iMPD System Study and High Voltage Power Supply Subsystem Development at IRS

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Extensive research and optimization work has been carried out at the Institute of Space Systems (IRS) on the Pulsed Magnetoplasmadynamic Thruster (iMPD) ADD SIMP-LEX (Stuttgart Impulsing Magnetoplasmadynamic Thruster for Lunar Exploration) leading to an optimized iMPD engineering model. It features world leading thrust efficiencies around 30% together with russian APPT's by RIAME MAI, further demonstrating projected components like the award winning Helix-PTFE-feeder holding two patents. With a full follow on funding by the German Aerospace Center (DLR) and the German Federal Ministry of Economics and Technology (BMWi), a new project has now been launched at IRS in 2010 for the next logical step in iMPD development within three years: The setup and study of a complete laboratory iMPD-system, able to fully operate inside of a test facility in a space relevant environment. A programatic overview of the scheduled project work is given, including the motivation, objectives, current status and projected milestones. The iMPD-system is broken down into components with their specific features being described in detail. Special focus is put on the development and assembly of an iMPD-High-Voltage-Power-Supply (HVPS) unit by the ASP Equipment GmbH.

Nomenclature

c_e	= Effective exhaust velocity
E_0	= Initial discharge pulse energy
g_0	= Gravity of earth
I_{sp}	= Specific impulse
m_0	= Initial total mass
m_e	= Final total mass
P	= Electric power
Δv	= Maximum change of speed
RLC	= Circuit consisting of resistor, inductor, and capacitor

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I. Introduction

More than 25 years of experience have been gained in the field of electric propulsion at IRS. The expertise includes a wide variety of thrusters and numerical codes.[1] Experimental activities aim at optimization of electric thruster with respect to mission parameters and system related sizes, depending on the mission. At IRS this refers to development of new hybrid systems like TITHUS and CETEP, as well as arcjets, steady state and applied field MPD-thrusters, ion-thrusters and Pulsed Plasma Thrusters (PPT's). The first satellite equipped with PPT's was the russian Mars fly-by attempt ZOND-2 in 1964. The concept of this thruster type remains up to date.[2] It uses the pulsed operation mode to increase the available electric power for propulsion regarding the often scarce power budget on most satellites equipped with solar panels. Accordingly the energy for a single pulse must only be provided in between discharges, which grants a PPT a unique flexibility since its power consumption is generally low. Since the first flight, a wide range of investigations have focused on understanding a PPT's physics and working principles.[3–7]

It is important to note here, that probably the most significant quality of a PPT is the unmatched simplicity of its basic design and handling.[8] Despite this advantage, understanding the pulsed operation mode is a very challenging scientific objective and a long shot from being completely understood. The extremely short discharge is complex to monitor and simulate, yet leaving many questions on the plasma conditions inside the thruster during discharge open for investigation. On the other hand, a discharge time of some microseconds can create very high discharge power levels to very rapidly accelerate a given bit of propellant mass, even at low energy levels. Even though PPT's have a generally low thrust efficiency [3,8,9], they feature a high I_{sp} of up to several $1000\,s$. This can significantly reduce the required overall propellant mass for a given Δv, thus allowing for an increase in payload mass.

The aforementioned advantages grant the PPT's a wide field of possible application.[2,10–13] Small and repeatable impulses can provide outstanding pointing accuracy for earth observation, attitude control, detumbling or formation flight. The simple design bolsters reliability and often allows for operation beyond the projected thruster lifetime. Further, no propellant losses allow for long mission durations over several years for drag or drift compensation. The work on a PPT propulsion system at IRS, using pulsed magnotplasmadynamic thrusters or iMPD's, was first published in 2004.[14] Continuous efforts to research and investigate this type of thruster finally led to the introduction of the ADD SIMP-LEX design in 2008.[15] The accumulation of substantial expertise and facilities at IRS further acts as a catalyzer for cooperation, exchange of research personel and technology development. All these achievements are based on a clear philosophy of development for research, that has not changed since 2001. This translates into present days commitment for sustaining iMPD development at IRS and the motivation of the project described within this paper, which is also represented by a very long and close cooperation with the russian Kurchatov and RIAME Institutes and the University of Tokyo in Japan as well as further mutual collaboration with the other members of the international PPT and iMPD Working Group.

A. Motivation

For the reasons given above, iMPD's are mainly developed for secondary propulsion tasks on small satellites, for which they are well suited.[10–13] For the Small Satellite Program at IRS, a cluster of four iMPD ADD SIMP-LEX thrusters is investigated as the primary propulsion system to transfer the $200\,kg$ satellite Lunar Mission BW1 to the Moon.[16] Although the actual thruster development is outside of the scope of this project, the work can help to lay the groundwork for a possible future application at IRS. The first iMPD project at IRS, funded by the DLR started in 2005. The work's objectives focussed on developing an engineering model of an iMPD-thruster, establishing methods for thruster investigation and characterization, setting up test facilities and subsequent parameter variation studies for thrust efficiency and electric circuit optimization. The objectives were all met beyond expectations.

