# PPTCUP lifetime test results

## IEPC-2013-164

*Presented at the 33rd International Electric Propulsion Conference,*
*The George Washington University • Washington, D.C. • USA*
*October 6 – 10, 2013*

S. Ciaralli[1]
*University of Southampton, Southampton, UK, SO17 1BJ*

M. Coletti [2], F. Guarducci[3]

*Mars Space Ltd, Southampton, UK, SO14 5FE*

*and*

S. B. Gabriel[4]
*University of Southampton, Southampton, UK, SO17 1BJ*

**PPTCUP is an ablative pulsed plasma thruster designed to provide translational control for Cubesat platforms. The engineering model presented in this paper has been developed by Mars Space Ltd, Clyde Space Ltd and the University of Southampton to optimize the performances whilst keeping lifetime long enough to fulfill the mission requirements. A lifetime test campaign has been carried out to prove the thruster and the conditioning electronics lifetime. The experimental campaign achieved more than 1,800,000 shots. The results gathered will be presented, showing that overall performances are not influenced by the thruster aging.**

## Nomenclature

A-PPT= Ablative Pulsed Plasma Thruster
$C$ = capacitance
$E$ = energy
EM = Engineering Model
QM = Qualification Model
GSE = Ground Support Equipment
$Ibit$ = impulse bit
$Isp$ = specific impulse
$I_T$ = total impulse
$m_{bit}$ = mass bit
MSL = Mars Space Ltd
SEM = Scanning Electron Microscope
EDX = Energy Dispersive X-ray
$t$ = time
UoS = University of Southampton

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[1] PhD student, Physical Sciences and Engineering, sc2d11@soton.ac.uk
[2] Director, michele.coletti@mars-space.co.uk
[3] Propulsion Engineer, francesco.guarducci@mars-space.co.uk
[4] Professor, Physical Sciences and Engineering, sgb2@soton.ac.uk

$V_0$ = initial capacitor bank voltage
$\alpha$ = propellant divergence angle
$\eta_{th}$ = overall efficiency

## I. Introduction

CUBESATS are one of the fastest growing sectors in the space industry, allowing for cheap access to space. They are normally launched into sun-synchronous or LEO orbits with an altitude of about 600-650 km. They are currently limited by their lack of orbit control and their lifetime is therefore determined by the natural, drag-induced, de-orbiting. Ablative Pulse Plasma Thrusters (A-PPTs) have been proven to be suitable for Cubesat applications, thanks to their high scalability in terms of geometry, power input and performance and to their relative low cost. Developed in the late 60s, A-PPTs represent the first example of electric propulsion successfully employed in space with Zond-2 (USSR) and LES-6 (USA) the first satellites to have used plasma thrusters[1]. From then on, A-PPTs have been designed and developed, focusing not only on high or very high energy (up to 100 J) devices[2], but also on low energy (< 10 J) thrusters that may be used for the orbital and/or attitude control of pico, nano and micro satellites[3].

Mars Space Ltd (MSL), Clyde Space Ltd, and the University of Southampton (UoS) successfully completed a research study funded by the ESA ITI program producing the design of the first version of PPTCUP able to double a 3U Cubesat lifetime and consequently increasing its economical attractiveness[4]. Starting from that design, the PPTCUP engineering model (PPTCUP-EM) has been developed at MSL to optimize its performances whilst keeping lifetime long enough to fulfill the mission requirements and to deliver a total impulse $I_T$ = 44Ns to use for drag compensation and/or translational control in Cubesat missions. The orbit keeping capabilities shown in Table 1 are an example of a possible application of PPTCUP, that can double the lifetime of a 2U Cubesat orbiting at an altitude of 250 km.

A lifetime test campaign has been carried out to demonstrate PPTCUP-EM lifetime and to qualify the unit for space flight. In this paper the design of the thruster and the experimental results are reported.

**Table 1 – A-PPT orbit keeping capabilities**

| Altitude | CubeSat Size | Natural Life | Life with PPTCUP | Life increase |
|---|---|---|---|---|
| 250 km | 1U | 5.7d | 17d | +200% |
| | 2U | 11d | 22d | +100% |
| | 3U | 17d | 28d | +66% |
| 350 km | 1U | 2m 8d | 5m 21d | +150% |
| | 2U | 4m 16 d | 8m | +75% |
| | 3U | 6m 24d | 10m 8d | +50% |
| 450 km | 1U | 1y 5m | 3y 3m | +133% |
| | 2U | 2y 10m | 4y 8m | +67% |
| | 3U | 4y 2m | 6y | +44% |

100 $cm^2$ area, $C_D$=2.2, NRLMSISE-00 atmosphere

## II. Thruster Design

In this section the thruster design will be briefly presented. The breadboard PPTCUP (PPTCUP-BB) configuration[4,5] has been used as a guideline for the updated thruster design. Efforts were aimed at reducing the carbonization phenomenon, which is conventionally indicated as the main life limiting mechanism for A-PPTs[1,6,7]. Its main effect is the deposition of a thin layer of amorphous carbon (a-C) on the discharge chamber walls that could eventually create a conductive path between the two electrodes, which may short the electrodes and cause a definitive thruster failure. Many authors had studied and tried to solve this issue[5,7,8]. The PPTCUP-EM discharge chamber, nozzle walls and electrodes have been modified according to these results.

