TEST RESULTS OF H2020 EUROPEAN DIRECT DRIVE ARCHITECTURE STUDY

EDDA project –
Grant Agreement n° 870470

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KEYWORDS: Direct Drive, Hall Effect Thruster, Highly Efficient Multistage Plasma Thruster, Direct Drive Unit, regulation for electric propulsion.

ABSTRACT:

The space industry is undergoing a major breakthrough. The evolution of the space business enables the emergence of new opportunities and the subsequent adoption of disruptive technologies and architectures that can help in facing the increasing demands on compactness, cost reduction, performance, and flexibility. One of the numerous keys to meet this demand lies in high-voltage (250V-400V) electric propulsion. Preliminary European study HV-EPSA demonstrated the feasibility of increasing power bus voltage to several hundred volts thereby allowing to directly supply Hall Effect Thrusters (HET) or Highly Efficient Multistage Plasma Thruster (HEMPT) by the solar array without any voltage conversion.

European Direct Drive Architecture (EDDA) study aims to validate the performances of the closed loop between a simulated solar array and two HETs supplied in parallel or one HEMPT. Conversion removal provides a better end-to-end efficiency, less thermal dissipation, mass reduction as long as high voltage-related drawbacks are mastered (arcing due to Paschen's law within the spacecraft, or due to conductive plasma outside, mainly around solar array because of the high voltage).

The main principles of Direct-Drive (DD) Architecture are presented through this article, applications and key benefits this new technology could deliver to the space industry, and test results.

1. CONTENT

§2 deals with description of direct drive and its spacecraft use cases .
§3 shows the architecture chosen to supply thrusters from solar array and battery.
§4 provides numerical results for thruster behaviour.
§5 describes hardware used during testing.
§6 gives main results at power regulation, HETs and HEMP level.
§7 proposes a conclusion

2. Description of Direct Drive and spacecraft use cases

Direct Drive is a way to supply anode thruster directly by the solar array without any power conversion. It saves power electronics (mass, volume, dissipation) and then improves overall efficiency.
This requires from the solar array to be able to provide a high voltage. For EDDA, the maximum bus voltage was 400V, based on a previous H2020 EU study called HV-EPSA.
In Figure 1, power is delivered to the spacecraft at 100V, and PPU increases it to anode voltage (>300V). In figure 2, anode is directly supplied by

the solar array (between 250 and 400V, according to the mission and solar illumination).

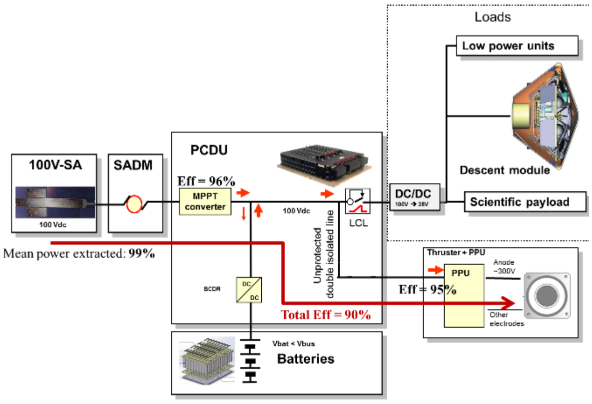

Figure 1. Current electrical power supply (Vbus=100V) for spacecraft.

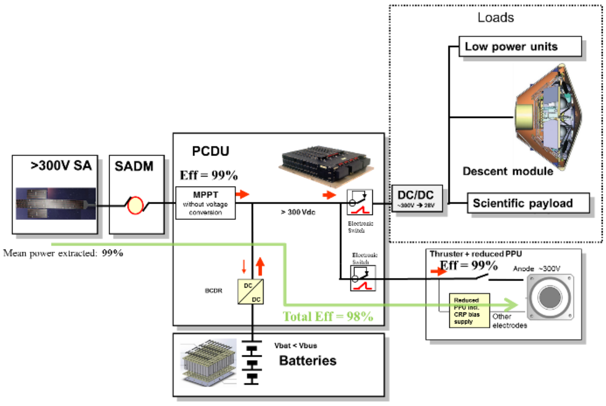

Figure 2. Direct drive architecture with bus voltage up to 400V supplying Electric Thruster without power conversion providing end to end improved efficiency.

