Applied Ion Systems

AIS-TR-015

AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V6
Ignition Test 6 - 08/21/2020
Testing Report and Summary

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I. TEST PARAMETERS

- **System:** AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V6
- **Fuel:** EMI-BF4
- **Maximum Chamber Pressure During Testing:** 1.9 x 10^-5 Torr
- **Testing Status:** COMPLETE
  - **Phase I:** Fueling – NOT REQUIRED
  - **Phase II:** Ignition – SUCCESS

II. OVERVIEW

This test is the sixth and final ignition test for the initial development phase 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.

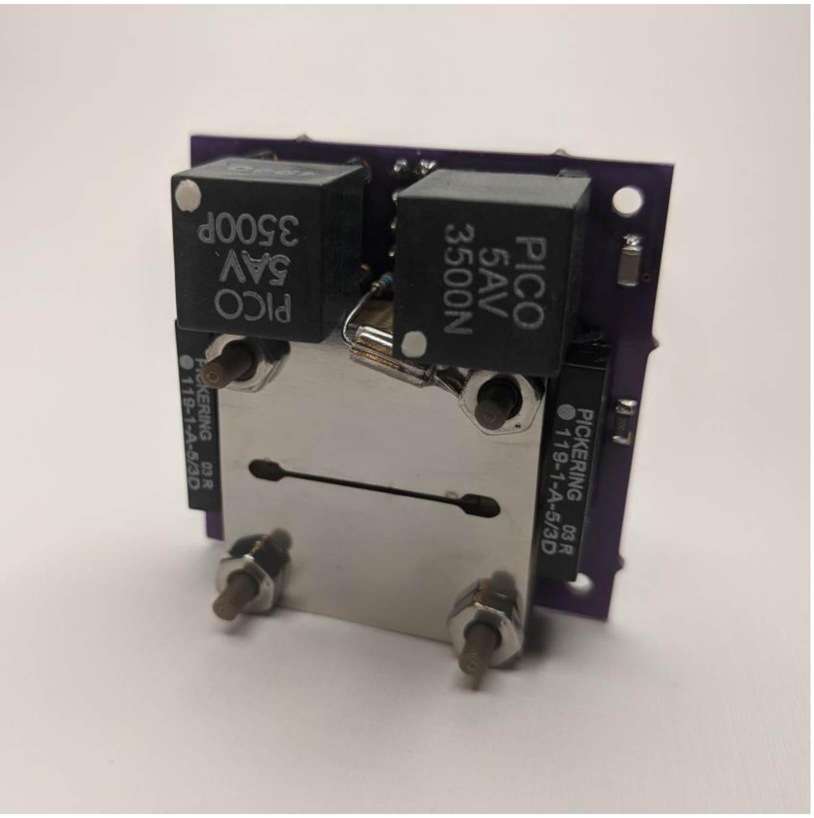

FIGURE 1: *Completed AIS-ILIS1 V6 thruster assembly with enhanced extractor*

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 with enhanced extractor with a 0.5mm aperture, 0.1mm vertical shim, and modified housing, as well as analysis, results, and conclusions moving forward for future testing and system improvements.

III. PRELIMINARY THRUSTER MODIFICATIONS

During the prior ignition test 5, the ILIS1 was run with the standard 0.75mm wide linear slit extractor, achieving average beam current of 0.5uA with a peak output of 2uA. However, emission was concentrated at one corner of the porous glass ridge emitter. In order to increase field enhancement and more uniform field distribution across the length of the porous glass ridge emitter, eliminate emission at the corners, and increase overall thruster output, the new enhanced extractor design was used, which incorporates flared aperture ends at the corners, and a narrower central slit region at 0.5mm wide. The original extractor plate was 0.1mm thick, where the new plate was increased to 0.25mm thick.

