Scalability of the HEMP-T technology for station keeping and orbit raising

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B. van Reijen[1], A. Lazurenko[2], S. Weis[3], R. Heidemann[4], J. Haderspeck[5], A. Genovese.[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: The HEMP-Thruster technology is reaching maturity through the qualification within the HEMP-TIS project, funded by the DLR. The HEMP-T 3050 has shown remarkable flexibility in the range of operation in terms of applicable anode voltage and current. A demonstrator model of the HEMP-T 30250 was developed through an ESA TRP and exhibits a similar throttleability and anode voltage flexibility.

The development of a multi-purpose thruster, which can be applied to a wide range of scenarios such as EOR and SK as well as space transportation means or science missions, capable of dual-mode operation would greatly reduce development, qualification and production costs.

Measurements were taken on the HEMP-T 3050 and HEMP-T 30250 and showed remarkable constant behavior of these differently sized thrusters with respect to performance parameters such as the power-to-thrust-ratio and specific impulse. Despite the geometrical difference in discharge channel diameter both thrusters exhibit a smooth transition of these parameters and thus a linear scaling of the thrust from 45mN to 220mN with the specific impulse ranging between 1700s and 3000s. This result underlines the flexibility, throttleability and scalability of the HEMP-Thruster technology.

Clustering of two HEMP-Thrusters could be a cost-effective alternative to the development of new thrusters. HEMP-Thruster tests in close proximity on a common floating ground proved successful and demonstrated stable operation, no performance degradation, virtually no cross-neutralization and ease of operation.

[1] Components R&D Manager, Plasma Devices, benjamin.reijen@thalesgroup.com.
[2] Testing Manager, Plasma Devices, alexey.lazurenko@thalesgroup.com.
[3] System Engineering Manager, Plasma Devices, stefan.weis@thalesgroup.com.
[4] Components Developer, Plasma Devices, ralf.heidemann@thalesgroup.com.
[5] System Engineer, Plasma Devices, jens.haderspeck@thalesgroup.com.
[6] Testing Engineer, Plasma Devices, angelo.genovese@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

Nomenclature

CC	=	Conduction Cooled
DLR	=	Deutsches Zentrum für Luft- und Raumfahrt
EM	=	Engineering Model
EOR	=	Electric Orbit Raising
EUT	=	Equipment Under Test
HEMP-T	=	High-Efficiency-Multistage-Plasma-Thruster
PTTR	=	Power To Thrust Ratio
RC	=	Radiation Cooled
SK	=	Station Keeping

I. Introduction

ELECTRIC propulsion for satellites can be applied in the field of station keeping and orbit raising, ranging from small scientific to large geostationary telecommunication satellites. The power available for the propulsion system of such satellites varies greatly with its purpose and size, from a few watts to tens of kilowatts. The success of a multi-purpose electric propulsion thruster technology is based upon the scalability of this technology with respect to the available power input range.

Thales has developed and is currently qualifying the HEMP-T 3050 (High Efficiency Multistage Plasma Thruster) for the application of station keeping for small geostationary satellites within the HEMP-TIS project[1,2], funded by the DLR. This thruster provides 44mN of thrust at 2800s specific impulse, for an anode input power of 1.38 kW, but has shown stable operation at a wide field of operation, ranging from 300W up to 2.8kW at various parameters of the discharge current and anode voltage. From previous investigations it was already known that the HEMP-T 3050 exhibits negligible discharge channel erosion, resulting in a high lifetime expectation. Moreover an 8000h endurance test has shown stable performance throughout the test campaign. Upscaling of the HEMP-T 3050, while maintaining the high lifetime property, the performance parameters and wide range of operation, is the best prerequisite for a multi-use product line covering a wide range of input power. Additionally a clustering of 2 or more thrusters could be a cost-effective alternative to expensive and time-consuming development and qualification of thruster models.

This paper discusses the test campaigns with the HEMP-T 3050 and HEMP-T 30250 and their results, with special regard to the scalability of the HEMP-Technology.

