PETRUS 2.0 PPT and its CubeSat-size PPU: Testing and Characterization

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Abstract: This paper discusses current test results of the coaxial breech-fed pulsed plasma thruster (PPT) PETRUS. Two major aspects are investigated. First, the influence of different anode geometries to thruster specific parameters like impulse bit, mass bit, and thrust efficiency. Second, a laboratory model of a CubeSat-size Power Processing Unit (PPU) is developed and tested. With a total mass of 400 g and a volume of 0.5 U, the PETRUS propulsion system is a compact and self-contained.

For determining the effect of different anode geometries, eight expansion ratios from 1 to 2.4 were examined at respective pulse energies of 3 J, 5 J and 7.68 J. Operating PETRUS at its nominal energy of 5 J a thrust efficiency of 9.1 % Is reached at a nozzle expansion ratio of 1.54. Here, the Isp is 862 s and the mass bit is 12.86 µg. Moreover, it is determined that the mass bit minor varies throughout a constant pulse energy and the different nozzle expansion rations.

During the commissioning phase of the PPU, the maximum pulse frequency, the charging time and the EMS sustainability was characterized through testing. Further, thermal tests of critical subassemblies were carried out and a first endurance test was successfully performed. In total more than 32000 pulses are done without any failures. An electrical efficiency of 76.1 % is reached and the charging time of the capacitor bank is 872 ms for 5 J. The average power input is 7.8 W. In a long duration test with 11177 pulses the critical electrical components, i.e. transformer and resistor reached a maximum temperature at 76 °C and 61 °C respectively. These values are below the maximum rated temperature of 150 °C. Finally yet importantly, the PPU triggered the ignition of two clustered PETRUS PPTs, separately and simultaneously.

I. Introduction

The development of the Pulsed Plasma Thruster (PPT) PETRUS and its Power Processing Unit (PPU) aim towards a compact, coast-efficient and lightweight propulsion system for CubeSat applications. From top to bottom PPTs consists of a capacitor bank, a pair of electrodes, an ignition electrode, an insulator and the propellant e.g. Polytetrafluorethylene (PTFE) – also known as Teflon®. By being one out of four PPTs developed at the Institute of Space Systems (IRS) [1], PETRUS is a miniaturized coaxial, breech-fed PPT designed for a nominal pulse energy of 5 J. A description of the development history and the thruster design can be found in literature [2]. The current investigation focus lies on maximization of the thrust efficiency through adaption of the discharge channel geometry, which affects the plasma creation and acceleration. The procedure, boundary conditions and test results are detailed discussed in the first section of this paper.

The PPU is a stand-alone system controlling the operation of the PETRUS PPTs, either separately or simultaneously. Generally, the PPU consists of a controller, a high voltage unit for triggering the ignition electrodes, a high voltage unit for charging the capacitor bank and a feedback loop monitoring the discharge process. Including the cluster of four thrusters and the PPU, the system mass shall not exceed 400 g at a volume of less than 0.5 U. The average nominal power consumption is less than 8W. Development and tests of the PPU are described in the second section of the paper. The operating principle of the overall system is depicted in *Figure I.1*.

