Progress and Developments of Open Source Electric Propulsion for Nanosats and Picosats at Applied Ion Systems

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I. Introduction

With the advent of nanosats and picosats such as Cubesats and PocketQubes, as well as the increase of satellite launch opportunities to LEO and decreasing price of launch, space and satellite technology has never been more accessible. In particular, Cubesats have gained rapid acceptance in the field as low-cost and powerful tools for research, education, and new space startups. In more recent years, the fast-growing PocketQube community has also helped further reduce the cost and barrier of entry to space, opening unprecedented access to satellite building and LEO missions for numerous educational and enthusiast groups around the world.

These developments have also been accompanied with increasingly open initiatives in the communities that drive them. From open source ground stations and satellite tracking, to simulation software, Cubesat and PocketQube hardware simulation platforms, and open source satellite designs, the barriers of entry into satellite technology has significantly progressed in the last decade. Full satellites with power, solar, communications, and basic payloads can be built for as little as a few thousand dollars, with ride-share and dedicated deployers for these satellites at several tens of thousands of dollars. Despite these major advances, there are several technologies that have remained out of reach for most nanosats and picosats due to the extremely high barrier of entry. One of these major technologies includes electric propulsion systems.

Electric propulsion (EP) is an expansive and diverse multidisciplinary field of propulsion technologies that leverage electrical heating and acceleration of fuel rather than chemical combustion. Due to the physics of operation, while thrust is very low, on the order of micronewtons to millinewtons, efficiency is very high, allowing satellites to operate with significantly less onboard fuel. In most cases, fuel for EP is inherently inert and safe, reducing further risks involved with combustible or explosive chemical fuels. However, despite the numerous advances over the decades in the field, cost and accessibility of propulsion has remained prohibitive for lower funded educational, startup, and enthusiast groups. With current trends in research initiatives and funding models for propulsion development, there is currently no market incentive to pursue low-cost simplified propulsion solutions outside of those for critical defense, military, space-agency, and major corporations for the new wave of Cubesat and PocketQube builders. Due to the nature of development, technical aspects of these thrusters remain closely guarded secrets by companies developing them, or restricted to limited information published in academic papers. In addition, since EP requires vacuum infrastructure for testing, the barriers of entry remain further higher with the need of specialized knowledge and expertise in vacuum engineering, as well as access to vacuum chambers and technology.

Applied Ion Systems (AIS) is working to radically lower the barrier of entry for these propulsion technologies. AIS started as a DIY hobby effort, rapidly growing as the first and currently only maker-based fully independent open-source R&D program for the development of EP for nanosats and picosats, and as currently a one-man propulsion development company, supported and funded through enthusiasts around the world. Through open source development of these EP systems, as well as closely working with and engaging the Cubesat and PocketQube communities, AIS aims to make EP technologies more accessible and affordable for any nanosat and picosat team, and show that such advanced technologies can be developed at a small fraction of a cost than conventionally done in research and academia, and providing propulsion builds at an order of magnitude and greater cost reduction compared with current systems on the market. AIS produces open-source thruster designs, as well as full build details, documentation, live thruster testing, and educational resources for the community, allowing for an unprecedented look at the development of complete propulsion systems, from initial sketches to end-of-life testing. The work through AIS has already generated numerous fully integrated micro-EP system designs compatible to the power and size constraints down to PocketQube class satellites, several of which are already on their way to being flown aboard satellite platforms in LEO, as well leading a new wave of unconventional development of EP systems at a hobbyist level budget.

II. Pulsed Plasma Thrusters

Since the successful firing of a pulsed plasma thruster aboard the Zond 2 in the 1960s, marking the first use of EP in space, pulsed plasma thrusters (PPTs) have enjoyed significant study throughout the decades. PPTs are fundamentally one of the simplest and lowest cost forms of electric propulsion, and being one of the few EP technologies that can inherently leverage scaling to extremely small and low-power systems, this makes them ideal for low-cost, entry-level, robust thrusters for both main propulsion and attitude control systems at the nanosat scale.

PPTs are a form of pulsed ablative thruster, with several stages of operation. In its most basic form, a PPT consists of just three electrodes and a fuel source, most commonly in the form of solid Teflon blocks. A capacitor is charged up to several thousand volts between the anode and cathode electrodes, with the Teflon fuel block between the two electrodes. Discharge is initiated by a third trigger electrode, situated near the Teflon fuel surface and the cathode, which sends a high voltage, low-energy arc between the trigger and the cathode. This initial pulse partially ablates and ionizes the Teflon surface, causing a plume of ionized gas to expand between the anode and cathode inside the discharge chamber. This expanding ionized gas eventually bridges the gap between the anode and cathode, allowing the main capacitor to conduct and discharge through the plasma, dumping its energy, which further ablates and ionizes more fuel, and accelerates the plasma out the exit of the thruster via electromagnetic and electrothermal forces. This exhaust of plasma generates thrust, which acts on the satellite. Each pulse lasts for a brief period, on the order of several microseconds, at repetition rates on the order of a few pulses per second.

Despite its simplicity and relatively low cost, PPT development and available systems on the market still tracks with that of other EP systems, making them largely too expensive for most teams. However, PPTs are physically simple to construct, with the drive circuit being analogous to flash camera circuitry, where the xenon flash bulb is replaced with the PPT. Due to its simplicity and low-cost nature, PPTs represent a large bulk of development at AIS, covering a range of thruster prototypes to fully integrated systems with the thruster and electronics embedded together in a single package. Currently, there have been two completed PPT systems designed and operated at through AIS to date, built off of several initial stand-alone prototype thrusters. These systems are orders of magnitude cheaper to build, with off-the-shelf components and simple construction, allowing any nanosat team or educational lab to explore PPT technology as a simplified, entry-level thruster.

The initial motivation for PPT development at AIS was to design a simple, low-cost PPT that could fit aboard a 1P PocketQube. Having only a volume of 5x5x5cm, this creates significant constraints on size for the thruster. In order to minimize depth of the thruster into the PocketQube body, an unconventional flat-stacked topology was leveraged, allowing for depth to be minimized and construction simplified, at the cost of lower fuel capacity. The flat stacked geometry became the gPPT series, starting with the first gPPT1 prototype.

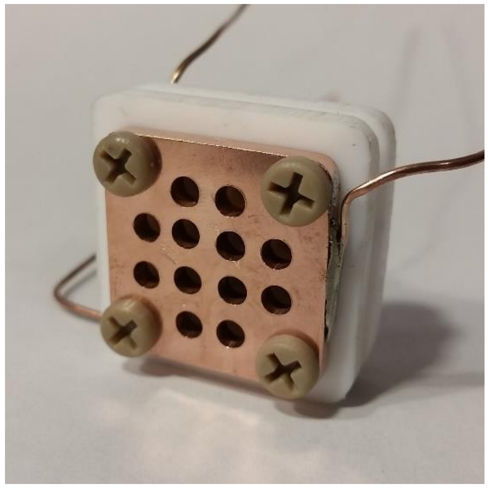

Figure 1: AIS-gPPT1 thruster assembly

The thruster itself consists of several flat plates of copper and Teflon, serving as the electrodes, insulators, and fuel. The gPPT1 was made with multiple discharge channels to increase useable lifetime. The bottom plate with soldered pins connected to the trigger supply, with the middle plate serving as the cathode, and the top plate as the anode. The bottom Teflon plate functioned as an insulator between the igniter and cathode, and the top Teflon plate as the fuel. Nonconductive PEEK bolts are used to hold the thruster together.

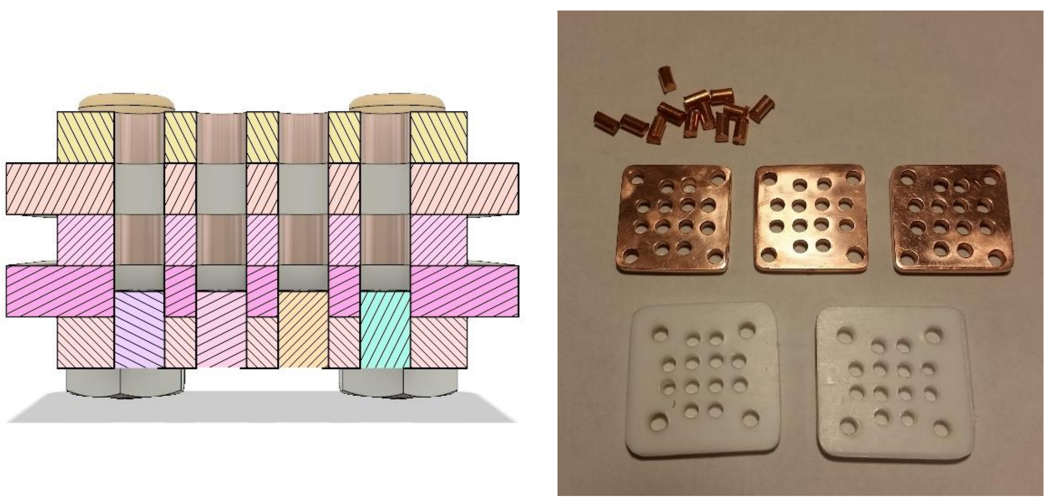

Figure 2: gPPT1 cross-section (left), fuel/insulator/electrode plates (right)

The thruster was operated with an external HV power supply, capacitor, and thyratron trigger pulser. The thruster was only succesfully fired once due to the excessive spacing between the trigger pins and cathode, however this initial test paved the road for additional testing and developments of micro-PPTs at AIS.

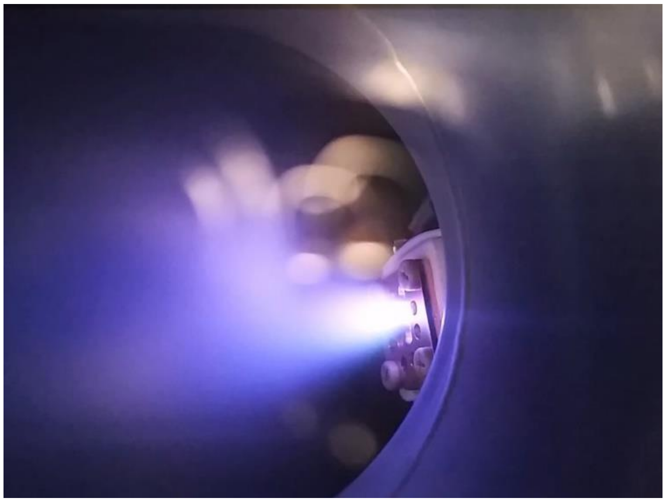

Figure 3: gPPT1 firing in high vacuum

Taking lessons learned from the gPPT1, a simplified version was designed, the AIS-gPPT2-1C, which leveraged a single discharge channel, significantly reducing size, mass, and making it more useable at the PocketQube scale. The total thruster volume was less than 1.5x1.5x1.5cm.

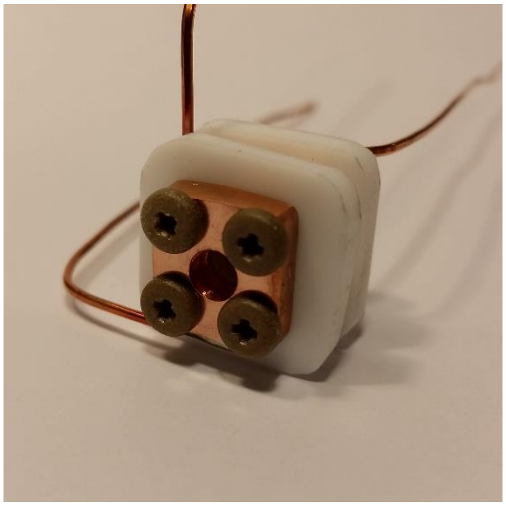

Figure 4: AIS-gPPT2-1C thruster assembly

Like the gPPT1, the gPPT2 follows the same stacked geometry. However, in this case, the cathode is reversed to the bottom plate, and the igniter was made as the center plate, to allow for simplified connection for future integration with a dedicated PCB. In additon, the cathode pin, soldered to the bottom cathode plate, extends up into the igniter plate bore, significantly reducing distance between the cathode and ignitier to make ignition more reliable.

