

Modifications and Experimental Analysis towards an Update of the Pulsed Plasma Thruster PETRUS

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Abstract: Pulsed Plasma Thrusters (PPT) are used for space applications like Attitude and Orbit Control since the 1960s (Zond 2). These PPTs were designed for large satellites and subsequently are higher in energy consumption compared to miniaturized PPTs developed these days. Especially the CubeSat standard created by Stanford University and California Polytechnic State University initiated the miniaturization of low energy PPTs for CubeSat applications.

Thus, one of many projects of the Institute of Space Systems (IRS) at University of Stuttgart is to develop and investigate PPTs. The latest thruster developed at IRS is the compact and low energy consuming Pulsed Plasma Thruster “PETRUS” which is a coaxial PPT having an inboard ignitor. PETRUS is based on the know-how gained by the long-term development as well as investigation of thrusters like ADD SIMP-LEX, PET as well as PETRA. The thruster is designed to be operated as a clustered primary propulsion system performing a controlled deorbit maneuver of the CAPE satellite. Most significant characteristics of PETRUS are the maximum mass of 600 grams and restriction of consuming a volume of only 0.5 U. Both constraints include the thruster itself, the capacitor bank and the power processing and ignition unit. During first series of experiments, PETRUS already showed promising results in terms of characteristic discharge curves and design verification. Nevertheless, limitations regarding the lifetime were determined.

This paper describes the investigations of the lifetime issues, e.g. discharge distribution, and possible solutions. Moreover, an updated thruster design is introduced and analyzed.

I. Introduction

The Pulsed Electric Thruster of University of Stuttgart, shortly PETRUS, is the fourth Pulsed Plasma Thruster (PPT) at the Institute of Space Systems (IRS) at University of Stuttgart. PETRUS is a coaxial, breech fed and low energy PPT for CubeSat applications operating in the energy class $E < 10 \text{ J}$ [1]. The thruster uses polytetrafluoroethylene (PTFE) as propellant having the advantage of being non-toxic and temperature resistant. Compared to a gaseous or fluid propellant no extra tank structures and valves are necessary. Moreover, PTFE is already space proven and, as literature shows, enables high thruster performance and reliability. One exemplary application of PETRUS would be for example the mission “CubeSat Atmospheric Probe for Education” (CAPE) coordinated by the IRS and the small satellite student team KSat e.V. [2]. The mission scenario of CAPE encompasses a controlled de-orbit maneuver from an orbit similar to the one of the ISS to an altitude of about 150 km using a cluster of PETRUS thrusters as primary propulsion system. Once the target altitude is reached the micro return capsule

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(MIRKA 2) is separated from the CubeSat, which then performs a reentry to conduct atmospheric measurements and to investigate a high performance heat shield material [2].

First test campaigns, already proved the operability of the initial PETRUS design (PETRUS 1.0). The thruster ignited at about 2000 V showing that the design of the ignition electrode works. Moreover, the propellant feeding system was successfully tested and the voltage discharge curve of the capacitor bank was investigated showing only minor oscillations [1]. Finally yet importantly, a first long-term test with 5600 pulses was accomplished, also pointing out limitations of PETRUS 1.0. Especially charring of the PTFE surface is an issue. After the long-term test most of the ablation surface was affected by charring reasoned by poor manufacturing tolerances of a ceramic insulator located between cathode and inboard igniter electrode. This leads to an insufficient ignition distribution meaning that the initial ignition usually occurred at the same spot where the distance between cathode and igniter is closest. Even though the ignition itself operates very reliable, the results of the long-term test of PETRUS 1.0 are not sufficient in order to pulse the thruster for some hundreds of thousands times. Consequently, design improvements are necessary to operate the thruster properly. Figure I-1 depicts the design of PETRUS 1.0.

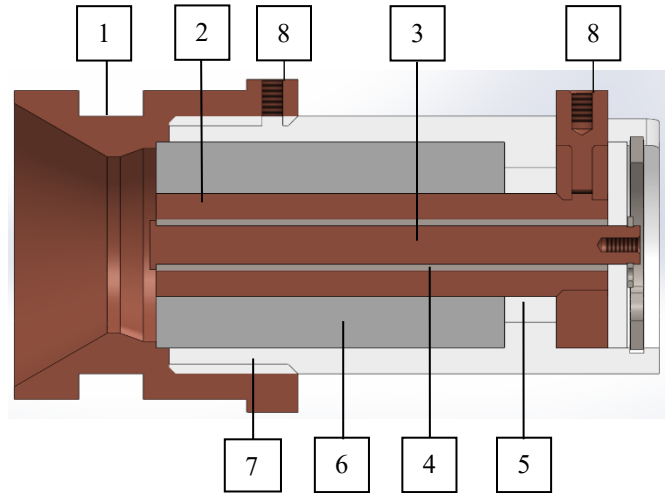


Figure I-1: Section of PETRUS 1.0. 1) Anode, 2) cathode, 3), inboard igniter electrode, 4) insulator, 5) propellant supply system, 6) propellant, 7) casing and 8) connection points for capacitor bank [1].

Within this paper, further design iterations and results of test campaigns are described, which reduce the amount of charring at the PTFE surface and improve the ignition distribution. In order to receive these enhancements an extensive design change of PETRUS 1.0 had to be done leading to an updated thruster architecture, named PETRUS 2.0. In the following, the development history is explained comprehensively.

II. Design Investigations and Improvements of PETRUS 1.0

Because PETRUS 1.0 suffered from heavy charring during long-term tests some detailed design investigations had to be done. Within experiments, it was determined that the design of the igniter seems to be the reason. In addition to inconsistent ignition distribution the first test campaigns also showed that charring is reasoned by the convergent part of the convergent/divergent copper anode of PETRUS 1.0 [1]. Since the thruster is designed to investigate thermal effects as well as magnetoplasmadynamic effects (MPD) two different anode adapter were designed from the very beginning [1]. In order to minimize the charring the straight cylindrical anode replaces the nozzle within the following investigations. The results of both, the analysis of different igniter setups as well as the effect of the cylindrical copper anode are pointed out in the following.

A. Anode Design Investigations

In order to know about the influence of the anode design in terms of charring two tests at same conditions were performed. Both test setups were done with a capacitor bank energy of $E_0 = 1.35 \text{ J}$. Using two $0.675 \mu\text{F}$ capacitors at 1400 V. As investigated only one sixth of the PTFE surface is included into the plasma creation. To calculate the energy density per pulse only the effective ablation area is considered.

$$A_{eff} = \frac{A}{6} = 0.25 \text{ cm}^2$$

In experiments, it was investigated that only 16.66 % of the PTFE surface is affected by the plasma creation using the thruster configuration shown in Figure I-1. This results in an energy density per pulse of 5.4 J/cm², which is slightly above the average energy density (2,77 J/cm²) of already developed thrusters. Here, only PPTs with $E_0 \leq 20 \text{ J}$ are considered (Figure II-1 and Table V-1).

