Applied Ion Systems

AIS-TR-011

AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V5

Fueling and Ignition Test 2 - 07/21/2020

Testing Report and Summary

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I. TEST PARAMETERS

- **System:** AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V5
- **Fuel:** EMI-BF4
- **Maximum Chamber Pressure During Testing:** 3 x 10^-5 Torr
- **Testing Status:** COMPLETE
  - **Phase I:** Fueling – SUCCESS
  - **Phase II:** Ignition – PARTIAL SUCCESS

II. OVERVIEW

This test is the second attempt at fueling and ignition of the AIS-ILIS1 ionic liquid ion source electrospray thruster for nanosatellites. This thruster is one of many open-source, ultra-low cost, advanced electric propulsion systems in development at AIS, and is currently the most advanced thruster build at AIS to date.

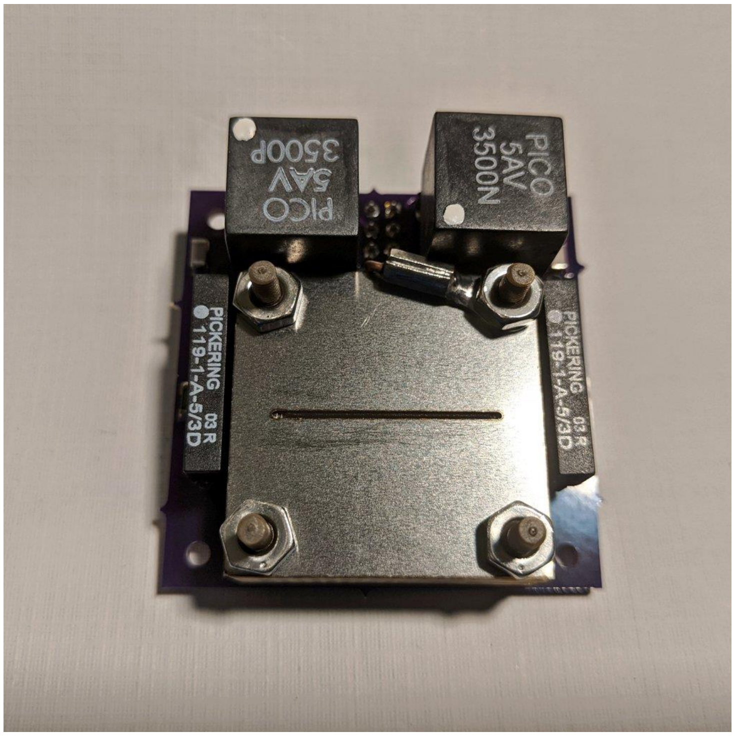

FIGURE 1: *Completed AIS-ILIS1 V5 thruster assembly*

The AIS-ILIS1 aims to solve issues of ion thruster scaling and accessibility for nanosatellites, at 10x cost reduction to currently available micro-ion thrusters on the market, as well as being the first ever PocketQube class compatible ion thruster, in size, power requirements, and fueling restrictions. The ILIS1 represents a new and fundamental shift in micro-ion thruster technology development, allowing for performance ion thrusters to be available for any nanosatellite team, serving a wide range of uses from main propulsion for station keeping, orbital transfers, collision avoidance, formation flying, and deorbiting, to secondary propulsion for fine attitude control.

The following report details the fueling and ignition tests of the ILIS1 using the V5 thruster board, as well as analysis, results, and conclusions moving forward for future testing and system improvements.

III. PRELIMINARY THRUSTER MOIFICATIONS

During prior inspections of the thruster and tolerances after the first ignition test and subsequent thruster post-test analysis in preparation to use the Ultem 1010 printed housing, it was found that the top of the case, which is supposed to be 2mm thick from the top surface to the surface that mates with the extractor, was actually 2.5mm. This means that the 2mm high emitter ridge was 0.5mm too low during prior testing. This most likely contributed to the inability to achieve turn-on even at max voltage of +/-3.5kV during the first ignition test.

FIGURE 2: *Emitter protrusion height from the Ultem 3D printed housing*

Inspecting both the prior used SLA prints and the new FDM prints, both were found to be out of spec at the top. In addition, the Ultem 1010 print inner bore that houses the emitter and reservoir was out of spec, to the point that manual modification of the bore was required to allow for the components to fit inside the casing properly. In addition to the bore, the top of the Ultem printed case was careful ground by hand using fine sandpaper on a glass plate to bring the top thickness to exactly 2mm.

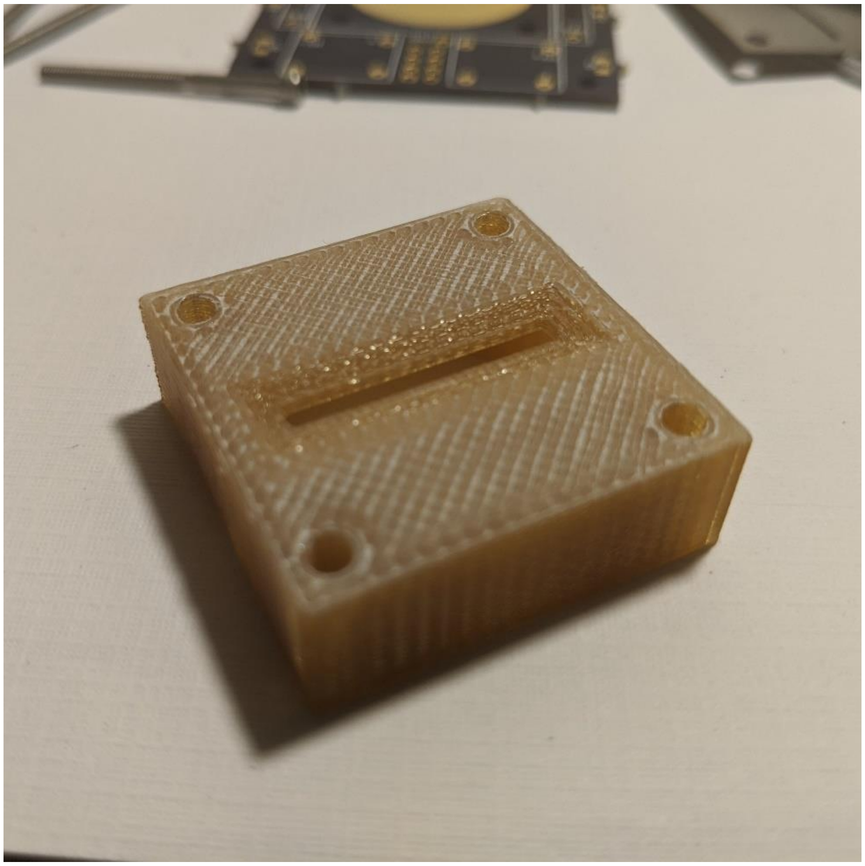

FIGURE 3: *Modified Ultem 3D printed housing*

In addition to the thruster case modifications, the prior used 1mm wide aperture extractor was switched out for a thinner 0.75mm wide extractor to help increase the field strength at the emitter and allow for lower turn-on voltage. All HV points from through-hole soldered components on the board were also filed smooth as a further precaution to minimize the probability of spurious breakdowns or arcing on the board during operation. All silkscreen was also removed from the board to eliminate additional potential sources of outgassing.