The work enabled IRS to raise the thrust efficiency of ADD SIMP-LEX to about 30 %, which is on a very high level together with the APPT thruster family[6] of the RIAME Mowscow Aviation Institute and a result of the ongoing close cooperation between the two Institutes. Figure 1 shows an overview of the thrust efficiency of several PPT's, including ADD SIMP-LEX. The first project was successfully concluded in 2008. Based on the achievements and analysis of the available results, objectives for a follow up project were defined to:

- Improve understanding of iMPD operation,

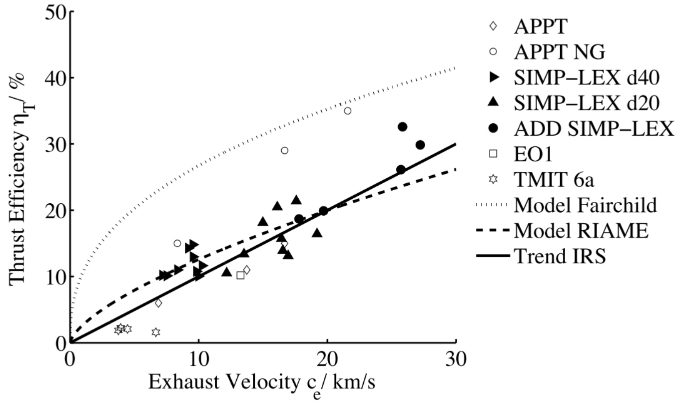


Figure 1. Thrust efficiency against exhaust velocity for different PPTs.[15]

- Create an iMPD system research and development platform for laboratory testing and scaling,
- Increase space environment relevance for system operation,
- Expand iMPD operation range and performance,
- Maintain access to pulsed electric propulsion technology.

Until 2009 the development work at IRS had, among others, a strong focus on the thruster unit, especially the thruster head. However, preparatory activities with respect to the power unit were performed together with leading to design and application of a power unit breadboard during this development phase. Given the level of success, continuation required a shift of focus to new aspects to add to the research that had been left out. Therefore, after the optimization of ADD SIMP-LEX, the next step in development is concluded to be the setup of a complete system around a modified version of the iMPD thruster unit. This would, for the fist time, grant access to a complete research and development platform, significantly improving the possibilities to investigate system parameters during the iMPD operation. In addition to including the system aspect into future research, the decision was made to also include the investigation of environmental effects of a space related environment on the ADD SIMP-LEX. While the ambient pressure in space can be adequately reached inside of the IRS test chambers, the cost and complexity for adding thermal scale are out of budget. The workaround requires a compact system setup and new interfaces to grant mobility of the system itself for testing in specially suited facilities.

Usually laboratory operation of an electric thruster requires special equipment that is set up around the test chamber. The off the shelf equipment can cause undesired electric issues to the point of effecting thruster operation. The spread out configuration is prone to interfering effects due to long and bundled cables, alternating high voltages, electric feed throughs and grounding issues to name a few. A compact iMPD-system can overcome these drawbacks. All parts will be tailored to the specific needs of the system and distances between them are short. This can open up into future component technology development, i.e. upgrading, standardization and scaling. The overall system is intended to become more operationally representative and transparent as a result.

Advancing the operational range of the ADD SIMP-LEX includes several aspects. The foremost job is the expansion of operating life. Continuous operation of the iMPD has not been demonstrated beyond several 10000 shots at IRS.[15] More conclusive data on erosion and life limiting factors is required. From literature and preliminary testing at IRS, the igniter life, electrode erosion and carbon layer build-up are expected to have a major influence. Substancial research effort will be wrapped around gaining a deeper understanding of the corresponding mechanisms. As a first approach, accessible means of adjusting the discharge plasma are being investigated since it is assumed to be a system point involved in all the aforementioned life limiting influences. Additional groundwork for this has been layed twofold, on the one hand with the investigation of plasma sheet measurement techniques by Nawaz et al.[17,18] and on the other hand by characterizing the discharge plasma by Tony Schönherr.[19] The understanding of the discharge plasma and techical means of adjusting it can improve identification of possible future applications of pulsed plasmas as a result. Within the presented system study, ADD SIMP-LEX operation is aimed at being demonstrated to about 10 million continuous shots. Another aspect that is closely connected to component design, yet based on another remarkable feature of PPT's with respect to thrust control. For non-pulsed mode electric thrusters, the input power is directly linked to the thrust efficiency and the I_{sp} since it governs the energy available for accelleration of the propellant over time. Therefore lowering the input power will not only affect the thrust level, but also lower the I_{sp}.

$$\Delta v = I_{sp} \cdot g_0 \cdot \ln \left(\frac{m_0}{m_e} \right) \tag{1}$$

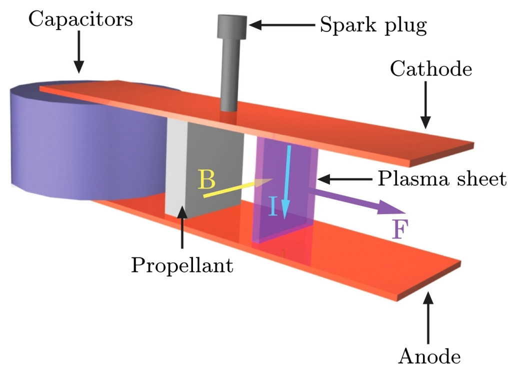
Acoording to the well known Equation 1 by Tsiolkovsky this will either reduce the total Δv the thruster can generate or increase the amount of propellant necessary for a given total Δv, which in turn can lower the payload mass. However, an iMPD only draws energy between pulses so lowering the input power doesn't affect the energy per pulse. As a result, the thrust can be throttled by changing the input power without losses in total Δv. Only the pulse frequency of the iMPD will change. This is also useful to grant a higher power margin for the payload or other parts of a small satellite. The upper threshold for the pulse frequency of an iMPD is rooted in the solid propellant. As a thumb rule, the power $P = E_0 \cdot f$ should not exceed $100\,W$ with virgin polytetrafluoroethylene (PTFE), better know as Teflon^{TM}. A too strong structural heating may even lead to depolymerization processes that can cause propellant ineffciencies. Options to increase this threshold will be investigated by means of PTFE-compounds. Until today a number of fruitful national and international cooperations have been established supporting the development process of iMPD's at IRS. The partners for the presented project are gathered in the PPT and IMPD working group (Japan, Russia, England, Austria, Germany) as well as further partners in Germany and Switzerland. The goal is to expand the achieved mutual work with the partners to stimulate exchange of knowlegde, experience, research data and scientific personnel. The cooperations contribute to all aspects of the project, from research, development and optimization of the iMPD-system to system study, data analysis, numerical particle code development and evaluation of simulations. The goal of the presented future work is to facilitate research of iMPD's and work towards a sustainable solution for future space exploration strategies.

