Applied Ion Systems

AIS-TR-010

AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V4

Fueling and Ignition Test 1 - 07/04/2020

Testing Report and Summary

Michael Bretti – 07/13/2020

I. TEST PARAMETERS

- **System:** AIS-ILIS1 Ionic Liquid Ion Source Electrospray Thruster V4
- **Fuel:** EMI-BF4
- **Maximum Chamber Pressure During Testing:** 2 x 10^-5 Torr
- **Testing Status:** COMPLETE
    - **Phase I:** Fueling – SUCCESS
    - **Phase II:** Ignition – FAILURE

II. OVERVIEW

This test is the first 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.

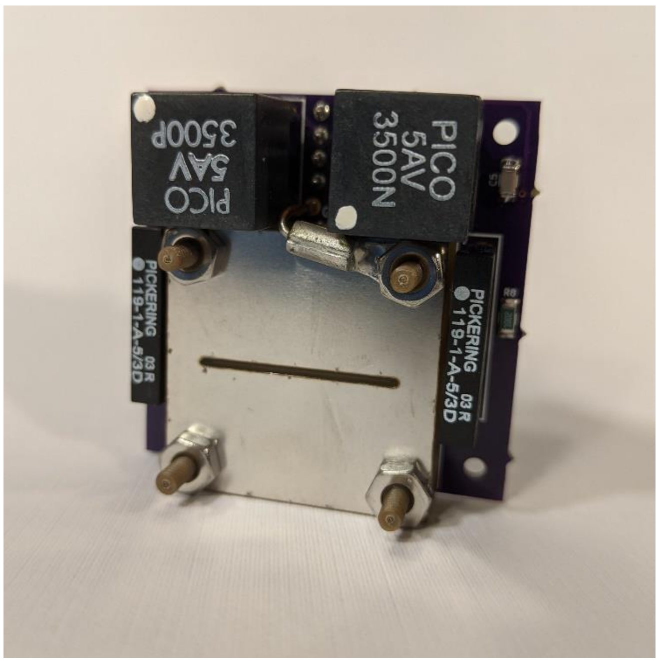

FIGURE 1: *Completed AIS-ILIS1 thruster assembly*

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 first fueling and ignition tests of the ILIS1 using the V4 thruster board, as well as analysis, results, and conclusions moving forward for future testing and system improvements.

III. TEST PHASE I - FUELING

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.

For the first fueling attempt, it was decided to build a fueling station that would allow the porous glass structures and fuel to be degassed separately, then the emitter and reservoir loaded into the degassed fuel, and allowed to further saturate for several hours, all in high vacuum. To do this, a simple 1-axis linear motion driver was constructed to push the emitter and reservoir into fuel holding cups after the initial degassing phase.

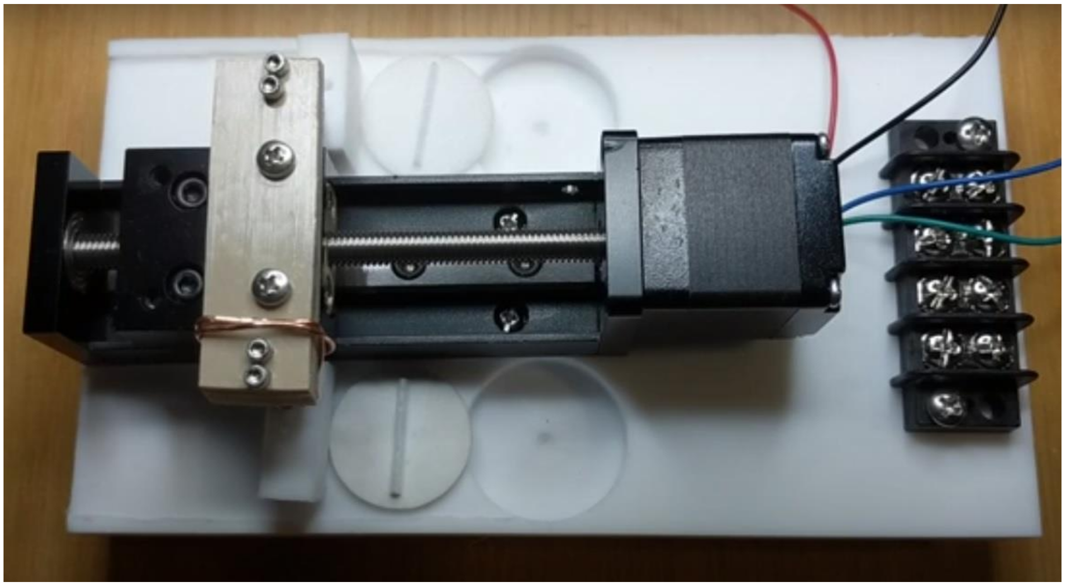

FIGURE 2: *AIS-ILIS1 in-vacuum fueling station with two test emitters*

The ILIS1 fueling station was first loaded into the high vacuum chamber dry, and tested with the control software to make sure all of the connections were correct. Once wired and checked, the porous glass reservoir and emitter were loaded into the fueling channels, and EMI-BF4 ionic liquid was loaded into the fuel holders. About 5mL of EMI-BF4 was pipetted into each fuel holder. The chamber was sealed, and pumpdown began.

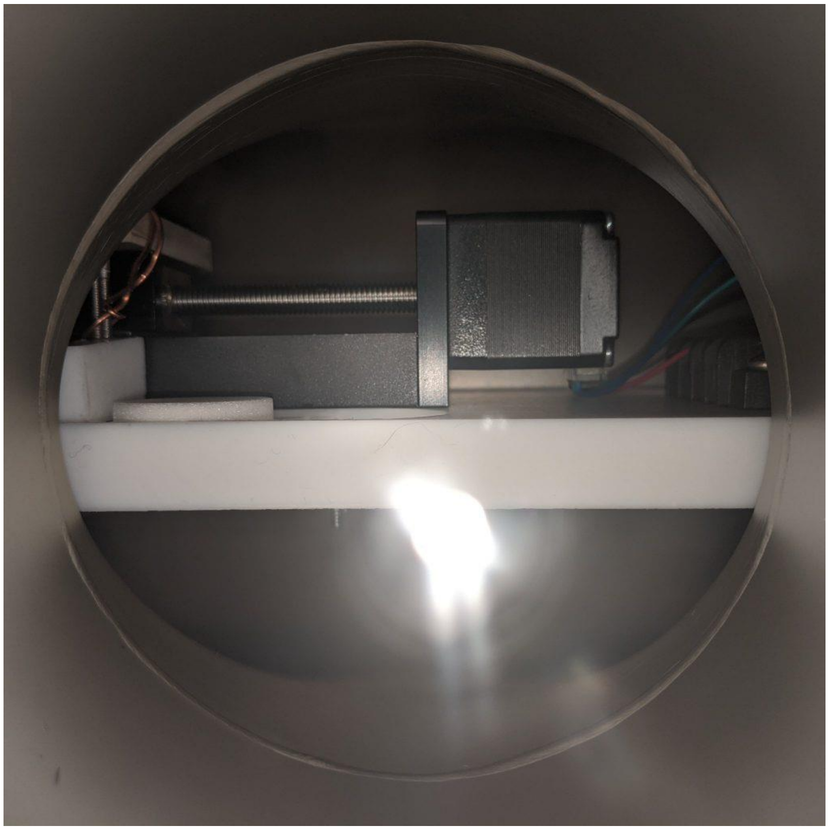

FIGURE 3: *ILIS1 fueling station with reservoir, emitter, and fuel loaded in chamber*

The roughing pump was started, with the foreline isolated from the main chamber. Once dropping below 1 Torr, the isolation valve was opened to begin evacuation of the main chamber. Immediately upon the start of pumping the main chamber, a significant amount of liquid was seen depositing all over the chamber. Pumpdown was stopped immediately to inspect the system.

