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Flight results of the miniature 1J pulsed plasma thruster PETRUS

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Abstract
The Institute of Space Systems (IRS) is has developed PETRUS, a family of scalable, solid propellant, coaxial PPTs. They can be scaled to different mission requirements and versions with discharge energies between 1 J and 68 J have been tested in our laboratory. This paper gives an overview of PETRUS and presents results from the ongoing cubesat mission GreenCube that demonstrated the first operation of a PETRUS thruster in space. Additionally, the upcoming mission SONATE-2 is described, where a more advanced version of PETRUS will be used to augment the 6u Cubesats attitude control system.

1. Introduction

PETRUS is the Pulsed Electric ThRuster of the University of Stuttgart. It is not a single thruster design but a scaled thruster family developed at the Institute of Space Systems (IRS) of the University of Stuttgart. The PETRUS families' design is characterized by the coaxial architecture with a nozzle shaped anode and a central cathode (Fig. 1). The solid propellant PTFE is fed from the back making it a breech fed ablative thruster.

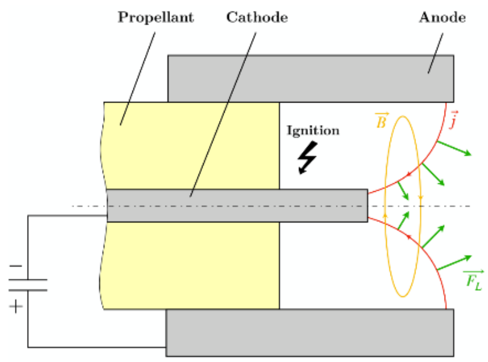

Fig. 1: Simplified schematic of the PETRUS family's operating principle.

Compared to regular ablative PPTs (APPTs), which use either thermal or iMPD acceleration effects, PETRUS combines both processes. The anode enables the utilization of thermal acceleration, whereas the collinear electrode configuration is used for iMPD acceleration. Once the electrical circuit is closed by electrons created by triggering the ignition electrode, the electrical circuit between anode and cathode is closed. Consequently, the capacitor bank

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discharges across the propellant surface, ablating and ionizing the top layer of PTFE. Followed by that thermal as well as the iMPD acceleration processes take place. Heat created during a PPT's pulse inside the enclosed discharge region is used for thermal expansion and thus acceleration. Additionally, the charged particles are accelerated and focused by the self-induced magnetic field and the current between anode and cathode (see Fig. 1). By having an outer anode and an inner cathode, the heavy ions are majorly used for the creation of thrust by focusing them to a plasma jet in the direction of the thrust.

With pulse energies from 1 J to 68 J, overall, six PETRUS thrusters were developed and investigated throughout the years. Depending on their design specific pulse energy the following naming is used: PETRUS 1J, PETRUS 5J, PETRUS 17J, PETRUS 34J, PETRUS 51J, and PETRUS 68J**.** Fig. 2 depicts the entire PETRUS family.

Focus, however, was the design of a small and lightweight PPT system for CubeSat applications with low energy consumptions. Moreover, the thruster design shall enable a lifetime of some hundred thousand pulses with consistent performance. Usually, thermal PPTs, which are commonly used for such low energy applications reach their lifetime limit at about 40000 pulses with decreasing performance throughout the operation [1, 2]. For developing a miniaturized PETRUS thruster, scenarios such as the 3U CAPE mission set the boundary conditions for the propulsion system [3]. As a result, PETRUS 5J was object of development and baseline for the scaled PETRUS versions. The up-scaled 17J to 68J PETRUS versions were designed and tested for better understanding of the scaling behaviour of the coaxial breech fed APPT architecture. Here, the capacitor banks of ADD SIMP-LEX were used and set the boundary conditions for the thruster dimensions [1]. Moreover, a miniaturized laboratory Power Processing Unit (PPU) was developed for CubeSat application [4]. The gained experience within the PETRUS as well as PPU development were of utmost importance when developing a PPT propulsion system for University of Rome's GreenCube [5].

Fig. 2 From top left to bottom right. PETRUS 68J, PETRUS 51J, PETRUS 34J, PETRUS 17J, PETRUS 5J, and PETRUS 1J.

2. Overview of the GreenCube mission

GreenCube is a 3U CubeSat aimed at testing an autonomous laboratory for microgreens cultivation on-board a CubeSat platform. The satellite mission has been conceived by the S5Lab research group at Sapienza University of Rome, together with ENEA and University of Naples "Federico II" and the coordination and support by the Italian Space Agency.

