Applied Ion Systems

AIS-TR-001
AIS-uPPT1 Micro Pulsed Plasma Thruster
Phase I - Ignition Testing - 05/05/2019
Testing Report and Failure Analysis
Michael Bretti – 05/15/2019

I. TEST PARAMETERS

- **Main Bank Capacitor** – 3uF polypropylene film capacitor
- **Main Bank Charging Voltage** – 0-2kV
- **Ignition Circuit** – hydrogen thyratron pulser
- **Ignition Capacitor** – 0.01uF plastic capacitor
- **Ignition Voltage** – 0-5kV
- **Pulse Repetition Rate** – 1Hz
- **Maximum Chamber Pressure During Testing** – 1 x 10^-5 Torr
- **Testing Status** – Unsuccessful

II. TEST SUMMARY

This test represents Phase I of testing and development for the AIS-uPPT1 Micro Pulsed Plasma Thruster. The purpose of the test was to verify successful and reliable ignition of the thruster utilizing an unconventional large-surface area concentric igniter electrode in a triaxial electrode configuration.

The AIS-uPPT1 thruster was mounted to the conflat feedthough adapter utilizing a combination of Teflon clamps and a stainless-steel hose clamp. Connections to the high voltage feedthroughs were made with set screw clamps at the feedthrough end, and wire-wrapped connections to the thruster test connections at the other. Kapton tape was used to insulate the wire-wrapped connections for ease of demounting after the test. 18 AWG bare copper wire was used for the cathode, igniter, and anode connections.

Testing was performed in the Micro Propulsion Testing Chamber using the Integrated High Vacuum Test Stand. Pumpdown conditioning of the system was achieved several days prior on 05/01/2019, which was pumped for 3 hours, achieving an ultimate vacuum of 6 x 10^-6 Torr with new materials. Ignition testing vacuum levels were first verified at 1 x 10^-5 Torr maximum before attempting ignition. Both the main high voltage charging supply and the thyratron trigger pulser supplies were started at 0V, and slowly raised. The ignition pulser was raised to levels until an excess of 5kV was achieved, where breakdown was observed between the cathode board and the ignition board in the PCB socket assembly. Voltages were reduced, and main bank voltage was increased to an initial voltage of 1.3kV. After repeated failed ignitions, the main bank voltage was raised to 2kV, and the ignition pulser voltage raised to peak levels over 5kV. A few random main bank discharges were observed at the rear of the socket assembly in timed synchronization with the ignition pulse, however the thruster failed to operate as designed. Ignition arcing continued to occur behind the cathode board, until the test was terminated.

During the test, external arcing occurred between the conflat feedthrough connection pins between the ignition supply and ground, as well as the main bank and ground. These external arc faults caused the Arduino Mega to crash, losing prior stored pumpdown data.

III. FAILURE ANALYSIS

Several key failures were identified during and after the Phase I ignition test. During the test, as ignition voltage was increased, the ignition pulse could eventually be observed flashing at the set repetition rate of 1Hz, corresponding with the timed firing of the thyratron ignition pulser, behind the cathode connection board of the PCB socket assembly. It was initially suspected that this arcing may have occurred between the exposed cathode socket trace on the underside of the board, and the beryllium-copper fingerstock on the top of the ignition board. Upon demounting of the thruster from the chamber and disassembly, this arcing hypothesis was confirmed. Discoloration can be seen on several of the Teflon spacers between the cathode and ignition board from the arcing in *Figure 1* and *Figure 2*. Close visual inspection, as well as inspection under an optical microscope, also reveals ablation of the gold-plated cathode trace underneath the cathode connection board in *Figures 3-5*. Light discoloration of the ignition board fingerstock can also be observed.

