

Pulsed Plasma Thruster – Subsystem Engineering at IRS

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Matthias Lau¹ and Georg Herdrich¹
Institute of Space Systems, University of Stuttgart, Stuttgart, Baden Wuerttemberg, 70569, Germany

The Institute of Space Systems in Stuttgart (IRS) has developed a Pulsed Plasma Thruster subsystem demonstrator as part of a three year development program to take the step from equipment to S/S level. The iMPD project, funded by the German Aerospace Center, has recently been successfully concluded at IRS. The demonstrator builds on the heritage iMPD thruster ADD SIMP-LEX. Modification of the thruster has achieved integration of the self-contained high TRL propulsion subsystem and internationally competitive thruster performance levels. The next step at IRS is to consolidate subsystem engineering and verification to demonstrate compliance with relevant space standards and requirements. Design options are described to ensure compatibility with identified coarse mission level and system level design drivers for the iMPD. The goal at IRS is to prepare for a qualification of an iMPD propulsion system.

I. Introduction

THE Institute of Space Systems in Stuttgart has a long heritage in design, testing and numeric analysis of electric propulsion thrusters.¹ This includes magnetoplasmadynamic thrusters for high specific impulse applications. A type that has kept its potential for applications for over 40 years is the Pulsed Plasma Thruster (PPT), also known as Pulsed Magnetoplasmadynamic Thruster (iMPD). This thruster combines the advantage of a simple and affordable design with high mission flexibility and low programmatic risk.

The secret to the thruster's potential lies in its simple operation and setup. Few parts are required, a capacitor, two electrodes and an ignitor. The inert propellant is in solid form to allow hazard free storage, handling and feeding. The propellant mass flow is self-regulated. There is no need for complex and expensive electronic hardware, like for Hall Effect Thrusters or Ion Thrusters.

A predefined amount of stored energy is released into a discharge by the ignitor plug. The plasma discharge is controlled by the geometric and electric parameters of the iMPD. The resulting short and high current is sufficient to provide the ionized propellant and the accelerating magnetic field. As a result, pulses of thrust can be generated with high repeatability. The thrust is also easily modulated by changing the pulse frequency or the pulse energy to satisfy the mission needs of high controllability and high thrust level in a single design. The iMPDs can tolerate very low power input levels, to overcome system limitations without degradation of the total achievable impulse.

It is for these reasons that research on PPTs continues in Europe undeterred despite the fact that it is mostly overlooked in selection and harmonization loops. It is concluded that work towards qualified subsystems is required to bridge the gap between mission requirements and available hardware and to confirm low programmatic risk.

¹ Guest Researcher, Space Transportation Technology, lau@irs.uni-stuttgart.de.

² Head of Plasma-Windtunnels and Electric Propulsion, Space Transportation Technology, herdrich@irs.uni-stuttgart.de.

The recently completed iMPD subsystem demonstrator at IRS is the logical answer to perform this process. It is a unique platform in Europe to support consolidated subsystem engineering, verification and standardization. In the long term this will offer a European technology first flight opportunity.

II. Programmatic Overview

The international development of PPTs has achieved a high level of maturity, which is expressed in the availability of dedicated propulsion systems and flight opportunities.²⁻⁶ However, European technology is behind in comparison and kept out of the competition.

The missing availability of off the shelf components for PPTs is often misunderstood as low technological maturity in Europe. This causes PPTs to score low in harmonization and selection processes in comparison with other electric propulsion technologies, despite their flight heritage and demonstrated performance. In fact, the achieved readiness of the iMPD system at IRS is already above the low TRL assigned by the agency.

This confirms the need to provide the technical and programmatic arguments to demonstrate that PPT-systems are a valuable and versatile contribution to European space exploration. It allows independent access for Europe to this technology by increasing its scores in selection processes.

The programmatic approach at IRS is based on development phases. The current development status is presented in Fig. 1 together with a coarse timeline to indicate major leaps forward.