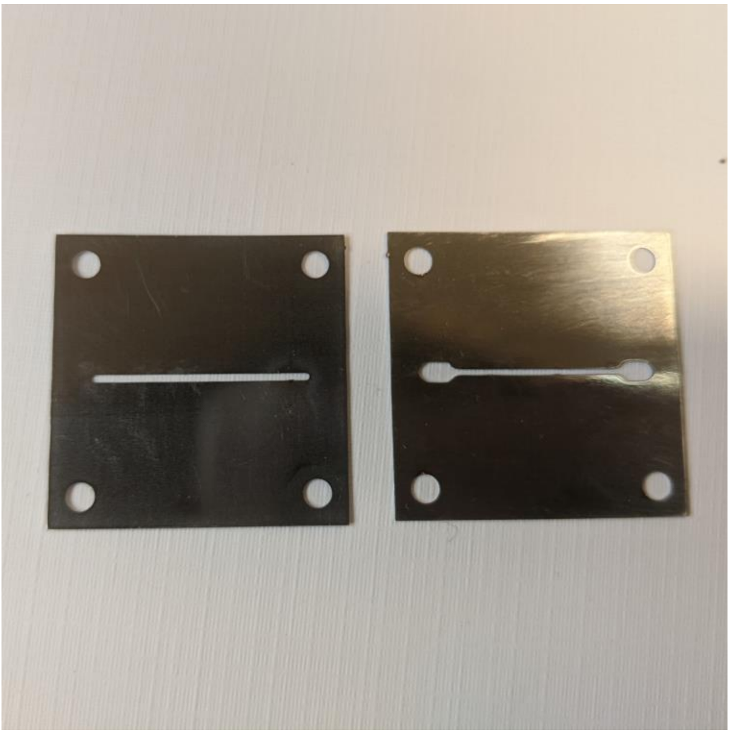

FIGURE 2: *Original 0.75mm linear extractor (left) and new enhanced 0.5mm flared extractor (right)*

During the third ignition test, this same extractor was used, however it was found that spacing was too tight with 0mm vertical clearance between the top of the emitter and the bottom of the extractor plate aperture, causing immediate shorting and failure of the thruster. To compensate, 0.1mm shims were used, cut from a spare extractor plate, to increase the vertical spacing between the emitter and extractor to 0.1mm.

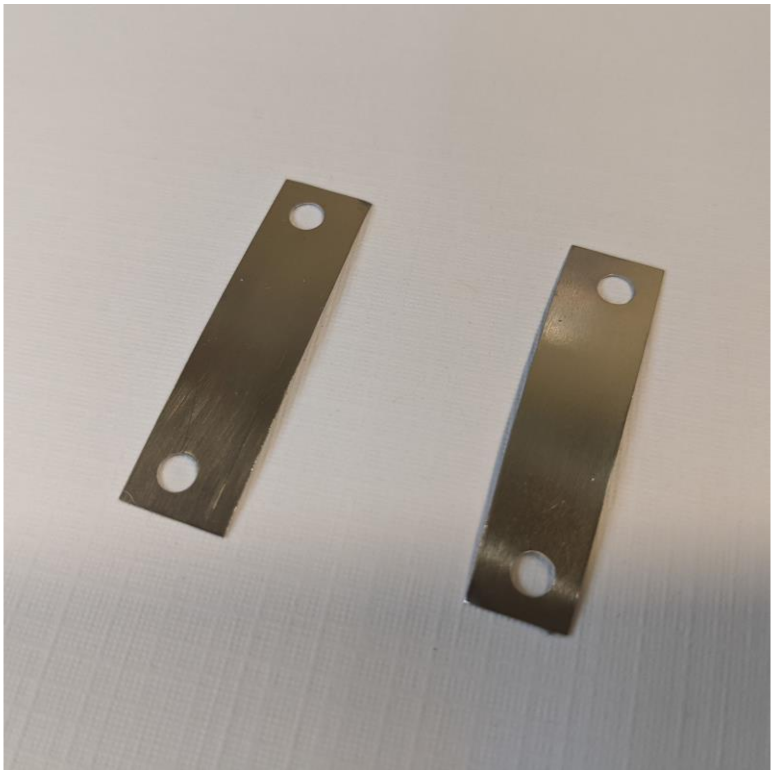

FIGURE 3: *0.1mm thick vertical shims*

During the prior test, the new V6 board was also qualified for the first time at extended operation at high voltages of up to 4.8kV without any issues during testing. This far exceeds the original design specifications of 3.5kV, and is attributed to the addition of new 100k surge protection resistors placed between the outputs of the HV relays and the HV emitter contact pad, the HV filter capacitor and HV emitter contact pad, and the extractor and ground.

