HEMPT Strategy to address current and future Space Market

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Abstract: Thales began in the late 90's with the development of the HEMPT (Highly Efficient Multistage Plasma Thruster) concept. Since then, a thruster design has been qualified and has seen an extended life test. The first flight units were manufactured for the German Heinrich Hertz satellite, to be launched in 2021. Many successful improvements were incorporated throughout its development, highlighting the unique advantages (such as flexibility, extended lifetime, large throttle ability range, simple and cost effective design, using different propellants without any modifications) of the HEMPT technology. Following these achievements, Thales was selected for the European EPIC program. Today, Thales is able to deliver HEMPT thrusters or complete HEMPT based EP systems for satellite applications from LEO to GEO. New markets and exciting possibilities are being investigated in collaboration with customers. HEMPT has many benefits for different market segments thanks to its unique abilities. This paper will discuss ~~the~~ HEMPT's unique capabilities (krypton usage, cost effectiveness, flexibility and long lifetime and high total impulse) based on customers' needs and perceived value. We will analyze each electric propulsion market segment, and review the most important value drivers. Following this analysis, we will confront HEMPT differentiators to those market drivers and review HEMPT positioning for each market segment. To conclude, we will highlight the main value proposition of HEMPT.

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Nomenclature

HEMPT = *Highly Efficient Multistage Plasma Thruster*
HET = *Hall Effect Thruster*
GIT = *Gridded Ion Thruster*
GEO = *Geostationary Earth orbit*
MEO = *Medium Earth orbit*
LEO = *Low Earth orbit*
OR = *Orbit Raising*
SK = *Station Keeping*
EOL = *End-Of-Life*
TTPR = *Thrust to power ratio*
ISP = *Specific impulse*
mN = *Micro-Newton*
Ns = *Newton-seconds = unit of total impulse*
ppm = *parts per million*
TWT = *traveling-wave-tube*

I. Introduction

Thales Microwave and Imaging Subsystems business line has developed and qualified a completely new type of ion propulsion for satellites, the HEMPT (Highly Efficient Multistage Plasma Thruster) technology. First conceptualized in the late 90's, HEMPT is a unique technology based on permanent magnets for ions confinement and on a clear separation between ionization and accelerations zones.[3] This technology was derived from the Traveling-Wave-Tube technology developed and mastered by Thales for the past 40 years.[4]

Based on this technology, Thales has developed the HEMPT 3050 thruster for DLR's program HEMPT-TIS. Fully qualified in 2018, this first product is intended to provide high-ISP station keeping for small GEO satellites. Thales is also in charge of providing a complete system of propulsion, including power supply and fluidics. This so-called HEMPT Assembly (HTA) is being integrated on OHB's SmallGEO geostationary satellite platform to perform altitude and orbit control maneuvers.

Following the success of the first product development and the unique benefits of the HEMPT propulsion system, HEMPT was selected by the different spaces agencies (ESA, DLR) and European commission as one of the three major EP technologies for the EPIC program. Thales is leading the HEMPT-NG consortium for HEMPT products.

II. HEMPT products & differentiators

Thales' HEMPT is a unique class of thrusters, combining several advantages and properties from other technologies like HET, GIT and other less mature technologies. In this article, we will compare technologies in a general way, but also products and current state of the art thruster manufacturers, to highlight the differentiators of each technology.

[3] H.-P. Harmann, N. Koch, G. Kornfeld: "Low Complexity and Low Cost Electric Propulsion System for Telecom Satellites Based on HEMPT Thruster Assembly", 30th International Electric Propulsion Conference, Florence Sep. 2007, Paper 114.
[4] N. Koch, G. Kornfeld, H.-P. Harmann: "Physics and Evolution of HEMPT Thrusters ", 30th International Electric Propulsion Conference, Florence Sep. 2007, Paper 108.

A. Differentiators

HEMPT technology has been considered for several years as a serious and competitive alternative to the two "well-adopted" EP technologies, HET and GIT. Thanks to some of its unique advantages, Thales expects HEMPT to become the baseline for EP systems in the future. While HET has the high TTPR and the GIT has the high ISP, the HEMPT can be operated in dual mode. This flexibility drives the HEMPT between HET and GIT for an "average" comparison. However, with adapted working point, HEMPT can reach a TTPR similar to HET as long as an ISP similar to GIT.

