

Pulsed Plasma Thruster Endurance Operation Stress Testing at IRS

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Work on ablative pulsed plasma thrusters at the Institute of Space Systems (IRS) in Stuttgart is driving system development based on successful thruster optimization. The best acceleration mechanism depends on the initial pulse energy of the thruster. An energy of several joule suggests electrothermal operation to compensate for limitations of current and magnetic field. Two thruster system prototypes developed at Stuttgart, pulsed electrothermal (PET) and pulsed electromagnetic (iMPD), were experimentally examined. Early stage endurance stress testing was performed to assess stability and failure modes. The goal was to demonstrate a total number of pulses relevant for space applications to raise the system technology readiness level. Laboratory equipment was used to operate the thrusters. Discharge behavior and health were monitored during and between test intervals. A count of $4 \cdot 10^4$ pulses was demonstrated for the PET after which it became inoperable. The iMPD-test was concluded after 10^6 pulses including successful demonstration of Teflon side-feeding. Results showed no failures, but suggested technical improvements. Side-feeding of the Teflon propellant was found to require special consideration, i.e. separation of the two Teflon bars. Testing results are compared to preflight testing reports in literature.

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I. Introduction

Pulsed Plasma Thrusters (PPTs) have long been identified as one of the key technologies for research and development to support the full range of future in-space missions.¹ They are simple, robust and affordable and represent a viable alternative to cold gas thrusters. They even excel in areas of specific impulse, system handling and minimal impulse without increasing the risk of failures or interference with the satellites communication.^{2,3,4} Feasibility and safe application have been proven for mission-critical tasks. A study for the VULCAN satellite platform showed that significant savings in cost are possible over comparable stationary plasma thrusters (SPTs).⁵ The domain of PPTs are primary and secondary propulsion of small satellites up to several hundred kilograms for drag and drift compensation, precision attitude control, mission life extension and formation flight. A promising application is deorbiting to decrease the risk at End of Life (EOL) and to allow for higher orbits for piggyback satellites. Recent focus on Cubesat development for affordable accumulation of heritage and fostering of new technologies can greatly benefit from this. Small thrusters make many scientific missions possible in the first place. To cover this demand, the step from thruster development to system development requires demonstration of the thruster operation life.

The Institute of Space Systems (IRS) in Stuttgart has introduced the efficiency optimized magnetoplasmadynamic Pulsed Plasma Thruster ADD SIMP-LEX (Advanced Stuttgart Pulsed Magnetoplasmadynamic Thruster for Lunar Exploration) for development of a vacuum capable thruster system. The components of the system and the development have been described elsewhere.⁶ The IRS is closely working with cooperation partners in this effort, leading to a satellite vacuum facility equipped with a twin-iMPD at the University of Tokyo.⁷ Research efforts in Tokyo are focused on continuous optimization of the pulsed plasma properties to complement system development at Stuttgart. The iMPD by IRS is leading in efficiency together with the APPT designs by RIAME MAI. In 2011, PET microthruster development branched from this effort. Goals are investigation of technology scalability, PPU design, facility improvement and throttability for nN to mN thrust satellite applications. For sustained operation, efficiency and endurance are opposing hardware requirements. Stress testing is needed at the earliest possible stage to find a good balance by design, to proof stability, evaluate system requirements, to identify failure modes and assess risks. A first step towards thruster qualification at IRS as part of system development was made for a small and medium pulse energy PPT.

II. Motivation

Insufficient data was available of the behavior of the new ADD SIMP-LEX under sustained operation. According to literature, an increase of energy flux to the Teflon propellant by increasing the energy density in the accelerating channel and by optimizing the energy transfer can reduce losses to increase efficiency.⁸ This is achieved when increasing the initial pulse energy but also by reducing the energy per Teflon face area.^{9,10} A usually desired high efficiency results in high discharge currents, creating undesirable thermal loads under sustained operation. Test are needed to confirm thermal stability. Thermal failure may affect propellant utilization, i.e. proper Teflon feeding, late time ablation, macro particle ejection. Thruster temperature further impacts electrode erosion and contamination, as well as thermal housekeeping requirements.

By investigating the effects of many collective pulses, stress testing data is a direct source for evaluation of discharge models and thruster design. Pulse-to-pulse variations are averaged and can be observed on a change of trend basis. The parameters for an optimum ratio of energy used for ablation and acceleration are not conclusively identified. The amount of depositions with residual propellant on surfaces of and near the thruster is an important indicator to trace issues with energy coupling and plasma process stability.

Thruster endurance testing is needed to confirm the choice of component technologies and demonstrate feasibility of the system as a whole. The issue of life limitation by component wear-off was not covered by prior work on ADD SIMP-LEX. Because of its few components, failure of any part of the thruster will render the system inoperable. Critical parts need to be identified. Redesign for endurance is undesirable at a late point in the development. Testing in ground facilities can cause interaction issues between the thruster and the facility. Typically electromagnetic interference (EMI), bad grounding and plasma interactions point to limitations of the facility and can have detrimental effects on the thruster. It is important to distinguish these effects for the study of performance stability.

The endurance of a PPT is expressed by the number of possible controlled discharge pulses rather than operation hours. Raising of the Technology Readiness Level requires pulse capability demonstration relevant

to a mission. At IRS this is the Lunar Mission BW1¹¹ for which a cluster of iMPD's is planned as the primary propulsion system. More than 10^7 pulses are required per thruster. Numerous durable PPT setups performed flight demonstration in low earth orbit. Preflight-testing reports show that duty cycle stress testing is necessary to demonstrate spacecraft compatibility. The presented results of this work are a first step to address this issue at IRS. Sustained operation for stress testing is possible only at low pulse frequency, making the process time consuming. Accelerated testing beyond several hertz is, although increasing thrust by the pulse rate, not representative and restricted by self-depolymerization of overheated Teflon. A relevant part of endurance testing is the time of thermal transition when the electrodes of the thruster are heating up. Effects on thruster performance allow for identification of a cold and a hot impulse bit at the limits of the transition. The hot impulse bit is not recognized as an integral parameter, as usual characterization is performed with cold electrodes. Methods of systematic investigation can help diminish transition effects and determine parameters for rapid transition between cold and hot. This issue has not been addressed in experimental investigations so far and has been included in this work.

A. Literature research

The RIAME APPTs have demonstrated counts beyond $2 \cdot 10^6$ at 50 J in sustained operation, also called frequency mode.¹² The order of pulses is accepted for generating meaningful results in a first test step and was also chosen for this work. Variation of the discharge channel due to Teflon consumption was found to change integral thruster performance in the tests, making side-feeding susceptible to instabilities. This creates a non-thermal transient burn-in phase for the iMPD until the bars have reached their steady shape. Altogether 200 g of Teflon were used, with no significant electrode erosion. Thermal stability was confirmed for up to 2 Hz repetition rate, with analysis suggesting capability for further increase. Component temperature away from the thruster head was moderate. EMI was not tested.