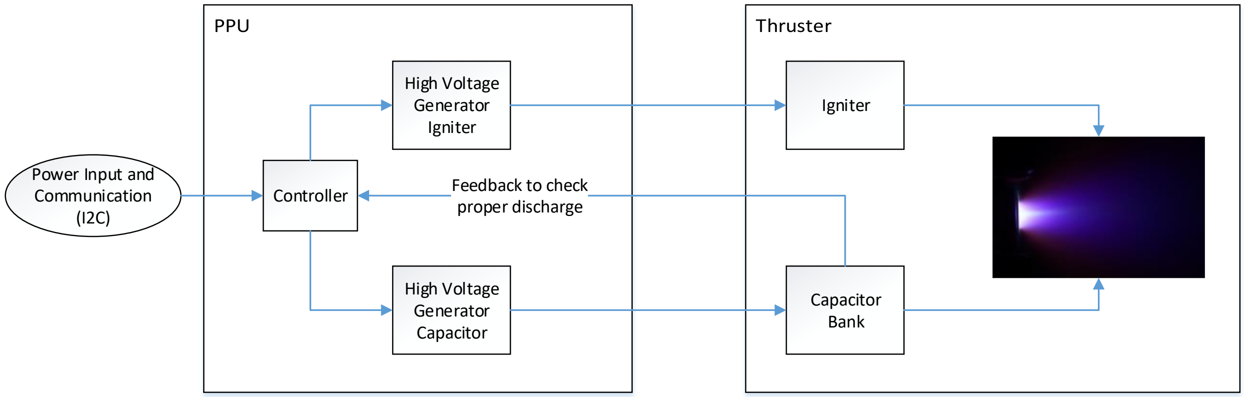

Figure I.1 Schematics of the PPT propulsion system including PETRUS and PPU.

II. Investigation of the Discharge Channel Geometry

Three major aspects must be considered when optimizing a PPT. First, the characteristic discharge behavior has to be an underdamped oscillation to ensure an efficient energy coupling to the plasma. This strongly depends on the thruster's electrical circuit design. Second, the ratio between the propellant surfaces and the pulse energy is an important design criterion to avoid charring effects. The third influencing factor is the discharge channel geometry. As shown in literature, the optimization of the discharge channel geometry affects the plasma acceleration process. For parallel plate PPTs, which mainly use the MHD effect, it turned out that flared and tapered discharge channel geometry improve the plasma acceleration and subsequently the thrust efficiency [3, 4]. A similar effect applies to the coaxial PPT design being traditionally operated purely thermal [5]. Here, the expansion ratio of the nozzle influences the plasma acceleration [6]. PETRUS' electrode configuration makes use of both acceleration processes, making it a hybrid device. The MPD part focuses the plasma and forms a theta pinch [7]. The cylindrical anode (nozzle) enables an enclosed discharge channel transforming thermal energy to motion energy.

Even though all three mentioned aspects are in close correlation, it is tempted to determine the effect of one by keeping the others constant. The variation of the discharge channel geometry is investigated for eight nozzle expansion ratios reaching from 1 to 2.4. Test campaigns with all expansion ratios and pulse energies are accomplished. The main oscillation circuit, capacitance and the electrode connection are unchanged. In each of the 24 test campaigns, 500 pulses are performed to determine the mass bit. Additionally, 40 impulse bit measurements per campaign were done, 20 measurements in the beginning and 20 at the end determining a possible drift. A detailed description of the automated impulse bit measurement system can be found in literature [8, 9]. For reasons of comparability, before each test campaign the propellant surface is machined. The reason for this are slight surface changes after 500 pulses. The test results of the mass bit and impulse bit measurements are depicted *Figure II.1*. Throughout the mass bit investigations, it was determined that the ablated mass per pulse seems to be independent from the nozzle expansion ratio (*Figure II.1*, left). The slight variation can be explained by uncertainties of the propellant surface machining. Comparing the impulse bit results of all three pulse energies, two specific characteristics are found (*Figure II.1*, right). First, with increasing expansion ratio the impulse bit slightly rises for the three pulse energies. This might be reasoned by the expansion ration only. However, the effective distance the plasma travels along the anode's wall also increases with the expansion ratio. Consequently, an increasing ΔL can be expected, which is responsible for an improved electrical efficiency and an improved energy coupling to the plasma [10]. The investigation of both effects is still ongoing. Second, each impulse bit curve has a significant peak at an expansion ratio of 1.54. The 3 J case reaches up to 63.6 µNs, the 5 J case reaches 108.8 Ns and the 7.68 J case ends up at 169.2 µNs. Followed by a drop, the impulse bit of all three pulse energies slightly increases again between an expansion ratio of 1.47 and 2.4. *Figure II.2* depicts an exemplary Gaussian distribution for testing an expansion ratio of 1.54. A significance level of 5% was chosen. By analyzing the thrust efficiency, a very similar behavior is investigated (*Figure II.3*and *Figure II.4*).