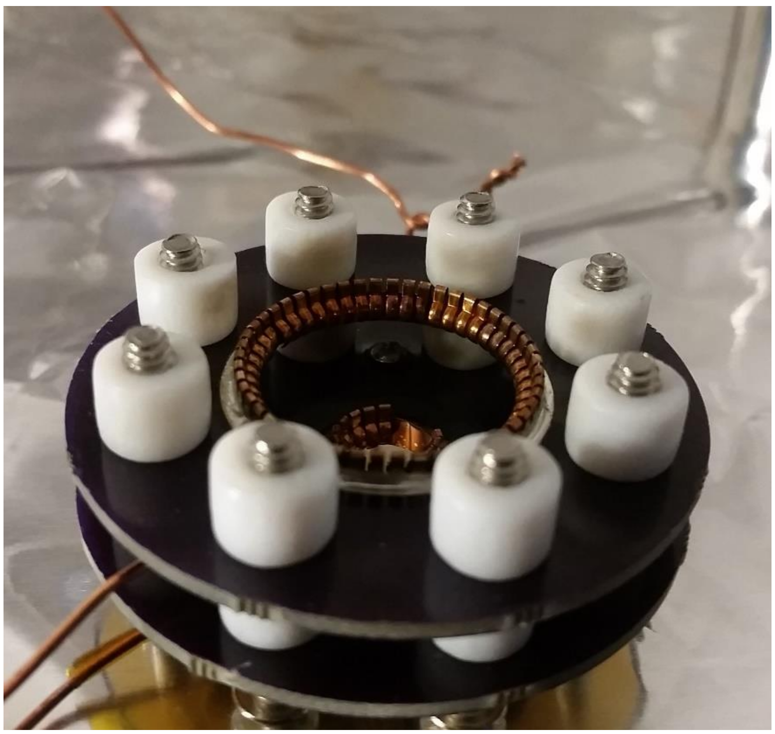

FIGURE 1 – Cathode-Igniter board Teflon spacer charring due to ignition discharges.

FIGURE 2 – Cathode-Igniter board Teflon spacer charring due to ignition discharges.

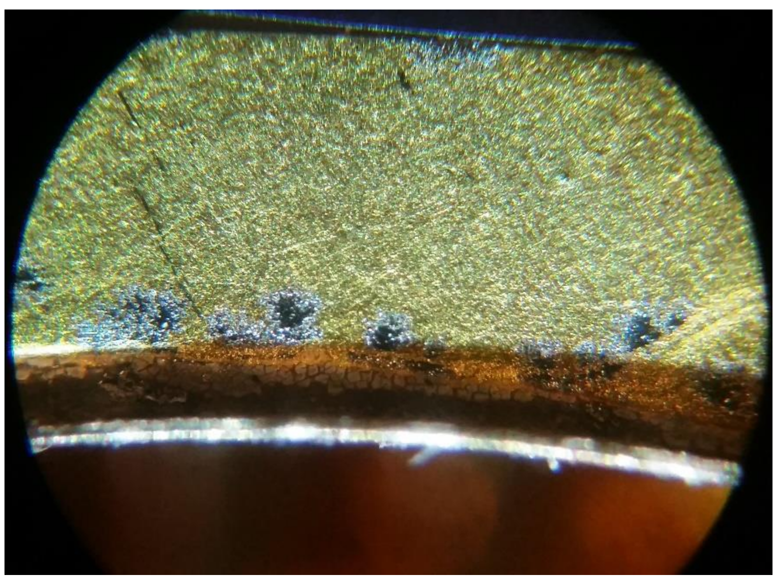

FIGURE 3 – Cathode board trace ablation from ignition arcs.

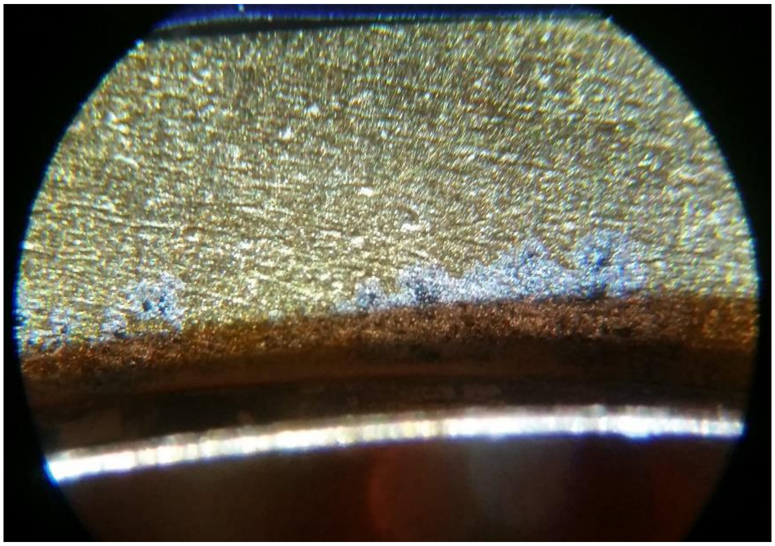

FIGURE 4 – Cathode board trace ablation from ignition arcs.