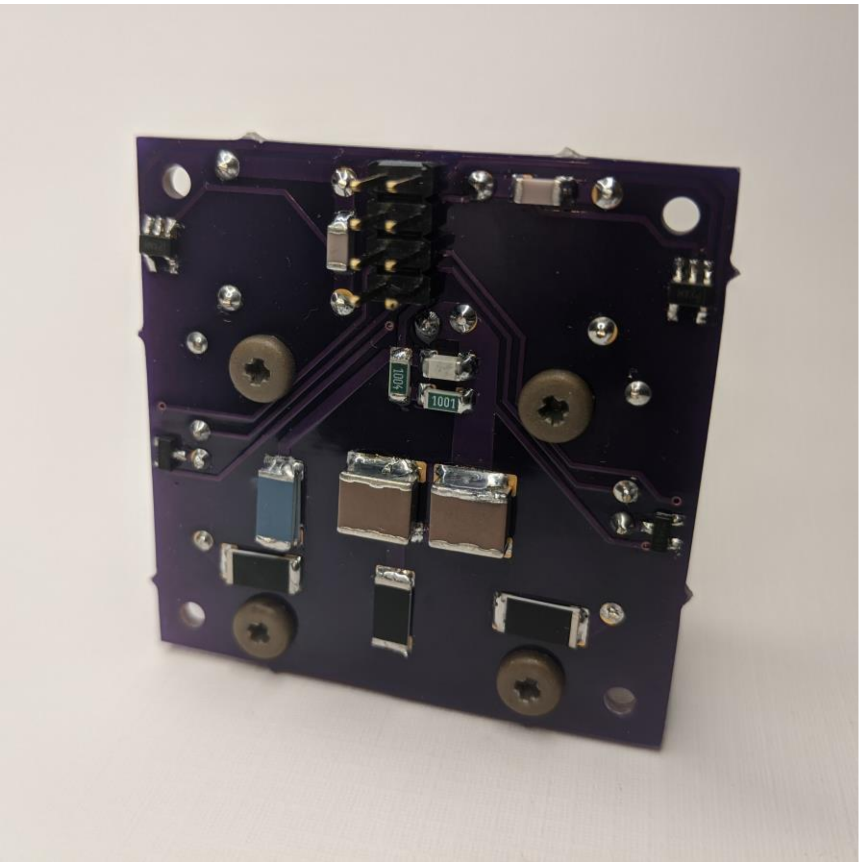

FIGURE 4: *V6 thruster board back with HV rated 100k SMT surge protection resistors (black resistors at the bottom of the circuit)*

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 was 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. Due to operation of the thruster during the prior test, fuel charring was present on the edge where emission occurred, as well as on the housing where liquid creep and eventual arcing occurred. Both of these areas were carefully cleaned to remove all traces of burnt fuel.

