PLEGPAY: A Plasma Contactor Experiment on the International Space Station*†

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Abstract

PLEGPAY (PLasma contactor Electrical Grounding PAYload) is an experiment for the in-flight validation of the plasma contactor as an active device for the prevention/control of electrostatic charging on large space structures orbiting in LEO and for addressing scientific investigations on plasma/spacecraft interactions.

The validation of the plasma contactor technology will be carried out also in view of possible future applications/utilizations on board the ISS where "Tethered Systems" are deployed from the ISS, with the purpose of performing electro-dynamic experiments or to pursue technology applications (e.g. power generation or "re-boosting").

PLEGPAY has been selected by ESA for accommodation on the EuTEF, the European Technology Exposure Facility, developed by. Carlo Gavazzi Space under ESA contract to provide the logistics support for different experiments during the ISS early utilization.

The development/qualification of PLEGPAY is currently underway under ASI contract and ESA co-ordination.

The plasma contactor device is directly derived from the cathode/neutralizer technology developed by LABEN/Proel for Electric Propulsion applications [1], [2].

In this field LABEN/Proel has developed and qualified cathodes/neutralizers for electron currents in the range 0.3 – 5 A. Recently the development of a 20 A device has been started.

In the paper a detailed description of the PLEGPAY assemblies, as well as of the foreseen in-flight experiments, is addressed. An overview of the mass, envelope and power budgets related to the payload is also presented. PLEGPAY is expected to be integrated on the EuTEF by 2003. The launch is foreseen at the beginning of year 2005.

Introduction

The plasma contactor technology, based on hollow cathode plasma generation, is retained the most viable technology to be used in space to face problems/applications and exploitations related to the “spacecraft/ space environment interactions”.

Currently two types of main applications are identified for the technology in space utilization:

- control/prevention of the electrostatic charging of a spacecraft/ space infrastructure
- electro-dynamic experiments/applications based on “Tethered Space Systems”.

The International Space Station (ISS) can assume the role of both a “direct user” and a “spaceborne test bed” for the plasma contactor technology operational

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validation, with reference to the applications above introduced.

First of all, the ISS itself can take direct advantage of the plasma contactor technology to prevent/ mitigate possible drawbacks associated to the electrostatic charge accumulation on the ISS exposed surfaces.

In fact, when the ISS Solar Arrays (operating at output voltages of 140-160V) are producing power, the ISS frame structure will also tend to float to voltages as large as –120 V with respect to the space plasma. Under these conditions, the ISS could be subjected to electrical problems like arching or uncontrolled fast discharges between its surfaces and the external space plasma environment. The arising of electrical discharges could be of serious concern, other than for interferences/ malfunctioning in the electronic on board apparata, also, and most of all, for the manned EVA and the "rendez vous" / "docking" maneuvers, necessary for the surviving, servicing, maintenance and development of the ISS itself.

In order to avoid these problems the structure can be forced to "ground" to the local space plasma potential by using plasma contactors.

This plasma contactor technology utilization on the ISS is presently foreseen by a US program [3] aiming at endowing the ISS sections under direct US responsibility with plasma contactor device/s developed and supplied by US Companies in cooperation with NASA [4], [5].

Beyond this application, the ISS can take advantage of the plasma contactor technology if, as most likely foreseen in the next future, "Tethered" systems will be deployed from the ISS to perform either electro-dynamic experiments and/or to generate electrical energy or alternatively thrust (depending on the sense of circulation of the electric current within the tethered system) for the "servicing" of the ISS itself.

In shadow, the actuation of the plasma contacting process can allow the generation of electric power for direct on board utilization. Conversely, in sunlight, the current in the Tethered System could be forced in the opposite sense (using, as well the plasma contactors and a suitable voltage supply) to allow the generation of a propulsion thrust, usable to eventually re-boost the ISS.

In addition to the direct utilization of the plasma contactor technology for the ISS needs, the ISS can be used as a "test bench" for allowing the full characterization/validation of the technology also in view possible utilizations on future space vehicles and satellites.