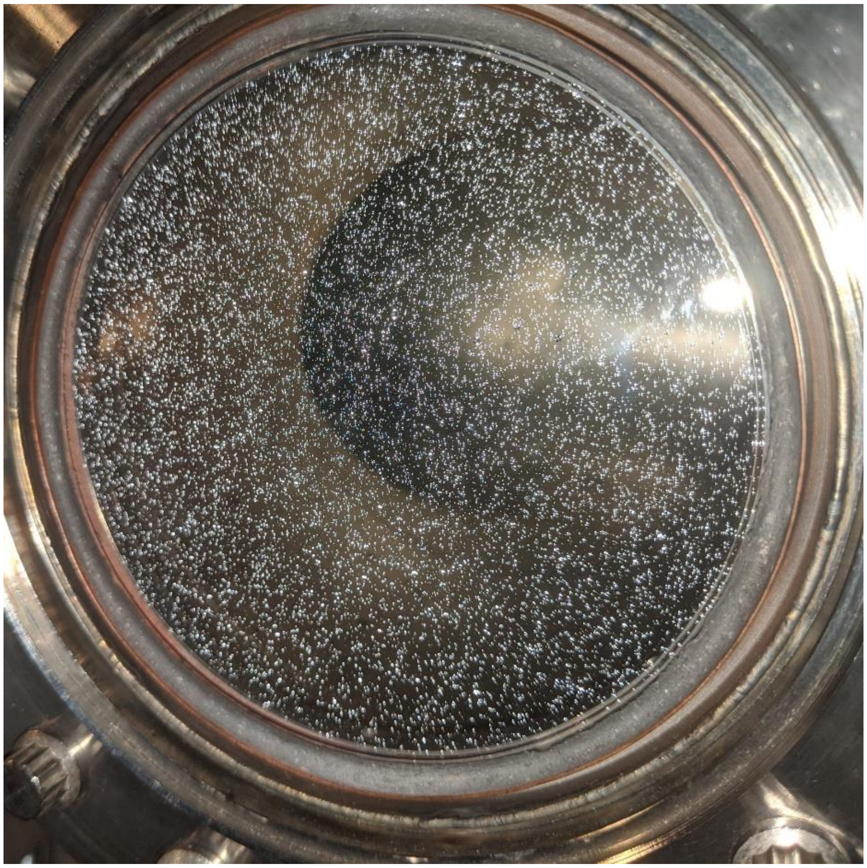

FIGURE 4: *EMI-BF4 chamber contamination during first fueling attempt*

Upon inspection, it was found that significant contamination of the chamber occurred, with a large amount of the ionic liquid fuel depositing inside the chamber. Fuel did not make it into the main diffusion chamber however, and the system was thoroughly cleaned using wipes, acetone, and isopropyl.

FIGURE 5: *EMI-BF4 chamber contamination*

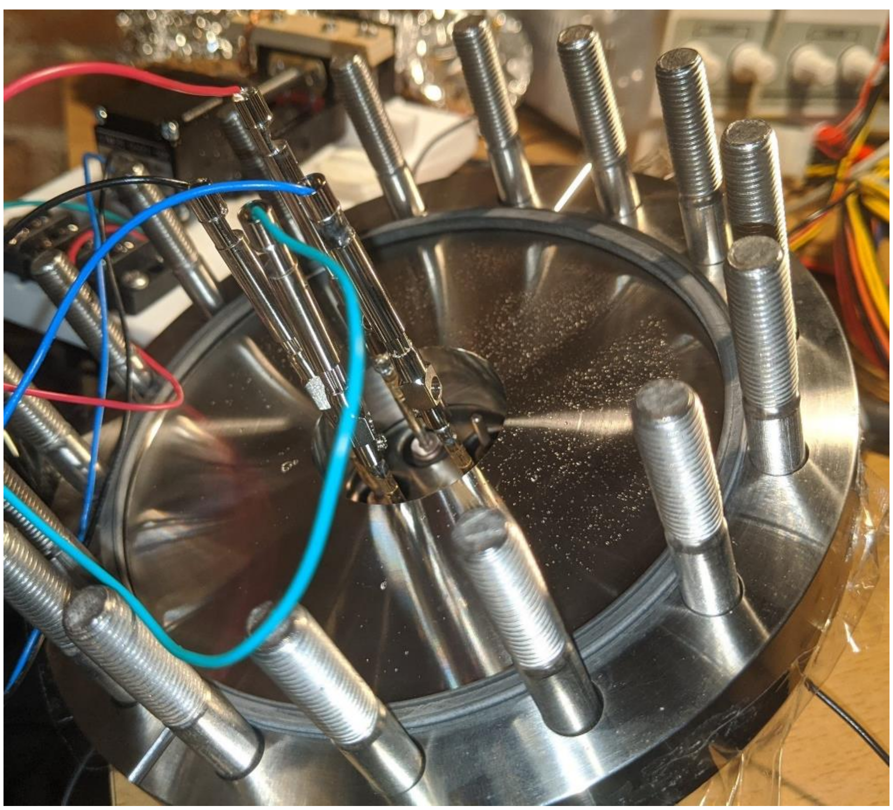

FIGURE 6: *EMI-BF4 contamination of chamber feedthrough*

Originally it was thought the fuel spraying was due to the sudden pressure change from atmosphere to vacuum due to opening the isolation valve from the roughing line to the main chamber. The fueling station was therefore refilled, and pumpdown started again, this time with the roughing isolation valve barely opened to choke pumping speed to slowly bring down pressure in a more controlled manner.

Despite the very slow pumpdown, at about 1 Torr there were again immediate signs of liquid spray in the chamber, though at a slower rate than the prior attempt. The vacuum system was shut down, and again the fueling station was removed, and the chamber cleaned. Despite the original goal of degassing the porous glass emitter and reservoir separately before loading in vacuum, it was clear that the fuel could not be degassed in an open container.

A third attempt at fueling was made to try to saturating the glass in the ionic liquid in atmosphere, and pump down on the loaded glass structures afterwards. The glass structures were directly dropped in the fuel holding cells, and the cells were refilled fully with liquid.