Qualification testing of the LES6-satellite thruster for MIT in 1967-68 included accelerated life cycle testing at up to 4 Hz for the flight model prototype.² The demonstrated pulse count was at 10^7 , an order required by the mission. The so tested thruster later performed 18a months of east-west station keeping in orbit. Tests showed no serious EMI issues. Temperature stability and possible environmental dependency between discharges were main criteria for high pulse repetition rates. A reported stability issue was arc discharge initiation spot movement due to propellant coverage. This had an impact on integral thruster performance by causing intermittent behavior. Redesign to limit the arc spot movement improved operations. A chemical reaction between the plasma and back streamed pump oil was noted, that compromised thruster insulation and performance. This facility limitation was identified critical for evaluating maximum system life capability.

Contamination and life testing was part of the acceptance testing in 1996 at NASA GRC for a 3-day EO-1-mission iMPD-PPT in-space duty.¹³ Thruster design considered long life for later missions as a primary program goal. Contamination was studied with satellite mockup surfaces over the first half of the tests. Minimal differences were observed between exposed and control samples. Thrusters were tested for a pulse count of $2 \cdot 10^5$, at 1 Hz and 18.7 J pulse energy. Tests ran multiple days with the PPT shut down overnight. This procedure was adapted for the presented work. No failures or operation issues are reported.

Life testing to demonstrate mission life extension capability was performed for MightySat II.1, to prove operation stability and spacecraft compatibility.¹⁴ The intended mission cycle was 30-45 days at 2-3 Hz and an input power of 100 W. Potential issues in the order of concern are contamination, EMI and thermal loads. Aluminum housing and transformer shielding were used to filter EMI. Housing was not provided to the thruster in the work presented here. Components were tested separately to speed up the process. Capacitors were tested for more than $8.3 \cdot 10^6$ pulses. Thermal properties have been evaluated during a 7 hour full power demonstration. A drop of 3.2 percent in capacitor efficiency was reported with raising capacitor skin temperature.

At low pulse energy, testing requirements are tipped towards operation stability, since the electromagnetic pulse as the source of the EMI becomes significantly weaker. Stringent budgets for power, mass and dimensions govern design. Microthruster systems are still in their infancy. Although field effects are much reduced electrothermal, electrodynamic and hybrid¹⁵ PPT operation modes are pursued. Life testing is more accessible due to reduced efforts and short duty cycles, reducing pulse counts to a range between 10^4 - 10^5 . System simplicity, especially Teflon feeding, is much reduced. Reports show that higher sensitivity of the Teflon ablation process often leads to unstable thruster performance over the duty cycle.

In preparation for the FalconSAT-3 mission, micro-PPTs were tested to assess insufficient firing results

and spacecraft compatibility, i.e. solar panels and communication.³ Short test runs were limited to 5 minutes at a pulse rate of 2 *Hz*. Driving factor for the tests was AFRL customer satisfaction more than mission application. No failures or communication interference are reported.

Development at TMIT for the μ -Lab Sat II include operation of the Micro-iMPD-system TMIT-BBM at 3.6 *J* and 1 *Hz* for a pulse count of $5 \cdot 10^5$.⁹ Tests showed a sensitivity of the feeding and charring processes to pulse energy. This result suggests lower design margins for the energy distribution to ablation and acceleration processes. Operation below the energy limit of 3.6 *J* made proper Teflon feeding susceptible to instability and non-uniform ablation was reported as an issue. Electrode erosion was found to be severe for brass material. It was noted that the electrode hood for contamination and EMI-shielding can decrease thruster performance. Charring affected sustained thruster operation at a hood angle of 15 degree and below. Life cycles of 10^6 pulses have been reported up to date with an improved PPT-system called TMIT-B20.¹⁶

Continued development led to coaxial electrothermal PPT life testing without Teflon feeding at TMU.¹⁶ Stress testing revealed a duty cycle of $1.5 \cdot 10^4$ pulses at 10 *J* which was deemed insufficient. Ignition problems started occurring at about 10^4 pulses. Tests also revealed steady decrease of the achieved impulse bit due to the expanding discharge cavity diameter. EMI and contamination were not tested. Later electrothermal PPT tests at a higher energy of 75 *J* demonstrated a maximum impulse bit of 6.4 *mNs*. Sustained operation was demonstrated for a pulse count of $4.68 \cdot 10^5$, while impulse decrease over operation life remained an issue. Operation issues reported are failure of the capacitor and thruster isolation. Due to the high pulse energy and low specific impulse, high amounts of residual propellant contaminated the thruster and caused malfunctioning.¹⁷

Extensive EMC-testing of PPTs was reported in preparation for the ETS-IV satellite.¹⁸ Impulsive thruster noise was found to require countermeasures such as floating the thruster, shielding and installing filters to fulfill technical specifications. Compatibility was successfully evaluated. Preflight stress testing has not been reported but the PPTs were operated for $3 \cdot 10^5$ pulses in space at an energy of 2.27 *J*.¹⁹

At the Osaka Institute of Technology (OIT) a pulsed electrothermal microthruster similar to the TMIT design was endurance tested for the PROITERES mission, including a version with Teflon side feeding.¹⁵ An optimum cavity shape was determined in pretests with pulse counts of 10^4 at 1 *Hz* repetition rate and 2.43 *J*, as well as at 0.5 *Hz* and 8.8 *J*.²⁰ As with the TMIT PET, uneven ablation was found to cause performance and contamination issues. Dependence of this effect on the axial plasma density distribution was suggested, as the parameter for energy coupling into the propellant. Rapid decrease of the thruster impulse bit during the first 3000 pulses was also reported, acknowledging results found at TMU. A maximum pulse count of $5.3 \cdot 10^4$ was achieved for 2.43 *J* at 1 *Hz* sustained operation. It is interesting to note, that a multi-cavity design was proposed and tested to solve the issue of decreasing impulsed bit. It is noted here that this is suggested to increase thrust density and propellant utilization efficiency over the duty cycle. This would imply a great step towards increasing micro-PPT mission flexibility.

III. Pulsed Plasma Thrusters

Two PPTs were stress tested, which are presented here. They are part of ongoing propulsion system development for micro- and small satellites at IRS.^{6,21} The classification is presented elsewhere.²² Ultimately, system development is performed to operate all components inside a vacuum together with the thruster. For this, thruster testing is the first step to assess system environmental, functional and technical requirements. As was pointed out in literature, requirements can change dramatically during system development³, which is why this approach is also a precaution for system integration.