In 2002, the historic foundation was laid by a small satellite program at the Institute of Space Systems in Stuttgart. The goal is a lunar exploration satellite to be built and operated by students with the support of industry. This beacon project is pursued as a flagship for German aerospace know-how. A push for massive support of this sector is also evident in the UK, where focused efforts provide technologies and processes needed to seize opportunities for future economic utilization and exploration of space.

The Lunar Mission BW1 satellite of the IRS in Stuttgart shall be the first to demonstrate that primary propulsion, i.e. orbital transfer to the moon, can be achieved at low cost by a cluster of iMPD-thrusters to push the technical limits. But this ultimate goal also requires the availability of a capable European iMPD propulsion system.

The first phase from 2002 to 2008 provided an evolution of thrusters to achieve working thruster hardware. Thruster component specifications were identified for design iterations and parameter studies. Optimizations of the iMPD performance finally lead to the ADD SIMP-LEX thruster engineering model. It demonstrated full functionality and leading performance. For this phase, the subsystem hardware was simulated by standard laboratory equipment.

A high flexibility is provided to adjust the thruster design point to a range of top level drivers:

- Thrust level,
- Total Impulse,
- Operation life,
- Input power,
- Mass and Cost.

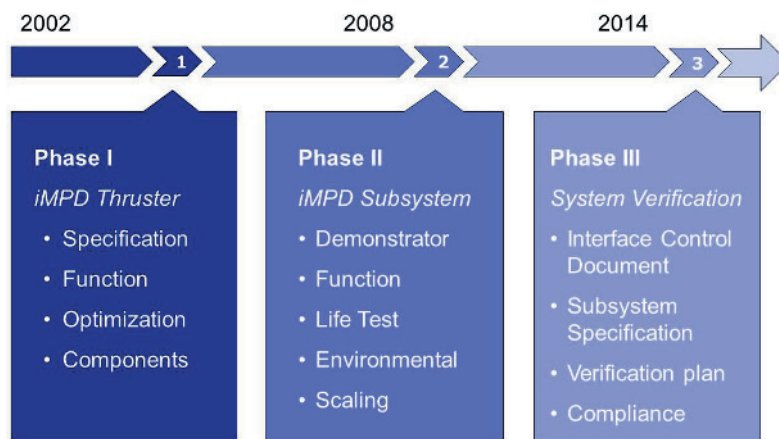


Figure 1. iMPD Subsystem Development Logic

The second phase until 2014 replaced the laboratory equipment with subsystem hardware that is able to perform in a space relevant environment. The combined ADD SIMP-LEX thruster and vacuum capable equipment are forming the subsystem demonstrator.⁷

The demonstrator is fully functional representative and provides a platform for the development of all aspects of consolidated subsystem engineering and concurrent design at IRS. Follow up priority activities supported by the iMPD platform are:

- European Harmonization,
- Space Exploration,
- Technology Transfer,
- Technology Development, and
- Education.

Along with the setup of the iMPD propulsion subsystem, the facilities and testing capabilities at IRS were extended to support functional tests, coupling tests and life tests. This is also an input to consider facility limitations and capacities for qualification testing. An affordable testing concept is key to ensure low programmatic risk of the propulsion system.

The successful conclusion of phase two in 2014 has provided IRS with an invaluable amount of scientific data and technical heritage for years to come. All outputs support the continuation of the iMPD technology and its positive impact to strengthen the academic and the industrial competitiveness of European spaceflight. Subsystem Engineering will ensure that performance of the hardware is fully compatible with the work of the upcoming verification development phase at IRS.

The current phase three is the step to prepare the subsystem for consideration in selection and harmonization processes and to work towards a fully qualified iMPD propulsion system. This includes drafting of the documentation provided in Fig. 1. The approach is to confirm a low programmatic risk by showing detailed cost, lead times and the availability of required processes and documentation. The required depth of this top down approach for scientific or industrial standards will be considered. The required support of system and operator level activities after an acceptance must also be outlined in this phase. A challenge in this phase is the limited availability of dedicated agency standards. The selection of suppliers will require efforts for either certification or component level qualification.

