# Applied Ion Systems

**AIS-TR-014**

**AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V6**

**Ignition Test 5 - 08/18/2020**

**Testing Report and Summary**

**Michael Bretti – 09/01/2020**

## I. TEST PARAMETERS

- **System:** AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V6
- **Fuel:** EMI-BF4
- **Maximum Chamber Pressure During Testing:** 2 x 10^-5 Torr
- **Testing Status:** COMPLETE
    - **Phase I:** Fueling – NOT REQUIRED
    - **Phase II:** Ignition – PARTIAL SUCCESS

## II. OVERVIEW

This test is the fifth ignition test 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.

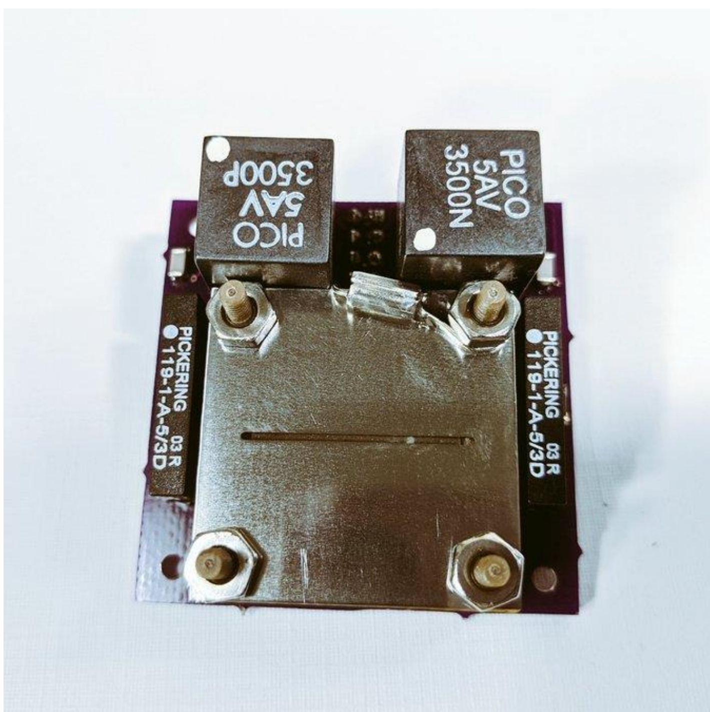


***FIGURE 1:*** *Completed AIS-ILIS1 V6 thruster assembly*

The AIS-ILIS1 aims to solve issues of ion thruster scaling and accessibility for nanosatellites, at significant 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 ignition test of the ILIS1 using the new V6 thruster board and standard 0.75mm aperture slit extractor, as well as analysis, results, and conclusions moving forward for future testing and system improvements.

## III. PRELIMINARY THRUSTER MODIFICATIONS

During the prior test, beam current and low-level ion emission was observed with the standard 1mm wide aperture slit extractor. In order to increase field enhancement at the porous glass ridge emitter, and increase thruster output, a narrower 0.75mm wide slit extractor was selected. This aperture was used during the second ignition test of the ILIS1 with the V5 thruster board and original thruster housing. Due to the thruster housing design, the thruster failed after a short period of operation due to liquid creep along the surface, bridging between the emitter and extractor, in which the high voltage conducted through and charred the fuel. In addition, issues with the V5 board caused failure of the –HV supply, only allowing the +HV supply to operate. The new housing design aimed to mitigate these liquid creep issues, and the new V6 board was designed to allow for more stable operation.

Taking lessons learned from the prior tests, the original extractor was post-processed by polishing the slit edges, as well as top and bottom surfaces of the extractor plate with 3000 grit sandpaper. This allows for significantly cleaner and smoother edges at the extractor, and more polished surfaces helps inhibit breakdown.

## IV. TEST PHASE I – FUELING AND BAKEOUT

Since only the extractor was changed between the prior test and this test, and the thruster being held in vacuum until the extractor swap, fueling and bakeout was not necessary to prepare for this current test.