A. Working principle

The thruster design depends on the targeted acceleration mode, while the choice of the best acceleration mode depends on thruster pulse energy. Pulsed electrothermal acceleration is more suitable at low pulse energies to compensate for limitations of the generated pulsed fields and ionization degree. While best operated at high pulse energies, the magnetoplasmadynamic mode is less demanding on electrode geometry than on electric parameters. Schematic overviews of both thrusters show the differences in design (Fig. 1).

A PPT consist of only five parts: The capacitor bank, two copper electrodes, a block of solid polytetrafluoroethylene (PTFE) and an igniter. If present, propellant feeding is realized by a simple mechanic spring, being the only moving part. The difference of an electrothermal PPT is the coaxial electrode configuration

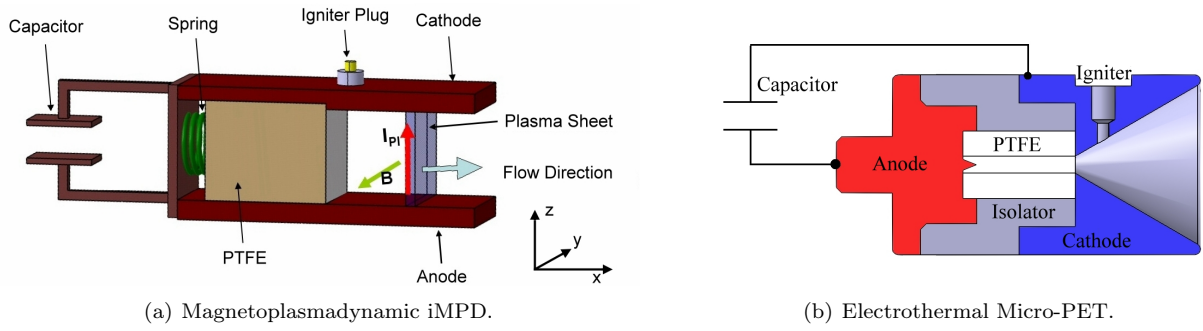


Figure 1. Schematic Overview of magnetoplasmadynamic and electrothermal PPTs.

(Fig. 1(b)), instead of parallel rails (Fig. 1(a)). The working principle of both operation modes is similar until acceleration of the propellant. The capacitor is charged to a voltage in preparation of a pulse. The igniter triggers controlled operation by injecting fast electrons into the interelectrode gap. Vaporization of electrode material creates a pressure increase over the PTFE surface until the Paschen condition is met for breakdown, starting the thruster pulse. A high current pulse driven by the capacitor runs over the PTFE-surface, ablating and partly ionizing it into a plasma. In magnetodynamic mode, ionized particles travelling through the current induced magnetic field, accelerate by means of the Lorentz force. The rail electrodes offer space for directing particles out of the thruster, limiting the plasma pressure and temperature. In electrothermal mode, neutral PTFE particles are ablated and heated in a narrow cylindrical discharge cavity. Acceleration occurs by gasdynamic forces, often with neglectable magnetodynamic force. The cathode is shaped into a supersonic nozzle, to support thermal expansion of the exhaust gas.

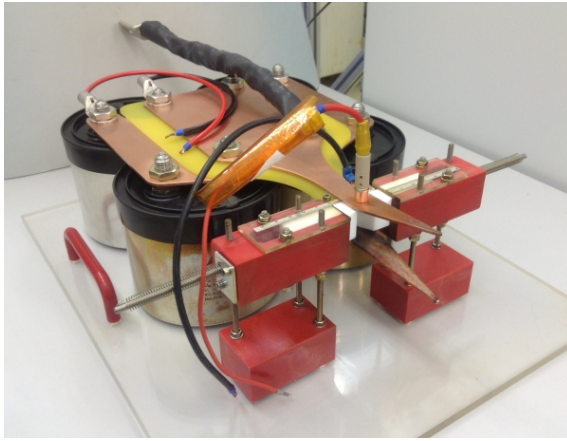
B. Thruster Specification

Technical specifications for the endurance testing of both thrusters are summarized in Table 1. One of the tested PPTs is the iMPD thruster "ADD SIMP-LEX", which is short for Advanced Stuttgart Pulsed Magnetoplasmadynamic Thruster for Lunar Exploration.

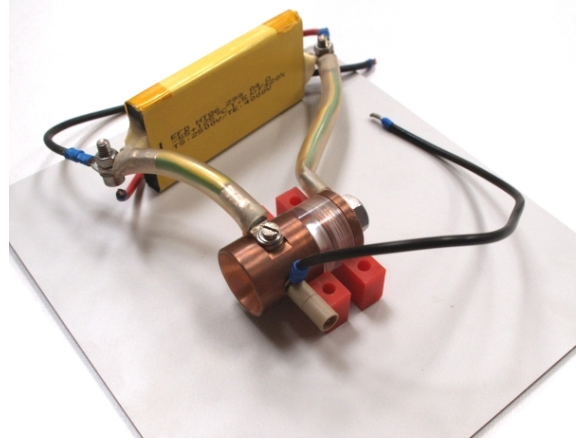
The second thruster is named PET1-DS for Pulsed Electrothermal Thruster. The number describes the model while the two letters stand for the nozzle type and electrode gap respectively. Both thrusters were operated with a ceramic igniter, originally designed for the PET1 and later adapted to be accommodated in both thrusters. The semiconductor material normally used for ADD SIMP-LEX failed due to sporadic misfire after about 3000 pulses into pretests. Since EMI was no testing goal, thrusters were operated without housing

Table 1. Experimental thruster parameters for endurance stress testing

Characteristics	ADD SIMP-EX	PET1-DS
Operation Mode	Magnetodynamic	Electrothermal
Pulse Energy, J	67.6	3
Capacitance, μ F	80	1.5
Charge Voltage, V	1300	2000
Igniter Voltage, V	1000	1000
Pulse Rate, Hz	1	0.5
Thruster Dry Weight, kg	6.5	0.49
Propellant Feeding	Yes	No
Input Power, W	80	2
Electrode Material	Copper	Copper
Electrode Gap, mm	21 x 20 (H x W)	2 x 20 ($\varnothing_{BOT}$ x L)



(a) ADD SIMP-LEX thruster.



(b) PET1-DS thruster.

Figure 2. IRS thruster setups at begin of testing (BOT).

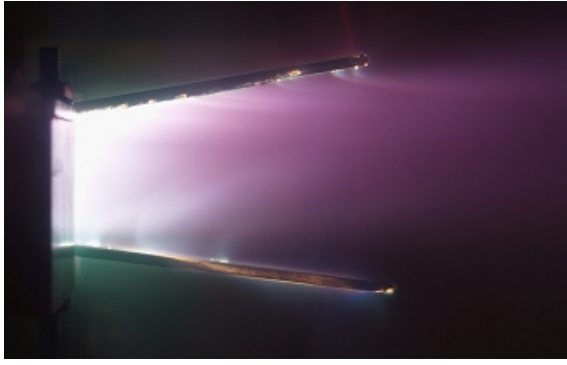
or electrode hood. It is noted here again, that a hood can impact thruster performance and contamination behavior.⁹ This will be investigated in future studies at IRS. Images of the thrusters in Fig. 2 show the configuration at the begin of testing (BOT).