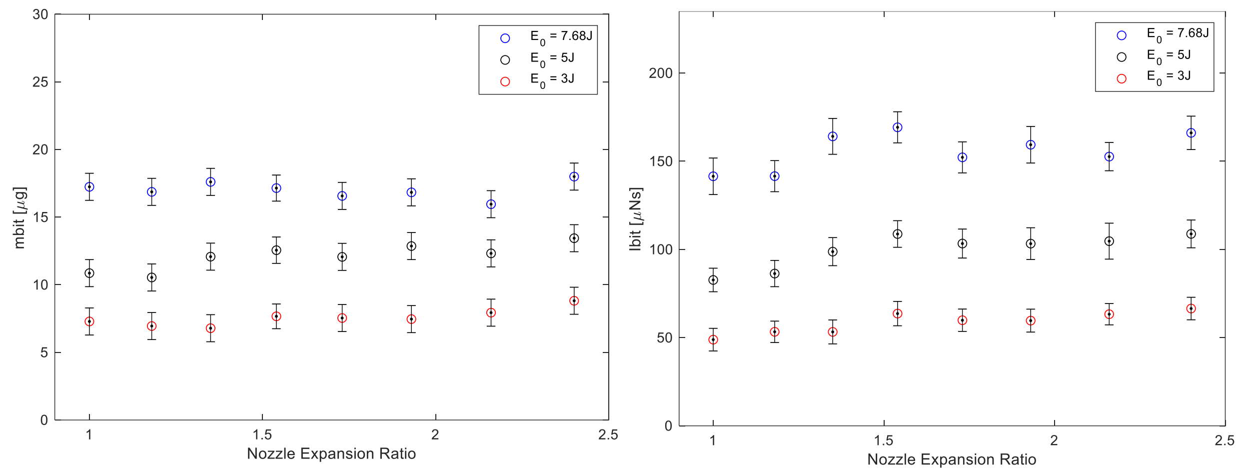

Figure II.1 Left, correlation between mbit and nozzle expansion ratio for 3J, 5J and 7.68J. Right, the respective Ibit distribution.

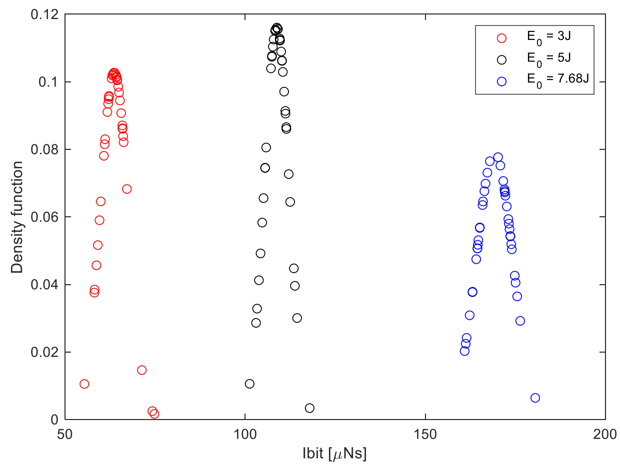

Figure II.2 Exemplary Gaussian distribution for all three pulse energies for an expansion ratio of 1.54. The significance level is 5%.