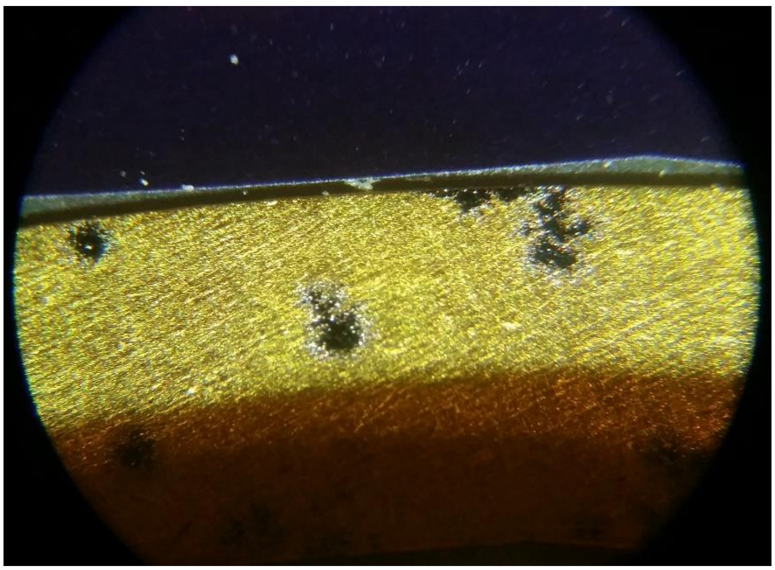

FIGURE 5 – Cathode board trace ablation from ignition arcs.

A second failure was noted during testing. For several random pulses after ignition, the main capacitor discharged a plasma pulse further back in the PCB socket assembly. This only occurred when the main capacitor was brought to its maximum voltage level of 2kV. Upon disassembly and inspection of the thruster, it was immediately noticed that the thruster fired an ablative pulse of the Teflon fuel at the rear of the thruster socket, between the central anode connection fingerstock, and the outer stainless steel assembly bolts, which also serve as low-inductance ground connections for the cathode. This shows successful firing and ablation of the Teflon fuel radially, however this occurred in the wrong part of the thruster. Charring from the ablation of the Teflon fuel can be seen in *Figure 6*. *Figure 7* shows board damage and charring due to the firing of the thruster in the wrong area along the anode board surface under the Teflon fuel. *Figure 8* shows subsequent charring of the Teflon spacers between the ignition and anode boards. *Figures 9-11* show microscope photos of the charring damage of the board due to ignition on the Teflon fuel. In particular, *Figure 11* shows evidence that this ignition was initiated between the central anode socket fingerstock trace, and a cathode connection solder hole. In *Figure 12*, the back of the anode board shows ablation of the surface traces due to arcing. A close-up microscope shot in *Figure 13* reveals significant ablation around the same hole where the suspect initial discharge occurred and was identified in *Figure 11*. It is suspected that the initial ignition arcing in the PCB socket assembly raised localized pressure within the socket due to ablation of the traces during the pulse to allow for the main capacitor to discharge between the anode and cathode connections in the socket assembly.

FIGURE 6 – Teflon fuel charring from ignition on the anode board surface.

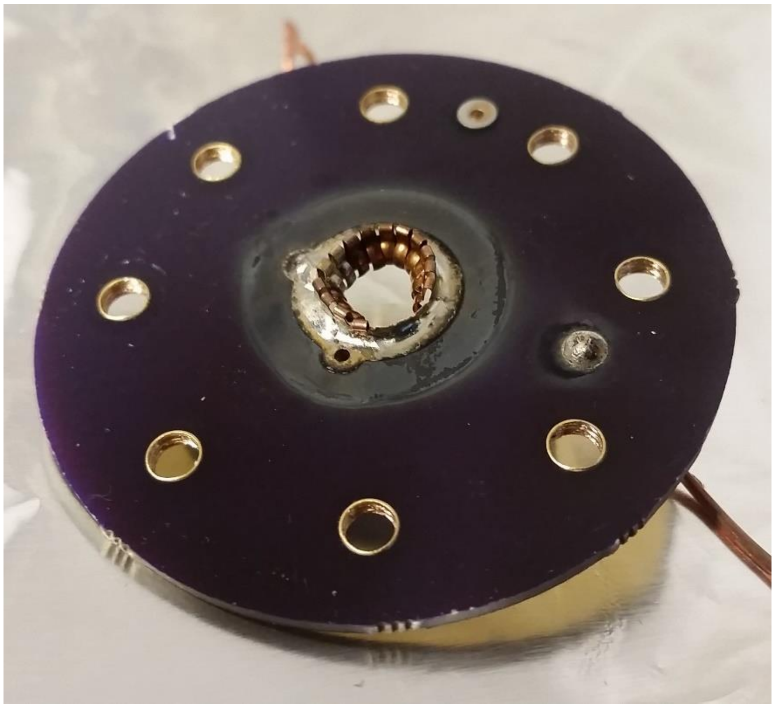

FIGURE 7 – Charring of the anode board surface due to ablation of the Teflon fuel.

