PPT development for Nanosatellites applications: experimental results

IEPC-2013-198

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

M. Coletti[1]
Mars Space Ltd, Southampton, SO14 5FE, UK

S. Ciaralli[2] and S. B. Gabriel[3]
University of Southampton, Southampton, SO17 1BJ, UK

A PPT for Nanosat applications has been designed built and tested. Its performances have been characterized in terms of electrical parameters, mass bit, impulse bit and specific impulse in two different configurations varying the capacitor bank inductance. The PPT was found to be compliant with all mission requirements set at the beginning of the study in particular delivering an Isp of 640s that is 16% higher than the requirement. Preliminary EM noise measurements have been performed. The spark plug discharge was found to be the main source of noise. The noise has characteristic frequencies of the order of some MHz hence it can be inferred it is mostly radiated.

Nomenclature

A	=	propellant area exposed to the discharge
C	=	capacitance
E	=	energy
g_0	=	gravitational acceleration, 9.81 m/s^2
HV	=	high voltage
I	=	discharge current
Ibit	=	impulse bit
Isp	=	specific impulse
L	=	inductance
L'	=	inductance variation per unit length
LV	=	low voltage
R	=	resistance
Ψ	=	current parameter $\Psi = \int I^2\,dt$

I. Introduction

THERE is a growing technical interest for the use of nano-satellites within the aerospace community. However, the extent to which nanosats will be disruptive will depend heavily on the availability of suitable miniaturized propulsion systems. Due to resource limitations on nanosatellites such as mass, volume and power, a new generation of micro-propulsion systems is needed. A consortium formed by the University of Southampton, Mars Space, Clyde Space, OHB Sweden and NanoSpace has performed a survey of the potential mission classes which could benefit

[1] Director, Mars Space Ltd, Michele.coletti@mars-space.co.uk
[2] PhD student, ECS, University of Southampton, sc2d11@soton.ac.uk.
[3] Professor, EEE Research group, ECS, University of Southampton, sbg2@soton.ac.uk

from the use of a micro-thruster module and a trade-off leading to the selection of the most promising propulsion technology to develop [1]. At the end of this trade-off pulsed plasma thruster technology was selected and a thruster designed and manufactured [2]. In this paper the mission requirements and the thruster design will be quickly presented, after this the results obtained during the test campaign in terms of current parameter Ψ, mass bit, impulse bit, specific impulse, and conducted noise will be reported in detail and compared to the mission requirements. In an attempt of obtaining more experimental results that could be used in the future to optimize the thruster, measurements were performed outside of the nominal working conditions of the PPT in a shot energy range going from 1J to 5.5J. These data will also be presented and discussed.

II. Mission requirements

There are several kinds of Nanosatellite mission that can benefit from the use of micropropulsion as reported in [2]. For the scope of this activity it was decided to design a micropropulsion system able to provide attitude and translational control for a 20 kg nanosatellite. The module will be comprised of 6 PPTs each of which will have a wet mass lower than 500g. The propulsion system will have to deliver a total ΔV of 40 m/s equivalent to a total impulse of 800Ns. The power consumption of each thruster has been limited to a maximum of 10W and the volume available to 0.0016m^3. The propulsion module requirements are summarized in Table 1.

Table 1. Propulsion system requirements

Requirement	Propulsion system	Single thruster unit
ΔV	40 m/s	
Total impulse	800 Ns	133Ns
Number of thrusters	6	
Max Volume		0.0016 m^3
Max wet mass		500 g
Max Power consumption		10W

III. Pulsed Plasma Thruster Design

After completing a trade-off comparing the most promising propulsion technologies for Nanosat it was decided to design a breech fed pulsed plasma thruster [2]. Considering the power available and aiming at a pulse frequency of about 1Hz, a discharge energy of 5J was selected. The discharge energy density has been fixed at 2.5 J/cm^2 to obtain good performances at the same time allowing a compact thruster design. Considering the selected *E/A* ratio of 2.5 J/cm^2 an *Isp* of 550s is expected according to [3], considering the required total impulse and applying a 20% margin on the propellant mass a total of 30g of PTFE will be used in each PPT.

A copper tungsten alloy has been selected for the PPT electrodes, they will have a spacing of 2 cm and a width of 1 cm resulting in a h/w ratio identical to the one used in PPTCUP [4]. The electrodes are about 2cm long and have a tongue shape and are flared at 20° for better performances [5]. The spark plug uses a copper spark electrode surrounded by a thin ring of Teflon propellant delivering reliable discharge ignition at a voltage of about 7-8kV in line with what has been used in the PPTCUP lifetime test [6].

The discharge energy is stored in a capacitor bank made of 20 ceramic capacitors charged at a nominal voltage of 1720V (equivalent to 5J of energy). The capacitor used are the same that were successfully tested to 1,800,000 discharges in the frame of the cubesat PPT lifetime verification [6].

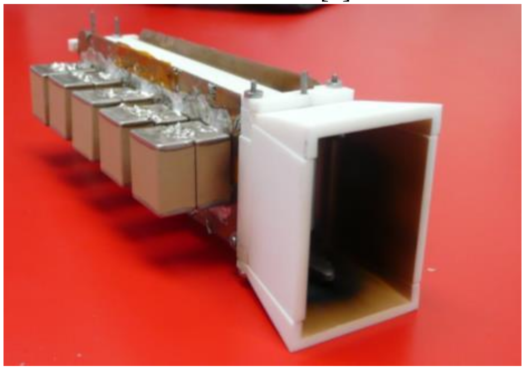


Figure 1: Assembled Breech-fed

A dedicated PPT electronics board has been designed and manufactured by Clyde Space Ltd. The electronics is split over two boards: one containing the RS 232 digital interface used to communicate with the satellite and one containing the HV circuitry needed to deliver the required capacitor bank and spark plug voltage.

To allow for performance investigation the capacitor charge voltage can be varied in the range 900 to 1850V via the RS323 interface. The spark plug voltage is instead fixed at 8kV. The electronics board assembly has an overall mass of about 100g and an envelope of about 120x60x30 mm.