In this framework, the PLEGPAY experiment (PLasma contactor Electrical Grounding PAYload) on the ISS has been conceived and defined. The experiment aims at performing a comprehensive experimental investigation, in space, of the plasma contacting process as well a study of the spacecraft/space environment interactions in LEO, with reference to the electrostatic charging phenomena and possible impacts on the solar array operation.

The PLEGPAY experiment can furthermore be retained a further opportunity to confirm the plasma contactor as a tool for safeguarding the spacecraft electrical environment. This technology, in the very near future, could be extensively proposed and used as a standard facility at disposal of the commercial and scientific satellite community.

PLEGPAY overview

The PLEGPAY experiment, proposed By LABEN/Proel, has been technically evaluated and selected by ESA for accommodation on the EuTEF (European Technology Exposure Facility), i.e. on the physical and operational infrastructure which provides the support and logistics for a wide range of in orbit investigations and experiments during the ISS early utilization.

The development and qualification of the PLEGPAY hardware is sponsored by the Italian Space Agency (ASI) which has awarded the relevant contract to LABEN/Proel.

The main achievements expected from the PLEGPAY experiment/payload are here below summarized:

- Validation of the performances of the plasma contactor through the determination of the current-voltage characteristics, when used as a device for grounding the spacecraft frame structure.

- Verification of the plasma contactor charging prevention capability under induced spacecraft charging conditions from the environment

- Characterization, through the plasma diagnostic package, of the environmental modification induced by the plasma contactor operation

- Evaluation of the plasma contactor technology performance through long term operation.

- Assessment of interaction effects between a solar cell sample and the plasma contactor emission plume.

The PLEGPAY hardware is composed by the following main units/assemblies:

- Plasma Contactor Assembly (PCA), including the plasma contactor device and associated services

- Body Conditioning Assembly (BCA), used as a reference structure for "forced" charging/discharging experiments

- Plasma Diagnostic Assembly (PDA), including a Langmuir Probe (LP) and relevant front-end electronics

- System Control Unit and Bus Adapter (SCUBA), including the experiments control/signal exchange and the power distribution

- Solar Cell Assembly (SCA), including a solar cell sample and discharge detection electronics

The experiments addressed by PLEGPAY

A sets of 4 experiments and a long duration test are planned to be performed using the PLEGPAY hardware. In order to better visualize the experiments philosophy and the most significant hardware items involved, the sketch of Fig. 1 is presented.

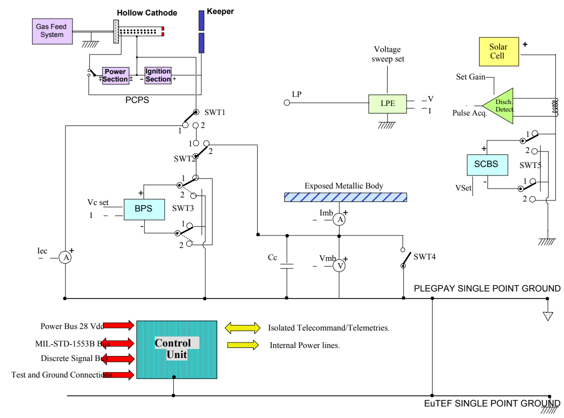

Fig. 1: PLEGPAY experiments functional scheme

Experiment 1: Plasma Contactor I-V characterization

This experiment has the purpose of validating the plasma contactor technology in the actual ionospheric environment, through the measurement of the device capabilities to exchange electric currents, as function of potential unbalance.

This characterization is obtained by biasing, with a suitable power supply (whose voltage swings in absolute value between the keeper voltage and 100 V), at different positive & negative potentials, the plasma contactor w.r.t. the S/C frame and measuring the exchanged current with the space plasma.

Experiment 2: S/C Charging Control

This experiment aims at verifying the plasma contactor capability to control the S/C electrostatic charge build-up. If, during the orbit, there are some environmental conditions for which the S/C frame is charged w.r.t. the space plasma, the plasma contactor is operated to force the S/C active discharging.

During the experiment the LP is used to provide an indication of the S/C potential with respect to the local space plasma potential.