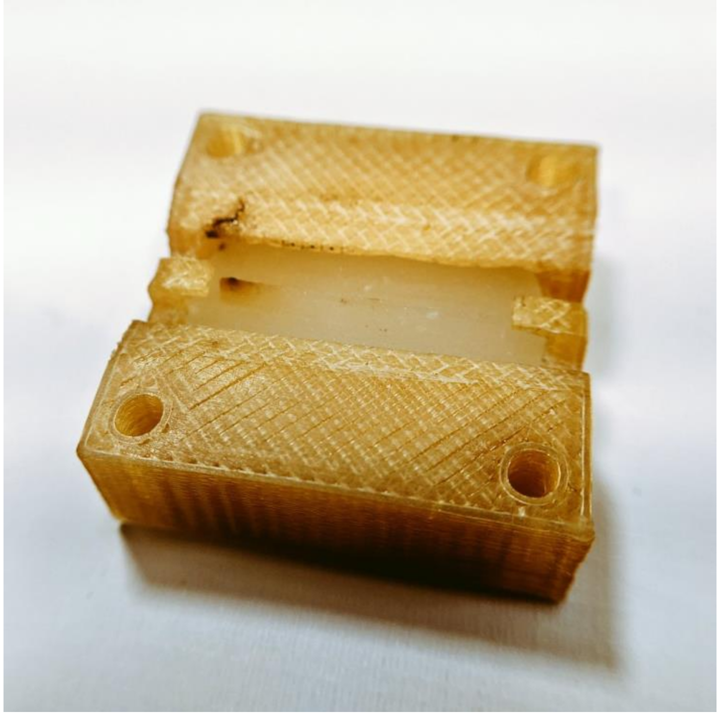

FIGURE 5: *Fuel charring from prior ignition test*

The thruster was re-assembled, with the emitter and extractor centered and aligned by sight, with the addition of the two 0.1mm vertical shims, running parallel with the ridge across the two top mounting holes and two bottom mounting holes. While prior attempts to align the 0.5mm slit by eye proved to be a significant challenge, the addition of the 0.1mm shims, as well as practice over several tests, made alignment significantly easier and more reliable. 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.

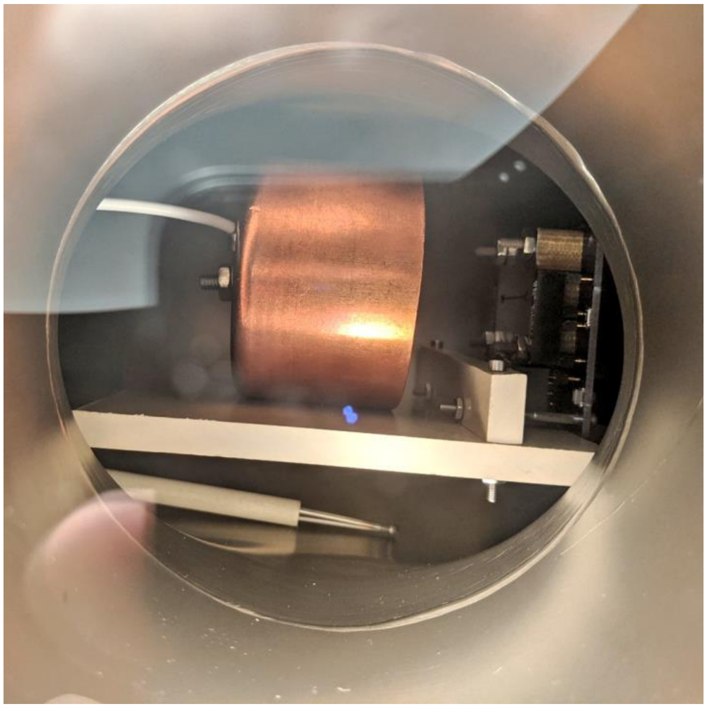

FIGURE 6: *ILIS1 and Faraday cup test stand mounted inside chamber*

VI. TEST PHASE II – IGNITION

The chamber was evacuated to a pressure of 1.9x10^-5 Torr before starting up the thruster. The thruster was first started with an initial warm up phase for a period of 10 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. Power was slowly increased until a visible glow was seen across the central region of the emitter, confirming not only success of the new enhanced extractor design, but that stable multi-mode emission was being achieved across the central region of the emitter for the first time.

After the initial warm up phase, the thruster power was further increased for another 5 minutes prior to switching to bipolar operation. Once stable emission was confirmed, thruster control was set to automatic bipolar mode at 30 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 +/-3.7kV. Readout from the oscilloscope looking at the Faraday cup with 100k shunt resistance was at +/-50mV, indicating +/-500nA of beam current. During the course of the first 40 minutes of operation, thruster output fluctuated, rising and lowering until stabilizing out at +/-500nA at an increased voltage of +/-4.6kV. The thruster plume glow had reduced in intensity by this point, however emission remained at stable levels.