II. The iMPD ADD SIMP-LEX

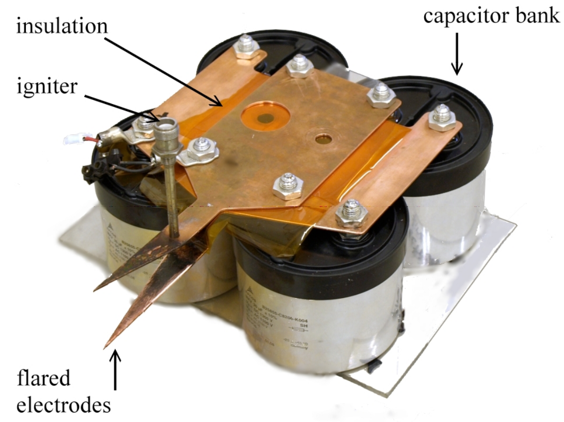
The Pulsed Magnetoplasmadynamic Thruster, or iMPD, is a type of PPT, using electromagnetic fields to accelerate the propellant along a pair of parallel electrodes. It represents an electric setup, that can be described by means of a series RLC-circuit.[3] Thus both, electric and geometric parameters act together to distinguish the discharge behavior. As the name suggests, it operates in a pulsed mode, replenishing its energy after every discharge pulse. Its simple and robust setup only requires four main elements. The first is a pair of parallel plate electrodes, the anode and cathode, typically made of copper. The second is a capacitor to store electric energy. Each of its terminals is connected to one electrode. A solid block of insulating polytetrafluoroethylene (PTFE) is fit between the electrodes, sometimes fed by a mechanical spring which represents the only moving part of the thruster. The final element is a cathode mounted igniter plug, acting as an electron donor next to the propellant surface between the electrodes. A schematic overview is given in Fig. 2(a).

Prior to a discharge pulse a voltage of several kV is applied to the capacitor to charge it with energy and create an electric field between the electrodes. The ambient vacuum and electrode insulation prevents any unwanted breakdown. To initiate the iMPD, the igniter is triggered by a High-Voltage-Pulse of up to $20\,kV$ peak value. The igniter discharge causes a pressure raise near the propellant surface, that increases conductivity and closes the loop, causing the capacitor to break down across the surface. Subsequently the discharge current builds up a magnetic self-field around it and creates a plasma either from electrode material and from the propellant that is partly ablated from the surface. The total amount of propellant ablated during a single pulse is called mass-bit. The applied electric field transfers energy to the ionized plasma particles of the running current between the electrodes. The magnetic self-field then interacts with the ionized particles by means of the Lorentz-force, diverting them away from the thruster. As a result, the majority of the plasma is accelerated and a thrust is produced.

Between 2004 and 2008 the iMPD SIMP-LEX has been developed into an engineering model for parameter variation studies at IRS. From this model, the advanced design of ADD SIMP-LEX was derived in 2009. Figure 2(b) shows the design in detail. While this design will be used for the iMPD-system, modifications



(a) Working principle of a PPT.



(b) ADD SIMP-LEX iMPD thruster.

Figure 2. ADD SIMP-LEX thruster and working principle.

to the configuration, for example the electrodes and the capacitor bank, are in order to fit into the new system. Further modifications are subject to the lifetime optimization. The thruster characteristics of ADD SIMP-LEX are summarized in Table 1.

Table 1. ADD SIMP-LEX Characteristics

Capacitance	$20\,\mu F, 40\,\mu F, 60\,\mu F, 80\,\mu F$
Max. Pulse Energy	$\leq 68\,J$
Impulse Bit	$\leq 1.4\,mNs$
Thrust Efficiency	$\leq 32\,\%$
Ignition Frequency	$1\,Hz$

III. iMPD-System Overview

The block diagram in Fig. 3 shows a schematic overview of the iMPD-system and its components. Its driving requirements are:

- Compact size,
- Long term operation inside a vacuum chamber at IRS,
- Scaleability,
- Mobility.

The HVPS as well as parts of the sensor package are developed and assembled by subcontractors. The sensor package will allow for in-situ monitoring of the discharge voltage signal and discharge current signal as well as ignition success, capacitor charge status, propellant consumption and subsystem temperatures.

The system structure is to provide stiff mounting and grounding interfaces for all components as well as for additional scientific instrumentation. It includes screw terminals for mounting of the system to a table inside of the test chamber. The overall mass is to be kept as low as possible. A protective casing will be attachable for storage and transportation of the system. As blank metal surfaces near the thruster head can lead to misbehaviour, insulating materials will be used for sensitive areas.