The spacecraft design will allocate 2 CubeSat units (approximately 20 cm x 10 cm x 10 cm) for the cultivation laboratory, consisting in a pressurized vessel containing all the resources, sensors and actuators and actual volume that will be occupied by the growing plants during the experiment execution. The other spacecraft unit will be dedicated to the spacecraft bus, while the additional volume (the so-called "tuna can") will be occupied by an additional propulsion system, named PETRUS, developed by IRS at University of Stuttgart and to demonstrate its design and be used as a back-up attitude control system. GreenCube is shown in Figure 3.

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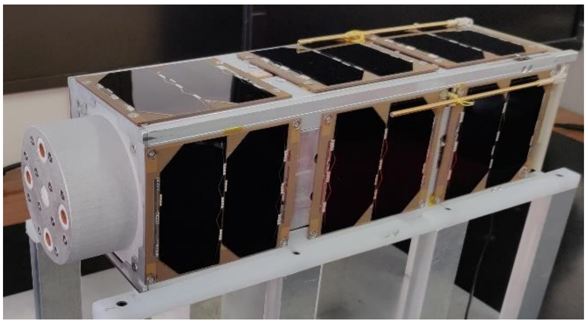

Figure 3: GreenCube with the PETRUS propulsion module on the left side

The GreenCube payload unit i.e., the Biological Life Support System (BLSS) hosting the microgreens cultivation system, is comprised in an aluminium shell that will be pressurized at 0.5 atm to allow for the cultivation of plants. Inside the vessel, a secondary on-board computer will be monitoring the plant growth while automatically actuating its implemented systems. The plant seeds are watered only after the deployment in-orbit, when all the subsystems' checks are successful in the commissioning phase and when the lighting conditions are deemed sufficient for carrying out a complete life cycle of the plants. The seeds are housed in a seed matrix, complete with substrate, enclosed to allow growth in micro-gravity and mounted on a 3D printed grid. The spacecraft BLSS includes a small tank of air that is used to compensate the plants' photosynthetic and respiration cycles when needed. The experiment will also verify the self-sustainability of the plant's growth in terms of air composition management. Besides the tank, the air will be filtered by carbon filters for reducing the content of ethylene. Finally, the air recirculation and humidity reduction will be made possible through a fan and a small radiator placed inside the vessel. The lighting is provided by a white LED matrix, already tested at ground for a complete plant growth. The LEDs are activated for 16 hours a day during the in-orbit execution of the experiment, simulating on-ground lighting cycles for the growing plants.
The BLSS sensors are composed of cameras, able to monitor the effective growth of the plants, air composition and humidity sensors, temperature sensors placed in convenient locations of the vessel, etc. The secondary OBC, supervising the plants growth, will store all the needed data inside its independent memory before data down link.
The spacecraft bus is composed of the traditional set of subsystems for CubeSat platforms:

- A ferroelectric-RAM On-Board Computer OBC), managing all the main functions of the satellite.
- An Electric Power System based on six Li-Ion cells, a power distribution unit connecting all the subsystems to its dedicated power line, twelve solar panels mounted on the lateral side that ensure sufficient power generation for carrying out the mission.
- An attitude determination and control subsystem mainly based on Inertial Measurement Units (IMUs) and magnetometers for attitude determination and on magneto-torquers for control.
- An additional attitude control system represented by the PETRUS PPT propulsion system. The spacecraft will be maintained spinning alongside its major inertia axis for the duration of the main mission to equalize the vessels inner temperatures.
- A communication system based on S-Band transmission (for high speed down link) and UHF band transceiving (for housekeeping data down link and telecommand uplink).

The satellite communicates with the ground stations located in Rome, Italy, and Malindi, Kenya. The spacecraft was launched on-board the maiden flight of Vega-C on July 13th 2022 into Medium Earth Orbit, at approximately 6000 km of altitude and 70 degrees of inclination. The spacecraft operations profit from very long passes (up to 3 hours) of the satellite over every designated ground station. After an initial commissioning phase, the main mission of the satellite was carried out for 20 days. The satellite operations will continue up to six months for completing data down link, to conduct the secondary payload mission of the PETRUS propulsion module and to verify the operation of all the on-board components in the extremely challenging operational environment. If successful, the GreenCube mission can suggest a further implementation of the designed cultivation system for a fast in-orbit test of small-scale cultivars. In this sense, GreenCube can be supporting the in-orbit experimentation of plants for future nourishment of the astronauts during long-term missions, such as Lunar or Martian manned missions. [6]