We can group the HEMPT key advantages in four categories:

- **Reliability**
  - HEMPT cathodes are based on Thales MIS expertise of TWTs. Thales TWTs account for more than a billion hours of operation in space, with more than 23.000 TWTs delivered. Thales' cathodes are very reliable.
  - HEMPT3050, as a technology demonstrator, passed its qualification for GEO ESK mission.[5] Internal studies today demonstrated a theoretical reliability of over 99.9% for EV0.

- **Performance stability**
  - Thanks to ~~the~~ permanent magnets, HEMPT has zero erosion inside the discharge channel and very small erosion on the exit. This minor erosion is not significant in terms of performance degradation or in terms of its lifetime, leading HEMPT products to have a very high total impulse compared to the same class of power HET and GIT thrusters.

- **Cost effectiveness**
  - HEMPT products were made in line with design-to-cost objectives.
  - HEMPT has the unique feature of being compatible with any noble gas with the same design with no modifications required. Thanks to this unique feature, HEMPT can save a lot of money at constellation level, switching from Xenon to Krypton. (Krypton is around 10 times more present in earth atmosphere, 1ppm, compared to Xenon, 0.08ppm, and considered 10 times cheaper.)

- **Shorter lead-time**
  - HEMPT products were designed for manufacturing and testing with the target of addressing the constellation market. Thanks to the technology basics (permanent magnets, self-radiation, and neutralizer), the manufacturing of a HEMPT thruster is simpler than other technologies, while its reliability allows a reduced testing, which allows Thales to reduce the lead time manufacturing by 2 to 3 compared to traditional technologies. Thales' industrial excellence combined with longstanding TWT, also allows HEMPT to reach summits in terms of production rates and high volume manufacturing.

B. Current product portfolio

Thales' portfolio is comprised of 5 products at different steps of development:

- HEMPT 3050 as the technology demonstrator and first qualified product specifically designed for GEO station keeping at 1,400W and first flight on H2Sat in 2021
- EV0, a 500W-class thruster designed specifically for constellation (with a range of power from 100W to 700W)
- EV1, a 1500W-class thruster designed to be modular and flexible for applications from LEO to GEO. (with a range of power from 1000W to 2,500W)
- EV2, a 5000W-class thruster designed for full-electric satellites. (with a range of power from 3000W to 7000W)
- EV3, a 20kW-class thruster focusing on interplanetary missions.

[5] Status of HEMP-T Electric Propulsion Flight Hardware for Heinrich Hertz Satellite

Each product is based on HEMPT technology and has the same basic properties, common to all the HEMPT thrusters. However, based on their power-class, those products are not addressing the same markets and will not have the same properties and parameters in terms of lifetime, complexity and costs.

III. Electric propulsion market segmentation

Since the commercial development of EP for GEO, the appearance of full electrical satellites, and the constellations and Newspace wave, the EP market mutated a lot: some historical actors disappeared, many newcomers entered the market, and several new technologies emerged. The usage of the electric propulsion also changed and widened, pushed by those new market needs.

A. EP missions typologies

Electric propulsion is today no longer seen as an innovative solution for space propulsion, but has become a baseline for numerous projects and applications. An EP thruster mission can be divided between several simplified phases or typologies that we will use to analyze market needs:

- **Orbit Raising** (OR): to reach the operational orbit of the satellite after separation with the launcher.

- **Station Keeping** (SK): to keep the satellite on the right orbit (generally)
    - for GEO, can be latitude SK (NSSK) or longitude SK (EWSK).
    - for LEO, we will consider orbit adjustment, drag compensation and orbit maintenance.
    - Avoidance maneuvers (AM): to avoid debris using propulsion to move from operational orbit and then come back to the right orbit. It will be considered a part of SK in order to simplify the work.
    - Orbit Topping (OT): to reach the operational orbit of the satellite after the shutdown of a main chemical propulsion system to be considered as SK.

- **End of life maneuver** (EOL): to clear operational orbit when the satellite reaches its end-of-life
    - for GEO/MEO, moving to a higher orbit, called cemetery orbit.
    - for LEO, deorbiting the satellite to have it burned in the atmosphere or having controlled descent to oceans.

In this paper, we will mostly focus on the 3 missions in bold (OR, SK & EOL).