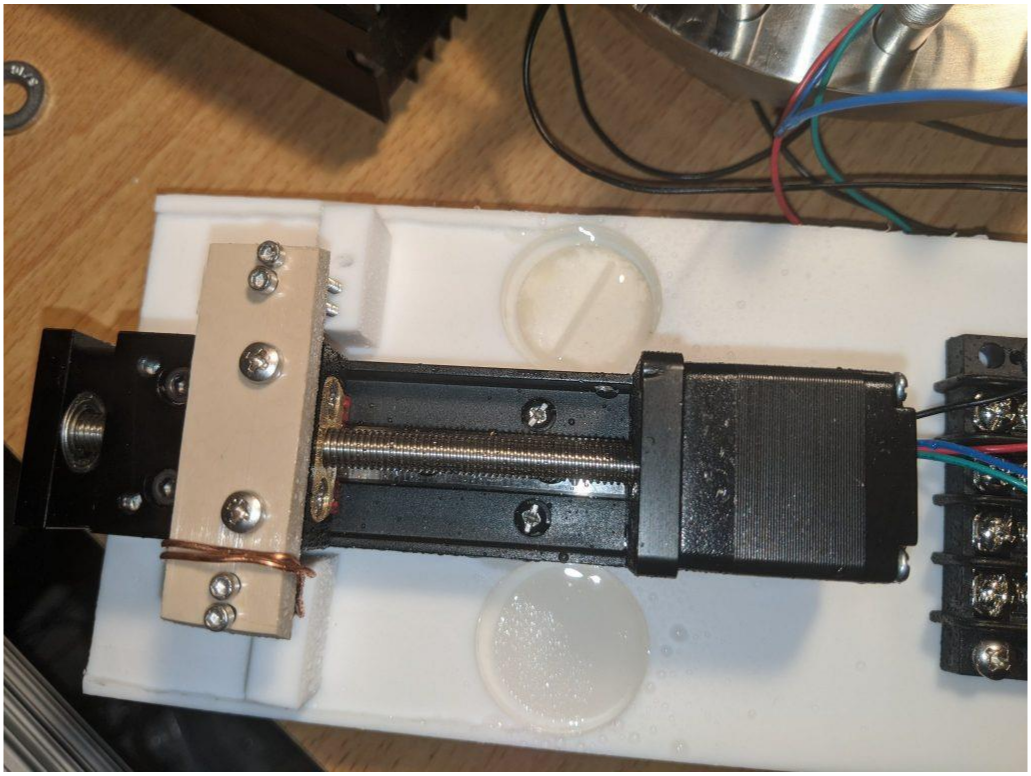

FIGURE 7: *Atmospheric fueling attempt with emitter (top) and reservoir (bottom)*

While the larger pores of the reservoir filled without issue, it was immediately apparent that the smaller pores of the emitter were not saturating properly. The EMI-BF4 ionic liquid is quite viscous, and the central part of the glass emitter was not wicking up the liquid. This confirmed that the glass structures must be saturated in vacuum to achieve complete filling of the glass pores with the fuel.

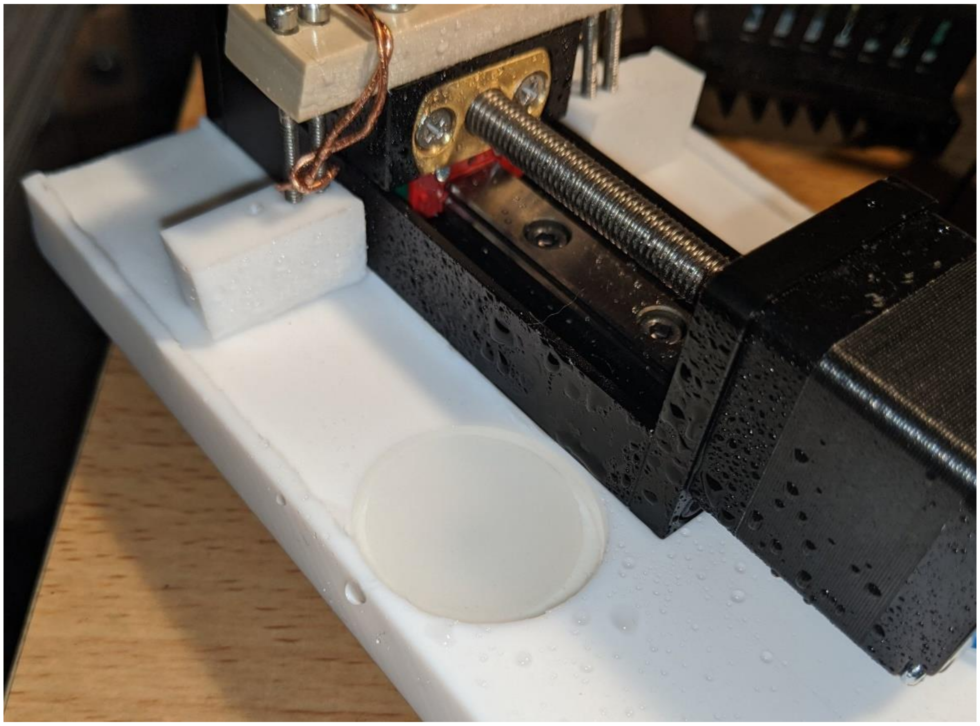

FIGURE 8: *Complete saturation of the reservoir with EMI-BF4 in atmosphere*

FIGURE 9: *Incomplete saturation of the emitter with EMI-BF4 in atmosphere*

In order to meet all of the fueling requirements (in-vacuum degassing and saturation in a closed container to prevent system contamination), it was decided to use a simple glass jar filled with a small amount of fuel, dropping the emitter and reservoir in, and lightly covering the top of the jar with aluminum foil. The aluminum foil was placed securely but not air-tight over the top, to still allow gases to escape during pumping.

FIGURE 10: *Degassing and saturation of emitter and reservoir in vacuum in covered glass container*

Pumpdown was started again. This time, violent bubbling was noticed from the bulk liquid, with significant splashing inside the jar. Due to the high concentration of absorbed gases and water vapor in the ionic fuel, the liquid spray prior observed was in fact due to the degassing process. Severe degassing continued into the low milli-Torr range during the roughing cycle of pumping. However, no liquid spray was further observed in the chamber. The high vacuum pump was turned on, and the fuel and glass structures were allowed to continue to degas and saturate in high vacuum for several hours, until an ultimate pressure of 8x10^-6 Torr was achieved. With this, adequate degassing of the fuel, as well as saturation of both porous glass structures were successfully achieved. The system was shut down, and preparations were made for the Phase II ignition test attempt.

IV. 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 40 grams, a difference of 1 gram higher from the dry mass of 39 grams found previously. 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.

