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Innovative Liquid Micro Pulsed Plasma Thruster system for nanosatellites

Rendicontazione

Informazioni relative al progetto

L-μPPT

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Final Report Summary - L-µPPT (Innovative Liquid Micro Pulsed Plasma Thruster system for nanosatellites)

Executive Summary:
The current interest for micro-spacecrafts essentially proceeds from the wider availability of enabling technologies (micro/nano-fabrication), and from the desire to reduce development and launcher costs. Nanosatellites and picosatellites are also potentially useful as a mean to increase a mission's reliability by distributing a large payload over a fleet of small spacecrafts. However, the application range of micro-spacecraft is currently restricted by the lack of sufficiently compact, lightweight, high specific impulse micro-propulsion systems. Such micro-propulsion system could also prove useful for fine positioning required by space-based telescope interferometers, imaging arrays and formation flying missions.

Due to their simplicity, reliability, scalability and low weight, Pulsed Plasma Thrusters (PPT) are currently considered one of the most suitable electric propulsion option for small delta-V missions on nano/picosatellites.

PPTs are electromagnetic propulsion devices which store electrical energy in a capacitor to periodically form a high current arc discharge across the propellant (typically Teflon). The energy of the arc vaporizes or ablates the propellant, thus creating an ionized gas which is subsequently accelerated out of the channel to high velocities by the Lorentz force.

A novel type of Pulsed Plasma Thruster (PPT) based on an open capillary design and on a non-volatile liquid propellant has been carried out within the Liquid Micro Pulsed Plasma Thruster FP7 project (L-µPPT). Functional results from prototype testing provide an Isp ~ 1300s, Ibit 25 µNs @ 1000V and 46 µNs @ 1000V, presenting a Ibit/E ratio beyond 40 µN/W. Its design is expected to improve over PTFE-based PPTs by providing significant increase in total impulse, increased propellant utilization, lower impulse bit variability and the possibility to balance propellant requirements between several thrusters with a common tank.

Project Context and Objectives:
PROJECT OBJECTIVES

The L-µPPT project is committed to developing and assessing the functionality of a novel PPT technology based on liquid propellant, expected to enable significant improvements over Teflon-based PPTs in terms of propellant utilization and impulse bit predictability through a tight control of the mass of propellant injected.

By leveraging state-of-the-art MEMS technologies, the L-µPPT project strives to develop a compelling propulsion technology for microspacecrafts offering the scalability and robustness of conventional PPTs with performances in par with modern electric propulsion systems for large satellites.

The L-µPPT project roadmap bases on a two-step implementation which comprehends the development of a first prototype, followed by the design of a fully functional prototype. Each prototype shall have an associated system specification phase, and subsequent design and development phases for each system subcomponents (thruster, injector, electronics, thrust balance and vacuum stand).

Notwithstanding the above-mentioned improvements over state-of-the-art PPT technology, liquid propellant PPTs have several prospective advantages over competing microspacecraft propulsion technologies such as:

• Large specific impulse in comparison to cold gas thrusters or resistojets. While the specific impulse of cold gas thrusters and resistojets is of the order of 50-100s and 200-500s, respectively, PPTs typically offer specific impulses in the range 1000-3000s. This gain in specific impulse translates into an accordingly greater delta-V for a given propellant mass, which considerably widens the scope of missions accessible to microspacecrafts.

• Non-hazardous propellant and components. The use of a non-hazardous technologies has a beneficial impact on the propulsion system safety and reliability, and contributes to reduce its development span and qualification cycle. The safety of the system is of utmost importance as it may affect not only the integrity of the host spacecraft, but of the whole launch vehicle and its payloads. In many cases, the lack of hazardous materials is a strict requirement for satellite developers, as for instance in the CubeSats specification.

• Predictable and precise impulse bits, allowing thus simpler attitude control for nanosatellites, but also precise positioning as may be required for instance by formation flying missions.

These expected advantages must be of course weighted against potential issues associated with this novel technology. In particular, the increase in system complexity incurred by the use of a liquid propellant will be given special consideration so as to preserve as much as possible of the simplicity and robustness inherent to solid propellant PPTs. The development of an affordable and reliable propellant feeding system is in this respect a central challenge to be addressed by the L-µPPT project.

The L-µPPT project is articulated around the following specific technological objectives:

Objective 1 (O1): Definition of the L-µPPT system specifications.