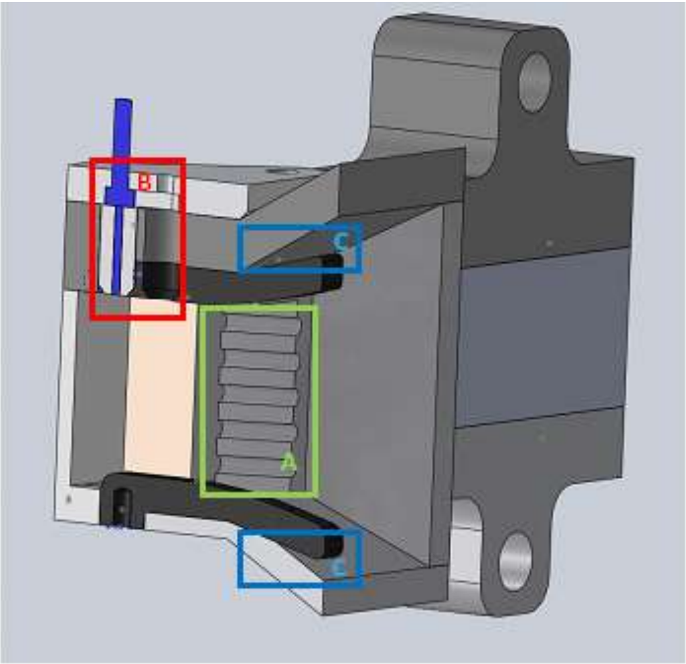


**Figure 1 – 3D CAD of PPTCUP-EM. Highlighted in the figure: lateral groves on the discharge chamber (green square A), spark plug slots (red square B) and gap between the electrodes and the nozzle walls (blue squares C).**

To prevent the electrodes short circuiting, lateral grooves have been included on the lateral walls of the discharge chamber. Moreover the electrodes and the divergence angle of the nozzle walls have been modified to create a gap between them and avoid direct contact (Figure 1).

The PPTCUP-EM design allows the spark plug to be located in two different slots inside the cathode to assess of the spark position affects the performances of the thruster.

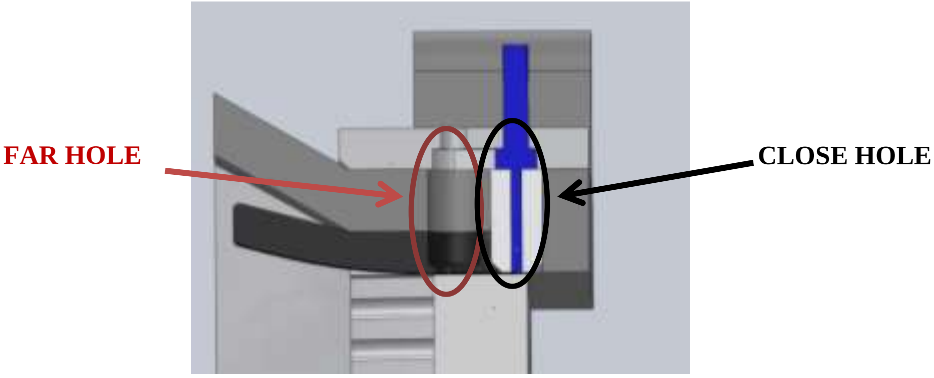


**Figure 2 – 3D CAD of the two possible spark plug configurations.**

As shown in Figure 2, the two slots are named “Far” and “Close” holes. The former is the closest to the nozzle outlet; the latter is located on the inner edge of the cathode.

Finally, a 1.6 μF capacitor bank has been used to store the initial energy *E*. It consists of a parallel of 8 ceramic capacitors[9] rated up to 2000 V and with a nominal capacitance $C$ = 200 nF.

## III. Experimental results

In this section, the experimental results acquired during the test campaign are reported and summarized. As the aim of the study is to prove the PPTCUP-EM lifetime and, at the same time, to optimize its performances different configurations have been tested and their performances compared. These configurations are characterized by different positions of the spark plug and of the PTFE propellant bars. In fact, PPTCUP-EM has been tested both in the side-fed and in the V-fed configuration[10].

The test campaign was divided in two phases. In the first one PPTCUP-EM was tested using a suitable ground support equipment (GSE) to provide the capacitor and spark plug voltage and it was focused on the evaluation of the impulse bit ($Ibit$), mass consumption ($m_{bit}$), specific impulse ($Isp$) and of the overall efficiency ($\eta_{th}$) during the entire thruster lifetime, i.e. 1 million shots. In the second part of the test campaign, the thruster was driven by the HV board prototype produced by Clyde Space Ltd in the frame of the PPT study for Nanosat application [11]. The test was mainly focused on the demonstration of the electronic board lifetime and reliability and on the characterization of the noise produced during the main discharge. It has to be noticed that, even if the PPTCUP electronics will not be identical to the HV board of the Nanosat PPT, they will most likely share the same architecture and overall design. Thus it has been decided to perform a second extended test using the Nanosat HV board to test the suitability of such design to deliver the required lifetime. In fact a premature failure of this board could be interpreted as the sign of a major flaw in the design whereas if the board will be able to deliver a number of shots of comparable magnitude to those needed to demonstrate the full PPTCUP-EM lifetime, this might mean that the chosen architecture does not have any major problems at least in a Nanosat form factor.

The whole test campaign has been performed at $E = 2.00 \pm 0.02$ J, which corresponds to an initial voltage $V_0$ = 1720 ± 10 V.

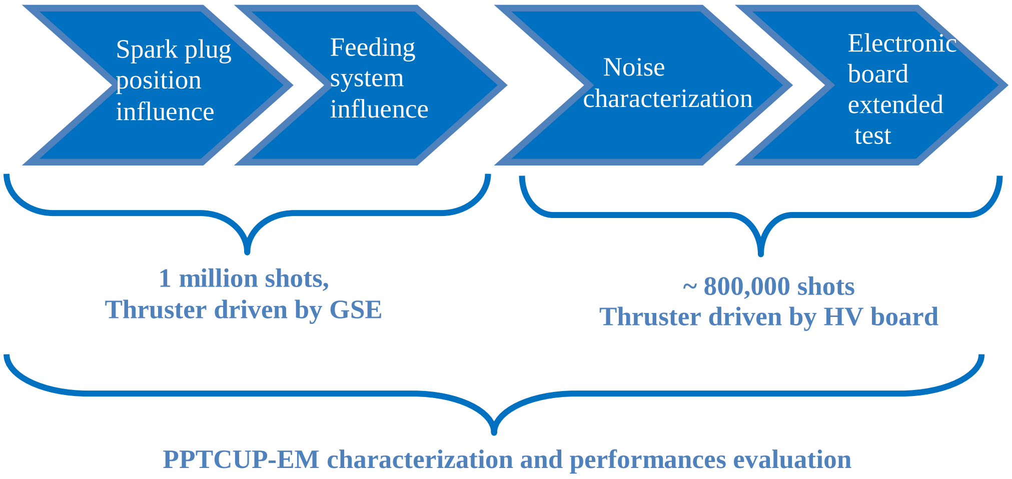


**Figure 3 – PPTCUP-EM test campaign sequence.**

### A. Test set up

The PPTCUP-EM test campaign has been carried out at Mars Space Ltd propulsion lab. The vacuum chamber used is an L shaped chamber with the cylindrical portion 60 cm in diameter and about 1 meter long (Figure 4). It is pumped by a Pfeiffer TPH 2200 turbo pump with an Edwards E2M80 rotary pump used as a backing pump achieving a base pressure of about 7E-7 mbar and an operating pressure of about 1E-5 mbar.