A. HOKA Current Sensor

The HOKA Current Sensor of the ETH Zürich is based on the principle of a Rogowski coil. It can safely and accurately measure high magnitude high frequency currents.[21] Two versions are planned for single

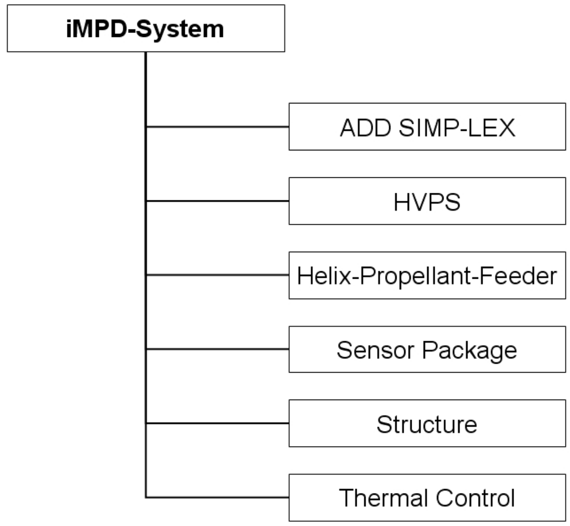


Figure 3. Component breakdown of the iMPD-system.

and combined capacitor measurements. Since ADD SIMP-LEX must be compact for performance reasons, i.e. parasitic inductance, the sensor will be directly integrated into the electric insulation at the capacitor terminals. The following specifications are met:

- Measurement of pulsed currents up to $20\,kA$ per capacitor,
- Electric Insulation Strength of $1.5\,kV$,
- Measurement Bandwith of $1\,MHz$,
- Optical Data Interface.

Figure 4 shows an example of a HOKA used for experimental investigation at IRS.

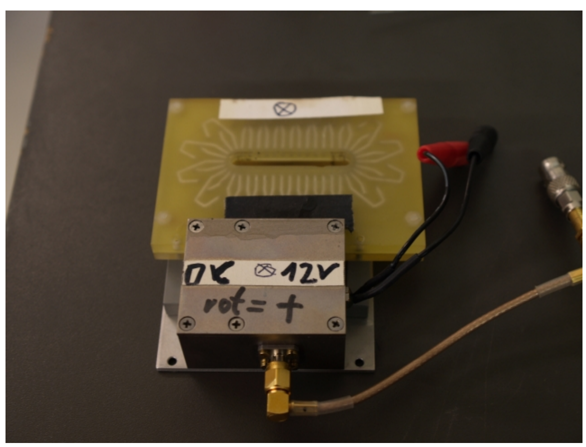
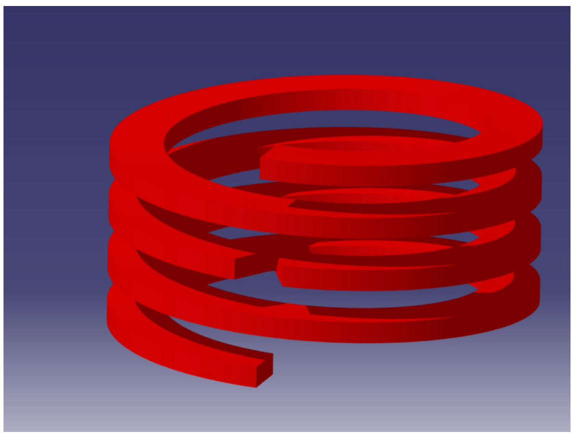


Figure 4. Example of a HOKA Current Sensor.[15]

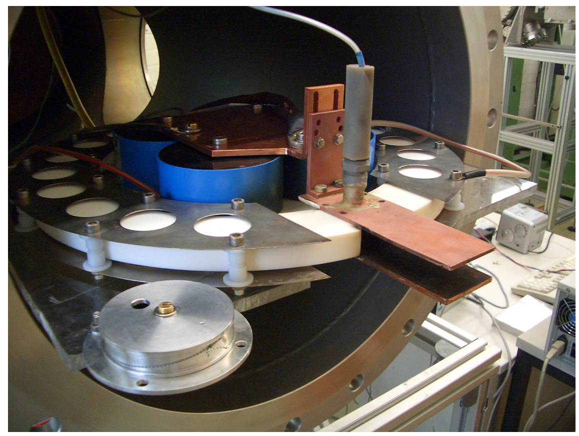
B. Helix-Feeding Demonstrator

Using an iMPD for primary propulsion requires the ability to store and feed high amounts of propellant. For the Lunar Mission BW1 cluster the total required PTFE-mass per iMPD, assuming an effective exhaust velocity of $c_e = 15\,km/s$, was estimated to $10.2\,kg$[15], including margins. A straight breach-fed PTFE-bar would protrude from the satellite by several meters, showing the need for a more sophisticated design. The solution is to use a 3D-Helix-Structure and embed the iMPD into it. The PTFE is then being fed to the iMPD from the sides. An example for a 3D-Helix without the thruster is given in Fig. 5(a). The feasibility of the priniciple has already successfully been tested at IRS by means of a 2D-Demonstrator-Model, side-feeding two PTFE-Semicicles. The feeding was realized by a torsion spring hauling in a bolt-guided string that was mounted to the end of the PTFE-Semicircle. The relatively dense PTFE has a very low surface friction, which implies its utilization not only as propellant but for guiding elements as well. Feeding of a semicircle has been demonstrated in one fluent motion and without any jamming, showcasing the ability to feed up to several PTFE-circles.

The 2D-Demonstrator is depicted in Fig. 5(b), with the torsion spring in the lower left corner. Jamming of the 3D-Helix is critical, so the goal must be to eliminate inner tensions of the PTFE during the manufacturing process. Also the relatively flexible surfaces of PTFE increase tolerances. The ElringKlinger Kunststofftechnik GmbH in cooperation with the IRS, has developed a complex process, involving multistage tempering, to ensure minimal tension and small tolerances. It was chosen to build the helices for the 3D-Helix-Demonstrator. The design was awarded with the DuPont-Plunkett Award in 2007 and has two patents[22,23]. A 3D-Helix-Feeding-Demonstrator will be set-up and tested as part of this project to demonstrate, for the first time at IRS, the feeding of a helix.