3. EDDA power architecture

Two electrical architectures compatible with direct-drive have been defined for space applications during the project. They are presented in Figure 3 and Figure 4.

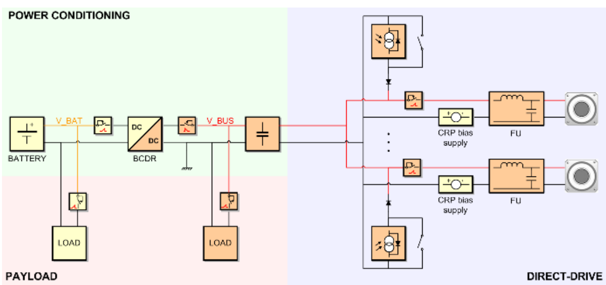

Figure 3. Concept of direct-drive space architecture, with the solar array sections and the thrusters directly connected on the power bus.

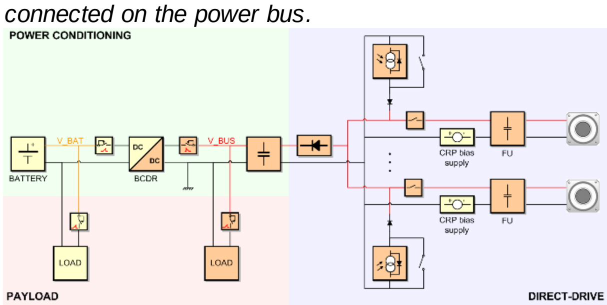

Figure 4. Concept of direct-drive space architecture, with the solar array sections and the thrusters isolated from the power bus with a diode.

The power conditioning part of both architectures is composed of a battery, of a DC/DC converter called Bidirectional Charge and Discharge Regulator (BCDR), with its input and output switches, and of a capacitor.

The loads could either be connected on the battery or on the bus. However, the battery bus is not regulated. It is currently intended to place them on the bus.

The solar array sections and the thrusters with their Filter Units (FU) constitute the direct-drive part of the architecture. They are either directly connected on the bus (Figure 3) or connected through a diode (Figure 4). The aim of the diode is to passively protect the bus from a short-circuit of the thruster, but also to protect a thruster from the discharge of the bus capacitor in case of normal short-circuit of this thruster. The bus voltage must then be compatible with the voltage ratings of the thrusters, between 250V and 400V.

As for the CRP bias supply, its purpose is to minimize the common mode current of the thruster by acting on the cathode voltage.

Finally, these two architectures can be used with two operating modes. During the orbit raising, the Maximum Power Point of the solar array can be tracked by acting on the bus voltage to provide as much power as possible to the thrusters. And once in orbit, the bus voltage can be regulated to a fixed value, and the solar array sections can be switched to supply the current required by the satellite (or the spacecraft).

4. Thruster numerical modelling

4.1 HET modelling

Within the frame of the EDDA project, the two-dimensional hybrid particle-in-cell (PIC)/fluid code HYPHEN, developed by EP2 [6,7], has been used to simulate the HT5k thruster unit operating with xenon. The code has been successfully adapted to the simulation of magnetically shielded (MS) HET's, including magnetic singular points.

The numerical model and settings for the HT5k simulations are detailed in Ref. [8]. The electron module of HYPHEN features a turbulent collisionality for electron transport, which is adjusted to reproduce the experimental data on discharge current I_d and thrust F with relative errors below 5%. The adjusted turbulent collisional parameter follows a classical step-out profile, which depends on the operational point, defined in terms of the source voltage V_S and the propellant mass flow rate injected at the anode $\dot{m}_A$.

The simulations presented here feature a surface cathode approach, which is well suited for the modelling of the central cathode of the HT5k thruster. Along the cathode surface, a prescribed xenon neutral flow is injected. The position of the cathode and its extension is schematically represented with a black rectangle in Figures 6, 8, 9 and 10. The model also implements a RLC circuit connecting the anode and the cathode, as in the real thruster. The influence of this RLC filter on the discharge behaviour is found to be negligible in the anode-to-cathode electrical response.