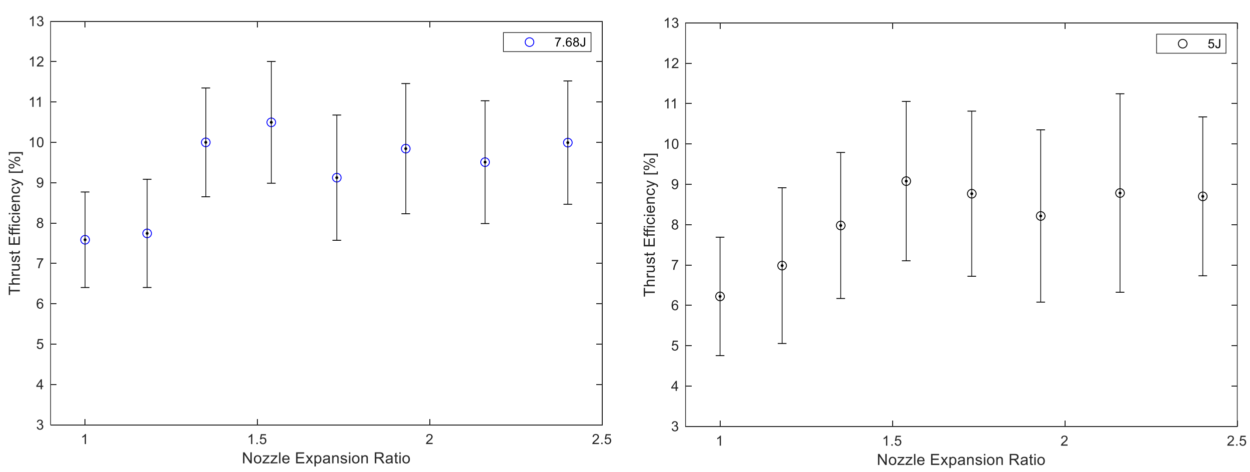

Figure II.3 Left, thrust efficiencies vs nozzle expansion ratio operating PETRUS with 7.68 J.Right, thrust efficiencies vs nozzle expansion ratio operating PETRUS with 5 J.

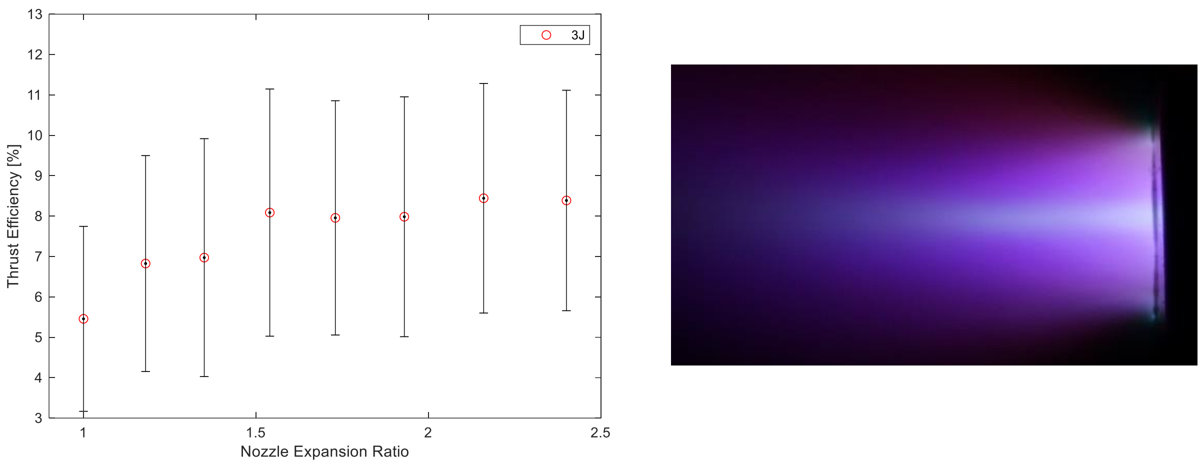

Figure II.4 Left, thrust efficiencies vs nozzle expansion ratio operating PETRUS with 3 J. The right shows PETRUS while pulsing at 5 J with an anode expansion ratio of 1.54.

All their pulse energies reach their maximum thrust efficiency at an expansion ratio of 1.5. The 3 J case peaks 8.1 %, the 5 J case at 9.1 % and the 7.68 J case at 10.5 %. Since there is no significant decrease in mass bit for these cases nor any changes within the mean inductance and resistance, an improved acceleration caused by thermal effects is assumed. At the right in *Figure II.4* PETRUS is depicted while pulsing and being operated at a capacitor bank energy of 5 J. The nozzle expansion ratio is 1.54.

III. Development of the Power Processing Unit

In order to operate PETRUS on a CubeSat a miniaturized Power Processing Unit (PPU) is indispensable. The main tasks of the PPU are the charging process of the capacitor bank, triggering the ignition and the recognition of successful ignitions as well as misfiring. Within the development of PETRUS, such a PPU is designed and tested (*Figure III.1*). Main goal was to build a PPU for laboratory use, which also fulfills first CubeSat requirements like a maximum dimension of 100 x 100 x 30 mm^3 and PC/104 boards shall be used. By integrating the PPU into the fully automated IRS PPT testbed thruster and PPU can be tested at the same time [8] [9].