The iMPD is driven by a bank of four capacitors. The electrodes are flared and tongue shaped. An isolation piece made of MACOR ceramic is placed behind the Teflon bars to shield the thruster from the plasma and provide an even background for the Teflon to run on. Its purpose is also to prevent unwanted deposition of residual propellant between the electrodes which could lead to malfunction. Pretests with less heat resistant high performance plastic shield materials resulted in thermal failure and deformation of the shield and eventually in thruster malfunction. The iMPD is equipped with a two barrel side-feeding mechanism (Fig. 2(a)) adjustable in all 6 degrees of freedom. Pull-springs push a ram against the back of a Teflon bar to apply a steady feeding force. The barrels are made of polyethylene (PE) and feature transparent lids with tape measures to survey propellant consumption. The springs and barrel length are designed to accommodate Teflon for about 10^6 pulses. The width and height of the bars are according to the gap dimensions given in Table 1.

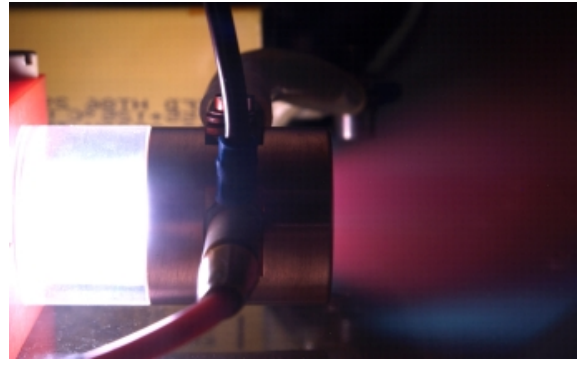
The PET design tested has not been subject to any optimization. It was chosen because of its easy handling and the possibility to remove and survey the state of the Teflon cylinder. A goal was to evaluate trends from characterization testing at IRS before implementing improvements. It was also intended to reproduce results and experiences reported in literature.^{16,20} The anode was formed into a sharp tip at one end of the discharge cavity, to focus electric field lines and support ignition and operation stability.

IV. Endurance Stress Testing

Two cylindric vacuum chambers were used to conduct endurance testing. Thrusters were placed inside and connected via vacuum tight feed throughs to the laboratory equipment. High voltage lines allowed for capacitor charging and igniter operation and were driven by breadboard level power processing units (PPUs) with 28 V input power. The ADD SIMP-LEX PPU was build by ASP. For PET-operation a self developed CubeSAT PPU has been used, which is described elsewhere.²¹ The ignition frequency was controlled by a Stanford DG535 trigger generator. Surface temperature was measured with type k thermocouples on the anode of ADD SIMP-LEX only. Due to the low pulse energy of 3 J and relatively large copper electrodes, thermal loads of the PET were considered noncritical and were not recorded at this point. Off the shelf calibrated thermocouple voltage transducers with a 3-way galvanic isolation were used to protect the data acquisition unit. Each chamber is equipped with a two stage rotary vane prepump and a turbomolecular pump with pumping capacities of 330 l/s and 80 l/s for the big and small chamber respectively. Chamber pressure was maintained below 10^{-4} mbar during sustained operation and monitored with Pfeiffer PKR-251 gauges. Thrusters were shut down overnight and grounded at the cathode inside the chamber for safety reasons. The igniter tip ohmic resistance was checked during tests to survey contamination effects. It remained infinite



(a) ADD SIMP-LEX discharge plasma (cathode top electrode).



(b) PET discharge plasma.

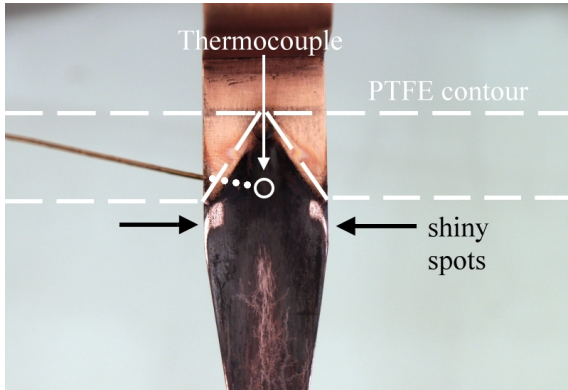
Figure 3. Integral DSLR-camera images of the thruster discharge plasma (flow from left to right).

regardless of contamination. Capacitor health was checked by means of an Phillips RLC-meter at 1 kHz frequency. Images of the PPTs during operation are shown in Fig. 3.

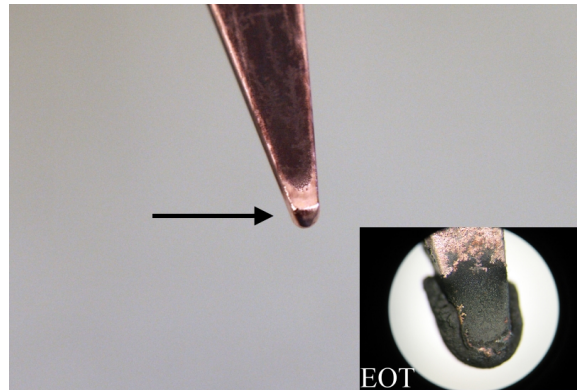
A. ADD SIMP-LEX Operation

No failures or critical misbehavior were detected over a full 10^6 discharge pulses stress test. However, several observations suggest improvement of the thrusters components to increase operation stability.

Total eroded electrode mass was below the detection threshold. During testing visible erosion was limited to two anode locations, one near the Teflon bars (Fig. 4(a)) and the other one at the tip (Fig. 4(b)) until 10^5 pulses. Later into the test the visible locations got gradually covered by depositions as well.



(a) Anode from above with traces of erosion.



(b) Rounded anode tip and tip covered with carbon deposition at end of testing (EOT).

Figure 4. Locations of visible erosion during stress testing after $5 \cdot 10^4$ pulses.