II. Dual-mode and upscaling

The flexibility of the HEMP technology was demonstrated on the HEMP-T 3050[3,4], which has shown stable operation between anode voltages of 400V and 1kV, between 0.3A to 5.6A. Although the RC thermal design of the

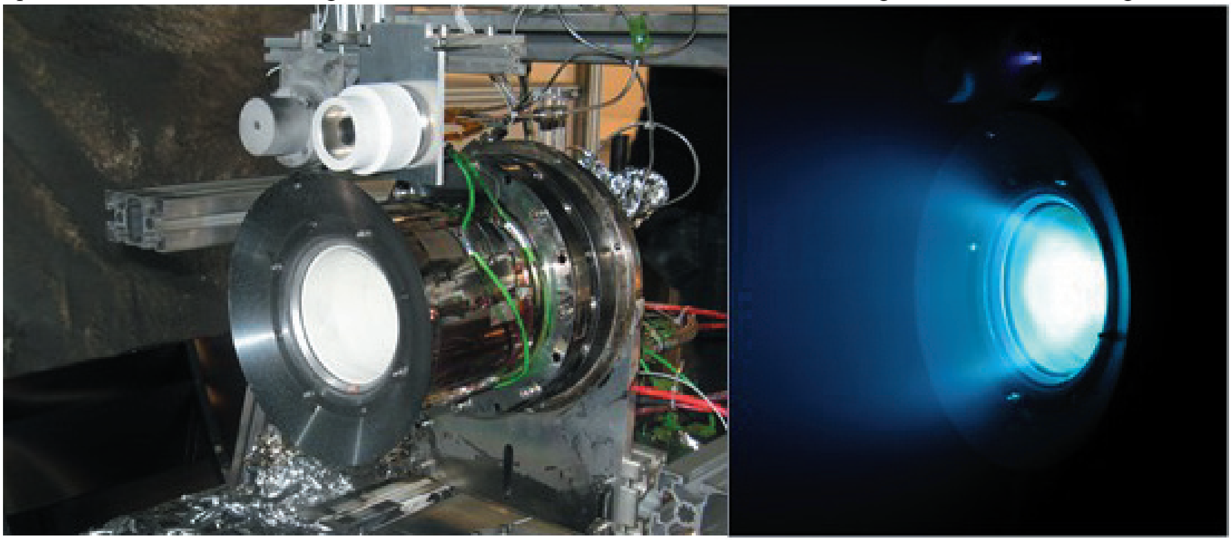

Figure 2.1. HEMP-T 30250 installed in the vacuum chamber (left), in operation (right).

3050 is limited to 1.4kW, this wide performance range enables the HEMP-T to offer dual mode operation, consisting of high specific impulse at medium thrust for station keeping or high thrust at medium specific impulse for high thrust applications such as EOR and deorbit maneuvers.

The HEMP-T 3050 was intended for small geostationary satellites up to 3 tons, yet it can be operated at a higher power operating point: at an anode input power of 2.8kW this thruster provides 84mN of thrust and is suitable for SK of satellites in the 6 ton range. Although the increased anode power requires an upscaling of the radiator, the magnetic field topology of this upscaled HEMP-T 3050 is identical to that of the HEMP-T 3050. For this reason only a thermal redesign is required, lowering development and qualification risk and cost. In addition to the higher power point of operation this thruster would provide dual mode capability by lowering the anode voltage from 1kV to 500V, therefore enabling EOR at 110mN of thrust for smaller geosats and constellations[4].

An extension of the power range up to 10kW anode power is covered by the larger HEMP-T 30250[5], see Fig. 2.1, of which a CC version was developed under an ESA TRP. This thruster covers anything between 2.8 and 10kW, between 400V and 1kV, providing up to 320mN of thrust. This covers EOR and SK for large geosats as well as future space transportation and scientific missions.