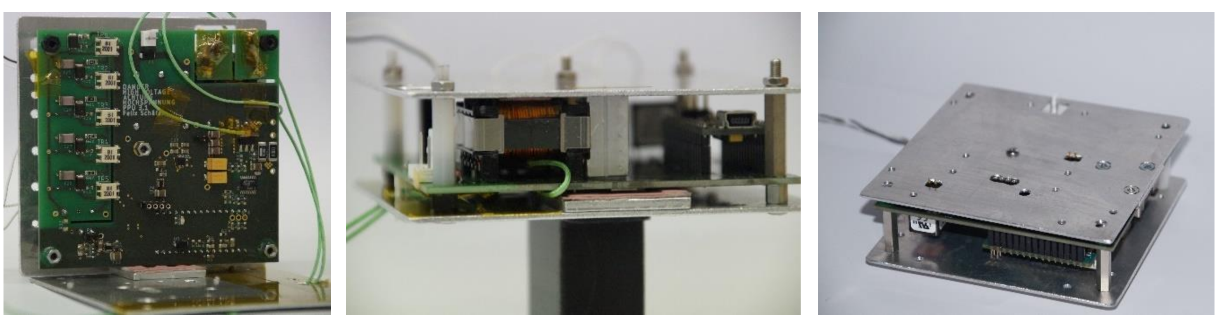

Figure III.1 Miniaturized laboratory PPU model.

A. **PPU Design Considerations**

For designing the PPU, boundary conditions are established (*Table III.1*) describing the operational use within the laboratory environment and a future CubeSat application. Major aspect of developing the PPU is to demonstrate the feasibility of a miniaturized PPU to operate PETRUS at its nominal conditions meaning that a 6 µF capacitor bank is charged within 1 s to an energy of 5 J.

Table III.1 Primary and secondary objectives considered within the PPU development.

#	Priority	Consideration	Status	Confirmed by
1	Primary	The PPU shall charge the capacitor bank in the range between 200 V and 1300 V.	Fulfilled	Charging test and single ignition test, cycle test
2	Primary	The PPU shall trigger the ignition of PETRUS.	Fulfilled	Cycle test
3	Primary	The PPU shall charge PETRUS to 5 J and trigger the ignition within 1 s.	Fulfilled	Cycle test
4	Primary	The PPU shall trigger up to four PETRUS thrusters.	Partly fulfilled	Ignition of two thrusters
5	Primary	The PPU shall be able to be controlled from outside the vacuum tank and must provide the following actions for the user: • Configuration of the final charging voltage • Execution of a single charging process • Execution of a single ignition process • Execution of multiple charging- and ignition processes • Configuration of the charging- and ignition cycle time • Selection of the thruster to be triggered.	Fulfilled	Charging test and single ignition test, cycle test, integration test
6	Secundary	The PPU shall recognize misfiring and send the status to the user.	Fulfilled	Thermal test
7	Secundary	The PPU shall charge the capacitor bank between 200 V and 1600 V.	Fulfilled	Charging test and single ignition test, cycle test
8	Secundary	The PPU shall ignite the thruster up to a frequency of 4 Hz.	Fulfilled	Integration test

Since the overall propulsion system is designed to be operated with up to four PPTs the PPU also shall be able to trigger the thrusters separately from each other or simultaneously. If triggering the four thrusters simultaneously it must be considered that the maximum pulse energy per thruster currently is roughly 2 J. This is reasoned by the single capacitor bank connected to the cluster of thrusters. However, in future the PPU shall be able to trigger the ignition up to 4 Hz investigating the thruster and propellant behavior at different pulse energies. Needed for the CubeSat application, the PPU is also able to recognize successful ignitions as well as misfiring. For both cases, the PPU will output a user information. The following tests were performed to verify that the required objectives are met.

1) **Charging test**: The capacitor bank is charged in less than 1 s to the required 1300 V (E_0 = 5 J).
2) **Single ignition test**: After charging the capacitor bank, a single ignition is performed to prove that the ignition system of the PPU operates correctly.
3) **Cycle test**: For running a long-term test, the PPU charges and triggers the ignition of PETRUS multiple times within an automated loop.
4) **Ignition of multiple thrusters**: A cluster of PETRUS thrusters connected to a single capacitor bank is operated.
5) **Integration test**: The PPU is operated by connecting and implementing the device to the IRS automated PPT testbed.
6) **Thermal test**: The PPU is operated in vacuum within a long-term test. Thermocouples are mounted to critical electronic components, i.e. transistor, transformer. A reference temperature and the casing temperature are also measured.