## V. IGNITION TEST SETUP

After the new extractor plate was polished and cleaned, the ILIS1 was taken out of the vacuum chamber, which was still held to roughing levels from the prior test earlier that day. No charring or damage to the emitter was observed from the prior test. The thruster was re-assembled, with the emitter and extractor centered and aligned by sight. Due to the 0.75mm wide aperture size, alignment was relatively easy to achieve visually, by holding the thruster up to the light and looking across the thruster from either side with the HV relays removed, as well as visual alignment to center the ridge from the top. The thruster was then mounted to the Faraday cup test stand, and the assembly was mounted into the micro propulsion testing chamber, centered in full view in the 6” conflat viewport, and wired up for thruster power and control.

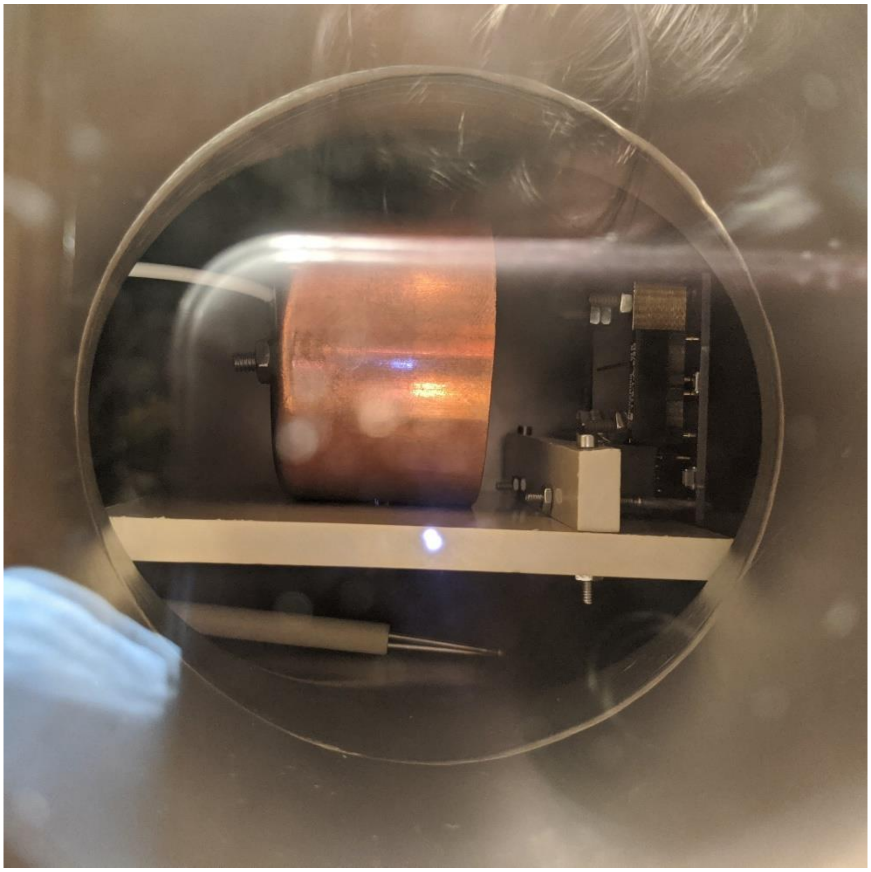

***FIGURE 2:*** *ILIS1 and Faraday cup test stand mounted inside chamber*

## VI. TEST PHASE II – IGNITION

The chamber was evacuated to a pressure of 2x10^-5 Torr before starting up the thruster. The thruster was first started at minimum power in manual monopolar mode, first with +HV for several minutes, then switching to –HV to make sure the circuit was operational as expected and to establish minimum output. A very faint, barely visible glow was confirmed at the corner during this warm-up phase, indicating emission had started.