After 1 hour of operation in this mode, thruster cycling times were decreased to 10 seconds per polarity with a 1 second transition between polarity reversals. After a few minutes, the cycling time was further reduced to 5 seconds per polarity with a 0.5 second transition. After another 10 minutes, the thruster cycling time was further reduced to 3 seconds per polarity with a 0.5 second transition time. At this cycling frequency, some instabilities were seen in both beam as well as occasional glitching of the controlling, requiring several reboots. Some arcing was observed inside the 3D printed housing, however emission continued.

After another 5 minutes of operation, emitter current significantly increased to almost 5uA of beam current on the positive cycle, although the negative cycle seemed to be lagging by less than half that value. At this point the voltage had increased to +/-5kV, the highest values run yet with the ILIS1 board. Finally, after 5 minutes of operation in this higher mode of emission, emission ceased with evidence of arcing between the emitter and extractor, confirmed visually and with thruster readouts. Thruster power was shut down, and the test was ended.

VII. POST TEST VIDEO ANALYSIS

During the test, several extended videos were recorded of thruster operation. Immediately at the beginning of the test, and throughout the test, for the first time ever during this development phase of the ILIS1, clear, long-term, and stable multi-site emission was achieved across the central region of the emitter, indicating that not only the enhanced extractor functioned properly, but the 0.1mm shims allowed for operation without immediate shorting. In addition, no emission or arcing was seen at the corners of the ridge emitter for the duration of the test. Due to the more uniform emission and better alignment of the ridge to extractor aperture, beam divergence was significantly reduced from prior tests.

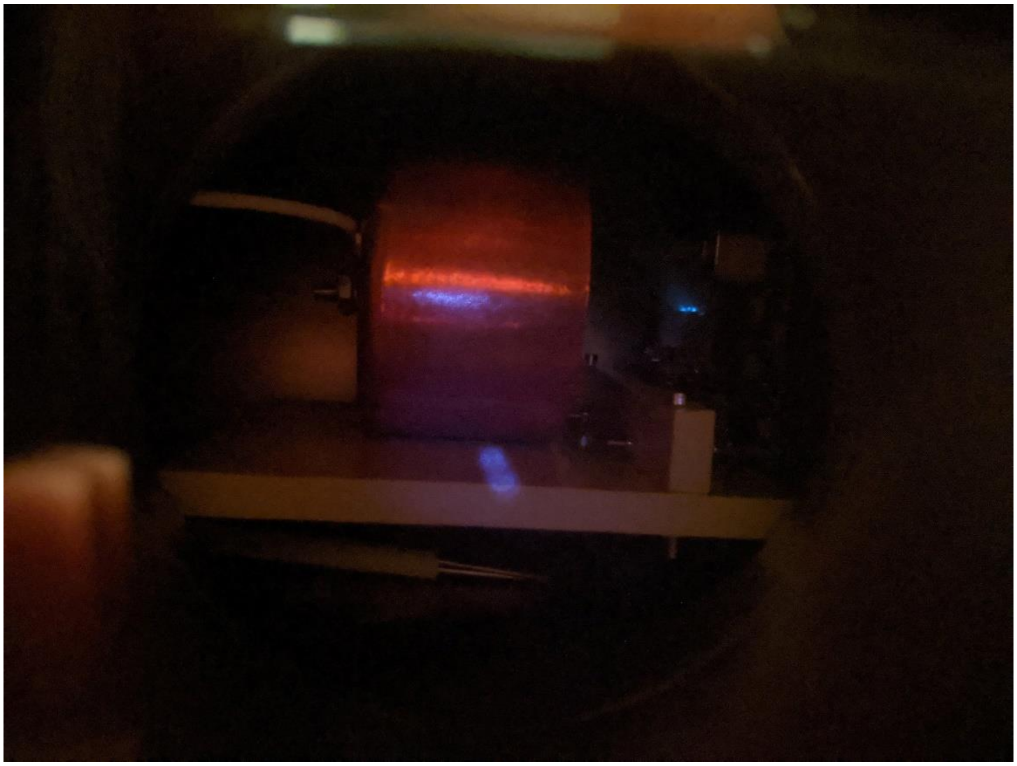

FIGURE 7: *Multisite ion beam emission occurring across the central region of the emitter*

Assuming purely ionic emission, we can calculate some rough initial performance estimates. For initial thrust estimates, let's assume PIR with 50% monomers and 50% dimers. Let us first examine stable operation at 500nA of beam current. Averaging this for both monomer and dimer emission with EMI/BF4 beams, max theoretical thrust is around 0.06uN. 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 0.04uN. Now looking at the peak beam current of 5uA, with the similar assumptions stated above, this gives us a rough corrected peak thrust estimate of around 0.4uN, the highest thrust recorded yet for the ILIS1.