As listed in Table III.1 all design considerations are fulfilled, but number four. Here, a test campaign with only two clustered PETRUS PPTs was successfully performed. A cluster with four thrusters is simply not build yet. Both thrusters were connected to a single capacitor bank enabling separate and simultaneous pulses. *Figure III.2* depicts a time exposure where the two thrusters were ignited separately from each other. The results of the charging, ignition, cycle and integration tests can be seen in *Figure III.3*. All were accomplished within the thermal test campaign. Generally, there is a cycle of nine pulses, whereas a single charging and ignition process is accomplished within 872 ms. Throughout all tests no failure the PPU was recorded. In total more than 30000 pulses were performed successfully within single, long-term and thermal tests. Operating the PPU inside the vacuum tank right behind the thruster also showed no failures, proving the functional capability in vacuum exposed to the magnetic field of the PPT. A deviation of less than 3 % was measured between true output voltage and adjusted output voltage (*Table III.3*). To be sure that the temperature of the critical electrical components transformer and transistor are not exceeded a thermal test was done having the PPU operated in vacuum for more than 3 hours and 11177 pulses at 1Hz. The thermocouples type K were located directly at the transformer, the transistor, at the front and back panel of the housing. As reference temperature, a thermocouple was connected to the vacuum tank. In *Figure III.3*, it can be seen that a maximum temperature of 76 °C was reached at the transformer. The transistor reached 61 °C. Both components are below the rated 150 °C. The reference temperature also increased throughout the test, which might be because of the heat created by the pumps and the increasing laboratory room temperature over time. The sudden temperature changes along each curve are artifacts created through the magnetic pulse of the thruster. However, it also can be recognized that the are temperatures decreases after 5000 s, 7000 s, 9000 s and 11000 s. Comparing all curves, the transformer's temperature decreases the most. The reason for the temperature variations are short pauses, where the thruster's status was checked in terms of charring and electrode abrasion. The housing temperatures represent the local maximum, where the transformer and the transistor transfer their heat. After finishing the long-term test, the vacuum was kept for another 75 minutes to investigate the cooling characteristics of each component. The temperature was determined with an accuracy of ± 1 K at a resolution of ± 0.25 K. To know about the explicit thermal behavior and before designing a flight model PPU based on the current device a more detailed thermal analyses and tests are necessary.

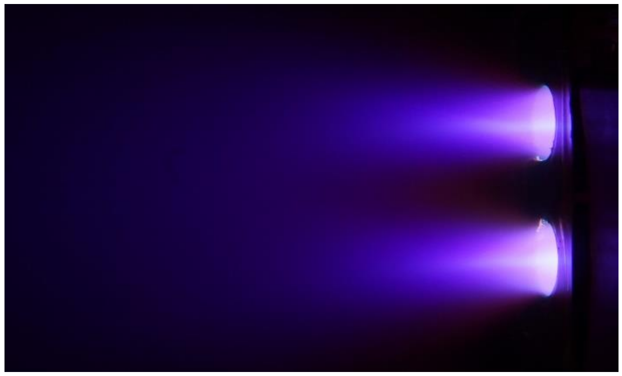

Figure III.2 Time exposure of two separately triggered pulses of two PETRUS thrusters.