After the warm up phase, the thruster control was set to automatic bipolar mode with the same timing sequence as the prior test, at 10 seconds per polarity, with a 2 second interval between polarity transitions. Input voltage to the thruster was slowly increased until the output readout indicated the thruster was operating at +/-4kV. Readout from the oscilloscope looking at the Faraday cup with 100k shunt resistance was at +/-20mV, indicating +/-200nA of beam current.

After about 10 minutes operating stably like this, the time per polarity was increased to 30 seconds, and the voltage slowly raised to +/-4.5kV. At this point, beam readout was still at +/-200nA of current. After 30 minutes of continuous operation, beam current began to rise to +/-500nA, with thruster voltage at +/-4.6kV.

After 40 minutes total run time of operation at +/-500nA, thruster power was further increased until the thruster reached a peak beam current of +/-2uA. Voltage peaked at +/-4.8kV, however during operation settled back down to +/-4.7kV. The thruster was operated in this higher emission mode for a period of 10 minutes before the thruster arced between the emitter and extractor, leading to shorting failure. Overall, the thruster was operated stably for a period of 50 minutes total during the ignition test.

## VII. POST TEST VIDEO ANALYSIS

During the test, video was recorded of both thruster operation as well as the oscilloscope readout. Unlike the prior test, very clear and bright ion beam emission was easily observed during testing.