Five operation points within the operational range V_S = [250-400] V, $\dot{m}_A$ = [10-14] mg/s are simulated. For each operation point, HYPHEN provides a fully 2D characterization of the plasma discharge of the HT5k thruster. The results presented here correspond to the operation point with V_S = 400 V and $\dot{m}_A$= 14 mg/s, for which the experimentally measured performance data are I_d = 14.2 A and F = 308 mN

The characterization of the discharge current, I_d, oscillations is relevant for the correct integration of the thruster within the DD architecture. Figure 5 shows the time evolution of I_d, whose time-averaged value is I_d = 14.8 A. The main oscillations correspond to the so-called breathing mode. For all the operation points studied, the dominant frequency of the simulated I_d oscillations ranges from 15 kHz to 23kHz, and the peak-to-peak half amplitude of the simulated oscillations, ΔI_d, ranges between 4% and 13% of I_d. Both numerical results are consistent with the experimentally measured values.

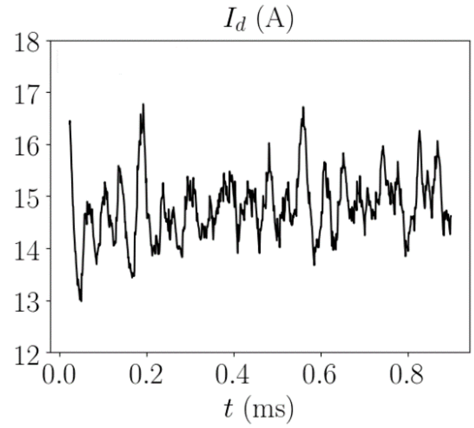

Figure 5. Time evolution of the discharge current

In the following, all the results are time-averaged over several Id cycles. Figure 6 shows the time-averaged plasma density 2D map in the simulation domain. The results reveal a uniform plasma density distribution inside the chamber, with a maximum at a central location within the chamber, close to the magnetic singular point. Higher plasma density values than in conventional HETs are found, revealing a large propellant utilization. In the near plume, a secondary plasma plume created by the ionization of neutrals injected through the cathode merges with the main one. Figure 7 reveals low electron temperature isolines around the chamber walls, which is the key achievement of the magnetic shielding concept, thus yielding low ion impact energy (below typical thresholds for erosion) and reducing the power losses to the walls. The electric potential contour in Figure 8 shows the position of the acceleration zone, which is located outside the thruster chamber. Moreover, the electric potential is found to be nearly flat inside the thruster chamber, which is also beneficial from the point of view of erosion. Figure 9 shows the electron current paths in the thruster discharge. The electrons are injected through the cathode and then, go towards the chamber to ionize the Xe gas, or flow downstream to neutralize the ion stream. The current neutralization of the beam is observed in Figure 10, which depicts the electric current density. It has been found that the injection of neutrals through the cathode noticeably improves the cathode-plume electric coupling.

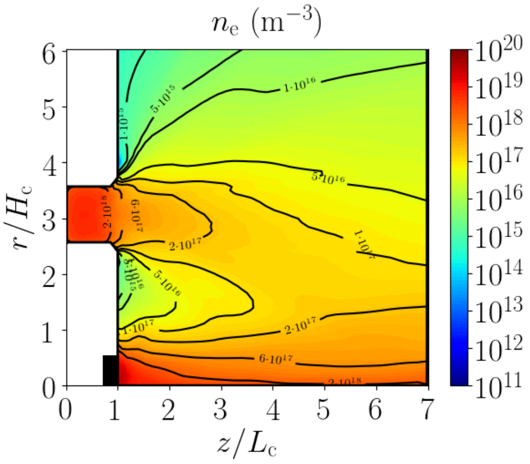

Figure 6. Time-averaged plasma density 2D contour of the discharge

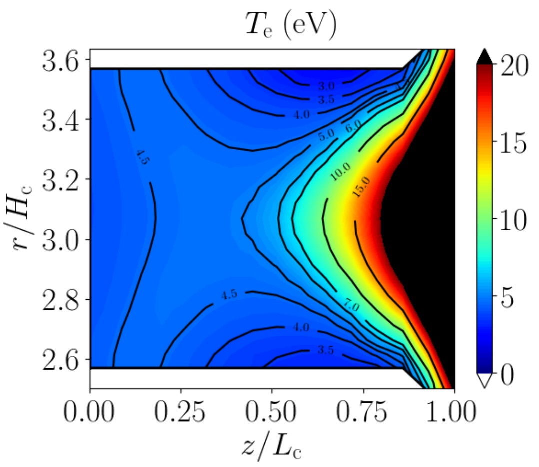

Figure 7. Time-averaged electron temperature 2D contour. Detail of the thruster chamber