IV. VACUUM CHAMBER TVAC MODIFICATIONS

In addition to thruster modifications, modifications were also made to the micro propulsion test chamber, to allow for thermal bakeout of the thruster, components, and fuel. A 10′, 500W, 1400C output rated ceramic braided heat tape with heavy insulation was added to the main part of the chamber. Several thermocouples were also installed for surface reading and control. The main chamber was wrapped with layers of aluminum foil and high temperature insulation.

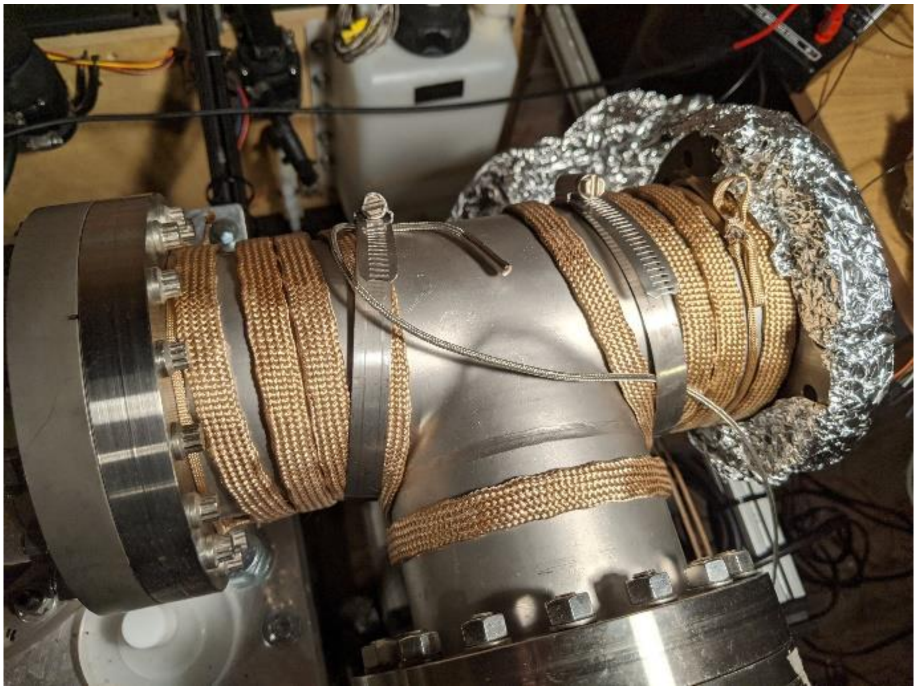

FIGURE 4: *TVAC heater element installation*

FIGURE 5: *Completed TVAC upgrade for thermal cycling and bakeout*

To accommodate thermal readouts inside the vacuum chamber during high vacuum operation, an additional tee section extension was added to the opposite end of the chamber, allowing for a thermocouple feedthrough to be used for in-vacuum temperature measurements.

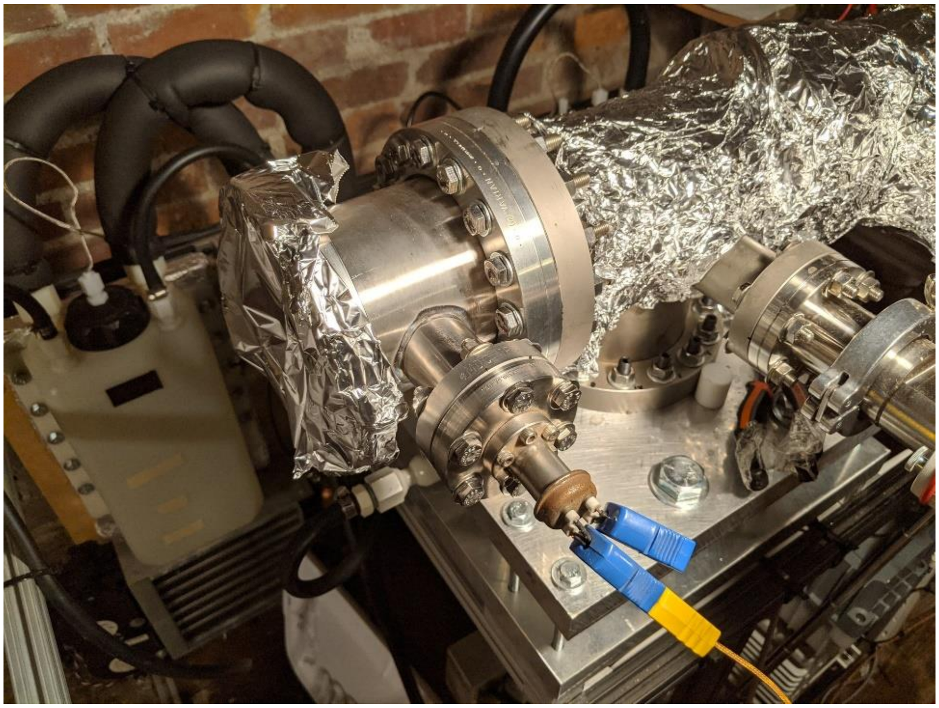

FIGURE 6: *Thermocouple feedthrough chamber adapter*

V. TEST PHASE I – FUELING AND BAKEOUT

The ILIS1 is a type of ionic liquid ion source electrospray thruster that relies on room temperature molten salt ionic liquid fuel. Due to the nature of operation, fuel is passively fed from a porous reservoir to a porous emitter, where high field strengths at the emitter tip causes the formation of Taylor cones, which allows for the extraction of ions after some critical turn-on voltage. Unlike most prior work on ILIS electrospray thruster technology, which utilizes micro-machined arrays of capillaries or porous glass spikes, the ILIS1 focuses on a more recent development utilizing CNC machined macroscopic scale emitters leveraging bulk site emission. For the ILIS1, standard porous glass chemistry filter frit was selected for the reservoir and emitter. EMI-BF4 was selected for the ionic liquid fuel, being the most well studied electrospray fuel to date, and exhibiting high emission stability, high temperature stability, and negligible vapor pressure at high vacuum.