Experiment 3: Potential control of a floating metallic body

In this experiment the plasma contactor is operated to perform the "grounding" of a structure electrically insulated from the S/C frame. The structure is a reference metallic body that is artificially charged to the desired potential by a voltage source, being the assumed voltage continuously monitored through an electrometer or a high impedance voltage meter.

The plasma contactor operation can be tested w.r.t. two different conditions:

continuous injection of current from a current source (that practically can be the power supply used for the plasma contactor I-V characterization), to simulate a constant shower of charged particles onto the S/C. The plasma contactor operation in this case should limit the potential growth beyond a certain value;

charging of the body at a certain potential, disconnection of the current source and operation of the plasma contactor to verify its capability to completely discharge the charged body. Within this experiment the dynamics of the possible "natural" discharging (without the plasma contactor operation) can be also studied.

Experiment 4: Solar Array plasma interactions

The solar cell sample is biased at growing potentials (positive & negative), simulating thus the conditions in which a solar cell patch is operating, within a large solar array. Possible discharge events are detected and characterized with, and without, the plasma contactor operation.

When plasma contactor is operated two configuration can be used:

- plasma contactor connected to the S/C frame
- plasma contactor floating (configuration whose adoption has to be verified with the ISS authority for Safety aspects).

It is expected that second configuration can allow the characterization of the solar cell sample operation in presence of a “plasma cloud” not referred to ground and eventually the detection of “plasma triggered” discharge events.

The plasma environment monitoring during the accomplishment of the experiment is performed by operating the Langmuir Probe.

Experiment 5: Plasma Contactor Long Duration test

This experiment aims at validating the plasma contactor technology suitability in view of long term operation and missions on the ISS itself or on other European Spacecrafts.
For the lifetime validation of Plasma Contactor the device will on/off operated with a suitable duty cycle (e.g. 1 hour on / 1 hours off).

During the plasma contactor lifetime test the Langmuir Probe will be operated to detect impacts of the plasma contactor operation (or non-operation) on the environment surrounding the ISS.

PLEGPAY hardware composition

As mentioned before, PLEGPAY instrument is mainly composed by the following assemblies:

- Plasma Contactor Assembly (PCA)
- Body Conditioning Assembly (BCA)
- Plasma Diagnostic Assembly(PDA)
- System Control Unit and Bus Adapter (SCUBA)
- Solar Cell Assembly (SCA).

Plasma Contactor Assembly (PCA) is composed by:

– Plasma Contactor Device (PCD)
– Gas Feed System (GFS)
– Plasma Contactor Power Supply (PCPS), including the power and ignition sections and related telemetries.

Body Conditioning Assembly (BCA) is composed by:

– Metallic Body Electronics (MBE) which includes the exposed Metallic Body (a metallic plane of about 150 mm ∅ with insulated mechanical supports), the switches, the storage capacitance, the body voltage monitor
– Bias Power Supply (BPS).

<u>Plasma Diagnostic Assembly (PDA)</u> *is composed by:*

- Langmuir Probe (LP)
- Langmuir Probe Electronics (LPE) including Conditioning and Pre-processing Electronics.

<u>System Control Unit and Bus Adapter (SCUBA)</u> *is composed by:*

- Experiment Control Unit + Memory (ECU)
- TLM/TLC Interface (TIF)
- Power Distribution (POD).

<u>Solar Cell Assembly (SCA)</u> *is composed by:*

- Solar Cell Sample (SCS)
- Discharge detection and sample voltage bias Electronics (DBE).

The Plasma Contactor Device is directly derived from the "high performance" cathode/neutralizer developed by LABEN/Proel (under ESA/ASI contract) to fulfill Electric Propulsion applications, in particular with the PPS 1350 plasma thruster (SNECMA) [6].