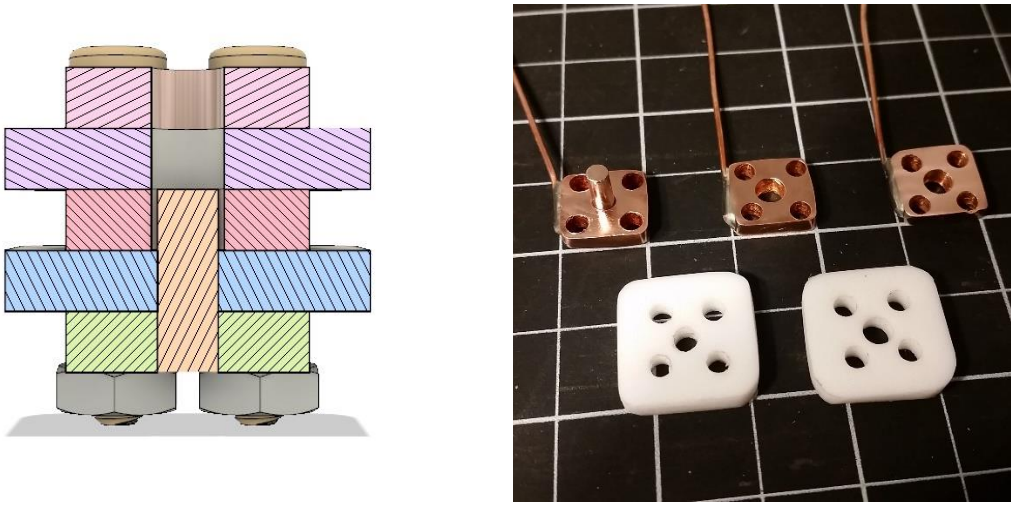

Figure 5: gPPT2 thruster cross-section (left), fuel/insulator/electrode plates (right)

The thruster was fired using the same external supplies, however to a significantly higher degree of success. A 1uF capacitor charged up to 1500V was used. The thruster was able to operate at repetition rates up to 2Hz, for a total of around 400 shots before charring of the Teflon fuel caused shorting.

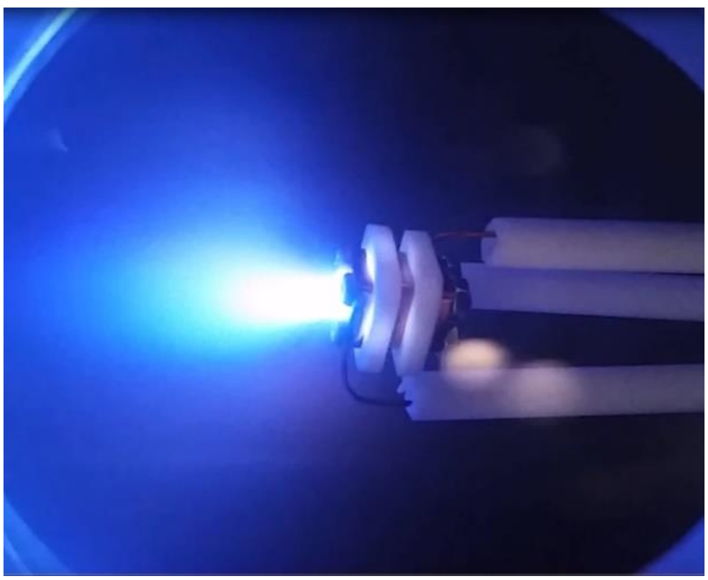

Figure 6: gPPT2 firing in high vacuum

Thrust measurements were conducted using a simple micro-pendulum with fine wire and a small Kapton head. The pendulum body was made from scrap Teflon sheet bolted together and slid into the chamber. A pendulum stop made from several wires was used for setting the pendulum back to the same starting point for each firing. By knowing the mass of the pendulum, as well as the length and deflection, estimates of thrust can be found. Measurements on micro-pendulum yielded thrust levels around 1-2uN thrust.

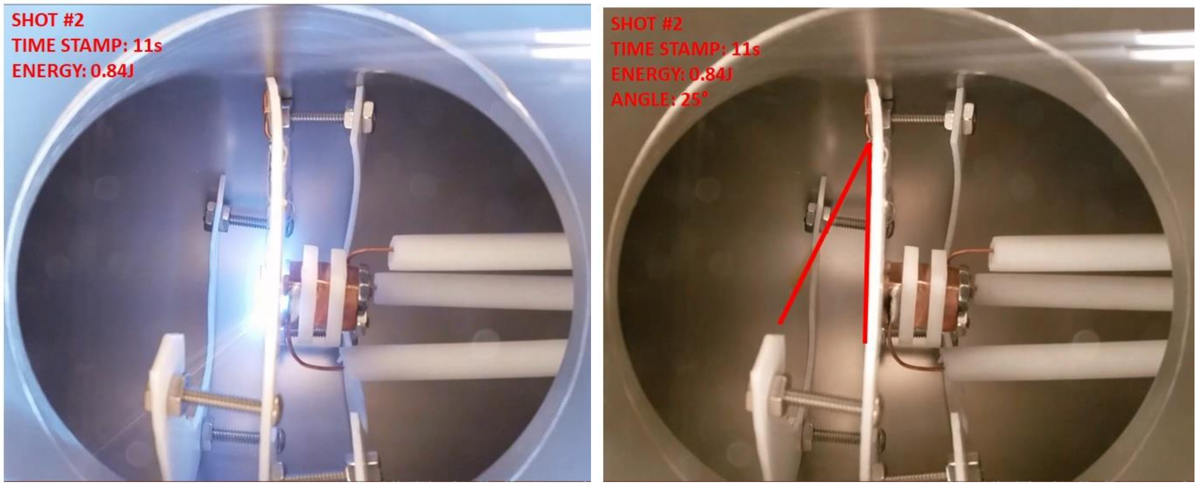

Figure 7: Thrust analysis using video captures of a micro-pendulum deflection. Plasma plume interacton with the pendulum head (left), resulting peak deflection (right).

The next iteration, the AIS-gPPT3-1C builds off of prior tested concepts of miniaturizing PPT technology to an extreme level, utilizing the same flat-stacked plate geometry and coaxial electrode configuration with several improvements and direct integration to electronics. This thruster was the first of the gPPT series that was CNC machined for higher precision. The first plate is the cathode, held to 0V, which interfaces directly to the thruster PCB. A Teflon insulator plate separates the cathode and igniter plate. A thicker Teflon fuel plate with a narrow bore is placed between the middle igniter plate and the upper anode to increase total useable fuel. The anode plate included tapped holes to eliminate the extra nuts for assembly. Due to its coaxial geometry and operation at sub-Joule energy levels, electrothermal forces of acceleration are dominant, which can be further improved with a magnetic nozzle. A small neodymium ring magnet is embedded into the anode in a routed channel to further concentrate and accelerate the plasma out the thruster.

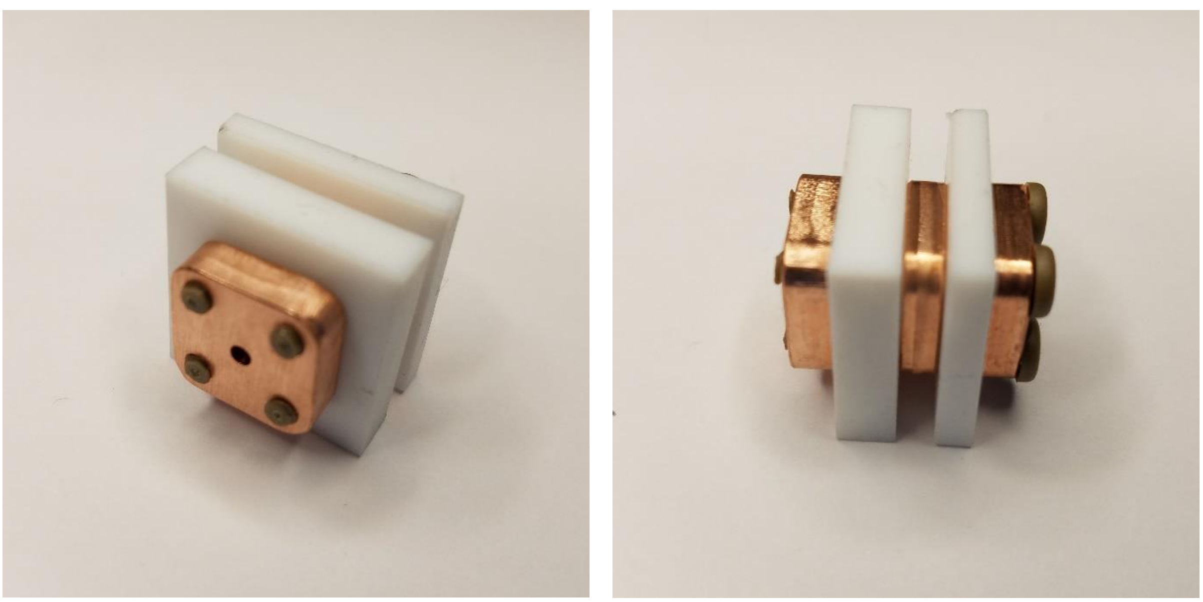

Figure 8: AIS-gPPT3-1C thruster assembly

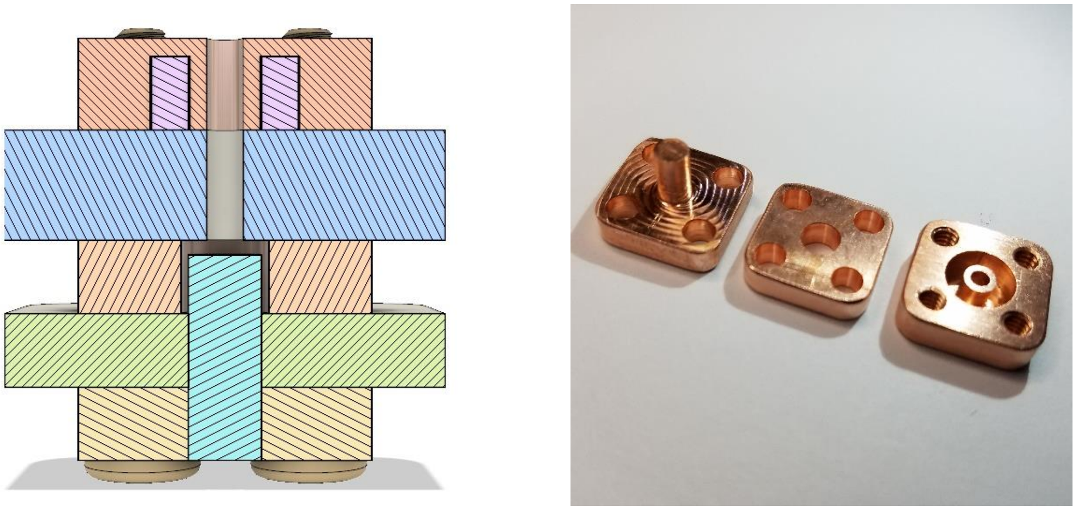

Figure 9: gPPT3 thruster cross-section (left), machined electrodes from left to right - cathode, igniter, anode (right).

This thruster was also the first of the thruster systems at AIS to be fully integrated into a complete propulsion module, as the AIS-gPPT3-1C Integrated Propulsion Module.

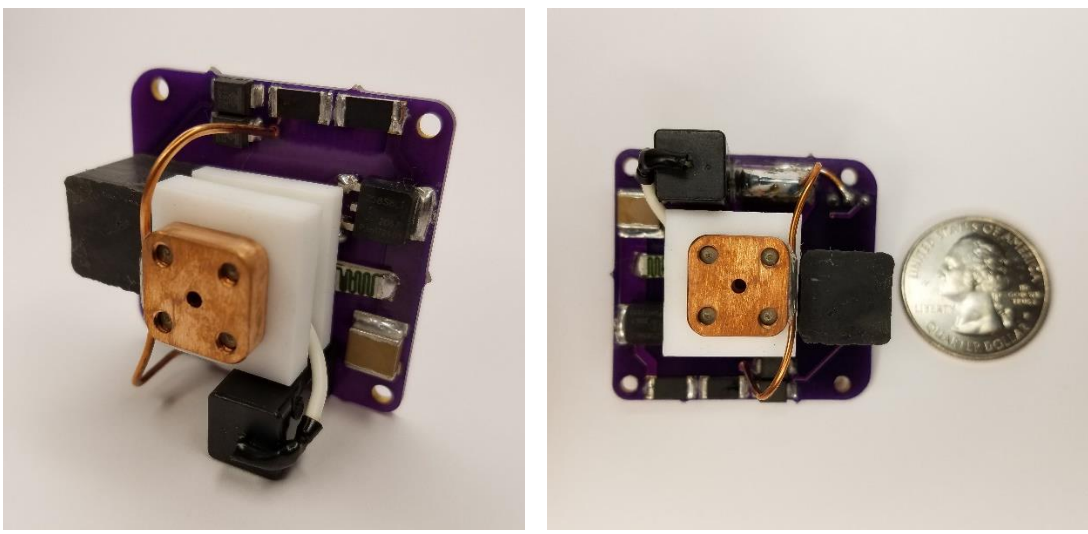

Figure 10: AIS-gPPT3-1C Integrated Propulsion Module assembly

The gPPT3 system measures at only 40x38x24mm in total size, requiring a max power of 500mW, with average power draw of 150mW during nominal operation at 0.3Hz. An onboard micro high voltage DC-DC converter provides up to 2kV (1kV at 0.3Hz) for the main pulse capacitor bank. The high voltage rail is also tapped off to provide over 300V to the ignition circuit, which consists of a smaller pulse capacitor, 10kV flash camera trigger transformer, and a thyristor for triggering. The main bank consists of two 0.068uF MLCC ceramic capacitors, which at 0.3Hz has a total stored energy of only 0.09J, bringing this thruster to the lowest energy end of PPT technology.