**Figure 4 – Vacuum chamber used during the test campaign.**

In the first phase of the test campaign, the thruster was fed by the dedicated GSE, which was specifically designed at MSL to charge the PPTCUP main capacitors, to trigger the main discharge powering up the spark plug and to provide synchronization between these processes.

The voltage discharge curves were measured using two high voltage probes and they have been acquired at every PPTCUP shot. The discharge current curves were measured using a Rogowski coil at the beginning of the test. These data have been acquired by a Tektronix oscilloscope.

To measure the Ibit, a torsional micro-thrust balance has been used. Developed and fully characterized at MSL in collaboration with the University of Southampton, the balance provides reliable *Ibit* measurements in a range between 20 and 120 µNs with a relative error smaller than 8.8% [11, 12].

The thruster mass bit consumption has been measured using a Mettler Toledo high precision scale with an accuracy of 10 µg. The averaged $m_{bit}$ consumption has been derived weighing the whole thruster before and after a sequence of at least 1,000 shots, then subtracting those two values and dividing by the number of performed shots. *Isp* and $\eta_{th}$ were calculated[5] using equations 1 and 2 once *Ibit* and $m_{bit}$ are known:

$$\boldsymbol{Isp = \frac{Ibit}{m_{bit} \cdot g_0}} \qquad 1)$$

$$\boldsymbol{\eta_{th} = \frac{Ibit^2}{2 \cdot m_{bit} \cdot E}} \qquad 2)$$

where $g_0$ is the standard gravitational acceleration $g_0 = 9.81$ m/s$^2$

Since the typical $m_{bit}$ values for low energy PPTs vary[5] between 3 µg and 20 µg, the high precision scale balance combined with the 10,000 shots sequences allows MSL to measure the averaged $m_{bit}$ with an uncertainty smaller than 0.5 %.

In the second phase, the thruster was fed by a HV board prototype. The grounding scheme that is representative of the thruster operation in space has been employed and its schematic shown in Figure 5. The low voltage (LV) ground of the board and of the power supply units was connected to the chamber ground and then to the earth ground, whereas the HV ground, i.e. the reference ground for the electrodes and spark plug potential, has been left floating. The noise characterization has been carried out measuring the AC signal on the power line and in air in front of the vacuum chamber door using a differential voltage probe. The noise test points are highlighted in Figure 5.

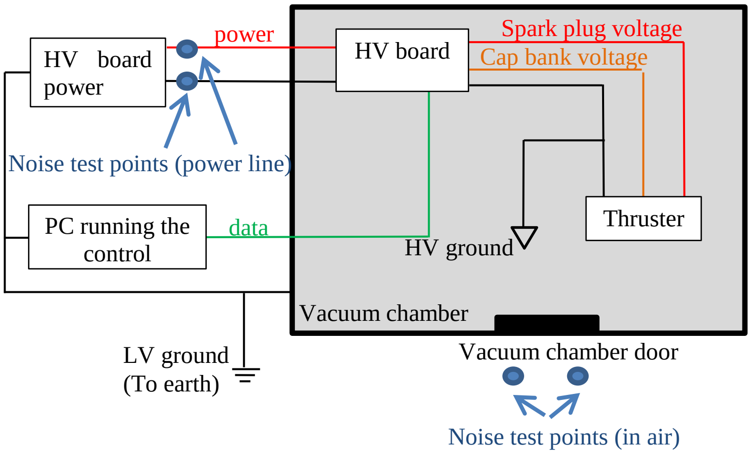


**Figure 5 – PPT driven by HV board grounding scheme.**

### B. Spark plug position performances influence

At the beginning of the test campaign, PPTCUP-EM has been tested in both spark plug configurations, measuring the current and voltage waveforms, *Ibit*, $m_{bit}$ and then calculating the *Isp* and $\eta_{th}$. During this test phase, in which the propellant was in the classic side-fed configuration, a total of about 3,000 shots were performed.

Figure 6 shows the comparison of the current and voltage curves for the two tested configurations. The curves have been obtained averaging the data of twelve different shots. The curves are very similar for the two configurations and show a trend that is very similar to the one that characterizes the PPTCUP-BB [4,5] and shown in Figure 7. The voltage and the current measurement were also noticed to be very repeatable with a standard deviation of the first positive peak of the current curve of 0.77% and 0.41% and a standard deviation of the first negative voltage peak of about 3.6 % and 3.0%, respectively for the Far and Close Hole configuration.