III. Demonstrator Hardware and Testing

The modified ADD SIMP-LEX thruster for integration in the iMPD propulsion system demonstrator is presented in the Fig. 2. Technical data is provided in Table 1.⁸



Figure 2. Modified ADD SIMP-LEX

Table 1. Thruster performance data

Parameter	Value
Thruster Dry Mass	< 6.5 kg
Electrode gap (h x w)	21 x 20 mm ²
Propellant	Solid PTFE
Capacitor Voltage	1300 V
Igniter Voltage Capability	Up to 20 kV
Impulse per Pulse	1.5 mNs
Specific Impulse	up to 2650 s
Mass per Pulse	60 µg
Thrust Efficiency	~ 30 %
Demonstrated Pulse Life	2 Mio.
Demonstrated Total Impulse	3000 Ns

The design modifications for the subsystem demonstrator are the outcome of a trade-off between thruster performance, interfaces and operation life. It also includes lesson learned from previous models and technical changes. The main improvements include:

- Current sensor accommodation
- Power train optimization
- Mass reduction
- Plasma contamination shielding
- Low voltage ignition
- Erosion prevention

A thruster life test of two million of successive pulses at a frequency of 1 Hz showed no relevant degradation. High pulse life an order of magnitude above is achieved with a proper propellant feeding mechanism. Capacitor mass is driving the overall weight. A decrease by a factor of two is possible based on demonstrated performance of available capacitor technology. The impulse bit per pulse of 1.5 mNs decreases manoeuvre times and high specific impulse ensures low propellant consumption.

A. Thruster Power Supply Module

The operation concept of the iMPD requires only two simple functions, the charging of the capacitor and the firing of the ignitor. The Power Processing Unit (PPU) EQM for the Subsystem demonstrator built by Advanced Space Power Equipment (ASP) is presented in Fig. 3a below.^{7,9}

The unit features ECSS compliant processes at reduced part quality and testing level to keep the cost minimal for the demonstrator. The recurring price per unit including acceptance tests is expected one order of magnitude lower than for typical electric propulsion units. Cross strapping capability will be added to allow redundancy. Most parameter adjustments do not require costly developments.

Telemetry for control and FDIR to cover all known failure cases on system level is already included. The PCDU power input is standard 28 VDC. Weight is 1.4 kg but will be reduced by dropping the ignition voltage from 20 kV to 5 kV. The supply can drive 1 Hz thruster operation with a power of 85 W. Interfaces are fully analogue.

Miniaturization for compatibility to the sub-5W power range was demonstrated at IRS with affordable and reliable standard electronics.

B. Current Sensor

The HoKa current sensors measure contact free to protect the interface from high voltage.¹⁰ An additional barrier for the high voltage is an optical fiber interface between the sensor data input and output. A sensor consists of the coil element and the integration electronics. The weight of a sensor is about 280 g. The output can be digital or analogue. Multiple sensors provide redundancy to monitor ignition success, misfire, capacitor health and power supply failure. Sensors have a long life and an accuracy error of less than three percent absolute.