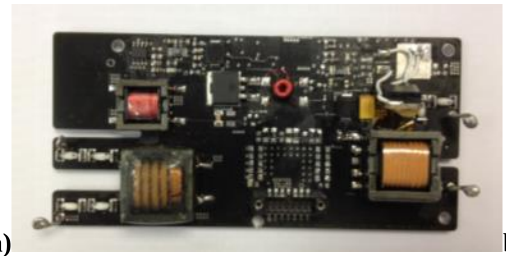
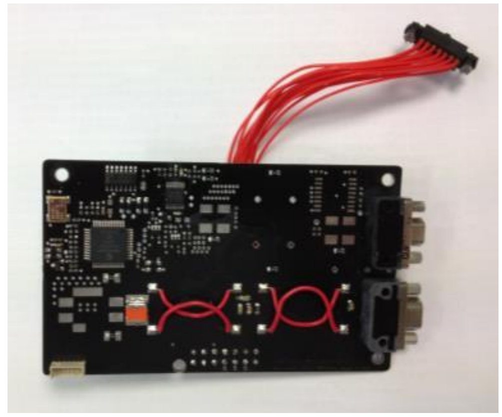
a)  **b)** 

Figure 2 – PPT electronics a) HV board b) digital board for communications and telemetry

Table 2. PPT design parameters

PTFE bar geometry	Breech fed
PTFE mass	30g
PTFE bar length	6.8 cm
Required *Isp*	550 s
Discharge energy	5 J
Nominal capacitor charge voltage	1720V
Bank capacitance (not including derating)	4uF
E/A	2.5 J/cm2
Thruster wet mass	240g
Electronics mass	100g
Total wet mass	340g
Electronics power output	5W
Electronics Efficiency	~75%
Electronics capacitor bank charge voltage	900 – 1850V
Electronics spark plug voltage	8kV

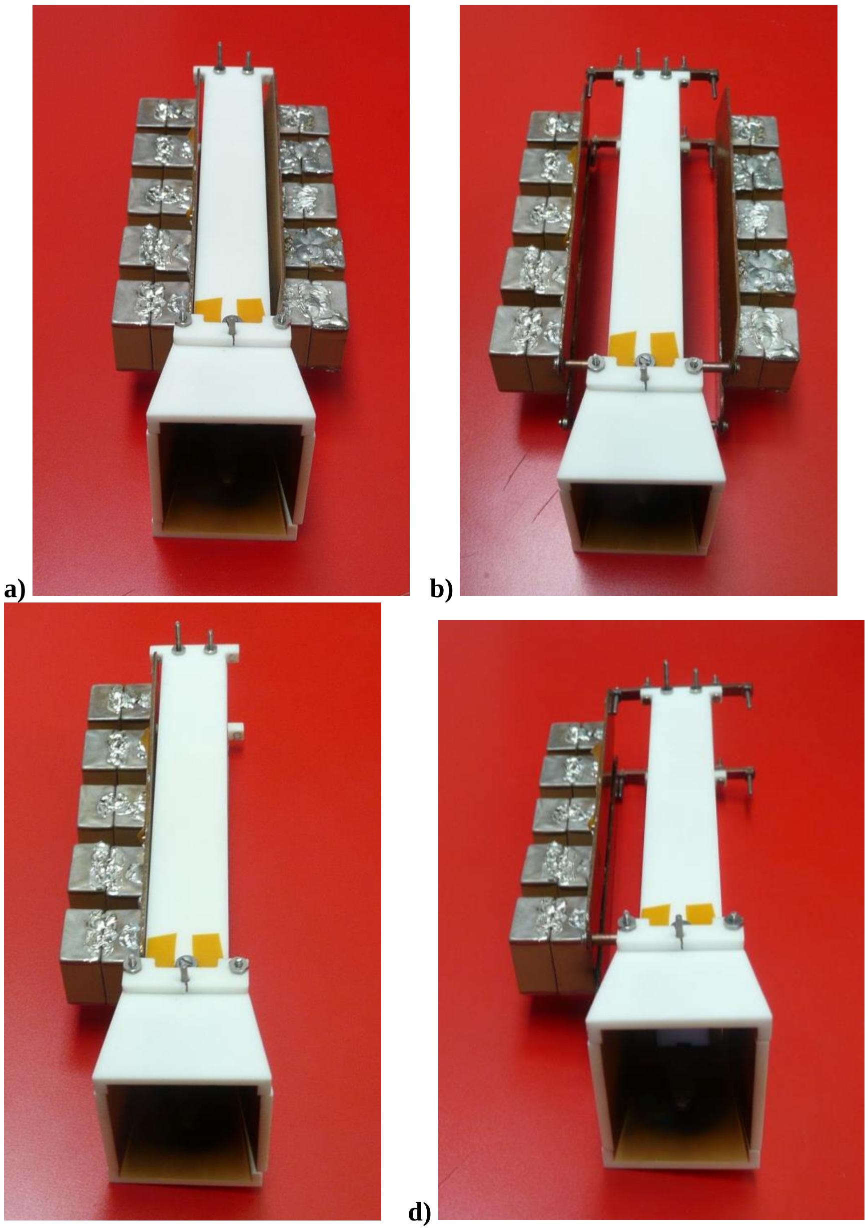
IV. Test Campaign

The main aim of the experimental campaign was to verify the thruster performance against the requirements. Nevertheless to obtain more data that can be used in the future for thruster optimization it was decided to perform testing over a wide range of energies (from 2 to 5.5J) and also to perform tests using only half of the nominal capacitor bank in a 1 – 3 J energy range.

The thruster has been tested in a total of four different configurations for a range of discharge energies. The four different configurations are characterized by the total thruster capacitance and by the use of Rogowski coils. In fact the capacitor bank is mounted as close as possible to the thruster body to limit the circuit inductance hence it does not normally allow for the use of Rogowski coils. The four different configurations are reported in Table 3 and in Figure 3.

Table 3. PPT configuration

Configuration	description
1 – nominal configuration	4uF capacitor bank
2	4uF capacitor “wide” bank to fit Rogowski coil
3	2uF capacitor bank
4	2uF capacitor “wide” bank to fit Rogowski coil



a) **b)** **c)** **d)**

Figure 3 – a) PPT configuration: a) configuration 1, 4uF bank, b) configuration 2, 4uF “wide” bank, c) configuration3, 2uF bank, d) configuration 4 2 uF “wide” bank

During the test campaign current and voltage curves, impulse bit, mass bit and conducted noise have been measured. The measurements performed in each configuration are reported in Table 4.

