Qualification of a Pulsed Plasma Thruster for Cubesat Propulsion (PPTCUP)

IEPC-2015-208／ISTS-2015-b-208

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

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PPTCUP (Pulsed Plasma Thruster for Cubesat Propulsion) is an ablative pulsed plasma thruster designed to provide translational and orbital control to Cubesat platforms. The qualification model presented in this paper has been developed by Mars Space Ltd, Clyde Space Ltd and the University of Southampton to produce a versatile “stand-alone” module that can be bolted on the Cubesat structure, allowing the orbital control along the X or Y-axis of the satellite. An extensive test campaign to qualify the unit for space flight, which includes electromagnetic compatibility (EMC) characterization, thermal cycling and mechanical tests, has been performed according to the NASA GEVS procedures. PPTCUP is characterized by an averaged specific impulse of 655 ± 58 s and a deliverable total impulse of 48.2 ± 4.2 Ns. Finally, it has been found that the unit is compliant with the EMC requirements and can successfully withstand the thermal and mechanical loads typical of a Cubesat space mission.

Nomenclature

BB = Breadboard Model
C = Capacitance
E = Energy
EM = Engineering Model
EMC = Electromagnetic Compatibility
EMI = Electromagnetic Interference
g_0 = Gravitational Acceleration
GSE = Ground Support Equipment
HV = High Voltage
I = Discharge Current
I_{bit} = Impulse Bit
I_{sp} = Specific Impulse
I_T = Total Impulse
LV = Low Voltage

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m_{bit} = Mass Bit Consumption
PPT = Pulsed Plasma Thruster
QM = Qualification Model
R = Resistance
V_0 = Initial Capacitor Voltage
η_{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 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 (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 60s, 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, 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-B program producing the design of the first breadboard version of a PPT for Cubesat application called PPTCUP with the aim of increasing the lifetime of a 3U Cubesat and consequently its economical attractiveness [4]. This thruster delivered satisfactory performance but could not provide the requested lifetime. Subsequent to this study an engineering model (PPTCUP-EM) was designed to optimize performance and achieve the required lifetime. PPTCUP-EM successfully passed a lifetime test campaign and the results showed a total impulse capability of 42.9 ± 3.9 Ns delivered in about 1,125,000 shots [5]. An example of the orbit keeping capabilities of PPTCUP is shown in Table 1. Nevertheless, PPTCUP can also be used to perform small orbit changes and to maintain satellites in formations enabling Cubesats to perform complex formation flying missions.

Table 1 – PPTCUP 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 16d	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

Starting from the PPTCUP-EM design, a PPTCUP qualification model (PPTCUP-QM) has been designed and manufactured as part of an ESA ITI-C funded activity to design a potential flight qualified product. Therefore, an extended qualification test campaign, including electromagnetic compatibility (EMC) characterization, thermal cycling, and mechanical tests, has been performed.

The PPTCUP-QM is a “stand-alone” module that can be bolted on the Cubesat structure at the top/bottom of a Cubesat or in the middle of it using a standard payload adapter. Such an approach is becoming popular among Cubesat manufacturers because it allows the production of subsystems that are isolated from the main Cubesat ([6] and [7]). In this paper, the PPTCUP-QM design, the experimental apparatus and the test results are presented.

II. Thruster design

In this section the QM thruster design will be briefly presented. The PPTCUP-QM module consists of three main parts: the discharge chamber, which is an ablative side-fed PPT, the conditioning electronics and the external box. The overall dimensions are $100\text{x}100\text{x}33\text{mm}^3$ and the total mass about 270 g.

The QM configuration allows the thruster and electronic board design not to be limited by the presence of the PC/104 connector that was included in the first PPTCUP-BB model [4]. Moreover, the external box provides shielding from the radiated noise and assures that no arcing can occur between the thruster and the rest of the satellite. Thanks to this design approach, the same thruster unit can be used to deliver thrust along the X or Y-axis of a Cubesat (depending on how PPTCUP is mounted in the structure), hence resulting in a more versatile product and avoiding the need for expensive and lengthy requalification programs.

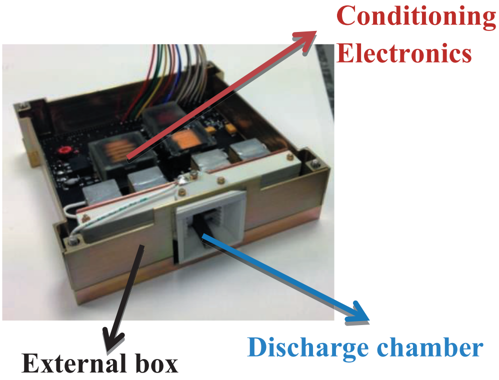


Figure 1 - PPTCUP-QM module (without the box lid).

