Applied Ion Systems

AIS-TR-018

AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V7

Ignition Test 7 - 10/14/2020

Testing Report and Summary

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I. TEST PARAMETERS

- **System:** AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V7
- **Fuel:** EMI-BF4
- **Maximum Chamber Pressure During Testing:** 5 x 10^-6 Torr
- **Testing Status:** COMPLETE
    - **Phase I:** Fueling – SUCCESS
    - **Phase II:** Ignition – SUCCESS

II. OVERVIEW

This test represents the seventh test of the AIS-ILIS1 ionic liquid ion source electrospray thruster for nanosatellites, and a new phase of development for the thruster series. In the prior *AIS-TR-015* report documenting the sixth ignition test of the ILIS1, it was expected to be retired for new developments. However, the system was brought back into active development to further collect data and experiment with new improvements for the thruster to better qualify additional features that would be incorporated into the next development phase.

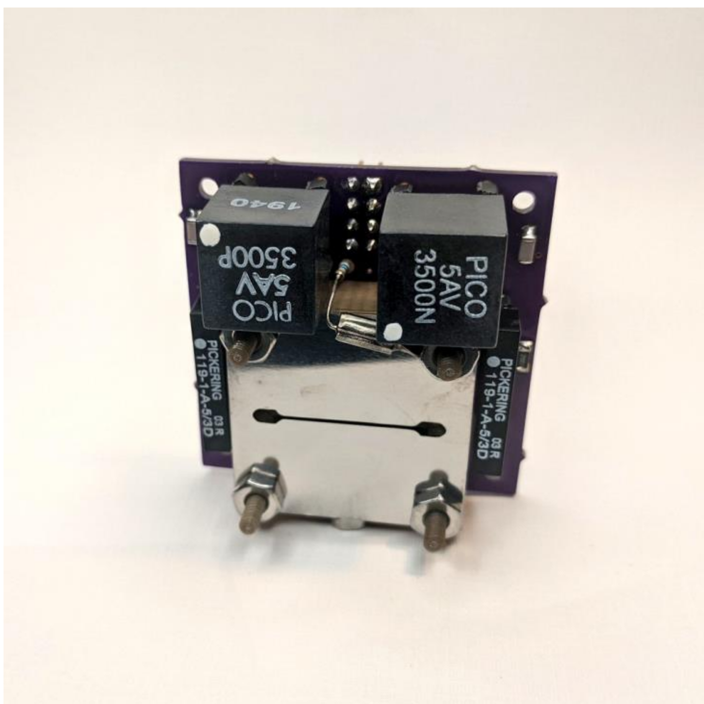

FIGURE 1: *Completed AIS-ILIS1 V7 thruster assembly*

The AIS-ILIS1 is part of an ongoing development effort at AIS to create micro ionic liquid electrospray thrusters aimed at solving 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 thrusters 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 V7 thruster modifications, featuring a new housing design and the incorporation of a shield electrode for the reduction of liquid creep failure.

III. NEW V7 DESIGN FEATURES

During prior testing, peak emission was achieved driving the thruster at very high voltages of up to 4.7kV, resulting in thrust levels of around 0.4uN at 500nA of beam current. Multisite emission was also achieved across the central region of the linear ridge emitter. However, during all tests run at excessive voltages with increases output, thruster failure always occurred due to liquid creep, where the ionic liquid would be slowly drawn up from the surface of the porous glass emitter disc, onto the 3D printed housing, and eventually come in contact with the extractor electrode, causing shorting. This type of failure can also be seen in literature with testing of similar macro-ILIS thrusters at very high voltages. In order to mitigate, and hopefully eliminate this issue, several design changes were incorporated for the V7 test. The housing was redesigned to further reduce any direct paths for the ionic liquid to creep up and make contact with the extractor plate. In order to further suppress this effect, a simple shield electrode was designed and fabricated out of 0.2mm thick stainless steel. A slit through the center allows for only the ridge emitter to protrude through, covering the rest of the porous glass disc.