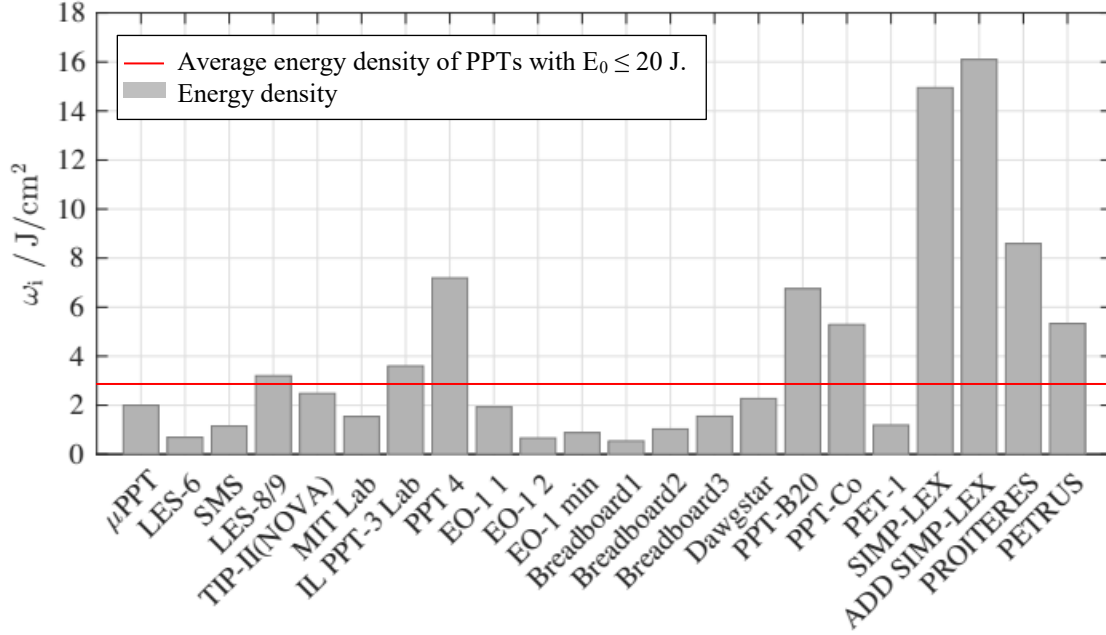


Figure II-1: Energy density of already developed PPTs compared to PETRUS. The red line represents the average energy density of thrusters with $E_0 \leq 20 \text{ J}$.

This means that the effective energy density of PETRUS 1.0 still is high enough to prevent charring in the region where the initial ignition occurred. Figure II-2 shows the PTFE surface of both thruster configurations before the test and after 5600 pulses⁴. As it can be seen in the second picture of Figure II-2, where the test with the convergent/divergent anode was performed, the PTFE surface heavily is affected by charring. All the surface of the PTFE where the initial ignition did not happen is afflicted. Performing the same test, but using the cylindrical anode an improved lifetime behavior is determined. The design can be seen in the third picture of Figure II-2.



Figure II-2: From left to right. Convergent/divergent nozzle as anode before the test. Convergent/divergent nozzle after 5600 pulses. Cylindrical anode before the test. Cylindrical anode after 5600 pulses.

At the very right of Figure II-2 the PTFE surface after 5600 pulses is depicted using the cylindrical anode. First, it can be seen that there are two spots at the PTFE being free of deposit, reducing the overall amount of charring. Even though the discharge distribution improved, no regularity of this was determined in further test campaigns. A reason for this can be the alternating initial ignition affecting PTFE regions close to the discharge. Another reason for less

⁴ Igniter design „configuration 2“ described in II.B. is used.

charring intensity with the cylindrical anode might be the missing convergent part, which creates particle back flux to the ablation surface. However, no charring between anode and cathode is created where the discharge occurred being a hint of a well operating propellant feeding system once issue the charring is removed. The convergent/divergent anode is going to be further investigated once an evenly distributed initial ignition can be guaranteed. Therefore, the cylindrical anode is preferred for now.

B. Igniter Electrode Investigations

In order to improve the ignition distribution and to minimize the charring during long-term operations, various igniter electrodes, cathode and ceramic insulator designs were investigated. In total four different configurations were tested:

1. Configuration 1:

This version was designed for the very first version of PETRUS 1.0 causing heavy charring due to the poor manufacturing tolerances of the ceramic insulator (Figure II-3). The wall thickness of the ceramic tube differs from 0.51 mm to 0.65 mm. Moreover, the outer diameter varies between 3.31 mm and 3.77 mm. This results to an improper alignment of the inboard igniter electrode with minimal and maximal distances to the cathode, which leads to a lower dielectric strength at the closest region. Once the voltage to the ignition circuit is applied, the initial ignition will happen at the closest spot. Other parameter like sharp edges, which create locally high electrical field strengths, may also have an influence regarding the ignition distribution. Nevertheless, this effect seems not to have any influence within configuration 1, as it was proven by performing tests with smoothened edges. Consequently, the improper alignment of the igniter electrode is the major issue in terms of a poor discharge behavior. A detailed description of the ignition process of PETRUS and the characteristic charring behavior of configuration can be found in literature [1].

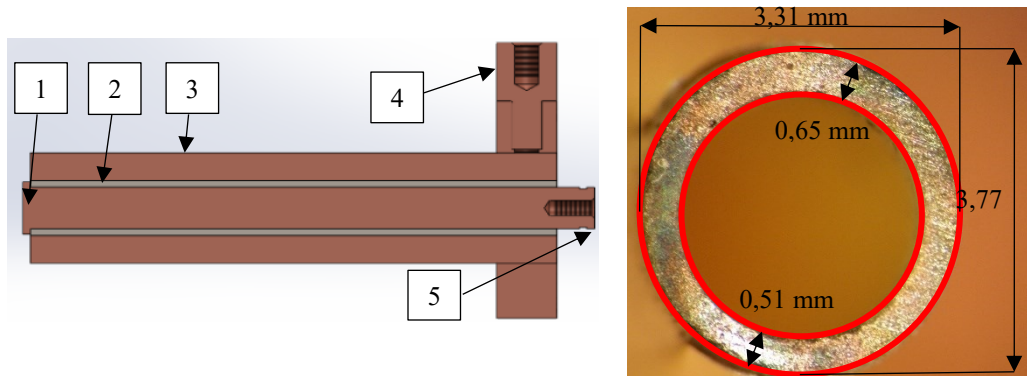


Figure II-3: Left, first igniter/cathode configuration with: 1) igniter head, 2) ceramic tube, 3) cathode, 4) connector for capacitor bank and 5) cable connector for igniter. Right, front view of the ceramic insulator showing the poor manufacturing tolerances causing the unevenly initial discharge distribution.

2. Configuration 2:

As an alternative to the ceramic tube in configuration 2 ceramic bushings are used. Major advantage of the bushings are the higher accuracies of the wall thicknesses and the concentricity. In order to use the bushings, the cathode design had to be modified. Due to the dimensions of the bushings the radius of the igniter head increased by 1.05 mm. However, the initial discharge still occurs between the circumference of the igniter head and the cathode (red encircled at bottom left of Figure II-4).