Table 4. PPT measurements

Configuration	Measurements
1	Voltage curves Impulse bit Mass bit EMC noise
2	Voltage curves Current curves
3	Voltage curves Impulse bit Mass bit
4	Voltage curves Current curves

V. Test setup

The tests were carried out at the University of Southampton. The vacuum chamber used is a vertical cylinder with 6 CF flanges and a 50 cm port on the side surface and two 40 cm flanges on the bases and has a volume of 0.35 m^3. The vacuum chamber is provided with a pumping system comprised by an Edwards roughing pump and by a Pfeiffer Balzers TPH 450 H turbo molecular pump with a pumping speed of 450 l/s backed up by a MD4TC Vacuubrand membrane pump achieving a base pressure of about 5E-6 mbar.

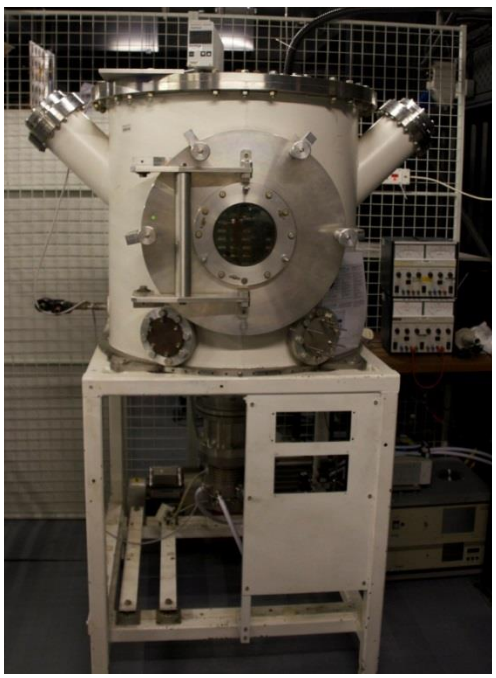


Figure 4: Test facility at the University of Southampton.

The physical and electrical setups are reported in Figure 5 and Figure 6.

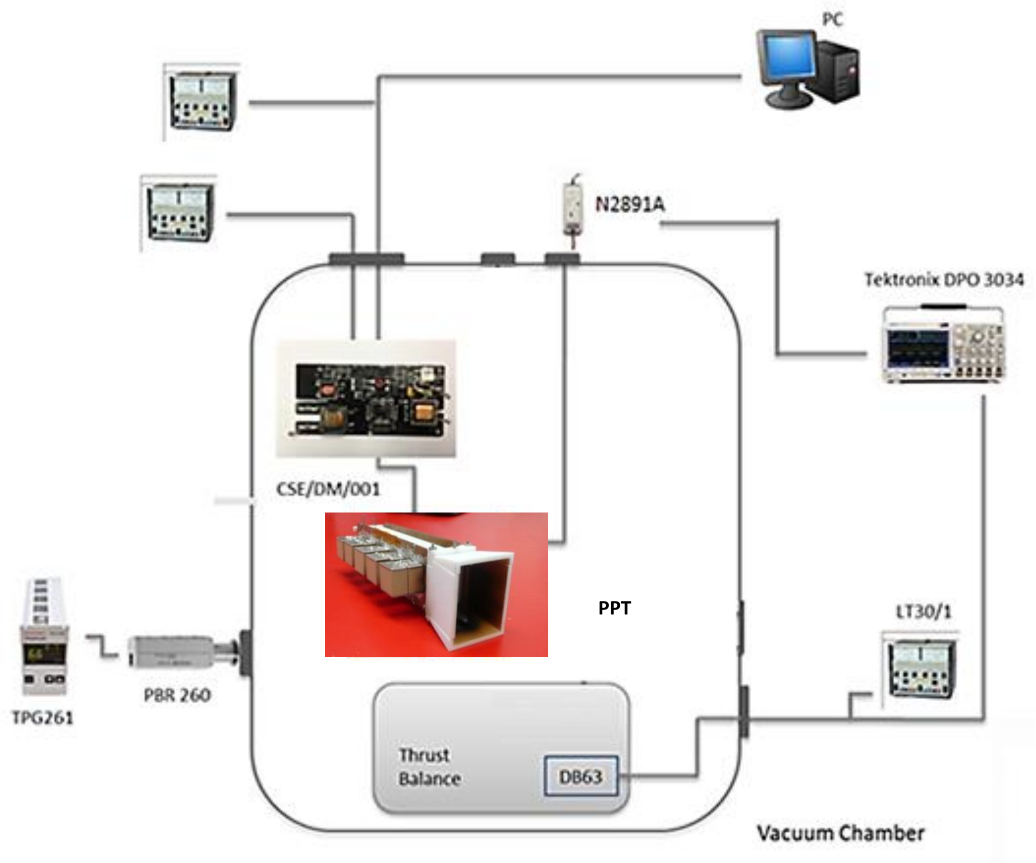


Figure 5 – Physical test setup

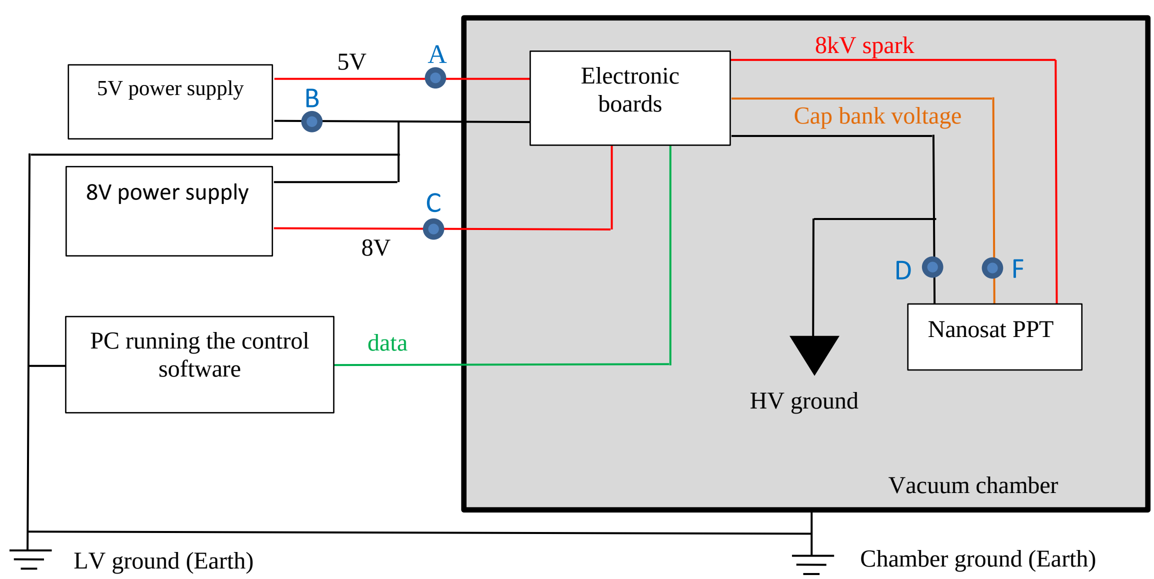


Figure 6 – Electrical test setup

The thruster impulse bit was measured with a direct impulsive thrust balance developed in-house; a more detailed description of the balance can be found in [7].