A research action will be undertaken to define the PPT propulsion system specifications:

• Selection of technologies for L-µPPT sub-systems. A TRL (Technology Readiness Level) Matrix will be used to choose suitable technologies, 3 for each L-µPPT sub- systems (thruster, injector, electronics)., and the operational characteristics of the thruster (discharge energy, propellant consumption, ...).

• Design of thruster requirements. Thruster target performance in terms of impulse bit and specific impulse shall be determined. Technological constraints (size, bus voltage, etc) and environmental constraints shall also be identified. In addition to the general requirements of speed, acceleration, and environmental factors, specific requirements such as velocity profile and vehicle characteristics (dimensions and weight) will be established.

• Definition of the system electronics dedicated to the control and monitoring of the PPT (capacitor charge, discharge ignition, thrusters valves in the case of a liquid propellant PPT).

• Specifications of the thrust balance needed for in-vacuum PPT thrust measurements will be defined in accordance with the targeted system performance.

• Design of the vacuum facility and its subsystems (pumps, pressure gauges, etc) to be used for prototype testing.

• Specifications of the supervisory and DAQ (Digital Acquisition) system to be developed for semi-autonomous monitoring of thrusters testing.

• Identification of the tests to be performed to assess the system functionality, reliability, endurance and consistency with initial system requirements. Space qualification of the system is, however, outside the scope of the project.

Objective 2 (O2): Design and development of the L-μPPT propulsion components (first prototype) and of the thrust stand:

• All the components for the prototype thruster will be designed and built based on the results of the definition phase. Parallel to this task, a thrust stand adapted to the IPPLM vacuum facility shall be designed.

• Conventional industrial power electronics and printed circuit boards will be used to develop the power management and control electronics associated to the main propulsion thrusters.

• Routine functionality tests will be carried out at the subsystem and system levels.

Objective3 (O3): Functionality assessment of the first prototype L-μPPT system:

• Vacuum tests will be performed to determine the actual thruster performances (specific impulse, impulses bit, thrust efficiency, power consumption) and the PPU/control unit performances.

• Basic electrical tests will be carried out in a laboratory environment, and simple electrical and structural tests shall be performed under vacuum conditions.

• Reliability tests will be carried out to assess long-term repeatability, lifetime and failure rates.

Objective 4 (O4): Design and manufacturing of final prototype:

• A final assessment of the first prototype will be performed with a view to design an improved prototype. A final prototype will be manufactured and tested.

Objective 5 (O5): Functionality, reliability and endurance characterization of the final prototype:

• A complete assessment of the functionality and long term performance of the final prototype will be performed, followed by a critical evaluation of its compliance with initial specifications.

Objective 6 (O6): Design and development of an automated test-bench for the simultaneous real time characterization of the L-μPPT operation:

• A DAQ system enabling semi-autonomous monitoring of the thrusters parameters shall be be developed and exploited in the experimental investigations of the first and final prototypes.

Although the Liquid-propellant Micro Pulsed Plasma Thruster is primarily meant to address the electric propulsion needs of class II microspacecrafts, its field of application is relatively wide and covers in particular:

• Main Attitude and Orbit Control System (AOCS).

• Formation flying for small satellites. Flying in formation vastly increases the mission range of small satellites. Satellites may then work together, for example by creating array antennas. They may also share capabilities by communicating with each other, or simply provide redundancy to the whole system in case of failure of one of satellites. It is also possible for a small satellite to fly in formation with another object and perform inspector mission. All of those applications require fine thrust control, which is also one of the main advantages of L-μPPT.

• Orbit correction manoeuvres for small satellites (post insertion correction, orbit decay correction). It is essential for some satellites to achieve and sustain optimal (with regard to mission requirements) orbit. Indeed, the precision of initial orbit insertion is often unsufficient. Moreover, the various forces acting upon a satellite such as air drag and solar pressure may cause orbit to decay over long periods. For those reasons it may be necessary for satellites to perform orbit correction manoeuvres. Such a capability may be acquired by using the L-μPPT propulsion system.

• Deorbitation of small satellites in decommissioning phase. The building up of space debris by decommissioned satellites remaining on orbit has prompted new initiatives to define rules and legislation that would force satellite operators to deorbit or put satellites on graveyard orbits past the mission end. For LEO satellites, deorbiting is usually the best solution and can be initiated by an adequate change of orbit that significantly increases atmospheric drag and eventually results in a rapid orbit decay. Again, fuel efficiency is an enabling factor for such maneuvers, which would make the L-μPPT a very competitive solution.