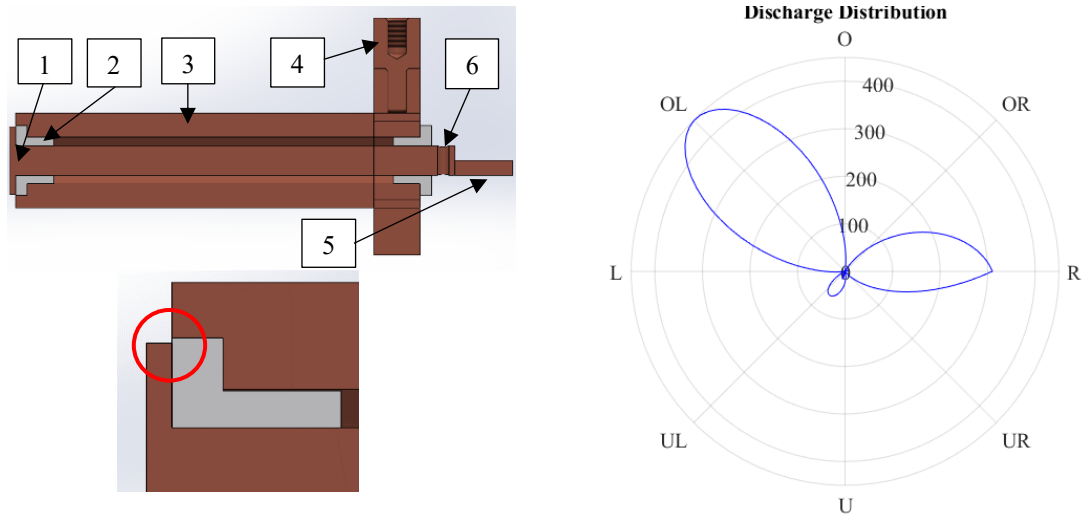


Figure II-4: Top left, is the second configuration showing 1) the igniter electrode, 2) the ceramic bushing, 3) the cathode, 4) the connector for the capacitor bank, 5) the cable connector for igniter and 6) the bore for a locking pin. Bottom left, zoomed section of igniter head showing the spot of ignition (red encircled). On the right, the discharge distribution of configuration 2 is depicted. More than 1000 pulses were performed.

Moreover, Figure II-4 depicts the cross sectional view of configuration 2 (top left) and an exemplary distribution of the initial discharges (right). At the circumference the designations represent divisions of the PTFE surface, e.g. R is the right, OR is top right, O is top etc.. In total, the surface is divided into eight equivalent regions. The radial designation, from 0 to 150, is the number of pulses for each region. Since the position of the initial discharge was at the same spots, after 1000 pulses the mapping was stopped. Nevertheless, it can be seen that most initial discharges for this specific case occurred at the top left and top right. In total four tests were performed using configuration 2. The test result after 5600 pulses can be seen in the right of Figure II-2.

As depicted on the top left of Figure II-4 the igniter electrode is not completely covered by the ceramic insulator anymore. Therefore, two ceramic bushings are mounted inside the front and the back of the cathode guiding the igniter. In order to prevent any type of unwanted short-circuit inside the cathode, the space between the inner of the cathode and the igniter's shaft is set to 0.73 mm. Additionally, the igniter's shaft is covered with insulation spray. Since the distance between cathode and igniter head is set to 0.1 mm the initial discharge is expected to occur there [1]. Next to the updated ceramic insulator, the clamping of the igniter inside the cathode also was modified. Instead of using a circlip, a lock pin (component 6 in Figure II-4) is used, simplifying the process of assembling the igniter inside the cathode. The best-case scenario reached within the campaign can be seen in the very right Figure II-2, where two regions of the PTFE surface are free of charring (46 % of the total ablation area). Even though the outcome is an improvement, the requirement of an ablation area being completely free of charring is not met yet. Moreover, the other three tests with configuration 2 showed an ablation area, which is less than 23 % free of charring concluding that the setup does not operate reliable yet.

3. Configuration 3:

Since configuration 2 does not guarantee a deposit free ablation area in a long-term test, further igniter configurations are investigated. Major issue of the previous design are the alignment of the inboard igniter, which causes deviations in distance between igniter head and cathode. Due to this configuration 3 aims towards a design, which is less dependent on the insulator's accuracy and radius of the igniter head. This is done by increasing the radius of the igniter head causing the initial discharge to be between the rear surface of the head and the front surface of the cathode (Figure III-7). A detailed overview of the design and the discharge distribution can be seen in Figure II-5.

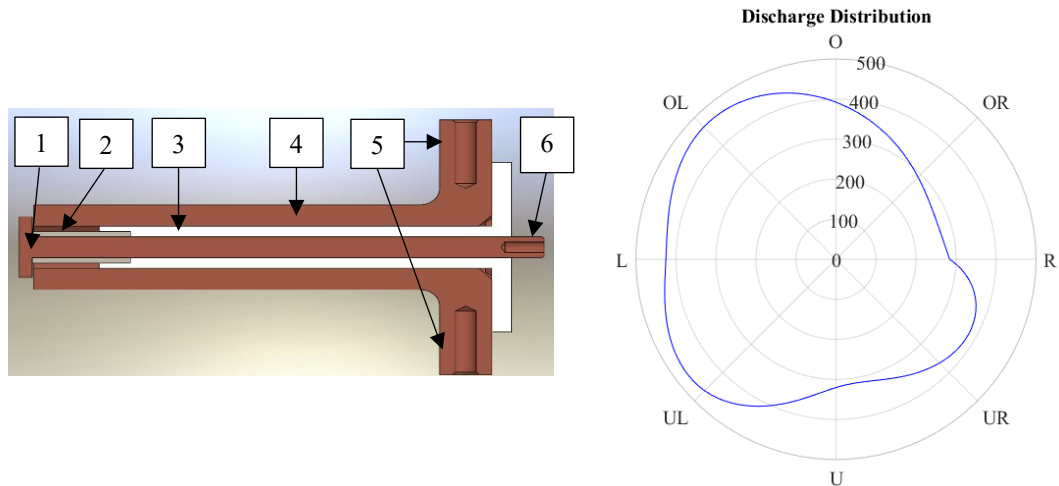


Figure II-5: : Top left, third configuration showing 1) igniter electrode, 2) ceramic spacer, 3) PEEK insulator, 4) cathode, 5) connectors for capacitor bank and 6) cable connector for igniter. On the right, the discharge distribution of configuration 3 is depicted. Circa 2500 pulses were performed.

An in-house manufactured PEEK insulator exchanges the purchased ceramic insulators (component 3 in Figure II-5). Compared to the ceramic components higher manufacturing accuracies are possible leading to an improved alignment of the inboard igniter. In addition to that, at the very front of the PEEK insulator a small ceramic tube is located. Since previous ceramic insulators proved to withstand the high temperatures and forces created during the initial ignition a small ceramic tube between igniter head and PEEK insulator is used. As experienced in previous tests the ceramic tube does not meet the requirements regarding its wall thickness and concentricity. The length of the tube does meet the necessary accuracy though. Therefore, using the small ceramic tube as a spacer, which only is responsible for setting the distance between cathode's front and the back of the igniter's head seems feasible. As seen in Figure II-5 and Figure II-6 the outer diameter of the ceramic tube is much smaller than the inner diameter of the cathode. As experimentally investigated, this design prevents a discharge along the surface of the insulator caused by pollution and carbon deposit created during the lifetime.