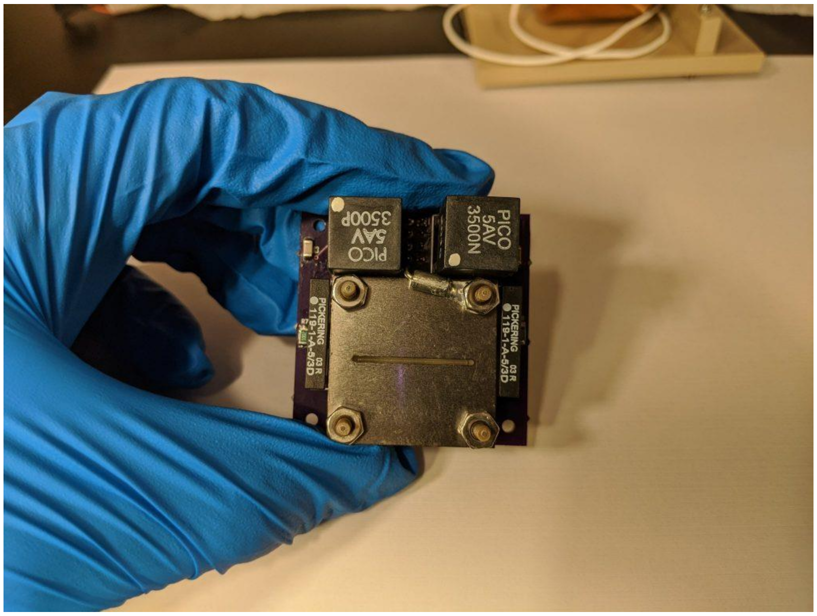

FIGURE 11: *Fully assembled and fueled AIS-ILIS1 electrospray thruster*

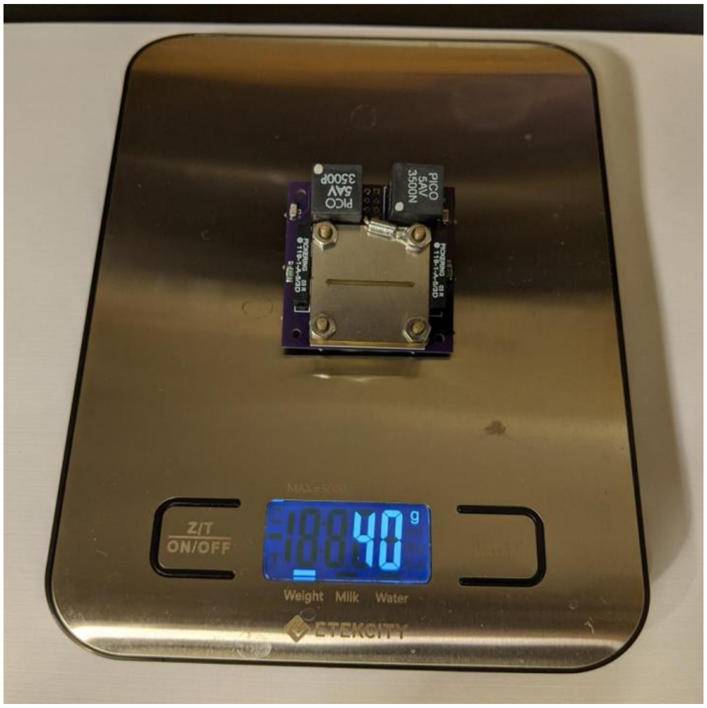

FIGURE 12: *Final wet mass of the fueled and assembled AIS-ILIS1*

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.

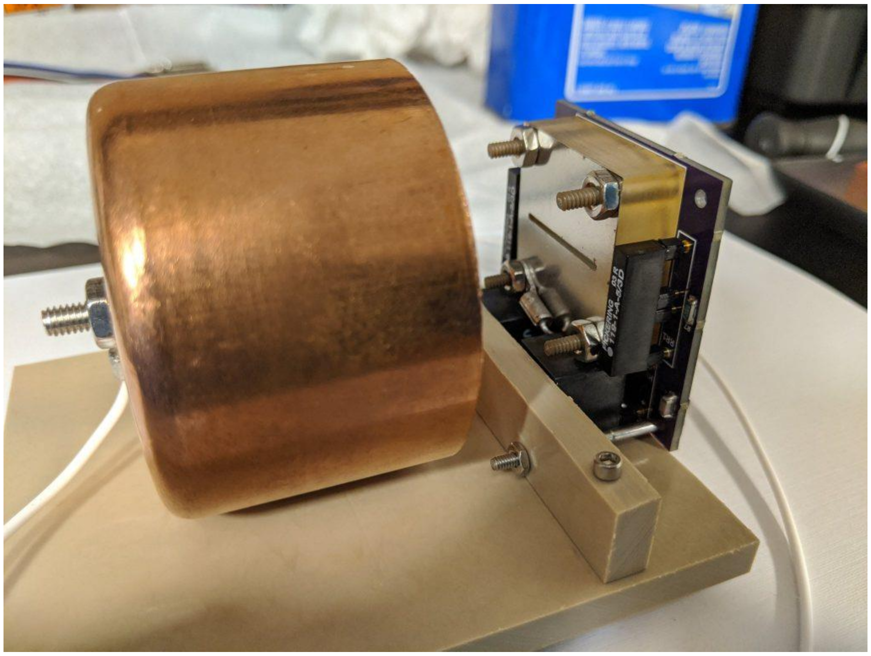

FIGURE 13: *ILIS1 mounted to Faraday cup test stand*

After mounting the thruster to the Faraday cup test stand, the vacuum feedthrough flanges were prepared for the test. First, the Faraday cup instrumentation output feedthrough was prepped and mounted to the chamber. The Faraday cup and thruster assembly was slid in prior to final bolting, and the connector was attached before the flange was mounted and tightened.

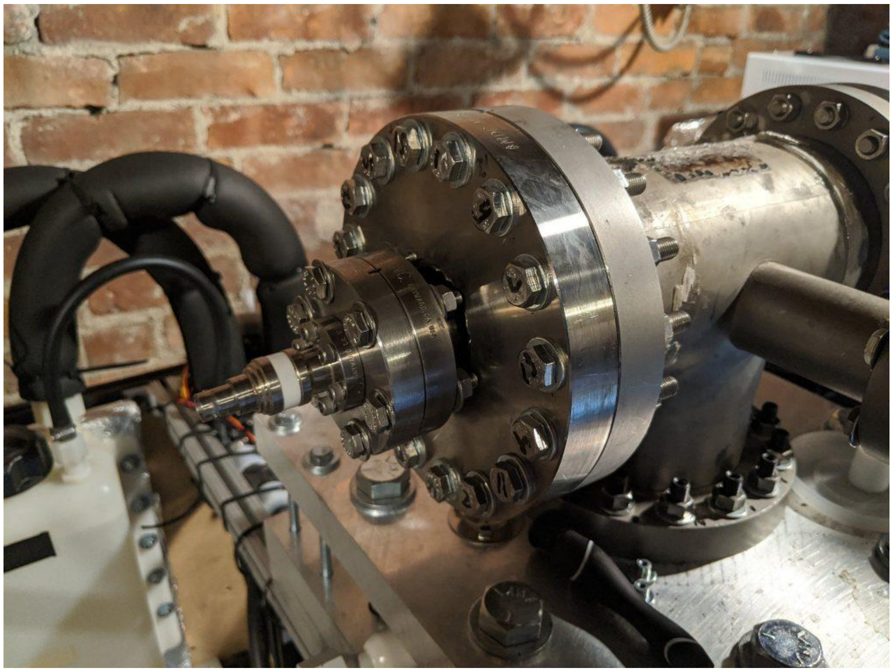

FIGURE 14: *Faraday cup readout vacuum feedthrough*

Next, the thruster power and control wires were connected to the vacuum side of the thruster control flange, and the thruster and faraday cup assembly was positioned in full view of the chamber viewport, before sealing up the chamber.