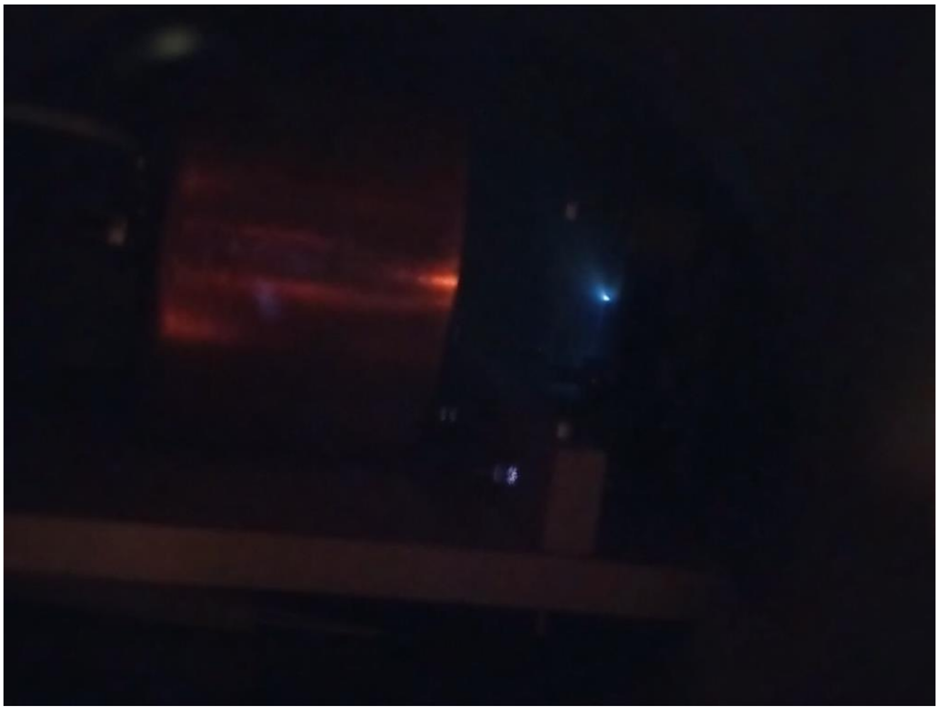

***FIGURE 3:*** *Ion beam emission during testing at 500nA of beam current*

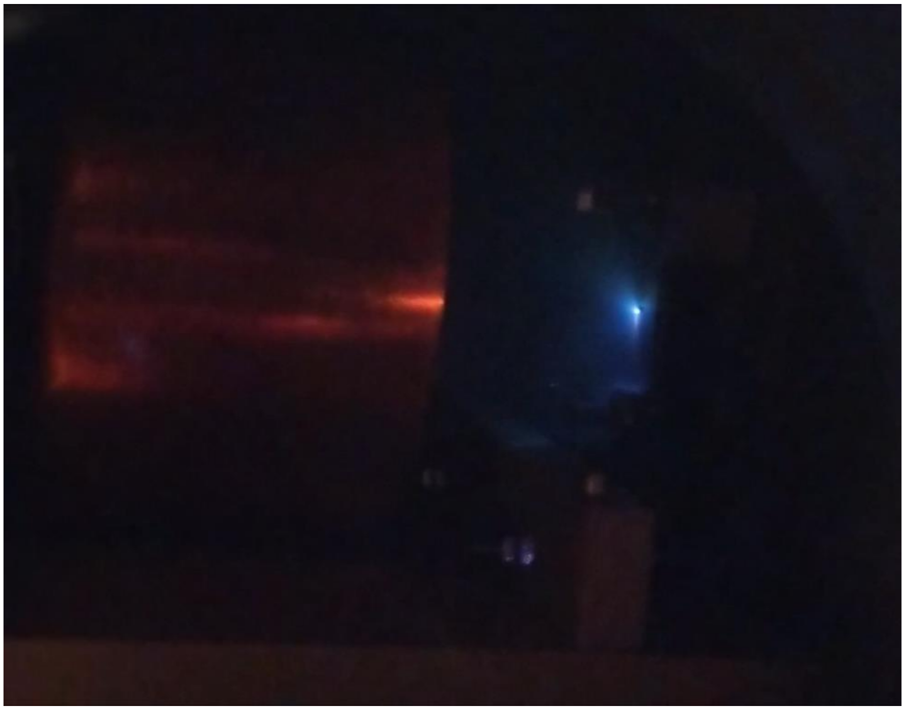

***FIGURE 4:*** *Ion beam emission during testing at peak beam currents of 2uA*

Beam readings from the oscilloscope corresponded to polarity switches and pauses in operation. Slight fluctuations in beam were observed during testing, however arcing of the thruster did not occur until the very end of the test.