A picture of the cathode, currently under qualification under the ESA/ASI contract, is shown in Fig. 2

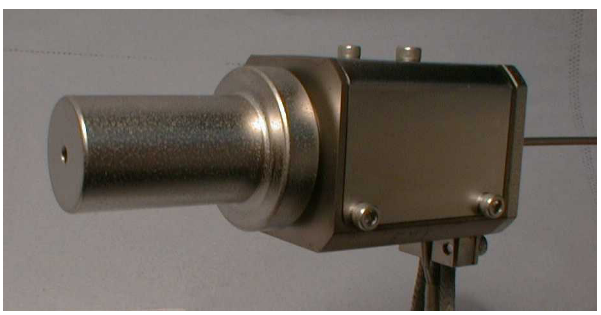

Fig. 2: High Performance Hollow Cathode assembly (HCA) developed for the PPS 1350 Plasma Thruster (SNECMA)

The main features of the cathode are summarized in the following table

- Discharge Current: 2-5 A
- Nominal Gas flow rate (Xe, purity 99.999%): 0.2-0.6 mg/s
- Ignition voltage: 100 V
- Oxygen/Humidity absorber: included in the cathode body
- Heater characteristics:
  - *resistance : 0.25 ohm (cold), 0.6 ohm (hot)*
  - *voltage: 10 Vdc, Max*
  - *current: 6 Adc, Max*
  - *power: 60 W, max*

- Start up time: 200 sec
- Steady state power (cathode-keeper discharge): 25-45 W
- Steady state oper. Temp. (heater switched off): 950-1000 °C
- Dimensions: ϕ 20 x 100 mm
- Mass: 150 g (without cable and connector)
- Electrical connections : 3 wires (body, heater, keeper)

The PDA is practically based on a sub-set of the Electric Propulsion Diagnostic Package (EPDP) that LABEN/Proel has developed and qualified for the European satellites STENTOR and SMART-1 (see Fig. 3).

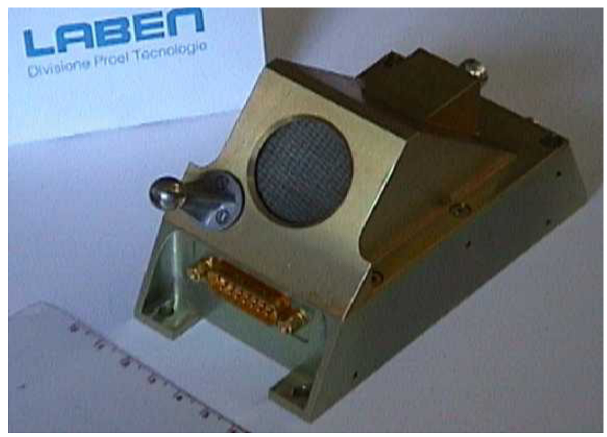

Fig. 3: Plasma Probe developed for the SMART-1 satellite (the LP is located to the left)

Within the PLEGPAY experiment the LP is used to measure the plasma parameters in the vicinity of the plasma plume generated by the Plasma Contactor, nominally the plasma density, the plasma potential and the electron temperature.

The LP hardware is basically composed by a metallic probe (spherical) whose diameter is 13 mm. The LPE contains the sweep generator for the voltage swing to be applied to the LP, the conditioning electronics for the acquired current signal (I-V characteristics), the automatic range selection/adjusting device and the DC/DC sections for the generation of the necessary reference voltages.

PLEGPAY budgets

The PLEGPAY mass, envelope and power budgets are summarized in the following table:

Parameter	*Value*
Mass	About 15 kg
Envelope	253 x 258 x 555 mm
Peak power	180 W
Idle mode power	70 W

PLEGPAY Architecture definition and accommodation on the EuTEF

Each payload allocated on the EuTEF (including PLEGPAY) will comply with requirements fixed by ESA/Gavazzi. Therefore, any experimenter shall:

- Arrange the experiment/ hardware configuration to fit the foreseen geometrical envelope.
- Comply with mechanical and thermal constraints.
- Perform "ad hoc" detailed design, rather than use in house existing standards .