A. Discharge chamber design

The PPTCUP-EM configuration, which is described in detail in [5], has been used as a guideline for the QM discharge chamber design. The PPTCUP-QM is a side-fed ablative PPT. The main electrodes are made in Cu-W alloy; they are about 5 mm wide with a flared angle of 15^0. This design have already successfully passed an endurance test that proved the reliability of a design able to reduce the carbonization phenomenon that is conventionally indicated as the main life limiting mechanism for PPTs ([8] - [11]) and one of the main issues found during the testing of PPTCUP-BB [12]. The initial mass of the propellant is about 8 g. The whole test campaign has been performed at $E = 2.00 \pm 0.02$ J, which corresponds to an initial voltage $V_0 = 1720 \pm 10$ V. The spark plug, which is used to trigger the main discharge, operates with an initial energy of about 0.01 J and an applied voltage of 7.5 kV. As for the engineering model, PPTCUP-QM has a 1.6 µF capacitor bank, used to store the shot energy E. The bank consists of a parallel arrangement of 8 ceramic capacitors rated up to 2000 V and with a nominal capacitance $C = 200$ nF. These capacitors have been chosen after an extended test to prove their reliability when used for pulsed applications to avoid failures similar to those occurred during the PPTCUP-BB test campaign [12].

B. Conditioning electronics

The QM conditioning electronics is based on the design of the high voltage (HV) board prototype that has already proved its lifetime and reliability, being able to drive about 1,000,000 shots without failures ([5] and [13]).

The board is specifically designed to charge the main capacitor bank, to trigger the main discharge, to provide synchronization between these processes and to communicate with the rest of the Cubesat via I2C protocol. The board needs two dedicated lines: a + 3.3 V line for the digital circuit and a + 7.6 V line for the power. At last, a 15 pins micro connector is used to electrically interface the unit with the ground support equipment (GSE), when the unit is operated in a laboratory, or with the rest of the satellite, if the unit is operated in space. As shown in Figure 2, the reference potential for the main electrodes and the spark plug is left floating and insulated from the low voltage ground using suitable opto-couplers.

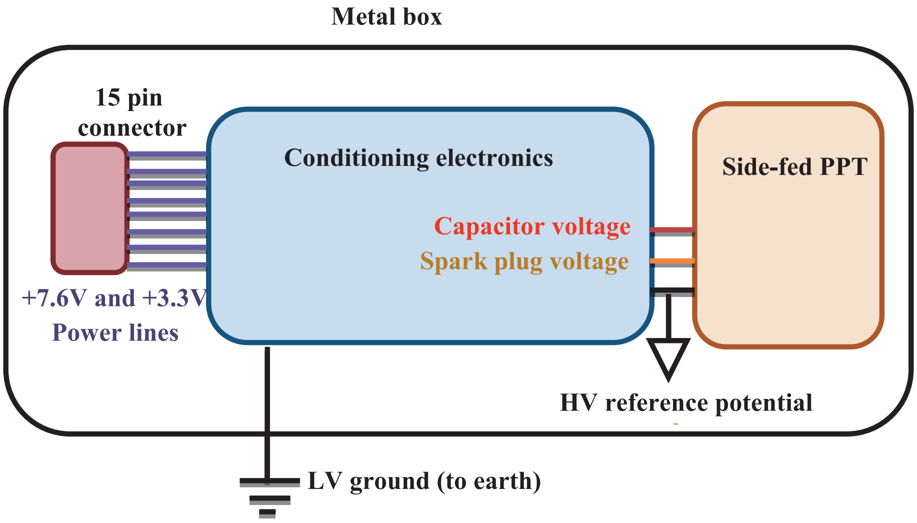


Figure 2 - PPTCUP-QM grounding scheme.

C. External box design

The aluminium external box, which is 1 mm thick, provides shielding from the noise radiated during the main discharge and assures that no arcing can occur between the thruster and the Cubesat systems. Alocrom 1200 was chosen as final surface finish treatment to protect the box from corrosion. A dedicated structural analysis has been performed to find the lightest design that can sustain the typical loads in a Cubesat mission without permanent deformations, providing enough stiffness to the whole structure and avoiding mechanical resonance coupling. In particular the box has been designed to have its first natural frequency to be compliant with the Cubesat requirements (i.e. $f_n > 150$ Hz, as reported in [14]).

III. Test campaign overview

A. Test sequence

The aim of the qualification test campaign is to fully characterize PPTCUP-QM for space flight. The test sequence consists of a thermal cycling test, vibration test, EMC characterization and lifetime test. Moreover, two performance tests are included after the thermal and the vibration tests to verify that no failures occurred during these tests. The unit has been always be fired at its nominal initial stored energy $E = 2.00 \pm 0.02$ J and it nominal firing frequency of 1 Hz.

B. Test set-up

The GSE used for the thermal cycling test was connected to the unit with cables introduced inside the chamber using a suitable thermal insulated feed-through (F/T). The chamber, shown in Figure 3, can be remotely programmed to provide the required temperature profile. The temperature was measured using two K-type thermocouples: one was placed inside the chamber whereas the other one was placed in the center of the PPTCUP-QM box lid.