An alternative to upscaling, yet able to increase the thrust output without the necessity to develop and qualify a new type of EP thruster is to cluster multiple engines together[5]. This is a potentially cost-effective scaling of the power throughput, but thruster-thruster interaction and issues such as cross-neutralization need to be investigated and, if present, resolved. The HEMP-Thruster technology exhibits a few features which reduce the risk of potential compatibility issues as well as ease the thruster start-up. The presence of the permanent magnetic field effectively blocks electron currents to the anode in the absence of propellant within the discharge chamber. For this reason two thrusters can be attached to a single anode potential and yet start and stop the thrusters independently by regulation of the propellant influx without leak currents from the one cathode to the adjacent thruster. Such a system topology would enable a seamless transition from low thrust to high thrust application, thus maximizing thrust flexibility.

III. Test Description

In order to verify the scalability of the HEMP-Thruster technology under representative conditions, a test campaign was conducted at AEROSPAZIO Tecnologie s.r.l. in a 120m^3 vacuum chamber with a pumping speed up to 200.000l/s for Xenon[6]. During operation of the thrusters the resulting chamber pressure is maintained between $2x10^{-6}$ mbar and $1x10^{-5}$ mbar for Xenon. The EUT consisted of a RC HEMP-T 3050 EM and a CC HEMP-T 30250.

The HEMP-T 3050 was operated from 500W up to 2.8kWat various anode voltages and propellant flows. Since the radiator of the HEMP-T 3050 is designed for an anode input power of 1.4kW, the thruster was operated in thermal transient up to 1h for powers exceeding this value. The thruster was operated in both grounded and floating operation. A thermal shroud provided the ambient thermal environment and protected the thruster from sputtered material from the vacuum chamber in order not to have the thermo-optic characteristics of the radiator changed by deposited material, see Fig. 3.1. The HEMP-T 3050 EM is identical in form and function as the qualification and flight models for the HEMP-TIS project.

The CC HEMP-T 30250 was operated between 2.8kW and 6kW. Although the HEMP-T 30250 is ill-suited for operation in the 2.8kW regime due to its size and therefore its weight, it allows a seamless comparison between two very differently sized magnet systems. This enables an analysis of the scalability and throttleability of the HEMP-Technology. The Thruster was also operated in grounded and floating mode, a thermal shroud was not required due to the water cooling at the thruster baseplate.

Additionally a test was performed with two HEMP-T 3050 EM models, installed within the vacuum chamber at close proximity to each other and operated on the same EP-ground potential. One thruster was mounted on a thrust balance for performance monitoring.

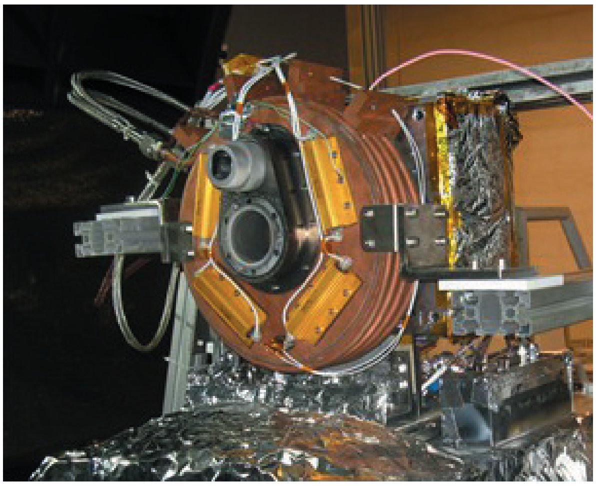

Figure 3.1. A HEMP-T 3050 EM mounted upon the thrust balance and surrounded by a protective shroud