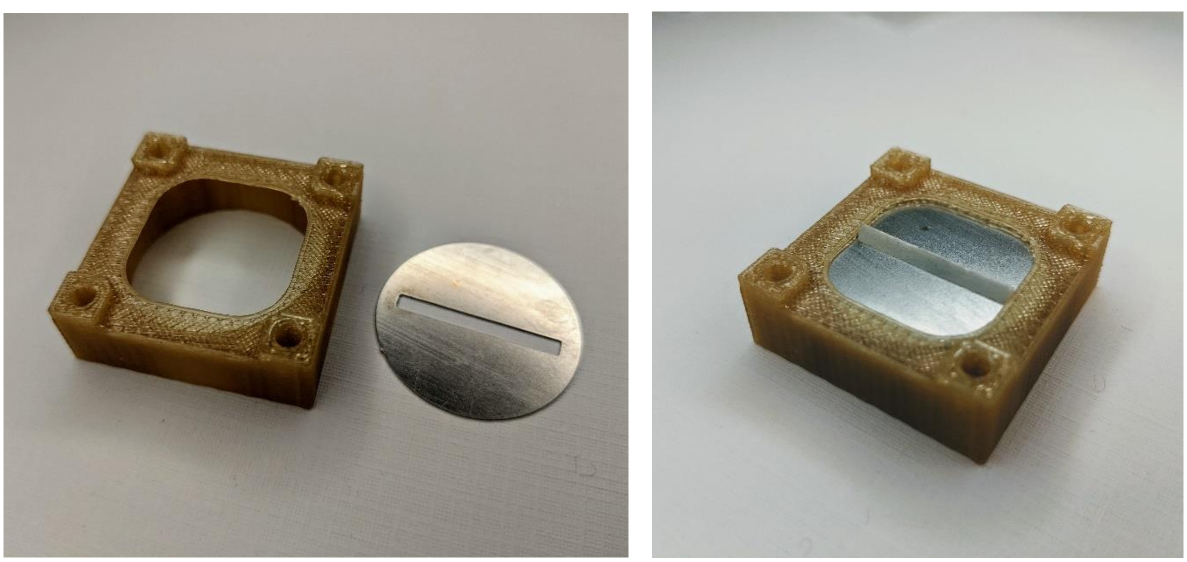

FIGURE 2: *New 3D printed housing design and shield electrode (LEFT), shield electrode with housing and test emitter for fit check (RIGHT)*

IV. TEST PHASE I – FUELING AND BAKEOUT

Fueling and bakeout preparations for the ILIS1 test followed the same procedures adopted in prior testing. The porous glass emitter and reservoir are placed in separate Pyrex beakers, partially submerged in ionic liquid. Stainless steel wool is then placed in the remaining volume of the beaker to act as a liquid trap to prevent splashing and spray of the fuel during degassing, as well as prevents the discs from bouncing around during outgassing, which can be violent during initial pumpdown due to the trapped gases and water vapor in the porous glass and ionic liquid fuel. Aluminum foil is then used to cover the tops of the beakers to further prevent any fuel spray during degassing. The beakers, along with the Ultem 1010 3D printed housing, and thermocouple gauge for bakeout are placed onto a PEEK baseplate to prevent direct contact with the heated chamber walls. The chamber is pre-pumped and pre-baked to roughing levels up to 80C for several hours, then sealed off and cooled overnight. The system then undergoes full vacuum pumping and bakeout the next day, pumping down to 10^-5 Torr and baking to 80C for at least two hours.