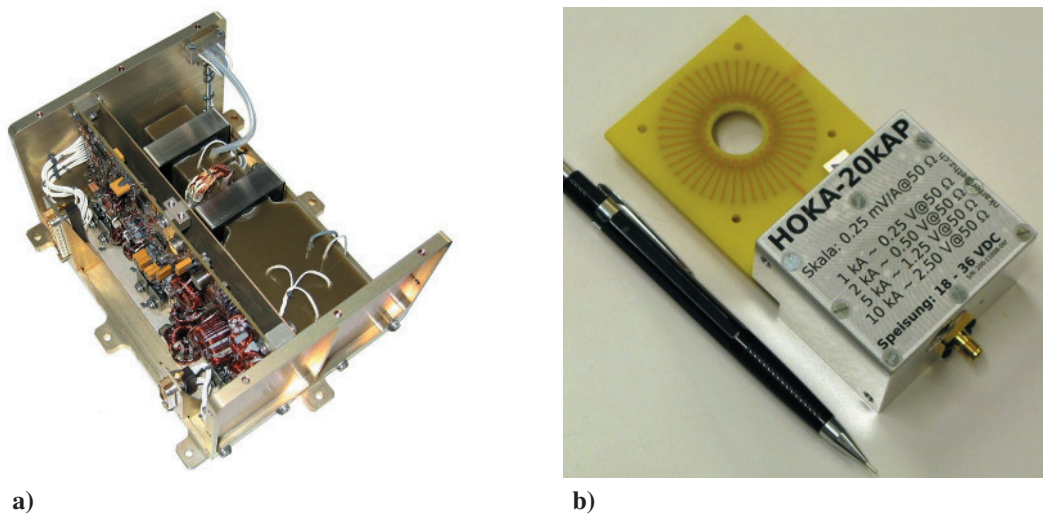


Figure 3. iMPD Propulsion Subsystem Components



Figure 4. IRS Pulsed Electric Thruster Test Facility

C. Subsystem Demonstrator testing

Development and testing at IRS is performed in four high vacuum facilities (see Fig. 4). Each facility is specialized to provide experimental capabilities for component testing, plasma characterization, operation-life testing and performance measurements. The table 2 provides an overview of individual features.

Table 2. Test Facility Features

Tank No.	Length, m	Ø, m	Pressure, mbar	Purpose	Test Equipment
16	1.6	0.5	10^{-5}	Performance, Functional	μ N-Impulse pendulum, High Voltage / Current, Forced cooling
17	1.0	0.3	10^{-6}	Plasma characterization	3D-diagnostic probe table, Intrusive Probes, Emission Spectroscopy, Cameras
18	0.6	0.4	10^{-6}	Operation life	High Voltage / Current, Data-logger
19	0.5	0.3	10^{-6}	Component, Microthrusters	High Voltage / Current, Mobile facility

For a full functional checkout, received components are first acceptance tested in vacuum for offgasing, thermal stability without cooling and electric isolation strength before integration in the subsystem demonstrator. Coupling tests with the hot thruster are then performed to confirm subsystem operability.

The integrated system performance is analyzed to detect differences from laboratory equipment operation. Compatibility to the simulated satellite interfaces outside of the test facility is checked by running a full electrical check on the demonstrator. With all tests passed, the propulsion system demonstrator is approved.

Life testing and performance testing are performed to characterize the operation of the iMPD propulsion system. Propulsion performance has increased, which is attributed to the thruster modifications. Life testing has shown to require careful preparation of the facility to prevent long term contamination, plasma interactions and damage to the vacuum equipment. Thermal vacuum testing capability is limited to water based cooling.

IV. Requirements

The driving requirements for the setup of the iMPD subsystem demonstrator at IRS in phase two are derived from its main applicability to the iMPD program:

- Vacuum compatibility
- Compact setup
- System portability
- Facility compatibility
- Affordable high quality components
- Limited number of simple interfaces

The demonstrator is compliant to all program requirements to support the subsystem engineering approach. The program uses the new hardware platform to assess the proposed S/S design's compliance to key drivers identified by

a flow down of mission and system requirements into the subsystem. Non compliances must be understood with respect to the possibility for inducing risks and impact on cost calculation and development schedule.

On the other hand, the knowledge of technical performances provided by the propulsion demonstrator testing serves as an input to component requirements by confirming technical limitations and feasibility. These are vital to evaluate and trade suppliers and available qualifications on the market.

The minimum design aspects for building a subsystem level requirements reference for iMPD propulsion systems are addressed similar to other chemical or electrical systems:

- Budgets (mass, propellant, power, ...)
- Redundancies
- Thrust performance
- Operational concept
- MAIT activities
- Operation life (duty cycles, thermal cycles, propellant throughput)
- Cleanliness
- Interfaces
- Compatibility (Environmental, Thermal, Mechanical, Electromagnetic, ...)
- Propellant (Handling, Gauging, Green propellant, Passivation, ...)

The iMPD thruster is a simple and robust design. This shall be directly reflected in the specification. A solid propellant promises huge cost savings, even by cold gas propulsion standards. Its inert form and high demisability makes it ideal for EOL operations and effortless integration.