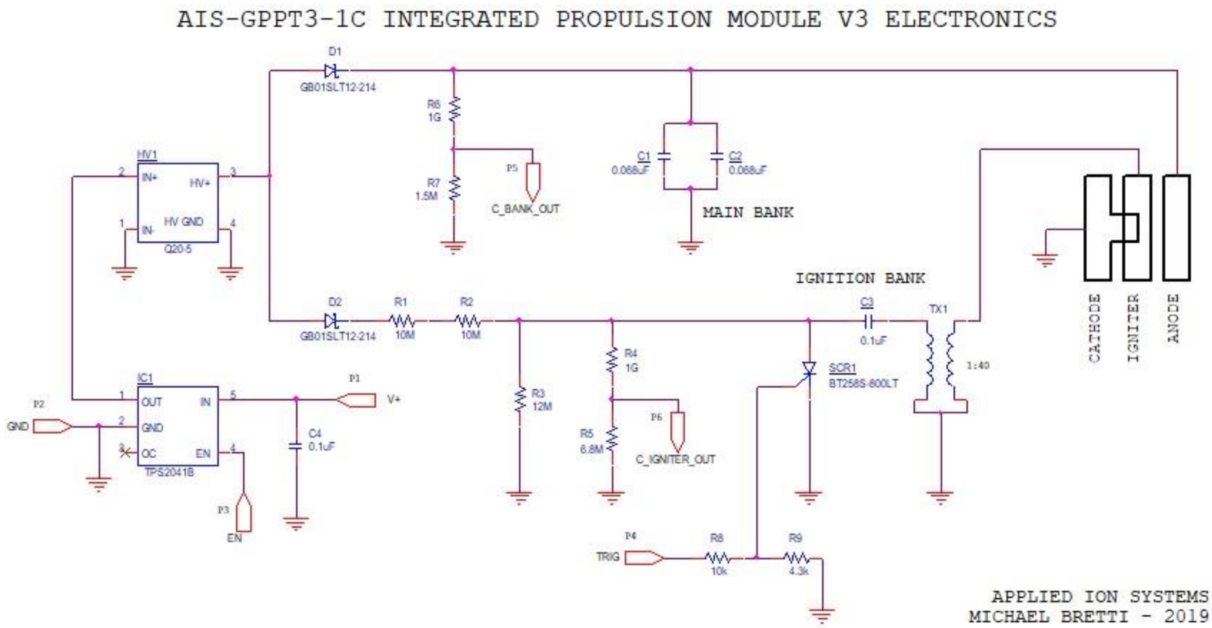

Figure 11: AIS-gPPT3-1C Integrated Propulsion Module electronics schematic

Voltage input ranges from 3.3-5V, with voltage input directly related to total lifetime and ignition performance reliability, with 3.3V offering the longest lifetime but lowest reliability, with 5V operating at the highest rate of ignition reliability with the lowest lifetime, due to extreme stresses seen on the main pulsed capacitor bank. Thruster operation is simplified with only power, enable, and trigger commands needed. At 4V input, operational lifetime is rated to about 1200 shots, with a 25% misfire rate. The thruster also has two outputs, where the main bank and ignition bank voltages can be monitored for troubleshooting and tracking operation of the thruster.

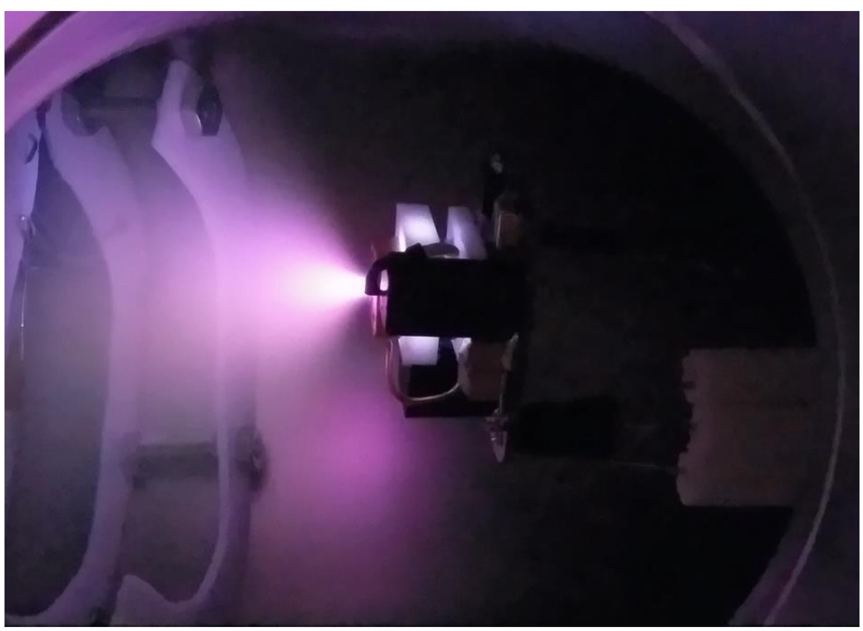

Figure 12: AIS-gPPT3-1C Integrated Propulsion Module firing in high vacuum

Thrust measurements with the thrust stand show an average thrust of around 0.22uN at 0.3Hz, with an impulse-bit of around 0.66uN per shot.

Figure 13: Thrust analysis using video captures of a micro-pendulum deflection. Plasma plume interacton with the pendulum head (left), resulting peak deflection (right).

Currently, two AIS-gPPT3-1C thrusters have been successfully integrated onto the AMSAT-Spain GENESIS N and L PocketQubes. Each GENESIS picosat is 1.5P in size. The thrusters are being flown as onboard demonstration payloads, scheduled to launch at the end of 2020. If successful, the GENESIS PocketQubes will be the first PQs to ever successfully demonstrate propulsion in orbit, marking a major advance for this extremely miniaturized class of satellites. In addition, the AIS-gPPT3-1Cs will also be the first ever fully open source, independently designed and tested plasma thrusters to be flown in space, marking a major advance for the open source space hardware community.

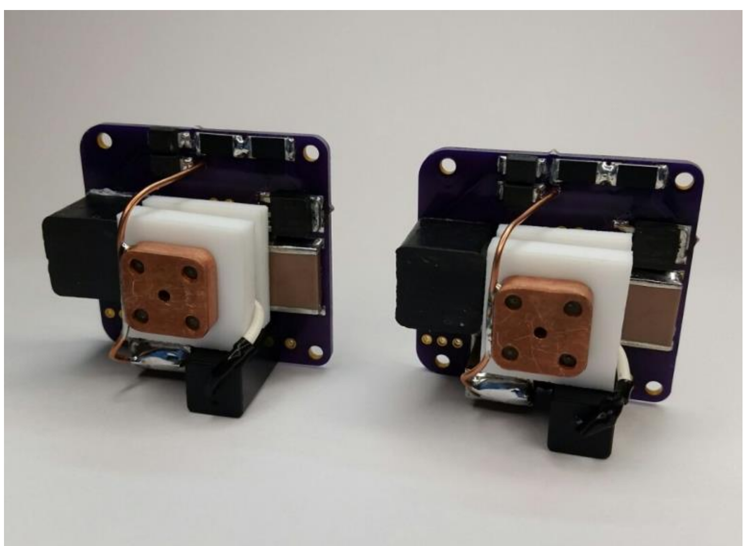

Figure 14: AIS-gPPT3-1C Integrated Propulsion Modules for the GENESIS N and L PocketQubes

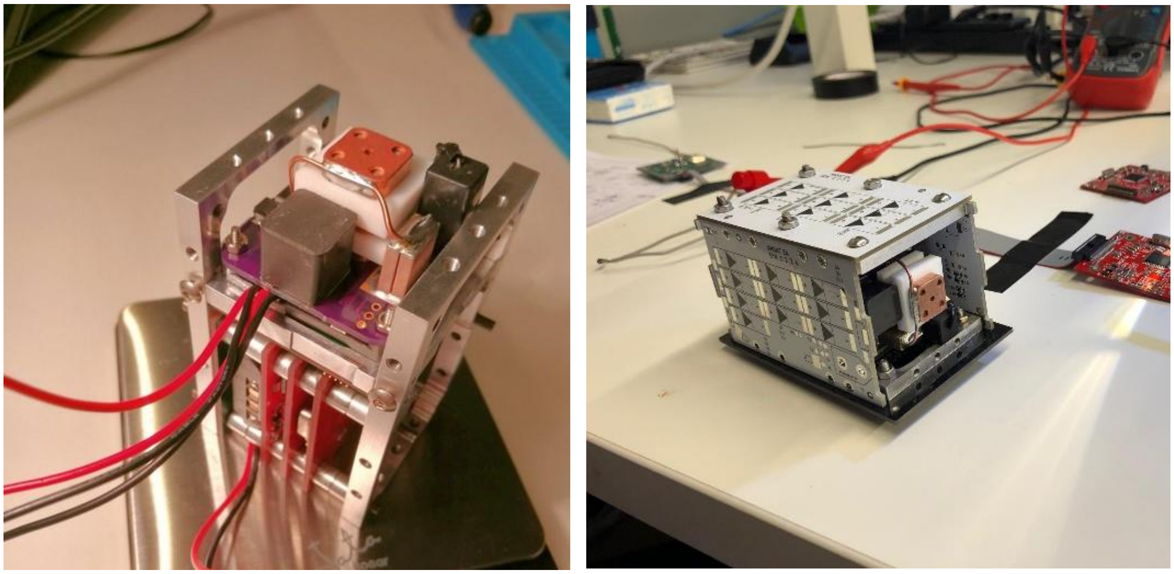

Figure 15: Assembly and integration of the AIS-gPPT3-1C with the GENESIS PocketQubes

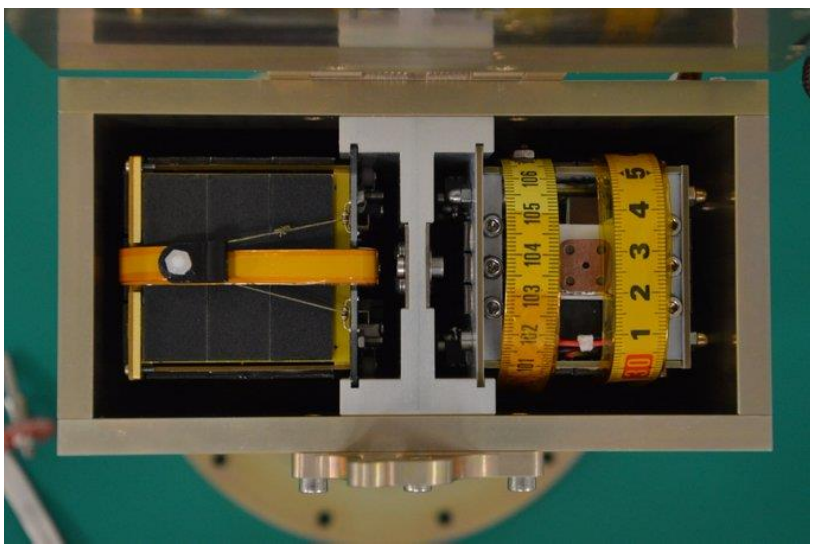

Figure 16: Fully assembled GENESIS satellites with AIS-gPPT-1C thruster in the deployer

The newest PPT in development, the AIS-EPPT1, aims to take the lessons learned from the original gPPT thruster series development, and further improve thruster reliability and performance while reducing total cost, and simplifying manufacturing and assembly of the thruster. Improvements include dual ignition pulse transformers, larger thyristor, and increased trigger circuit input voltage, spring fed Teflon fuel, higher efficiency and higher power onboard HV supply, and a 3D printed housing that fully integrates fuel, electrodes, electrical connections, and mounting, eliminating the need for custom machining and further reducing total thruster cost.