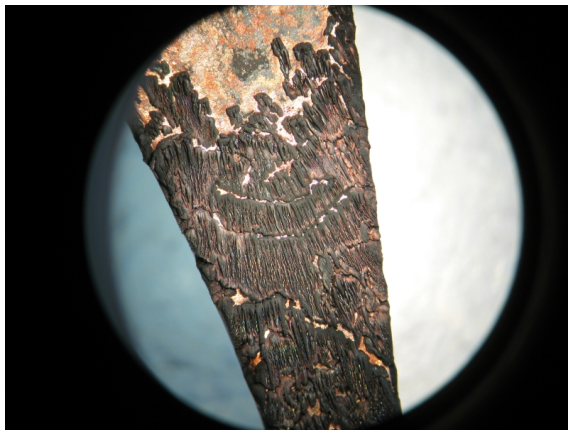
Residual Teflon propellant was observed on electrode surfaces but did not inhibit thruster operation. Electrode erosion can decrease in the presence of protecting layers that shield particle bombardment, especially during discharge initiation. A balance of deposition and erosion could extend the duty cycle. Teflon consists of carbon and fluorine, of which carbon builds up structured surface layers. These layers are electrically conducting but reduce the effective copper surface area for the discharge. The backflow of particles from a plasma is increased for areas of decreased plasma temperature and density. The surface layer pattern therefore holds information on plasma to surface interactions. Electrode conditions in the discharge channel at EOT are compared in Fig. 5.

Contamination is more severe on the cathode and concentrates in a region in the middle of the tongue (Fig. 6). This suggests this region to be less subject to particle bombardment and more to particle backflow from the plasma. The area near the Teflon is kept clean by the discharge current, while the tip region collects

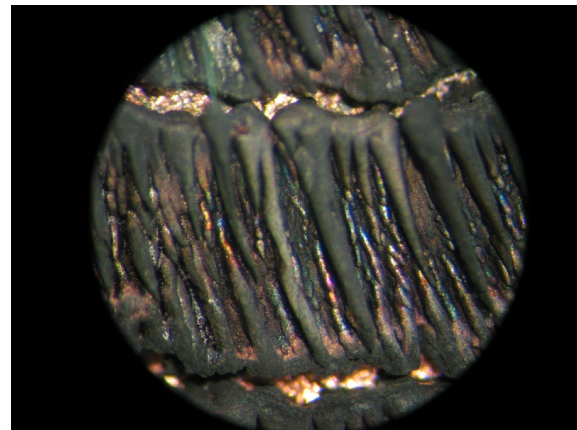


Figure 5. Cathode (left) and anode (right) depositions (top) and erosion (bottom) at the end of testing (EOT).

particles following the concentrated electric field lines. In Fig. 5 top left, a deposition trace originates at the lower right igniter and progresses to the lower edge of the middle contamination region. This trace was caused by the wake of a one sided arc attachment on the Teflon, deforming the discharge channel over time. This may lead to thrust vector misalignment.



(a) Image 6x magnified.



(b) Image 20x magnified.

Figure 6. Microscope images of cathode tongue middle region depositions.

The observation is mirrored by the contamination pattern on the anode. Here, depositions are minimal and confined to the rim of the electrode. The surface is covered with delicate ramifications, suggesting more even utilization. Less severe deposition might also be caused by the higher anode surface temperature, compared to the cathode as well as less overall and more uniform particle bombardment and interactions. Camera images support this assumption by showing more emission, i.e. heavy particle interaction, over a pulse near the initial cathode (Fig. 3(a)). This also supports the idea of a particle stream with temporally varying deviation originating from an emitting current zone near the Teflon, rather than a current sheet moving downstream. The implication in terms of acceleration would be to optimize a thruster for fast transition to the optimum particle stream deflection and to maximize the duration of this condition.

To assess the electrode erosion pattern, the electrodes were cleaned (Fig. 5 bottom) at EOT. The relief shows erosion areas dark against the electrode surface. In Fig. 5 bottom left, the igniter wake mentioned before is now clearly visible. In the tongue middle region, the formerly covered copper surface is unchanged as expected. However, diversion of the current to uncovered copper has created trench-like formations perpendicular to the flow direction (compare Fig. 6). It was concluded, that shortening of the electrode length would help to contain layer deposition and trench erosion. Less heavy particle interaction could also improve thruster performance. What is also needed is more information on the dependence of layer buildup

on the pulse energy, especially in terms of throttability.

The thruster condition was checked in predefined pulse count intervals or in case of observations, by interrupting the operation and taking the thruster temporarily out of the vacuum chamber. The iMPD was operated for a maximum of 10 hours per day. The Teflon ablation characteristic for side-feeding demonstration was documented by camera images. A total of 70 g of Teflon were used. Measurement of the mass bit was done for the first pair of propellant bars. The thruster was taken out of the chamber at 522000 pulses to replace the consumed Teflon bars, earlier than intended by design. Data from parameter investigations at IRS showed a mass bit of $53.4 \mu\text{g}$ per pulse for ADD SIMP-LEX. Analysis of the mass bit data of the endurance test however revealed higher ablation (Fig. 7).

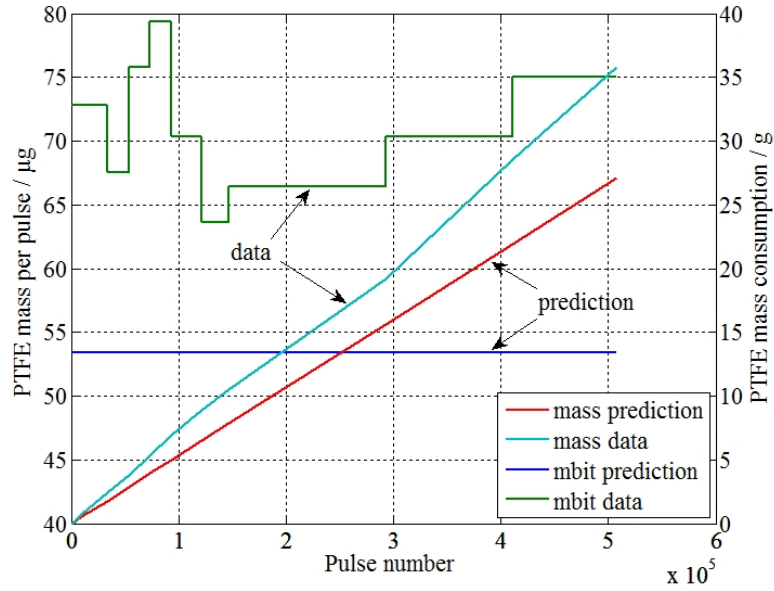


Figure 7. Comparison of predicted and measured mass bit and mass consumption for the first set of PTFE bars.

The highest measured mass bit surpassed the prediction by almost 50 percent, leading to increased PTFE consumption. After 507000 pulses, this had led to an excess consumption of 32 percent, or 8.69 g of Teflon. For the following 15000 pulses until bar replacement, sporadic misfire at a rate of 1 in 100 pulses was observed. Investigation of the discharge channel showed unusual carbon deposition and shape of the channel. The reason was found to be insufficient Teflon bar alignment by the barrel leading to thermal deformation of the remaining bar tip (Fig. 8). As a result, less length of a Teflon bar was available for consumption until replacement was needed. The second pair of Teflon bars for test continuation was manufactured to fit tighter into the barrel to improve bar alignment.