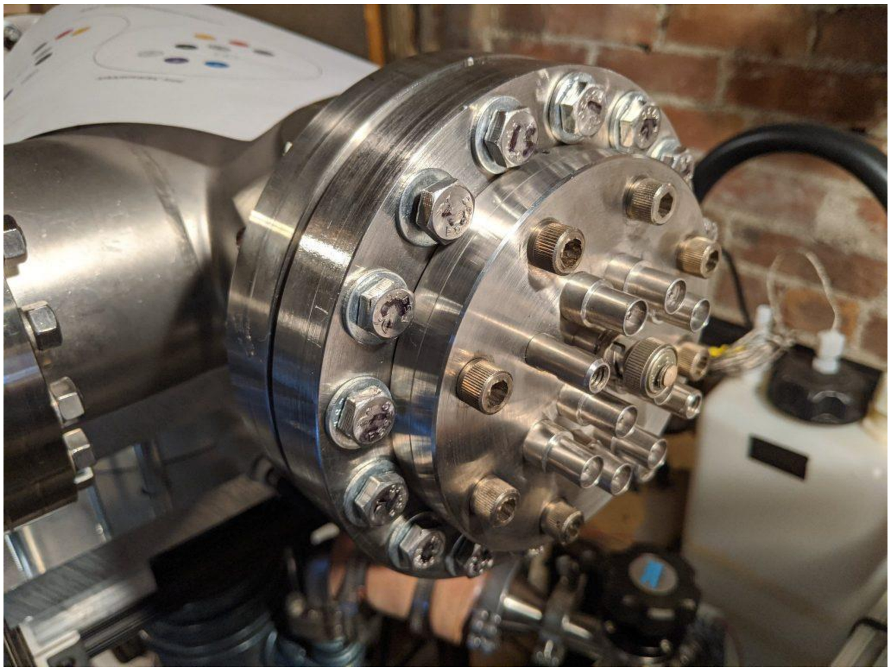

FIGURE 15: *Thruster power and control feedthrough*

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

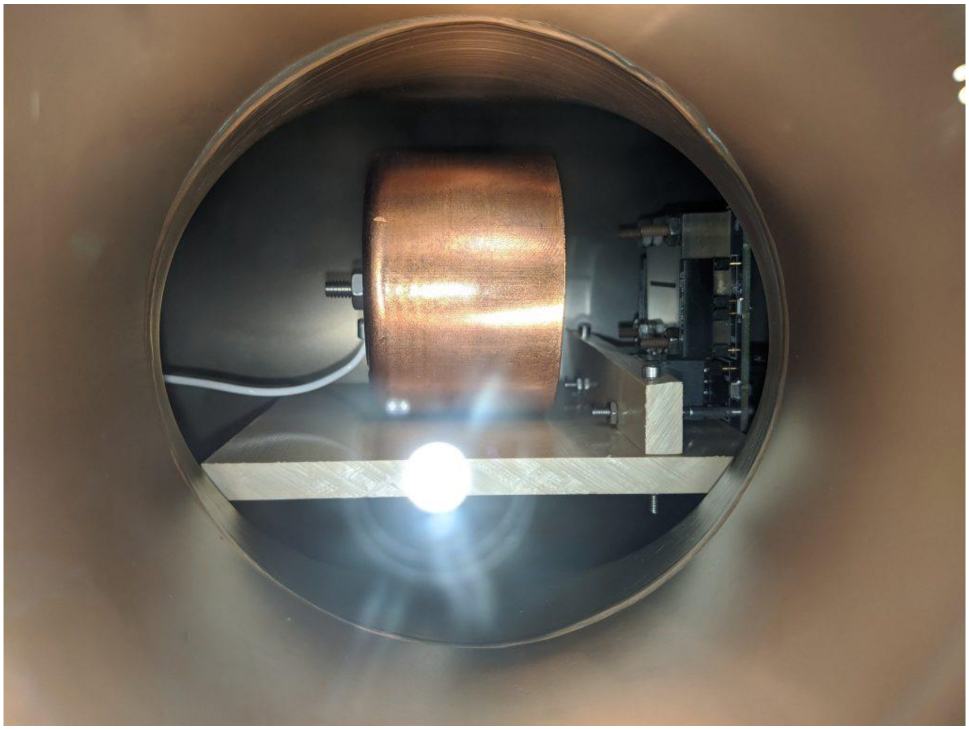

FIGURE 16: *ILIS1 and Faraday cup test stand final mounting inside vacuum chamber*

V. TEST PHASE II – IGNITION

Ignition attempts were started at 2×10^-5 Torr after several hours of pumping. The thruster control sequence started at 1Hz cycle, with thruster power slowly brought up. The Pico 3500P/N supplies turned on at about 2.5V, with a starting output around 800V.

For the first part of cycling, the thruster emitter voltage could not be raised above 850V without something causing the Arduino controller to glitch and trip. No arcing or visible faults were observed. This continued for several minutes, slowly pushing the voltage higher. Eventually higher voltage of several kV was established on the emitter, however faults continued to occur. The cycling time was switched to 0.5Hz, then 0.25Hz to allow more settling time at the +/- voltages to help with conditioning and try to stabilize operation.

At this point there was some noticeable arcing occasionally on the board, appearing on the bottom front edge and top of the back of the board. The voltage was slowly pushed higher to attempt to condition the thruster and start achieving emission. Continuous faults and trips occurred with the system. Eventually full voltage of +/-3.5kV was established for brief periods on the system in between frequent glitches. While no stable emission was achieved, there were a couple of instances of spurious emission, where the characteristic light bluish glow was seen from the extractor slit for a brief flash.

Towards the end of the test, the negative supply readout suddenly dropped to zero, with increased current draw from the power supply. No arcing was seen during the negative cycle, but it was clear that there was direct shorting somewhere on the board. It was during this time that a highly unusual observation was made. The positive cycle still achieved full voltage, however the thruster block glowed dull red during each positive cycle, not from heat, but ionization occurring inside the clear amber 3D printed housing.

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.

VI. POST TEST THRUSTER INSPECTION

Upon disassembly of the thruster, no signs of arcing damage on the emitter, extractor, or circuit board were found. In addition, no liquid droplet spray or deposits were found between the emitter and extractor, and no fuel leak was observed on the board or inside of the casing.