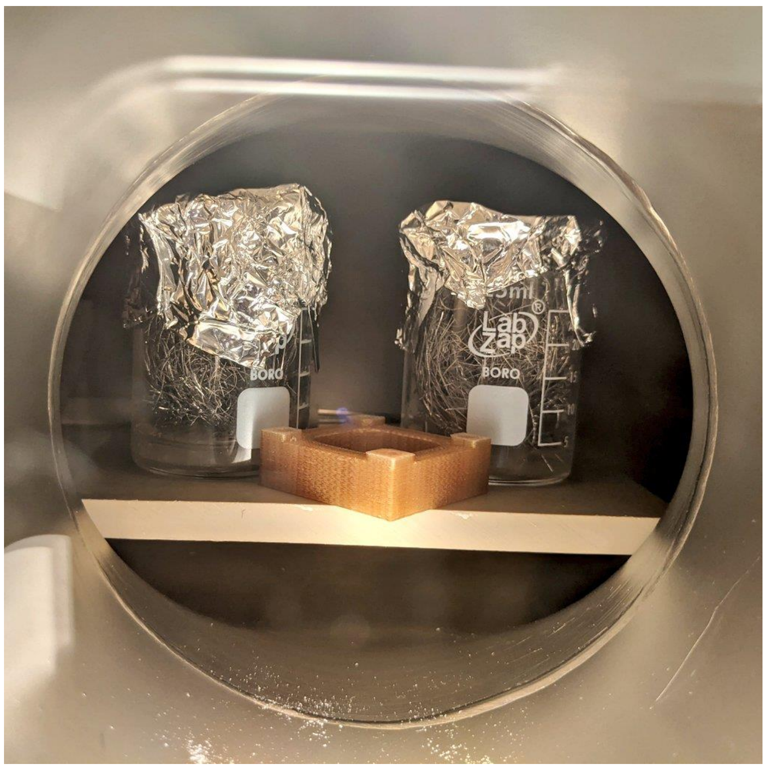

FIGURE 3: *Bakeout and degassing of the EMI-BF4 fuel, emitter, reservoir, and 3D printed thruster housing*

V. IGNITION TEST SETUP

After baking and degassing of the fuel and housing, the fuel and housing are removed from the chamber and prepped for assembly. The emitter an extractor are removed from the beakers and lightly patted down with a clean Kimwipe to remove excess liquid. The thruster was reassembled, with the emitter and extractor centered and aligned by sight. 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.

