EPS), such that on the one hand high thrust at maximum available power is provided during orbit raising to minimize transfer time and radiation exposure and on the other hand high specific impulse is available for payload maximization during the station keeping phase. These different modes of operation are mutually exclusive: none of the current commercially available EPS can provide these two modes with only one type of thruster. The flexibility and long life of the HEMP-T make it the ideal basis for an EPS capable of operating at both these modes with the same thruster. The HEMP-T capability of operating anywhere between 500V and 1kV with a throttleability of the anode power from 500W up to 3kW enables this unique option. The HEMP-T based EPS is currently under qualification for in-orbit verification on the SGEO HAG1 mission in course of the HEMP-TIS program. Only minor modifications to the current hardware, in order to allow increased power throughput, will be necessary such that effort and time for a delta-qualification is minimized. Additionally a clustering of the modified thruster increases reliability and lowers cost.

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Nomenclature

$PTTR$ = power to thrust ratio (W/N)
P = power (W)
T = thrust (N)
U_{eff} = effective acceleration potential (V)
M_{prop} = propellant atomic mass (kg)
α_{eff} = effective exhaust angle (°)
Isp = specific Impulse (s)
$\dot{m}_{prop}$ = propellant massflow (kg/s)
g = earth constant of acceleration (m/s^2)

I. Introduction

Thales Electronic Systems currently develops and qualifies a novel type of ion propulsion system based upon the High Effiency Multistage Plasma Thruster HEMP-T. In course of the HEMP-TIS project (HEMP-Thruster In Orbit Verification on SmallGEO) the German Aerospace Centre (DLR) funds the development and qualification of this propulsion system for the SmallGEO HAG1 mission with the purpose of North/South and East/West station keeping.

Since the Announcement of Boeing in 2012 to having acquired a contract to build four all-electric satellites, the 702SP, and the European's reaction with Electra within the ESA Artes 33 framework, there is an increased interest in electric propulsions systems (EPS) which are not only capable of station keeping but can also provide the transfer into geostationary orbit. Additionally the trend towards increased satellite launch mass calls for higher thrust and total impulse requirements. The simplicity, robustness and flexibility of the HEMP-T technology provides excellent adaptability and makes it an ideal thruster candidate as a basis for an electric propulsion system for these new demands with minimal changes to the system and its qualification status.

This paper will describe the possibilities and advantages of an EPS for an all-electric satellite based upon the HEMP-Thruster. To achieve this, a description of the EPS components for HEMP-TIS is provided first, after which the requirements for orbit raising/topping and station keeping are discussed. This results in the proposed EPS configuration based upon the HEMP-T, operated in two separate modes with each specific performance characteristics.

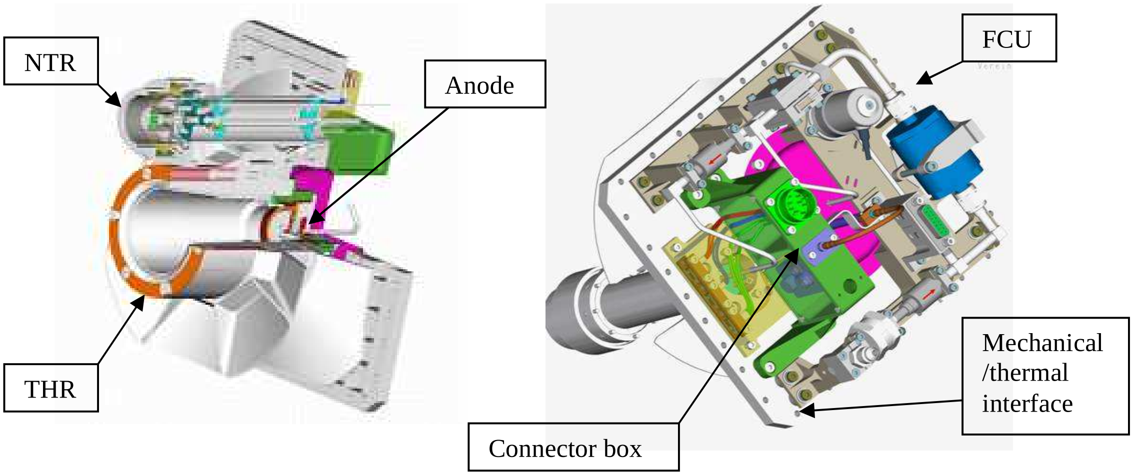

Figure 1. Location of all vital components of the HTM-3050 as designed within the framework of the HEMP-TIS program.