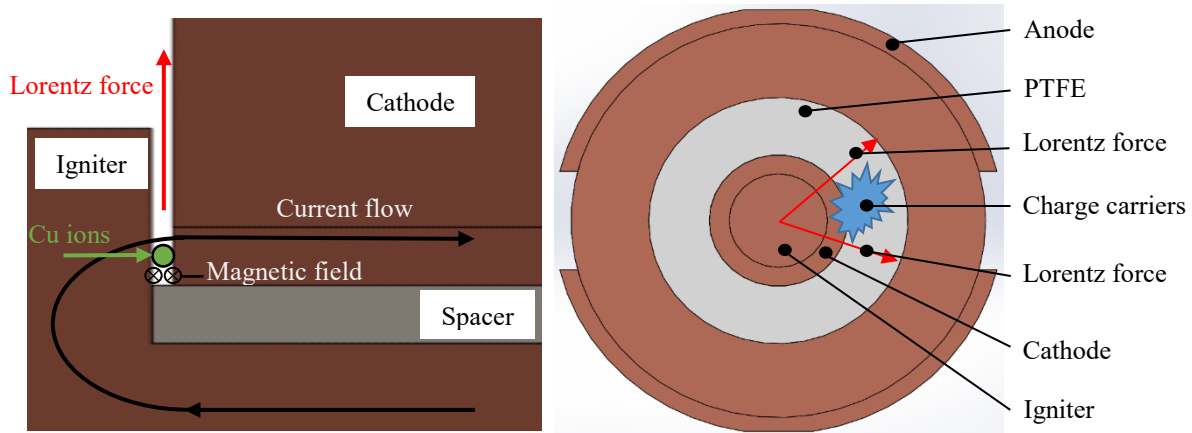


Figure II-6: Left, schematics of the acceleration process of charge carriers of the initial discharge. Right, front view of PETRUS illustrating the fan shaped charge carrier plume, caused by the Lorentz force and the magnetic field.

Figure II-6 depicts the operating mechanism of igniter configuration 3. Similar to a parallel plate PPT, the movement of the charge carriers, created by the initial discharge, is influenced by the Lorentz force. In this case, the direction of motion of the copper ions is from the thruster's center towards the cylindrical anode. Additionally, the magnetic field forces the ions to a rotational motion around the inboard igniter. By combining both effects a fan of charge carriers from the center of the thruster to the anode is created. Since the charge carriers move directly towards the thruster's anode this supports triggering the main discharge. Moreover, the fan of charge carriers also increases the PTFE area affected by the main discharge Figure II-7.

As seen in the results of the discharge distribution, depicted on the right in Figure II-5, the design changes in configuration 3 majorly improved the ignition behavior. Even though, the discharge distribution improved throughout all test campaigns, an irregularity was determined. Moreover, it was identified that every once a while up to hundred initial ignitions occurred at a similar region. Although, the spot of ignition varied afterwards again, a long-term test could form charring in regions where the initial discharge occurred less. Even the best-case scenario illustrated in the plot in Figure II-5 shows minor ignitions at the top and top left of the thruster. Figure II-7 depicts another test result. There, three ignition spots dominate the rest of the PTFE surface is affected by light charring again.

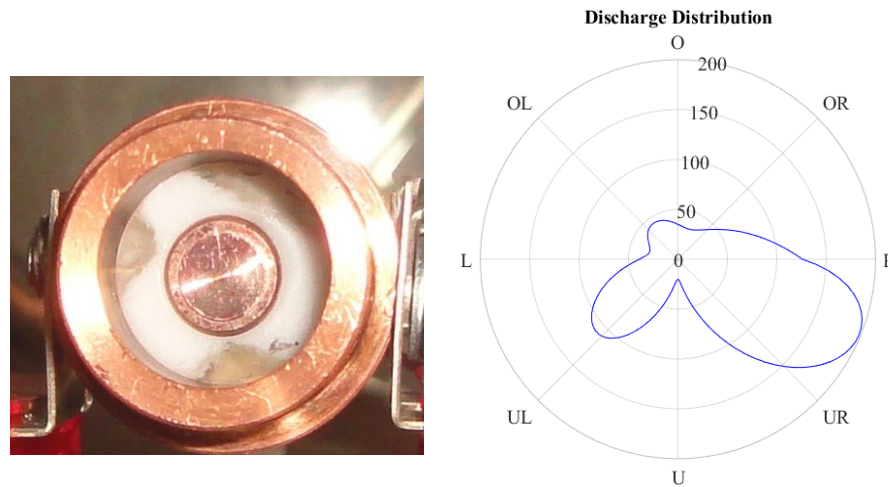


Figure II-7: Left, front view of PETRUS 1.0 after 560 pulses showing 3 bright spots without charring. Right, discharge distribution for the test, respectively.

C. Lessons Learned

Comparing the results of configuration 1 with configuration 3 a significant reduction of the charring creation was achieved. Nevertheless, the overall outcome does still not fulfill the requirement of a charring-free operating thruster. Especially, long-term tests point out the limitations of the design. In the following, the limitations are summarized in order to guide a rework of the thruster design.

- 1) As determined in tests, only a minor section of the PTFE surface is affected by ablation per pulse. When updating the thruster design this has to be considered. A further miniaturization might be a consequence.
- 2) Main issue of the charring was the unevenly distributed initial discharge, which also caused a sectional ablation. Due to a further miniaturization of PETRUS 1.0 an independency of the location of the initial discharge is expected. Especially, test campaigns with configuration 1 of PETRUS 1.0, where the initial discharge was not as a fan towards the anode, showed that the plasma between anode and cathode affected a certain area. The charring free area of configuration 1 can be used for a first approach for decreased ablation area (no charring).
- 3) Since the convergent/divergent anode increases the amount of charring the first design of PETRUS 2.0 should be operated with a cylindrical anode.
- 4) Within the design iterations of PETRUS 1.0 it was investigated that venting bores or slits are necessary in order reduce the outgassing time before igniting the thruster. In tests, it was determined that encapsulated components are surrounded by rest atmosphere, which caused an unwanted discharge inside the thruster.

III. PETRUS 2.0

Main goal of redesigning PETRUS 2.0 is the reduction of charring when operating the thruster in a long-term test. Therefore, the aforementioned key points determined in previous tests are necessary to consider. The major aspect of the redesign is the further miniaturization, which equals in size the spot being free of charring in configuration 1 to configuration 4 of PETRUS 1.0. This means the ablation should decrease from 1.5 cm^2 to approximately 0.3 cm^2 to 0.5 cm^2 . However, in the following breadboard models ablation areas between 0.37 cm^2 to 1.06 cm^2 are investigated by decreasing it systematically. Moreover, designs, which were considered as operational, e.g. propellant feeding system, and anode design shall be adopted. Before designing a complete thruster model multiple breadboard models were set up and tested regarding their functionality, charring behavior and reliability. Especially, anode and cathode dimensions as well as materials are varied. The following Table III-1 gives an overview of the thruster characteristics. All configurations were operated with a capacitor bank energy of up to 5.12 J at 1600 V ⁵.

Table III-1: Overview of thruster breadboard configurations.