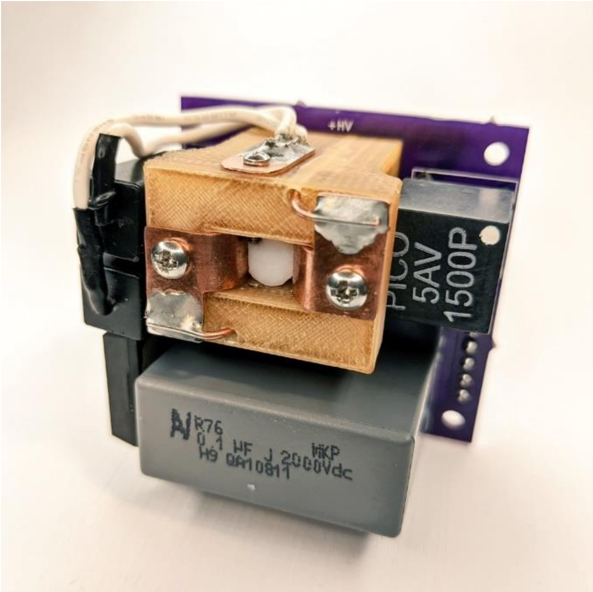

Figure 17: AIS-EPPT1 Micro Pulsed Plasma Thruster assembly

Unlike the gPPT3, which utilizes a coaxial electrode geometry and Teflon fuel bore, the EPPT1 consists of a more classic diverging rail electrode geometry with a conventional spring-fed Teflon fuel bar between the electrodes. Since divergent rail electrodes are dominated primarily by electromagnetic acceleration via Lorentz force, efficiency is improved of electrothermally dominated coaxial versions. The igniter electrode consists of a simple bolt that passes through the body near the cathode, serving a dual purpose as both the ignition pin as well as the fuel stop for the spring loaded Teflon bar.

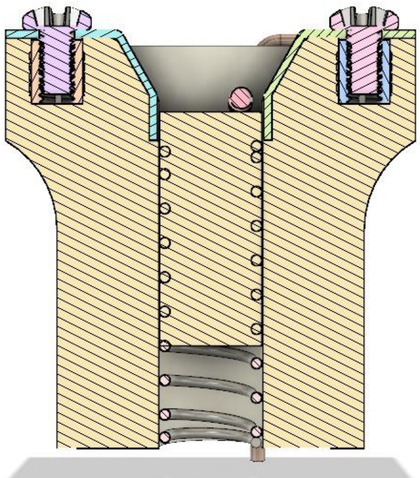

Figure 18: AIS-EPPT1 thruster cross section

In order to make the thruster highly compact, while significantly increasing fuel capacity, performance, and reliability, 3D printing is heavily leveraged for the thruster body housing. Utilizing 3D printing, the electrodes, fuel, and thruster connections can be fully integrated into the body, making the system compact, and allowing for a highly custom geometry to be constructed at very low costs. The housing uses fused deposition (FDM) printing with Ultem 1010 filament. This performance thermoplastic is a well-qualified vacuum-compatible material, with very high dielectric strength as well as being mechanically extremely durable. Although Ultem is a high performance filament, costs of manufacture are significantly lower than with conventional CNC. Total cost of the 3D printed housing is less than $50, where a conventional CNC version with Ultem or PEEK stock would cost hundreds.

The EPPT1 is also designed to be highly modular, allowing for significantly extended fuel capacity by simply increasing the length of the body. In addition, low-cost high voltage standard polypropylene film capacitors are used to replace the more expensive MLCC ceramic capacitors used in the original gPPT3 for the main bank, improving operational lifetime, with the electronics board designed to accommodate multiple sized capacitors, to tailor performance for different thrust levels, repetition rates, and main bank energies. Current bank energies range from 0.09J up to 0.5J. The EPPT1 leverages the same electronics layout as the gPPT3, with the above additions to the circuitry. The thruster currently draws a max of 1.5W peak, with lower average power during pulsed operation.

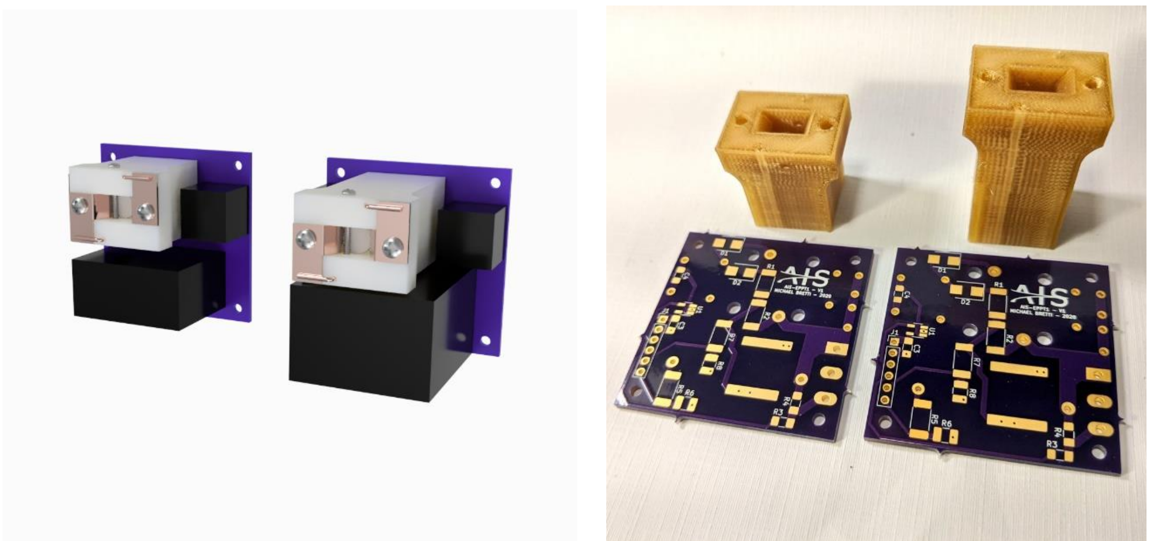

Figure 19: AIS-EPPT1 CAD renders for standard fuel/low energy and extended fuel/high energy versions (left), circuit boards and prototype 3D printed Ultem housings (right)

Initial ignition testing of the thruster has been completed, with two rounds of ignition testing at high vacuum. In the most recent configuration, the thruster has been modified in an unconventional way for PPTs, triggering to the charged anode vs. the grounded cathode. The ignition pulse consists of a -10kV, 1A, 300ns pulse, provided by dual onboard pulse transformers. Since the anode is at 1.5kV, where the cathode is at 0V, a higher total potential is seen between the anode and igniter, allowing for arcing to more easily occur. With this igniter pulse to the anode, a small portion of the stored energy in the main bank is discharged through the initial ablation arc and through the secondary of the pulse igniter transformer, increasing the total ablation energy, making the ablation arc ore intense and allowing for easier ignition. In this configuration, the thruster has been successfully fired to rep rates up to 2Hz, with the igniter fired up to 3Hz. Although the current configuration is at the same bank energy of 0.09J as the prior gPPT3, the plasma plume is significantly larger, due to the larger opening as well as increased fuel surface area. Thrust measurements will be performed during the next round of testing, although it is anticipated that at the higher rep rates and larger plume volume, thrust will be significantly higher than the gPPT3. With a blue color vs. purple, indicating a higher degree of plasma ionization, and diverging rail electrodes, efficiency, and hence ISP, is expected to be much higher.

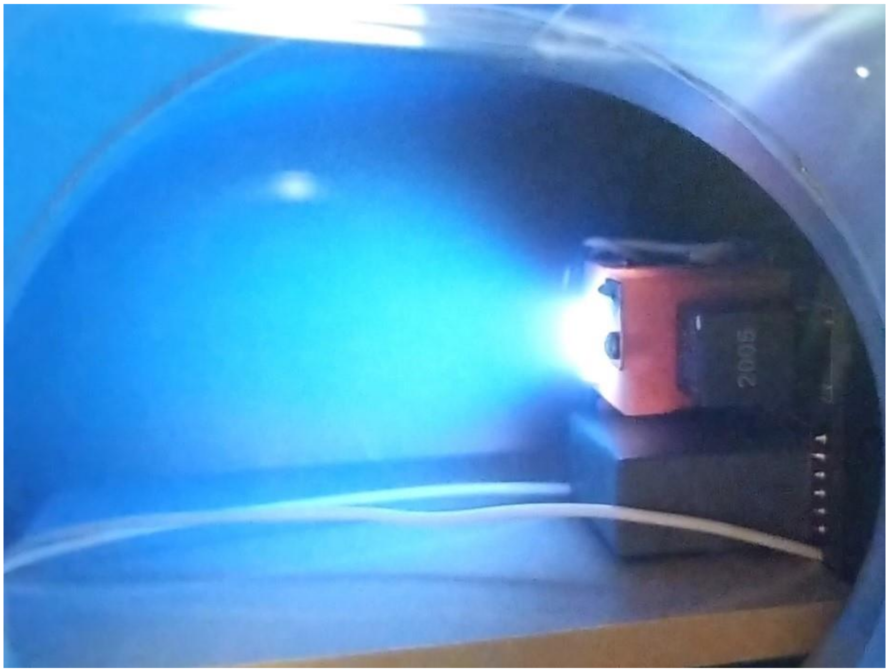

Figure 20: AIS-EPPT1 thruster firing in high vacuum

New modifications are already underway to allow for reliable ignition at 3Hz. This includes a narrower discharge chamber and thinner fuel bar for closer electrode spacing, longer chamber for expansion of the ignition plasma to better make contact between the anode and cathode, inset channel into the body for the igniter connection, and the igniter bolt sharply angled towards the anode at the center of the fuel rod surface for more consistent triggering location as well as utilizing anode-side triggering.

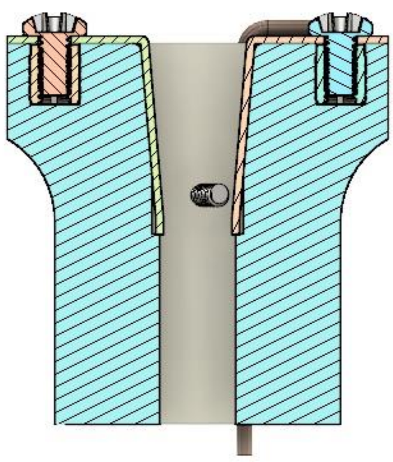

Figure 21: AIS-EPPT1 V2 housing assembly with narrower/extended discharge chamber and angled ignition pin

III. Ionic Liquid Ion Source Electrospray Thrusters

Ionic liquid ion source (ILIS) electrospray thrusters represent one of the most recent advances in micro-ion thruster technology. There are three major types of electrospray thruster technologies: colloidal, which consists of charged droplet emissions, usually utilizing glycerol doped fuels, FEEP or field effect electric propulsion, which utilize liquid metal fuels such as indium, gallium, and cesium to create metal ion beams, and ILIS, which utilizes ionic liquids to create positive and negative polarity beams from the fuel. In all cases of electrospray, the basic principles of operation are the same. Liquid fuel is fed and held in some capillary or porous emitter structure, which a high voltage is applied between the emitter and an extraction electrode. At a critical field strength, microscopic Taylor cones form at the surface of the liquid, in which droplets, ions, or a combination of both are pulled from the cone tip and accelerated through the extractor aperture. This beam of charged particles produces a net thrust – however, like conventional ion thrusters, this beam must be neutralized to prevent charge buildup of the spacecraft.