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3. Design of the GreenCube propulsion module

To demonstrate the function of a PETRUS thruster on a CubeSat an experimental propulsion module was designed. The development of this module began in early 2020. For the small dimensions and low power available on the CubeSat, PETRUS 1J, a scaled down version of the previously tested PETRUS 5J was designed and four of these thrusters with a shared capacitor bank are housed in the tuna can of the satellite. The thrusters are controlled, charged and ignited by the PPU mounted in the CubeSat unit next to the tuna can. PETRUS 1J is so far the smallest and lowest energy thruster of the PERTUS family.
The constraints for this development were:

- A maximal mass of 450 g
- The PPT system must fit into the "tuna can" with an additional volume of 20 mm x 100 mm x 100 mm of a CubeSat unit
- The average power consumption over a whole orbit should not exceed 1 W
- The module should contain a cluster of multiple PETRUS thrusters
- The thrusts should be able to operate at a pulse frequency of at least 1 Hz
- The thrusters should each be able to produce at least 100.000 pulses
- The electronics of the module should be based on existing PPUs used in the laboratory and be constructed of COTS parts

The goal of the PETRUS mission on GreenCube is to demonstrate its operation in orbit and collect thrust estimations and lifetime data to compare to ground based tests.
Each of the four thrusters can be triggered separately by the PPU. The nominal operating frequency of the system is 1 Hz but can be increased to 3.85 Hz maximum. To run the PETRUS thrusters a 0.8 J ceramic capacitor bank is used with a total capacity of 2.5 µF and a maximal charging voltage of 800 V. Unlike the other PPTs at IRS such as ADD SIMP-LEX, the capacitors are in series and not in parallel connection. This increases ESR and ESL and is not ideal. The reason for this compromise design was the availability of high-power capacitors at the time needed for the project. The discharge energy of 0.8 J is also below the nominal discharge energy of the 1 J for this thruster. The thrusters itself are very similar to the design of the PETRUS 5J thruster. A maximum performance is achieved with a nozzle expansion ratio of 1.5 with PETRUS 5J. Due to this, PETRUS 1J thrusters have the same expansion ration. Moreover, the anode and cathode ratio are kept the same throughout the PETRUS family. To minimize the overall weight the individual thruster length of PETRUS 1J was reduced to a minimum, which allows the compliance to the maximal necessary pulse number and also fitting into the "tuna can" at the same time. Compared to PETRUS 5J the weight per thruster was reduced from 39.6 g to 4.2 g. Considering the overall system's mass, the mass decreased from 760.6 g for PETRUS 5J (thruster and capacitor bank) to 419 g for PETRUS 1J (four thrusters, capacitor bank, PPU and satellite structure).
To protect the PPU from electromagnetic interference the thrusters with their capacitor bank are located inside the "tuna can", whereas the PPU occupies 20 mm x 90 mm x 90 mm of the 1U satellite structure. The thrusters and the capacitor bank are fully insulated from the satellite structure by an insulation containment. In case of an internal uncontrolled discharge between the capacitor banks' connections or between the thrusters' electrodes, no satellite components will be affected. Moreover, the "tuna can" is covered by a metal lid fully encapsulating the thruster and the capacitor bank to mitigate EMI effects towards the PPU and the rest of the satellite. Additionally, the PPU is covered by another metal lid to separate the PPU from the rest of the satellite, see Fig. 4 and Fig. 5.
Most of the thruster assembly components such as insulation parts, copper connections of the thrusters, thruster housings and anodes are produced by additive manufacturing. This brings the advantage of enabling unconventional designs to reduce weight but keep stability at the same time. Additionally, less soldered, and screwed connections are necessary, which improves the electrical resonance circuit of the system for a better performance. Made from an aluminium alloy, the "tuna can" satellite structure is also built by additive manufacturing, see Fig. 4 below.

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Fig. 4 Left, PETRUS 1J EM front view. Right, PETRUS 1J EM “tuna can” rear view showing enclosed thruster assembly for EMI protection.