	Anode (A)	Cathode (C)	Igniter (I)	Materials	Comments
Breadboard 1	12 mm	3 mm	0.5 mm	A=Cu, C=Cu, I=Cu	C - Cu alloy
Breadboard 2	12 mm	3 mm	0.5 mm	A=Cu, C=W, I=Cu	C – with a tip, I - wire
Breadboard 3	7 mm	1 mm	0.5 mm	A=Cu, C=W, I=Cu	
Breadboard 4	7 mm	1 mm	0.1 mm	A=Cu, C=W, I=W	C – with a tip, I - wire

In order to enable a quick investigation of the operability of each thruster configuration the setup was kept as simple as possible. This means that for example, the propellant feeding mechanism was not implemented and cable connections between thruster and capacitor bank are used. In PETRUS 1.0 the capacitor bank was directly connected to anode and cathode [1]. Consequently, the design of the breadboard models is not optimized in terms of their RLC circuit. Once a proper operating thruster design is developed this will be done. Moreover, the design consists of plug mechanisms, e.g. the anode is plugged on the hollow PTFE cylinder, the cathode is plugged into the hollow PTFE cylinder and the igniter is plugged/pressed between cathode and PTFE cylinder. Due to this, assembling and testing the breadboards is time optimized. In the following all breadboard models described.

A. Breadboard 1

Breadboard version 1 consists of a 12 mm (diameter) copper anode and 3 mm cathode. The ignition copper wire has a diameter of 0.5 mm and is next to the inboard cathode. A thin layer of protective varnish insulates cathode and ignition wire from each other. Only the tip of the ignition wire and the front of the cathode sticking out of the PTFE are free of the protective varnish. The setup of breadboard version 1 is depicted in the following Figure III-1.

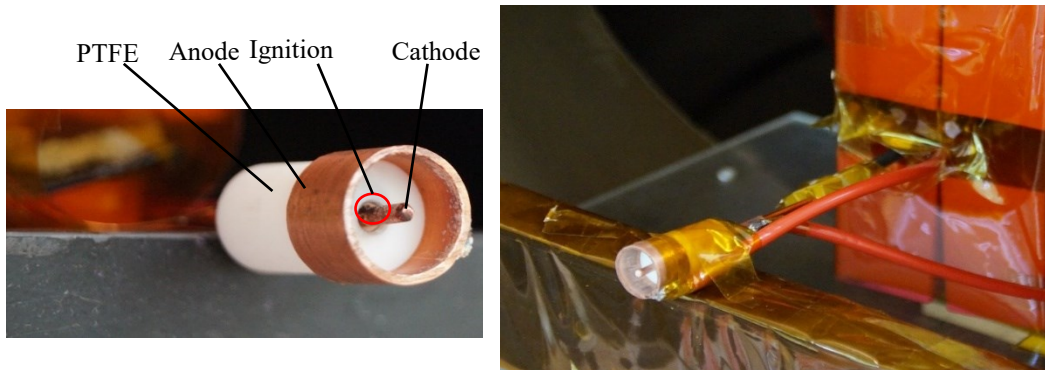


Figure III-1: Left, isometric view of the thruster breadboard version 1. Right, thruster breadboard version 1 showing the thruster itself, the cable connections and the capacitor bank.

As seen in Figure III-1, the cathode does not end at the PTFE surface as in PETRUS 1.0, but at the anode's front. The distance between PTFE surface and anode's front is 5.6 mm. The reason for the protruding cathode is the use of the MPD effects forming the plasma front as well as accelerating and focusing the plasma [3]. In the Figure III-2 and

⁵ Due to lifetime issues, the capacitors of the original PETRUS were exchanged to capacitors with higher reliability for pulsed applications.

Figure III-3 below, an evenly plasma distribution on the PTFE surface can be seen. The pictures were taken with ISO-100, $F = 18$ and $t_{\text{aperture}} = 3.2 \text{ s}$.



Figure III-2: Left side, front view of breadboard version 1 at 2 J (1000 V). Right, front side view of breadboard version 1 at 5.12 J (1600 V).

Figure III-2 illustrates a first success of the updated thruster design. Compared to previous experimental series, with PETRUS 1.0, the complete PTFE surface is covered in plasma. The image left in Figure III-2 was taken during a discharge, where the capacitor bank had an energy of 2 J. The image shown on the right hand side of Figure III-2 depicts a discharge at an energy of 5.12 J. Moreover, it can be seen that a brighter region in the center of the thruster exists. This can be explained by the higher energy density. The emitted electrons decrease their energy level, which results in emission of light. In the image on the left side it can be recognized that the bright spot is off centered. Since the image is taken with long exposure time, it is assumed that the process of the initial discharge is reason for this. Moreover, in the image on the right hand side it can be seen that the anode of the thruster is surrounded by plasma. Especially, at the bottom right, where the cable is soldered, the plasma interacts strongly with the anode. A reason for this can be the missing kapton covering the soldering joint. Due to this, charged carriers can travel to the outside of the anode once they left the discharge channel. Moreover, the solder joint between cable and anode ring might contain some contamination from the soldering process, which supports the external discharge. In follow up tests, the soldering joint is covered by kapton leading to a decreased plasma interaction.

The following Figure III-3 depicts the side view of the thruster while pulsing. Left, at 2 J and right at 5.12 J again. The image on the right hand side clearly shows the interaction of the plasma with the soldering joint.



Figure III-3: Left side, side view of PETRUS mini at 2 J (1000 V). Right, side view of PETRUS mini at 5.12 J (1600 V).

Moreover, the side view also depicts a focused plasma plume in the center of the thruster. This phenomenon also was investigated in tests with the other breadboard models. Reason for this is the centered cathode creating an electric field from the anode to the cathode guiding the ions. Due to the Lorentz force, the ions are accelerated towards the exit of the anode. As a result, of the strong electric field at the tip of the cathode the ions collide and form the plasma jet. Due to the focused plasma jet, the thrust vector majorly is along the thruster's axis reducing the losses of a diffuse plasma plume. Additionally, the closed coaxial design enables the focus of thermal radiation along the thruster axis minimizing the losses as appearing in a parallel plate PPTs. Combining both effects an increased thruster performance is expected. In order to prove this, tests like impulse bit measurements and specific impulse measurements have to be performed. However, voltage discharge curves already were measured (Figure III-4).

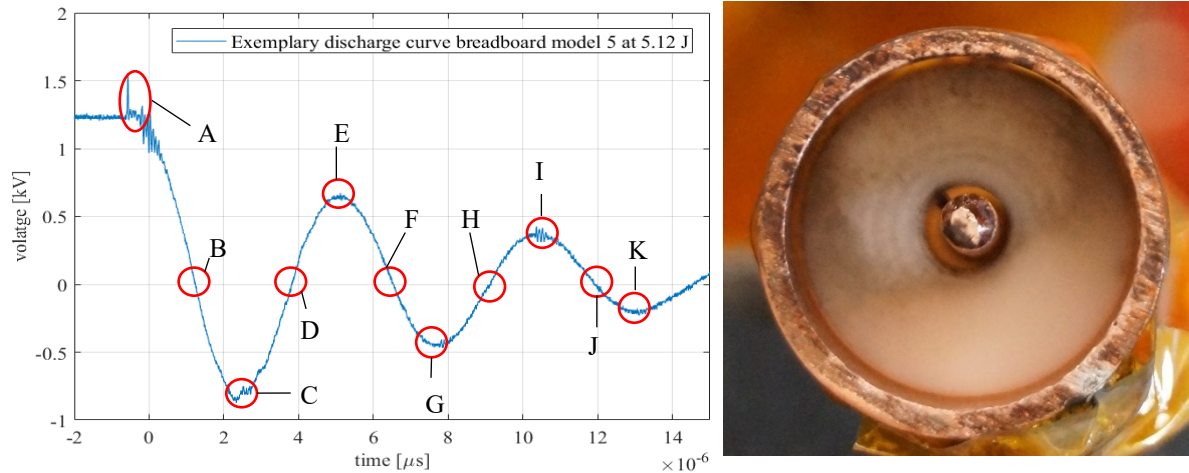


Figure III-4: Exemplary voltage discharge curve of breadboard version 1. A) peak created by the igniter. B), D), F), H) and J) are zero crossings. C), E), G), I) and K) illustrating peaks of the capacitor bank's energy. Right, charred PTFE surface of breadboard version 1 after the test campaign.