The redundancy concept is driven by the number of simultaneously operating thrusters and single point failure tolerance. No loading, unloading, drying or flushing activities are required during integration. A simple analogue interface is compatible with most OBDH concepts by design. Impact of the satellite power bus voltage on the thruster power supply can lead to additional effort for compliance.

A thorough discussion of these aspects is beyond this paper. However there is high confidence that full compliance can be achieved with affordable effort and that the subsystem engineering approach will provide confidence in the selection of the iMPD thruster for mission applications.

A high thrust level is often preferred in the scoring to allow shorter manoeuvres and mitigate the complexity of AOCS design. The iMPD can offer superior cost efficiency, low operational risk, risk free disposal and unlimited storage time to justify the effort in mission design where possible.

V. Subsystem architecture design

The current iMPD subsystem demonstrator functional layout is presented in Fig. 5 below.

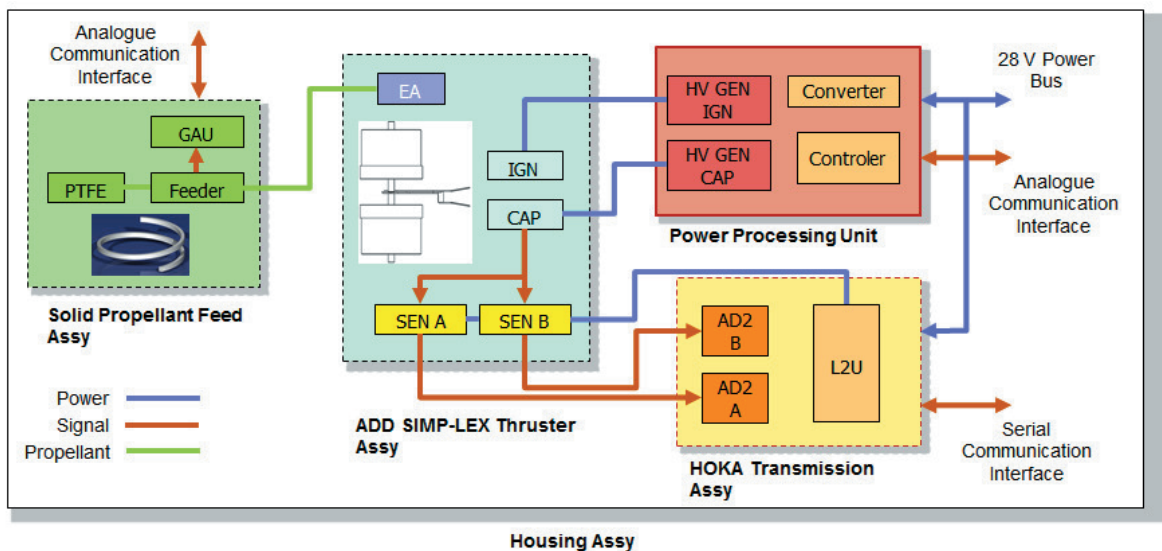


Figure 5. iMPD subsystem demonstrator layout

The S/S features an ADD SIMP-LEX thruster with redundant current sensors (SEN). Thermal monitoring is provided by a redundant thermistor on the electrode assembly (EA). Four capacitors provide redundancy in case of a failure. One igniter provides pulse control. Solid PTFE is provided by a mechanical feeder assembly with redundant spring elements. Gauging is provided by an electric feeder position sensor as well as by the book-keeping method

The power supply provides a DC charging circuit for the capacitors and a pulse inducer. The two HOKA current sensors have completely redundant drivers. A single converter (L2U) connects them to the galvanic decoupled telecommand interface. In its current form this interface is compatible to the USB 2.0 standard.

The architecture represents a minimum configuration, which could be used to fulfil the 25 year de-orbit requirement for S/C in LEO. Complexity is added to the design depending on the number of thrusters required for the mission and a required simultaneous operation.

Two S/S architecture approaches are identified, which can be realized with the available subsystem demonstrator hardware:

- Single thruster integrated S/S
- Clustered thruster S/S

The single thruster scenario is feasible for low thrust applications with very limited resources or when no single point failure tolerance is required, e.g. de-orbits. It can be built very compact into a self-contained interchangeable module.