Taking lessons from the prior test, the fueling procedure was changed for this attempt. For fueling, both the porous glass emitter and reservoir were placed in their own separate Pyrex beaker, just large enough to fit the 25mm diameter discs. The beakers were then filled with ionic liquid just barely over each of the discs. The rest of each beaker was filled with 316 stainless steel wool at the top to act as a baffle to prevent excessive splattering as well as keeping the discs from bouncing around. The tops of the beakers were then covered tightly with aluminum foil to further prevent any droplet spray into the chamber during pumpdown and degassing.

FIGURE 7: *Porous glass emitter and reservoir saturated in EMI-BF4*

The filled beakers, as well as newly modified Ultem printed housing, and vacuum thermocouple, were mounted on a scrap PEEK baseplate that rested inside the chamber, to prevent direct heating from the chamber during bakeout. Baking was particularly important for this test preparation to better degas the plastic casing to prevent any spurious ionization due to outgassing as seen in the first ignition test, as well as better prepping the ionic liquid fuel. The system was pre-pumped with the roughing pump the night prior and sealed to facilitate faster pumpdown during the fueling phase of the test.

FIGURE 8: *Saturated porous glass emitter and reservoir with Ultem housing on PEEK baseplate for baking and degassing*

During the roughing cycle, the new heater system was warmed up. The heater was controlled with a simple variac and monitored manually, adjusting the temperature as needed. The large glass viewport in the chamber has a maximum rate of rise of about 2-3C per minute. Direct thermal conductivity to the viewport seems to be fairly low, and with just a single wrap of the heat tape on the viewport extension, heating could be brought up a bit faster while maintaining a slow rate of rise on the glass itself.

The fueling and degassing phase went significantly smoother for this test, with no observed issues. With significantly less fuel in each beaker, outgassing was greatly reduced. Though splashing did occur at the beginning inside the beaker, the stainless steel wool baffle proved excellently in mitigating spray, and the aluminum foil cover prevented any droplets from contaminating the chamber. The internal temperature was maintained between 65-80C for a duration of 3 hours, at which the chamber was kept at a vacuum level in the low 10^-5 Torr range. After the baking and degassing cycle was complete, and the system shut down and allowed to cool, preparations were made for the second phase of the test.

VI. IGNITION TEST SETUP

After fueling was completed, final assembly and system preparations were made for the next phase of ignition testing. The thruster components were cleaned, and with the fully loaded emitter and reservoir, assembled into the final thruster. With the final assembly of the thruster with the reservoir and emitter loaded with degassed ionic liquid fuel, the final wet mass could be found. The final wet mass of the thruster was found to be at 39.358 grams. Since the porous glass emitter and reservoir were pre-saturated from the last test, dry mass of the thruster could not be taken prior. However, it is expected that the fuel capacity still remains at 1 gram, which was found during the prior test. Despite the small amount of fuel, operating in the purely ionic regime of emission, 1 gram of fuel can last many hundreds of hours of operation at the anticipated 20uN of thrust for the final target of the ILIS1 system.

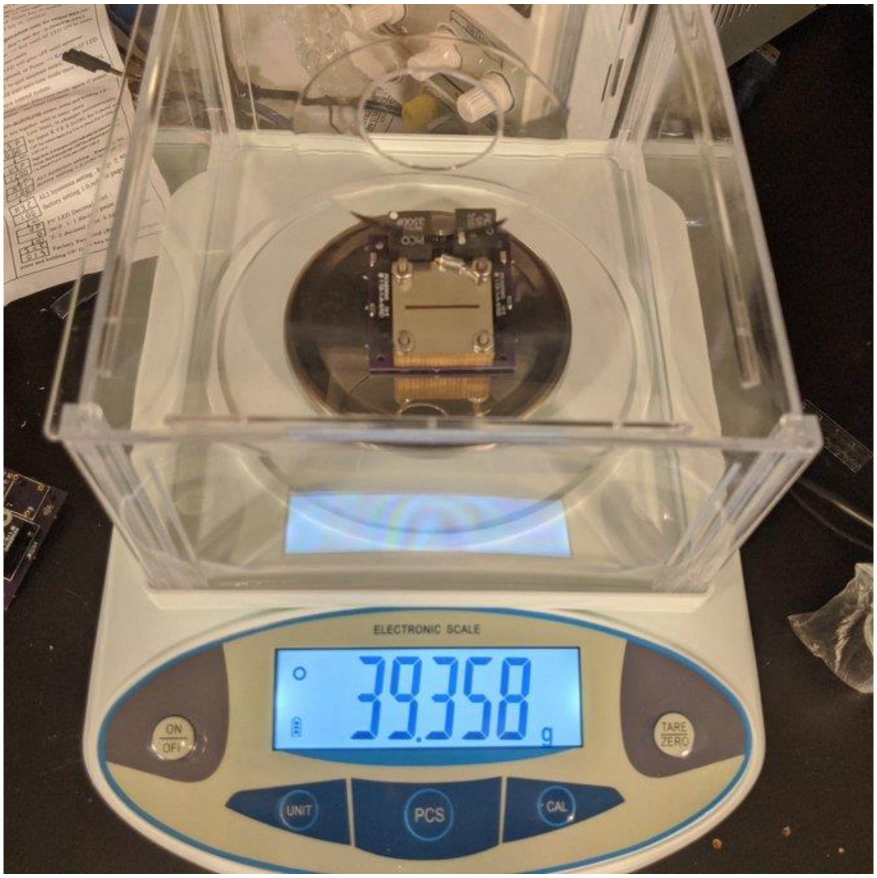

FIGURE 9: *Final wet mass of the fueled and assembled AIS-ILIS1*

The thruster was then mounted to the Faraday cup test stand, which is used to collect and measure beam current, verifying operation of the thruster, and giving initial estimates of thrust and ISP performance. The stand also allows for simplified placement and mounting within the chamber, as well as alignment of the thruster to the Faraday cup input.