As it can be seen, the discharge curve is strongly oscillating meaning that the capacitor bank's energy is not fully coupled in one pulse, but in multiple small pulses within one purposely-triggered pulse. The optimization of the RLC circuit will be done in future investigations, when a concrete thruster design is chosen. Even though the plasma covers the whole PTFE surface when pulsing breadboard version 1, charring still can be recognized after the test campaign (Figure III-4). One reason can be the heavy oscillation of the discharge curve preventing a fully energy coupling into the plasma or the ablation surface of 106 cm^2 still too large, which is most likely. The red encircled regions highlight the capacitor status "not charged" and "charged". B, D, F, H and J represent a not charged capacitor bank, whereas, A, C, E, G, I and K represent a charged capacitor bank. Due to the heavy oscillation of the RLC circuit, the capacitor bank discharges and charges multiple times during one triggered pulse. Consequently, the PTFE surface is exposed multiple times to an energy input creating secondary discharges. In order to know make the secondary discharges visible for the human's eyes pictures with a high-speed camera were taken⁶ (Figure III-5). Depending on the position of the initial discharge, the location of the plasma plume changes. In order to track the plasma propagation each following image was taken with a certain delay time.

⁶ Each image is taken at a different pulse, but varied delay time.

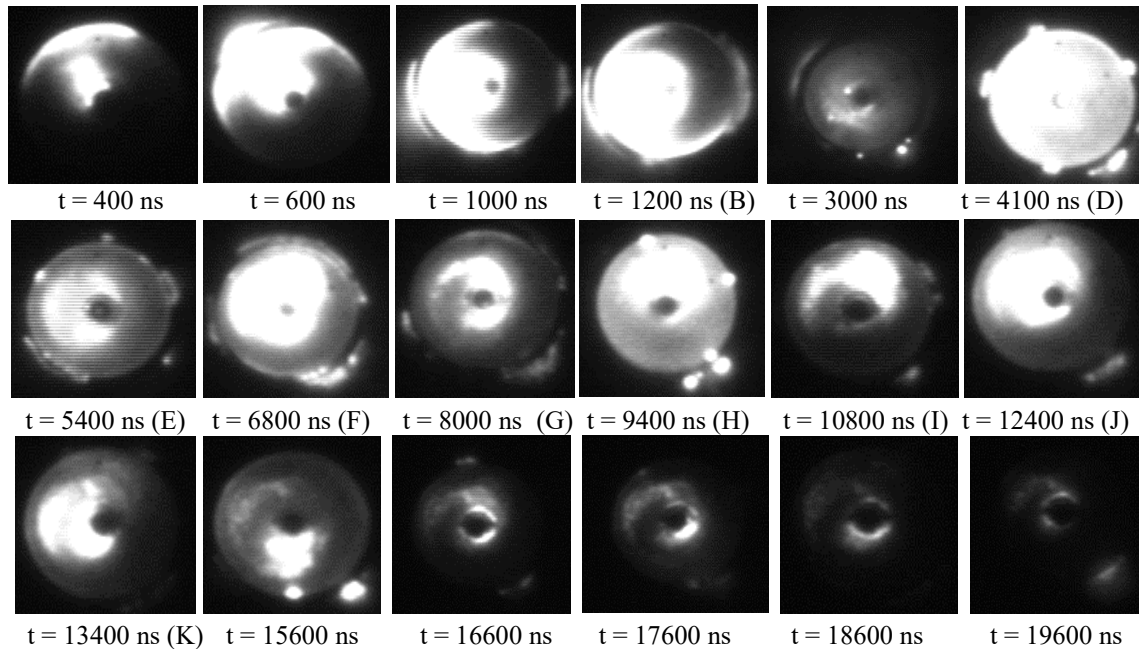


Figure III-5: High-speed camera images of breadboard version 1 showing the plasma propagation and secondary discharges.

As illustrated in Figure III-5, the thruster pulses multiple times once one pulse was triggered by the igniter. These images prove that a major part of the capacitor bank's energy, which should be in one pulse, dissipates in multiple secondary discharges making an optimization of the RLC circuit of very high importance. Moreover, it can be clearly seen, that the ablation of breadboard version 1 is too large. After 1200 ns (B) the capacitor bank is completely discharged the first time, but the thruster's ablation surface is not fully covered in plasma. Only the second (D) discharge enables a fully in plasma covered PTFE surface. The remaining and distributed charge carriers within the discharge channel provide beneficial conditions for a more uniform plasma creation. Nevertheless, the partial plasma coverage reflects the charring behavior of breadboard version 1 seen on right in Figure III-4. In order to know more about the plasma propagation in general, further high-speed imaging has to be performed in future.

B. Breadboard 2

Since the breadboard version 1 already operated very convenient regarding the plasma coverage of the PTFE surface, breadboard version 2 is designed similar, but with a 3 mm tungsten cathode having a tip. Main goal of this investigation is an increased electrical field at the exit of the thruster forming a more clear plasma jet. In order to prevent a heavy abrasion of the copper cathode if manufactured with a tip, copper was replaced by tungsten (Figure III-6).

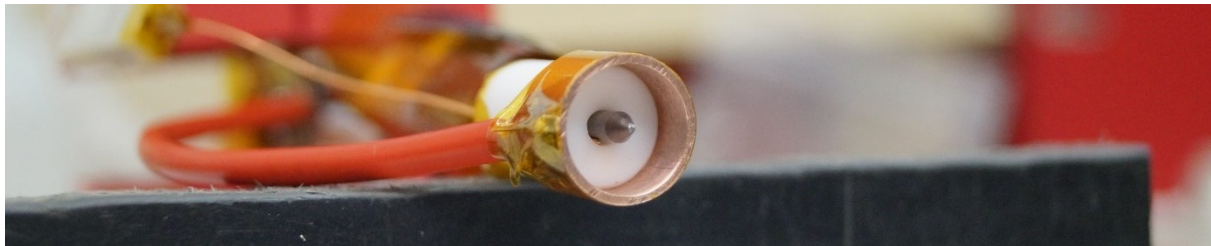


Figure III-6: Breadboard version 2 having a tungsten cathode with a tip.