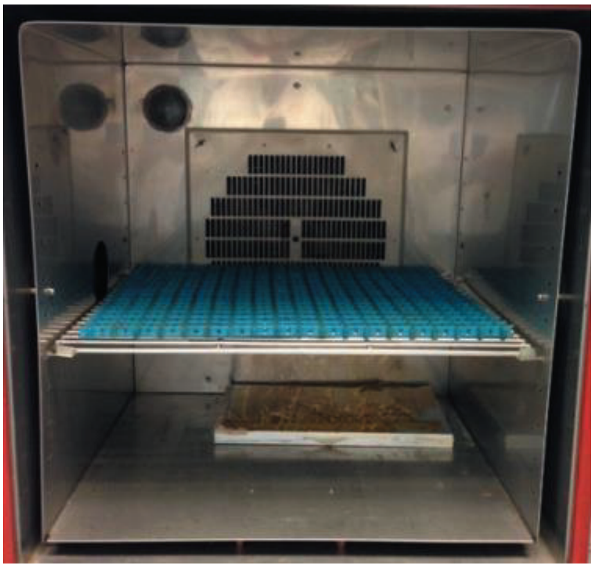


Figure 3 – Thermal cycling test facility.

The performance tests have instead been carried out using the vacuum chamber shown in Figure 4. It is an L-shaped stainless steel chamber with the cylindrical portion 60 cm in diameter and about 1 m long. It is pumped down by a Pfeiffer TPH 2200 turbo pump with an Edwards E2M80 rotary pump used as a backing pump, thus achieving a base pressure of about 7E-7 mbar and an operating pressure of about 1E-5 mbar.

Figure 4 – Vacuum chamber used for the performance test.

The discharge voltage curves were measured using a high voltage differential probe and acquired by a Tektronix oscilloscope. A torsional micro-thrust balance has been used to measure the impulse bit (*Ibit*). This balance provides reliable *Ibit* measurements in a range between 20 and 120 µNs with an error smaller than ± 8.8% [15]. The mass bit consumption (m_{bit}) has been measured using a Mettler Toledo high precision scale with an accuracy of ± 5 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. Since the typical m_{bit} values for low energy PPTs vary between 3 µg and 20 µg [1], the high precision scale balance combined with the shots sequences allows MSL to measure the averaged m_{bit} with an uncertainty smaller than ± 0.5 %.

The mechanical test was performed using a LDS V8-440 shaker table. As shown in Figure 5, a three axis accelerometer was placed in the center of the PPTCUP-QM box lid and used to measure the acceleration during the test.

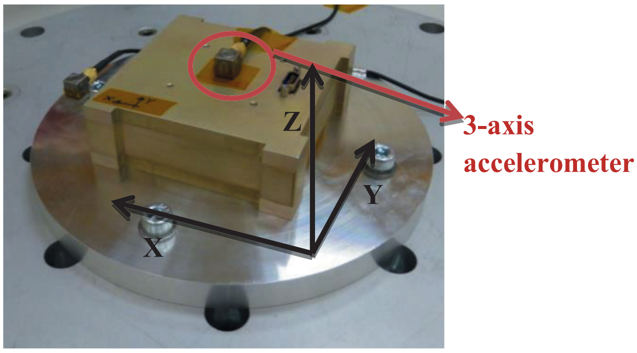


Figure 5 – Mechanical test set-up.

The EMC characterization test was performed using the bell jar shown in Figure 6 to run the test under vacuum condition. The bell jar has one KF flange located on the central main port on the top surface. A 4-ways cross is mounted on this flange to ensure that a pressure gauge, an “up to air” valve and an electrical F/T can be used during the test. The vacuum vessel is pumped down by a Pfeiffer TPH 520M turbo pump with an MD4TC Vacuubrand membrane pump used as a backing pump, thus achieving a base pressure of about 8E-6 mbar and an operating pressure of about 2E-5 mbar.

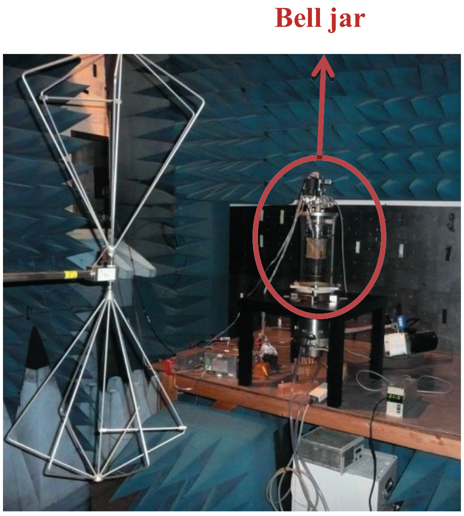


Figure 6 – EMC characterization test set-up.

IV. Experimental results

In this section the results of the test performed up to the date of the paper submissions are reported.

C. Thermal cycling test results

The aim of this test was to demonstrate that the unit can work correctly in the range of the operating temperatures, going from - 20 to + 65 °C, and survival temperature, from -30 to + 70 °C. The unit underwent a 2 hour soak at the hot and cold survival temperature limits before being raised to the operational temperature limits (from -20 up to 65 °C) and repeating the cycle in the operative temperature range eight times. Since the test was performed in air, it was not be possible to fire the thruster with the bank of capacitors charged within the thermal chamber. However, the telemetry and the command interface have been successfully checked during the whole test as it was always possible to communicate with the board.