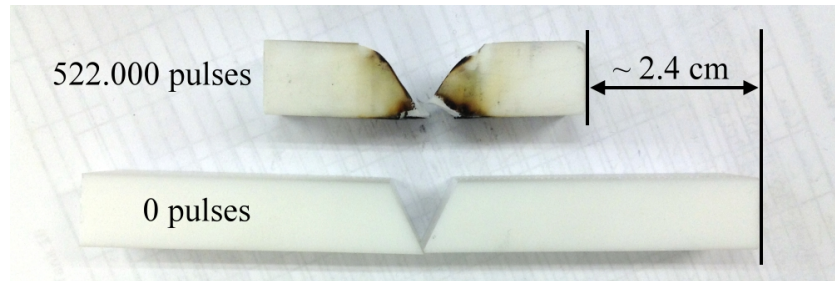


Figure 8. Comparison of used up and new set of PTFE bars for endurance testing representing an equivalent total impulse of 717 Ns in cold thruster mode.

This data supports the notion of a cold and a hot thruster thermal operation mode. Consequently, the thermal transition of modes coexists with the non-thermal transition to the stable shape of the discharge

channel due to ablation. At IRS, thrust measurements with an impulse pendulum first suggested a thermal transistion behavior. For an anode temperature increase of 50 K, an increase of impulse bit of the thruster of at least 15 percent was measured. It is therefore noted here, that there is strong indication the hot operation mode leads to improved thruster performance in terms of thrust and possibly efficiency. No reference in literature to adress this issue is available. To assess the duration of the thermal transition, the temperature at the bottom of the thruster anode was measured by a type k thermocouple (Fig. 4(a)). Measurements are presented in Fig. 9. The data shows, that thermal loads are well within tolerable limits, even under sustained operation. However, the achieved temperature end value varied between test runs. Two temperature records show the observed low and high value limits (Fig. 9). Also the slope at the end of test operation indicates are thermal equilibrium was not completely reached, suggesting that thruster performance parameters could change, however less severe, even beyond this operation point.

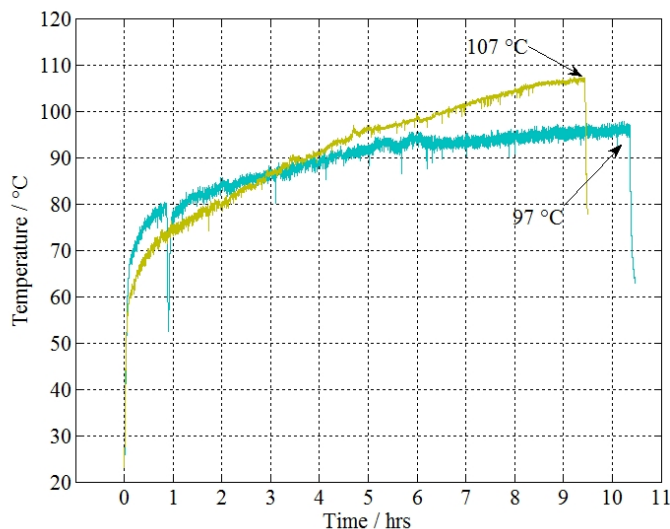


Figure 9. Anode temperature during sustained thruster operation for lowest and highest end value.

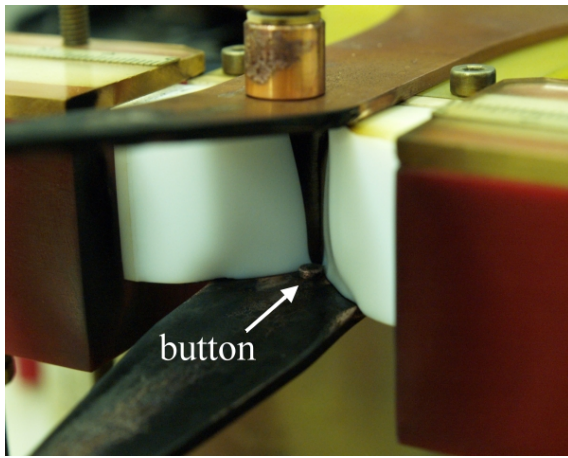
The variation of mass bit data in Fig. 7 is not explained by the measurement error and standard deviation alone, thus hints towards instabilities of the PTFE side feeding process and arc attachment. Ideally, feeding is continuous and equal for both side feeding directions. Higher variations are only expected during the discharge channel transition process at BOT. For the first pair of Teflon bars, sides were evenly consumed, with a fraction to overall consumption of 48 percent and 52 percent ablated from the left and right bar in Fig. 8 respectively. To investigate instabilities linked to the data in Fig. 7, camera images were taken of the discharge channel and the installed Teflon bars. The feeding progress for the first Teflon bar pair is shown in Fig. 10.

Feeding of the Teflon bars was first observed after 73000 pulses (compare Fig. 10). The motion was perceived as a discrete forward leap of the bar over relatively few pulses. These leaps occurred symmetrically on both sides. A second leap occurred after 147000 pulses. Feeding continued to leap until 411000 pulses, when continuous feeding at increasing mass bit set in (compare Fig. 7). It is assumed that in the event of a leap the mass bit rapidly increases due to the relatively sudden narrowing of the discharge channel. This could cause periodic fluctuations in the thruster performance.

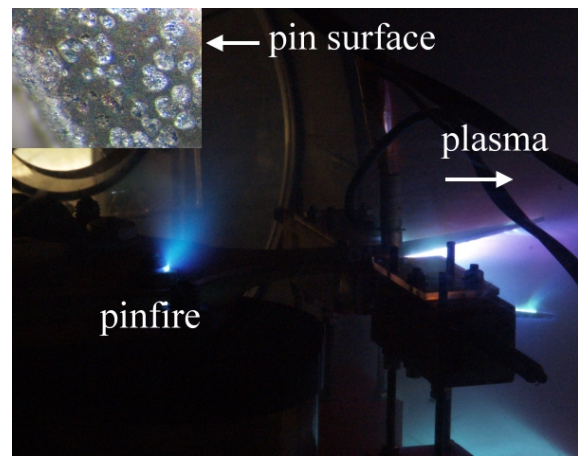
One of the reasons identified was the ability of the bars to get in contact with each other in the discharge channel. To ease feeding, the shoulder for the Teflon to rest against had been reduced to a small button on the anode. This turned out to have an converse effect, preventing proper ablation near the button and causing leaps (Fig. 11(a)). After a leap, the Teflon bars would push and melt together, causing instability of the feeding. As a result, a horizontal shoulder in the ceramic shield has been introduced into the design after the endurance testing. It is noted here, that up until a leap, the shape of the discharge channel agrees well with the findings at RIAME MAI.¹²



Figure 10. Anode temperature during sustained thruster operation for lowest and highest end value.