• Final orbital insertion. Because of the relatively high specific impulse of the L-µPPT propulsion system, large delta-V maneuvers can be performed over long periods of time. A practical case study for orbital insertion will be performed to estimate the required onboard propellant mass and typical trip-time for this application.

Project Results:

The L-µPPT project consortium is formed by three SMEs (JMP, NASP and KCI), a research institute (IPPLM), and two industrial partners (MECARTEX and NANOSPACE) As main results for project LuPPT we have a thruster ppt feeded with liquid propellant and a thruster stand using parallelogram based on flexures capable to register µNs range single impulse bit for discontinues operation mode as in PPTs. After period 3 consortium has reached all goals of the project into the planned time.

LIQUID PULSED PLASMA THRUSTER DEVELOPMENT

New concept of liquid feeding of a pulsed plasma thruster has been demonstrated up to TRL 4. Miniature thruster has been developed in two stages, first and second prototypes , having in mind future integration into cubesat´s dimensions.

LuPPT project has demonstrated the feasibility of an electric propulsion thruster based in pulsed plasma feeded with liquid propellant instead of traditional solid Teflon. Main advantages are:

- compactness, with one tank is possible to feed several thrusters

- balance the propellant needs in multi-thruster configuration

- improved usage of propellant mass. Very low remaining propellant at the end of use

- constant discharge geometry along its lifetime instead of solid Teflon block that are eroded and the Ibit varies through the lifetime

Identification and selection of propellant used has been key point for the success of this project. Water was discarded at the beginning in WP1 and substituted by specific liquid among PFPE family due to its characteristics, mainly, low vapour pressure and very similar chemical composition to traditional solid PTFE. No charring in propellant was observed, carbon deposition over exposed surfaces and electrodes occurs as in normal PPTs, but there is no charring signs at all in the dispensing frontal propellant surface, confirming that propellant selected (PFPE family) is one of the very few polymeric propellant suitable for PPTs discharge.

High Isp, 1300 s for second proto has been reached. This performance has been obtained when working at 1000 V with the 2,8 µF capacitor´s bank. In almost all tests performed, Isp has been above 1000 s.

There is a trade-off relating to Isp and T/P, the higher the Isp , the lower the T/P. Higher Isp can be achieved using a smaller propellant exposed area.

Impulse bit achieved 25 µNs (@ 1,5 J Energy shot). Impulse bit can be controlled by means of changing energy discharge (changing voltage in capacitor´s bank) or changing amount of propellant injected.Constant discharge geometry along its lifetime reduces Ibit variation that affects to solid Teflon PPTs due to block propellant eroding.

Thrust to power ratio, 15 to 25 µN/W (@ Isp = 1000 s) is well beyond figures coming from others liquid ppts. It is possible to trade-off Isp and T/P, and all results suggest that this can be done assuming a constant efficiency of 10%. Higher T/P can be achieved with a large exposed propellant area.

Efficiency has been above 10% in all testings. Higher efficiency than state of the art for traditional Teflon PPTs and very stable along different Ibits obtained with different discharge configurations (capacitance and voltages discharges).

Main application for this thruster can be cubesats sector and microsats. Due to compactness and flexibility of propellant feeding system design, a complete propulsion module (including tank and PPU) with 4 thruster can be fitted into a 0,5 cubesat module, extending cubesat´s range mission, allowing cubesat´s attitude control and/or micropropulsion.

Main challenges we have found in the development of the liquid thruster and lessons learnt are described in below paragraphs.

Asymmetric capacitors bank used in second prototype , very focused in facilitating layout adaptability for integration of the thruster into cubesat configuration have been found to have worst performance than symmetric, so this capacitors bank must be mandatory for future developments.

Ceramic high discharge capacitors have been found as critical element for life testing. Although experimental test carried out with single specimens have shown that several alone specimens can support more than 5 millions discharges , once soldered into a bank the life of the whole bank is very reduced compared with single experiments. From single specimens testing conclusion extracted was that millions discharges were reached when operating at maximum voltage 50% from nominal.

At the end of the project capacitors bank reached more than 55.000 discharges and continue operating. Special care must be applied in the design of soldering jigs and temperatures profile used in automatic soldering oven tunnel.