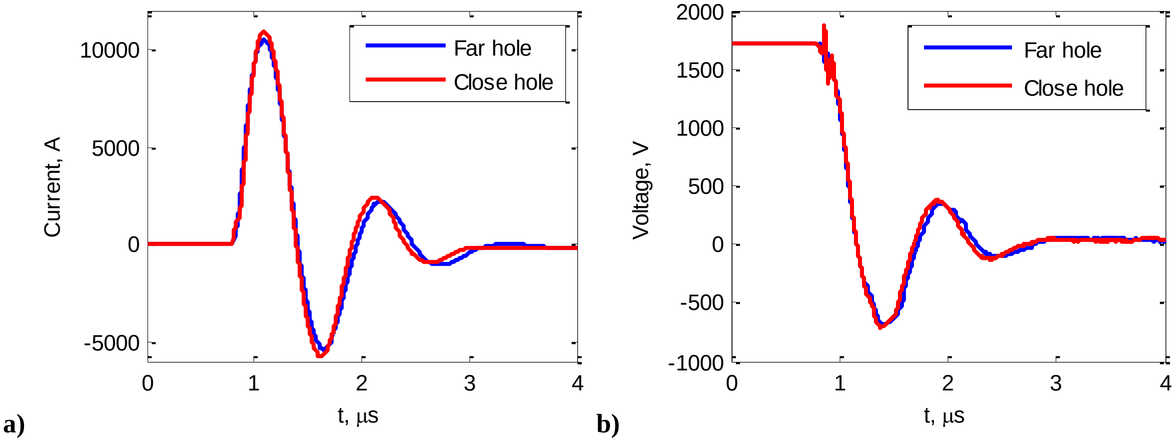


**Figure 6 – Comparison of the a) discharge current curves and b) discharge voltage curves.**

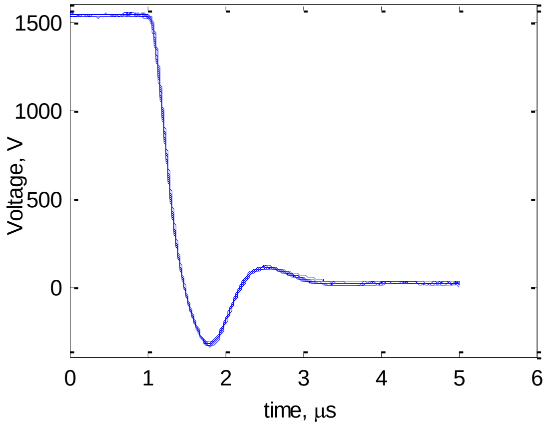


**Figure 7 – PPTCUP-BB typical discharge voltage waveform [4,5]. $E$ = 1.96 J.**

The thruster performances for the two configurations are reported in Table 2.

**Table 2 - Comparison of the different spark plug positions performances. Side-fed configuration**

| Parameter | Far Hole | Close Hole |
|---|---|---|
| $I_{bit}$ (μNs) | 37.8 | 38.2 |
| $m_{bit}$ (μg) | 7.4 | 6.4 |
| $I_{sp}$ (s) | 521 | 608 |
| $\eta_{th}$ (%) | 4.8 | 5.7 |

Even if the spark plug position does not significantly affect the impulse bit value, the mass consumption is reduced by about 13.5% when the Close Hole configuration is used. Therefore, this configuration is characterized by the best specific impulse and efficiency.

According to these results, the Close Hole configuration has been chosen as baseline to complete the test campaign.

### C. Propellant feeding performance influence

Once the spark plug position has been fixed PPTCUP-EM discharge chamber has started the lifetime test driven by the GSE. During this test the propellant feeding configuration has been changed to verify its effect over performance. Side-fed and V-shape propellant bars have been used. Figure 8 shows the details of the propellant surface shape and of its divergence angle α in the V-shape configuration.

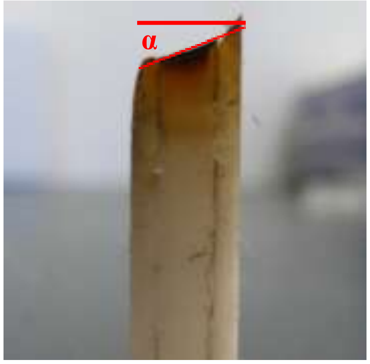


**Figure 8 – Propellant bar divergence angle in the V-shape configuration. Divergence angle α ≈ 18°.**

A graph showing the number of shots achieved to date by PPTCUP-EM and the configuration used is reported below together with a table comparing the average performance of the side fed and V-shape configuration.

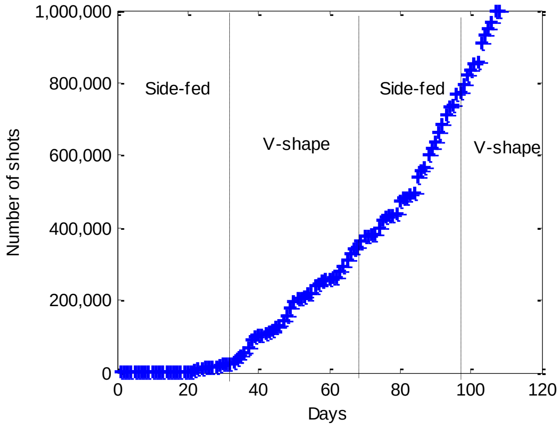


**Figure 9 – PPTCUP-EM driven by GSE shot counter.**

**Table 3 - Comparison of the different propellant bars configuration. Spark plug in the Close Hole**

| Parameter | Side-fed | V-fed |
|---|---|---|
| *Ibit* (µNs) | 38.2 | 50.3 |
| $m_{bit}$ (µg) | 6.4 | 10.7 |
| *Isp* (s) | 608 | 480 |
| $\eta_{th}$ (%) | 5.7 | 5.9 |

The choice of the configuration significantly influences the thruster performances. In fact, in the side-fed PPTCUP the combination of the *Ibit* and the $m_{bit}$ leads to a 27% higher *Isp*, if compared to the V-fed configuration. However the V-shape configuration is characterized by an Ibit which is about 24% higher.

An analysis of the possible performances decay during the PPTCUP-EM lifetime has also been performed during the whole test campaign.

Figure 10 shows the impulse bit measurements in both the configurations against the number of performed shots in each configuration. As it can be seen PPTCUP-EM seems not to be affected by any performances decay due to its aging. This is an important design improvement, as different authors [14,15] have shown that the *Ibit* decreases during the lifetime (see Figure 12).