B. Segmentation of satellites types and propulsion needs – Above 3,000 km

Above 3,000 km, the orbits can be divided in three categories:

- The Medium Earth Orbit (MEO) is located between around 3,000km to 20,000km. It is used for Navigation (above 15,000 km), telecommunications and also Earth observation. The typology of EP missions can be segmented depending on the application, Telecommunications or Navigation, and the size of the spacecraft.
- The Geostationary Earth Orbit (GEO) is located at around 35,786 km. It is used for several applications, including telecommunications. An object in such an orbit appears to ground observers as motionless, at a fixed position in the sky. The typologies of EP missions can be segmented based on the size of the satellite and the presence of chemical main propulsion or not.
- The Beyond Earth Orbit (BEO) is located beyond Earth orbit and comprising Cis-lunar, Interplanetary and Earth escape orbits.

Typology	1 – MEO constellation	2 – MEO nav.	3 – GEO small-satellite	4 - GEO hybrid	5 - GEO full-electric	6 – BEO transport.	7 – BEO small-satellite
Orbit	MEO	MEO	GEO	GEO	GEO	BEO	BEO
Application	Broadband constellation	Navigation or VHTS	Telecom.	Telecom.	Telecom.	Cruising or Explo.	Cruising or Explo
Satellite weight range (kg)	1000 – 2,500	2,000 – 5,000	200 – 1,500	2,000 – 6,000	2,000 – 6,000	10,000 - 100,000	50 - 1000
Typical mission lifetime	10 years	15 years	5 years	15 years	15 years	N/A	N/A
Typical total impulse (*)	2,5MNs	5MNs	2,5MNs	5MNs	10MNs	>30MNs	10MNs
Available max power range for EP (W)	5,000 to 15,000	5,000 to 15,000	500 to 2,500	1,500 to 4,500	10,000 to 20,000	20,000 to 100,000	50 to 1,000
OR percentage of total mission	95%	95%	60%	0%	60%	N/A	N/A
SK percentage of total mission	3%	3%	39%	99%	39%	N/A	N/A
EOL percentage of total mission	2%	2%	1%	1%	1%	N/A	N/A
Thruster power class to be used	1,500W – 5,000W	5,000W	500W - 1,500W	1,500W – 5,000W	1,500W – 5,000W	1,500W – 5,000W	<100W – 500W – 1,500W
Number of thrusters per S/C	1 – 2	2 – 4	1 – 4	4	4	N/A	N/A

(*) typical values, depending on the number of EP systems

Table 1. Summary of satellite segmentation typologies for EP above 3,000 km

With this segmentation, we can divide the EP for above 3,000km market into **7** big typologies of projects, each having its own specificity and needs. In the next chapter, we will analyze the needs in terms of EP for each typology and try to determine how HEMPT will fit those needs.

C. Segmentation of satellites types and propulsion needs – Below 3,000 km

Below 3,000 km, the orbit is Low Earth Orbit (LEO). This segmentation will be based on the application, the spacecraft size and available power for EP and the type of constellation. In this paper, we will not be considering spacecraft's with a mass below 100 kg.

Typology	**8 – Sciences or EO**	**9 – Non-telecom constellation**	**10 – Smallsat broadband constellation**	**11 – high-end broadband constellation**	**12 – broadband mega constellation**	**13 – Very Big satellite**
Altitude (km)	200 – 1,500	400 - 900	1,000 – 1,200	1,000 – 1,200	400 - 700	300 – 2,000
Application	EO / sciences	EO / SSA / etc.	Telecom	Telecom	Telecom	EO / sciences
Satellite weight range (kg)	100 – 1,000	500 – 1,000	150 – 450	800 – 1,200	300 – 600	>1,500
Typical ROM number of satellite per program	1	~50	~600	~150	~4000	1
Typical mission lifetime	7 years	10 years	7 years	12 years	7 years	7 years
Available max power range for EP (W)	200 to 1,000	400 to 700	150 to 700	1,500 to 3,000	500 to 700	200 to 2,000
Typical Total impulse (*)	250kNs	400kNs	150kNs	700kNs	400kNs	1000kNs
OR percentage of total mission	50%	0%	50%	50%	20%	60%
SK percentage of total mission	10%	60%	10%	10%	65%	20%
EOL percentage of total mission	40%	40%	40%	40%	15%	20%
Thruster power class to be used	500W	500W	500W	500W to 1,500W	500W	N/A
Number of thrusters per S/C	1	1	1	1 – 2	1	N/A

(*) typical values, depending on the number of EP systems

Table 2. Summary of satellite segmentation typologies for EP below 3,000 km

With this segmentation, we can divide the EP for below 3,000km market into **6** big typologies of projects, each having its own specificity and needs. In the next chapter, we will analyze the needs in terms of EP for each typology and try to determine how HEMPT will fit those needs.