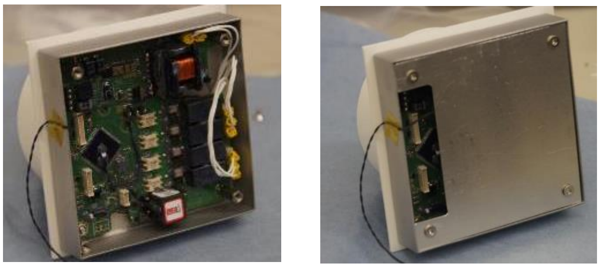

Fig. 5: Left, PETRUS 1J FM with PPU implemented and the white thruster protection cover. Right, covered PPU with metal lid to separate propulsion system from the rest of the satellite.

The power processing unit (PPU) controls the thrusters and supplies them with high voltage for the main capacitor bank and the high voltage pulses needed to ignite the thrusters. Before the development of dedicated PPUs for PERTUS separate high voltage supplies and ignition spark generators were used. The dedicated PPUs simplify operation and produce a more compact system.
The PPU that is used on the GreenCube satellite is an evolution of a previous PPU used in laboratory tests with the PETRUS 5J thruster. This PPU was built to be a first step towards a satellite PPU while remaining easy and cost-effective to manufacture as well as being able to be used flexibly with different thrusters and different test setups.
To achieve this the PPU was built exclusively from COTS parts and used an Arduino nano microcontroller board. To charge the capacitor bank, an isolated flyback converter controlled by a COTS charge controller IC was used. This greatly simplifies the operation of the charging circuit because the controller senses the output voltage through the transformer without requiring an opto-coupler or tertiary winding. The transformer for this converter was self-made from COTS-parts. This transformer works satisfactory for the PPU but is one on the main areas in which the PPU can be improved by use of better manufacturing processes and components.

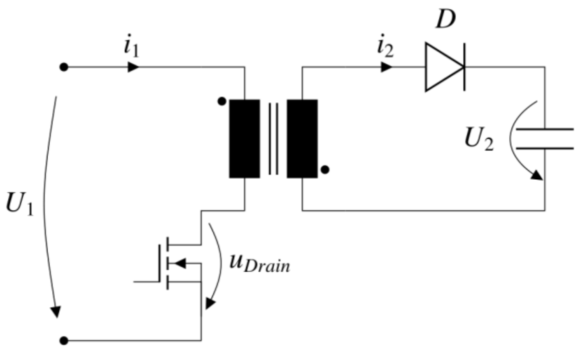

Fig. 6: Basic schematic of the flyback charger circuit

To ignite the thrusters the PPU is equipped with four identical igniter circuits. Each uses a miniature COTS high voltage trigger transformer. The primary side of these transformers is supplied with an industrial 300 V integrated high voltage supply which charges the capacitors of each igniter circuit. These capacitors can be discharged through

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thyristors to produce up to –10 KV high voltage spikes at the igniter outputs. The capacitors are then recharged through resistors. The igniter circuits are fast and can be retriggered after only 5 ms.

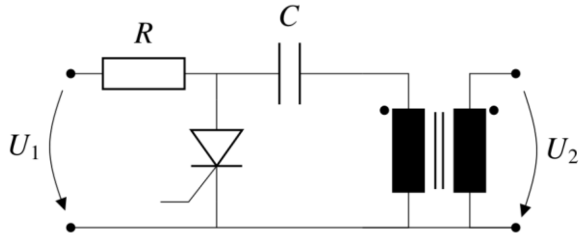

Fig. 7: Schematic of an igniter circuit

The PPU can detect failed ignitions of the thruster by measuring the charging time of the capacitor bank. If the measured time is shorter than the expected charging time, it can be concluded that the capacitor bank has not been fully discharged by the previous ignition. With this method all but the last pulse in a series of ignitions can be evaluated.

Table 1: Performance of the laboratory PPU

	Value	Note
PCB dimensions	90 x 96 x 25 mm	
Output voltage	200 – 1600 V	adjustable
Efficiency	75 %	
Pulse frequency	1.16 Hz	5 J thruster
Output power	6 W	

The PPU has fulfilled all requirements and is since in use for different PPT tests at the institute for space systems.

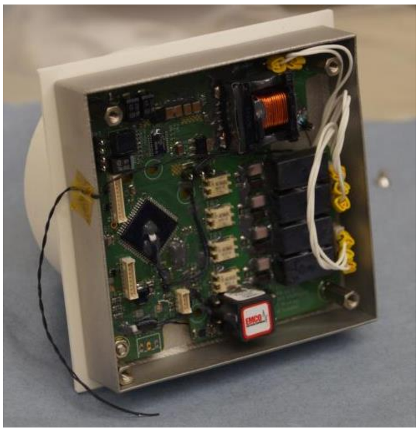

Fig. 8: PETRUS 1J PPU with the charger transformer at the top right. the igniters along right edge and the microcontroller in the centre left.