Up to three thrusters are usually combined in a cluster, e.g. for station keeping. The thrusters can be positioned and aligned freely to fulfil the required mission performance. A cluster can also combine thrusters to increase the thrust level for orbit manoeuvres or faster attitude changes. When multiple thrusters (or even clusters) exist on a satellite they can use a common power supply architecture combining a proper amount of modules.

For compact mounted thrusters, it is feasible to use to a common set of capacitors. This is usually reserved to CubeSat architectures but could be considered to reduce the required mass budget also on bigger satellites. Care has to be taken to avoid parasitic inductances.

It is preferable to have a standard power supply module (PPU) with cross strapping capability. The advantage is that the modules can be combined to provide redundancy. It is also possible to combine two modules to handle a higher input power instead of developing a dedicated module for each power setting.

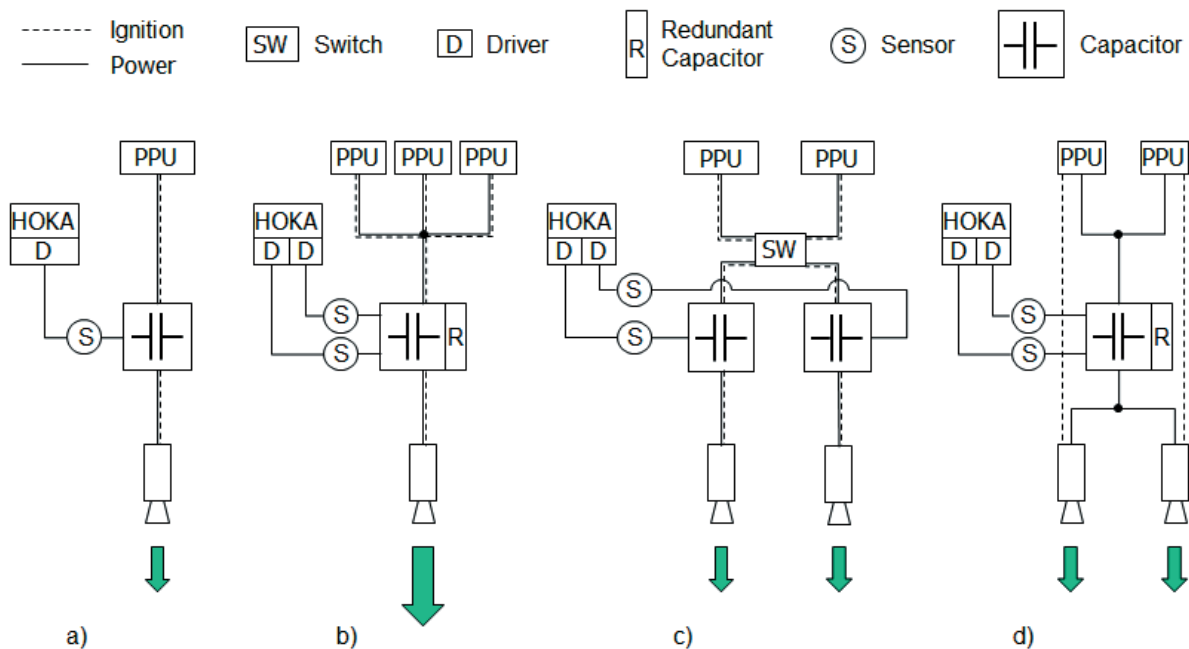


Figure 6. iMPD Subsystem Architecture Options

Capacitors are only connected to power lines. Multiple thrusters can be connected to the same capacitor without the need for a switch. Capacitor redundancy can be activated in case of a failure or performance degradation. It could also provide a pulse energy boost to temporarily raise the thrust level. It is noted, that no complex propellant feeding or tank design is required.