It must be noted that during the whole test campaign the electronics low voltage (LV) ground and the chamber ground were always connected to Earth whereas the high voltage (HV) ground was left floating. Test point D and F were used to perform the discharge voltage measurements whereas test points A, B and C were used in the EMC noise measurements.

VI. Experimental results

As already explained above the test campaign had the aim of both verifying that the PPT design will meet the requirement highlighted in Table 1 and Table 2, and to gather experimental data that can be used in the future to optimize the design. All the data collected will be reported below and commented according to both the experimental campaign aims.

A. Electrical characteristics

First of all the electrical characteristics of the thruster in terms of voltage and current curves were acquired. For each energy 10 shots were performed and the data averaged. The current curves for configuration 2 and 4 are reported below in Figure 7 for various energies, the calculated Ψ values are presented in Figure 9.

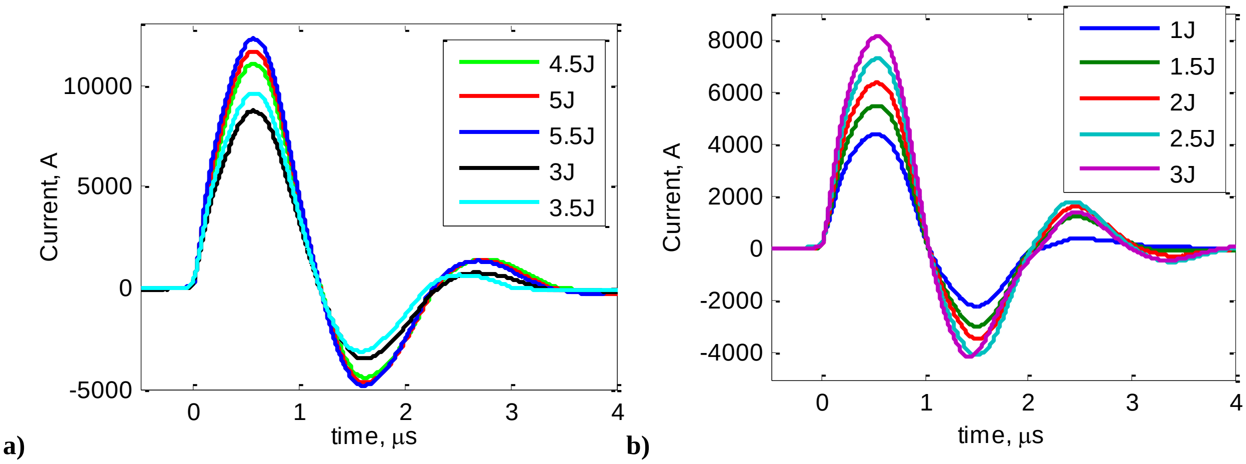


Figure 7 – Current curves for a) the full bank configuration (conf 2) and b) the half bank configuration (conf 4)

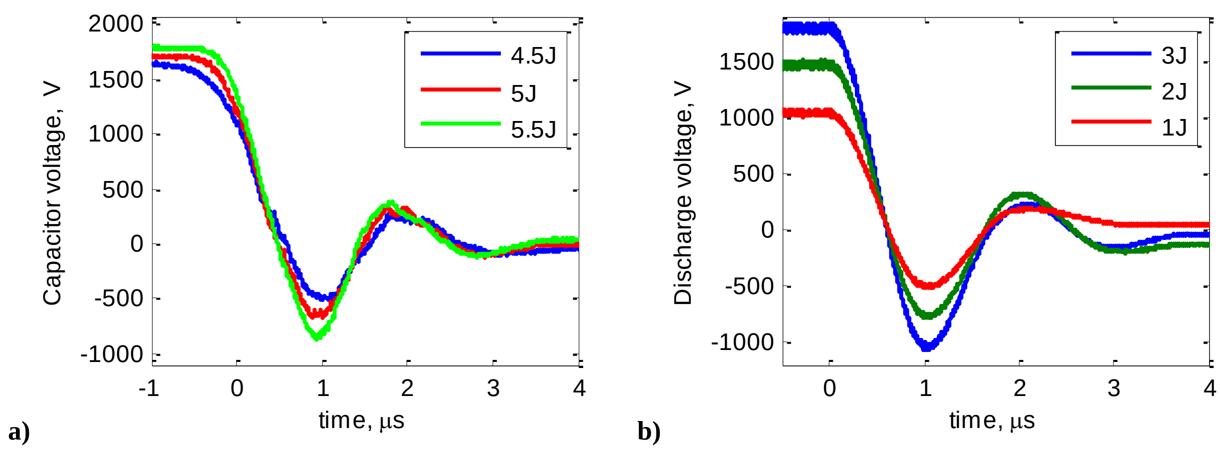


Figure 8 – Discharge voltage for a) full bank configuration (conf 2) and b) half bank configuration (conf 4)

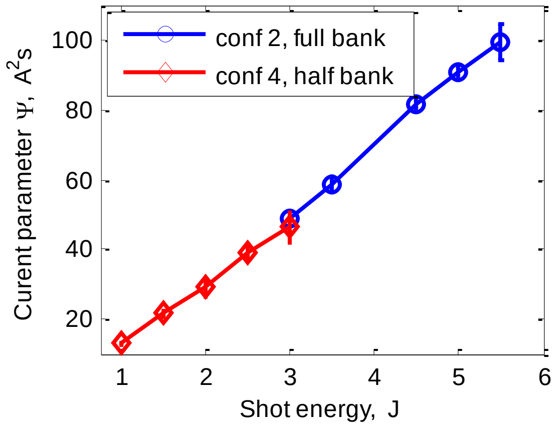


Figure 9 – Ψ trend with shot energy for the full bank and half bank configuration

The Nanosat PPT showed a under damped discharge that expires in about 1.5 cycles similar to the one that was measured on a cubesat PPT (called PPTCUP) developed previously [4]. The PPT also showed a very repeatable functioning with a standard deviation values for Ψ of less than 2% over the full range of energy that was tested.