For ISP, assuming the same PIR mode of operation with 50% monomers and 50% dimers, at +/-4.6kV during stable emission at 500nA of beam, this gives a max average theoretical ISP of around 8288s. 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 4144s. Now looking at the peak emitter potential of 5kV, factoring in the same assumptions stated above, this brings the rough corrected peak ISP estimate to 4320s, which is the highest estimated ISP to date for the ILIS1.

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 a couple of weeks at low vacuum levels after testing, the thruster was removed 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. This liquid bridging and creep was found to have originated at the disk surface near one side of the housing. This failure is consistent with the prior test during peak thruster operation. In addition, minor charring was observed along the ridge of the thruster. Fuel darkening was seen along the central region of the emitter, with no charring or evidence of emission at the corners, again confirming the successful operation of the new enhanced extractor geometry.

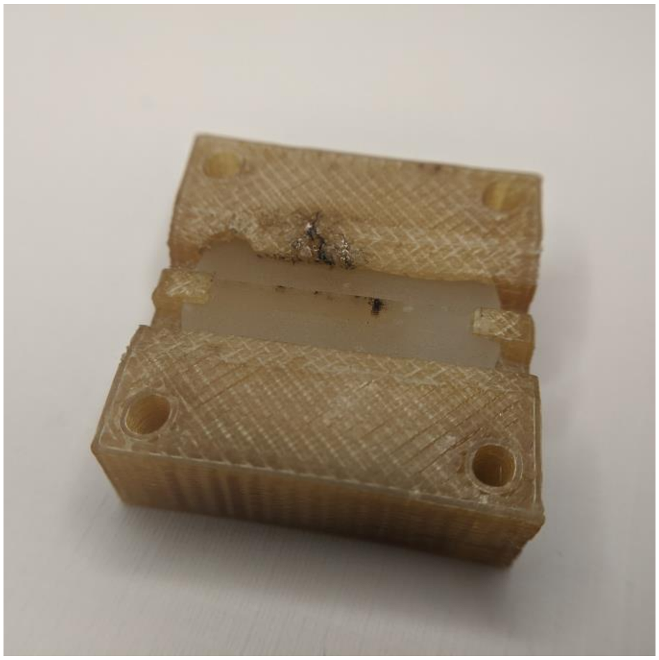

FIGURE 8: *Emitter and 3D printed Ultem 1010 housing during post test inspection. Fuel charring can be seen along the emitter where peak emission occurred, as well as liquid bridging failure due to liquid creep where the porous glass and housing meet.*

Inspecting the extractor electrode, corresponding areas of bombardment due to beam intercept, as well as fuel charring can be see, both long the emitter as well as where liquid creep occurred from the disc and along the surface of the thruster housing to the extractor.

FIGURE 9: *Bottom side of the extractor electrode where ion beam erosion and liquid fuel charring can be seen.*

IX. CONCLUSION

The sixth and final ignition test of the first phase of development of the AIS-ILIS1 ionic liquid ion source electrospray thruster was completed. During the test, stable multi-site emission was observed across the central region of the slit, with no early turn on or emission from the corners, indicating success of the new enhanced extractor design. The thruster was operated for a total duration of 1.5 hours during the test in automatic bipolar mode, the longest run time yet for the ILIS1. During the bulk of the test for the first hour the thruster was successfully operated stably at lower emission currents of 500nA, at 30 seconds per polarity in automatic bipolar mode, with a 2 second transition between polarities, at +/-4.6kV peak voltage. This corresponds to an estimated corrected thrust of 0.04uN and an estimated corrected ISP of 4144 seconds.