There are various styles of emitters that can be employed for ILIS thrusters. The most prevalent and widely studied form utilizes arrays of microscopic emitters, either in the form of MEMS semiconductor fabricated hollow capillaries, or laser ablation micromachined spike arrays in porous glass. Recently, in the past few years, there has been growing interest in CNC machined macroscale bulk emitters, which leverage the fact that multisite emission can occur across a large emitter along the pores, vs. single site emission at with micrometer scale capillaries or porous needles. While field strengths, and hence operating voltages must be higher for macro-scale ILIS, manufacture cost and complexity is significantly reduced as a result. Other forms of ILIS have been explored, including large capillary needle emitters, vertically grown CNT forest emitters, and cesium slit emitters used in FEEP modified for ILIS operation (IL-FEEP). ILIS thrusters can be made to operate in either colloidal mode, pure ionic mode, or mixed mode, depending on applied voltage, overall emitter geometry, and fuel flow rates. Typically, ILIS is passively fed via capillary action between the emitter and reservoir, however active feeding is possible like in conventional colloidal electrospray. In the case of passive feeding, emitter thickness, reservoir thickness, fuel type, and pore sizes can affect the passive fuel flow rates, which dictates the mode of operation. Because electrospray is a field emission process, no heat is generated from ion beam emission, unlike conventional gridded ion thrusters which extracts the ion beam from a plasma.

The heart of ILIS thruster technology is the unique fuel that is used, consisting of an ionic liquid. Common liquids include EMI-BF4 and EMI-Im, which are widely studied in numerous other chemistry fields. Ionic liquids consist of room temperature molten salts, which, unlike typical salt solutions, are made up of purely ion species. One of the major advantages of ILIS as opposed to prior types of electrospray technology is the elimination for the need of onboard heaters as well as beam neutralizers. Due to the nature of the fuel, which exhibits cryogenic cooling properties, the fuel can remain liquid at very low temperatures. More importantly however, is due to the nature of ionic liquids, both positive and negative ions can be extracted from the source fuel, allowing for beam neutralization to occur utilizing adjacent thrusters of alternating opposite polarity. Because of electrochemical effects, ILIS thrusters generally must experience polarity reversal cycles during operation to prevent degradation of the emitters as well as charge buildup in the fuel, eventually causing emission to cease, unless an external neutralizer is used. Polarity alternation is typically done anywhere from once to several seconds up to a few Hz, though higher frequencies are possible.

Due to their physics of operation, ILIS thrusters can also be scaled to extremely small form factors, down to single microscopic emitters, and with their high thrust/power potential, as well as high ISP, make them one of the most ideal candidates for micro-propulsion for nanosats and picosats. Thrust/power ratios can range anywhere from 14uN/W up to 57uN/W, with ISPs ranging from 800s in high thrust, low ISP thrusters, to over 5000s in low thrust, high ISP thrusters. Due to this wide combination range of high thrust/power and high ISP, ILIS is a more attractive solution at the PocketQube level than PPTs, offering significantly more performance for the same power and form factor, with reduced interference since the thruster operates in a quasi-DC mode versus high intensity pulses in PPTs, which can generate a significant amount of EMF and cause onboard computers to glitch or crash if not properly shielded. However, ILIS is significantly more complex to operate, and is much higher cost due to fabrication of the emitters. In addition, there are also fundamental lifetime issues that need to be addressed for the technology as a whole, typically limiting lifetime to several hundreds of hours, and for small ILIS systems, total impulse of less than 100Ns.

The AIS-ILIS1 is the first generation of ILIS thrusters at AIS, and represents one of the most advanced thrusters systems developed through this effort. The ILIS1 leverages the extreme scalability of ILIS technology for use down to PocketQube class systems. The ILIS1 takes advantage of the lower cost of macroscale CNC machined porous emitters, utilizing a single ridge emitter for this first iteration for low-cost and ease of manufacture while providing enough surface area to support higher extracted beam currents. The entire thruster, including thruster assembly, high voltage electronics, and fuel storage, is 45x45x16mm in size, rated for a max power draw of 1.6W.

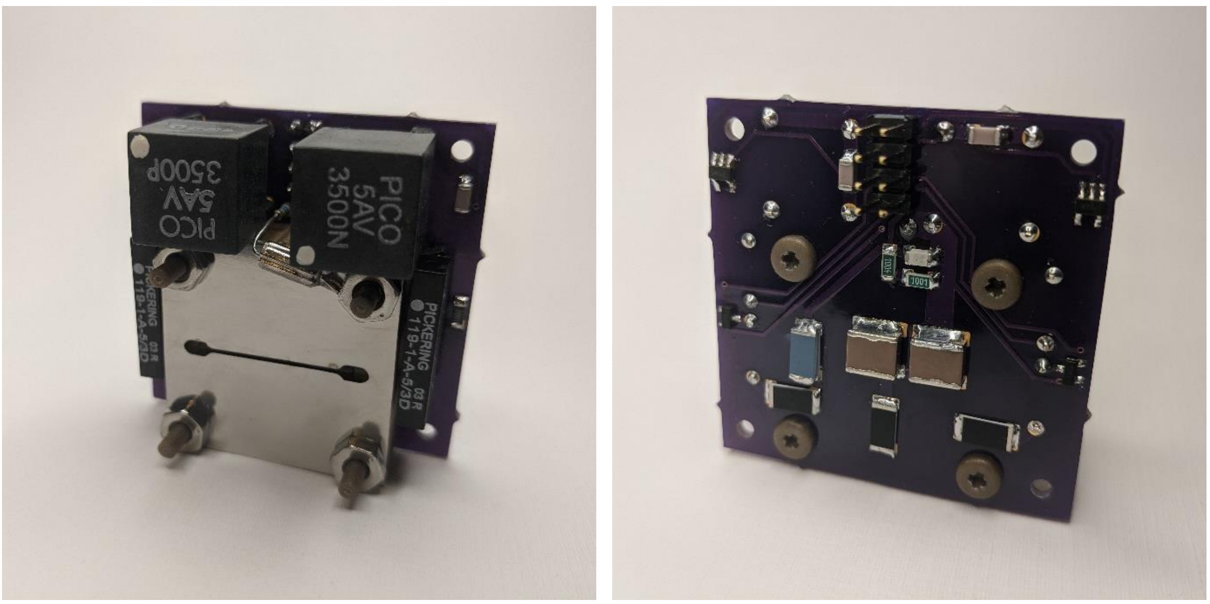

Figure 22: AIS-ILIS1 thruster assembly

The ILIS1 utilizes 3D printing technology to simplify manufacture and reduce costs. The housing is also constructed from Ultem 1010 like the EPPT1. Inside the housing includes the porous glass emitter, porous glass reservoir, nickel distal electrode contact plate, and wave spring to apply pressure to the assembly as well as make electrical contact with the PCB for high voltage to the emitter. The housing also includes mounting holes to directly bolt to the thruster PCB, as well as the extractor plat on the top surface. The housing itself has gone through multiple iterations in order to minimize liquid creep from the porous glass emitter surface to the extractor, which causes eventual thruster failure due to shorting.

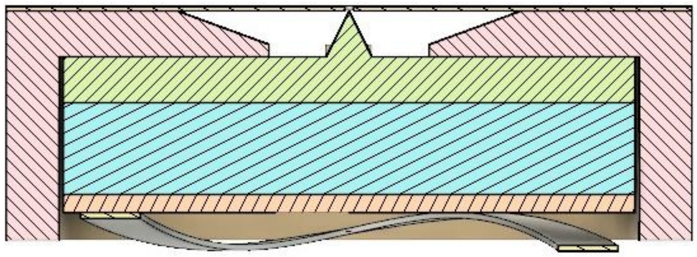

Figure 23: AIS-ILIS1 thruster cross-section

The critical component of the ILIS1 is the porous glass emitter, machined from standard P4 grade chemistry filter frit discs. A larger pore P3 grade unmachined disc is used as the reservoir, which is pressed against the back of the emitter disc from the wave spring at the bottom of the assembly.

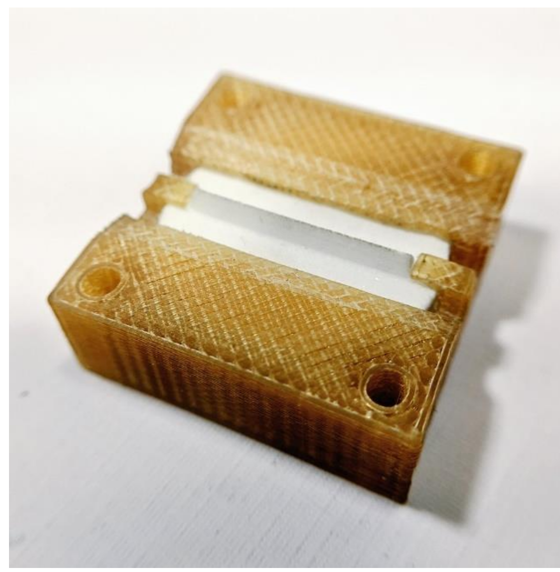

Figure 24: ILIS1 porous glass CNC machined ridge emitter (left), glass emitter test fit into a modified Ultem printed housing (right)

Since the EMI-BF4 fuel is hydroscopic, and can adsorb atmospheric gas, the fuel must be degassed in high vacuum to remove air and moisture. In addition, in order to better saturate the porous glass, and remove air from the glass structures while backfilling with the fuel, the emitter and reservoir must also be saturated at high vacuum. The fueling process is accomplished by placing the emitter and reservoir discs in small Pyrex beakers, filled with ionic liquid just to cover the discs. Stainless steel wool is placed above the discs to fill the rest of the volume in the beaker to prevent fuel splashing during degassing, and the top is covered with aluminum foil to further reduce droplet spray. Both beakers are placed in the vacuum chamber, and pumped down to high vacuum (10^-5 Torr), and baked from 60-80C for several hours. In addition, the Ultem 3D printed housing is baked and degassed prior to assembly as well to remove any volatiles, trapped gas, or moisture from the structure, which was found to cause arcing and flashovers in prior testing of non-degassed housings from SLA printed resins.

Figure 25: Baking, degassing, and saturation of the porous glass emitter and reservoir with ionic liquid at high vacuum, as well as baking of the Ultem 3D printed housing

Due to the cost and lead time of the custom machined emitters, the primary changes to improve performance for the thruster for this first iteration were centered around the electronics and extractor electrode, which could be readily changed. Numerous iterations of the electronics were explored to successfully achieve both switching and isolation of the high voltage supplies. High voltage micro relays were selected for the switching elements after testing various other semiconductor switches. The micro HV relays are highly compact, low-power, and offer over 3.5kV isolation. In order to safely switch and isolate the supplies, a special control sequence was adopted, independently controlling the HV supply turn-on and the relay turn-on to ensure that the relays had been actuated prior to energizing the HV supplies, allowing for the switching elements to be kept within spec. A transition delay is also included between the positive and negative cycles to allow charge to bleed off the HV filter cap before reversing polarity.

During the first several rounds of testing, board flashovers caused numerous issues during operation. As a result, all HV points on the boards were filed smooth, all silk screen was eliminated, and HV surge protection resistors were placed in the circuit to limit surge currents between the relays, emitter, and HV filter cap required by the HV supplies, significantly stabilizing operation and allowing for the thruster to work at voltages of up to +/-5kV without issue.

Typical slit based thrusters utilize linear slits in the extractor. However, due to the high field strengths at the corners of the ridge emitter, it was found that emission would concentrate at the edges, rather than across the length of the ridge, leading to excessive emission at the corners and early failure. Improved extractor geometries were eventually improved to reduce field enhancement at the corners, thereby eliminating emission at the corners and focusing the field along the central region of the emitter. Various extractor widths, as well as spacing between the emitter and extractor were tested to determine optimum emission performance.

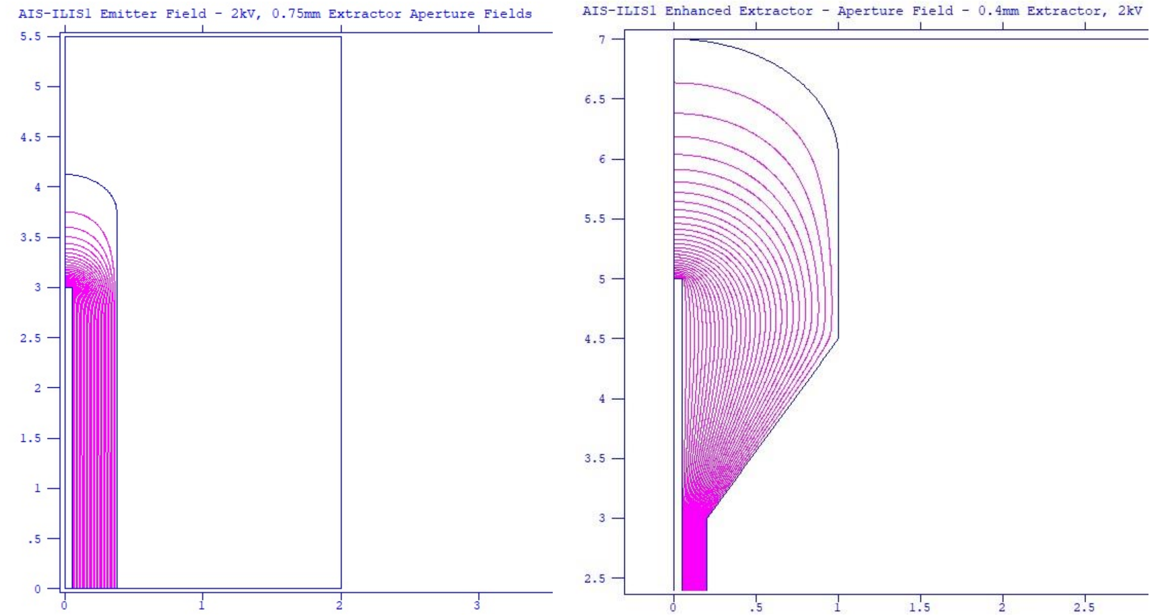

Figure 26: Electrostatic field simulation comparison between the standard linear extractor (left) and enhanced flared extractor (right) geometries. With the flare, field enhancement at the corner is greatly diminished, and with a thinner slit, focused along the central portion of the ridge.