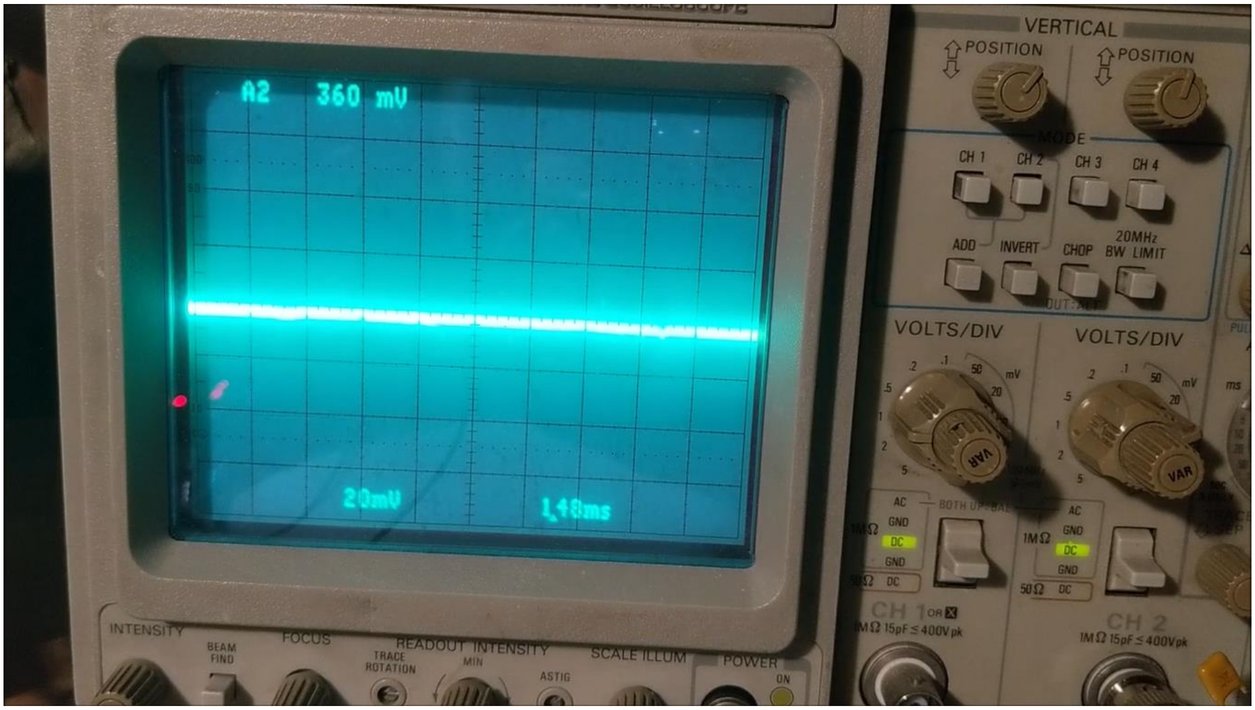


***FIGURE 5:*** *Oscilloscope readout – 20mV/div, thruster is currently off, no beam recorded*

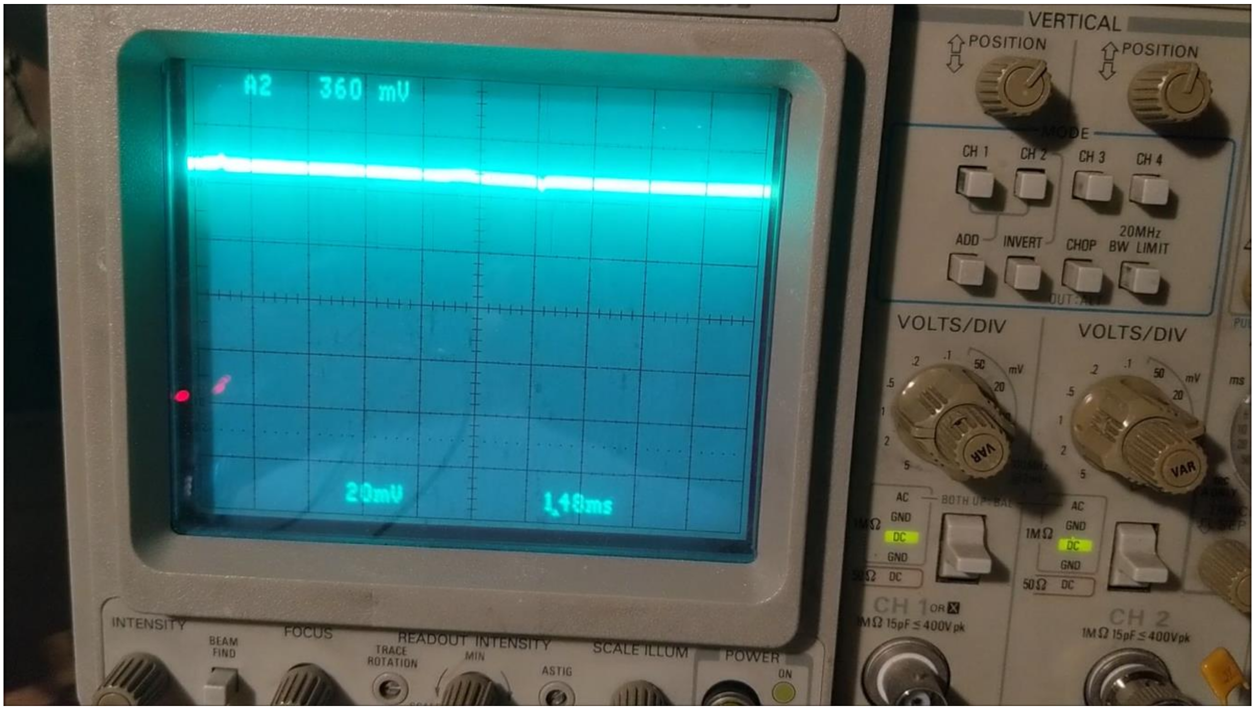


***FIGURE 6:*** *Oscilloscope readout – 20mV/div, thruster is currently operating in +HV cycle, with voltage reading of 45mV, corresponding to 450nA of beam current*