(a) Teflon resting shoulder button on the anode with Teflon bars after 93000 pulses.



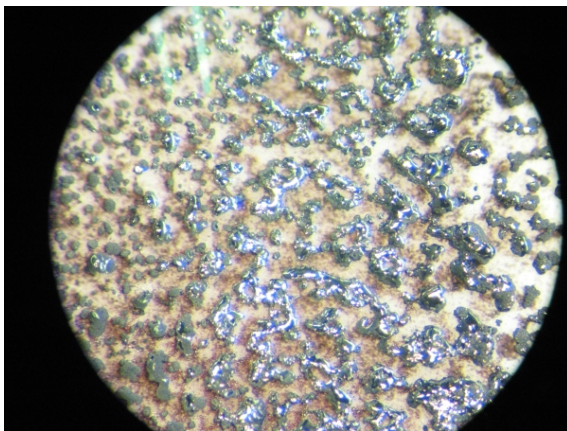
(b) Corona discharge "pinfire" during thruster operation after 205000 pulses.

Figure 11. ADD SIMP-LEX observations during operation.

In Fig. 10, the pulse count is given on the left Teflon bar, whereas the addition of pulses between images is given on the cathode. Also visible is the development of a carbon layer on the cathode created by a plasma vortex around the edges of the open electrodes. After 205000 pulses, corona discharges were observed on the forward capacitor terminals. Microscope images revealed a high impact crater density on the cathode capacitor terminals (compare Fig. 11(b)). The corona was created by bombardment with highly energetic particles that followed the electric field outside of the discharge channel towards the capacitor pins. Melting of the pin material creates a local pressure increase developing into a corona discharge. After these observations, the thruster was insulated with capton-foil, to eliminate direct particle impacts. During follow up checks small traces of carbon deposition were found on the capton foil covering the capacitor, but the shield proved effective.

All components of the ADD SIMP-LEX thruster as well as the facility were examined for their condition at EOT. Deposition with residual propellant on the test chamber walls around the thruster was extensive. Besides the flourine and carbon layer, dustlike macro particles were also found in small quantities, suggesting macro particle ejection from the thruster or accumulation of depositions around dust neclei that remained in the chamber during testing as cause.

A metallic gloss was noticed on some areas of the chamber wall and window in front of the thruster. After inspection of the thruster contamination shield behind the Teflon bars, failure of the MACOR-material was



(a) Microscope image of the MACOR shield surface (Image 20x magnified).



(b) Surface deposition on anode (left) and cathode (right) in PKR-251 cold cathode vacuum meter.

Figure 12. Investigation of test chamber and iMPD-thruster condition at the end of testing (EOT).

identified as the cause. MACOR is a glass-ceramic material that remains stable up to 1000 °C, avoiding outgassing and porosity. A microscope image of the block surface reveals accumulations of metallic depositions (Fig. 12(a)). It is assumed that the combined thermal and chemical load has destabilized and activated the MACOR surface, suggesting considerable loads. Traces of depositions as well as erosion are visible on the surface relief. Metallic gloss is likely to originate from metallic components of the MACOR, i.e. Mg, Al, K, B, Si. As a result, the material of the contamination shield will be changed.

Towards EOT, increasing inaccuracy and misreadings of the vacuum meter connected to the chamber was noticed. Maintenance of the meter showed unexpected amounts of deposition on the penning-element (Fig. 12(b)). The deposition prevented accurate readings rendering the meter moot. It is therefore suggested to use protection valves that can be closed after the testing background pressure has been confirmed.

B. PET1-DS Operation

The goals of PET sustained operation were to test the duty cycle. Assessment of the achievable pulse number and ablation behavior are the first steps to address the misfire and ablation issues with a coaxial non-feeding thruster configuration reported in literature.¹⁶ Performance data of the PET1-DS used in the test has been presented elsewhere.²¹ Performance change was not monitored and will be the subject of future investigations. Since expected pulse counts are below 10^5 and current PET-design parameters are still preliminary, the basis for performance optimization will be an improved thruster design emerging from the presented work. This will also feature modifications to the igniter and nozzle geometry.

The sustained operation testing was concluded after a total of 40664 pulses, after which the thruster became inoperable. Teflon for at least double this amount remained unused. None of the thruster components showed any signs of damage. Misfire was observed in intervals of 1000 to 2000 pulses. When occurring, the misfire lasted for up to 20 pulses, after which normal operation resumed. It is noted here, that the igniter was confirmed working without failure over the entire test cycle, including when the thruster became inoperable at EOT. The cause of the misfire and the failure at EOT is not clear. In both cases thruster ignition is suspended despite normal igniter spark generation. The recurring interval suggests a thermal issue, that resolves over the operation interrupt. A parameter for successful ignition is the roughness of the cylindrical Teflon surface of the discharge channel. Increasing deposition and nonuniform ablation could impede the electron hopping process or weaken the mechanical contact between the Teflon and the electrodes creating a higher surface resistance. Also, igniter positioning might play a role in this issue, which was outside of the discharge channel in the cathode.

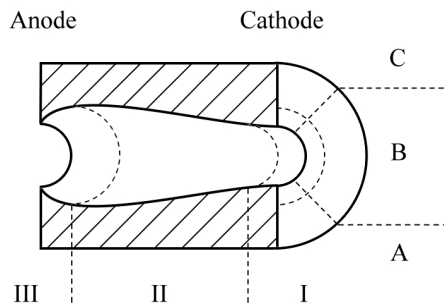


Figure 13. Section through Teflon cylinder with schematic overview of deposition quadrants.

For better visualization, the interior of the PET Teflon cylinder has been divided into quadrants (Fig. 13). Sections I to III indicate length quadrants, while sections A to C indicate angular quadrants. The inner shape of the Teflon cylinder qualitatively reflects the shape of the discharge cavity at EOT. A tendency to higher ablation near the anode has been observed, with the maximum diameter located at the intersection between quadrant II and III about 3 mm away from the anode. The cathode hole diameter at EOT had increased to 6 mm compared to the anode hole diameter of 5 mm. In quadrants I and III, carbon deposition was detected along the complete circumference, with less intensity in quadrant B. This trend was extreme for quadrant II, where almost all of the deposition was concentrated on the sections A and C, while B remained almost completely clean (Fig. 14). Also presented is the comparison of the Teflon cavity diameter at BOT ($\varnothing_{BOT} = 2 \text{ mm}$) and EOT ($\varnothing_{EOT} = 6 \text{ mm}$) in the left hand image, showing the Teflon mass margins of unused material at EOT.