The box and thermal chamber temperature profiles are reported in Figure 7, whereas Figure 8 shows the voltage and the current measured on the two power lines.

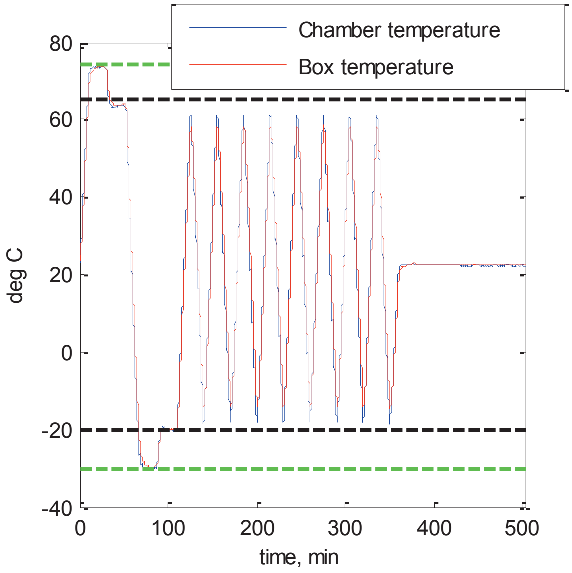
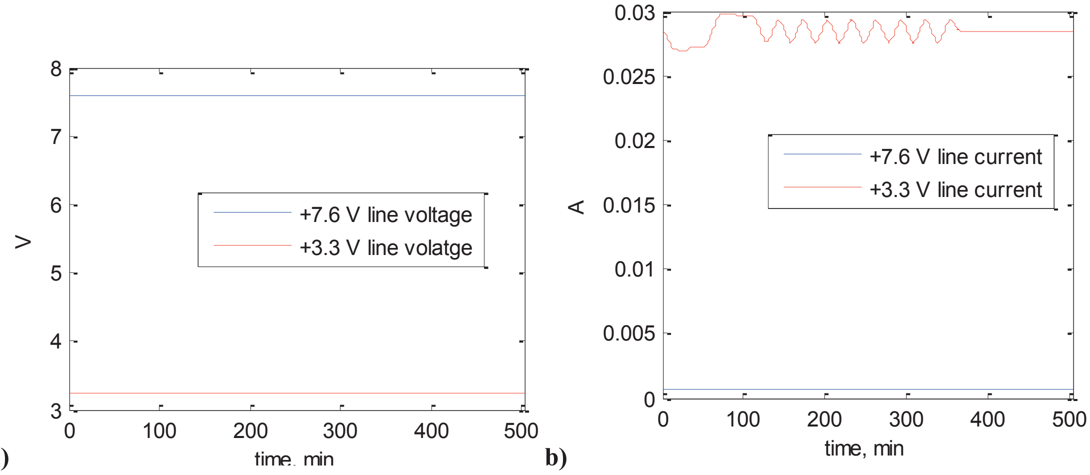


Figure 7 – Temperature profile during the thermal cycling. The black dotted lines represent the operative temperature range, the green dotted lines the non-operative range.

The quiescent current on the +3.3 V line was about 28 mA both at the beginning and at the end of the test (i.e. at ambient temperature). There was a maximum variation of the quiescent current between extreme temperatures of 2.9 mA. The variation is due to the long harnessing and connections between the power supplies outside the chamber and the unit and it corresponds to a resistive component as the maximum current consumption was found at the lowest temperature. At last, it has to be noticed that no current flowed on the +7.6V line because the thruster was not fired.



a) b)

Figure 8 – a) Voltage and b) current curves during the thermal cycling.

D. Mechanical test

High sine burst and random vibration tests were performed along each main axis defined in Figure 5 respectively to apply a quasi-static load to the thruster as a simulated strength test and to demonstrate that the unit can survive the vibrations at launch. Before and after the sine burst and after the random vibration, a low sine sweep test was carried out to assess the natural frequency of the unit (f_n). These measured frequencies have to be greater than 150 Hz to avoid resonance coupling with the Cubesat structure [14].

The high sine burst was performed from 5 to 50 Hz at 4g, whereas the low sine sweep test from 5 to 2000 Hz at 0.5g. The random vibration profile was in line with NASA-GSFC and is summarized in Table 2 and applied for 60 seconds.

No damage or failures were observed during the vibration testing. The natural frequencies acquired during the sine sweep checks are summarized in Table 3. It has to be noticed that all the measured frequencies are compliant with the requirements (i.e. f_n> 150 Hz) and no significant changes in the f_n values were detected. The only exception is the f_n measured along the Z-axis after the first random vibration test. This value changed by about 22% if compared to the one measured before the same test. Considering that this only happened once for the Z axis, and that no change in frequency was measured from that point onwards, it can be concluded that the reason behind it was likely to be small adjustments of the lateral walls of the external box that occurred during the first performed random vibration test.

Table 2 – Random vibration test parameters.

Frequency, Hz	Power spectral density, g^2/Hz
20	0.026
20-50	+ 6 dB/oct
50-800	0.16
800-2000	- 6 dB/oct
2000	0.026

Table 3 – Low sine sweep test results.