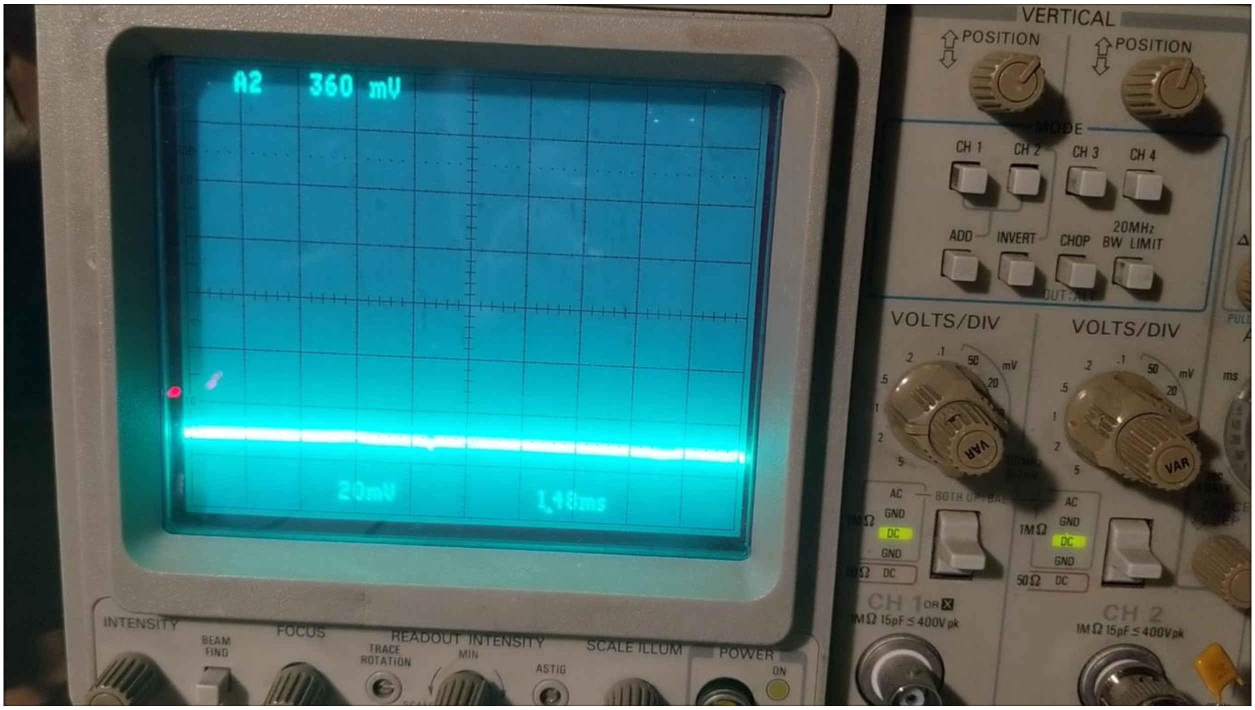


***FIGURE 7:*** *Oscilloscope readout – 20mV/div, thruster is currently operating in -HV cycle, with voltage reading of -50mV, corresponding to -500nA of beam current*

Assuming purely ionic emission, we can calculate some rough initial performance estimates. For thrust, let's assume PIR with 50% monomers and 50% dimers. Averaging this for both monomer/dimer emission with EMI/BF4 beams, max theoretical thrust is around 0.24uN. 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. This represents an increase in 3x the thrust at 39x beam current from the prior ignition test 4, which was estimated to have produced only 0.051uN of thrust.