IV. Electric propulsion technologies comparison per market segment

A. Propulsion needs – analysis of important parameters for thruster

With the mutation of the space industry, more and more parts of the spacecraft are becoming commodities. Satellite manufacturers are moving away from a customized and tailored purchasing to a commodity and standardized purchasing. In addition, the propulsion component, even if it is a critical subsystem, is rarely as important as the payload for the primes and will be seen as an enabler, but not as the target of the mission.

This new mindset is leading to simplified analysis of propulsion solutions. In general the 10 key basic parameters to purchase an EP thruster are (not in order of importance, as this varies based on the typology of project):

- **Price**
- **Reliability**
- **Thrust**
- **ISP**
- **Total impulse**
- **Lifetime**
- **Weight**
- **Stability of performance**
- **Reduction of cost of fuel (krypton usage)**
- **Delivery rate**

Based on previous articles and general knowledge, we can compare the three main EP technologies. (We will focus on the three mature and high TRL technologies with an offer above 200W.)

Parameter	HEMPT	HET	GIT
Price	Cost effective, thanks to simplification of its design	Cost effective	Expensive
Reliability	Theoretical reliability high, thanks to a robust design and high grade cathodes	Demonstrated reliability medium to high	Demonstrated reliability high
Thrust	Medium, with a high thrust mode that can reach good thrust	High	Low
ISP	Medium, with a high ISP mode that can reach high ISP	Medium	Very High
Total impulse	High, thanks to permanent magnets leading to almost zero erosion inside the discharge channel	Medium	Medium
Lifetime	High, thanks to self-radiating design & permanent magnets	Medium	Medium
Weight	Medium to high, with on-going improvements	Low	High
Stability of performance	High, thanks to permanent magnets.	Low	Medium
Krypton usage	Very good, HEMPT technology has its unique feature of being able to switch from Xenon to Krypton with zero modifications on design	Medium, degradation of performance	TBC
Delivery rate	High, thanks to Thales industrial capability and to a very simplified design to be mass manufacture	High	Low

Table 3. Comparison of HEMPT with other EP technologies[6]

[6] Table to compare only thrusters, with PPU in mind, but not comparing full systems

B. Needs for EP per typology above 3,000 km

In the table below, we will analyze each segment and review the importance of the parameters we reviewed in part "V.A. Propulsion needs – analysis of important parameters". Depending on the segment, some parameters will have a critical importance, while other ones will be merely good to have.

Example: For 5-GEO full-electric, the main criteria will be the reliability of the system and the thruster, as GEO satellites are very expensive. Price will be second, as it's mostly a commercial market, and thrust will also be a very important parameter as thrust is shaping the time of OR, and the shorter the OR is, the sooner the satellite starts to generate revenue. By opposition, for a BEO transportation mission, the stability of performance and the total impulse will be the main criteria, such mission being technology driven.

Importance of parameter	**1 – MEO constellation**	**2 – MEO nav.**	**3 – GEO small-satellite**	**4 - GEO hybrid**	**5 - GEO full-electric**	**6 – BEO transport.**	**7 – BEO small-satellite**
1	Price	Reliability	Price	Reliability	Reliability	Reliability	Reliability
2	Krypton usage	Thrust	Lifetime	ISP	Lifetime	Stability of performance	Price
3	Delivery rate	Price	Total impulse	Price	Thrust	Total impulse	Stability of performance
4	Reliability	Weight	Reliability	Total impulse	Price	Lifetime	Total impulse
5	Thrust	Lifetime	Thrust	Lifetime	Total impulse	ISP	Lifetime
6	*Total impulse*	*Total impulse*	*ISP*	*Weight*	*ISP*	*Thrust*	*ISP*
7	*ISP*	*ISP*	*Weight*	*Stability of performance*	*Stability of performance*	*Weight*	*Thrust*
8	*Lifetime*	*Delivery rate*	*Stability of performance*	*Thrust*	*Weight*	*Price*	*Weight*
9	*Weight*	*Krypton usage*	*Krypton usage*	*Krypton usage*	*Krypton usage*	*Krypton usage*	*Krypton usage*
10	*Stability of performance*	*Stability of performance*	*Delivery rate*	*Delivery rate*	*Delivery rate*	*Delivery rate*	*Delivery rate*

Table 4. Needs for EP per typology above 3,000 km

Based on those needs and our previous comparison of technologies, we can define the two best technology and thruster-class for each market segment.