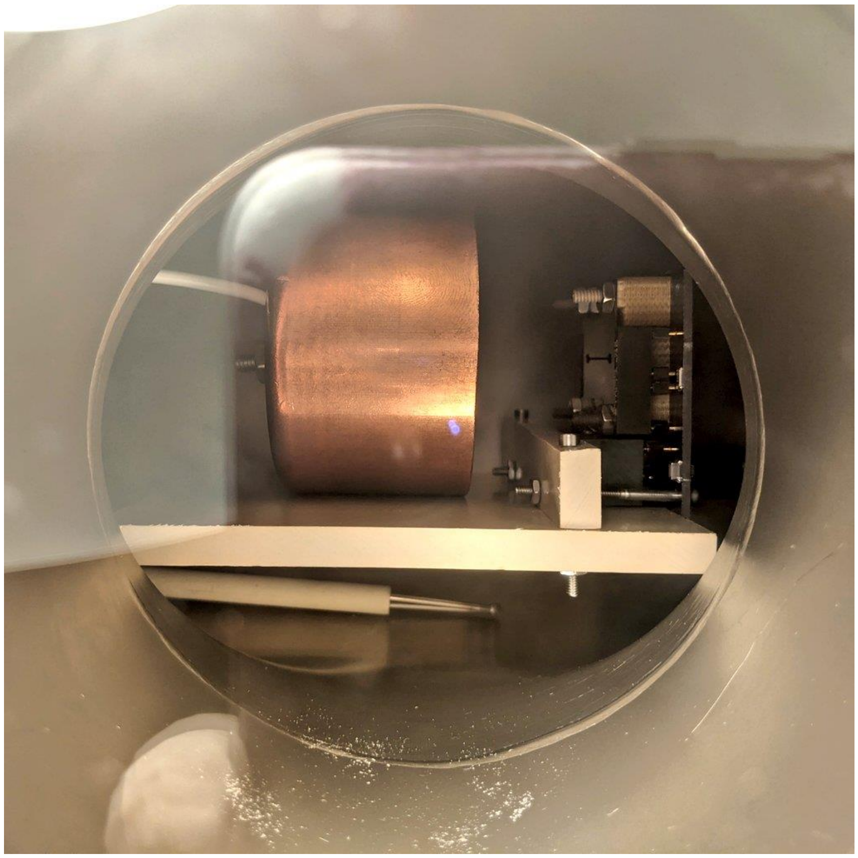

FIGURE 4: *ILIS1 and Faraday cup test stand mounted inside chamber*

VI. TEST PHASE II – IGNITION

The chamber was evacuated to a pressure of 4.5x10^-6 Torr before starting up the thruster. Power was slowly brought up on the thruster, monitoring the oscilloscope readout as well as visually checking the thruster through the viewport during operation. The thruster was operated in both bipolar and monopolar modes. However, like prior testing, it was very apparent that the negative emission was severely reduced compared to the positive emission, and not as stable. This became more evident at higher emission levels. Eventually, the thruster was switched to monopolar mode for stability at the peak of beam output during operation. It was observed that at lower beam currents, multisite emission was occurring across the length of the ridge thruster. However, at peak output currents, emission was focused exclusively in one area in the central region of the ridge.

At a voltage of 5.8kV, a peak beam current of 40uA was achieved on the Faraday cup, the highest yet by an order of magnitude from prior tests. Operation in this peak emission mode was stable for a short period of time. Finally, 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 videos were recorded of thruster operation, capturing the resulting ion beam plume, while beam current from the Faraday cup was monitored visually on the oscilloscope. At peak beam emission, a bright and noticeable plume can be seen emanating from the aperture of the extractor plate, towards the central region of the ridge emitter. At lower beam currents, a dull, multisite emission beam can be observed.