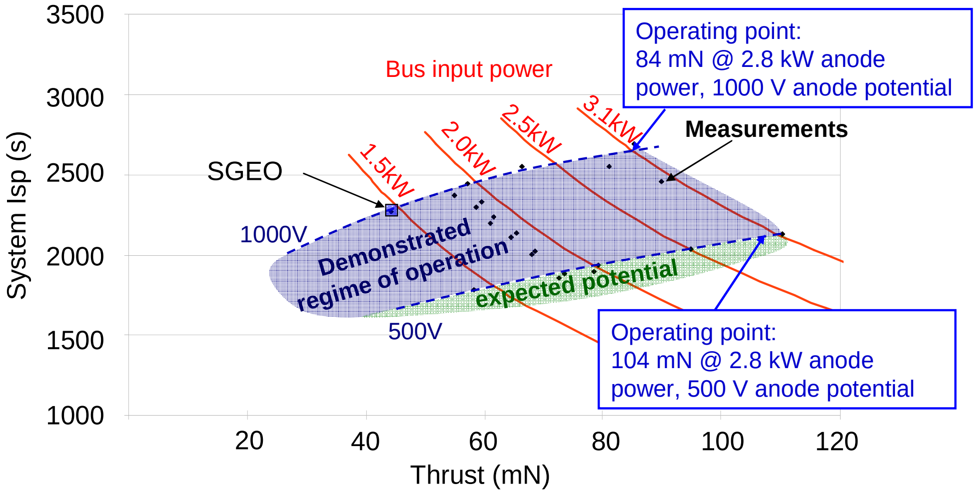

Figure 2. The demonstrated regime of operation for the HEMP-Thruster Module ranges from 500W to 3kW and from 500V to more than 1kV.

II. HEMP-T Qualification Hardware for SGEO HAG1

The HEMP Thruster Assembly (HTA) which is to be qualified in course of HEMP-TIS comprises of one Power Supply and Control Unit (PSCU) and four HEMP Thruster Modules (HTM). Each HTM contains the following components: one HEMP-Thruster, one neutralizer HCN5000, one Flow Control Unit (FCU) and one electrical connector box, all mounted upon a single mechanical structure which acts as the thermal and mechanical interface to the satellite, see Fig. 1.

The HEMP-Thruster consists of a dielectric discharge channel surrounded by a permanent magnet system where the axially magnetized ring magnets are orientated in opposite direction: the periodically arranged permanent magnet system (PPM system)[1]. The downstream end is open whereas at the upstream end the anode is located. The anode assembly provides the acceleration voltage and acts as the propellant inlet. The magnetic topology of the PPM system causes a magnetically confined plasma to be generated within the discharge channel as soon the high voltage is applied and an ionizable gas is present within the discharge channel. One of the key characteristics of the HEMP-T is that no discharge or leak current will occur when the high voltage is applied to the anode, but no gas is present inside the discharge channel. This enables the configuration as used for SGEO HAG1, where all thrusters are connected to a common anode potential. In this case all thrusters are energized but do not draw power or produce thrust until gas is fed through the FCU into the thruster. This characteristic is especially useful in configurations where only one thruster is active at a time, such as is the case for an EPS for station keeping. From the point of thruster ignition the HEMP-Thruster exhibits a very smooth current ramp-up, this is due to the linear relation between the propellant influx, the anode current and the generated thrust. This means a very precise control of the thrust level is possible by control of the propellant flow. The HEMP-Thruster has already displayed a stable field of operation for a wide variety of anode potential[2] from 500V up to more than 1kV and anode currents from 0.3A to 9A, see Fig. 2. This flexibility combined with an erosion-free discharge channel opens up a wide variety of applications for the HEMP-T.

The HCN5000 Neutralizer is based upon the extensive cathode flight experience of the Thales traveling wave tubes (TWT) with more than 500 million accumulated hours in space. The Thales Barium impregnated Tungsten-Osmium mixed-metal matrix life is mainly determined by the cathode temperature[3]. This dependency has been extensively researched for the TWT cathodes and a life prediction model was verified. The HCN5000 runs at temperatures well below 1000°C and has a life prediction of over 100 kilohours[3,4]. The HCN5000 is capable of a nominal neutralization current of up to 5A. An important feature of the Thales cathode is that the keeper ignition voltage is around 17 Volts, such that no high voltage puls is required to ignite the keeper discharge and thus power supply complexity is reduced. Like any Barium impregnated hollow dispenser cathode also the Thales cathode is sensitive to humidity. For this reason an extensive storage qualification was successfully performed to ensure the life capability of the cathode even after exposure to air for extended periods of time during the MAIT phase and waiting time on the launch pad within the launcher fairing[3].