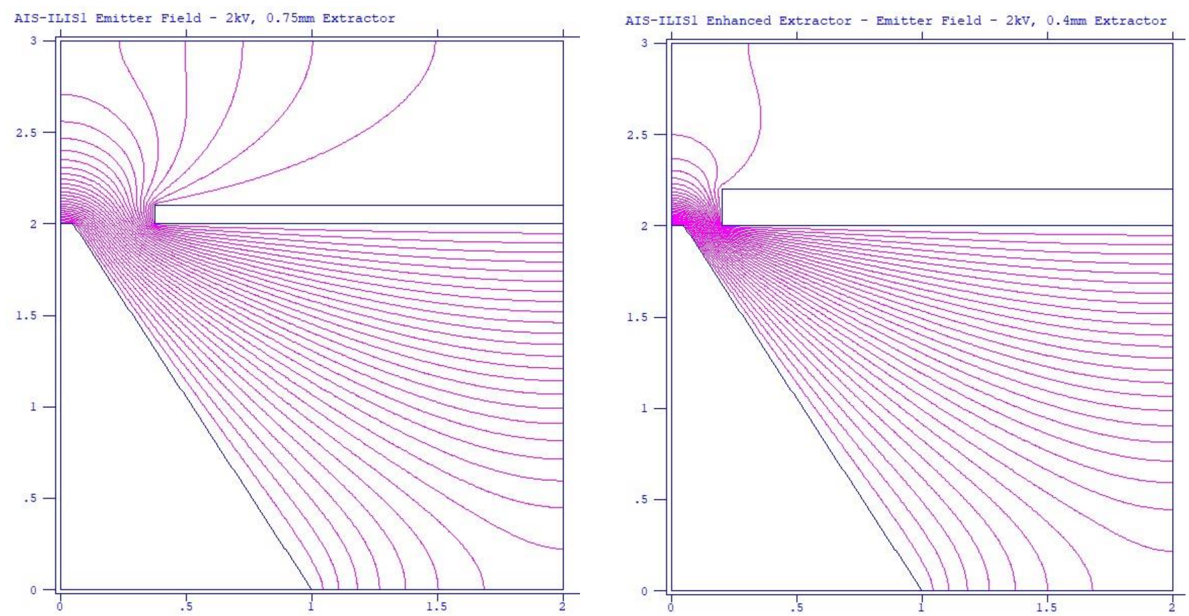

Figure 27: Electrostatic field simulation comparison between the thinner 0.1mm standard linear extractor (left) and the thicker 0.2mm enhanced flared extractor (right) geometries. With a thicker plate, field divergence is diminished.

During testing with the conventional linear slit extractor with a width of 0.7mm and a spacing between the emitter and extractor of 0mm, peak emission currents of +/-2uA was achieved at +/-4.7kV accelerating voltage, with longer term stable operation at +/-0.5uA of current. Due to the higher field enhancement at the corner of the ridge, emission was concentrated at the corner, leading to shorter thruster lifetime. Bright ion beam emission can be observed, with a very widely divergent beam. After testing, fuel charring was found at the corner where emission occurred, as well as evidence of shorting due to liquid creep between the emitter and extractor.

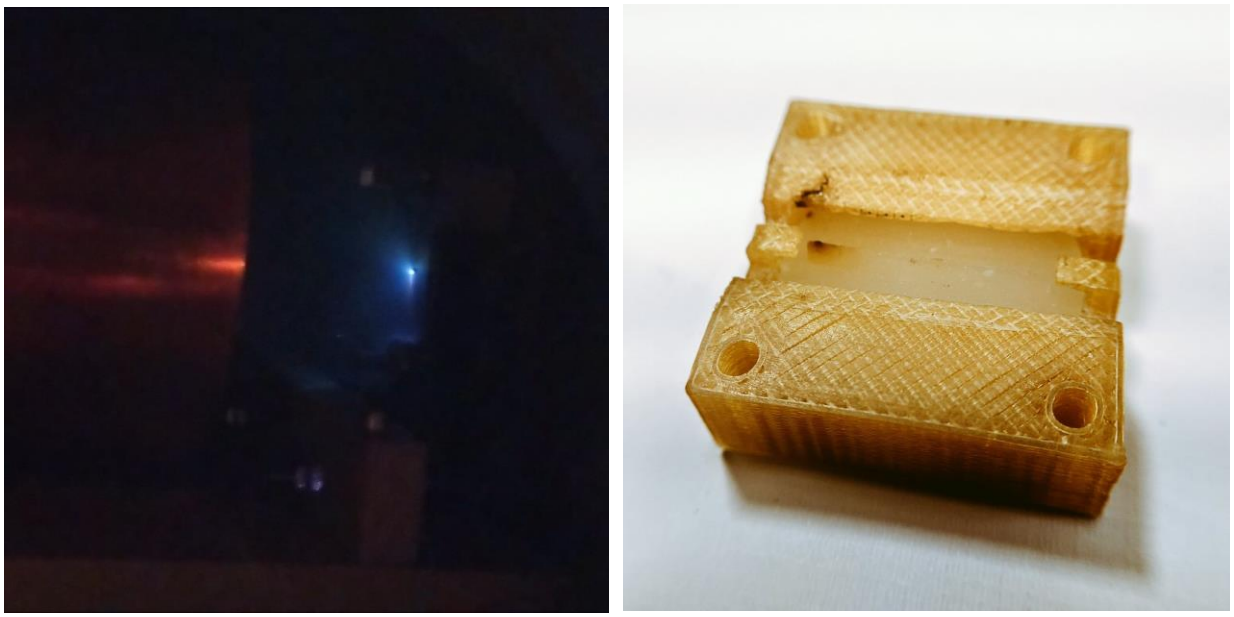

Figure 28: Ion beam emission from the ILIS1 with the linear slit extractor (left), evidence of fuel charring and emission from the corner, as well as shorting due to liquid creep (right)

Assuming purely ionic emission, initial performance can be estimated. For thrust, assuming pure ionic mode with 50% monomers and 50% dimers, averaging thrust for both monomer and dimer emission with EMI/BF4 beams, max theoretical thrust is around 0.24uN at 2uA beam current. Taking into consideration non-ideal real-world operational losses due to thruster inefficiencies, assuming 30% for reasonable losses, this gives an average thrust of around 0.17uN. For ISP, assuming the same PIR mode of operation with 50% monomers and 50% dimers, at +/-4.7kV this gives a max average theoretical ISP of ~8380s. However, in literature it has been shown that there is about a 50% discrepancy between measured ISP and theoretical max ISP, most likely due to polydispersive losses in the beam, which factored in gives a more realistic ISP of 4190s.

During the most recent test, with the enhanced extractor with a central width of 0.5mm and a distance between the emitter and extractor of 0.1mm, peak emission of up to 5uA was achieved at acceleration voltages of +/-5kV, with stable long-term operation again at 0.5uA at +/-4.6kV. This test also represented the first time multi-site emission was achieved across the central region of the ridge emitter as opposed to the corners, validating the initial design predictions for the enhanced flared extractor. Although beam brightness was physically less, peak beam current was more than double the prior testing, with more evenly distributed emission, as well as nominal operation at lower thrust at lower extraction potential. Beam divergence was also significantly reduced, resulting in a more flat, linear beam. Looking at initial performance estimates using the same above assumptions, peak corrected thrust at 5uA is estimated around 0.4uN, with peak corrected ISP at 5kV estimated around 4320s, the highest numbers to date for ILIS1 testing. The thruster was operated for a duration of 2 hours for the longest ILIS1 run to date.

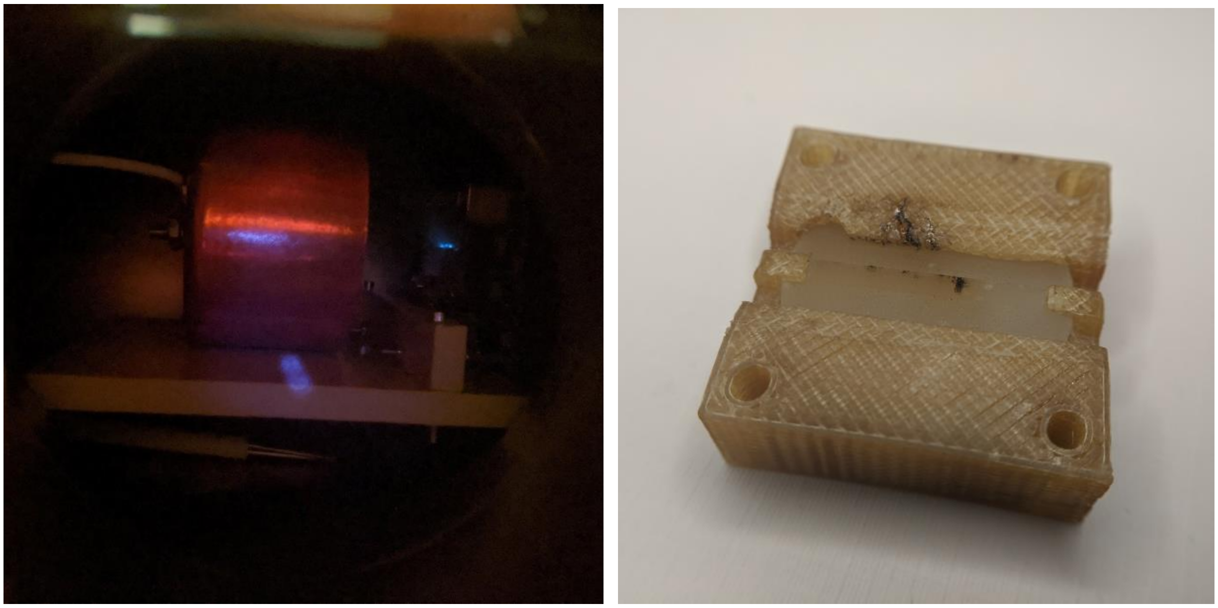

Figure 29: Multisite ion beam emission from the ILIS1 with the enhanced flared slit extractor (left), evidence of fuel charring and emission along the central region, as well as shorting due to liquid creep (right)

The next round of testing on the ILIS1 will include the addition of a shield electrode and revised housing geometry to mitigate early failure due to liquid creep of the ionic liquid from the porous glass emitter to the extractor, which has been the primary cause of failure to date for the ILIS1.

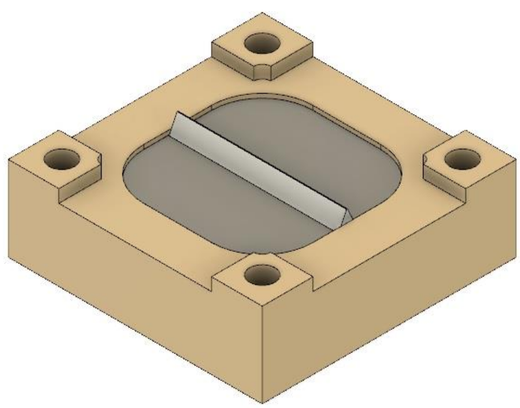

Figure 30: Newest ILIS1 prototype concept modifications with improved housing geometry and shield electrode

One of the major advantages of electrospray technology is its ability to scale via clustering. Unlike conventional higher power thrusters, which relies on physically larger thrusters, electrospray works better through clustering multiple small modules, allowing it to be highly configurable for a wide range of applications. Preliminary work is being done to look at the development of an AIS-ILIS Cubesat cluster, leveraging several individual PocketQube scale thrusters tied together with a central control board.