For the flight of PETRUS 1J on GreenCube it was decided to develop the laboratory PPU into the satellite PPU. The overall setup of the PPU was retained. However, the charging power was halved, the output voltage was fixed to the nominal operating voltage of the thruster and the input voltage as well as the electrical interfaces were matched to GreenCube. The Arduino control board was replaced by a microcontroller integrated onto the PCB. Overall, the design was slightly simplified, and lessons learned during the operation of previous PPU were implemented. Through these changes the dimensions of the PPU could be reduced.
However, because of the continued exclusive use of COTS parts, the radiation resistance of the components is not known. This is a risk that had to be taken, since the budget and the short development time did not allow for a redesign using radiation hardened components.

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Table 2. Performance of the GreenCube PPU

	Value	Note
PCB dimensions	84 x 84 x 15 mm	
Output voltage	800 V	fixed
Efficiency	75 %	
Pulse frequency	3 Hz	Typ. 1 Hz
Output power	3 W	

For future developments of the PPU three areas of improvement are envisioned: efficiency, reliability, and miniaturization.
The efficiency of the PPU can be improved with an optimization of the charger using more advanced components such as GaN-transistors, advance converter topologies and better manufacturing techniques especially of the charger transformer. The high voltage supply of the igniters is another source of losses in the PPU. It could in future be replaced with a more efficient system or be coupled to the charger circuit.
The reliability of the system could be improved by using a space-rated radiation hardened microcontroller and charge controller. This would however require a significant redesign of the whole system.
To further reduce the size of the PPU the focus is on the highest components on the PCB. These are the charger transformer and the igniter high voltage supply. If the maximum height can be reduced the volume taken up by the PPU could be significantly reduced. This would free up space for a larger capacitor bank or other systems of the CubeSat. Another way that volume can be reduced are the igniter circuits. They are near identical to the previous laboratory PPU, which was meant to operate with a wide range of thrusters. Therefore, it produced very high output voltages that can ignite PPTs with wide spark gaps. This would also allow for smaller igniter capacitors and would reduce the overall footprint of each of the four igniter circuits. Additionally, the single PCB could be split up into smaller modules, that can be mounted more flexibly in the propulsion module and thereby use currently empty spaces.

4. Ground based testing results

In total the PETRUS 1J EM successfully accomplished over 30000 pulses without failure of thruster or PPU. The thruster was operated for more than 10000 pulses at the IRS for a first endurance test as well as performance investigations. 20000 pulses were done at ESA ESTEC's ISO 9001 and ISO 17025 accredited Propulsion Laboratory (EPL) within an interlaboratory comparison campaign between IRS and EPL [7]. Nevertheless, the main characterization process of PETRUS 1J EM was performed at the IRS facility. The tests included initial ignition procedures of the thrusters, an endurance test, thermal stability tests and performance investigations. No failure was detected and throughout the test campaigns no corona discharge or uncontrolled ignition occurred. Moreover, the PPU operated within the thermal limits. Fig. 9 depicts PETRUS 1J in operation. Note: The image is a long exposure shot - meaning that each of the thrusters was pulsed one by one.

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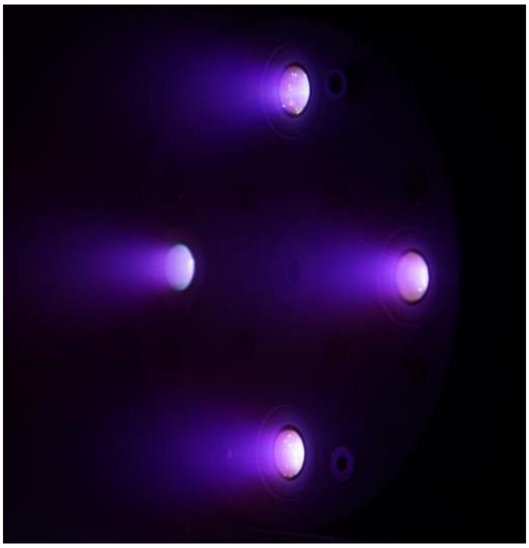

Fig. 9 PETRUS 1J EM long exposure shot. The thrusters were triggered one-by-one.

The following Table 3 shows the performance data of PETRUS 1J EM, whereas Table 4 illustrates the results of PETRUS 5J for comparison. The impulse bit measurements were done with the vertical impulse pendulum of IRS described in literature [4].