FIGURE 8 – Charring of the Teflon spacers between the anode and igniter boards.

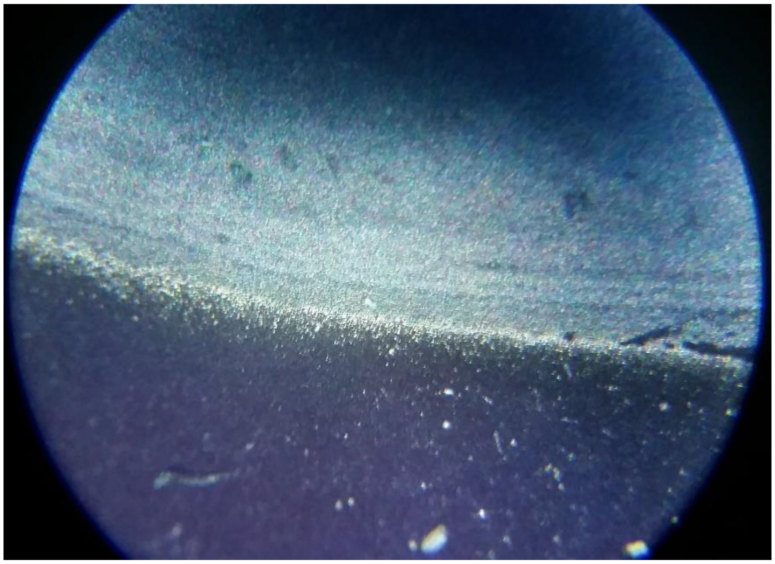

FIGURE 9 – Charring and ablation of the anode board surface due to ignition of Teflon fuel. Comparison between boundary layer of ablation and normal board surface.

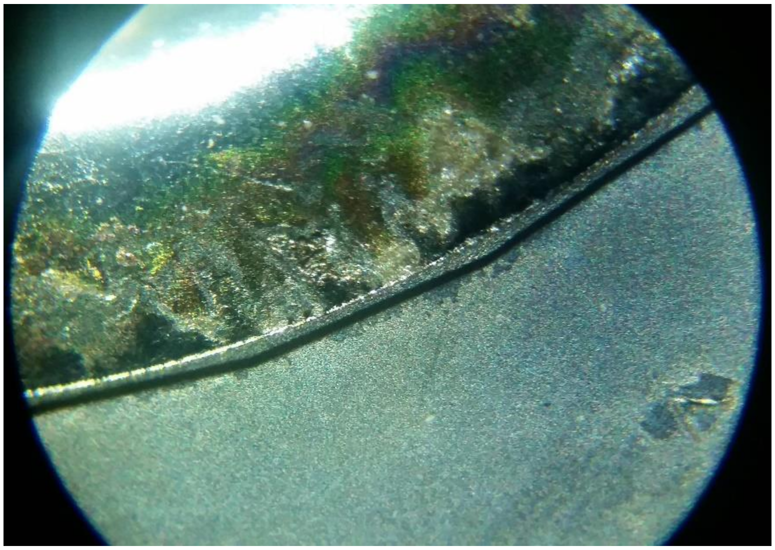

FIGURE 10 – Charring and ablation of the anode board surface due to ignition of Teflon fuel. Comparison between fingerstock solder trace and the ablated area of the board.

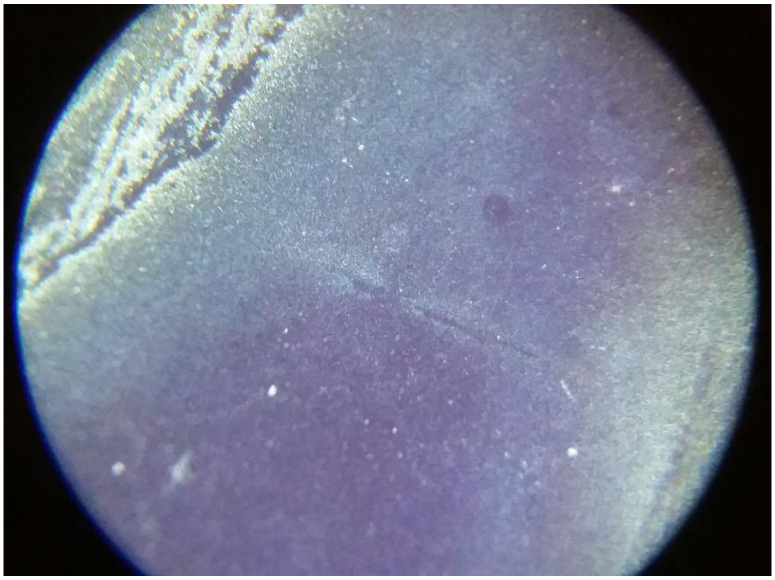

FIGURE 11 – Charring and ablation of the anode board surface due to ignition of Teflon fuel. Possible arc ignition and formation source between anode fingerstock connection (left) and cathode solder point connection (right).