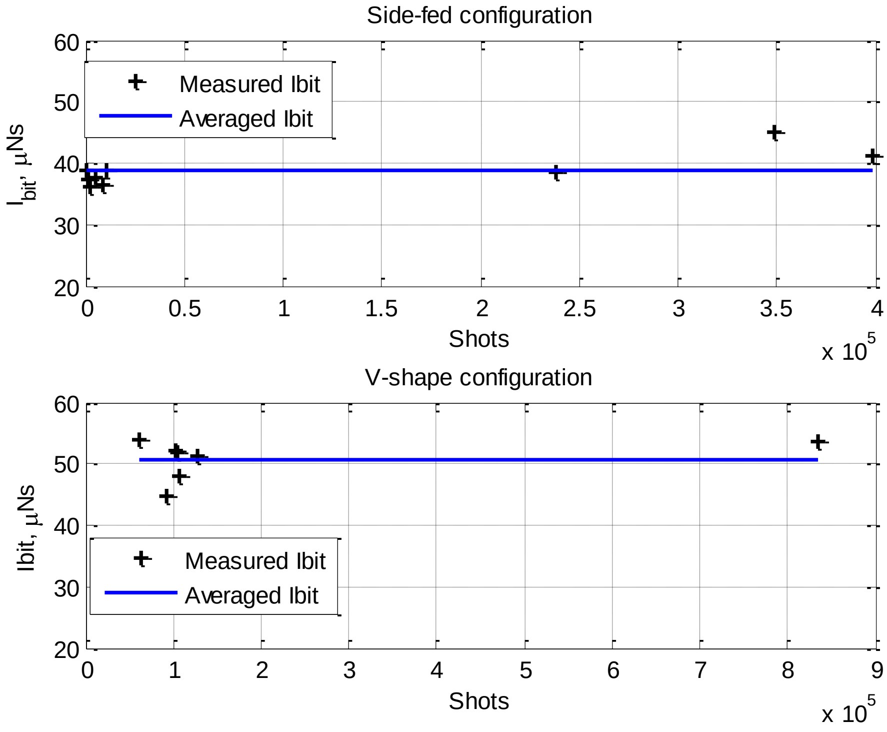
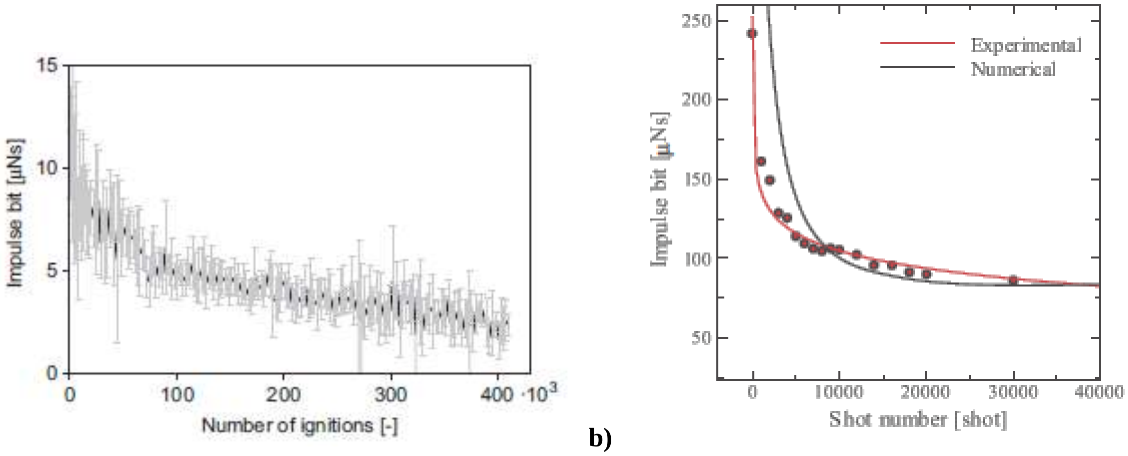


**Figure 10 – PPTCUP-EM *Ibit* measurements (both propellant configurations).**



a) b)

**Figure 11 – Examples of typical A-PPT performances decay, a) from RD[14] b) from RD[15]**

### D. Carbonization and propellant charring

During the lifetime test campaign, visual inspections have been carried out to monitor the carbonization phenomenon and the propellant bar charring.

Figure 12 shows that a layer of amorphous carbon has been deposited on the discharge chamber and nozzle walls and on the electrodes surface during the tests. PPTCUP-EM did not shown any kind of problem which could be related to the possible conductive path between the electrodes. As it has been always possible to charge the capacitor bank, the updated thruster design has up to now prevented the growth of a carbon layer big enough to short the electrodes hence causing the thruster failure.

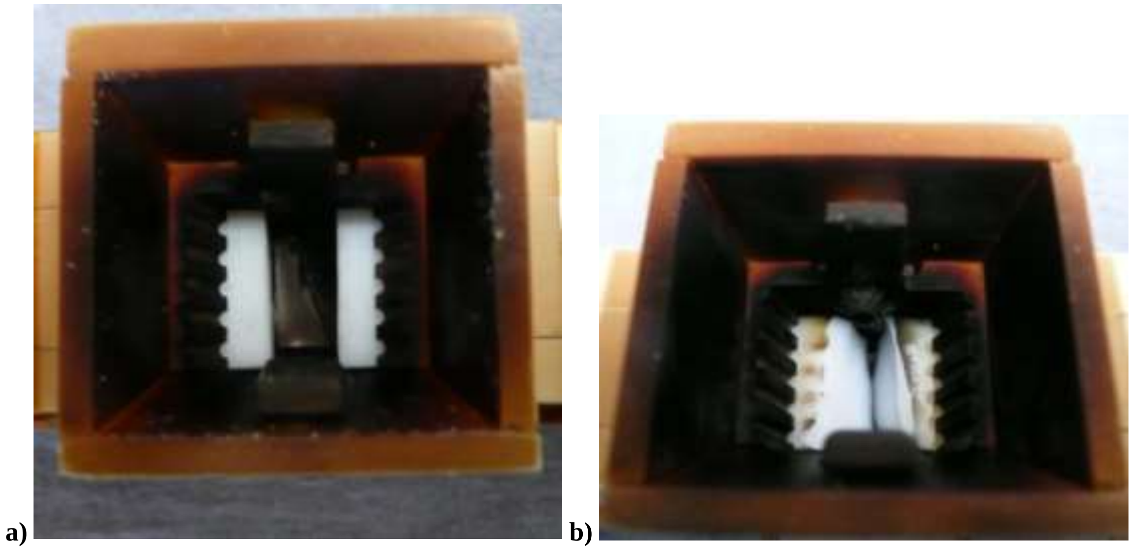


**Figure 12 –PPTCUP-EM discharge chamber. a) Side-fed configuration after ≈ 7.3E5 shots; b) V-shape configuration after ≈ 8.4E5 shots.**

At the end of the test campaign, SEM (Scanned Electron Microscope) scanning and Energy Dispersive X-ray (EDX) spectroscopy have been performed to analyze the electrodes surface exposed to the main discharge.