(a) Example of a 3D-PTFE-helix.



(b) 2D-PTFE-feeding-demonstrator with SIMP-LEX.

Figure 5. Helix-propellant-feeder for ADD SIMP-LEX.

IV. Scheduled Activities

The main goal of the presented project is the research of iMPD's and the work towards a sustainable solution for investigation of pulsed plasmas in space and future space exploration.

It builds on the achievements and experience of a scientific project run from 2005 to 2008 at IRS, funded by the German Space Center (DLR). The follow-up project presented in this paper was started in late 2010 and is scheduled for a period of three years. It is funded by the DLR and the German Federal Ministry of Economics and Technology. To achieve the goals, meet all requirements and reach all objectives, the project aims at the development and assembly of a laboratory iMPD-system, including the ADD SIMP-LEX thruster.

To realize this, the project is devided into two phases. The first phase ensure test readiness of the iMPD-system until the end of 2012. It includes development and assembly of all components as well as their successive integration into the system. This will be accompanied by functional testing at IRS. The phase also includes the set-up of a new facility at IRS to increase testing capabilities. The facility is required for handling the test schedule in the second phase. To include margins in the time schedule, it also acts as a back-up to expedite component testing in the first phase. In the mean time, this has been accompanied by further activities at IRS since the start of the project. An imparative work on suggesting a classification of PPT's has been carried out, revealing important patterns for the future.[2] Further, the 2^{nd} interantional PPT and iMPD Workshop has been held at IRS in May 2011, successfully facilitating mutual collaboration, research and classification efforts among the working group. To support the University of Tokyo after the

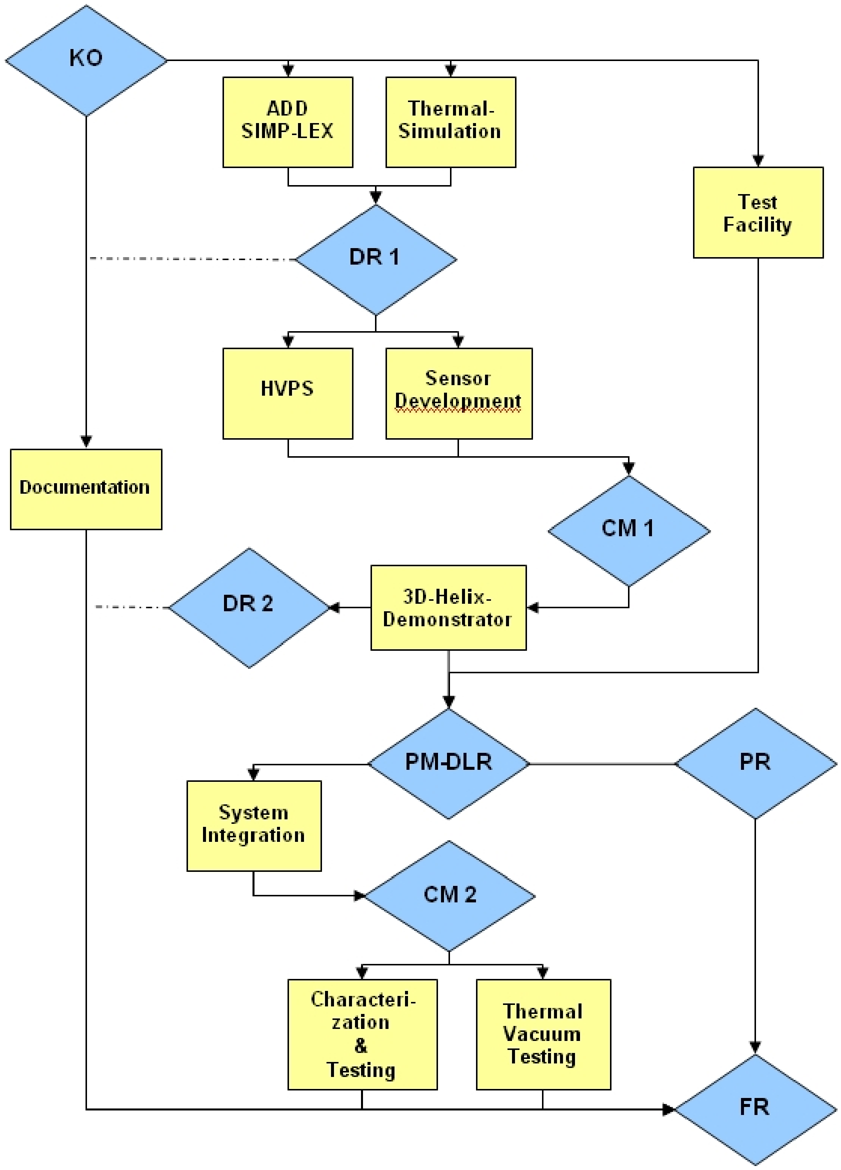


Figure 6. Overview of iMPD-project workflow.

catastrophic events in 2011, a study of the temporal and spacial distribution of the magnetic field of ADD SIMP-LEX to be done in Tokyo was transfered and carried out at IRS. However, the described activities are out of the scope of the presented paper and will not be described in further detail.

The second phase creates data output with an extensive test program for the iMPD-system. The tests aime at characterization of the system and subsequent research with respect to all given objectives. Investigations will include thermal-vacuum-testing at the German Aerospace Center (DLR) in Göttingen, Germany enabled by the mobility of the iMPD-system. The phase is to be completed in late 2013, also concluding the project. Work packages were defined and linked to schedule the jobs of the two phases. An overview of the workflow is given in Fig. 6.