The FCU feeds xenon propellant to both the thruster and the neutralizer. The FCU inlet contains a two-micron inlet filter followed by an isolation valve, after which the mass flow is separated into neutralizer and thruster feed lines, both limited by flow restrictors. The neutralizer line includes an exit isolation valve and a getter for oxygen, water, carbonic oxides, non-methane hydrocarbons and hydrogen[5], to prevent these contaminations from reacting with the hot cathode during operation. The thruster line is defined by a flow control valve instead of an isolation valve. The current to this proportional valve is supplied by the PSCU, through a PID controller in which the thruster current acts as the feedback signal; this is possible due to the linear proportionality of the anode current with respect to the propellant throughput. The advantage of the proportional valve is a very exact control over the thruster current and thus its thrust. Through this valve the FCU enables throttling capability of the thruster anode current and thus the thrust down to 20% of its nominal operational point.

The PSCU has a modular design and provides the low voltage power forms for up to four neutralizers and FCU's simultaneously, as well as the high voltage power form to all thrusters simultaneously, through a common anode line. The PSCU incorporates two high voltage modules, each capable of providing 1.4 kW. For SGEO HAG1 the second module is used in cold redundancy, multiple thrusters could however be operated simultaneously, providing 2.8 KW to one thruster, or distributed over several thrusters. Distribution over several thrusters is possible through the Anode Current Measuring Unit (ACMU), which contains a sensing channel for each thruster. Control over thruster firing sequences, telemetry acquisition and failure handling is performed by the PSCU ICAU module, minimizing the control efforts required on the spacecraft bus side[6].

III. Orbit Raising, Orbit Topping and Station Keeping

Orbit raising and orbit topping are maneuvers to position a satellite in its final orbit, where orbit raising uses only EP from injection orbit to target orbit and orbit topping is performed by a combination of chemical propulsion and EP. Whereas these orbit maneuvers can be absolved within a few orbits by chemical propulsion, the application of EP and thus reduced thrust values by a few orders of magnitude brings one main restriction into focus: the transfer time. A longer transfer time has two effects: the longer a satellite takes to reach its final position the longer it takes for the satellite operator to reach its return of invest: depending on the injection orbit transfer times can take 60 to more than 100 days. Additionally, as long as a satellite is injected with the orbit perigeum below 10.000 km each orbit takes the satellite through the lower Van Allen Belts[7,8]. This region, populated by high energetic protons, has a degrading effect on satellite electronics and reduces the power output of the solar arrays. For this reason the duration and orbits at these regions should be kept at a minimum. For the duration of the orbit transfer the full satellite electrical power is available to the EPS minus the power required for housekeeping and thermal control, the logical conclusion is to maximize the thrust with respect to the available power und thus reduces the transfer time. The available power, dependent upon the satellite size, ranges from 5kW to more than 15kW.

Station keeping, when compared to orbit raising or topping, is the opposite. Although a minimum thrust level is required to keep the maneuvers around the orbital nodes efficient, the available power is limited by the EOL available power and the power demand from the commercial payload, meaning a low power-to-thrust ratio (PTTR) would be beneficial. The total impulse requirement for station keeping is approximately equal to the amount needed for the orbit raising, the time factor however is no longer critical. For this reason increased propellant efficiency leads to increased mass for more transponders or reduced satellite wet mass. Increasing the anode potential for station keeping would increase the thruster's exhaust velocity and thus higher specific impulse (Isp) than a thruster for orbit raising. The downside is that both a low PTTR and high Isp are mutually exclusive, this is seen from comparing eq.(1) with eq.(2).

$$PTTR = \frac{P}{T} \propto \sqrt{\frac{U_{eff}}{M_{prop}}} \cdot \cos\alpha_{eff} \tag{1}$$

$$I_{sp} = \frac{T}{\dot{m}_{prop} \cdot g} \propto \sqrt{U_{eff}} \cdot \cos\alpha_{eff} \tag{2}$$

In conclusion, an EPS used for both orbit raising, topping and station keeping is forced to comply with two different sets of performance requirements, for orbit raising high thrust performance is needed whereas for station keeping a high Isp is desirable as long as the minimal thrust is guaranteed.

IV. The HEMP-T Solution for Orbital Maneuvers

The unique ability of the HEMP-T to perform in a wide operational range, with high thrust on the one hand and high Isp on the other, makes it the ideal technology as a basis for the EPS to perform both the orbit raising maneuver as well as station keeping with the identical type of thruster. This approach removes the necessity for the expensive development of different types of thrusters, increases production volume and thus reduces costs.