Table 3: Performance overview of PETRUS 1J GreenCube.

	Value	Error	Comment
m_{sys}	419 g	± 1g	All components
E_0	0.8 J	± 0.08 J	
I_{bit}	10.22 µNs	± 0.45 µNs	
m_{bit}	1.49 µg	± 0.0084 µg	
η_{eff}	0.04	± 0.0063	
I_{sp}	699 s	± 50.15 s	
I_{total}	3.373 Ns		Per thruster
n_{pulses}	330000		Max. m_{prop}

Table 4: Performance overview of PETRUS 5J [4].

	Value	Error	Comment
m_{sys}	761 g	± 1g	Thruster + capacitors
E_0	5 J	± 0.5 J	
I_{bit}	107.5 µNs	± 0.74 µNs	
m_{bit}	12.86 µg	± 0.0084 µg	
η_{eff}	0.089	± 0.011	
I_{sp}	852.4 s	± 56.18 s	
I_{total}	22.58 Ns		Per thruster
n_{pulses}			

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210000	Max. m_{prop}

Depending on the thruster length the maximum propellant capacity and consequently the total impulse can be adapted to any mission specific needs. Moreover, with a different number of thrusters in a cluster these parameters also can be adapted.
In preparation for the next flight of PETRUS on the CubeSat SONATE-2 of the university of Würzburg [8], an improved version of PETRUS 1J has been tested. This prototype thruster has been assembled out of spare PETRUS 1J GreenCube parts and connected to a more appropriate capacitor bank. This capacitor bank is constructed of ten 880 nF 500V C0G multilayer ceramic capacitors in a 5p2s configuration giving a 2.2 µF 1000 V capacitor bank storing a discharge energy of 1.1 J. While the setup in GreenCube operated the 1J thruster below its nominal discharge energy this one operates it slightly higher and therefor achieves higher thrust, specific impulse and efficiency. It does however put more stress on the electrodes of the thruster which might erode faster and uses more propellant per pulse.

Table 5: Performance overview of PETRUS 1J prototype for SONATE-2

	Value	Error	Comment
E_0	1.1 J	± 0.11 J	
I_{bit}	24.16 µNs	± 2.5 µNs	
m_{bit}	3.40 µg	± 0.0084 µg	9234 pulses measured
η_{eff}	0.078	± 0,0019	
I_{sp}	724.4 s		

The preliminary results in Table 5 show that the new prototype is much closer to the 5J version in regards to specific impulse and thrust efficiency and produces more than double the impulse bit of the thruster used on GreenCube. It is to be expected that its lifetime is much shorter as it consumes more propellant per pulse and stresses the electrodes more. Lifetime test have not been conducted yet but it was already able to produce more than 9000 pulses without noticeable deterioration of the thruster. These values are a better indication of what a PETRUS thruster of the discharge energy class of 1J is capable of, when connected to a suitable capacitor bank.

5. In-orbit operation and results

The planned in orbit operation of PETRUS 1J will consist of an initial commissioning phase followed by a repeating routine of thrust measurements and lifetime tests of the thrusters. During the commissioning phase the subsystems of the PPU will be tested and checked for negative interferences with the rest of the satellite.

Next the initial ignition success rate of each thruster is measured and the thrusters are cleaned by igniting them with large amounts (100-200) ignitions sparks per pulse. After all thrusters have been made operational in this manner the first thrust measurements can begin.

The four thrusters are split into two groups Thrusters 1 and 3 will only ever be operated at a maximum frequency of 1 Hz which is their nominal operating frequency. Thrusters 2 and 4 will be operated at up to 3.85 Hz which is the maximum power of the PPU. This is done to determine the impact of higher frequency operation on the lifetime of the thrusters. A higher operating frequency leads to higher cathode as well as propellant surface temperatures.