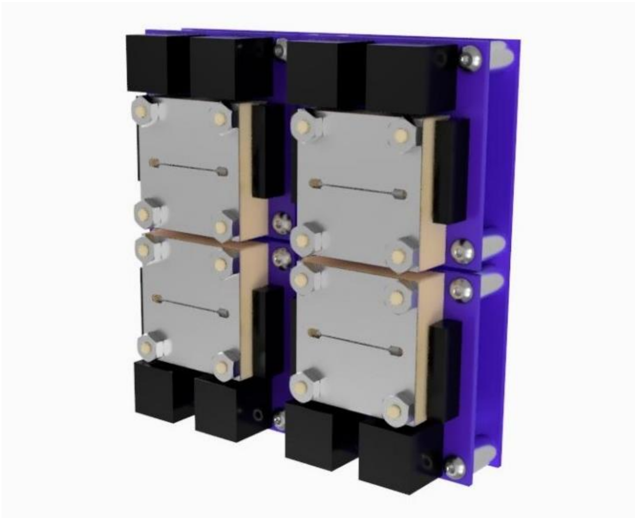

Figure 31: Conceptual CAD concept render for an ILIS1 cluster for Cubesats

The next iteration of ILIS development with focus on refining the emitter geometry, utilizing a much sharper emitter ridge to further increase field enhancement along the ridge surface, increasing emission and thrust, as the AIS-ILIS1.2.

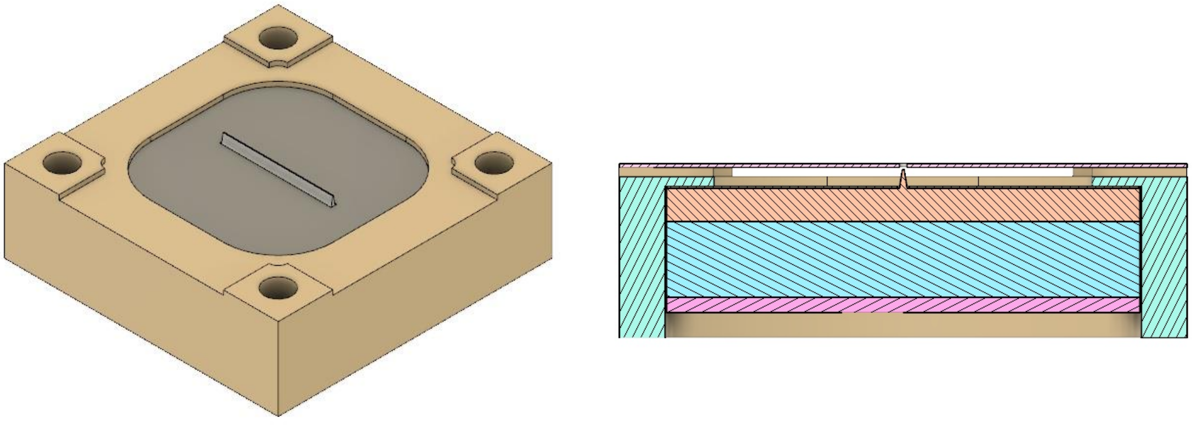

Figure 32: CAD renders of the improved ILIS1.2 design with sharper ridge emitter

Finally, the ultimate iteration of the ILIS development will begin with the AIS-ILIS2, which moves to a higher emission density macroscale spike array. The current design utilizies 169 individual spikes, allowing for significant beam current and higher thrust than the ridge version at high ISP. The design will also include a dedicated processing and control board to allow for automated control of thruster start-up sequences and montiroing during nominal operation.

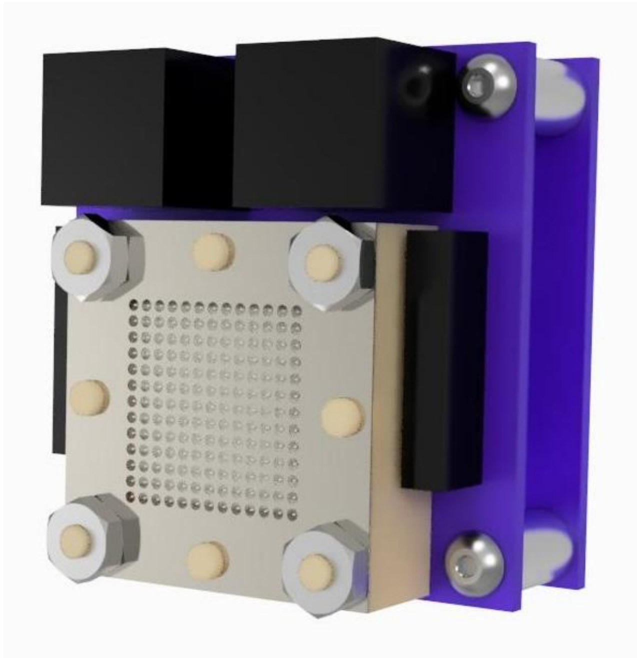

Figure 33: CAD render of the proposed ILIS2 with CNC machined spike array and control board add-on

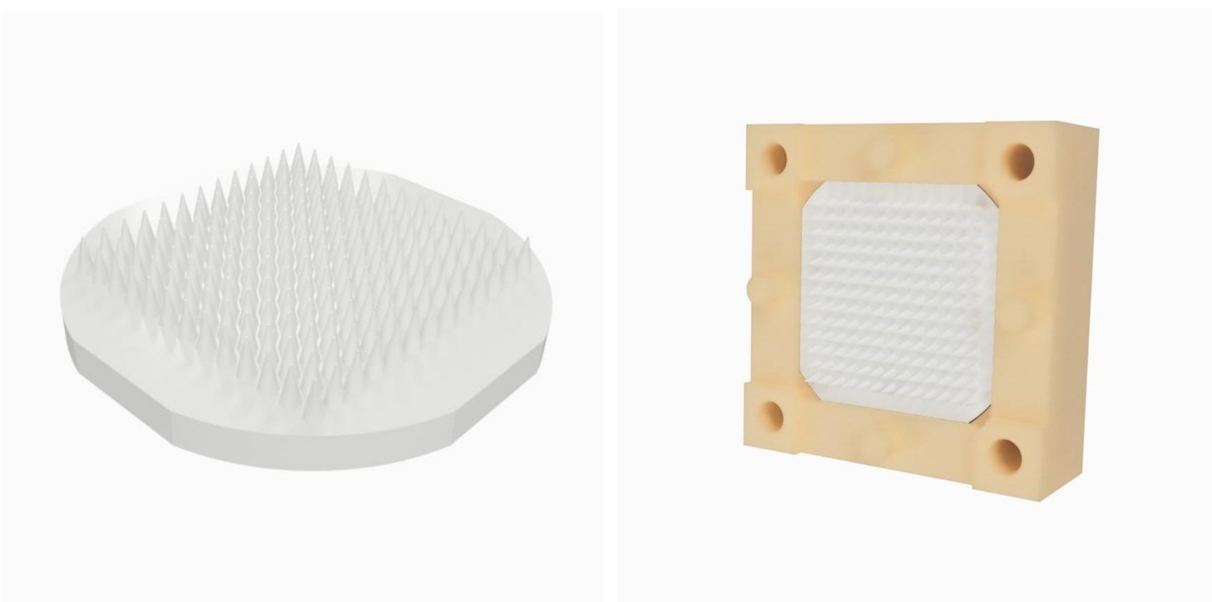

Figure 34: CAD renders of the ILIS2 spike array emitter (left) and emitter mounted into the housing (right)

IV. RF Gridded Ion and RF Plasma Thrusters

In addition to extremely low-power micro plasma and ion thrusters for PocketQubes, more conventional medium power thruster technoliges are being explored for larger Cubesats at AIS. Two common types of thrusters seen typicaly at higher power levels include the gridded ion thruster and the RF plasma thruster. Gridded ion thrusters reprisent the most classic form of ion propulison, where an ion beam is extracted from an ionized plasma, with an external electron source used to neutralize the beam. Ionization of the fuel can occur through a variety of means, by either electron bombardment via thermionic emitters, hollow cathodes, or through RF excitation. Gridded ion thrusters can operate with a wide range of fuels, although fuel selection is typically inert gases such as Xenon. Gridded ion thrusters typically exhibit low thrust at high ISP, from hundreds of uN to several mN of thrust, and thousands of seconds of ISP. Gridded ion thrusters are also known for extremely long lifetimes, with the largest thrusters being tested to continuous operation of 40,000 hours or more.

RF plasma thrusters rely on RF excitiation of the fuel, ionizing the fuel into a plasma, further heating and accelerating the plasma exhaust out to provide direct thrust. In most cases, the plasma acceleration is further enhanced through the use of magnetic nozzles, either by field coils or permanent magnets. Since the exhaust is in the form of a plasma, which consists of both ions and electrons, no neutralizer is required. RF excitation of the fuel can occur anywehere from low MHz levels up to GHz levels, with the latter easier to achieve at higher efficiency, but requiring more power for similar operating condtions. RF plasma thrusters can also be run with virtually any gas, however most common systems rely on conventional inert thruster gases such as Xenon, with growing interest in iodine and water vapor. In terms of performance, RF plasma thrusters generally range at medium to high thrust for EP in the mN range, at medium to low thrust levels typically less than 1000s. Since there are no extraction grids, grid erosion does not occur, leading to extended lifetimes for RF plasma thrusters. However, at the lower ISP levels, significantly more fuel is needed for equivalent operating times as gridded ion systems.

Because RF excited gridded ion thrusters and RF plasma thrusters share the same core excitation method of the fuel in the discharge chamber, a new design has been developed to leverage modularity and interchangeability between these two systems. In addition, conventional fuels such as Xenon are very costly, and the need for pressurized tanks, valving, and flow control further complicates the design and increases cost. The AIS Io Series attempts to simplify design by utilizing a solid iodine fuel delivery system directly integrated to the back of the thruster discharge chamber.

Figure 35: AIS Io Series RF Gridded Ion and RF Plasma Thrusters

This core module utilizes a simple ceramic heater, contact plate, and presser plate with springs to hold the solid iodine fuel against the heat source, which is sublimated and delivered directly to the discharge chamber. In this way, fuel delivery complexity is significantly reduced, and allows both thrusters to share the same fuel delivery system.

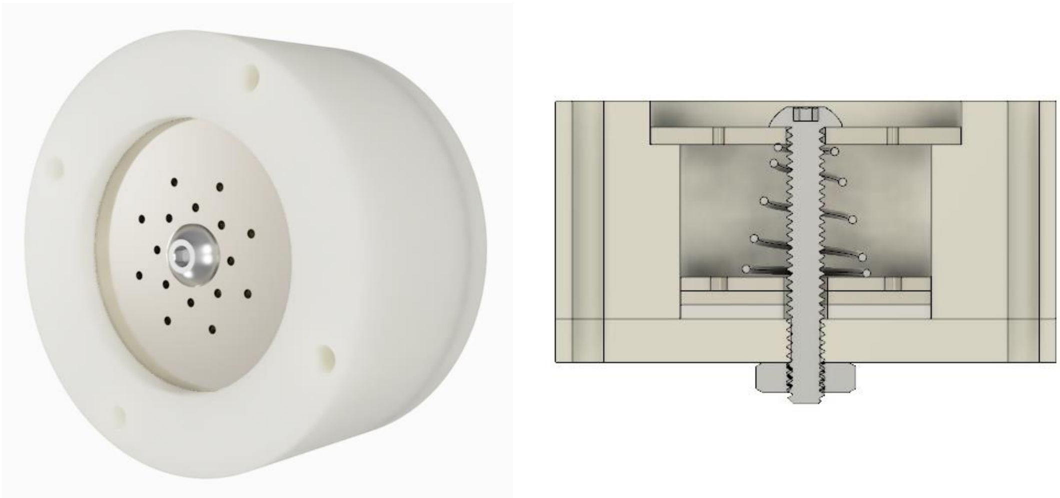

Figure 36: AIS Io Series heated iodine fuel delivery module

The RF discharge chamber utilizes a simple coil antenna, embedded into a 3D printed housing, lined with a standard alumina ceramic tube, driven to 13.56MHz. However, other antenna designs, such as helicon sources, can be used with simple design modifications.