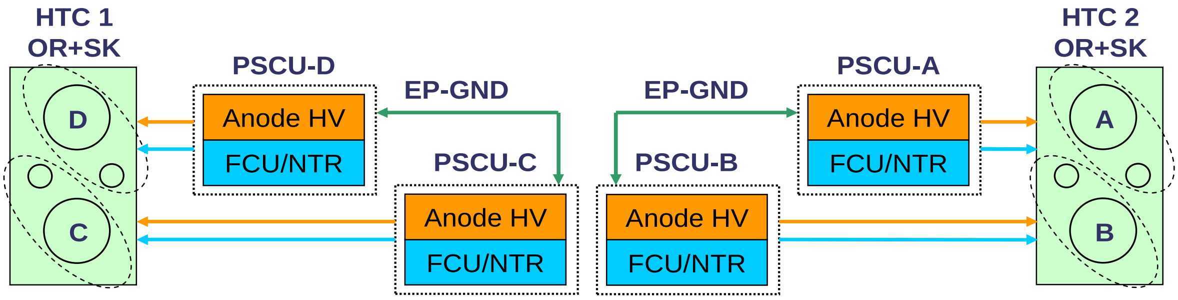

Figure 3. Schematic of a HTC based EPS where both orbit raising and station keeping are performed with the same set of thrusters and PSCUs. The HTCs are mounted upon TOMs.

Thales proposes an EPS based on the HEMP-Thruster, where multiple thrusters are clustered together for high power throughput. Mounting of such a HEMP-Thruster Cluster (HTC), see Fig. 5, on a Thruster Orientation Mechanism (TOM) would enable the system to perform both the orbit raising/topping as well as the consecutive station keeping in north/south and east/west direction, including momentum wheel offloading, see Fig. 3. Due to the long neutralizer life and the absence of erosion of the HEMP-T discharge channel, verified by the 8000h endurance test results on the HTM 3050, no life-limiting effect could be determined and thus it is believed the amount of total impulse (depending on the satellite mass this ranges around 3MNs) can be provided by an EPS based upon the HEMP-T. Alternatively the TOM can be omitted by doubling the number of thrusters, but using the same amount of PSCUs, coupling one orbit raising thruster and one station keeping thruster to the same anode line, see Fig. 4. The station keeping thrusters can also be mounted separately such that four separate orientations can be accommodated.

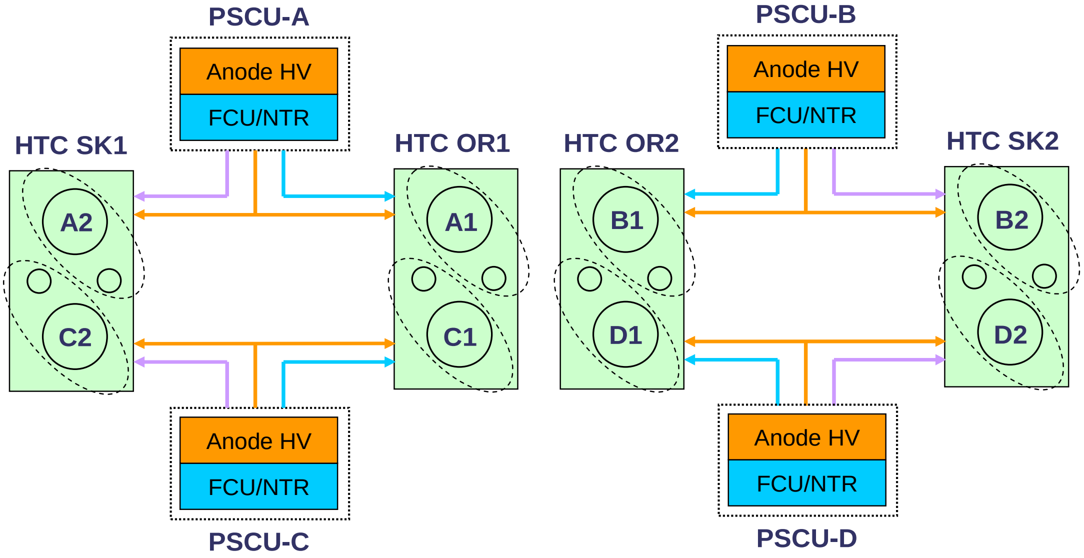

Figure 4. Schematic of a HTC based EPS where orbit raising and station keeping are performed with the same set of PSCUs, but separate sets of thrusters, removing the need for TOMs