5.1 Thrust measurements

To measure the thrust of PETRUS, the fact that the thrust-vector of each single thruster does not point through the centre of gravity of the satellite is used. Each pulse does not only impart a translating impulse into the satellite but also a small rotational impulse. In normal operation of all thrusters at the same time this torque could be cancelled out by the thrusters on the opposite side. But if only one thruster or two adjacent thrusters are operated,

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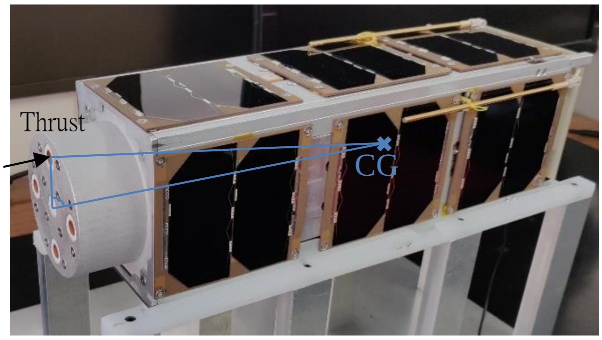

Fig. 10: Visualization of the thrust measurement of PETRUS on GreenCube

This setup of the thrusts is not ideal for thrust measurement is not ideal, since the angle between the thrust vector and the vector between the thruster and the centre of gravity is very small. This means that each pulse of the thruster only imparts very little rotation into the satellite. With the simplifying assumption that the centre of gravity of GreenCube is in the centre of the XY-plane pulse of a thruster should cause the angular velocity of the satellite to change by $9.72 * 10^{-3}°/s$. The true centre of gravity is not exactly in the middle of the XY plane, however this simple model is still useful for rough estimation of thrust. A more detailed three-dimensional model yields the rate changes listed in Table 6. This model is based on the centre of gravity derived from the CAD of the CubeSat. Because of the flow of nutrient solution and air during the main biological experiment the centre of gravity might have shifted.

Table 6: Expected rate changes from 1000 pulses

Thruster	**1**	**2**	**3**	**4**
$\Delta\omega_x$[°/s]	0.3372	1.3017	0.3372	-0.6272
$\Delta\omega_y$[°/s]	-1.0023	-0.0379	0.9266	-0.0379

Table 6 shows the significant effect of the location of the centre of gravity has on the expected rotations. It is close to the Y-axis but has a significant deviation on the X-axis. This causes thrust from thrusters 1 (X+) and 3 (X-) to cause rotation in both axis and thruster 2 (Y+) to cause more rotation than thruster 4 (Y-).

5.2 Lifetime tests

After the first thrust measurements a part of the thrusters projected lifetime of 330,000 pulses is used up and the ignition success rate is recorded. After a number of pulses, the thrust measurements are repeated to detect changes in thrust over their lifetime. This cycle of thrust measurements and lifetime test are repeated until the thrusters run out of propellant or fail and can no longer be operated. The exact number of pulses between thrust measurements is dependent on the power available during the mission.

5.3 Results of the commissioning phase

The first two passes were used for the commissioning. During this phase all systems (microcontroller, charging, ignitions and sensors) worked as expected as long as no actual pulses were performed with the PPTs. If pulses were performed the OBC of the satellite reset. However, since the power to the PPU is not interrupted during a reset and all relevant data of a test is stored in the PPU, so the tests could be performed and the data recorded after the OBC had recovered after the tests. This makes testing slower but it is still feasible. The likely cause for this is the intense electromagnetic interference caused by the thruster pulses. This was not noticed on the ground as the thruster was only tested with a simulator of the OBC and not the actual OBC. Future Propulsion module designs will feature better EMI suppression to protect the rest of the satellite. Once the processes for the further operation were adjusted to this problem, the initial ignition success rate of the thrusters was determined. Thrusters 1 and 2 immediately operated at 100% success rate, but thruster 3 and 4 needed to by “cleaned” by attempting to ignite them with a large number of ignition sparks. This resulted in full operation of all four thrusters after 106 cleaning attempts (with 200 ignition sparks each). Thrusters 3 and 4 will in future be cleaned with 1-2 cleaning pulses before each test to ensure successful ignitions during tests.

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5.2 Results of thrust measurements

During the first thrust measurement of thruster 1 on August 28th with 1003 pulses at a frequency of 1 Hz the following change in angular velocity around the Y-axis of the satellite was recorded. Fig. 11: Angular velocity around the Y axis during the thrust measurement of thruster 1Fig. 11 only shows the rotation around the Y-axis as it is the most significant for this test. Changes around the X and Z axis could not be detected due to oscillations in these signals.