The PLEGPAY unit will be accommodate on the support structure of EuTEF (TBC) in order to take the advantage of having two radiating surfaces, as shown in Fig. 4

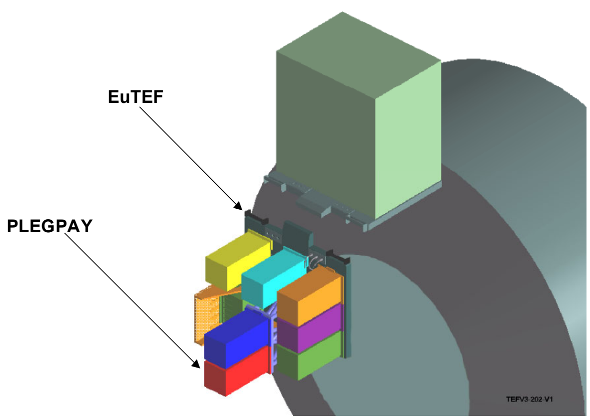

Fig. 4: PLEGPAY and EuTEF on Columbus External Payload Facility

This approach required much more development effort with respect to the allocation directly on the Express Pallet (foreseen in the early stage of development) and it has resulted very challenging for PLEGPAY whose hardware is characterized by:

- several technologies and materials, with their own operating temperature limits
- various types/concepts of power supplies
- power dissipation in excess of some tens of watts
- hardware weight in order of 15 Kg
- presence of a xenon, high pressure, tank.

For these reasons an extensive design/analysis activity has been necessary, addressing in particular:

- hardware reconfiguration and study of an "ad hoc" PLEGPAY flight hardware layout
- sophisticated thermal design and definition of internal/external provisions, considering the operating limits imposed by the EuTEF constraints
- study and definition and implementation of additional ground and flight procedures for the experiment control/safety
- Redefinition/refurbishment of the design of many PLEGPAY subassemblies.

PLEGPAY Development philosophy

PLEGPAY experiment will be developed at Proto-Flight Model (PFM) level. Prior to freeze the (PFM) design PLEGPAY concept/philosophy will be fully validated on ground through:

- Design and realization of a FDM (Functional Development Model) with the purpose of verifying the PLEGPAY experiment concept, by extensive functional testing in plasma
- Extensive computer modelization and thermal – mechanical simulation.

The FDM (phase B) will be functionally representative of PLEGPAY experiment main functions/features. Of course, for what concerns the mechanical configuration aspects, this model appears as a set of laboratory boxes, equipment or electronic racks, connected by laboratory harness and controlled/commanded by a computerized workstation.

The FDM will be extensively characterized in the LABEN/Proel vacuum facility where an additional tenuous plasma source will be used to render the on ground test environment "reasonably" similar to the space plasma environment.

For the definition of the PLEGPAY design, tools for thermal-mechanical modelization (ANSYS 5.7 code) and computer simulation of the PLEGPAY structure and internal sections, to assess the necessary strength margins, hot spots, operating limits, feasible in flight experimentation timeline, have been extensively used.

The development of the PLEGPAY PFM (Phase C/D) will be initiated with the procurement/ manufacturing of PFM model parts/ subassemblies. The PLEGPAY PFM hardware will be assembled in a single self-sustained structure featuring the mechanical and electrical interfaces with EuTEF.

The tests campaign on the PLEGPAY instrument will finally performed, with the aim of verifying the Proto-Flight hardware functional and performance operation. In particular the PFM test campaign will include:

- electrical/ mechanical checks at various levels
- functional/performance test
- thermal-vacuum test
- vibration test
- EMC test

Preliminary Results of the on ground experimental activities on the FDM

The baseline approach used to develop the plasma contactor has been to design a model that would accommodate both a large electron current emission capability and the thermal and mechanical interface requirements for the installation of the unit on EuTEF.
An experimental verification of such an approach has been performed by testing performances and functional requirements of the device and to simulate, at the large extent as possible, the operative sequences foreseen for the flight mission.

The electrical configuration reported in fig. 1 has been implemented through a dedicated EGSE formed by laboratory power supplies, potential and current monitors and switches for H/W items selection.

Fig. 5 shows the typical emission current characteristic versus the clamping voltage, in the case where the plasma contactor is negatively biased with respect to the ground facility (which simulates the space plasma)
As one can see, the emission current exhibits a significant increase at a clamping voltage of ≈ 30 V. The curves are referred to different values of the xenon mass flow rate.