Electronics have been redesigned several times in order to avoid EMI issues achieving a correct operation without microcontroller resetting. Fine control in voltage regulation (and thus in energy control) has been achieved for both ignition spark and main discharge. IGBT components have been founded to be more appropriate than MOSFET ones in order to transfer energy with higher efficiency from the PPU to the spark ignitor.

Fluidics dispensing has been one of the challenges tasks of the project. At the beginning a peristaltic MEMS valve was designed and due to large manufacturing process a syringe pump moved with a micro stepper motor was manufactured for injecting propellant into thruster body.
Testing of MEMS peristaltic valve with liquid (Water) found that there were some leakage issues, so after checking project development risks it was decided to follow an alternative dispensing method using a cots solenoid valve.

For first prototype there was a dual syringe body aluminium tank with a solenoid microvalve and this two parts were tested at a custom test bench for testing propellant delivery at vacuum and at different temperatures using peltiers cells as hot and coolers elements. Stick and slip effects occured into tank´s interface piston-cilinder movement due differences within static and dynamic friction coefficients.

For second prototype, tank was made of extruded PEEK and a filter was added into fluidics circuit. Valve characterization tests were performed and demonstrate that nanoliter dispensing range delivery was reached.

Bubbles in the dispensing has been a issue along the project, several ways to reduce the impact of this bubbles have been applied, several outgassings prior and after filling, new design for tank parts avoiding air trapped, purging procedures and use of Teflon AF tubing to let gas escape were applied but issue persisted in a reduced scale. For future developments a procedure for filling the tank into vacuum must be developed.

THRUSTER STAND DEVELOPMENT

The kinematic of the thrust stand is based on a simple four bars structure, This structure is basically a parallelogram, four rotary pivots allow both parties to guide the output parallel to the base in a circular arc. The choice of this kinematic was driven by the compactness of a such structure, and also for the possibility of adding a stiffness compensation device to reduce the natural frequency.

On a pendulum structure, the possibility of reducing the stiffness is possible, but not adaptive one time the vacuum chamber closed. MECARTEX has manufactured a really innovative concept for this solution. If the stiffness of the parallelogram can be reduced, thus means that a small horizontal force (impulse bit) will generate an horizontal displacement of the parallelogram, the smaller the stiffness, the greater the displacement. Reducing the dimensions of the flexures is one way to reduce stiffness but other is to preload the structure with a force that can be regulated, in order to look for the closest point to the inestability structural behavior.

The idea was to assemble 2 traction springs. One will be fixed, to have about 90% of the load that we need. The second spring will be mounted on an actuator which will let adjust the total force with enough sensibility.

For calibration a coil was designed to emulate an horizontal force as the impulse bit coming from the thruster, so if current injected to the coil is fine controlled a very stable force is inducted and can be used as calibration device. Also this device can be used for damping device to eliminate spurious movements after some time after impulse bits measurements.

Thruster stand has been developed and its performing has result very stable in the thrust range of few µN. With the inclusion of sensors for detecting position of actuators for fine regulation of stiffness and inclination of the surface, calibration procedure results very easy. Calibration shot from the voice coil has been set to 20 µNs in order to have a similar value than impulse bits.

Labview has been used for monitoring, controlling and recording the thruster measurements and interchanges data with labview control coming from Thruster control.

Using flexures in the structure as rotational joints provide several advantages for the thruster stand described hereafter:

Flexible blades = No wear and stick-slip. With the use of flexible blades to define the kinematics, the thruster stand has no wear and no stick-slip effects. This behavior is particularly well-suited to measure very low impulse or continuous force.

Innovative kinematics = Very low adaptive stiffness. The use of an innovative kinematics allow the user to change the stiffness of the Thruster stand. This means that it will be possible to measure different thruster with the same device. The variation of the stiffness is done automatically, by the use of a rotational actuator. It is possible to reach quasi zero stiffness, meaning a natural frequency lower than 0.3 Hz.

Calibration and damping. A complete device to calibrate the Thruster stand is already included. The same device is used to make an active damping to stabilize the stand after a shot.

Compact solution = small vacuum chamber. The Thruster stand is very compact. The active part, doing the measurement, calibration and damping, is about 172mm x 270mm x 60mm. Taking in account also the device to adjust the angle to compensate gravity effects, the complete Thruster stand is 400mm x 400mm x 190mm.