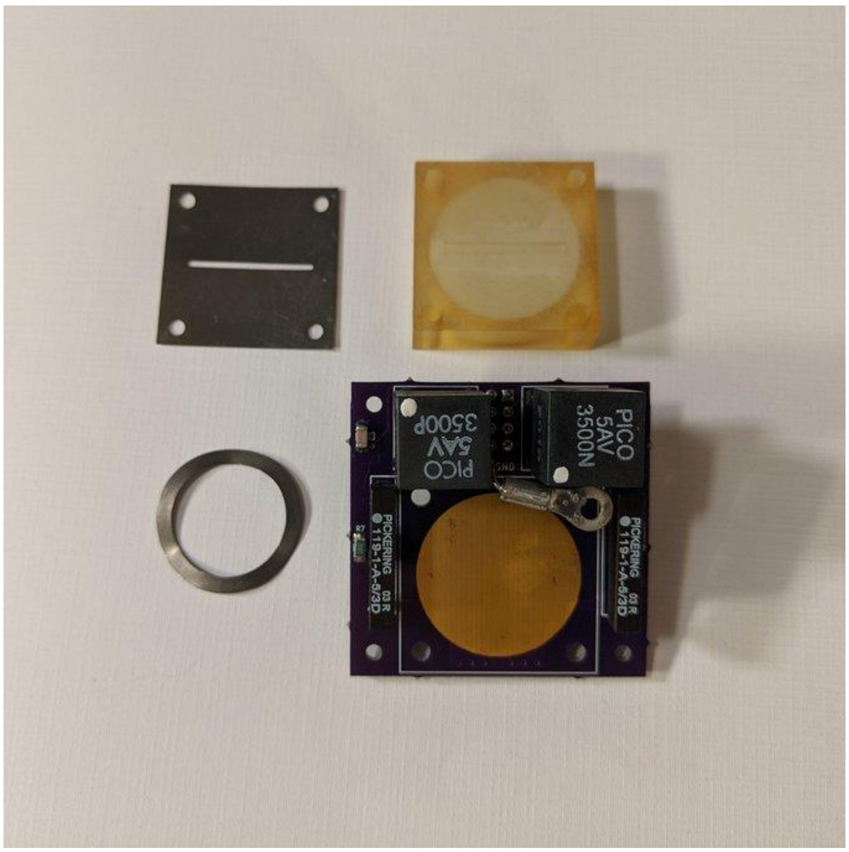

FIGURE 17: *ILIS1 disassembly post ignition testing*

VII. POST TEST VIDEO ANALYSIS

During the ignition test, several short videos were captured. Although full video of the entire test was not captured due to current equipment limitations, numerous key events, such as faults and spurious emissions, were successfully recorded. Video was taken with a Pixel 2 phone, recording from outside of the chamber through the viewport in low-light conditions.

During the test, numerous board faults were observed. There are two key areas identified on the board, both around the +HV relay. The first of these occurs on the front of the board at the +HV relay input. The diffuse glow shows that this is not an arc, but ionization of some outgassing product.

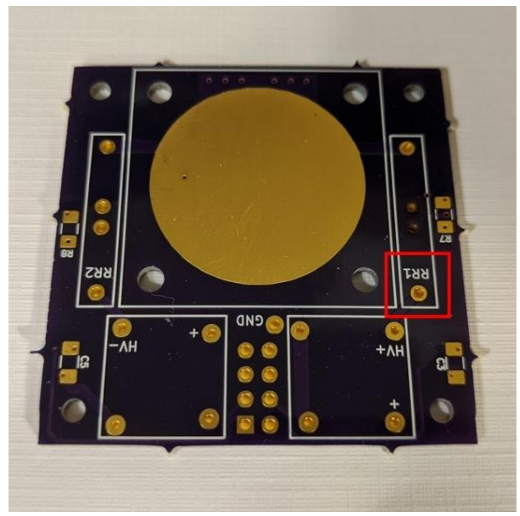

FIGURE 18 AND 19: *Ionization fault on board front near +HV relay input pin (LEFT), location of ionization fault on board (RIGHT)*

The second noticeable board fault occurs on the back near the +HV relay output. Here it can be observed that a much larger diffuse emission happens. Both of these board faults were seen numerous times, consistent in location and intensity. In both cases, there is a noticeable amount of silkscreen near these HV points. Since there was no arcing damage on the board, it is clear that no tracking faults occurred. However, based on the diffuse nature of the fault, it appears more like ionization of gas, which is most likely outgassing products from the silkscreen being ionized by sharp HV points on the board near the switching inputs and outputs of the HV relays.


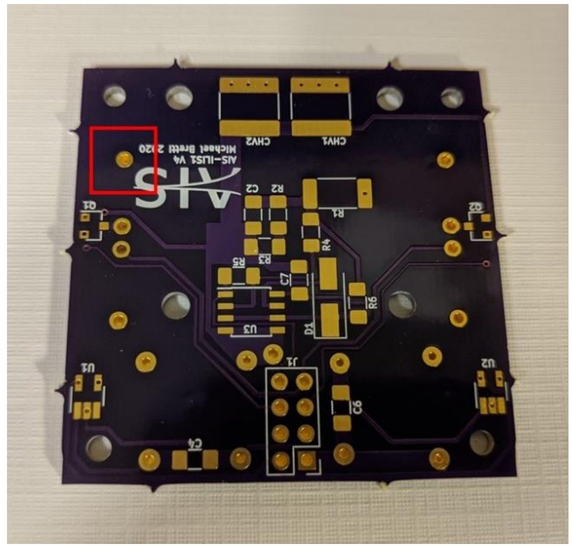

FIGURE 20 AND 21: *Ionization fault on board back near +HV relay output pin (LEFT), location of ionization fault on board (RIGHT)*

A third and unusual fault was noticed inside of the thruster casing itself. This was characterized by an orange glow within the casing, but no observable emission. This was seen numerous times near the emitter at the top as well as near the contact at the rear of the case. It is strongly suspected that outgassing products from the 3D resin printed case, which is a SLA print using Accura 48HTR resin of unknown vacuum compatibility, was playing a role in this spurious internal ionization.

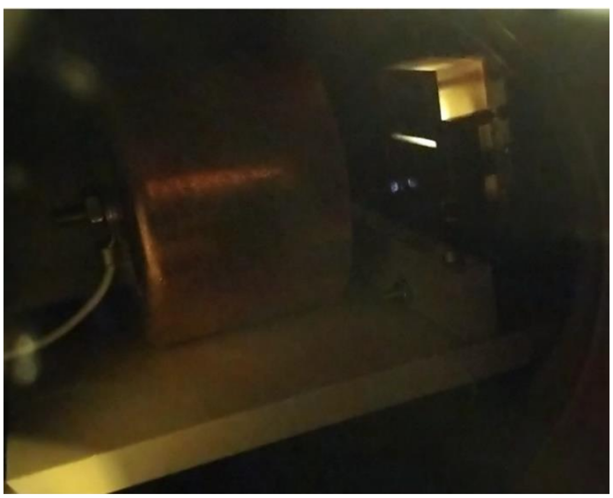


FIGURE 22 AND 23: *Internal ionization faults in 3D printed thruster housing*

Despite the numerous board faults, controller faults, and overall failure of the ignition test to achieve stable ignition of the thruster, several brief instances of ion beam emission were observed. The intensity was far too low in all cases to capture with the current monitor readout with the Faraday cup, however there is visual confirmation of some proper ionization being achieved.