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. This represents a large increase from the prior observed 3650s from ignition test 4, in which the thruster was operated at a maximum of +/-4kV.

Although these numbers are very rough estimates based on operating mode assumptions, beam current readings, and emitter operating voltages, this can give a reasonable first approximation of performance currently expected from the thruster during this test.

## VIII. POST TEST THRUSTER INSPECTION

After testing, the thruster was removed in the next few days to prepare for the sixth ignition test, as well as for post test inspection. During inspection it was discovered that the cause of shorting and thruster failure was again due to liquid creep along the surface of the 3D printed Ultem 1010 housing, allowing for a conductive bridge to form between the porous glass emitter and the stainless steel extractor plate. However, surprisingly the liquid bridging and creep was found to have originated not at the emitter like in prior testing, but at the disk surface near one side of the housing, on the same side that emission was occurring.

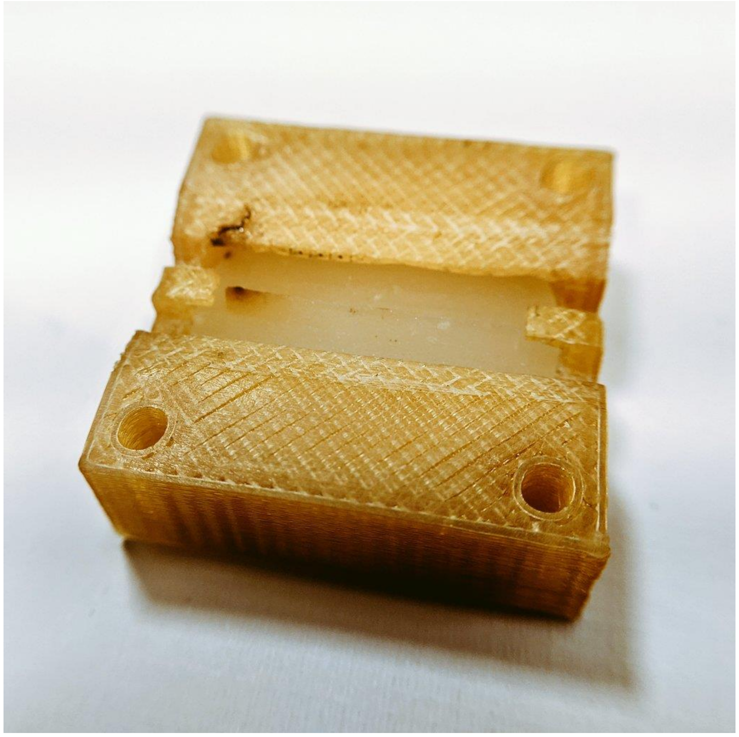

***FIGURE 8:*** *Emitter and 3D printed Ultem 1010 housing during post test inspection. Fuel charring can be seen on the left corner, as well as liquid bridging failure due to liquid creep on the same side where emission occurred where the porous glass and housing meet.*

Upon closer inspection of the thruster housing, it was also found that the arcing failure occurred through the bottom of the housing which touched the emitter disc, snaking its way through the 3D printed housing.

***FIGURE 9:*** *View of the Ultem housing where the arcing failure occurred due to liquid creep.*

In addition, emission was again shown to occur only at one corner of the emitter, which has proven to be a key weakness of standard linear slits as opposed to the enhanced extractor slit introduced in ignition test 3.