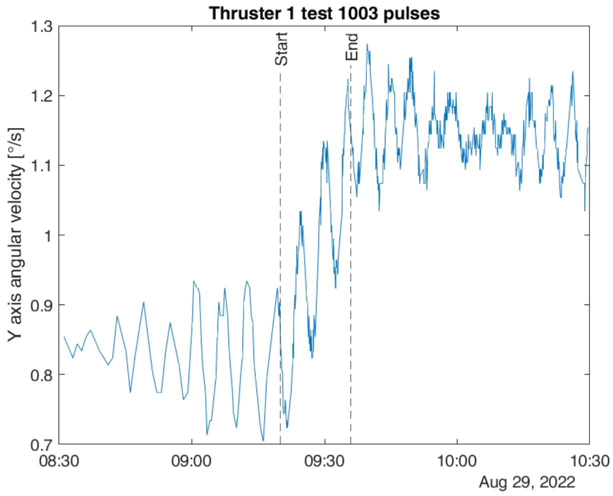

Fig. 11: Angular velocity around the Y axis during the thrust measurement of thruster 1

Fig. 11 shows that the angular velocity of the satellite changed exactly during the 16-minute time window in which the 1003 pulses were performed by the thruster. This shows that actual thrust was produced by PETRUS.
The angular velocity changed by 0.312 °/s. According to the simplified model mentioned above, a change of 0.976 °/s would have been expected. There are several hypotheses to explain the discrepancy between the expected and measured values. A shifted centre of gravity might have contributed to the values as well as magnetic effects that are discussed in the following paragraph. Disregarding the exact value of the thrust and the challenges for further thrust measurement, Fig. 11 is the first proof of actual thrust created by a PETRUS thruster in orbit.

During three following thrust measurements of the thrusters 1 and 3 no significant changes in angular rate was observed. This has so far been attributed to magnetic effects on the satellite. During the first thrust measurement the satellite was slowly rotating mainly around its Y axis instead of the for this satellite more typical Z axis. When the satellite was slowed down further after the first thrust measurement it assumed an attitude with the Z-axis parallel to the prevalent magnetic field lines and is now remaining locked there because this attitude is stable due to magnetizable objects in the long axis of the 3U CubeSat. It is hypothesized that the low torque of the PPTs is not able to overcome the stabilizing effect of the magnetic field and that the first thrust measurement only succeeded because of the unusual attitude of the satellite at the time.

Work is underway to modify the attitude control algorithm of GreenCube to allow it to point its Z axis perpendicular to the prevalent magnetic field to allow further thrust measurements. During this time no further tests are performed to not unnecessarily put the OBC under stress through the numerous resets that thruster testing produces. If this should not work, the next attempt will be to recreate the condition of the first thrust test and introduce a slow rotation around the X or Y axis. The third method will be to produce the most aggressive thrust that the propulsion module is capable of. This is achieved by operating thruster 2 at 3.85 Hz. Because of the higher frequency and the longer lever arm, this should generate five times more thrust that the first test, which might be sufficient to overcome the magnetic dipole moment. If this also does not yield results, lifetime test will be performed first and thrust test retried at a later time or completely abandoned.

5.3 Results of lifetime test

To date the propulsion module has not yet performed a full lifetime test cycle, but only pulses as part of the initial commissioning phase and the attempts at thrust measurements. At the time of writing a total of 4228 have been confirmed as successful (mainly on thruster 1 and 3). After the initial cleaning phase during which thrusters 3 and 4 had to be conditioned to operate correctly, all thrusters have shown a 100% ignition success rate. Future lifetime testing will show, how this success rate will change during the lifetime of the thrusters.

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6. Upcoming Mission SOANTE-2

Built on know-how of the GreenCube mission and in cooperation with the university of Würzburg we are now working on the development of a follow-up PPT-System on the 6U Cubesat SONATE-2 which is to launch in Q1 2024 [8]. On SONATE-2 a redundant pair of improved PETRUS 1J thrusters will be used to desaturate reaction wheels of one axis of the satellites attitude determination and control system (ADCS). Since the moment of inertia of these wheels is well known and their speed is precisely measured by the ADCS, this will allow for a more accurate thrust measurements of PETRUS in orbit. The components of the PETRUS 1J SONATE-2 thruster are currently in manufacturing and will be tested in the coming weeks. Table 5 shows the performance of the prototype for this thruster. It shares the same electrode dimensions as the GreenCube thruster but features an improved capacitor bank and a new mechanical assembly.

7. Conclusions

The initial in orbit results show that PETRUS can be used on CubeSats and other micro or small satellites in the future. Further testing and analysis will reveal if the thruster's behaviour in orbits is directly comparable to the ground-based test results.
The successful initial operation of PETRUS 1J in orbit has set an important milestone for the Institute of Space Systems of the University of Stuttgart as it is the first electric propulsion system developed by the IRS to operate in space.

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