A. Thermal Vacuum Testing at the DLR Göttingen, Germany

The DLR at Göttingen, Germany operates a unique facility for the investigation of thruster plume characteristics and interactions (STG). The ample facility can maintain very low pressures between $10^{-5}\,mbar$ and $10^{-7}\,mbar$ combined with ambient temperatures between $40\,K$ and $5\,K$ during thruster operation. The

STG uses a cylindrical liquid-helium driven cryo pump. For a more detailed description of the facility, please refer to literature.[24] Testing of the iMPD-system in the STG will commence in mid 2013. Measures will be taken to avoid contamination of the sensitive surface of the cryo pump with carbon from the thruster. The tests at Göttingen will complement characterization testing at IRS by providing important information on the system operation and healt in a thermal vacuum environment and contamination.

The latter aims at the investigation of surface contamination effects with propellant residuals close to the iMPD-thruster. The virgin PTFE consists wholly of fluor and carbon. Surfaces exposed to the plasma plume will become contaminated over time with layers of fluor and carbon, caused by a backflow of particles into areas with low plasma pressure and temperature.[25] In addition to a possible transmission degradation of photo-sensitive surfaces on solar panels and optical payloads, the conducting carbon layers could also lead to degradation of electric insulation capabilities. For the measurements, surfaces will be placed in close proximity to the electrodes to monitor the grade of deposition, layer build-up and composition. The results will be used for the modification and evaluation of an analytical iMPD-model developed at IRS.

Prior to testing, the STG will be prepared to allow for integration, instrumentation and operation of the iMPD-system as well as access for data recording. Due to the high costs to operate the cryo pump, the number of hot tests is limited. Therefore first tests will be run with the cryo pump offline to ensure safe operation of the facility and system.

B. ADD SIMP-LEX at the University of Tokyo

Through close and mutual cooperation between the IRS and the Komurasaki Laboratory at the University of Tokyo in Japan, an exchange of research personnel was performed, allowing Tony Schönherr to start his PhD-thesis in Tokyo.[26] A twin-setup of ADD SIMP-LEX was established and integrated into a new test facility in Tokyo. Data consistency was achieved between the setups in Tokyo and Stuttgart with respect to the discharge behavior. After this, investigation of the ADD SIMP-LEX in Tokyo successfully focussed on the performance and plasma diagnostics.[19,20] The work complements research efforts at IRS by delivering valuable insights into the composition and propagation of the discharge plasma.

V. High Voltage Power Supply

Special focus will be also put on the Development of a new Power Processing Unit (PPU). The operation of the iMPD thruster requires a specific high voltage power supply. On the one hand side there is a charge voltage to the capacitor of the iMPD. On the other side there is a High Voltage for the purpose of igniting the iMPD. Requirements like electrical values, safety, very high efficiency and control through a digital interface are design drivers. The mass of the unit was preestimated to approx. $3.5\,kg$, including conservative design margins and assumptions. A better estimation of the unit weight will only be available two months into the development process.

The focus of the development is put on a high efficient light weight design. The PPU provides two independent high voltages for the iMPD thrusters. The charge output provides a voltage of $1,3\,kV$ (tbc.) to charge up the capacitor of the iMPD. This ignition output provides a voltage of $20\,kV$ (tbc.) and is connected to the cathode of the iMPD in order to ignite the thruster. A special charge up circuitry provides a constant power charge up to the capacitor with the advantages of reduced required peak power at the input and reduced input filter requirements. For safety reasons a proper insulation is mandatory on the parts with High Voltage. Internal needed low level auxiliary voltages are generated by the PPU itself. The main requirements for the PPU are given in table 2.

Table 2. General PPU Requirements

Input Voltage	$24\,V$ to $32\,V$
Max. Input Power	$85\,W$
Charge Voltage	$1.3\,kV$
Spark Voltage	up to $20\,kV$
Ignition Frequency	$1\,Hz$

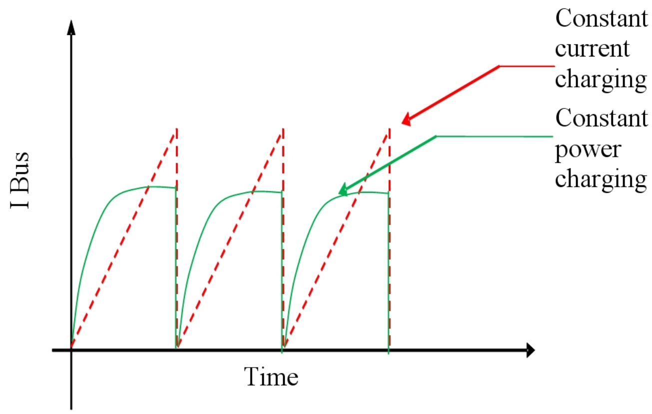


Figure 7. Input current of PPU comparing different charging methods.

A. Design Description

To charge the capacitor of the thruster the PPU uses a step down converter followed by a push pull topology for galvanic isolation and to perform a DC to AC conversion. A special charge up circuitry provides a constant power charge up of the capacitor with the advantages of reduced required peak power at the input and reduced input filter requirements. See Fig. 7.

The voltage required for the spark plug and the internal voltages are generated by a fly-back converter. The PPU is designed to charge up the capacitor in less than $1\,s$. This allows a firing rate of the thruster of $1\,Hz$. The efficiency of the PPU is approx. 85 %. In stand-by mode the PPU consumes less than $1.3\,W$.