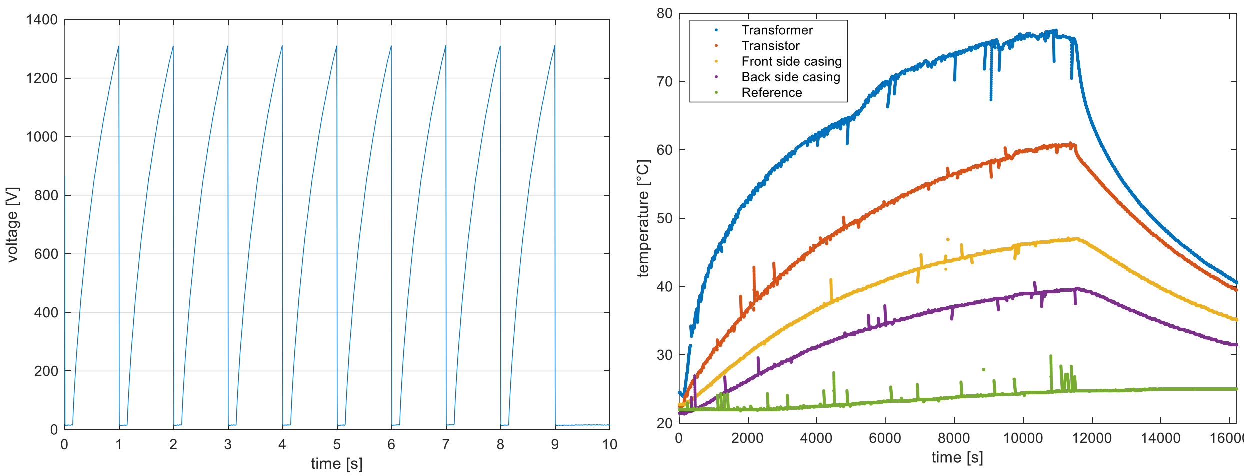

Figure III.3 Left, cycle test results of the PPU showing nine pulses of PETRUS. Each cylce is accomplished in 872 ms. Right, results of the PPU thermal test. With 76 °C the transformer reached the global maximum temperature. The transistor reached 61 °C. Both values are below the maximum rated temperature of 150 °C.

B. **PPU Requirements**

Next to the above-mentioned boundary conditions, several design requirements were also defined (*Table III.2*). Generally, the requirements can be break down into two groups: laboratory and CubeSat requirement. The laboratory requirements are necessary enabling the use of the PPU for ground tests. For operating the PPU inside a vacuum chamber the device must be able to be used in pressure regions below $1 \cdot 10^{-1} Pa$. For a future flight, ready PPU this requirement must be strengthened. In addition, it shall be enabled that the PPU can be integrated into the IRS automated PPT testbed. These allow a full characterization of the PPT system (thruster and PPU). Only commercial of the shelf components as well as no space proven parts shall be used yet, which utilize a cost-effective laboratory design. Dimensional constrains, input voltage restrictions and the average power consumption already aim towards a future flight model PPU, which must fulfill CubeSat requirements.

Table III.2 List of requirements, which had to be considered when designing the PPU.

#	Requirements	Status	Confirmed by
1	The PPU shall be able to be used at pressures below $1 \cdot 10^{-1} Pa$.	Fulfilled	Charging and single ignition test, thermal test
2	The PPU shall be able to be mounted and used on the impulse pendulum ([8, 9]).	Fulfilled	Design review
3	The dimensions of the PPU shall not exceed 100x100x30 mm^3.	Fulfilled	Measured
4	The PPU shall run with either 12 V or 24 V of input voltage.	Fulfilled	Charging and single ignition test, design review
5	The average power input shall be lower than 8 W if charging the thruster's capacitor bank to 5 J and operate PETRUS at 1 Hz.	Fulfilled	Cycle test
6	Controlling the PPU shall be done by using a commercial of the shelf board, e.g. Arduino board.	Fulfilled	Design review
7	The PPU shall be designed by using no space proven components yet.	Fulfilled	Design review

C. PPU Efficiency Analysis and Performance Overview

The charging time of PETRUS' capacitor bank at the rated operation energy takes less than the required 1 s. A detailed efficiency analysis of the PPU is shown in *Table III.3*. Therefore, the PPU's main operation region of 1000 V to 1600 V is investigated by measuring the charging time, the final capacitor bank voltage and input current. As a result, the average input and output power as well as the efficiency of the PPU can be determined. By charging the capacitor bank to a peak voltage of 1000 V only 0.551 s are necessary. Operating the PPU at its maximum output voltage of 1600 V, it takes 1.344 s to charge the capacitor bank fully. As mentioned in section III.A, the PPU only needs 0.872 s to charge the capacitor bank to 1300 V (rated operation mode). The calculated PPU efficiencies are 78.7 %, 75.1 % and 76.1 % respectively. Even though the PPU performance is adequate to meet the design requirements a future flight model PPU can be further improved. A major enhancement factor is the self-made transformer. If a customized professional manufactured transformer is used the PPU efficiency will further increase.