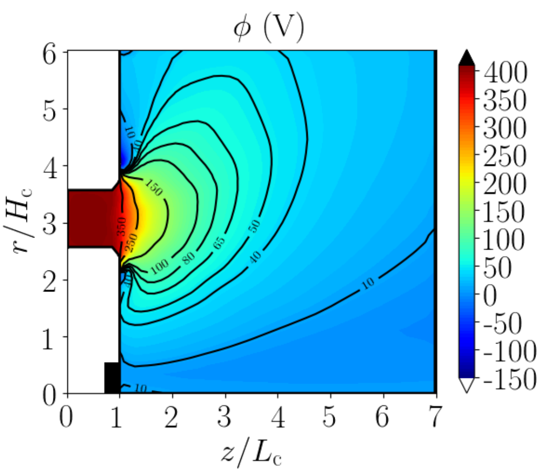

Figure 8. Time-averaged electric current 2D contour and streamlines.

The analysis of the global current and power balances obtained with HYPHEN shows that the magnetic shielding of the HT5k reduces (wall) power losses with respect to a conventional HET, while it barely has an impact on the ion current balance due to the relatively high plasma density inside the chamber; although the ion current losses to the anode are relatively high, likely due to a poor shielding associated to the presence of the magnetic singular point. For all the operation points simulated, the current losses to the lateral dielectric walls of the thruster chamber are about a 40% of the produced ion current, whereas the power losses to these walls amount only to a 7% of the discharge power. Moreover, the sum of the power deposited to the lateral walls and the power to the anode ranges from just 9% to 12%, which are low values compared to conventional HETs.

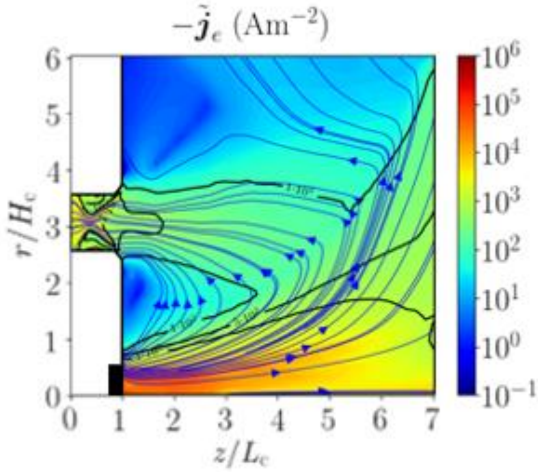

Figure 9. Time-averaged electron current 2D contour and streamlines

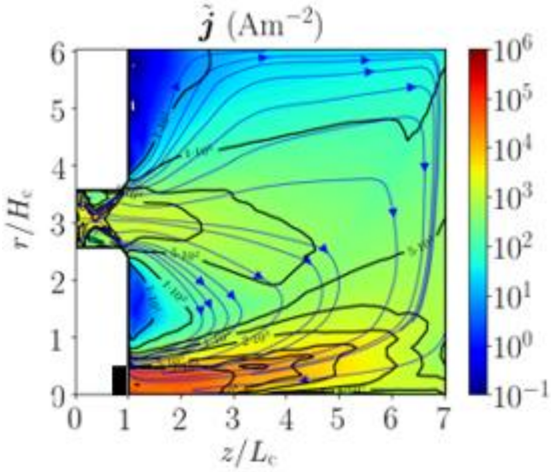

Figure 10. Time-averaged electric current 2D contour and streamlines

5. EDDA Power and thruster Hardware

5.1. Power

The power hardware of EDDA demonstrator was divided into 5 equipment : the Battery Simulator, the Solar Array Simulator (SAS), the active load, the Power Conditioning Unit (PCU) and the CRP bias supplies.