It is also interesting to note how the values of the current parameters obtained from the full bank and the half bank configurations lie on similar linear regressions. Looking at Figure 7 it can be seen how the discharge current for the half bank configuration shows a more oscillatory behavior than the full bank configuration. An analysis of the discharge curves lead to an estimation of the average PPT electrical parameters for the two configurations as reported in Table 5

Table 5. PPT electrical parameters

Configuration	R [mΩ]	L [nH]	C [uF]
2 – full bank	56	41.5	4
4 – half bank	64	63.7	2

The increase in inductance with a smaller capacitor bank is due to the fact that the full capacitor bank is made of two half banks (see Figure 3) connected in parallel, hence assuming that the two banks have the same inductance (since they are designed to be identical) the inductance of the full bank should be about half the one of the half bank. If we considered that in the full bank part of the real inductance will also be due to the mutual inductance between the two banks a ratio of 65% between the full and half bank inductance can be considered acceptable.

For what concerns configurations 1 and 3 when they were tested only the voltage curves were acquired since it was impossible to fit the Rogowski coils. The voltage curves so obtained are qualitatively similar to those in Figure 8, the only significant difference is a reduction in the discharge time due to the reduced inductance of configurations 1 and 3 (Figure 10) in comparison to configuration 2 and 4. Comparing the voltage curves relative to configuration 1 and 2 (Figure 10) a reduction in inductance of about 30% can be calculated based on the reduction in the discharge period and assuming that the resistance is constant and equal to the value in Table 5.

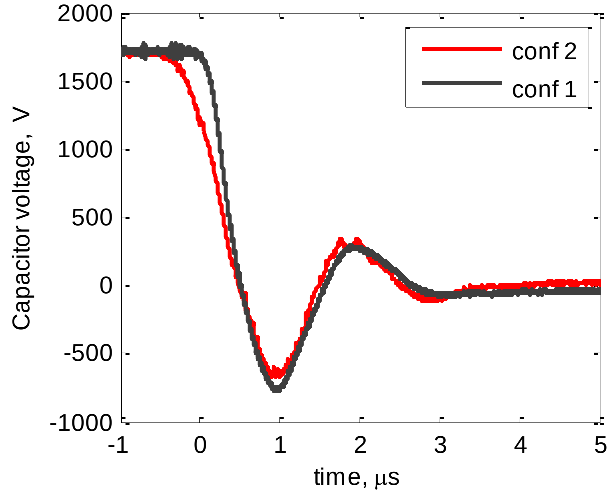


Figure 10 – Discharge voltage curve for configuration 1 and 2

B. Impulse bit

The impulse bit of the PPT was measured using the direct impulse balance described in [7]. For each energy value 10 measurement were taken and averaged, the value so obtained are reported in Figure 11 for the full and half bank.

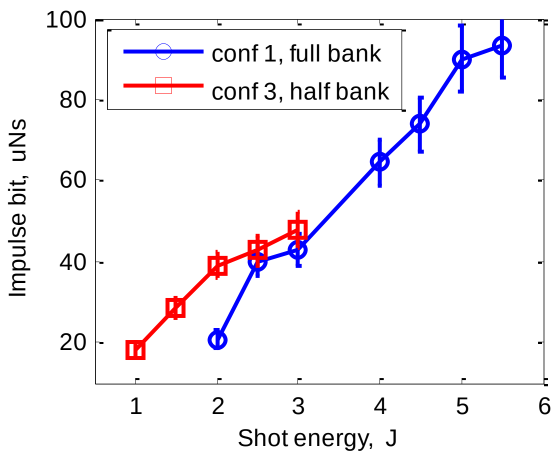


Figure 11 – Impulse bit trend with energy for the full bank and half bank configuration

During these tests the PPT delivered again very repeatable performances with a standard deviation of the impulse bit value of less than 3%. It must be noted that the error bars in Figure 11 include also the balance measurements error that has been quantified to be about 8% [7].

As it can be seen from Figure 11 the impulse bits for the full and half bank configuration do not follow the same trend with the half bank configuration delivering impulse bit values that are significantly higher than the one delivered by the full bank configuration at the same energy.

This was not expected considering that the value of the current parameters for the two configurations have very similar trends and also given the fact the half bank configuration showed higher values of initial inductance and resistance. One possible explanation for this is that the higher voltage at which the half bank operates when compared to the full bank at the same energy level (e.g. at 2.5J the half bank is charged at 1700V whereas the full bank at 1200V) improves the discharge efficiency but this is in contrast with the higher values of the plasma resistance derived in Table 5.

Nevertheless it must be noted that in the nominal configuration the PPT delivers and *Ibit* of about 90 uNs at 5J with an *Ibit/E* ratio of about 17uNs/J in line with the typical performances of breech fed thrusters [8].

C. Mass bit and Specific impulse

The thruster mass consumption has also been measured using a Mettler Toledo balance with an accuracy of 10ug and performing a minimum of 300 shots per energy (1000 shots were performed at energies below 3.5J) achieving a measurement error of less than 3%. The mass bit trend with energy is reported below together with the derived Isp values.