Active regulation to compensate gravity effects. The stiffness being very low, the effects of the gravity are visible. In fact, if the gravity vector is not perpendicular to the displacement axis of the Thruster stand, a projection of this vector, resulting in a force, is generate. This force will, in the worst case, put the stand against the end-stops. To avoid this effect, a complete device was developed, to let at the user the possibility to adjust actively the horizontal angle of the complete Thruster stand. In a such way, it is possible to compensate and reduce the effects of the gravity.

Easy connection interface. The mobile part of the thruster stand has a connection system based on 3 V-grooves at 120 degrees with a magnet to mount and dismount easily the thruster. You don’t need screws to change the thruster, limiting the effect on the thruster stand and the calibration.

Low Thermal sensitivity. Due to the use of Invar® material (near zero coefficient of dilatation<9 for the manufacturing of the Thruster stand, the measurements aren't sensitive to thermal drift and variations.

Thruster stand as it is now it is prepared for measuring single impulse bits in a discontinuos operation mode as usual in PPTs, but with a small modifications can be used for thrust measurements from thruster operating in a continuous mode.

Thrust range measurement can also be modified in the design to cover higher thrust ranges if it is needed.

Potential Impact:
POTENTIAL IMPACT

Today only very few micro/nanosatellites have propulsion capability at all, and L-μPPT offers a small, efficient and reliable propulsion system, the usefulness of these satellites could be greatly improved.

There are many scientific and earth observation missions that would benefit from small and controllable satellites. In some cases, propulsion capability on a micro/nano satellite can also enable new missions or applications. One example is inspector satellites, i.e. small spacecrafts that are manoeuvring around bigger satellites or the international space station.

Due to the advantages of the innovation of liquid feeding to PPT´s,:

- compactness, with one tank is possible to feed several thrusters

- balance the propellant needs in multi-thruster configuration

- improved usage of propellant mass. Very low remaining propellant at the end of use

- constant discharge geometry along its lifetime instead of solid Teflon block that are eroded and the Ibit varies through the lifetime

Due to low cost of the solution it can be focused for application into picosats sector (cubesats) and microsats.
LuPPT can be used as micropropulsion and/or AOCS system. As micropropulsion can be used for several manouvres:

- Drag compensation in LEO: overcoming drag can produce two advantages, longer mission range and allowing to operate in very low altitude LEO orbits.

- Orbit correction manouvres. Allowing to convert elliptical orbits into circular ones more appropriate for observing earth.

- Insertion into desired orbit: changing from initial launcher orbit to desired orbit for operation.

- Fast deorbitation (controlled EOL). In future regulations can modify time operation in space in order to reduce space debris.

- Formation flying: an array of nanosatellites could be positioned after separation in a precisely controlled formation creating a large synthetic aperture sensor; alternatively, loosely controlled constellation could be spread out to achieve continuous coverage around the globe. QB50 project is a perfect example.

- Space exploration, several missions are being studied nowdays, Moon and Mars observation are projects ongoing.
As AOCS system can be used as main AOCS system or as device for unload saturated reaction wheels.

Module with 4 thruster placed at the corners of a 3U cubesat has been modeled and several orbit maneuvers have been calculated. Simulation results demonstrate the capability of this thruster to allow propulsion and attitude control for this type of spacecrafts.

DISSEMINATION ACTIVITIES

A web project has been launched (www.liquidppt.eu) where general information about the project can be found and different contact possibilities are given. Private part of the web has been used for the different partners to interchange information for the development of the tasks.

Project brochure and information banners have been prepared and some merchandizing articles have been manufactured for promotion the project.

Project has appeared in several mass media (newspapers, tv, radio) given a comprenshible approach of the project to the general public.

Partners have been involved in elaboration of scientific papers and presentation of the project at different conferences related to space propulsion and small sats at worldwide. As remarkable success , paper presented at 33rd IEPC(Washington) by IPPLM was selected at best paper session.

Contacts with different Universities have been performed in order to present a capable propulsion method for educational future cubesats launchings trying to expand the mission range.

ESA is informed about the project´s development and results in order to be included in the study of next H2020 electric propulsion program.

EXPLOITATION ACTIVITIES

From the LuPPT we can extract two potential products, a low thrust electric propulsion system and a thruster stand capable of measuring very low impulse bits.