The Battery Simulator is a simple DC/DC

bidirectional power supply, able to provide up to 15kW. It was connected to the PCU which is composed of two main modules : the BCDR which adapts the Battery voltage to the bus voltage and the Sequential Switching Shunt Regulator (S3R) which acts on the sections of the SAS.

The anodes of the thrusters were connected on the bus through their Filter Units and the cathodes were connected on the bus return through their CRP bias supplies. For the test, an active load was connected in series with the CRP bias supplies to be able to apply a positive or negative biasing.

As for the active load, it was directly connected on the bus and was used to simulate either current transients or a constant consumption on a bus.

Apart from the CRP bias supply, all the power electronics was integrated inside two racks (see Figure 11).

Figure 11. Power hardware of the EDDA demonstrator, with the PCU rack on the left and the "power" rack on the right composed of the Battery Simulator, of the SAS sections and of the active load.

5.2. HETs

The test on the two HETs was carried out on two different SITAEL's 5 kW Hall thruster models. The first one, in the test labelled as HT1, is the HT5k DM3 (development model 3). The HT5k DM3 features the magnetic shielding of the ceramic channel and it was first tested in 2017 [1]. The HT5k DM3 was also previously tested in Direct Drive configuration in the frame of the ESA-funded *Experimental Investigation of a Direct-Drive Hall Effect Thruster System* programme [2].
The other thruster, labelled as HT2, is the new engineering model of the HT5k, the HT5k EQM. The design of the HT5k EQM derives from the DM3 and features the same magnetically shielded topology. The new HT5k EQM is now under qualification in the frame of the Ital-GovSatCom programme [3]. A picture of the two thrusters together is provided in Figure 12 and during firing in Figure 13.

Figure 12. HT5k thrusters used for the EDDA test. On the right, the HT5k DM3 (HT1), on the left the HT5k EQM (HT2).

The EDDA test was performed with two independent cathodes, SITAEL's HC20 for the HT1 and SITAEL's HC60 for the HT2, further details of the cathodes can be found in [4].

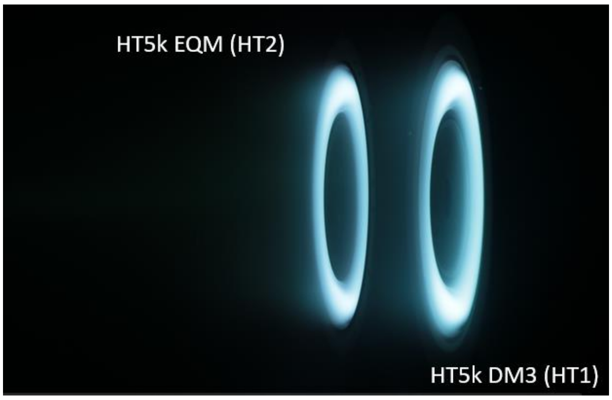

Figure 13. HT5k Hall thrusters during dual HET firing test of EDDA.

During the test, the two thrusters were isolated from the chamber ground and were mounted on a fixture plate that simulated the satellite structure. The thruster bodies plus the fixture were at the same potential. When the CRP bias supply was set at null voltage, we recreated the so called "cathode tied" configuration, which was tested on high power Hall thrusters such as the NASA HERMeS [5]. For all the test campaign, each thruster was kept at the nominal magnetic field topology and intensity. In addition, the mass flow rate of each cathode was always kept constant and controlled by SITAEL. On the other hand, the mass flow controllers of the anodes were always controlled by TAS-B with the D-Space software.

5.3. HEMPT

During EDDA test, this HEMPT unit has the capability to run up to 400V/20A. Different levels of voltage and current were tested.

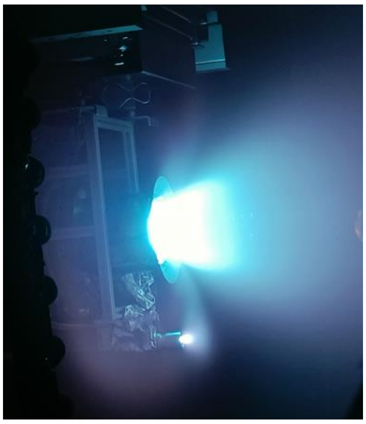

Figure 14. HEMPT firing test of EDDA.