Axis	Test case	Main natural frequency f_n, Hz
X	Before high sine	584
	After high sine and before random vibration	578
	After random vibration	453
Y	Before high sine	1137
	After high sine and before random vibration	1135
	After random vibration	1135
Z	Before high sine	679
	After high sine and before random vibration	676
	After random vibration	660

E. Performance test

In this section the results of the performance tests are reported. The specific impulse (Isp) and the overall efficiency (η_{th}) can be calculated using equations 1 and 2 once $Ibit$ and m_{bit} have been measured:

$$Isp = \frac{Ibit}{m_{bit} g_0} \tag{1}$$

$$\eta_{th} = \frac{Ibit^2}{2 \cdot m_{bit} \cdot E} \tag{2}$$

where g_0 is the standard gravitational acceleration $g_0 = 9.81$ m/s^2. Since $Ibit$, m_{bit} and E are independently measured, the relative errors of Isp and η_{th} can be calculated with the following equations [17]:

$$\frac{\delta Isp}{Isp}=\sqrt{\left(\frac{\delta Ibit}{Ibit}\right)^2+\left(\frac{\delta m_{bit}}{m_{bit}}\right)^2} \tag{3}$$

$$\frac{\delta\eta_{th}}{\eta_{th}}=\sqrt{2\cdot\left(\frac{\delta Ibit}{Ibit}\right)^2+\left(\frac{\delta m_{bit}}{m_{bit}}\right)^2+\left(\frac{\delta E}{E}\right)^2} \tag{4}$$

A comparison of the discharge voltage curves acquired after the thermal and after the structural tests is reported in Figure 9. The curves, obtained averaging the data of ten different shots in each test case, are very similar and show that the main discharge lasts about 2 µs, a time similar to the found during the PPTCUP-EM test campaign [5]. The voltage measurements were also noticed to be very repeatable with a standard deviation of the first negative voltage peak of about 0.87 % for the post-thermal and about 1.01 % for the post-vibration tests.

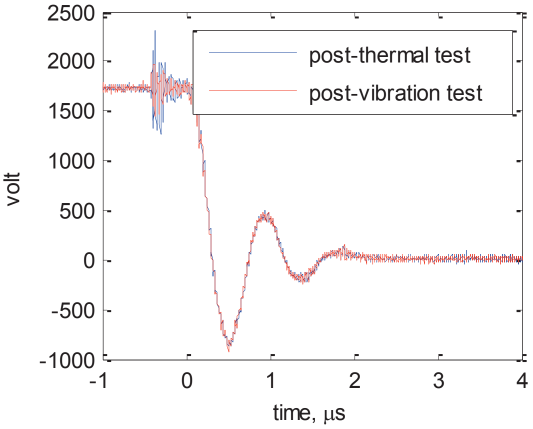


Figure 9 – Comparison of the typical discharge voltage curve.

The PPTCUP-QM performance is summarized in Table 4, together with the results obtained during the PPTCUP-EM test campaign. It has to be noticed that the PPTCUP-QM and EM performance in terms of I_{bit}, I_{sp} and η_{th} are in very good agreement and always within the error bars.

Table 4 – Performance test results summary.

Parameter	Post thermal test	Post mechanical test	PPTCUP-EM [5]
Ibit (µNs)	39.2 ± 3.5	40.0 ± 3.5	38.2 ± 3.4
m_{bit} (µg)	6.5 ± 0.1	5.9 ± 0.1	6.4 ± 0.1
Isp (s)	613 ± 54	696 ± 62	608 ± 55
η_{th} (%)	5.9 ± 0.7	6.8 ± 0.9	5.7 ± 0.7

F. EMC characterization test

This test was aimed at the characterization of the electromagnetic noise produced by the system. The EMC characterization was performed according to the NASA MIL-STD-461C and 462 standards [18] as already done in the past for other PPTs [19], [20], [21].

The tests covered:

- the conducted emissions on the power leads in the range between 100 Hz to 50 MHz (both in differential and in common mode);
- the radiated electric field in the range between 150 kHz and 1.8 GHz;
- the radiated magnetic field in the range between 20 Hz and 50 kHz;
- the radiated susceptibility due to radiated electric field in the range between 14 kHz and 1 GHz.

Since it is necessary to keep the bell jar pumping system (including the power supplies and the pump cooling system) on during the entire test, it has been decided to repeat each test case twice. In the first run, no shots were commanded and only the background noise (i.e. the noise generated by the pumping system and the power supplies) was detected. In the second run, the thruster was fired at nominal frequency of 1 Hz and the data acquired.

In previous publications regarding PPT qualification programs, it is has been pointed out that the MIL standards used by NASA GSFC 7000 [18] are unsuitable to characterize an inherently pulsed device having been developed for devices that work continuously. For this reason, to better judge the EMC results that will be gathered and to assess the suitability of PPTCUP to be used onboard of a spacecraft, the results will be compared to those acquired during the flight qualification of the PPT developed for the NASA Earth Observing 1 mission (from now one referred to as EO-1 PPT) [19], [20].