Related to the development of a low thrust electric propulsion system, the L-µPPT is mainly focused on the nano/microsatellites market. The current interest for microspacecrafts essentially proceeds from the wider availability of enabling technologies (micro/nano-fabrication), and from the desire to reduce development and launcher costs. Projections based on announced and future plans of developers and programs indicate between 2,000 and 2,750 nano/microsatellites will require a launch from 2014 through 2020. It reflects a significant increase in the quantity of future nano/microsatellites needing a launch.

The development of LµPPT was starting in end 2011 from TRL1 with for the main part of the system, i.e. the thruster, only a background of "Basic principles observed and reported" coming from the bibliography and published papers.

Very fast the TRL improved to TRL 2 with "Technology concept and application formulated" and further, in end 2012, TRL 3 was reached with "Analytical and experimental critical function and characteristic proof-of-concept" that were performed on the first prototype.

The second prototype in 2014 allowed to reach TRL4 "Component and breadboard validation in laboratory environment”. In parallel to the thrusters itself, the other components of the system (tanks, fluid distribution, thruster electronics, spark generation system, communication TCTM) have been breadboarded and progressively their design has been improved for being compatible with the intended use with the thruster.

According to Technology Readiness Levels definition, current LuPPT prototype is identified as TRL4. It means that it’s tested in a laboratory environment and the technological proof of concept has been reached. However, at this level, the thruster, as it is, is not a commercial product. Hence, from the exploitation perspective, the proposal is mature the thruster and increase the Technology Readiness Level, in order to go ahead into commercialization phase.

For this purpose a roadmap for future TRL enhancing has been defined, determining a minimum of 2 years project to reach TRL 9. This project continuation can be done through public or private funding ways.

For public funding ways, exploration of different possibilities are studied to continue with the improvement of this technology:

• H2020 is the new EU funding program for research and innovation running from 2014 to 2020. It has been submitted two proposals from the consortium for attending the EPIC (Electric Propulsion Innovation & Competitiveness project) meeting to be held on 25-28th November in Brussels, where activities related to electric propulsion will be exposed in order to provide a roadmap of activities and a master plan for upcoming calls in this field.

• ESA Innovation Triangle Initiative (ITI) supports the identification, validation and development of disruptive space innovations based on new ideas or concepts, giving preference to innovations coming originally from non-space industrial or research sectors. Three types of contract activities aimed at the different development stages: proof of concept (for inventors), demonstration of feasibility and use (for developers) and technology adoption (for customers). L-µPPT would fit in the technology adoption stage in order to be validated and tested under the key characteristics of the relevant environment (which normally for the proposed ITI activities is the space environment) - TRL 5.

• ESA EMITS System allows industry, institutes and national agencies to issue their own invitations to tender for space. L-µPPT project would comprehend the exploitation lines described in the ESA Roadmap Aims.

Different private companies related to small sats and propulsion systems should be considered in order to present LuPPT as a valid alternative for propulsion/AOCS subsystem:

o CU Aerospace offers both standardized and custom propulsion systems for CubeSats and other small satellites.
-Propulsion Unit for Cubesats (PUC)
-Cubesat High Impulse Propulsion System (CHIPS)

o Clyde Space is a supplier of small and micro spacecraft systems.
-CubeSat Pulse Plasma Thruster

o Busek has developed several types of thrusters systems for CubeSat missions and other small spacecraft.
-Electrospray Thruster
-Micro Resistojet
-Micro Pulsed Plasma Thruster
-RF Ion Thruster
-Green Monoprop Thruster

o Aerojet Rocketdyne offers a full spectrum of flight qualified propulsion products ranging from chemical and electrical propulsion systems to individual monopropellant, bipropellant, and electric propulsion engines
-CubeSat Modular Propulsion Systems (MPS-110, MPS-120, MPS-130, MPS-160)
-SmalSat Modular Propulsion Systems (MPS-220, MPS-230, MPS-250, MPS-260, MPS-270)

Related to development of the thruster stand, this product has found a novel maturity level and can be considered as a commercial product ready for market, being target customers propulsion laboratories. Two institutions have shown interest on it.

Thruster stand developed specifically for this project is ready for measuring single discontinuos operation mode (typical in PPTs) and the impulse bit measuring range is up to 100 µNs. This design can be adapted to measure propulsion systems working in a continuos operation mode and thrust range can be fitted up to several N.

List of Websites:
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