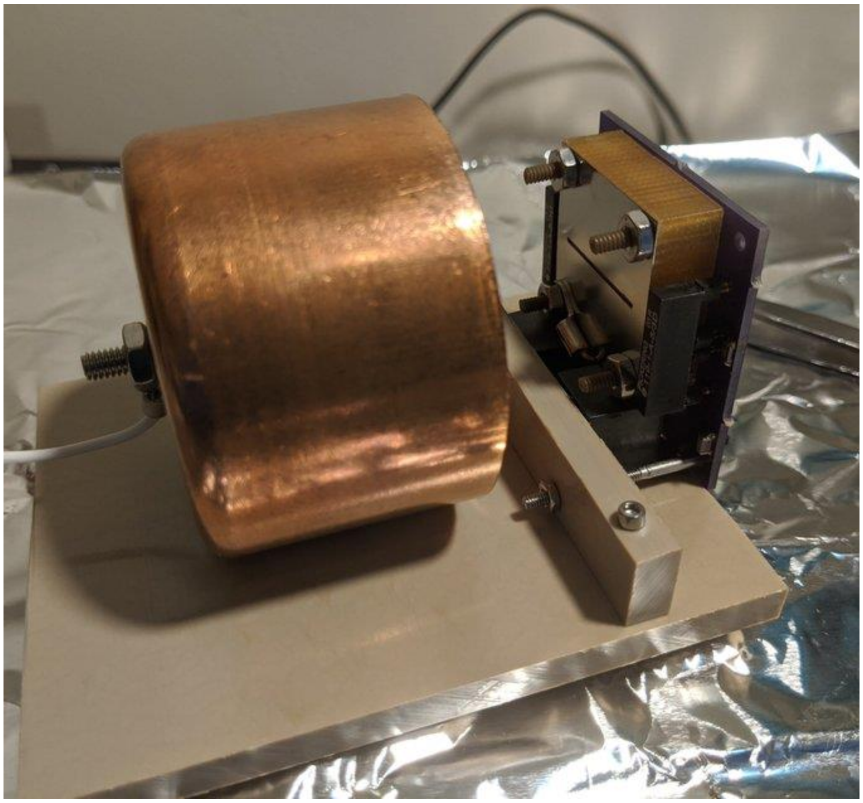

FIGURE 10: *ILIS1 mounted to Faraday cup test stand*

With the thruster in place and the chamber sealed, pumpdown could begin for Phase II of ignition testing.

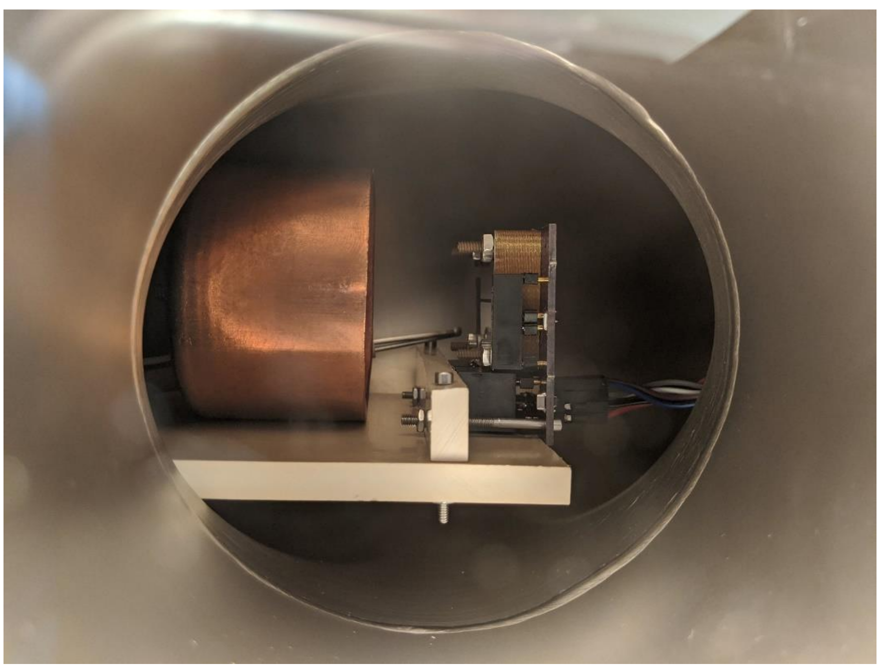

FIGURE 11: *ILIS1 and Faraday cup test stand final mounting inside vacuum chamber*

VII. TEST PHASE II – IGNITION

Pumping and a second light baking went without issue for several hours. Internal vacuum chamber temperature was kept to a maximum of 60C during this second bakeout and pumpdown with the full thruster assembly. Once a final pressure of 3×10^{-5} Torr was achieved, preparations were made to begin the ignition sequence.

Thruster timing was modified in the control software from the prior ignition test to slow down cycling significantly. Each polarity was set to be on for 5 seconds, with a several hundred millisecond pause and transition between polarity switches. It was discovered that too fast cycling under light loading last time caused over-voltage in the relays during operation, as the voltage was significantly higher than expected, and the HV filter capacitor on the Pico outputs did not have enough time to bleed off extra charge before the polarity switch. The longer transitions would help mitigate this issue, and allow for plenty of time for the remaining charge in the HV filter caps to bleed off. Longer time on for each polarity would also allow the thruster to condition and settle a bit more stably during operation.

The control sequence was first started without external power applied for the HV power input. External power from the adjustable power supply was then slowly brought up. The Pico HV supplies on board the thruster turn on with an input at about 2.5V.

Power was slowly increased to the thruster. Only one glitch in the Arduino occurred, requiring a quick restart, but no further issues were encountered after. The glow increased intensity until catastrophically shorting after further power increase. At this point the ignition test was officially terminated, and the system was allowed to cool down prior to opening the chamber and inspection of the thruster.

VIII. POST TEST VIDEO ANALYSIS

During the test, video was captured of the thruster during operation. Although emission only lasted about a minute, it was enough to collect data during the run. Due to the -HV side failing early on, only emission was seen during the +HV cycle. *FIGURE 12* shows a captured shot of the ion beam plume. Emission occurs from the far corner only, with each voltage cycle at 5 seconds long. A very clear and bright plume from the ion beam emission is present. Ideally, when full and complete ignition is achieved, the entire extractor slit would light up with a large plume emanating from it.