It has to be noted that the EO-1 PPT was successfully used in flight and that according to what reported in [22]: "*EO-1 PPT EMI emissions and plume effects DO NOT affect other spacecraft subsystems or sensitive earth imaging instruments. No impact to ALI image-taking during PPT operation. Hyperion functioned nominally after continued PPT operation. Hyperion image-taking during PPT operation to be tested at end of life. Atmospheric Corrector data during PPT imaging currently being evaluated. All spacecraft subsystems performed nominally during PPT operations*".

1. Conducted emission test results

The conducted emissions test have been performed using suitable Rogowski coils to measure the AC current flowing in the cables that feed the PPTCUP-QM in the range between 100 Hz to 50 MHz. Since the module requires two power lines (i.e. a +3.3 V and a +7.6 V) that have the two potential references in common and the testing requires the measurements of the noise both in differential and in common mode.

A total of five acquisitions have been performed: three for the differential mode (i.e. +3.3 V, + 7.6 V and ground) and two for the common mode (i.e. + 3.3 V and ground cables and +7.6 V and ground cables).

The results of the test performed in the differential mode on the ground line are shown in Figure 10, where the blues curves represent the background noise acquired without firing the thruster and the red curves represent the noise detected firing the PPT. The level of noise measured during the testing was often smaller than the requirements and it was not always possible to distinguish the PPT noise from the background noise. However, peaks exceeding the requirements have been found during the acquisitions. These peaks are mainly centred around 30 kHz and in the range between 2.5 and 15 MHz and exceed the requirements by a maximum of about 45 dB. Nevertheless, looking at the comparison reported in Table 5 between the PPTCUP data (Figure 10) and the EO-1 PPT data [20] (Figure 11), it is possible to notice that the magnitudes of the detected noise are similar.

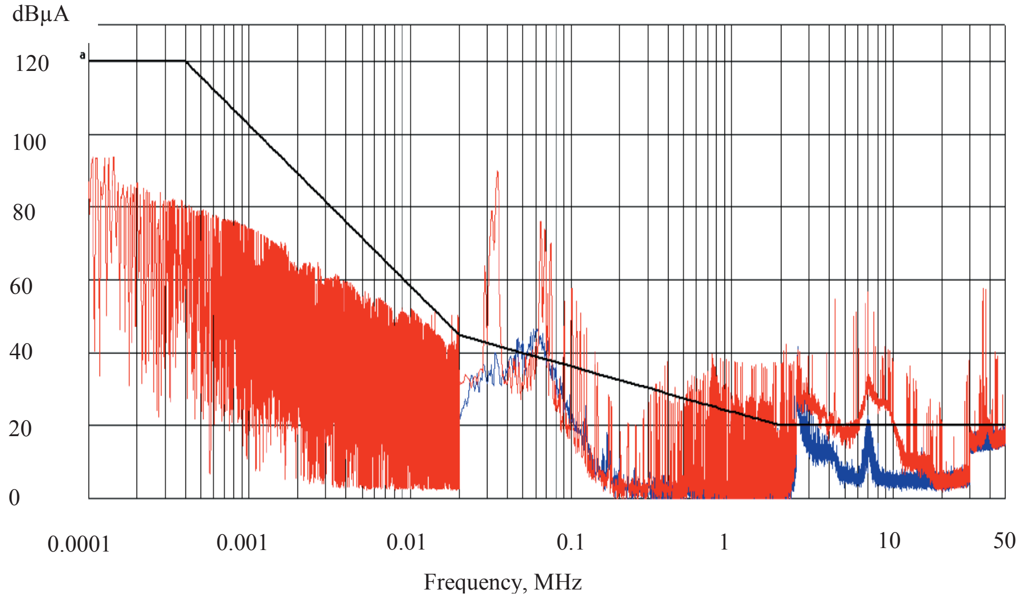


Figure 10 – Conducted emissions (ground line, differential mode) test results. The blue and red curves represent respectively the background noise and the noise with the thruster on. The black line indicates the requirements.

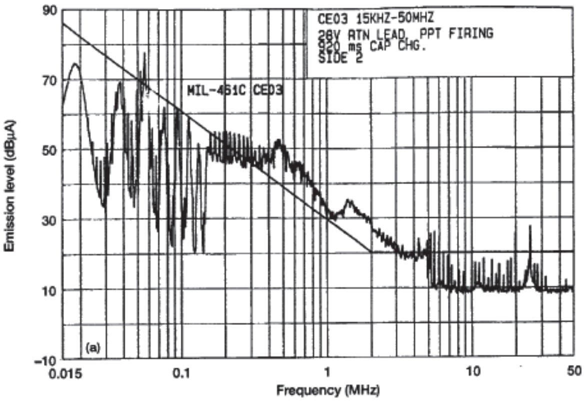


Figure 11 – EO-1 PPT conducted emissions [20].