	1 – MEO constellation	**2 – MEO nav.**	**3 – GEO small-satellite**	**4 - GEO hybrid**	**5 - GEO full-electric**	**6 – BEO transport.**	**7 – BEO small-satellite**
Best	**HEMPT**	HET	**HEMPT**	**HEMPT / GIT**	HET	**HEMPT**	**HEMPT**
Second-best	HET	**HEMPT**	HET	HET	**HEMPT**	GIT	HET

Table 5. Best technologies per typology above 3,000 km

Thanks to its competitiveness at thruster and system level, HEMPT with Krypton is the best choice for segment 1. With its long lifetime and high total impulse, HEMPT is the best choice for segments 6 &7 especially thanks to its performance stability. When power to thrust and fast orbit raising is key (Navigation or GEO comsat), then HET remains the best choice. However, as a technological alternative, HEMPT is the second-best choice for GEO and navigation, due to its dual mode.

C. Need for EP per typology below 3,000 km & HEMPT answer

In the table below, we will analyze each segment and review the importance of the parameters we reviewed in part "V.A. Propulsion needs – analysis of important parameters". Depending on the segment, some parameters will have a critical importance, while other ones will be merely good to have.

Example: For 12-broadband mega constellation, the main criteria will be the price of the thruster, and the krypton usage, to reduce the cost as much as possible. Another very important criterion will be the delivery rate, as those mega constellations are very high volume.

Importance of parameter	**8 – Sciences or EO**	**9 – Non-telecom constellation**	**10 – Smallsat broadband constellation**	**11 – high-end broadband constellation**	**12 – broadband mega constellation**	**13 – Very Big satellite**
1	Reliability	Price	Price	Price	Price	Reliability
2	ISP	Total impulse	Delivery rate	Reliability	Delivery rate	ISP
3	Total impulse	Stability of performance	Krypton usage	Delivery rate	Krypton usage	Total impulse
4	Price	Krypton usage	Weight	Total impulse	Total impulse	Thrust
5	Stability of performance	Reliability	Total impulse	Krypton usage	Weight	Stability of performance
6	*Lifetime*	*Delivery rate*	*Reliability*	*Thrust*	*Reliability*	*Price*
7	*Krypton usage*	*ISP*	*Thrust*	*ISP*	*Thrust*	*Weight*
8	*Thrust*	*Thrust*	*ISP*	*Lifetime*	*ISP*	*Lifetime*
9	*Weight*	*Weight*	*Lifetime*	*Weight*	*Lifetime*	*Krypton usage*
10	*Delivery rate*	*Lifetime*	*Stability of performance*	*Stability of performance*	*Stability of performance*	*Delivery rate*

Table 6. Needs for EP per typology below 3,000 km

Based on those needs and our previous comparison of technologies, we can define the two best technology and thruster-class for each market segment.

	8 – Sciences or EO	**9 – Non-telecom constellation**	**10 – Smallsat broadband constellation**	**11 – high-end broadband constellation**	**12 –broadband mega constellation**	**13 – Very Big satellite**
Best	GIT	**HEMPT**	**HEMPT**	**HEMPT**	**HEMPT**	GIT
Second-best	**HEMPT**	HET	HET	HET	HET	**HEMPT**

Table 7. Best technologies per typology below 3,000 km

As developed in the EPIC workshops, Thales' HEMPT appears to be the best technology for LEO constellations. With a power-class around 500W, and its flexibility by design from 200W to 700W, HEMPT EV0 is the best solution for all segments 8, 9, 10 & 12. This positioning is based on the combination of high value key advantages of HEMPT and Thales' capabilities:

- Cost-effectiveness and value for money, thanks to both Krypton usage and inherent competitive design,
- High delivery rate, with simplified and easy to manufacture design and high production capability and industrial robustness,
- Low mass of system and high ISP mode to reduce the weight of spacecraft and launch biggest batches.

Krypton usage is really the most important parameter, and HEMPT is the most stable thruster with Krypton in terms of performances degradation and lifetime.

V. Conclusion

HEMPT has been successfully developed by Thales in the past decade, starting from scratch with a new technology to reach high TRL products today. With a complete range of products, Thales is the reference of HEMPT technology, and has the biggest industrial capability. Thanks to those differentiators and advantages, Thales' HEMPT is expected to become the baseline for constellations' electric propulsion in the next decade. In a more competitive market than ever, HEMPT, thanks to the global cost of system and stability, can be seen as an enabler for innovative Krypton usage and lower cost constellations.

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