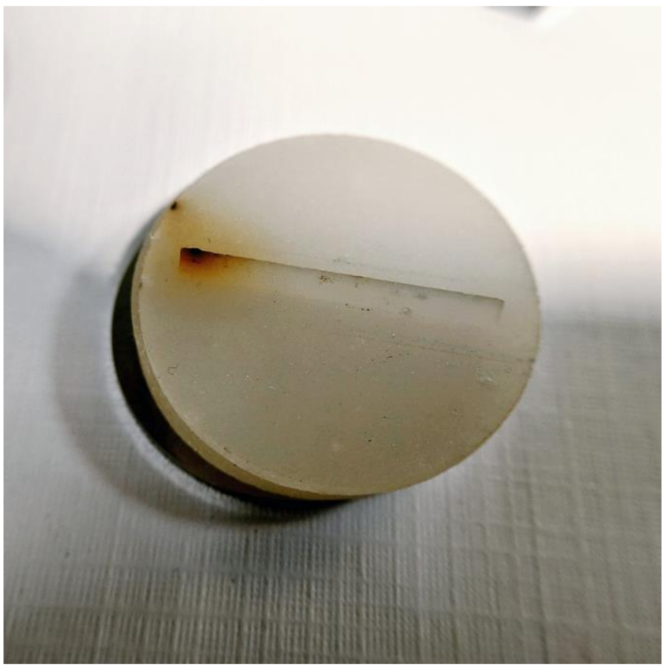

***FIGURE 10:*** *Fuel charring present at the emission corner of the ridge emitter, as well as the point on the periphery of the disc where liquid creep and arcing occurred.*

## IX. CONCLUSION

The fifth ignition test of the AIS-ILIS1 ionic liquid ion source electrospray thruster was completed. During the test, the thruster was successfully operated stably for a total run time of 50 minutes at 30 seconds per polarity in automatic bipolar mode, with a 2 second transition between polarity, at +/-4.7kV peak voltage, with stable emission at 0.5uA for the duration of the test, achieving the highest beam current yet recorded for the ILIS1 at the end of the test at 2uA. This corresponds to a rough corrected thrust estimate of 0.17uN, and a rough corrected ISP of 4190s. This represents a major advance in operation of the ILIS1, marking the first successful extended run in automatic bipolar mode at the highest recorded output yet.

Emission during this test was significantly more visible than the prior test, and matches the visual plume brightness levels consistently when the thruster was first run with the 0.75mm extractor during ignition test 2. However, this test marked a significant increase in lifetime and stability, with a jump from 2 minutes of operation to 50 minutes of operation with the 0.75mm extractor. This can be attributed to the improved housing design, as well as current limiting resistors in place with the V6 board. This test also showed again and consistently with prior tests that a standard linear extractor aperture with a ridge emitter produces undesirable emission concentration at the corner of the ridge.

The V6 electronics were further qualified and passed testing with very successful operation. The original design specifications targeted a maximum voltage of +/-3.5kV, however the thruster was operated to a level of up to +/-4.8kV without any arcing, damage, or glitches. Minor flashovers did occur a couple of times during testing, however this did not affect operation nor result in any damage to components of the circuit itself.

Although successful ignition across the ridge emitter was not achieved, this test marks a massive step forward in thruster output, operational stability, and electronics over all other prior tests with the ILIS to date. A summary of key takeaways from the test are as follows:

- 0.75mm width aperture slit presents a significant increase of extracted beam current over the prior 1mm slit as expected.
- Visual beam output is consistent with prior testing with the same extractor design and similar voltage levels.
- Liquid creep and bridging failure can occur in other areas besides the emitter, particularly where the housing and emitter disc meet.
- Due to the non-solid fill of FDM 3D printing, voids and gaps can present pathways for liquid bridging failures to potentially occur due to arcing from the liquid between the emitter and extractor.
- Thruster housing design must be further refined to reduce liquid creep failures.
- The thruster electronics can be operated stably for extended periods of time at significantly higher voltages than originally designed for.

Going forward, the enhanced extractor design must be implemented to eliminate excessive emission and early turn on at the ridge emitter corner, with widths between 0.5mm and 0.75mm, with spacing between the extractor and emitter at 0.1mm to 0.2mm. In addition, while the new housing design significantly improved lifetime, it is apparent that further considerations for improving design must be addressed in order to reduce the probability of shorting failure due to liquid creep between the emitter and extractor, which was found to have the potential to occur in places other than immediately around the emitter itself.