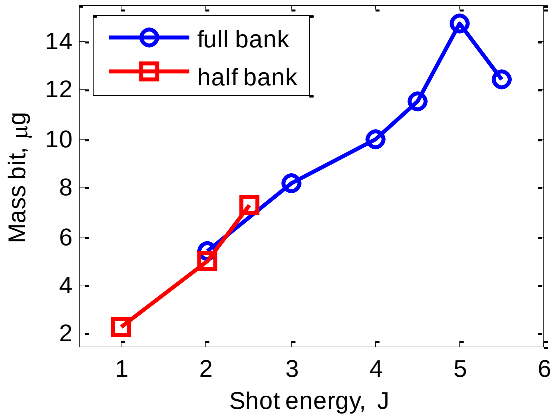


Figure 12 – Ablated mass bit for the full bank and half bank configuration

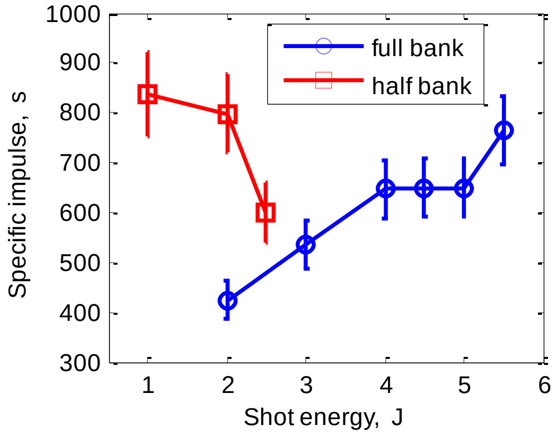


Figure 13 – Specific impulse for the full bank and half bank configuration

First of all it should be noted how the specific impulse value at the nominal energy of 5J is about 650s hence 18% higher than the requirement of 550s in Table 2.

Comparing the mass bit trend for the full and half bank configurations (conf 1 and 3) it can be seen how they are very similar as already seen for the current parameter *Ψ*. This, together with the higher *Ibit* measured for the half bank configuration (Figure 11), lead to specific impulse values that are sensibly higher for the half bank than for the full bank.

As for the *Ibit* this was not expected especially considering the *R* and *L* values reported in Table 5. A preliminary explanation can be found in the different discharge durations of about 2.5us for the full bank and 3us for the half bank. In fact, taking the 2J shot energy case as an example, and assuming that the discharge moves at an average speed equivalent to g_0·Isp, the distance covered by the discharge will be respectively 10 and 22 mm for the full bank and half bank case. If we consider that the electrodes are 20mm long, divergent and tongue shaped hence the value of *L'* will increase more than linearly moving downstream [5] it is can be seen how in the half bank case the discharge is able to reach the end of the electrodes hence experiencing higher values of *L'* consequently delivering higher electromagnetic impulse bits [8]. Nevertheless this possible explanation is to be considered very preliminary and will have to be confirmed at least by slug model simulation and by an accurate modeling of the L' trend along the electrodes length and possibly by a higher number of measurements. Unfortunately due to time restrictions this activities could not be performed in time for the conference.

D. Noise

The last part of the experimental campaign focused on the full bank configuration only and was aimed at performing preliminary measurement of the EMC noised produced by the PPT. Since no requirement was set on the PPT EMI levels the aim of this test will be to preliminary characterize them. Moreover to the best knowledge of the authors the level of noise produce by a PPT has been reported in the literature only once [9] hence this test might provide data that will be key in understand the PPT EM noise production.
For this test it was decided to measure the voltage ripple on the digital (5V) and power (8V) lines going to the PPT electronics across point A and B, and C and B in Figure 6. It must be noted that for these measurements (as for the rest of the test campaign) the power supplies and vacuum chamber were grounded to Earth whereas the PPT was left floating (meaning that the PPT cathode was not connected to Earth).

Measurements were performed only at energies close to the PPT nominal energy of 5J and only for the full bank configuration. In addition to this, measurements were also performed on these lines for a spark plug only shot. The measured data is summarized in Table 6 and Figure 14 to Figure 17.

Table 6. RMS noise values at different energies

Cap bank voltage [V]	Energy [J]	Measurements	Mean RMS value [V]
1632	4.5	8V line	2.27 +/- 0.63
1720	5	8V line	2.73 +/- 0.69
1804	5.5	8V line	2.51 +/- 0.72
0	Spark only	8V line	3.88 +/- 0.66
1632	4.5	5V line	2.44 +/- 0.59
1720	5	5V line	2.91 +/- 0.51
1804	5.5	5V line	2.7 +/- 0.61
0	Spark only	5V line	4.25 +/- 0.59