First, the use of a cathode with a tip did not visibly change the outgoing plasma jet compared to breadboard version 1. The plasma coverage of the PTFE surface is similar to results of breadboard version 1. However, sparking was investigated when pulsing the thruster, which can be affiliated to cathode abrasion. Even though tungsten was chosen instead of copper, at the tip of the cathode a pit was determined. This is a hint of heavy ion bombardment caused by the strong electric field. Moreover, heavy tungsten abrasion could be seen near the PTFE surface explaining the sparking. Compared to copper, the heat conductivity is about 2.23 times lower and the electrical resistivity is about

3.14 times higher. Both effects cause a local temperature increase while pulsing, which leads to melt tungsten. The PTFE surface again is charred after the test.

C. Breadboard 3 and Breadboard 4

The breadboard versions 3 and 4 are very similar in their design. Both have an anode diameter of 7 mm and a cathode diameter of 1 mm. The anode is made out of copper and the cathode is made out of tungsten. The ignition wire of breadboard version 3 is an insulated copper wire ($\varnothing = 0.5$ mm), whereas, the ignition wire in version 4 is a tungsten wire ($\varnothing = 0.1$ mm). The following Figure III-7 depicts breadboard version 4. At the left hand side, the general setup is shown. The center image shows the breadboard version 4 pulsing at 2 J. The image on the right illustrates the operating thruster at 5.12 J.

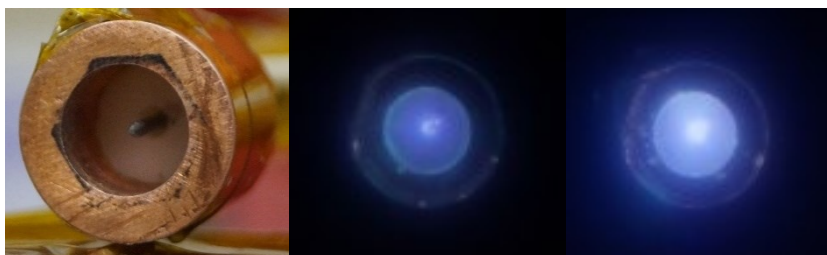


Figure III-7: Left, front view of breadboard version 4 with a copper anode, tungsten cathode and tungsten igniter. Center and right, showing the discharge at an energy of 2 J and right at 5.12 J.

Similar to the previous mentioned breadboard models, the PTFE surface in version 3 and 4 also is covered in plasma completely. As seen in the side view of the breadboards 3 and 4 a more distinct plasma jet is created compared to version 1 or 2.

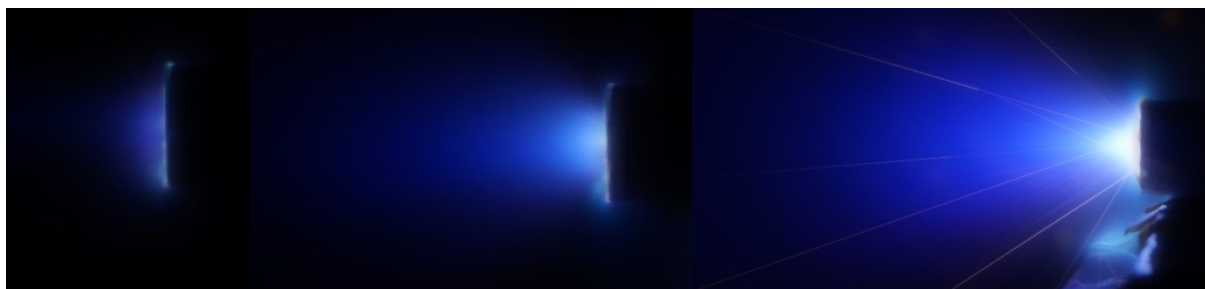


Figure III-8: Left, breadboard version 4 at an energy level of 2 J and at the center at an energy level of 5.12 J. The very right illustrates breadboard version 3 at 5.12 J showing heavy sparking.

Figure III-8 depicts the side view of breadboard version 3 and 4. From left to right, breadboard version 4 at 2 J and 5.12 J and breadboard version 3 at 5.12 J. Most of the pulses of both thrusters were accompanied by heavy sparking (right in Figure III-8). Consequently, the long-term test of version 4 had to be stopped after 2072 pulses. Due to the abrasion, the distance between cathode and igniter increased leading to a failure of the ignition, Figure III-9 shows the tungsten cathode and the ignition wire after the test.



Figure III-9: Tungsten cathode after testing breadboard version 4. Left, molten tip. Center, molten/worn cathode close to the PTFE surface. Right, molten ignition wire (tungsten).

Since sparking only was investigated when using the tungsten components, the design of the future PETRUS 2.0 should consider copper alloys for the electrodes. However, after the long-term test with breadboard version 4 the PTFE surface is completely free of charring (Figure III-10). The only deposit was determined at the anode's front. Comparing the result to charring issues of PETRUS 1.0 a major step towards a proper operating thruster was accomplished within these test campaigns.



Figure III-10: Left, breadboard version 4 after 2072 pulses showing deposit at the anode's front. Right, showing the PTFE surface after 2072 pulses.

D. Design of PETRUS 2.0

After investigating different anode, cathode and igniter configurations with the breadboard models, the design of PETRUS 2.0 includes the most promising results, which lead to an even further miniaturized model compared to PETRUS 1.0. PETRUS 2.0 will be 50 mm long with an outer diameter of 12 mm (Figure III-11). Even though breadboard version 3 and 4 showed that an anode inner diameter of 7 mm and a cathode diameter of 1 mm are promising regarding the operability of the thruster, the first version of PETRUS 2.0 will have an anode inner diameter of 8 mm and a cathode diameter of 1.5 mm. The reason for the increased dimension is the direct dependency of the ablation area to the impulse bit. A larger ablation area increases the impulse bit. If investigations show that charring is created the design of PETRUS 2.0 easily can be changed back to the dimensions of breadboard version 3 and 4. Only the anode and the cathode rod have to be exchanged, which enable the possibility of even more tests with different geometries in future. The copper igniter has an outer diameter of 2 mm and an inner diameter of 1.7 mm. At the back of the thruster, connectors for wiring are provided. Similar to PETRUS 1.0 the propellant feeding system consists of a propellant slider pulled by springs. In addition, the main structure of the thruster is the casing again, encapsulating propellant, cathode, igniter and propellant slider. The anode is screwed into the front of the igniter. As determined in experiments with PETRUS 1.0 venting bores or slits are necessary in order to enable a fast outgassing process of the thruster. Due to this, the casing of PETRUS 2.0 provides a slit at the rear part to prevent unwanted discharges between igniter and cathode.