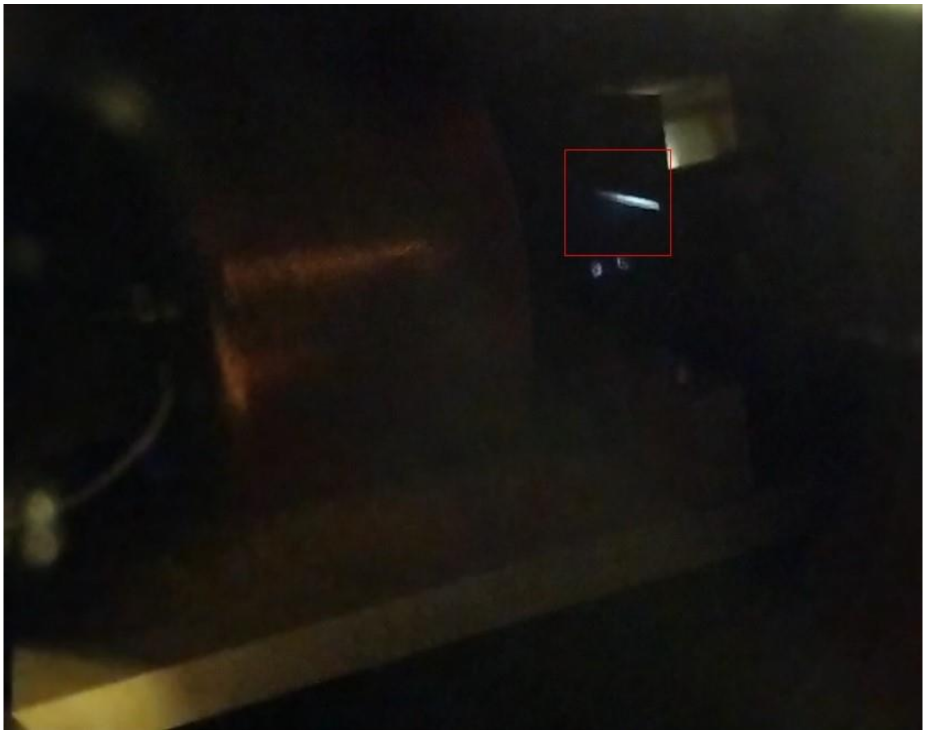

FIGURE 24: *Captured ion beam emission from extractor slit showing uniform ionization*

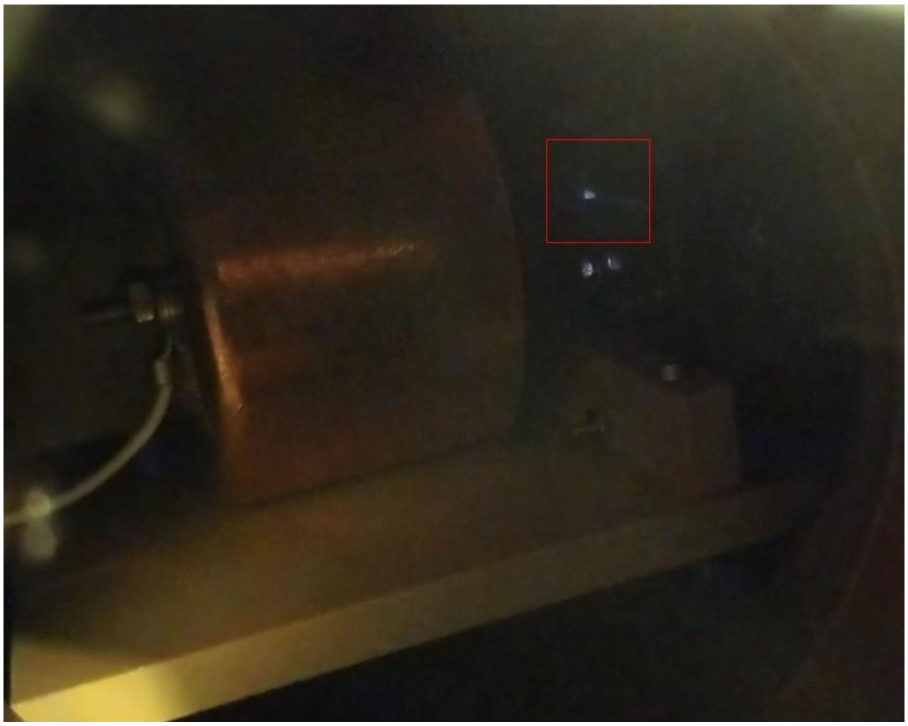

FIGURE 25: *Captured partial ion beam emission at far corner edge of the emitter*

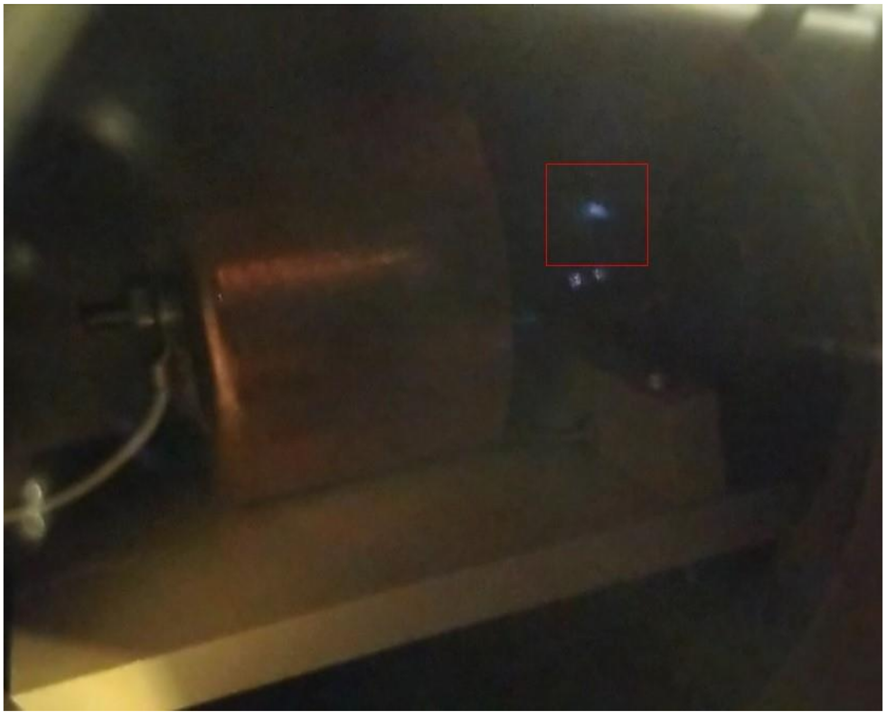

FIGURE 26: *Captured ion beam emission showing partial ionization from the central region of the emitter*

In several instances, a transition from emission to board fault can be observed, where emission first starts, but later dies out due to the board fault occurring. We can see this happening on both the front and back board faults identified earlier.