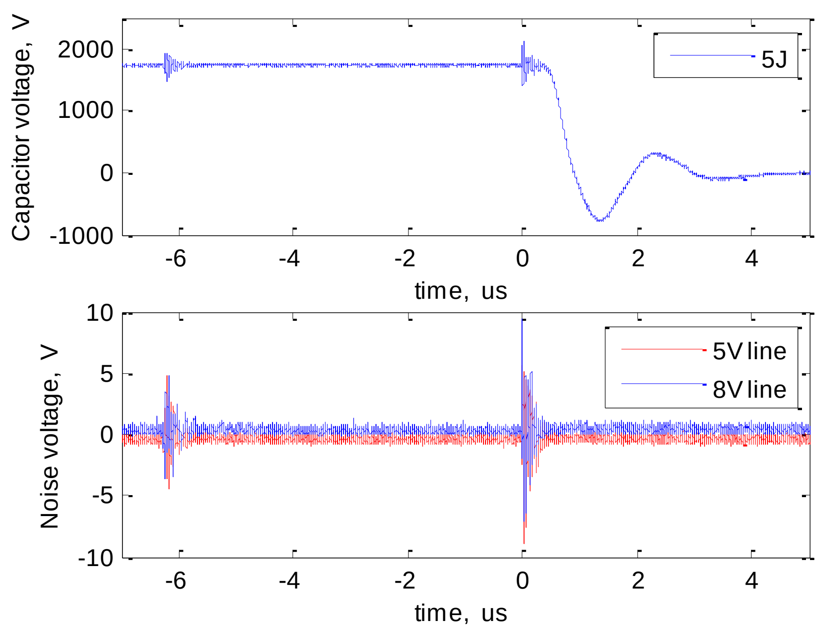


Figure 14: Noise and discharge voltage at 5J of shot energy

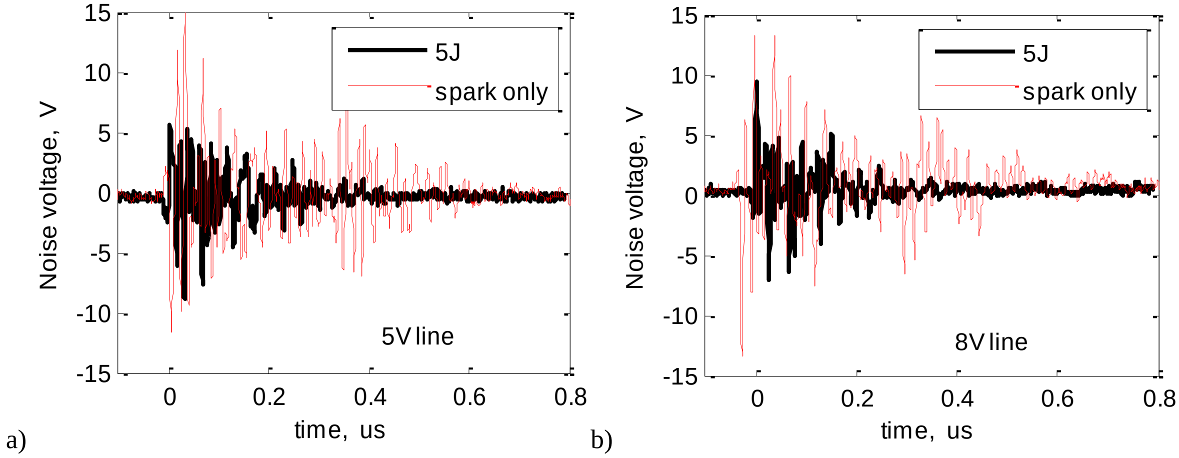


Figure 15: Comparison between the noise generated only by the spark plug and the one generated at 5J of discharge energy

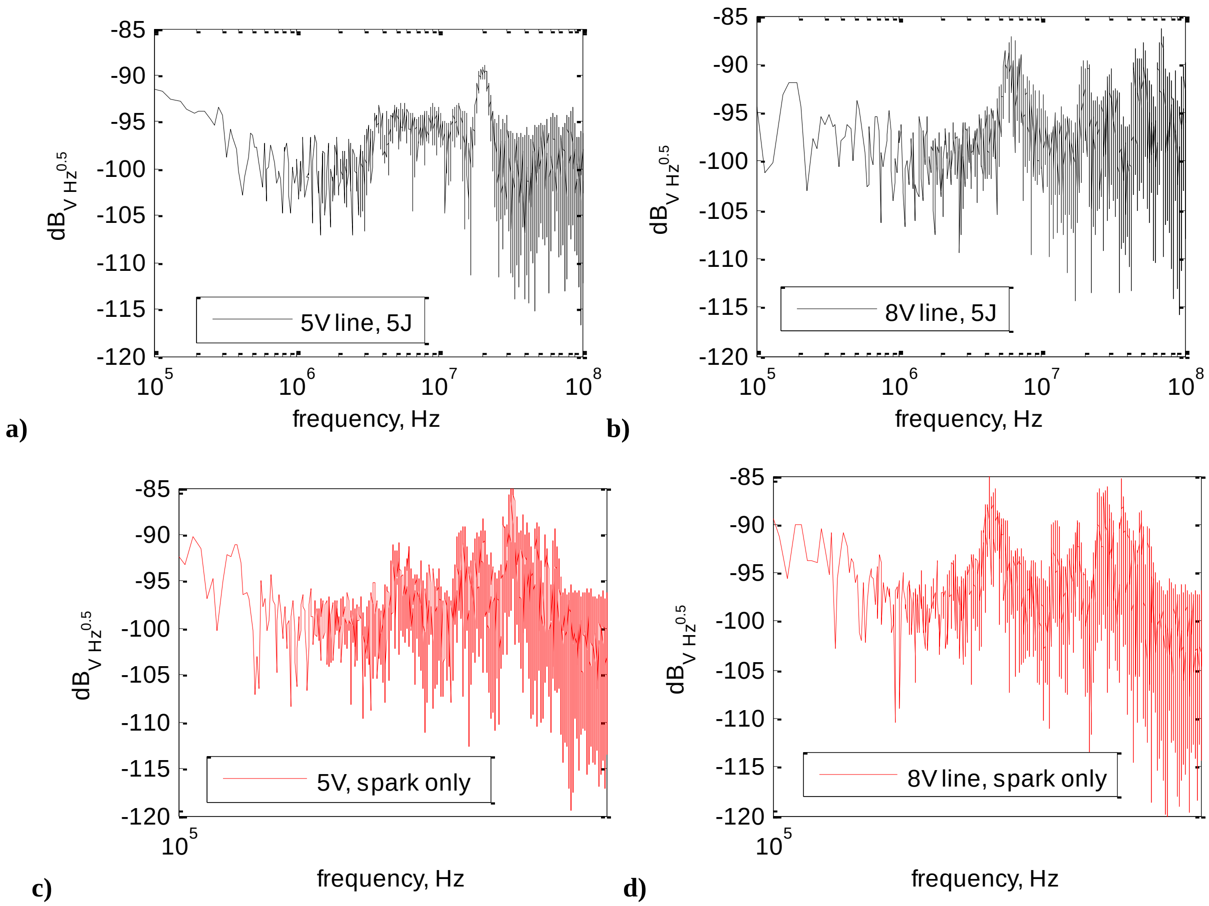


Figure 16: Noise PSD. a) 5J shot on the 5Vline, b) 5J shot on the 8V line, spark plug only on 5V line, d)spark plug only on the 8V line

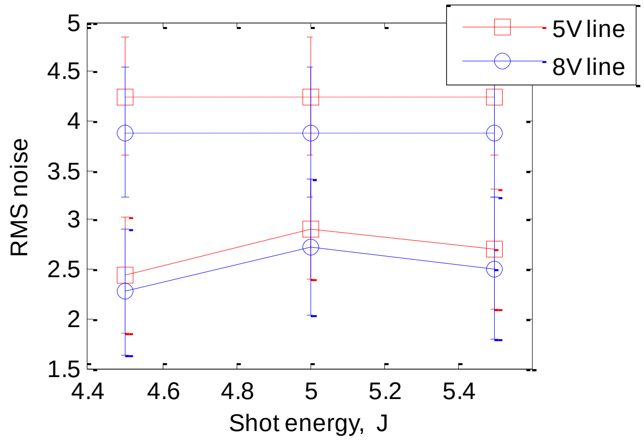


Figure 17: RMS noise levels at different energies and for spark only operation on the 5V and 8V lines

Looking at the data reported in Figure 14 and Figure 15 it can be seen how the noise generated by the PPT lasts for about 400-500 ns hence the RMS values reported in Table 6 have been calculated during this time.

Looking at the data in Table 6 and Figure 17 it can be noticed how the shot energy influence on the noise RMS level is very limited. In particular the change in noise level with energy is normally within the measurement error bars. More importantly it can be seen how the noise measured on the 5 and 8V lines are very similar and follow the exact same trend with energy and moreover how a spark only shot (meaning that the spark plug is triggered without charging the main capacitor bank) produces a noise that is higher than the one produced by the “full” shot.