B. Operating the PPU

The PPU is controlled via three bi-level commands:

- "Charge",
- "Ignition", and
- "Discharge".

These signals are galvanic isolated via optocouplers inside the PPU. For monitoring the status of the PPU three galvanic isolated open collector and two analog signals are provided:

- "PPU on/off status ", "50 % charge" and "Full Charge",
- "Capacitor Voltage" and "Temperature".

Once bus voltage is applied the PPU starts operating in stand-by mode (high voltage off). The "PPU on/off status" indicates the on-status. By applying the charge command the constant power charging process of the thruster capacitor is triggered. During the charging process the PPU is monitoring the voltage of the capacitor. Once the charge voltage of the capacitor has reached 50 % it will be indicated by the "50 % charge" telemetry signal which will not stop the charging process. If the capacitor has reached the end of charge voltage, the PPU keeps the high voltage constant at $1.3\,kV$ telemetry signal. In addition an analog signal is provided showing the discrete DC-voltage of the capacitor (tbd.V/kV). The PPU does not generate the ignition voltage automatically after the capacitor is completely charged. This gets controlled by an external signal which is called "Ignition". After receiving the ignition-signal, the PPU generates the ignition voltage of $20\,kV$ for approximately $100\,\mu s$. After this event the charging process starts automatically from the beginning. For operational and safety-drive reasons (eg. for on-ground operation) it is possible to discharge the capacitor of the thruster without ignition. Therefore, the "Discharge" command is implemented in the PPU. The temperature of the PPU gets monitored. The analog telemetry signal "Temperature" is provided at the interface of the PPU.

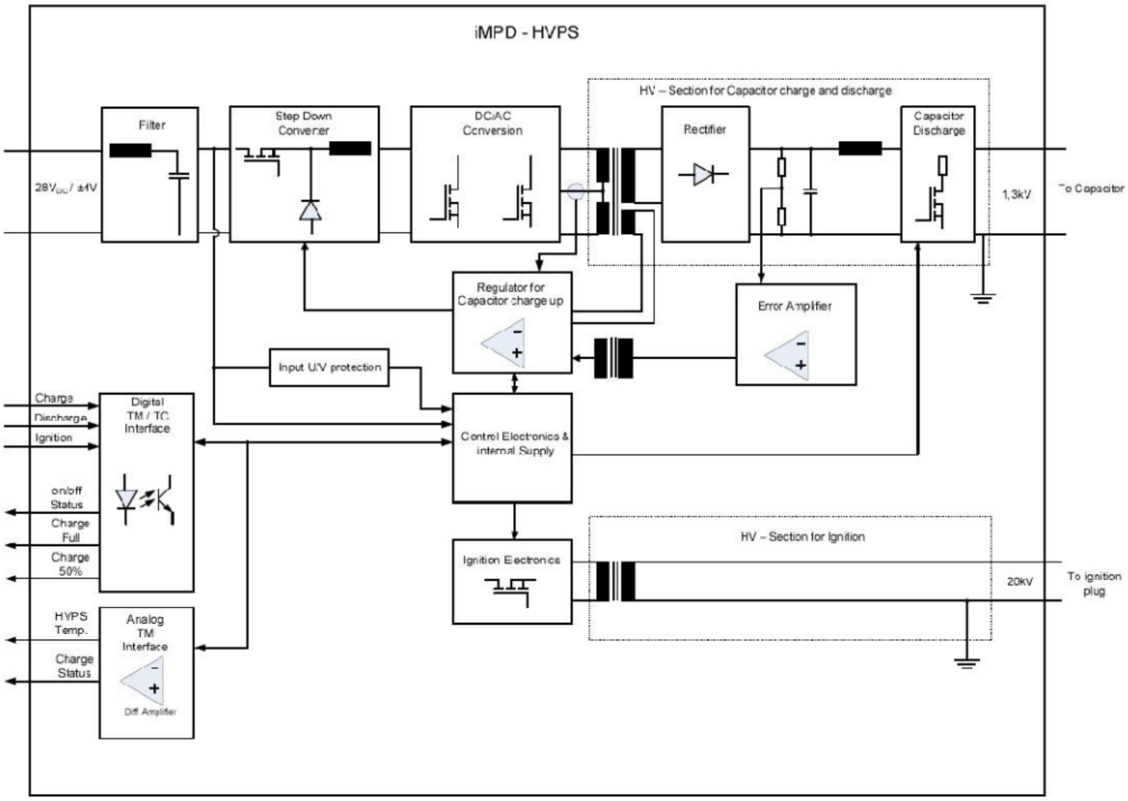


Figure 8. PPU block diagram

A functional diagram of the PPU is shown in Fig. 8. The PPU consist of two sections. The first is the low-voltage-section. The second is the high-voltage-section containing the functionality for the capacitor charge and the ignition spark.

C. The Low-Voltage-Section

This section includes:

- Input filter,
- Step down and push pull converter,
- Control electronics,
- Internal supply,
- Protection functions.