FIGURE 12: *Captured partial ion beam emission from the far corner of the ILIS1 ridge emitter*

IX. POST TEST THRUSTER INSPECTION

After testing the thruster was removed from the chamber for disassembly and inspection. Here we can see exactly where emission and eventual failure occurred on the underside of the extractor electrode, as well as the corresponding emitter corner and surrounding casing area.

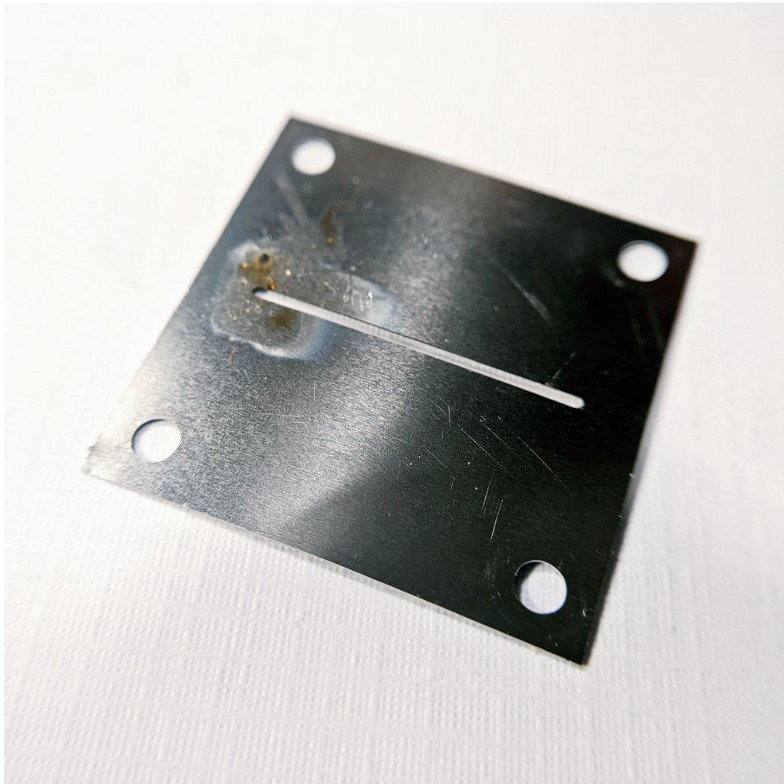

FIGURE 13: *Arcing and fuel deposit on the underside of the extractor*

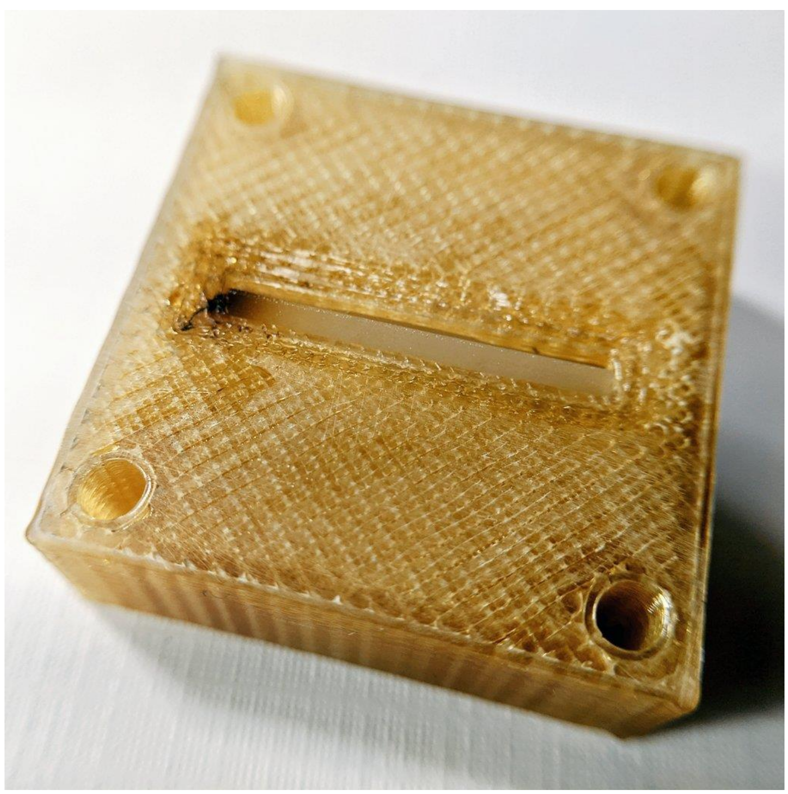

FIGURE 14: *Arcing and charring damage on the housing and corner of the ridge emitter*

Looking closer at the extractor under a microscope, we see where major arcing occurred resulting in charred fuel, leading to shorting.

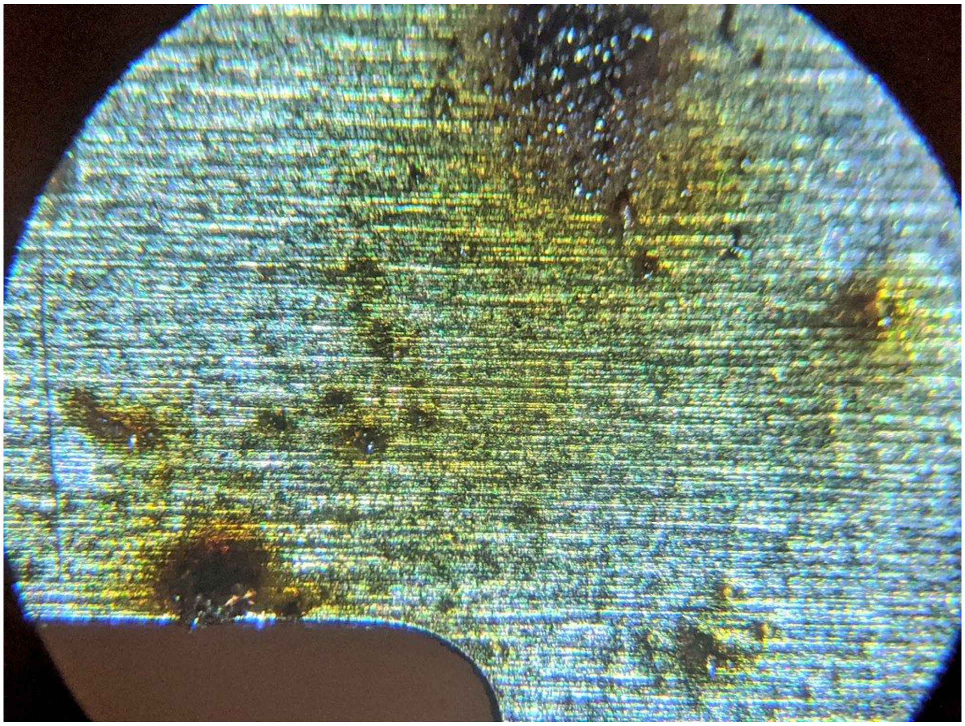

FIGURE 15: *Microscope view of fuel charring and deposit on the back side of the extractor*