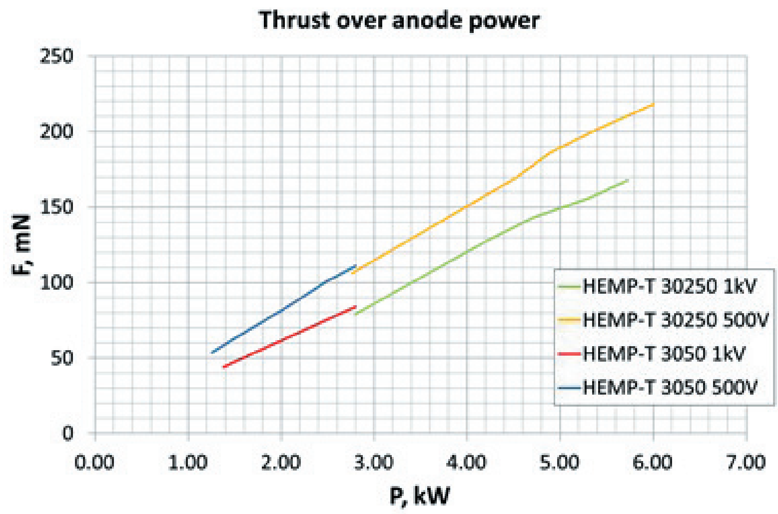

Figure 4.1. Measured thrust as a function of the anode power for two thrusters at two anode potentials each.

IV. Results

The results of the measurements on the HEMP-T 3050 and 30250 are given in the following graphs. Fig. 4.1 displays the dependency of the thrust on the applied anode power for both the HEMP-T 3050 and HEMP-T 30250 for an anode voltage of 500V and 1kV. It is clear from Fig. 4.1 that at the transition point of 2.8kW the thrust levels of the HEMP-T 3050 and HEMP-T30250 are very similar despite the large difference in discharge channel diameter and therefore (at equal current level) mean plasma density. It can also be deduced from the graph that the thrust has a linear dependence on the power (and thus the current), meaning a constant PTTR resulting in excellent throttleability for not only a single thruster, but various types of HEMP-Thrusters. This also shows the exceptional good scalability of the fundamental operation principal of the HEMP-Thruster family.

Fig. 4.2 shows the variation of the specific impulse over the applied anode power. Again both types of thrusters are shown for 500V and 1kV anode voltage. For both the 500V and 1kV anode potential measurements the specific impulse increases with increasing anode power and thus anode current. This is likely due to increased ionization yield, which shows increased propellant utilization. The 500V curve attaches smoothly at 2.8kW, displaying equal

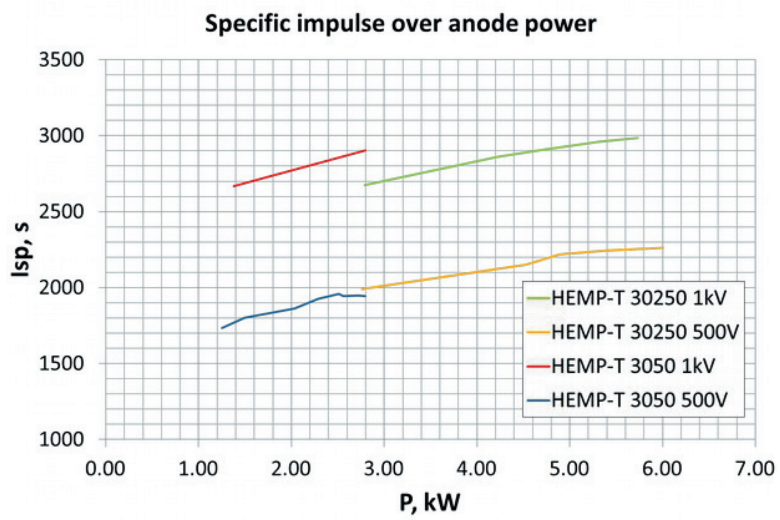

Figure 4.2. Specific impulse as a function of the anode power for two thrusters at two anode potentials each.