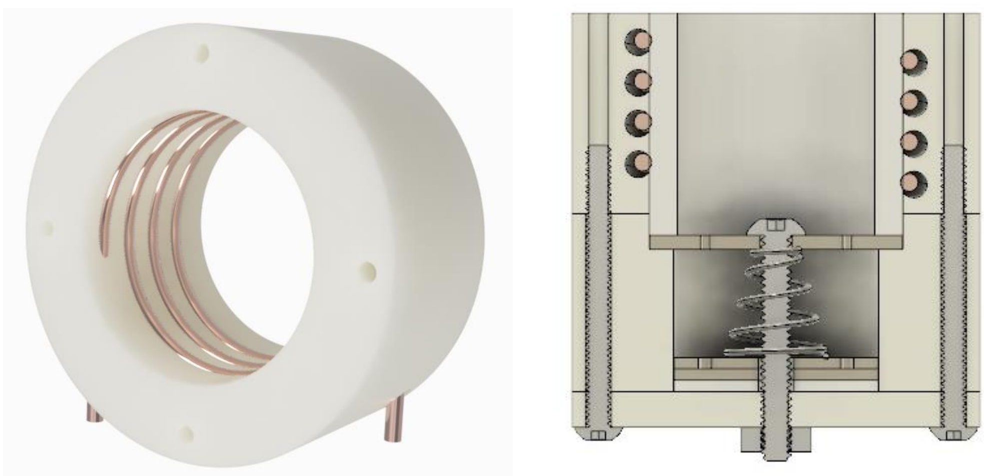

Figure 37: AIS Io Series RF discharge module (left), iodine fuel module, RF discharge module, and ceramic liner sub-assembly cross-section (right)

The design of the thruster allows selection between the RF gridded ion or RF plasma thruster variants by simply swapping out the output module. For the gridded ion variant, a set of grid electrodes are bolted to the output of the RF discharge chamber. For the RF plasma module, a permanent magnet ring magnet module is bolted to the front of the discharge chamber to create a magnetic output nozzle. Due to the highly modular and simplified design, the thrusters can be easily modified, as well as run on conventional fuel gases. The thrusters will also share the same electronics package, which will integrate and mount directly to the thruster assemblies.

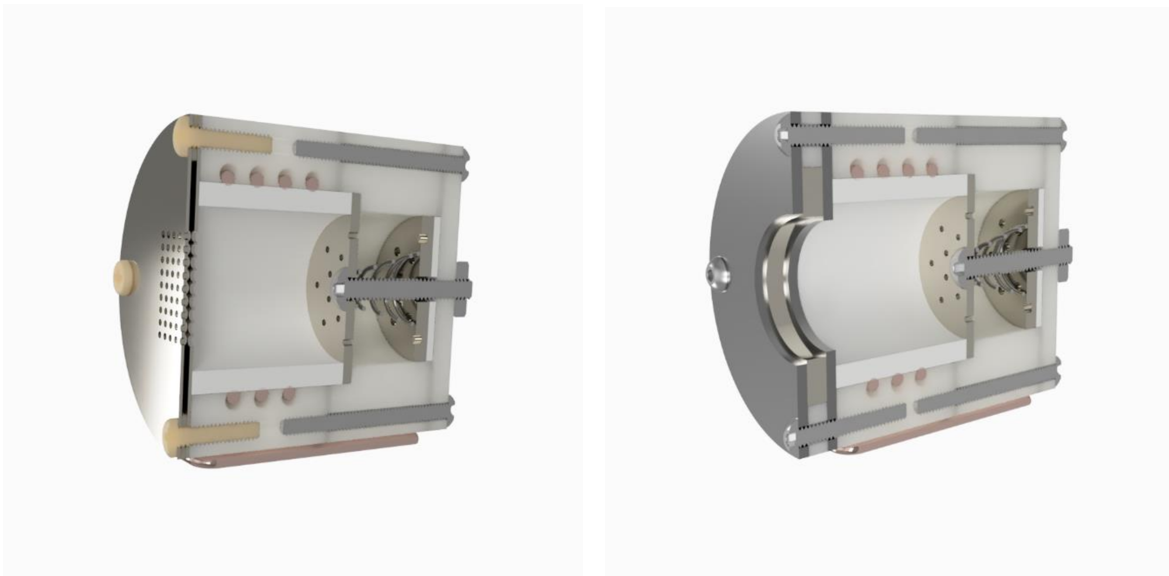

Figure 38: AIS Io Series RF Gridded Ion Thruster cross-section (left) and RF Plasma Thruster cross-section (right)

V. Other Advanced Thruster Concepts in Early Stage R&D

In addition to the several active parallel thruster builds, there are numerous other technologies being explored for development, with initial research and designs underway. These thrusters branch out into a diverse range of conventional as well as highly niche EP technologies.

The first of these technologies is a solid iodine fueled micro-resistojet for PocketQubes. Resistojets are essentially cold gas thrusters that impart additional acceleration to the fuel via resistive heating of the flow chamber. As the gas is heated, it further expands and accelerates out at a higher rate than if relying on pressurization by itself. Resistojet technology shows promising potential for miniaturization at the PocketQube level, with numerous works in literature leveraging MEMS resistojet developments. Although ISP is extremely poor, thrust is considerably higher than plasma and ion thrusters at a similar scale, on the order of hundreds of micronewtons to millinewtons for even the smallest MEMS resistojets. Generally, these developments at the PocketQube and Cubesat scale focus on the use of low-pressure fed water for fuel, either operating at the sublimation point for ice, or through vaporization of the water. In either case, the primary goal is to eliminate the need for additional pressurization of the water via bladder and compressed gas in the storage tank. Such thrusters show potential with operation at around 4W. However, this power level is still on the high side for most PocketQubes, with additional challenges dealing with freezing of the water fuel. As mentioned with the prior Io Series development, iodine fuel has significant promise for EP systems, with solid storage and very low temperatures for direct sublimation feeding. At even poor vacuum levels of several hundred milliTorr, iodine exhibits very high vapor pressure at only 25C, requiring significantly less power to heat and vaporize than water. Solid storage also makes storing of the fuel significantly easier. However, key challenges for any iodine system involves its corrosive nature with most materials. Despite this, materials such as Teflon, ceramic, nickel, and Viton show very good corrosion resistance against iodine, making such a small micro-resistojet feasible. Based on prior literature with heated iodine fuel feed systems for conventional Hall thrusters, and work done with water MEMS resistojets, initial heater tests have shown that temperatures needed for equivalent feed pressures as water-based MEMS systems can be achieved at close to half the input power, making iodine micro-resistojets more feasible for PocketQube propulsion in terms of power constraints. A prototype design is currently in the works that leverages off-the-shelf ceramic resistors for heating elements, and simplified machining to reduce the cost and complexity of such a system down to a level that is suitable for PocketQube teams.

A second technology being explore is the close cousin of the PPT, the vacuum arc thruster (VAT). Like PPTs, VATs, are also pulsed ablative thrusters. However, VATs generally rely on inductive stored energy, and often leverage triggerless operation. Unlike PPTs, where the fuel is typically Teflon, VATs also utilize metal fuel. While any metal or metal compound can be used, typical fuels include aluminum and titanium. VATs operate on the basic principle of vacuum flash over. Typically, the cathode serves as the ablative fuel. Between the anode and the cathode is an insulator with a thin resistive film or surface coating, typically graphite. Energy stored in an inductor fired through the switching action of an IGBT or MOSFET, creating a large voltage pulse on the cathode. Cathodic spots form at the interface between the cathode, insulator, and thin resistive film, initiating breakdown and subsequent plasma pulse, vaporizing, ionizing, and accelerating a metal plasma from the cathode fuel supply. Like PPTs, VATs also enjoy the ability to be scaled to extremely small sizes and low power levels, making them ideal candidates or Cubesat and PocketQube propulsion, and can be configured with a wide range of topologies including planar, coaxial, and ring. In addition, VATs typically exhibit higher thrust/power ratios, higher total impulse, and higher ISP than PPTs, at the cost of slightly increased complexity and physically larger power supplies. In recent years, numerous commercial VAT systems have been developed for Cubesats and now PocketQubes, and represents one of the emerging technology candidates for competitive EP at the nanosat and picosat level. Work is underway on the preliminary design for an AIS-VAT1 thruster to bring this technology to a more accessible and affordable level for all nanosat and picosat teams.

A third thruster technology being explored looks at the conversion of pulsed plasma sources to pulsed ion sources. Larger, more conventional ion thrusters such as gridded ion thrusters extract ions from a plasma, which is typically generated by ionizing the fuel gas via thermionic emission bombardment or RF excitation. However, ions can be extracted from any plasma source, including pulsed sources like those with PPTs and VATs. Historically, vacuum arc ion sources have been used as the primary source of metal ion beams for particle accelerators, and have been used to generate beams with virtually all metals from beryllium to uranium. Vacuum arc ion thrusters (VAITs) are a relatively niche and less studied ion thruster, and currently no VAIT has flown before. Although they are more complex, adding additional power supplies, ion optics, and a neutralizer in addition to the regular VAT auxiliaries, they offer much higher efficiencies and ISP than VATs. While reference has not been found to such a conversion for PPTs, it should be just as possible to extract an ion beam from a PPT plume in the same manner as a VAT plume, allowing for the creation of an analogous pulsed plasma ion thruster (PPIT), where the constituent beam would be made up of carbon and fluorine atoms when used with standard Teflon fuel. Preliminary work is underway for an add-on conversion for the AIS-EPPT1 to the AIS-EPPIT1 to explore this principle, as well as initial R&D into a similar AIS-VAIT1 conversion.

In addition to these advanced pulsed ion sources, low-power pulsed neutralizers are also being explored to couple with the VAIT and PPIT developments. Unfortunately, as mentioned before, all ion thrusters require some form of charge neutralization to prevent spacecraft charging during operation. Neutralizers are generally complex subsystems themselves, and often require a high amount of cost as well as power. For high power ion systems, hollow cathode neutralizers are the default choice, however these require high power levels as well as gas flow themselves, and are very complex systems. Thermionic emission neutralizers are the oldest and simplest form of neutralizer, consisting of a biased heated filament that emits electrons to neutralize the beam. However, lifetime is low, and thermionic filaments typically require high power levels to operate as well. While they are viable for Cubesat scale systems, the required power is generally still too high for PocketQubes. The lowest power neutralizer source utilizes field emission from carbon nanotubes (CNTs). Such neutralizers can operate from a couple of Watts down to sub-Watt levels, making them ideal for PocketQube and Cubesat neutralizers for low-power ion thrusters. However, CNT technology is typically costly, and requires very precise spacing and alignment of the grid, making manufacture currently difficult at AIS. Due to the pulsed nature of pulsed ion beams, similar technologies can be leveraged for the creation of pulsed electron beams, through various means such as pseudospark discharge. Such systems have very high lifetimes, very low average power requirements, and could potentially be scaled down to the PocketQube level. Work is underway to start exploring conventional larger, high powered systems for eventual studies into miniaturization.

Finally, some high power thruster concepts are being explore for experimental purposes. One such system includes the magnetoplasmadynamic (MPD) thruster. A low voltage, high current DC arc is generated between a coaxial anode and cathode, turning the fuel into a thermal plasma, heating and accelerating it out. This thruster is fundamentally very simple in construction, sharing many similarities with non-transferred arc plasma torches seen in processes such as plasma gasification and thermal plasma spraying. At lower power levels (tens of kW and less), external magnets are used to enhance performance. While these types of thrusters offer less performance at the kW range than conventional high power EP, the fundamentals of such a thruster can be explored in a very low-cost and simple manner. Initial research is being conducted into a kW-class MPD system.

VI. Educational EP Learning Kits

In addition to EP system development and testing, work has also been done to further make these technologies more accessible for anyone to begin exploring the basic principles of operation. With each completed thruster development, an open-source learning kit development is also launched. Each kit is a 1:1 scale analog of the actual thruster, with the same dimensions and controls, and similar output signals. Instead of providing plasma or ion beam outputs however, each kit controls onboard LEDs to mimic thruster output, housed inside a high-quality SLA printed thruster that bolts onto the board in the same fashion as the real thruster.

Figure 39: AIS-gPPT3-1C Integrated Propulsion Module Learning Kit prototype assembly

Figure 40: Testing of the thruster learning kit with the LED flash simulating a plasma pulse from the gPPT3 thruster

Additional kits will be developed and released upon the completion of the new AIS-EPPT1 and AIS-ILIS1, which, like the actual propulsion systems, will be released fully open source with all CAD, PCB, BoM, and related manufacturing files available.