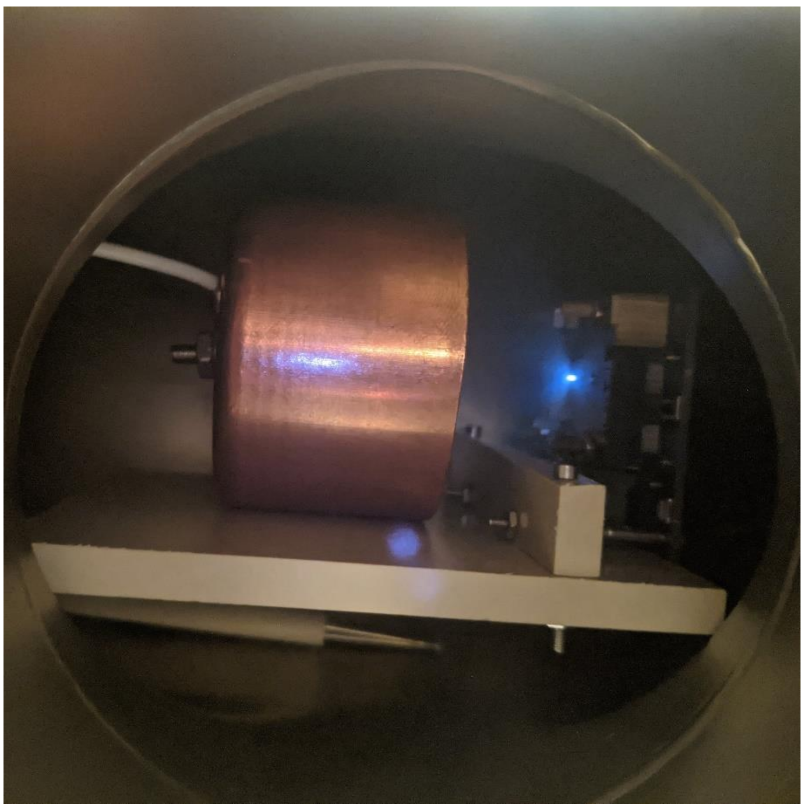

FIGURE 5: *Ion beam emission at peak emission of 40uA, 3uN*

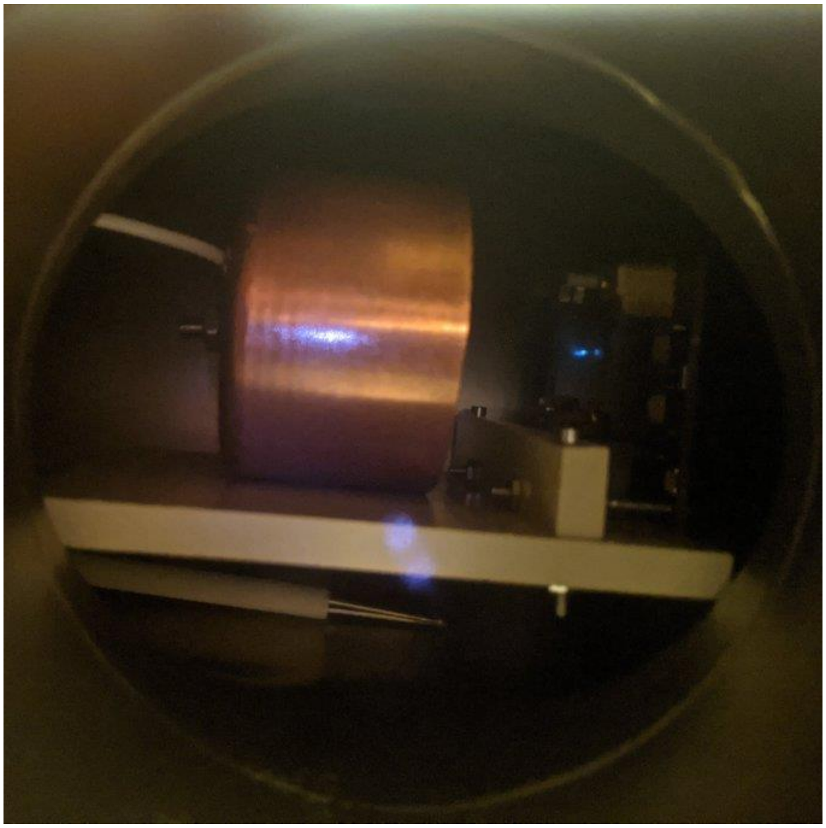

FIGURE 6: *Multisite ion beam emission at lower emission levels of 0.5uA*

Assuming purely ionic emission, we can calculate some rough initial performance estimates. For initial thrust estimates, assuming PIR with 50% monomers and 50% dimers and a peak beam current of 40uA, averaging this for both monomer and dimer emission for a +EMI beam and 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 3uN, the highest yet for the ILIS1, which is in agreement with macro-scale ILIS in literature at similar output beam currents.

For ISP, for peak operation at +5.8kV in monopolar mode, if we assume ideal PIR emission with 50% monomers and 50% dimers, and a beam of just +EMI species, along with factoring 50% losses due to polydispersity, averaging the ISP for both cases, this gives a rough estimated ISP of around 4500-4600s, the highest numbers yet for the ILIS1 as well.

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 disassembled and inspected, which confirmed the observations of thruster failure in the recorded test video. Liquid creep from the surface of the porous glass emitter disc to the extractor was successfully mitigated, however liquid bridging failure occurred between the ridge emitter and extractor plate. This is due to the excessively high voltages the thruster had to be operated at to achieve peak emission causing excessive beam impingement on the extractor, as well as liquid buildup and eventual shorting on the emitter ridge.