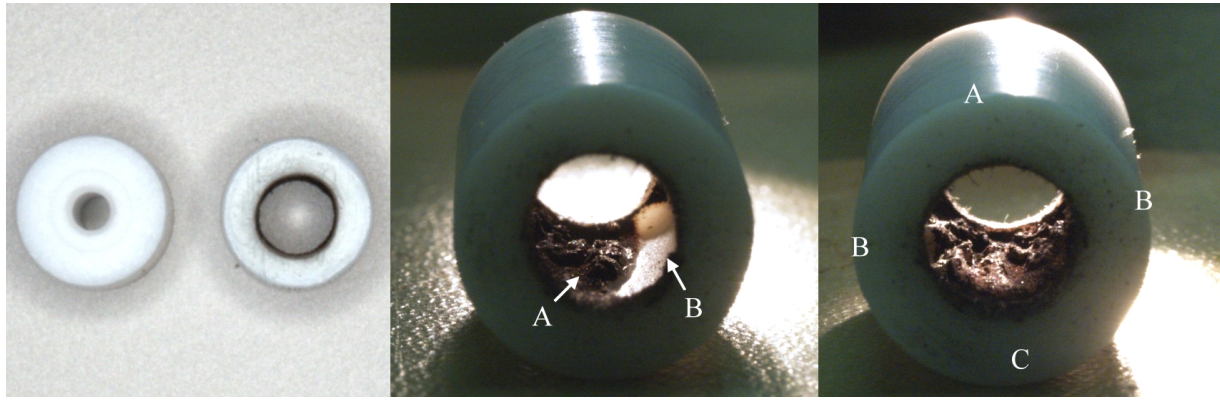
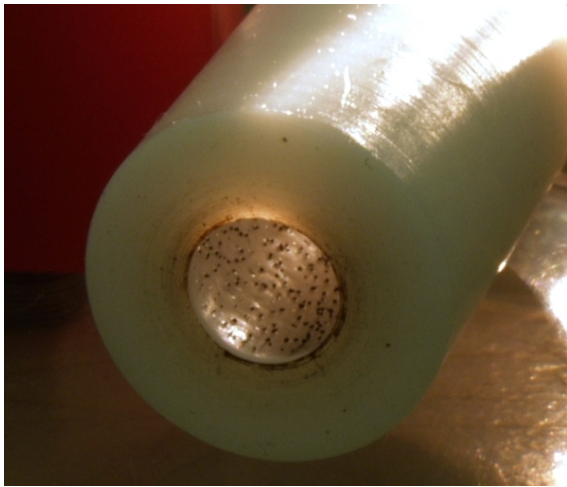


Figure 14. Camera images of the Teflon cylinder at end of testing (EOT) after 40664 pulses.

Strongest changes of surface and deposition over the test time occurred in section II. The transition to a full coverage of carbon was observed to start by point-shaped accumulations on the Teflon surface (Fig. 15). These point accumulations quickly change into dome-like structures that erupt from the surface. Structure growth then leads to wake formation on the surface facilitating merging of the separate structures into a full carpet layer of carbon deposition.



(a) Carbon nuclei accumulations on Teflon after 5600 pulses.



(b) Carbon dome deposition growth after 11000 pulses for transition to full carpet layer coverage.

Figure 15. Investigation of carbon deposition build-up processes in a Teflon cylinder for sustained pulsed electrothermal thruster operation.

Full carpet layer deposition state was reached after about 30000 pulses in quadrants A and C spanning the entire cavity length from I to III. No electrode erosion was detected due to the comparably low pulse count. The overall pulse count demonstrated in the duration test is insufficient for mission applications. Therefore, design changes are required especially to eliminate the interval misfire as well as to increase the life cycle. Improvements include geometric design changes of the cathode and anode shape, as well as reiteration of the igniter mounting position. Ignition inside of the discharge channel is assumed to have a positive effect on ignition success. Teflon cylinder shape design can help to either prevent carpet development inside of the cavity. A challenge however is the increase of cavity diameter which has a direct effect on plasma density via the energy per Teflon surface ratio. This impacts energy coupling and eventually propellant acceleration. It is assumed, that the formation of deposition in the cavity might act in a way to keep the energy to Teflon surface ratio constant or at least to counteract its decrease. The introduction of a convergent divergent nozzle will also be investigated at IRS in future studies.

V. Conclusion

Endurance stress tests were performed successfully on two pulsed plasma thruster at IRS to facilitate system design. Results for the iMPD ADD SIMP-LEX suggest improvements to electrode design and Teflon side-feeding. A strong sensitivity of side feeding to correct alignment and separation of the Teflon bars requires careful design of the thruster head and precise tension-free manufacturing, even for less demanding missions. Laboratory equipment and the thruster igniter performed without failure. Development in these areas will be focussed more towards efficiency optimization and miniaturization in the future. Observation of the carbon deposition pattern on electrodes supports doubts with regard to the traditional perception of the thruster working principle in terms of a moving current sheet. Depositions implicated higher heavy particle activity near the thruster cathode with implications for the thrust vector optimization.

A hot and cold thruster operation mode was suggested with impacts on thruster performance. Two transition processes have been discussed, a thermal transition as well as an ablation driven discharge channel formation. Very little data is available on their duration and impact parameters suggesting further investigation. Especially interesting yet challenging would be the measurement of the hot mass and impulse bit. Operation at pulse frequencies beyond 1 Hz, as reported by RIAME MAI,¹² are considered with care, since confirmation of the thermal stability of the contamination shield is needed. The most likely material for this is Aluminum oxide, which is stable up to 2000 °C. A negative effect of prolonged testing on a vacuum gauge was pointed out, recommending protectional measures. No detrimental effects on thrust performance are expected from the suggested improvements to thruster operation stability. It is noted, that testing beyond a duration of 10 hrs is needed to confirm thermal equilibrium and confirm propellant feeding, since the effect of repeated heating transitions on ablation characteristics and discharge channel variation is unknown.

The PET testing complemented parallel development of the thruster igniter and nozzle. Endurance testing results suggested improvements to the contact sections of the electrodes with the Teflon cylinder as well as Teflon cavity stabilization. The presented work is part of the setup of a more refined electrothermal thruster as the basis for future performance optimization. Investigation of the deposition build-up as a function of energy to the available clean Teflon surface was suggested, to develop ways to incorporate countermeasures into the thruster design. However, change of the discharge cavity by increase of its diameter is a challenging parameter for thruster operation stability. The causes for observed recurring misfire and the eventual failure of the thruster are unknown. No indication of failure of any component of the thruster was detected at EOT. The effect of increasing capacitor and igniter voltage as a possible countermeasure will be subject to future investigations at IRS.

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