6. Test results

Among the different performed runs, one based on 2 HETs used simultaneously, but also with the capability of individual control, has been selected.

The test sequence represents different operational phases for a geostationary satcom, from launch separation to telecom phase. It can be easily simplified to other types of spacecraft (Space-tug, transportation) where the main mission is electric propulsion.

Electric Orbit Raising (EOR) is the first phase from launcher separation to Geo, where the Solar Array can deliver more power than at End of Life. Maximum Peak Power Tracking is the regulation selected to extract the maximum power from the Solar Array to supply the thrusters.

On station, on geostationary orbit, a constant voltage regulation is selected to optimized telecom payload. Electric propulsion is then used for station keeping, at a much lower power than during EOR. In case of major failure on board, a Safe mode can be triggered which requires a maximum power for the thrusters, according to available power. Peak Power Tracking is the regulation used for this purpose.

In addition, some events that could happened during satellite life have been tested :

- Solar array string failure, corresponding to a 1.5A solar current decrease,
- Variation of power between the 2 thrusters, showing the capability to create a torque to change spacecraft thrust resulting orientation (HT1 min, then HT2 min),
- Variation of spacecraft platform consumption (+1200W, -1200W, +2400W, -2400W)
- Tracking maximum power from a minimum bus voltage (tracking from Vmin) or a maximum bus voltage (tracking from Vmax).

These different events appear on the following figures 15, where current and voltage of each of the two HETs are plotted.

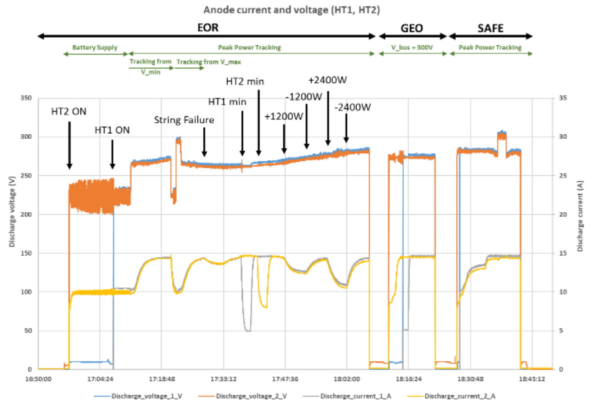

Figure 15 : 2 HETs at 16A, 300V with a common CRP biais supply

Identical sequence has been performed with (only) one HEMPT. Anode current and voltage are plotted in figure 16.

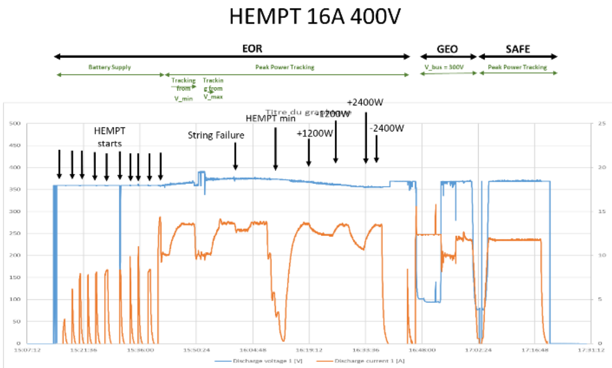

Figure 16 : HEMPT 16A, 300V

From the different runs, it was possible to verify the power regulation excellent behaviour (in MPPT or at fixed voltage) to adapt thruster power to available power. This regulation is compatible of both thruster technologies (HET and HEMPT).
This architecture showed also its capability to drive two thrusters at a time, though a higher number is possible.
And finally, the cathode supply limited very much the stray current.

7. CONCLUSIONS

All EDDA objectives were achieved, listed in Table 1.