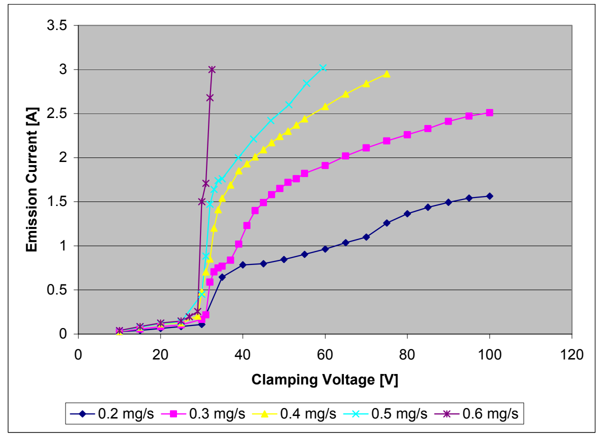

Fig. 5: Typical current-voltage characteristic in clamping mode

As regard the discharging capability, the transient waveforms associated with the natural decay and with the PCD operation are compared in the plot of fig. 6.
In the case of positive charging (+50V in the plot) of the metallic body with respect to the PCD, the drop of the target potential is significantly faster than the case in which the target potential would be initially set at a negative potential. This is due to the much more clamping effectiveness of the electron emission current with respect to situation in which electrons are collected at the keeper electrode

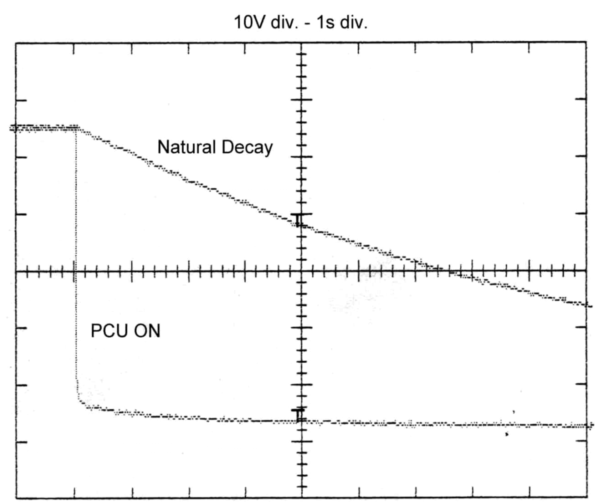

Fig. 6: Transient waveforms for the discharge of the metallic body (FDM test activity)

Conclusions

The confirmation of the effectiveness of the plasma contactor technology, based on the orificed hollow cathode, is of primary importance in view of future applications/utilizations on the ISS both referred to the electrostatic charge control issue and to electro-dynamic experiments based on "Tethered Satellite Systems".

PLEGPAY is an Italian experiment, selected by ESA for accommodation on the EuTEF, conceived for a comprehensive in-flight validation of the plasma contactor technology developed at LABEN/Proel.

The plasma contactor device of the PLEGPAY experiment is directly derived from the cathode/neutralizer technology developed by LABEN/Proel for Electric Propulsion applications.

The PLEGPAY payload is based 5 assemblies (plasma Contactor Ass.y, Body Conditioning Ass.y, Plasma Diagnostics Ass.y, System Control Unit and Bus Adapter and Solar Cell Assembly) and it has been conceived for allowing the performing of 5 sub-experiments (Plasma Contactor I-V characterization, S/C charging Control, Control of Potential of a floating metallic body, Solar Cell – Plasma interactions and Plasma Contactor long duration test).

The PLEGPAY development is, at the time of the writing of this paper, at the stage of manufacturing and characterization on ground of a Functional Development Model (FDM) functionally representative of the flight hardware. The preliminary results of the FDM characterization have been presented in the paper.

The PLEGPAY Proto-flight Model (FDM) is expected to be completed and integrated on the EuTEF by 2003. The experiment launch is foreseen at the beginning of year 2005.

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