- Option a offers no failure tolerance but represents the most basic electric propulsion system of all.
- The architecture of option b presents coupling of two PPU's to drive a bigger thruster, with a redundancy concept of 2 out of 3. It also offers redundant sensors over option a.
- The switch for option c allows all combinations of PPU's and thruster branches for superior system availability. Capacitor redundancy is not needed due to the two series redundant thruster branches. Simultaneous operation of both branches at full power is possible.
- Option d is a trade-off between availability and simplicity. Any additional thruster to be added to option d does require an ignition switch unit on one of the PPU's. Full single point failure tolerance can be provided for all options with two thrusters. Thruster can be operated simultaneously but at reduced power.

The described architecture options allow consolidation with other S/Ss in the satellite design loops through a high degree of modularity. Thrust level, plume interaction and propellant feeding are possible drivers for the accommodation and AOCS operational concept loops.

VI. Verification Testing

A set of applicable standards and requirements will be used for selecting procedures and resources necessary to prepare for a qualification program. Verification by test is considered a key demonstrator for compliance. Preference will be given to established best practice for testing. Given the lack of consideration of iMPDs in Europe in the past, the practiced standards for verification shall be modified and agreed to accommodate the features of the iMPD propulsion technology.

The pulsed operation mode and the solid propellant of an iMPD must be considered in new test standards that identify the proper measurement methods. Drivers are the thrust vector, duty cycle and plume impingement. Existing facilities are mostly unfit to support correct verification testing. This is why the iMPD S/S demonstrator was designed for utmost portability and compatibility.

A preliminary test flow plan is presented in Fig. 7. The first row covers thruster level testing. It is designed to demonstrate thrust levels to ensure compliance of the space segment in all thruster based operation modes. This includes reliable ignition control, pulse repeatability, thrust degradation and cold start.

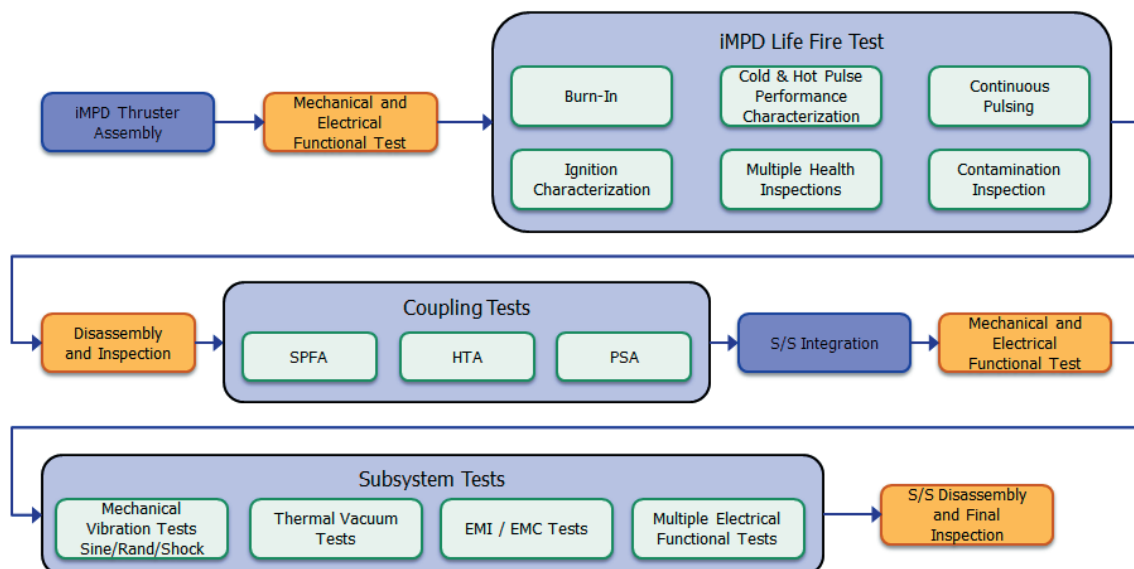


Figure 7. Draft Verification Test Plan for the iMPD Subsystem Demonstrator

The second row shows the intermediate integration phase. Limited testing will be required to confirm thruster function and selected performance parameters with the other subsystem components before integration. The advantage is a direct handle on anomalies for adjustments. Separate qualification of the other subsystem components will be provided outside of the scope of the flow by the suppliers.