During this test phase we also tried to acquire the noise generate on the 5V and 8V lines by a capacitor arc. Arcs were generated charging the capacitor bank at 5J of energy and increasing the chamber pressure until an arc across the capacitor bus bars occurred. Interestingly no noise was picked up by the scope in this case.

Moreover looking at Figure 14 it can be seen how noise is produced right at the main discharge ignition. From all this it can be inferred that the main source of noise is the spark plug discharge.

Looking at Figure 14 another interesting fact can be observed i.e. noise is generated also some microseconds prior to the shot. This was not seen at every shot, and sometimes noise was generated 3 or 4 times prior to the shot, sometimes only just at the start of the main discharge ignition. Also the lag between the first noise spikes and the main discharge ignition varied with lag times in the range 1 to 10 us. It should also be noted that the highest noise was always measured at the main discharge ignition (and the values reported in Table 6 have been calculated taking into account only this noise).

Considering that the shot was always commanded in the same way and that the occurrence of multiple noise “packets” appeared to be completely random we think that this phenomenon is not related to the way the electronics is operated. At present we do not have a clear understanding of why this is happening and more testing would be needed to investigate it. Anyway the presence of these multiple noise packets can be explained in three different ways:

a) The presence of multiple noise packets is relative to the electronics design
b) The presence of multiple noise packets is relative to some facility effect
c) The presence of multiple noise packets is relative to the way the spark plug discharge is created and to its characteristics

At present we do not have any data that will allow us to definitely exclude any of these hypotheses but it must be noted that a noise similar to that reported on the top part of Figure 14 was also observed during testing of a cubesat PPT [6] while powered by a GSE. In the GSE the spark was generated discharging a capacitor charged at high voltage (7-8kV) over the spark plug by mean of a HV relay. In the electronics used for the tests reported in this paper the voltage needed to ignite the spark plug was instead generated by the discharge of a low voltage capacitor over a pulsed transformer. The fact that curves similar to the one in Figure 14 could be observed in both cases might lead us to consider that the presence of multiple noise packets is not (or at least not only) relative to the electronics design.

Looking now at the noise PSDs (Figure 16) it can be seen how most of the noise power is concentrated on frequencies close to 20Mhz on the 5V line and 6MHz on the 8V line; it can also be noted that there are qualitative similarities between the PSD obtained with a thruster shot at 5J and the ones obtained with a spark plug only shot confirming the spark plug as the main source of noise. Considering the observed frequencies it can be preliminary concluded that most of the EMI is radiated and not conducted, and that what is measured on the 5V and 8V line is the noise that these lines pick up acting as antennas.

VII. Conclusions and Future Work

A pulsed plasma thruster for nanosatellite application has been designed built and tested. The PPT provided reliable and repeatable performances through the test campaign delivering a specific impulse in excess of the mission requirements. The PPT mass was also measured prior to the test campaign start and it was found to be about 30% lower than the maximum allowable limit. A compliance requirement matrix is reported in Table 7.

Table 7. Requirements compliance matrix

Requirement description	Requirement Value	Measured Value	Compliant
Micro thruster module wet mass	500g	350g	Yes
Power	<10 W	5 W	Yes
Max Volume	0.0016 m^3	0.000324 m^3	Yes
Isp	550s	640s	Yes
ΔV	40 m/s	56 m/s *	Yes
Total Impulse (for 6 modules)	800Ns	1130Ns *	Yes

*(based on 30g propellant and measured *Isp*)

As it can be seen the PPT is compliant with all requirements especially being lighter than the requirements and delivering higher Isp hence promising higher total impulse and Δv values.

During the test campaign measurements of the noise generated by the PPT were also performed. From the data collected it can be inferred that the noise is mostly generated by the spark plug discharge and that it is mostly radiated; RMS values of the order of 2-3 V were measured.

The PPT has also been tested with a half capacitor bank. The performance measured in this configuration were found to follow the same trend as those measured with the full bank in term of current parameter and mass bit values. The impulse bit instead showed a different trend for the half and full bank configurations that resulted in a higher Isp being delivered by the half bank. This is not in agreement with the expectations. A possible explanation has been formulated based on the discharge duration and the trend of L' along the electrodes length but more measurements and modeling will be performed in the future to analyze in detail this performance.

References

[1] A.Mingo Perez, M.Coletti, and S.B.Gabriel. *Development of Microthruster Module for Nanosatellites Application*. 32nd International Electric Propulsion Conference, Germany. 2011

[2] A.Mingo Perez, M.Coletti, and S.B.Gabriel. *A micro PPT for Nano-satellite applications: Design and experimental results*. 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Atlanta, USA, 30 July - 1 August. 2012

[3] P.Gessini and G.Paccani. Ablative Pulsed Plasma Thruster System Optimization for Microsatellites. 27th International Electric Propulsion Conference, IEPC-01-182. 2001

[4] M.Coletti, F.Guarducci, and S.B.Gabriel. *A micro PPT for Cubesat application: Design and preliminary experimental results* . Acta Astronautica, 69, 200-208. 2011

[5] A.Nawaz, G.Herdrich, H.Kurtz, T.Schonherr, and M.Auweter-Kurtz. *SIMP-LEX: Systematic Geometry Variation Using Thrust Balance Measurements*. 30th International Electric Propulsion Conference, Florence, Italy September 17-20. 2007

[6] S.Ciaralli, M.Coletti, and S.B.Gabriel. *PPTCUP lifetime test results*. 33rd International Electric Propulsion Conference, Washington D.C., USA, October 6- 10, 2013, IEPC-2013-164. 2013

[7] S.Ciaralli, M.Coletti, and S.B.Gabriel. *μ-PPTs diagnostics: a high accuracy impulsive thrust balance*. 33rd International Electric Propulsion Conference, Washington D.C., USA, October 6- 10, 2013, IEPC-2013-165. 2013

[8] R.L.Burton and P.J.Turchi. *Pulsed Plasma Thruster*. Journal of Propulsion and Power, Vol. 14, No. 5. 1998

[9] S.W.Benson, L.A.Arrington, W.A.Hoskins, and N.J.Meckel. *Development of a PPT for the EO-1 Spacecraft*. 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit. 1999