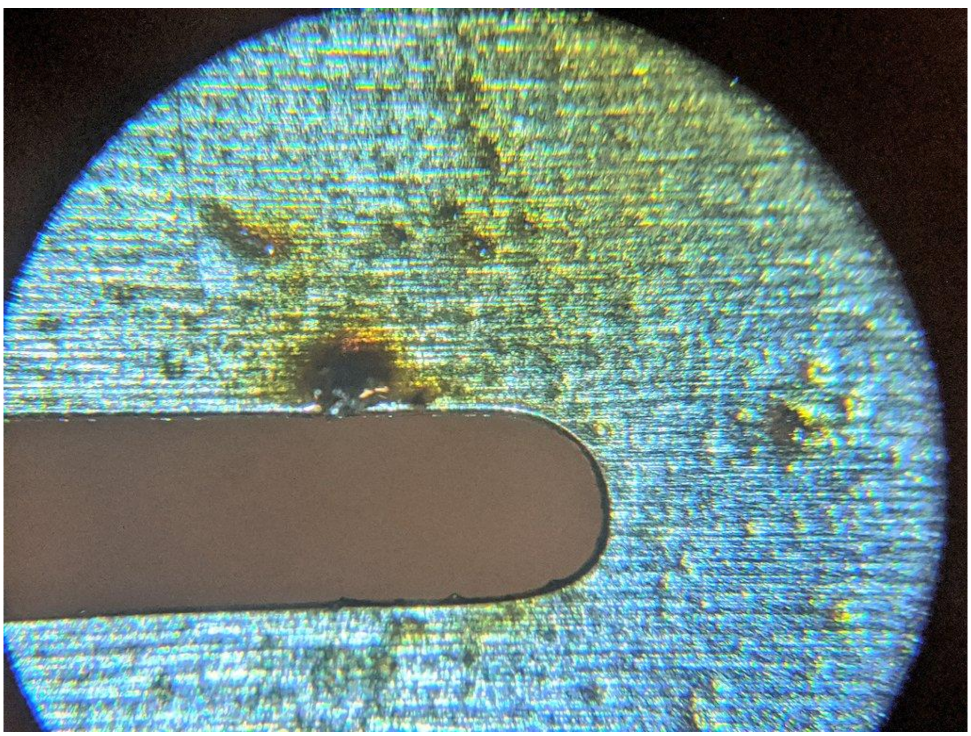

FIGURE 16: *Microscope view of fuel charring and deposit on the back side of the extractor*

Zooming in to the primary arc point, we see a large deposit of carbonized fuel, the primary area where the fault started, later tracking its way across the thruster, where the second deposit clump was seen in the prior posted pictures.

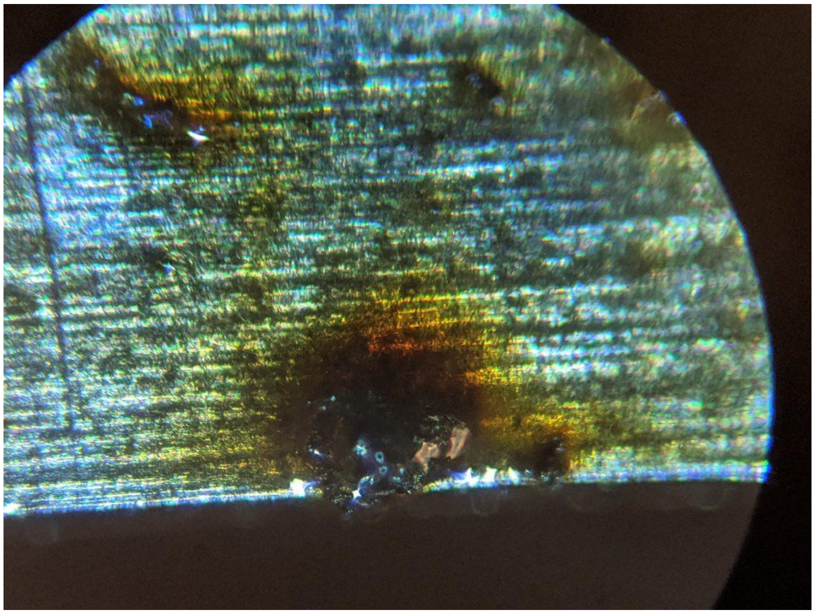

FIGURE 17: *Zoomed in view of the primary charred fuel deposit at the edge of the extractor slit*

Inspecting further along the length of the extractor slit, it was also discovered that fuel droplets had pooled and deposited on the underside of the extractor plate. This signifies that during this test, the ILIS1 was most likely operating in mixed mode, emitting both droplets and ions, rather than pure ionic mode. This subsequent fuel spray and pooling most likely caused the ultimate shorting failure, with the fuel bridging between the emitter and extractor, and eventually conducting the high voltage and charring.