Table III.3 Results of the PPU efficiency investigation.

Predefined voltage [V]	Measured charging time [s]	Measured voltage [V]	Input power [W]	Output power [W]	Efficiency [%]
1000	0.551	1021.4	7.22	5.68	78.7
1100	0.654	1125.5	7.44	5.81	78.0
1200	0.749	1218.8	7.73	5.95	77.0
1300	0.872	1313.4	7.81	5.94	76.1
1400	1.005	1420.8	7.82	6.03	77.0

1500	1.155	1527.9	8.00	6.06	75.7
1600	1.344	1647.3	8.07	6.06	75.1

Table III.4 summarizes the PPU specific parameter. The 8 Hz pulse frequency is as twice as high as the required value. Since the voltage generator will not provide the power, which is necessary to charge the capacitor bank an external high voltage power supply needs to be used to operate the thruster at this frequency. Nonetheless, pulse frequencies above 4 Hz certainly will wear the electrodes. These values are just usable for test cases or very low pulse energies. It must be mentioned that the overall dimensions are slightly above the requirements, which is reasoned by the self-made housing and transformer. A future iteration of the PPU with optimized components will be within the restrictions. The total mass of 327 g also is going to be lowered by, e.g. soldering the micro controller directly to the board instead of using a socket. However, the use of a socket is more applicable for a laboratory use, in case the micro controller needs to be exchanged. The final housing will also be lighter.

Table III.4 Overview of the PPU specific parameter.

Description	Value
Supply voltage	24 V
Maximum input current	400 mA
Maximum average input power	8.1 W
Average charging power	6 W
Output voltage range	200 V to 1600 V
Charging time at rating (1300 V, 6 µF)	0.872 s
Efficiency at rating (1300 V, 6 µF, 1 Hz)	74.8 %
Maximum tested ignition frequency	8 Hz
Dimensions of the board	90.17 × 95.89 x 24.6 mm
Dimensions of the housing	103 x 103 x 31 mm
Mass [g]	327 g

IV.Conclusion

To enhance the thrust efficiency of the pulsed plasma thruster PETRUS different nozzle expansion ratios for three pulse energies were investigated, whereas it can be said that the thrust efficiency increases throughout all expansion rations (1 to 2.4). However, at an expansion ratio of 1.54 the thrust efficiencies of the 7.68 J and the 5 J case clearly show a local maximum of 9.1 % and 10.5% respectively. Followed by a decrease at an expansion ratio of 1.73 the thrust efficiency slightly increases again. Since all thruster parameters are kept constant, but the expansion ratio it is assumed that the sudden increase of the thrust efficiency is a result of thermal expansion. The overall increasing thrust efficiency with larger expansion ratios might be caused by the characteristic acceleration path and respectively a larger ΔL, which rises with increasing expansion ratios. However, this phenomenon has not been entirely investigated yet and will be done in near future.

Next to the thruster development, a miniaturized PPU is designed and tested. Main goal was to build a device, which is applicable for the laboratory use to integrate the PPU into the automated IRS PPT testbed. In addition, first CubeSat restrictions like an average power consumption of less than 8 W, a pulse frequency of 1 Hz and a maximum dimension of 100 x 100 x 30 mm^3 are considered. Summarized it can be said that the established design objectives and requirements are all met. Within the test campaigns, the PPU successfully accomplished more than 300000 pulses being operated outside of the vacuum chamber, but also inside. Additionally, no failures caused by the thruster's EMS were detected at any point. The current efficiency at the rated operation point of 1300 V is 74.8 % charging PETRUS's capacitor bank within 872 ms. Within a thermal test campaign, the critical components, i.e. transformer and transistor, were investigated. After three hours of continuous operation, a maximum temperature of 76 °C was reached at the transformer. This means no component was close to the global maximum rated temperature of 150 °C.

V.References

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