Table 5 - Conducted noise comparison between PPTCUP-QM and EO-1 [20]

	PPTCUP-QM			EO1PPT			Requirement	
Freq. range, MHz	min, dB	mean dB	max dB	min, dB	mean dB	max dB	min, dB	max, dB
0.01-0.1	5	30	90	20	50	80	38	60
0.1-1	0	20	60	20	45	60	25	38
1-10	0	20	55	10	20	35	20	25
10 - 50	5	15	50	10	15	30	20	20

2. *Radiated emission test results*

The radiated emissions test have been performed using four different antennas to measure the radiated noise generated the PPTCUP-QM module, covering the range between 150 kHz to 1.8 GHz for the radiated electric fields and the range between 10 Hz to 50 kHz for the radiated magnetic field. The antennas were placed at approximately 1 m from the thruster. The results of the radiated electric and magnetic fields are shown in Figure 12 and Figure 13.

. The level of noise measured during the testing (i.e. the red curves in the figures) was often impossible to distinguish from the background noise (i.e. the blue curves).

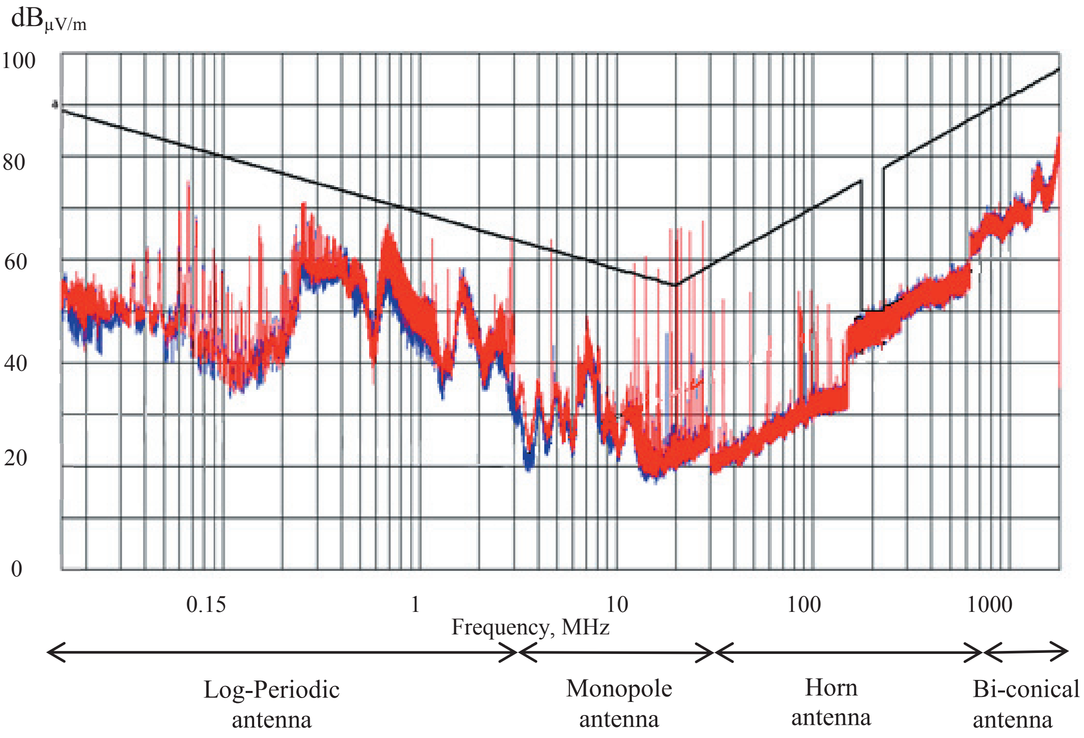


Figure 12 – Radiated electric field test results. The blue and red curves represent respectively the background noise and the noise with the thruster on. The black line indicates the requirements.

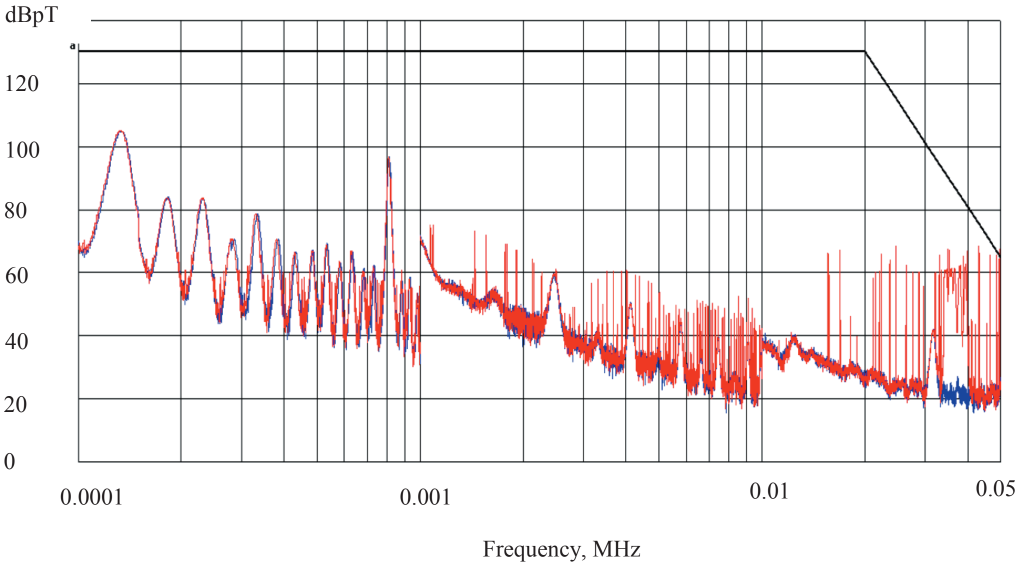


Figure 13 – Radiated magnetic field test results. The blue and red curves represent respectively the background noise and the noise with the thruster on. The black line indicates the requirements.