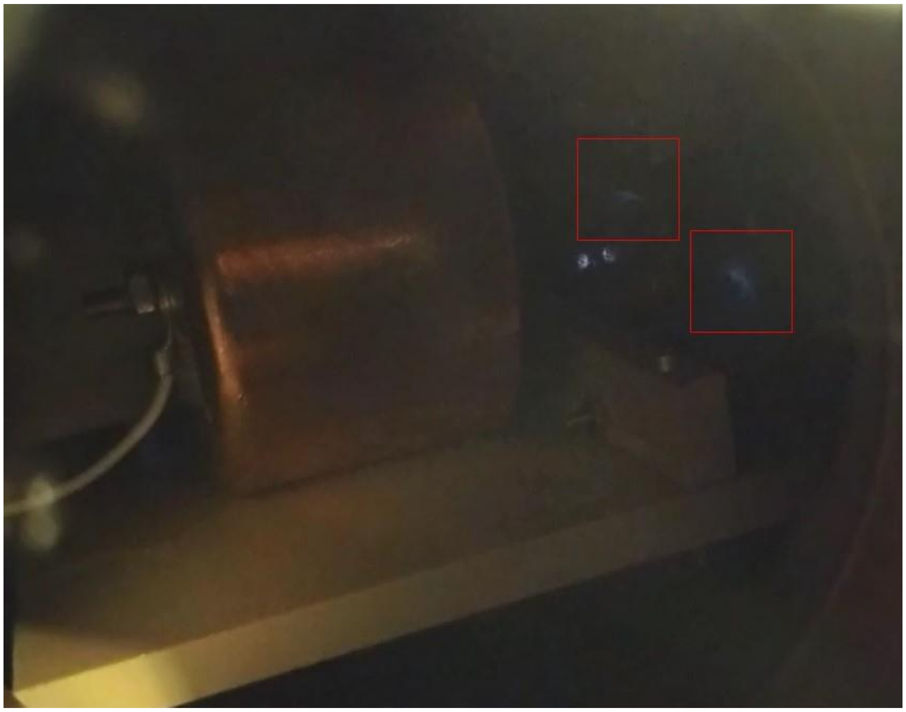

FIGURE 27: *Captured transition from partial ion beam emission to front board fault*

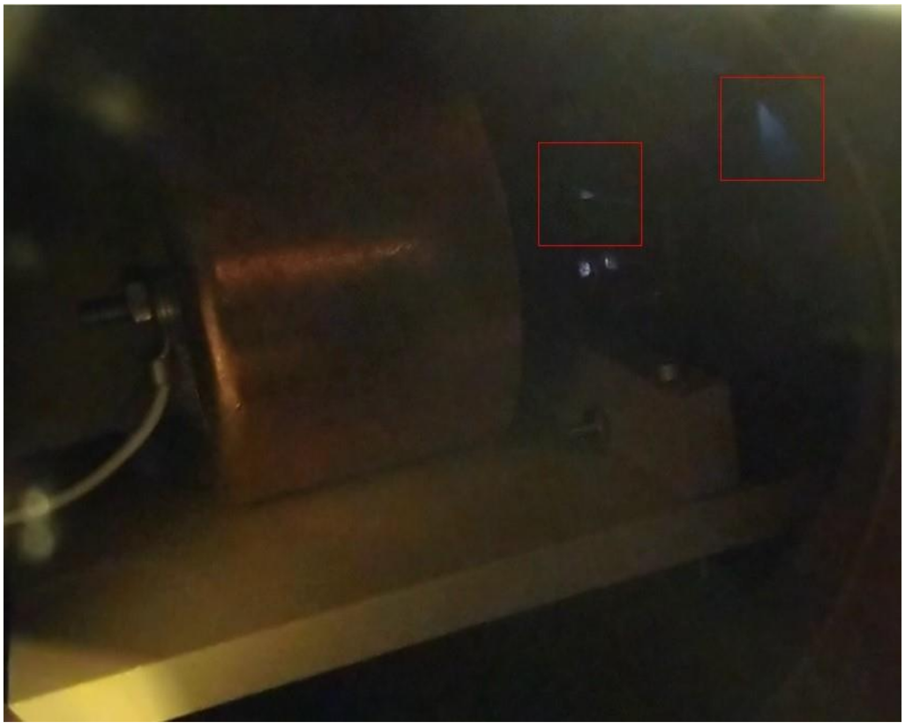

FIGURE 28: *Captured transition from partial ion beam emission to back board fault*

VIII. CONCLUSION

The first ever fueling and ignition test of the AIS-ILIS1 ionic liquid ion source electrospray thruster was completed. While fueling took several attempts, the porous glass emitter and reservoir were successfully degassed and saturated with EMI-BF4 ionic liquid fuel at high vacuum. However, stable emission could not be achieved during the ignition test, with numerous board and thruster faults occurring. Despite this, several instances of spurious ion beam emission were captured, and with data from the test, significant improvements are underway to achieve stable emission for the next test. Key takeaways of the test include:

- Fueling must occur in vacuum for full saturation of the porous glass structures
- Fueling must be done in an enclosed container to prevent fuel spray and chamber contamination during degassing
- Degassing of the fuel and porous emitters is crucial for proper thruster preparation
- Emission conditioning is needed prior to full power operation
- Faster cycle times is much more challenging for stability
- Extractor aperture must be as small as possible to reduce turn-on voltage level and subsequent ionization while minimizing liquid bridging.
- Outgassing from the plastic housing can cause ionization faults in the housing.

- Outgassing from the board silkscreens can cause ionization faults near HV switching elements and points on the board
- Ion emission is visible and can be captured on camera through simple means

Going forward, there are several major improvements that can be made to increase the chances of success. First, the fueling process should be better controlled. This will include more proper fueling and saturation of the glass in individual containers in the chamber, which high-surface area traps to capture liquid spray during degassing. In addition, baking during fueling at a low temperature (~100C) will greatly help the further removal of adsorbed gases and water vapor during pumpdown.

For the thruster PCB, all silkscreen should be minimized, if not fully eliminated from the PCB. All high voltage through-hole components such as the relay pins and power supply pins should be ground down smooth to the board to minimize field enhancement at sharp points. The thruster and all components, especially the housing, should be baked and degassed for several hours at reasonable temperatures. The thruster should also be baked a second time during pumpdown before ignition.

Based on a literature review of macro-scale CNC machined bulk emission ILIS, the turn-on voltage of the ILIS1 is anticipated to start at slightly over 2kV in its current geometry. For this test, a very wide extractor aperture of 1mm was selected to reduce the probability of liquid bridging. While liquid bridging and shorting failures are reduced, this forces the thruster to operate at much higher voltages, and in this case, the field strength at the emitter tip surface was not sufficient to achieve stable and complete ion emission, even at the full voltage of +/-3.5kV. Therefore, it can be concluded that a much narrower aperture extractor must be selected to increase field enhancement at the emitter tip, and lower the effective turn-on voltage. A 0.75mm and 0.5mm extractor are already prepared for the next round of testing to achieve lower turn-on voltage and improved emission stability.