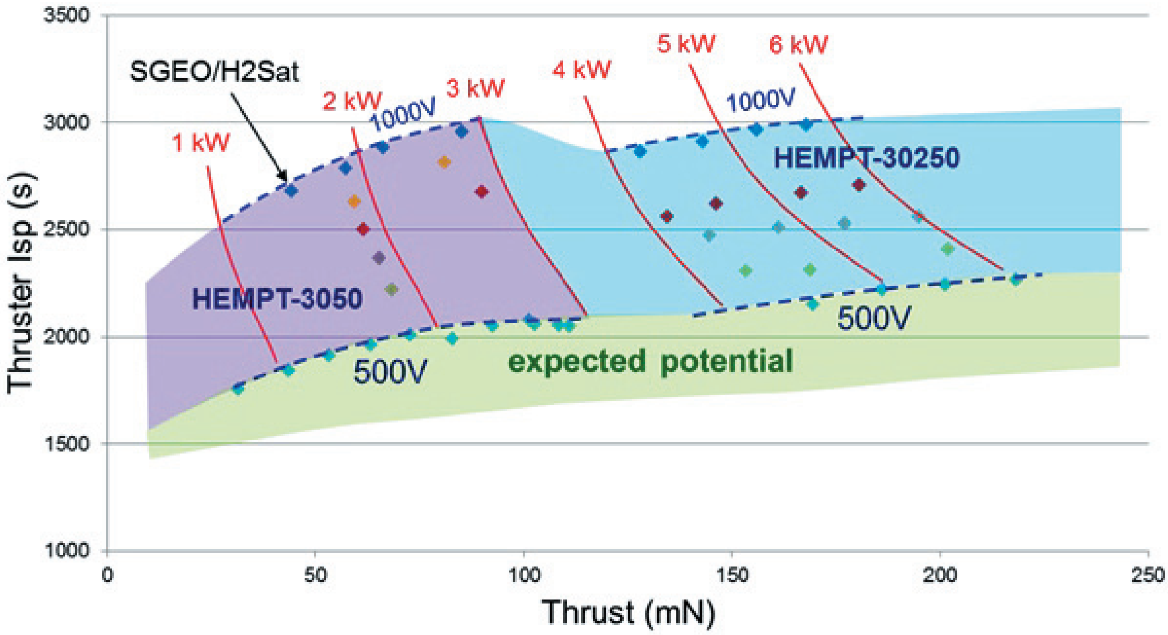

Figure 4.3. Measurement points within the stable range of operation for the HEMP-Thruster technology. The lines in red show the isolines of applied anode power, blue lines indicate isolines of applied anode voltage.

propellant mass efficiency for both thruster types, here a switch from a smaller to larger discharge channel has no noticeable effect on the ionization yield. As fundamental physics laws dictate at 1kV anode voltage the specific impulse is larger than at 500V, here however the function is discontinuous at the transition from the HEMP-T 3050 to the HEMP-T 30250. This discontinuity might rise from the effect caused by the reduced mass flow at high anode voltages: at 1kV the anode current and propellant flow into the discharge channel is about half in respect to the 500V values for the same power throughput. This reduced flow by a factor of two, combined with the larger discharge channel of the HEMP-T 30250 causes that the neutral particle densities within the discharge channel is lower than those within the HEMP-T 3050, as well as lower than for the 500V anode potential curves. This might result in non-optimal discharge conditions and therefore this could lead to lower ionization yield. To reach the same mass utilization and a specific impulse of 2800s as the HEMP-T 3050 at 2.8kW, the HEMP-T 30250 needs to be operated at 4.8kW and above. This could indicate that the HEMP-T30250 is oversized in term of propellant efficiency for an anode power below 4.8kW.
In Fig. 4.3 the specific impulse over thrust is displayed for measurement points of both thrusters in their respective valid range of operation. For an upscaled or downscaled HEMP-T 3050 this is between 500W and 2.8kW, for the HEMP-T 30250 this is between 4kW and 6kW although values up to 10kW are possible.

The variation of grounded versus fully neutralized mode showed no change in thruster stability and performance characteristics for either thruster.

The dual-firing test, see Fig. 4.4, of two HEMP-T 3050 in close proximity to each other on a common EP-ground potential demonstrated stable operation of both thrusters without performance degradation. The thrusters were at floating potential and the cathodes fully neutralized the ion beams at a low cathode-to-ground potential. The current between both cathodes was less than 20mA, indicating no issues due to cross-neutralization. Individual thruster start-up and shut-down were smooth and similar to the performance of a single thruster.