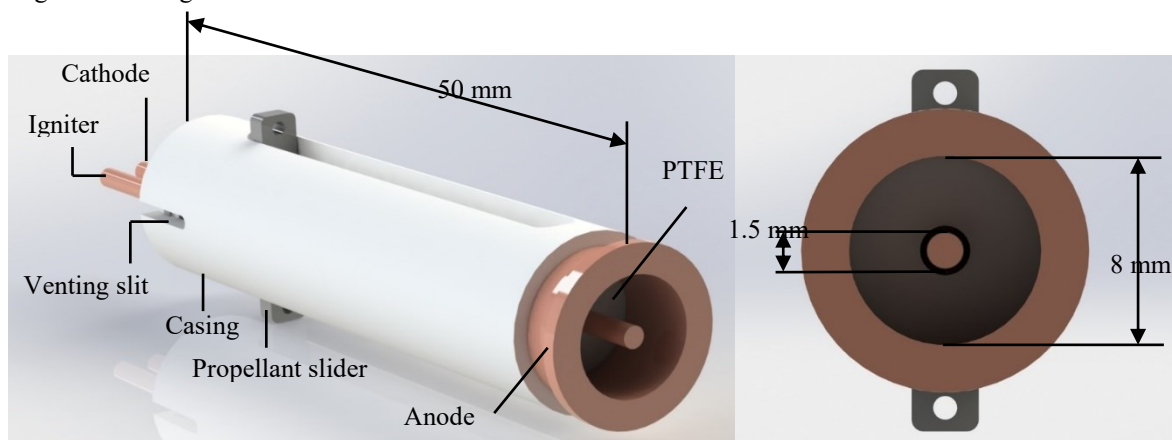


Figure III-11: Left, isometric view of CAD modeled PETRUS 2.0. Right, front view of CAD modeled PETRUS 2.0.

Due to the miniaturization of PETRUS the expected performance data have to be updated. The following Table III-2 compares thruster specific parameter of PETRUS 1.0 and PETRUS 2.0. As experimentally investigated and

explained in chapter II, the performance parameter of PETRUS 1.0 are determined by assuming a maximum ablation area of 0.30 cm^2 . Moreover, the data are updated in terms of the maximal capacitor bank's energy of 5.12 J. The impulse bit is determined by using Guman's approach [1].

Table III-2: Design and estimated performance parameter of PETRUS 1.0 and PETRUS 2.0.

Parameter	PETRUS 1.0	PETRUS 2.0
Design	Coaxial	Coaxial
Size	Ø 26 mm x 50 mm	Ø 12 mm x 50 mm
Mass (PPU and thruster)	≤ 600 g	≤ 500 g
Propellant	PTFE	PTFE
Propellant mass	9.4 g	1.77 g – 3.7 g
Capacitance	4 µF	4 µF – 6 µF
Charge voltage	Up to 1600 V	Up to 1600 V
Energy	5.12 J	2.88 J - 5.12 J
Typical frequency	0.25 Hz - 1 Hz	0.25 Hz - 1 Hz
Mass bit	1.3 µg (theor.)	1.7 µg - 2.7 µg (theor.)
Impulse bit	20.42 µNs (theor.)	15 µNs - 41 µNs (theor.)
Specific impulse	1668 s (theor.)	800 s - 1567 s (theor.)
Thrust per pulse (at 1Hz)	0.0204 mN (theor.)	0.015 mN – 0.042 mN (theor.)
Input power	Up to 8 W	Up to 8 W

Compared to PETRUS 1.0, PETRUS 2.0 provides a 23 % larger impulse bit than PETRUS 1.0, whereas, the specific impulse is 23 % smaller. Due to the smaller thruster, design of PETRUS 2.0 the overall mass of the system (incl. PPU and capacitors) dropped by 100 g.

IV. Summary and Outlook

Even though PETRUS 1.0 showed promising results in terms of characteristic discharge curves and design verification in first tests, limitations also could be determined. Most critical was the charring of the PTFE surface after some thousands of pulses, which were investigated to be reasoned by the unevenly distributed initial discharge and the convergent part of the nozzle shaped anode. Consequently, the igniter design was redesigned and tested. Additionally, a straight cylindrical anode replaced the convergent/divergent anode. The design changes of the igniter reduced the amount of charring and an improved initial discharge distribution was reached. Nevertheless, charring could not be removed completely, which lead to a redesign of PETRUS 1.0 towards a miniaturized thruster version called PETRUS 2.0. Already proven thruster components, like the propellant feeding system and the overall design of the casing were implemented into PETRUS 2.0. Major changes were done at the igniter and cathode design. Instead of having an inboard igniter, PETRUS 2.0 has a centered cathode and an ignition wire. Moreover, the PTFE surface is reduced to 0.47 cm^2 , which is similar to the charring free region of PETRUS 1.0 after long-term tests. Due to the reduction of the anodes inner diameter and the cathodes diameter, the plasma covers all of the ablation area. The operability of the PETRUS 2.0 was extensively tested via multiple breadboard versions. In the end, a thruster design was created, which only differs minor in performance data compared to PETRUS 1.0, but operates reliable in terms of plasma propagation and initial discharge.

In future investigations the optimization of the RLC circuit is of importance. As seen in tests with breadboard version 1 the oscillation of the voltage discharge curve also causes multiple secondary discharges reducing the coupled energy into the plasma at the first pulse. Moreover, the length of the cathode and anode from the PTFE surface has to be investigated in order to improve the formation of the plasma jet.

Summarized, the results of the design investigations majorly improved the reliability and operability of PETRUS.

V. Appendix

Table V-1: Overview of performance data of already developed PPTs considered for designing PETRUS.

#	Thruster	Geometry	Feeding	E_0 [J]	A_p [cm ²]	I_{sp} [s]	m_{bit} [μg]	I_{bit} [μNs]
1	μPPT [4] [5]	Parallel	Side	1.70	0.85	590	4.80	28.9
2	LES-6 [6] [7]	-	Breech	1.85	2.69	300	8.88	26.0
3	SMS [6]	-	Breech	8.40	7.32	450	28.56	133.0
4	LES-8/9 [6]	Parallel	Breech	20.00	6.25	1000	30.00	297.0
5	TIP-II(NOVA) [6] [8]	-	Breech	20.00	8.07	850	46.00	375.0
6	MIT Lab [6]	-	Side	20.00	13.02	600	56.00	454.0
7	IL PPT-3 Lab [6]	Coaxial	Side	7.50	2.08	600	75.00	450.0
8	PPT 4 [9]	Coaxial	Side	9.00	1.25	745	35.71	261.0
9	EO-1 1 [10]	Parallel	Breech	18.70	9.68	-	-	266.0
10	EO-1 2 [10]	Parallel	Breech	6.40	9.68	-	-	65.0
11	EO-1 min [11]	Parallel	Breech	8.50	9.68	650	14.11	90.0
12	Breadboard 1 [12]	Parallel	Breech	5.20	9.68	-	-	96.0
13	Breadboard 2 [12]	Parallel	Breech	10.00	9.68	-	-	97.0
14	Breadboard 3 [12]	Parallel	Breech	15.00	9.68	-	-	172.0
15	Dawgstar [13]	-	-	5.23	2.30	483	11.80	56.1
16	STSAT-2 [14]	-	-	1.80	-	800	13.00	25.0
17	PPT-B20 [15] [16]	Parallel	Breech	3.38	0.50	960	2.30	22.0
18	PPT-Co [16]	Coaxial	Cavity	9.96	1.88	320	200.00	634.0
19	PET-1 [17]	Coaxial	Cavity	3.00	2.51	142	43.40	61.7
20	SIMP-LEX [18]	Parallel	Side	62.80	4.20	2181	59.30	1261.6
21	ADD SIMP-LEX [19]	Parallel	Side	67.60	4.20	2718	53.38	1373
22	AFRL MicroPPT [20]	Coaxial	Breech	2.25	-	-	8.60	-
23	PROITERES [21]	Coaxial	Cavity	2.43	0.28	-	-	-

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