The input voltage gets monitored from the PPU. In case of an under voltage there will be an automatic switch-off. Once the input voltage returnes into the normal operating range, the PPU starts up again. A hysteresis of roughly $2\,V$ avoids ringing caused by the impedance of the bus. For the supply of the control electronics auxiliary voltages are generated from the bus for the start-up of the PPU. During normal operation the auxiliary power is generated from a small separate fly-back DC-DC converter. The input filter reduces the current ripple factor caused by the switched mode power supply to acceptable limits. Furthermore it reduces the susceptibility of the PPU against high frequency noise at the input lines. The capacitor charge process and end of charge voltage are controlled by the step down converter. To reduce the influence to the bus the capacitor will be charged with constant power instead of constant current. The maximum required input current is much lower when the capacitor is charged with constant power. Hence the maximum required

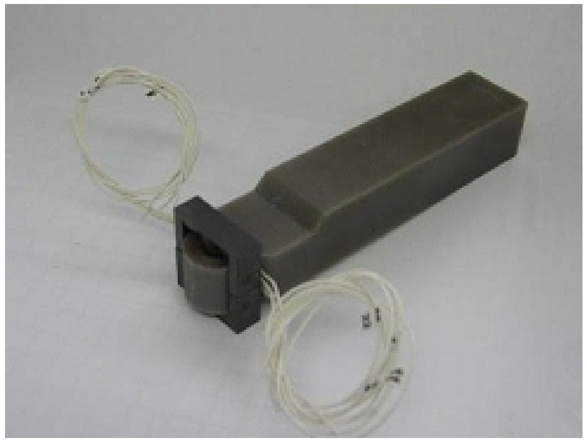


Figure 9. Example of a potted high-voltage-module

peak power is also lower. See Fig. 7. The error amplifier is located on the secondary side of the PPU. The output voltage will be compared to a reference voltage. The output of the error amplifier is transferred to the primary side of the PPU via a small transformer instead of an optocoupler. This has the advantage to be independent from radiation influence in space, which is typical to semiconductors. Using charge up regulator and the control electronics on the primary side, the charging process is performed as described above. The DC to AC conversion is realized by a push pull converter. This AC voltage will be increased by a transformer to $1.3\,kV$. This transformer and the rectifiers are included in the high voltage section of the PPU.

D. The High-Voltage-Section

This section includes:

- HV-Transformer for capacitor charge up and spark plug,
- Rectifiers and voltage dividers,
- Discharge electronics,
- Air-core coil to avoid reverse currents into the HV-Module.

A proper insulation to high voltage, especially in the partial pressure range, is a mandatory design requirement. All components having a high electric potential get potted with a special epoxy resin. See Fig. 9 as example. This kind of potting utilizes 15 years of flight heritage in various space programs. It also contains unique features like:

- A high insulation capability up to $30\,kV$,
- Same coefficient to expansion then electronic PCBs,
- Best possible thermal link to thermal radiating components including outstanding thermal conductivity,
- Operation in critical pressure range possible (Paschen minimum),
- Compact design due to high dielectrically strength,
- Reliable for long term operation.

These features support a high packing density of the high-voltage-section and end up in a small size low weight unit.

VI. Conclusion

The objectives presented in this paper point out the importance for advancing development of iMPD-thrusters such as ADD SIMP-LEX to allow and improve research on the acceleration of pulsed plasmas and their possible applications in space. Combined with a suggested further structuring of the landscape of existing PPT technologies, i.e. classes, standards, trade offs, mission proposals, cooperation mapping etc., desirable benefits for the implementation of sustaining space exploration strategies as well as for national and international research coordination become apparent. Attempts by researchers to advance this process in the past have yielded mixed results with respect to participation and thus often lag legitmization. A more decent forum to focus the flow of all the available information has yet to be established for the international PPT community.

The introduced laboratory iMPD-system represents a new research platform due to its compact size, mobility, advanced technologies and performance. It is expected to be leading in its class of energy and demonstrate new abilities important for increasing the operational range of iMPD at IRS. This includes life-time, space-relevant operation, secondary and primary propulsion capabilities, thrust control and component scaleability. The testing and improvement of the thruster life will take a substancial part of the work as the number of pulses is aimed to be raised to 10 million shots. The expected data output from the study will allow for the first time to draw a more conclusive picture of iMPD-system capabilities, environmental effects, life limiting factors and contamination. An important addition to this work is done on a twin setup of ADD SIMP-LEX at the University of Tokyo by optically investigating the discharge plasma and its propagation.

The new iMPD-system setup will generally improve ground testing at IRS, i.e. facility design and data integrity, by transferring most of the laboratory equipment directly onto the iMPD. This deals mainly with limitations of a common experimental setup with spread out equipment, which is relatively prone to electromagnetic interference. Comparison of data taken from both setups may also uncover differences during iMPD-operation. Also the improvement of measurement techniques is on the way and has recently been carried out at IRS with respect to measurements of the temparal and spatially distributed magnetic field of the ADD SIMP-LEX. To investigate the effect of low ambient temperatures and contamination, thermal vacuum tests will be run in the STG-facility at DLR in Göttingen, Germany to complement tests at IRS.

A new Helix-PTFE-feeding-demonstrator for the iMPD-system will be tested for the first time, using PTFE-helices manufactured by ElringKlinger Kunststofftechnik GmbH. A new temper process will be used to manufacture the Helices to rule out any inner tensions in the material that could lead to jamming. Within the project two subsystems are developed by subcontractors. The first, a HOKA-Current-Sensor, developed by the ETH Zürich will feature an optical data interface and a custom made design to best fit into the compact iMPD-system. An earlier version of this sensor type for the SIMP-LEX iMPD operates flawlessly at IRS since 2007.

The second commissioned subsystem is the High-Voltage-Power-Supply, which will be developed and assembled by the ASP Equipment GmbH in D-88682 Salem-Neufrach. By building on the experience drawn from the development of an existing ASP laboratory breadboard a unique combination of functional capability and cost efficiency is achieved. For laboratory operation in a test chamber at IRS, a thermal interface will be included in the HVPS-Design. The PPU is developed to support research activities in the context of the iMPD ADD SIMP-LEX. It gets operated through a commendable interface and utilizes space level safety means. The design is principally fit for space use, even if that is not intended for this particular PPU. In order to provide a cost effective solution commercial level EEE parts will be applied.

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