A HTC comprises of at least 2 thrusters where each thruster is powered by a single PSCU at an anode input power of up to 2.8kW. The neutralizers are positioned close to each other, in between the thrusters, to allow the option of cross-neutralization of one neutralizer with any other thruster. The thrusters are based upon the HEMP-T 3050, but modified in order that they are operated at an elevated thrust level. The modification involves an increase of the thruster radiator size, such that the magnet system is kept within the same thermal regime as it is the case for the SGEO HAG1 mission. Minor modifications to the FCU will result in a necessary increased propellant throughput while retaining the heritage design. The necessary changes are the flow resistance of the flow restrictors and the orifice size of the FCV. The current high voltage module of the PSCU will have to be adapted to accommodate at least two anode voltage setpoints as well as enable an increase of the available anode power. The neutralizer is designed for a 5A neutralization current, but an increase to 5.6A is believed to be possible without modification.

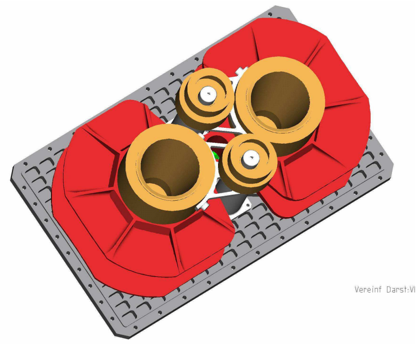

Figure 5. Design study of the dual thruster HTC

The HTC would have at least two separate points of operation. For orbit raising/topping each thruster would provide a maximum thrust of 104mN at 2200s Isp by operating at 2.8kW anode power at 500V, therefore a HTC with 2 thrusters would, including neutralizers and FCUs, provides 208mN of thrust at 2000s system Isp at 6.2kW PSCU input power. The thrust and thus the input power can be continuously reduced in case less power is available on the spacecraft bus side. In case more thrust is necessary and more power available an HTC with 3 thrusters can be chosen. For station keeping at least 2 HTCs are required with a total of four thrusters. An even number of thruster has the advantage that thrusters can be assembled with opposite magnetic field orientation, thus the permanent magnets do not cause magnetic momentum upon the satellite. During station keeping a high Isp is preferred over high thrust, therefore once the target orbit is reached the PSCU switches the output voltage to 1000V and drives the thrusters at their high Isp operational point. In this case each thruster provides 84mN of thrust at 2900s Isp with an anode power of 2.8kW. Only one thruster, neutralizer and FCU is operational per HTC, leaving the second set as cold redundancy, thus improving reliability. When a higher total thrust is required the second thruster can be operated, also at a reduced thrust level to better match the available power.

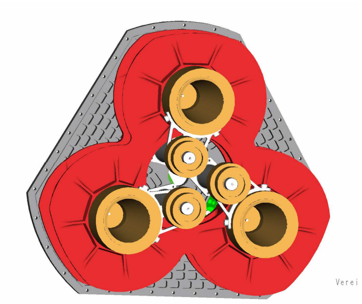

Figure 4. Design study of the triple thruster HTC

V. Conclusion

With the HTC Thales aims to provide a multi-use EPS for both orbit raising/topping and station keeping. A dual-mode PSCU can drive the thrusters at 500V or 1kV, therefore providing maximum thrust for the orbit raising/topping maneuver while enabling high mass efficiency for the station keeping phase. This way minimum orbit transfer time is combined with maximum payload mass.

Both required functionalities of high thrust at moderate Isp or high Isp at moderate thrust are made available by the unique feature of the HEMP-T of stable operation through a vastly variable anode voltage and power range. The high life prediction of the HEMP-T due to the erosion free discharge channel makes it possible to perform both types of maneuvers with the exact same thruster, thus negating the need for a second EPS or having to accept loss of time and/or mass efficiency. Alternatively qualification time and cost can be reduces by using a second set of thrusters for the station keeping phase, yet reusing the PSCUs by coupling each orbit raising/topping thruster with one station keeping thruster. This configuration would eliminate the necessity of a TOM.

Although a thermal redesign of the thruster, minor changes to the FCU and adaptation of the PSCU are required to enable the increased power output, most of the HEMP-T qualification for SGEO HAG1 will apply. Using the HEMP-T 3050 as the basis for the HTC and applying clustering instead of newly developing high power thrusters, combined with powering each thruster with a dedicated PSCU, severely reduces complexity, development time and cost, as well as increases production volume and reliability.

Due to the unparalleled flexibility of the HEMP-T Thales offers with the HTC a novel EPS solution for all-electric satellites for both orbit raising and station keeping at low cost and low complexity, yet maximum efficiency with regard to transfer time and available payload mass.

Acknowledgments

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