Both the electrodes appear to be covered by a carbon layer, as shown in Figure 15. The carbon layer revealed by the EDX analysis gets thicker moving towards the end of both the electrodes, in particularly starting from the divergent part of the electrodes where it is clearly visible a change of the surface aspect (Figure 14). However the presence of the thin film is not only acceptable, but even desirable, since it limits the electrode erosion: indeed, providing a homogeneous resistive path to the discharge arc, the carbon layer prevents the formation of large hot spots on the electrodes, minimizing sputtering and other wear out mechanisms[16].

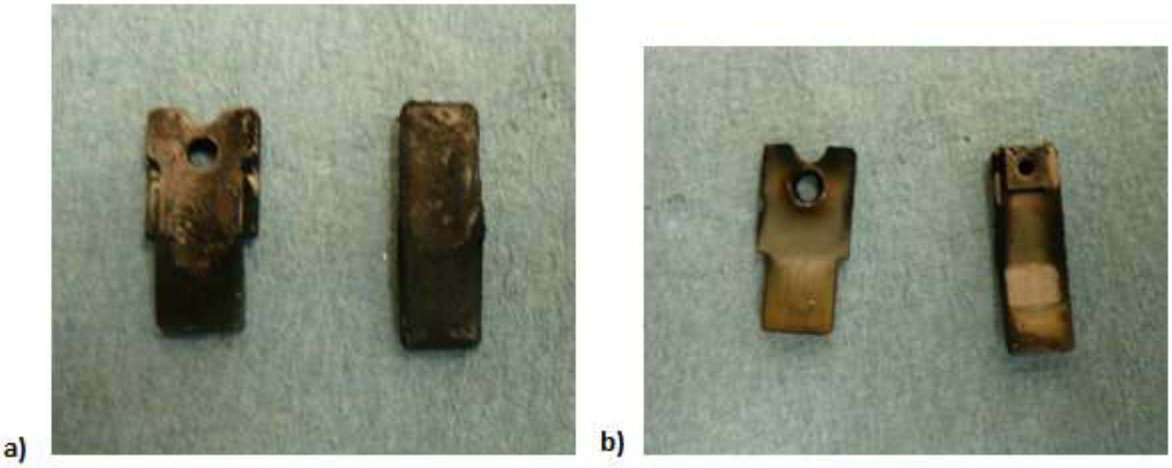


**Figure 13 –PPTCUP-EM cathode (on the left) and anode, a) discharge side b) rear side after 1 million shots**

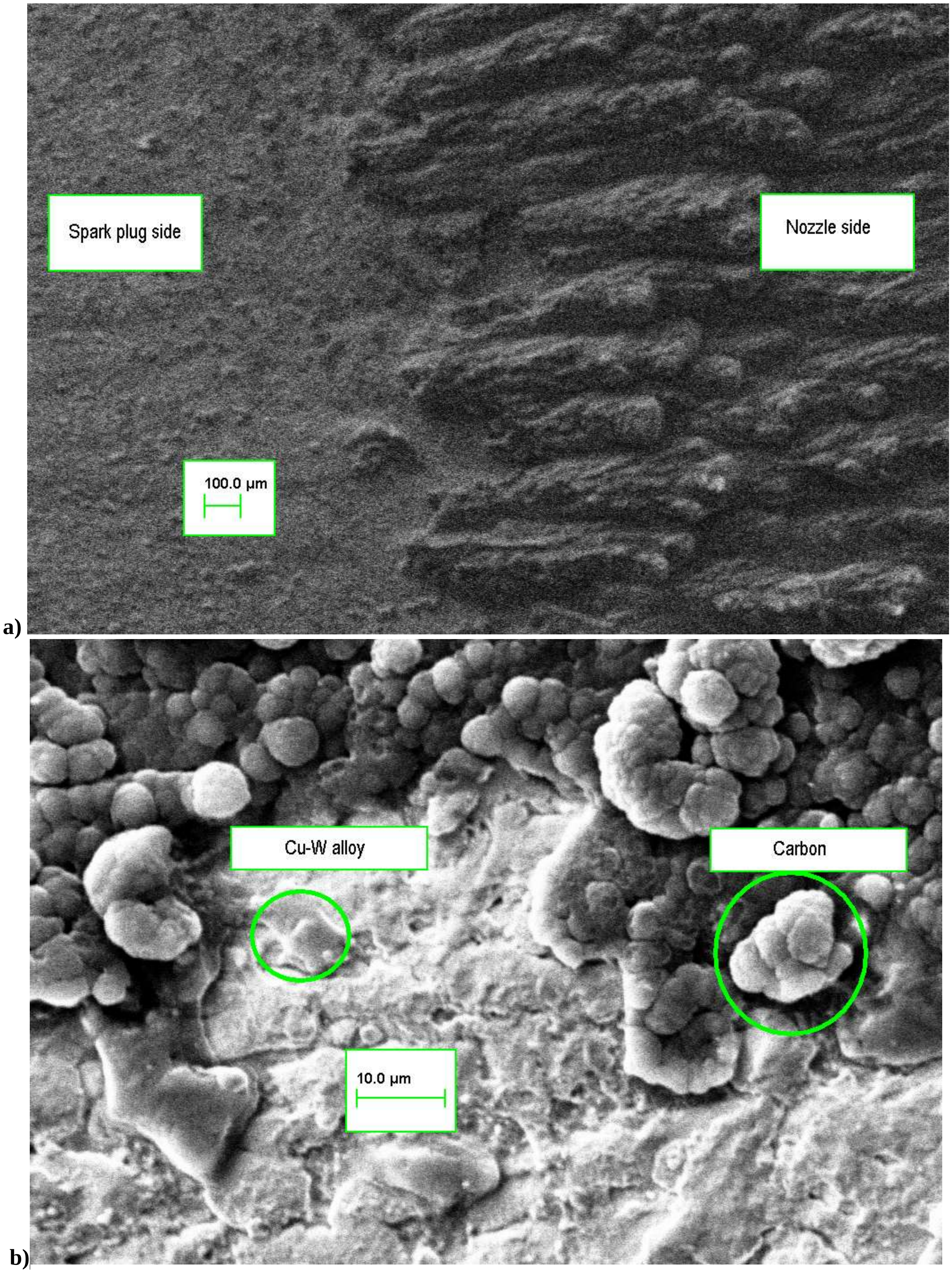


**Figure 14 – SEM pictures of a) anode and b) cathode after 1 million shots**

Regarding the propellant charring, all the investigated thruster configurations had shown a uniform consumption of the exposed propellant surface. Moreover, as shown in Figure 15, the surface is also very clean and smooth, particularly if compared to the breadboard PPTCUP propellant bars that appear dirtier after only 3000 shots[3]. This is a typical behavior in most of the A-PPTs whose capacitor bank initial voltage $V_0$ is high (> 1300 V)[17].

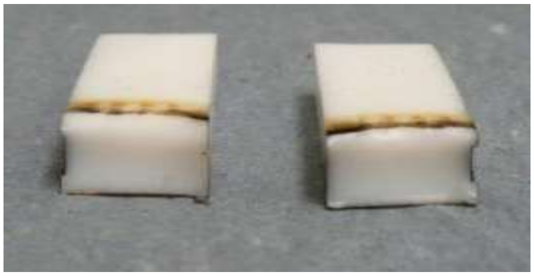
a)  b) 

**Figure 15 –PPTCUP-EM propellant bars: a) V fed engineering model (after ≈ 2.5E5 shots), b) breadboard model (after ≈ 3000) [4].**

## E. PPTCUP-EM test campaign with HV board prototype

### *1. Noise characterization*

Prior to the beginning of the extended test on the electronic board, about 1,000 discharge voltage curves have been acquired to verify the repeatability of the HV board operations. An example of comparison among five different discharge voltage curves is shown in Figure 16. The thruster functioning was repeatable and the noise generated by the spark plug on the thruster discharge voltage was about 500 V peak to peak as it could be expected[5].