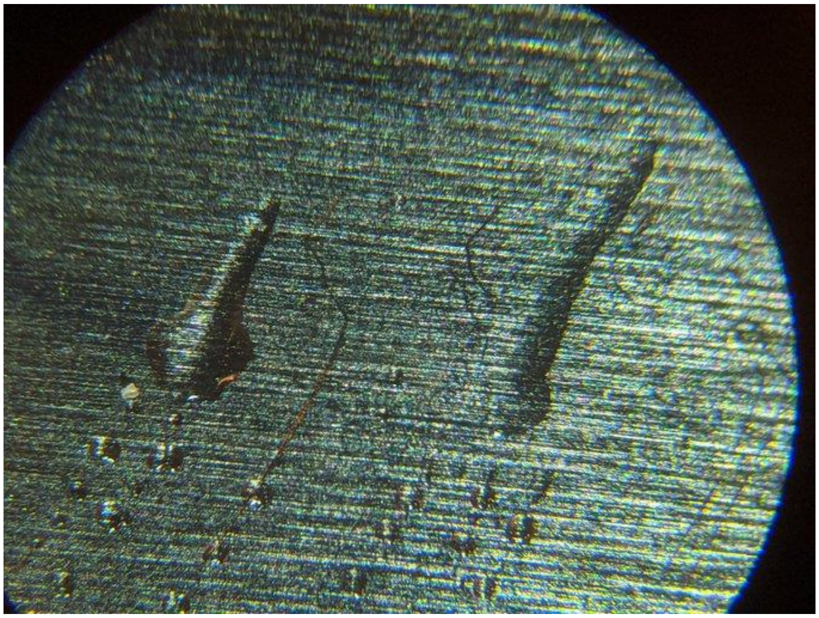

FIGURE 18: *Fuel droplets pooling on the extractor plate*

As voltage is increased past the point of stable emission, significant beam divergence and extractor intercept can occur. This means that unless operating in purely ionic mode, droplets now spraying onto the extractor can cause pooling and buildup. As liquid builds up, it can bridge between the extractor and emitter. Being conductive fluid, arcing can occur, causing charring of the ionic fuel. This can happen very rapidly, and stop emission within a minute or two, as seen exactly in this case.

Moving to the housing, we can see direct evidence of tracking due to this liquid bridging. A large clump of charred fuel is seen at the corner of the emitter, and a thin black snaking char line is seen, following the liquid as it conducted between pooled areas.

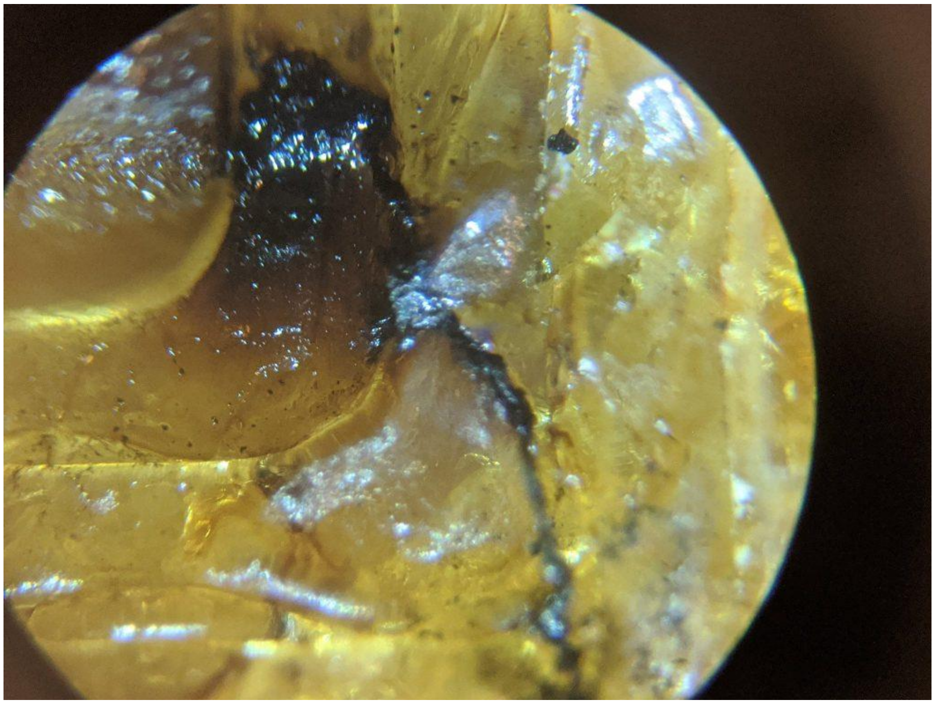

FIGURE 19: *Charred tracking along the 3D printed housing, emanating from the corner of the ridge emitter. A large clump of charred fuel deposit can be seen to the right of the extractor edge*

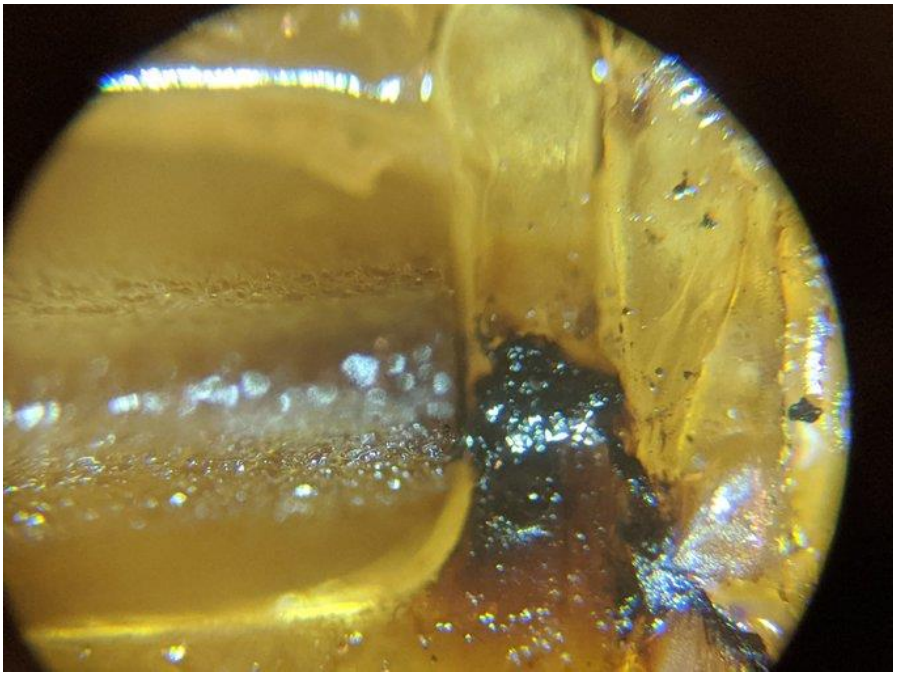

FIGURE 20: *Close-up of the charred fuel clump to the right of the porous glass emitter, where tracking occurred, causing a short between the emitter and extractor*

Looking at the porous glass emitter, we can immediately see discoloration at the corner where the arcing failure occurred.