V. Conclusion

The results from chapter 4 show a linear dependency between thrust and anode input power. More importantly the transition from the HEMP-T 3050 to the HEMP-T 30250 is remarkably smooth, despite the geometrical differences of the magnet system and discharge channel between both thrusters. The linearity of the thrust for each thruster separately shows the excellent throttleability of the HEMP-Thrusters, the smooth transition between the thrusters underlines the scalability of the HEMP-Thruster technology. The specific impulse exhibits the same smooth transitions for higher mass flows; for lower propellant mass flows however a discontinuity in the specific

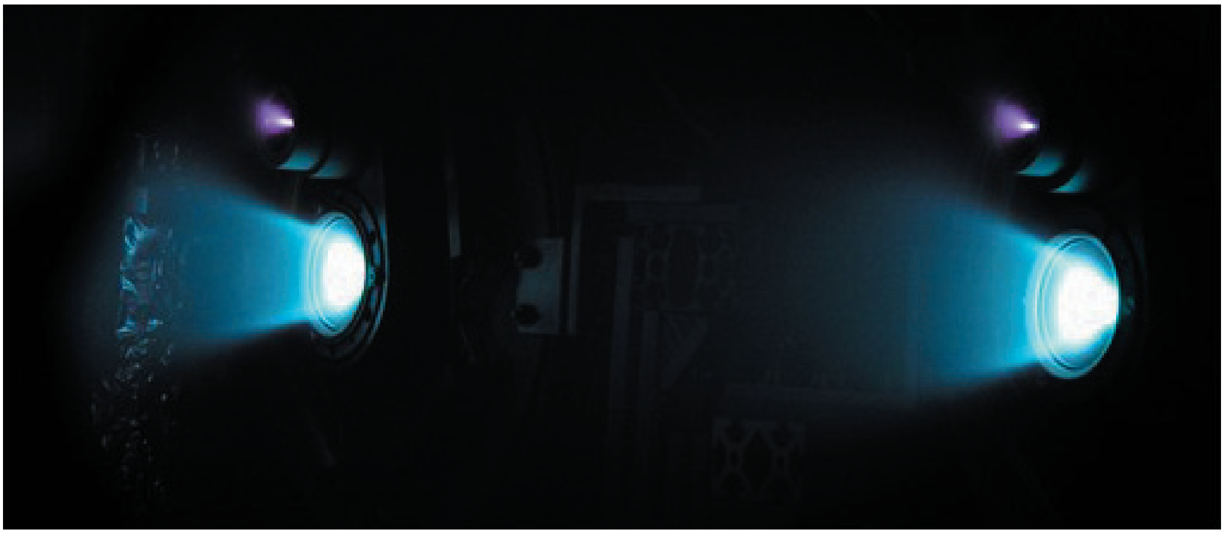

Figure 4.4. Parallel operation of two HEMP-Thrusters in dual-firing mode.

impulse function at the transition between both thrusters indicates that for this application the HEMP-T 30250 is oversized and an intermediate version would provide better ionization efficiency at the operating point between 2.8kW and 4.5kW. Since the HEMP-T 30250 is targeting the 4kW to 6kW power range with the ability to go up to 10kW, this discontinuity is only a minor downside.

In general it can be said that the type of behavior as observed from the HEMP-T 3050 and HEMP-T 30250 is ideal for a multi-purpose and dual-mode operation. The flexibility, throttleability and scalability are clear strengths of the HEMP-Thruster technology and are specifically shown by the measurements taken on both these thrusters under representative vacuum conditions.

Additionally it can be said that clustering of HEMP-Thrusters can be a cost-effective solution to an extensive range of thrust levels. The ease of operation, the absence of thruster-to-thruster interaction and cross-neutralization provide a wide range of applications for the HEMP-Thruster technology.

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