Towards the end of the test, thruster cycling times were decreased and successfully operated for the first time ever, with the most stable times at 5 seconds per polarity and 0.5 seconds between transitions. At the peak of emission, the thruster achieved 5uA of beam current at 5kV emitter voltage, giving a rough corrected peak thrust estimate of around 0.4uN, and a rough corrected peak ISP estimate of 4320s, the highest numbers achieved yet for the ILIS1.

In addition, the thruster electronics were pushed to their highest operating potentials yet, at a level of +/-5kV, far exceeding the original design specifications of +/-3.5kV. No arcing, board breakdown, board flashover, or electronic component failure occurred during the test.

This test broke significant ground with the first development phase of the ILIS1, achieving multi-site emission across the ridge emitter, as well as achieving the highest peak thrust, highest peak ISP, longest run times, highest operating voltages, shortest cycling times, and lowest beam divergence yet of any test to date with the thruster. A summary of key takeaways from the test are as follows:

- The enhanced extractor design with thinner main aperture and flared ends was successfully confirmed in achieving more uniform field distribution along the emitter while eliminating emission from the corners of the ridge emitter.
- A 0.1mm shim between the emitter and extractor provided optimal distance for successful operation using the narrow 0.5mm slit.
- Multi-site emission across the ridge length can be successfully achieved with proper extractor optics.
- Emission can fluctuate over the course of testing, and exhibit significant differences in max emission between positive and negative polarities.
- Emission can significantly increase after longer periods of conditioning, and can rise rapidly with small increases in voltage, which is expected due to the operation of the thruster as an ion diode.
- The design appears to have reached its maximum achievable output in its current configuration. Turn on and peak operating voltages remain significantly higher than initially expected, requiring significant redesign of the emitter.
- More emitters are required for increased output, and sharper edges are needed to increase field enhancement to allow for much lower turn-on and operating voltages.

- Liquid creep and bridging failure is currently the dominant failure mode of the ILIS1 at higher emission levels, occurring from the disc itself.
- Thruster housing design must be redesigned to eliminate liquid creep and bridging failures, which is the key lifetime constraint of the current design.
- The thruster electronics have been successfully qualified in bipolar mode operation from 30 seconds per polarity down to 5 seconds per polarity, and 2 second transition times to 0.5 second transition times without any issues.
- Cycling times of 3 seconds per polarity at 0.5s transitions introduces some instabilities in the current configuration.

This test successfully concludes the first development phase of the first generation of AIS-ILIS ionic liquid ion source electrospray thrusters for nanosats and picosats. Over the course of the development, tremendous improvements have been made at all levels, progressing from non-functional electronics and emission times less than a second, to fully stable bipolar operation of the entire thruster system with multi-site emission. With the successful operation of the ILIS1, this marks the first ever micro-ion thruster designed, built, and tested to be specifically compatible with the power and size restrictions down to PocketQube class satellites, and is currently potentially the smallest fully integrated micro-ion thruster systems in development in the field.

Going forward, it is clear that the emitter must be redesigned, not only to achieve lower turn-on and operating voltages, but to allow for full thrust output. The current goal for the AIS-ILIS series thruster modules is to achieve a minimum of 20uN per module, at an ISP of no less than 3500s. While ISP is relatively easy to achieve with higher operating voltages, thrust remains the key challenge, requiring significantly more emission sites, as well as sharper-featured emission sites to allow for additional bulk-emission turn on. Significant design considerations must also be given towards the housing design, which surprisingly remains the key lifetime constraint with liquid creep and bridging failures as the dominant failure mode of the thruster. Part of this may also extend to the fact that at excessively high voltages, droplet spray can occur, further necessitating lower operating voltages, as well as the need to move towards finer porosity glass emitters and reservoirs to further choke passive capillary fuel flow and force the thruster into fully PIR mode of operation. Work is already underway in designing the next generation thruster of the series, the AIS-ILIS2, which will incorporate significantly more emission features, either as numerous sets of ridges, or an array of spike emitters to achieve full target thrust at target ISP, and incorporate additional features such as onboard processing for automatic start-up, control sequences, and monitoring of the thruster during operation.