During this test the noise produced by the thruster was characterized acquiring the AC signal between test points shown in Figure 5 both during a complete thruster shot and during a single spark plug shot. The noise was measured on the power line and in air in front of the chamber door without connecting the probe to anything. Looking at the results reported in Table 4, it can be noticed how the main source of noise is the spark plug itself and not the main discharge. Moreover since noise levels similar to those measured on the power line were measured with the probe in air and not connected to anything (Table 4), it can be inferred that most of the noise is radiated rather than not conducted.

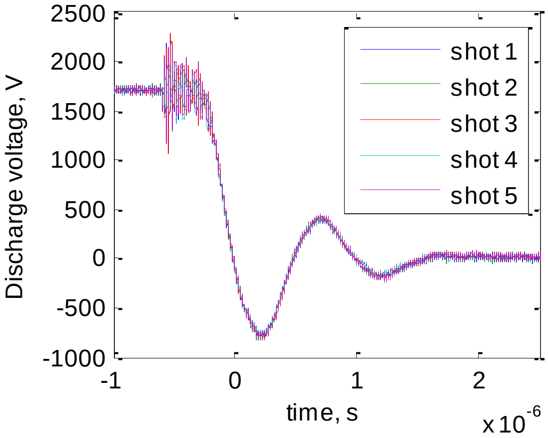


**Figure 16 –PPTCUP-EM discharge voltage curve when powered by the HV board**

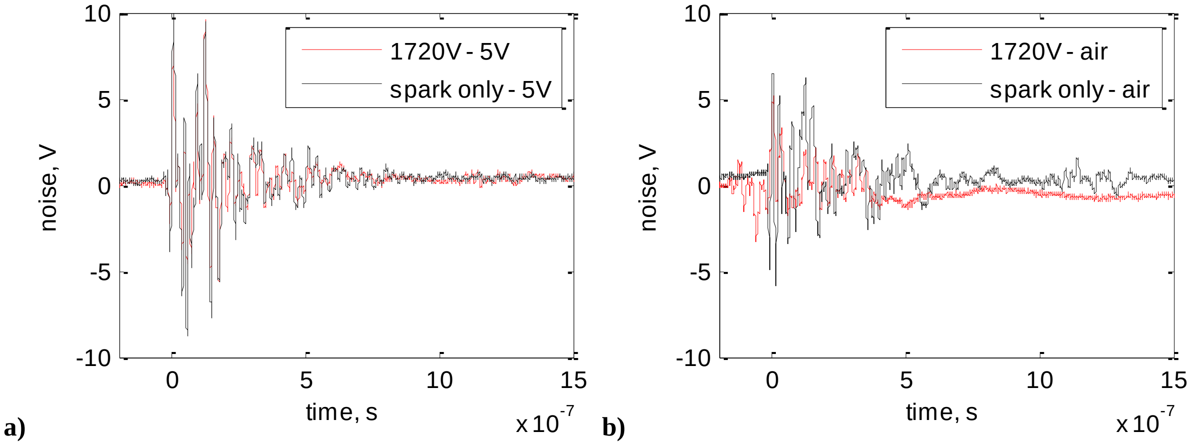


**Figure 17 - Noise measurements for a thruster shot (*E* = 2 J) and spark plug only shot a) measured on the power line, b) measured with the probe placed in air in front of the chamber.**

**Table 4 - RMS noise values**

| **Capacitor bank voltage (V)** | **Measurements** | **RSM value (V)** |
|---|---|---|
| 1720 | Power line | 2.47 |
| 0 | Power line | 2.86 |
| 1720 | Probe in air | 1.89 |
| 0 | Probe in air | 2.68 |

### 2. *HV board extended test*

After the measurements of the noise generated by the unit, the extended test has been carried out performing a shot every 1.5 s hence at a firing frequency of 0.66 Hz. PPTCUP-EM driven by the HV board has successfully completed more than 800,000 shots and is still operational. Side-fed configuration has been set up.