The third row envelops the typical system level qualification activities. This qualification is also vital input for preliminary platform design loops to trade the system impact of thruster options. This will be the most extensive effort for the iMPD qualification program since proper tests are performed in external facilities. Small launchers, like the Vega and GSLV rockets are first references for mechanical testing.

EMC/EMI compliance is not considered a driver as compliance heritage exists for on-ground and in-orbit worst case scenarios.¹¹

VII. Conclusion

The following main points are noted for consideration:

- The conclusion of phase two of the iMPD project at IRS provides the technological platform to push iMPD subsystem development for higher marks in selection and harmonization loops.
- The required inputs to achieve a full qualification for a European first flight opportunity have been identified for phase three.
- Subsystem engineering is required to bridge the gap between mission requirements and available hardware and to confirm low programmatic risk.
- Test facilities at IRS offer high standards for pulsed electric thruster testing. The use for qualification shall be as high as possible. Facility expertise is used as input to increase the availability of iMPD test capabilities outside of IRS.
- Subsystem demonstrator hardware and architecture approaches for compliance with standards and requirements have been pointed out in this paper, to cover a wide range of mission scenarios.
- Verification by analysis will be performed wherever compatible models or software tools are identified to mitigate the need for qualification testing.
- Compliance to ECSS standards is currently considered. Applicability to the iMPD propulsion system and the programmatic frame of the work at IRS must be checked and agreed. Output is considered to the ECSS committee and to a standardization handbook for electric in space propulsion system verification.

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References

- ¹Herdrich, G. et al., "Activities in Electric Propulsion Development at IRS", 2008-b-02, Transactions of Space Technology Japan, Vol. 7, No. ists26, pp. Tb 5-Tb 14.
- ²Popov, G. A., Antropov, N. N., "Ablative PPT. New quality, new perspectives," Acta Astronautica, doi:10.1016/j.actaastro.2006.02.009, No. 59, 2006, pp. 175-180.
- ³Igarashi, M., et al., "Performance Improvement of Pulsed Plasma thruster for Micro Satellite," 27th International Electric Propulsion Conference, IEPC-01-152, Pasadena, USA, 2001.
- ⁴Benson, S.W., Arrington, L.A., Hoskins, W.A., Meckel, N.J., Development of a PPT for the EO-1 Spacecraft, AIAA-99-2276, 35th Joint Propulsion Conference, Los Angeles, CA, USA, 1999.
- ⁵An, S.-M., Wu, H.-J., Feng, X.-Z., Liu, W.X., "Space Flight Test of Electric Thruster System MDT-2A," Journal of Spacecrafts and Rockets, Vol. 21, No. 6, 1984, pp. 593-594.
- ⁶Bock, D., et al., "Electric Propulsion Systems for Small Satellites: The Low Earth Orbit Mission Perseus," EUCASS Proceedings Series, doi: 10.1051/eucass/201102629, Vol. 2, pp. 629-638, 2011.
- ⁷Lau, M., Herdrich, G., Koch, M., Hintze, T., "iMPD Subsystem Design and Verification at IRS", 5th Russian German Conference on Electric Propulsion, Dresden, Germany, September 7-12, 2014.
- ⁸Lau, M., Herdrich, G., Grabe, M., Experimental Characterization of a Scalable Pulsed Magnetoplasmadynamic Propulsion System, Space Propulsion Conference 2014, SP2014_2980914, Cologne, Germany, 2014.

⁹Lau, M., Herdrich, G., Fasoulas, S., Röser, H.P., Koch, M., Hintze, T., iMPD System Study and High Voltage Power Supply Subsystem Development at IRS, IEPC-2011-150, 32nd IEPC, Germany, 2011.

¹⁰Lau, M., Herdrich, G., Karrer, N., “Power Train Configuration Study on a Pulsed Plasma Thruster with State-of-the-Art High Current Monitors”, AIAA-2013-4122, 49th JPC, San Jose, USA, 2013.

¹¹Garret, M.L., et al., Electromagnetic Emissions from DC to 17 GHz from a Pulsed Plasma Thruster, 30th International Electric Propulsion Conference, IEPC-2007-269, Florence, Italy, 2007.