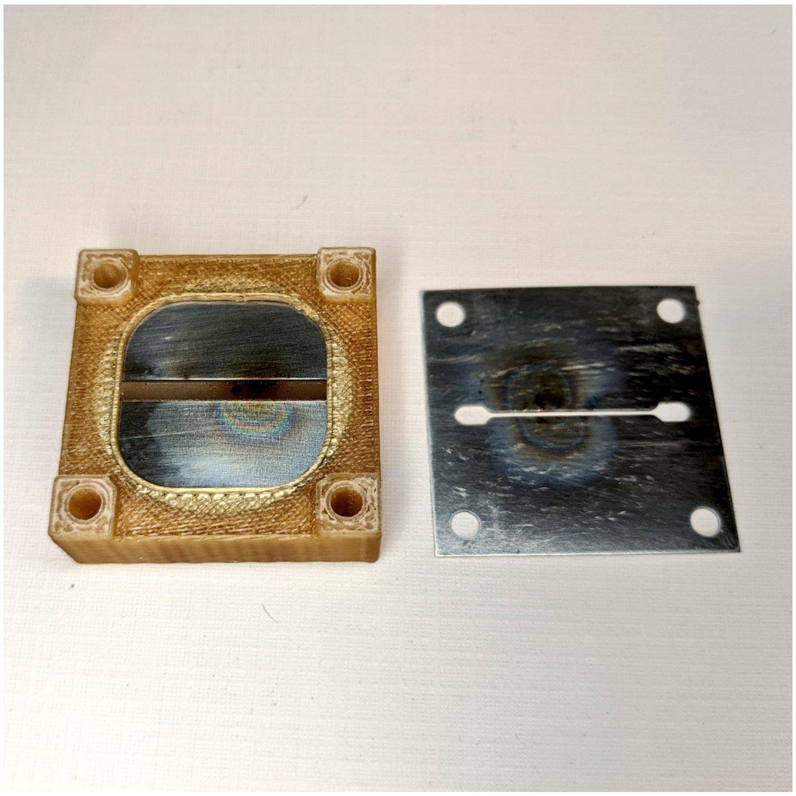

FIGURE 7: *Thruster assembly post-testing. Evidence of arcing, liquid bridging between the emitter and extractor, and beam impingement on the extractor can be seen.*

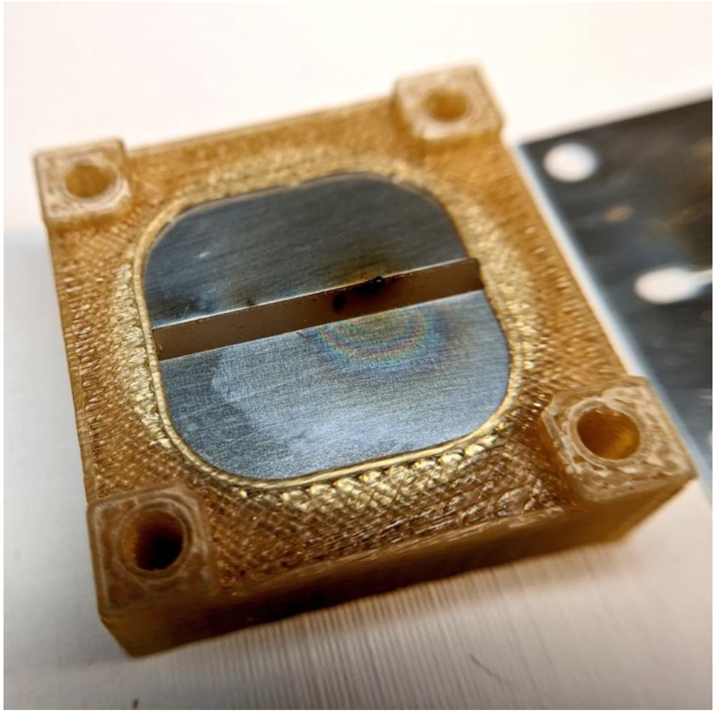

FIGURE 8: *Close-up of the emitter, which shows evidence of charred fuel buildup at the peak of the emission site.*