Objectives	Status
Check Quality of the bus in direct drive	Done, data acquired
Simulate the different operational phases of the spacecraft mission	Done, to be tuned with thruster performance

Confirm feasibility of direct drive	Done
Confirm feasibility of direct drive with several thrusters operating in parallel	Designed for several thrusters, Tested with 2 thrusters, with capability to adapt separately power to each thruster
Confirm feasibility of direct drive with 2 different thruster technologies	Done with HET and HEMPT
Confirm the concept of CRP supply for direct drive application	done
Confirm 2 regulation modes for direct drive	Done with Maximum power tracking or constant bus voltage.

Table 1 : Achievement of EDDA objectives

As the results are positive, further developments are needed before flight, mainly for some parts or units from development to space models.

8. ACKNOWLEDGMENT

EDDA study was funded by the EU H2020 Framework Programme under the Grant n°870470.

EDDA partners also thank Mrs F.BEYROUD and Mr A.PETRIDIS for their active supports as EU representatives (Project Officers) as well as the Program Support Activity members. Last but not least, the consortium is grateful for the fruitful exchanges and support of its Advisory Board (EUTELSAT, INMARSAT, CNES, ESA). An effective management of this study was done by Mr. M. Franc from Efficient Innovation.

On top of technical results, this study was also a nice human exchange between the different partners to develop Europe relationships.

9. ABBREVIATIONS AND ACRONYMS

CRP : Cathode Reference Potential
DD : Direct Drive
EDDA : European Direct Drive Architecture
EOR: Electric Orbit Raising
HET : Hall Effect Thruster
HEMPT : Highly Efficient Multistage Plasma Thruster
MPPT : Maximum Peak Power Tracking
PCU : Power Conditioning Unit
SAS: Solar Array Simulator

10. REFERENCES

1. A. Piragino, E. Ferrato, F. Faraji, M. Reza, T. Andreussi, A. Rossodivita, M. Andrenucci Experimental Characterization of a 5 kW magnetically shielded Hall thruster, Space Propulsion 2018, 14-18 May 2018, SP2018_427

2. Maryam Reza, Faraji Farbod, Tommaso Andreussi , Characterization of a high-power Hall thruster operation in direct-drive, January 2021, Acta Astronautica 178(1):392-405 DOI: 10.1016/j.actaastro.2020.09.008

3. Tommaso Andreussi, Vittorio Giannetti, Alena Kitaeva, Antonio Piragino, Christopher Andrea Paissoni, Eugenio Ferrato, Daniela Pedrini, Elena Casali, Angela Rossodivita SITAEL's high-power Hall propulsion systems, 72nd International Astronautical Congress (IAC), Dubai, United Arab Emirates, 25-29 October 2021. IAC-21,C4,5,x66437

4. Alena Kitaeva, Vittorio Giannetti, Maryam Reza, Daniela Pedrini, Eugenio Ferrato, Antonio Piragino and Tommaso Andreussi, Development of High-Current Hollow Cathodes at SITAEL, 71st International Astronautical Congress (IAC) – The CyberSpace Edition, 12-14 October 2020,IAC-20,C4,5,9,x60521

5. Peter Y. Peterson, Hani Kamhawi, Wensheng Huang, George Williams, James H. Gilland, John Yim, Richard R. Hofer and Daniel A. Herman, NASA's HERMeS Hall Thruster Electrical Configuration Characterization, AIAA 2016-5027, https://doi.org/10.2514/6.2016-5027

6. Adrián Domínguez-Vázquez. Axisymmetric simulation codes for Hall effect thrusters and plasma plumes. PhD Thesis, Universidad Carlos III de Madrid, Leganés, Spain, 2019.

7. Adrián Domínguez-Vázquez, Jiewei Zhou, Pablo Fajardo, and Eduardo Ahedo. Analysis of the plasma discharge in a Hall thruster via a hybrid 2D code. In 36th International Electric Propulsion Conference, number IEPC-2019-579, Vienna, Austria, 2019. Electric Rocket Propulsion Society

8. Jesús Perales-Díaz, Adrián Domínguez-Vázquez, Pablo Fajardo, Eduardo Ahedo, Farbod Faraji, Maryam Reza and Tommaso Andreussi "Hybrid plasma simulations of a magnetically shielded Hall thruster," Journal of Applied Physics, Vol. 131, No. 10, 2022.