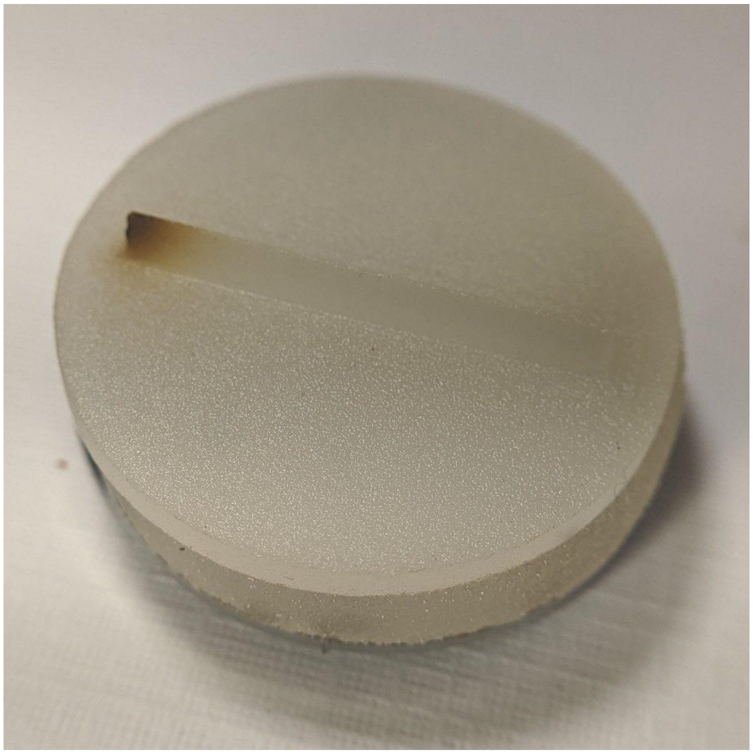

FIGURE 21: *Discoloration resulting from fuel charring due to arcing at the edge of the ridge emitter*

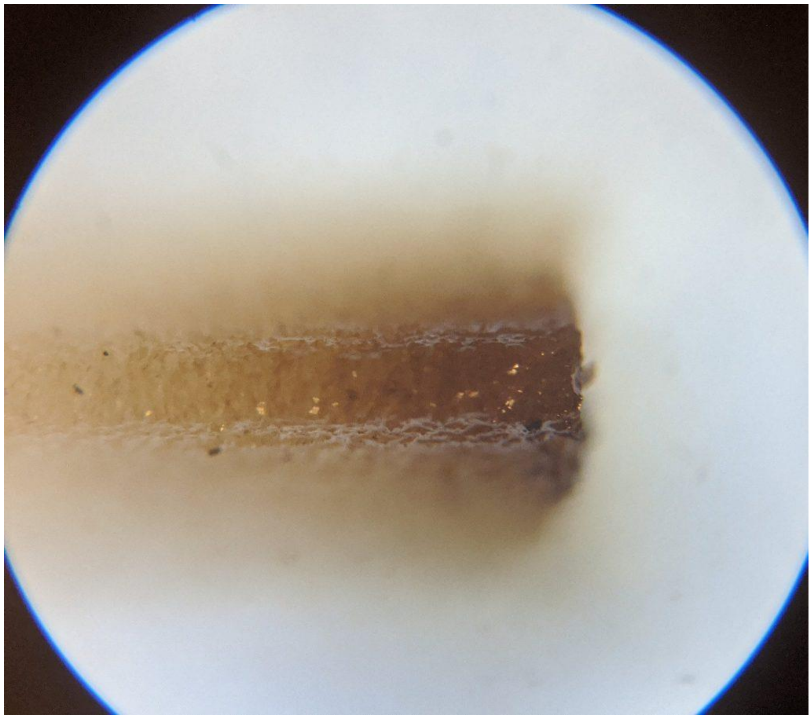

FIGURE 22: *Close-up of the charred fuel discoloration on the ridge emitter*

X. CONCLUSION

The second fueling and ignition test of the AIS-ILIS1 ionic liquid ion source electrospray thruster was completed. The fueling procedure was greatly improved from the first test, with no spraying of the fuel into the chamber during degassing. In addition, the new TVAC upgrade for bakeout was successfully qualified and run for the first time, to further help outgas the fuel and 3D printed thruster housing.

During testing, while the –HV supply rapidly failed, the +HV side operated stably for the short duration of the test, allowing for controlled cycling of the thruster, resulting in partial emission from the corner of the emitter. Although full ignition across the ridge emitter was not achieved, this emission marks a significant improvement from the first test, and from the collected data, significant improvements are underway to achieve further improved stable emission for the next test. Key takeaways of the test include:

- Fuel can be simply and easily degassed in covered beakers.
- Bakeout with Ultem eliminates any issues with outgassing faults from the thruster housing.
- No board faults were observed during testing, showing that the elimination of silkscreen and reducing sharp pints on HV through-hole components can help mitigate these issues.

- Improper housing design can make liquid bridging and tracking failures easier to occur.
- 3D printed tolerances must be addressed, with post processing necessary to bring them into spec.
- A change from a 1mm wide aperture slit to 0.75mm wide aperture slit increases field strength enough for more stable turn-on.
- Field strength is too high at the corner of the ridge emitter, causing excessive emission concentrated at the corner.
- Slower cycling allows for more stable operation.
- Mixed mode operation most likely caused liquid pooling and resulting failure, meaning the thruster is not yet operating in PIR mode. This is most likely due to excessive fuel flow rate, caused by too large pores in the reservoir.
- Better thruster conditioning procedures should be in place to safely raise thruster power.

Going forward, there are several major improvements that can be made to increase the chances of success. The thruster housing should be modified to eliminate the probability of liquid bridging due to liquid pooling and creep on the housing surface between the emitter and extractor. In addition, the extractor must also be modified to concentrate the field strength along the central length of the ridge emitter, while simultaneously reducing field enhancement at the corners. For protection of the emitter and to reduce the intensity of damage, surge protection resistors should be added to the circuit to limit fault currents in the event of shorting failures. The thruster should also be conditioned to help allow for stable emission to be safely achieved during operation. Instrumentation should also be set up to allow for reading of any collected emission current from the Faraday cup to better qualify operation.