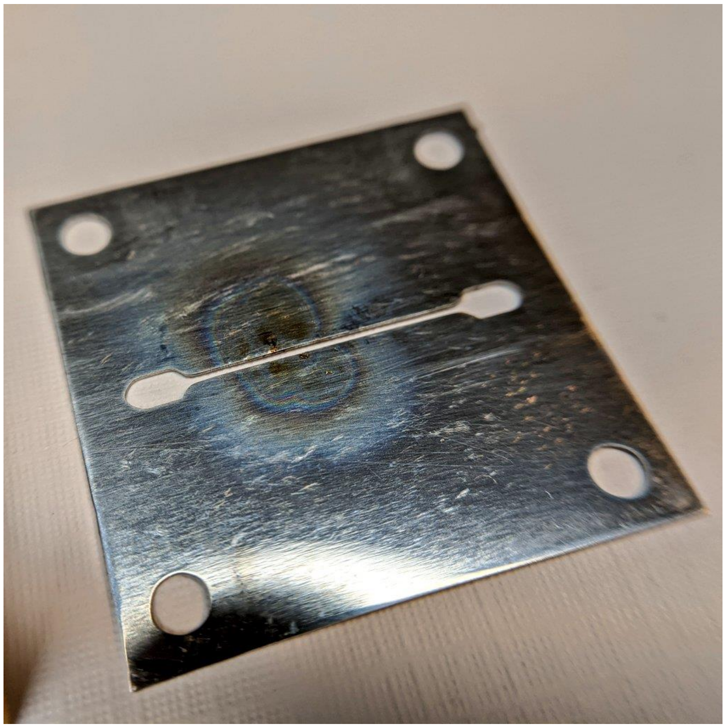

FIGURE 9: *Close-up of the extractor plate. Evidence of beam impingement can be observed.*

IX. CONCLUSION

The seventh ignition test of the AIS-ILIS1 ionic liquid ion source electrospray thruster has been completed. During the test, multi-site emission was observed across the central region of the slit in lower output-beam mode, with a single site of emission occurring in the highest output mode of the thruster. At a peak accelerating voltage of 5.8kV in monopolar mode, 40uA of beam was measured, correlating to about 3uN of thrust, and around 4500-4600s ISP factoring in inefficiencies and correction factors.

This test broke additional ground in the AIS-ILIS1 development, achieving the highest thrust by an order of magnitude, and the highest ISP yet for the system. A summary of key takeaways from the test are as follows:

- 40uA emission was achieved, correlating to 3uN of thrust, which is consistent with other macro-scale ILIS tests in literature.
- The shield electrode and new housing design allows the thruster to operate at higher output by mitigating liquid creep failures between the surface of the emitter disc and the extractor.
- Liquid bridging failure between the tip of the emitter and the extractor remains a key challenge.
- The ILIS1 design can be pushed to excessively high levels.
- While multisite emission is evident, at higher output levels emission is focused in one area along the ridge.

Going forward, it is clear that there remains several key challenges to be addressed. The biggest inhibitor to performance to date has been the excessive voltages the ILIS1 has had to run at to achieve reasonable outputs. This is most likely due to the fact that the ridge is still not sharp enough, resulting in too low field enhancement. With a sharper tip, and higher field enhancement, higher beam extraction can occur at lower voltages. With lower operating voltages, while ISP is reduced, beam impingement and droplet spray is also reduced.

Next, the design should shift away from ridge emitters to spike emitters. While multisite emission has been demonstrated and achieved, without sub-100 micron tip ridges, field enhancement is not high enough for large-scale bulk emission at higher levels. Using spikes, whether single spikes or arrays of spikes, field enhancement can be kept higher even with blunter tips, resulting in better beam extraction while easing manufacturing challenges associated with extremely sharp tips in the porous glass. In all testing with the ILIS1 to date, at higher outputs, operation naturally trends from multisite emission to strong emission from a single point.

Due to instabilities and severely reduced outputs with negative side emission, monopolar mode should be explored with the use of a conventional neutralizer. While thermionic emitters like filament neutralizers can be very cheap and simple, power draw would be excessive for PocketQube-class systems. As such, to keep power low, carbon nanotube based neutralizers should be explored for operation of the beam in positive emission monopolar mode, allowing for extremely low power draw and retaining the benefits of the high thrust/power ratio and high ISP inherent to ILIS technology.

Finally, extractor biasing will be further explored, in order to increase total potential across the emitter/extractor gap without relying on a single excessively high power supply, as well as allowing for additional beam forming and control.