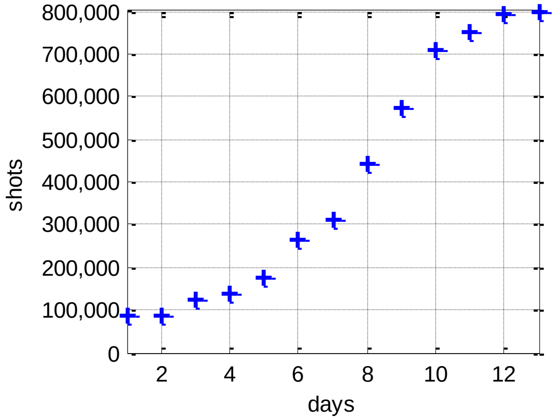


**Figure 18 – PPTCUP-EM driven by the HV board shot counter.**

## IV. Conclusions and future works

PPTCUP-EM discharge chamber has successfully completed about 1,800,000 shots. From the data gathered during the test it seems clear that the PPTCUP-EM design is able to resolve all the issues encountered with the PPTCUP-BB[4,5] testing also showing no decay of performance during lifetime. Propellant ablation was uniform in both the tested feeding configurations. Results show that the side-fed configuration is characterized by a higher *Isp*, whereas the V-shaped configuration can deliver a higher *Ibit*.

A prototype of the HV conditioning electronics board developed by Clyde Space Ltd in the frame of the PPT study for nano-satellites application[11] was successfully used to feed the discharge chamber, being able to command about 800,000 main discharges without failures. Noise level has been measured in a suitable set up, where grounding scheme was representative of the thruster operations in space. Preliminary results have shown that the main noise source is the spark plug itself rather than the main discharge and that most of the noise seems to be radiated rather than conducted.

Results from the whole test campaign show that PPTCUP-EM can work for its entire lifetime delivering an averaged *Ibit* = 38.2μNs in the side-fed configuration without performances decay caused by to the thruster aging that characterize other A-PPTs for pico and nano satellites [14,15]. Moreover the number of performed shots (1,800,000) proves the reliability of the thruster, being almost two times bigger than the nominal number of shots required to demonstrate the discharge chamber lifetime, i.e. one million shots, and it is almost three times bigger than the latest (at the time of this paper writing) endurance test performed on a μ-PPT [14]. At last, noise generated by the main discharge of a μ-PPT has been preliminary characterized and quantified for the first time, because the level of noise produce by a PPT has been reported in the literature only few times and for bigger PPT [11,18]. This is crucial for the design of a fight unit that has to match the EMC requirements to complete the qualification for the space flight.

In the next months a PPTCUP qualification model (PPTCUP-QM) will undergo an extensive and complete test campaign to qualify the unit for the space flight.

The PPTCUP-QM design is based on the evidences collected during the PPTCUP-EM testing. Considering the significant difference in terms of specific impulse between the side-fed and V-fed configuration (about 600 s of the side-fed against 500 s of the V-fed, as shown in Table 3), the use of a side-fed propellant configuration will be adopted.

However, bearing in mind that the scope of the activity is to flight qualify a potential product, it has been decided to produce a “stand-alone” module that can be bolted on the Cubesat structure. A 3D model of this is reported Figure 19 . Such an approach is becoming popular among Cubesat manufacturer since it allows the production of payloads and subsystem that are isolated from the main Cubesat[19,20].

This configuration allows the thruster and electronic board design not to be limited by the presence of the PC/104 connector. Moreover the external box provides shielding from the noise radiated during the main discharge and assures that no arcing can be possible between the thrust and the Cubesat systems, being insulated from the discharge chamber. The main drawback is the total weight of the unit that is slightly heavier because of the mass of the external box. Nevertheless the “stand-alone” approach has been chosen for the PPTCUP-QM design considering all the advantages related to this configuration and that CubeSat requiring a propulsion system are normally the high-end of the CubeSat missions and have to have ADACS units that come in stand-alone units [19].

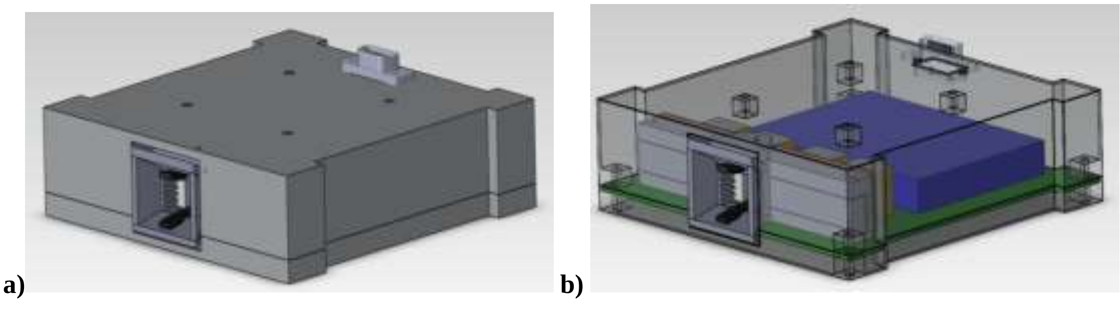


**Figure 19 –PPTCUP-QM preliminary design**

Qualification test campaign will include EMC characterization, thermal cycling, vibration and lifetime tests. It will start in November 2013 and its end is scheduled for the first quarter of 2014.

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