The radiated magnetic field is compliant with the requirements in the whole range of frequencies. For what concerns the electric field, it has been found that the noise generated by the unit is very similar to the background noise. When the thruster was fired, several spikes were detected in the range between 100 and 500 MHz. These are likely to be generated by the spark plug discharge that is characterised by a fundamental frequency of the order of hundreds of

MHz [5].The spark plug was already found to be the most likely main source of the noise during a the preliminary noise characterisation of the PPTCUP-EM [5]; this confirmed what was theorized for the first time during the development of the LES-6 and LES-7/8 PPTs between 1960s and early 1970s [23], [24].

It is instructive to compare the radiated E-field noise measurement with the EO-1 PPT data [19] reported in Figure 14. The comparison between these data reported in Table 6 shows that the PPTCUP noise levels are always lower than those of the EO-1 PPT hence providing confidence that the PPTCUP noise level will be acceptable to the rest of the spacecraft subsystems.

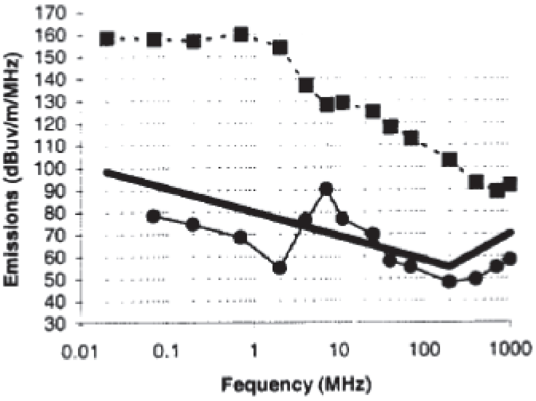


Figure 14 – EO-1 PPT radiated electric field test results [19]. The solid line is the limit set for the unit, the circle and square markers indicate the results obtained respectively with and without the additional shielding envelope.

These data confirmed that the use of an external box to enclose the PPT and its conditioning electronics is recommended to limit the radiated noise. However, it has to be noticed that the introduction of the EMI shield increases the total dry mass of the propulsion system.

Table 6 - Emitted E-field noise comparison between PPTCUP-QM and EO-1 PPT [19].

	PPTCUP-QM			EO1PPT			Requirement	
Freq. range, MHz	min, dB	mean dB	max dB	min, dB	mean dB	max dB	min, dB	max, dB
0.1-1	40	45	75	60	68	75	80	90
1-10	40	55	70	55	75	90	70	80
10-100	20	35	60	50	63	75	58	70
100-1000	20	25	65	50	55	60	55	70

3. *Radiated susceptibility test results*

The radiated susceptibility test was carried out over a frequency range of 14 kHz to 1 GHz. The applied susceptibility electric filed level was 2 V/m as described in the NASA EMC standards. The emitters were placed at approximately 1 m from the thruster. The test was successfully passed with PPTCUP-QM operating without failures during the test. Moreover no changes to the module functionality were found in post-test operations.

V. Conclusion and future works

A pulsed plasma thruster for Cubesat application (PPTCUP-QM) is undergoing an extended qualification test campaign and it has successfully completed the thermal cycling, vibrations and EMC characterization tests. The performance of the thruster has been checked after the thermal and the mechanical tests to verify that no damage occurred in the unit during these tests.

Results from the test campaign performed up to the paper submission date show that PPTCUP-QM works correctly in the operating temperatures range (i.e. from -20 to +65°C), withstands the mechanical vibrations during launch and has the main natural frequencies compliant with the requirements. The results of the EMC characterization test show that the electromagnetic noise generated during the main PPT discharge is mostly compliant with the requirements or small enough not to be distinguishable from the facility background noise. Moreover, the level of noise emitted by PPTCUP-QM was found to be smaller than or comparable to the noise measured during the EMC testing of the EO-1 PPT that has been successfully launched and used in space without creating issues to the other spacecraft subsystems [19], [20]. Finally, it has been found that the performance of the thruster is very similar to the one measured during the PPTCUP-EM test campaign [5], since the unit is characterized by an averaged $I_{sp} = 655 \pm 58$ s and a deliverable total impulse $I_T = 48.2 \pm 4.2$ Ns. This is again in line with the performance requirements (i.e. I_T of at least 44 Ns).

In the next months, PPTCUP-QM will complete the lifetime test to further confirm the reliability of the thruster and to quantify the actual total impulse that the unit will deliver. Moreover, future work will focus on developing a predictive PPT numerical model to be used to optimise the thruster design and maximise the performance. This work will be carried out thanks to funding from the UK Technology Strategy Board.

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