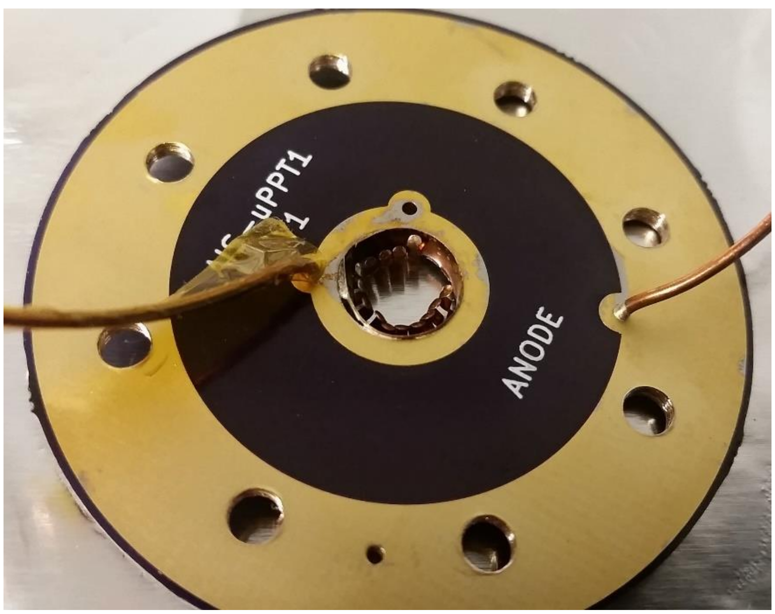

FIGURE 12 – Ablation of the anode board surface traces due to arcing.

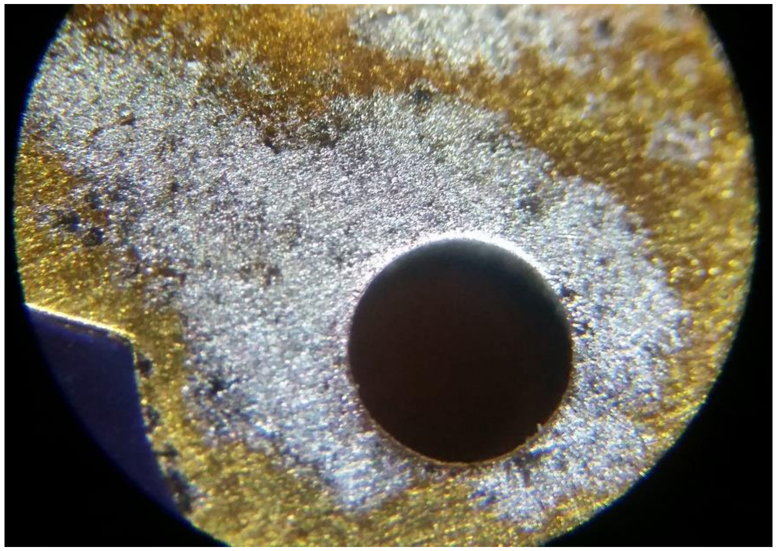

FIGURE 13 – Microscope picture of anode board surface trace ablation due to arcing. This ablation is present around the arc ignition point identified in Figure 11.

The primary underlying cause of ignition failure ultimately results from the inherent design of the thruster. Although the ignition electrode to cathode spacing is uniformly 0.028” concentrically between the two electrodes, and much closer than the 0.126” spacing between the ignition fingerstock and the cathode connection board trace, arcing still occurred in the wrong location, and failed to ignite the thruster. It is suspected that the highly polished and smooth stainless steel surfaces of the electrodes inhibited breakdown, where the sharp edges of the beryllium-cooper fingerstock in the ignition electrode connection PCB caused much higher local field enhancement, promoting discharge despite the wider spacing.

Finally, a minor equipment fault occurred and was noted during testing. On a few occasions, the high voltage pulser and main power supplies arced externally, causing the Arduino Mega used for the monitoring system to crash. As a result, all prior collected vacuum system pumpdown and cooling data was lost.

IV. FUTURE RECOMMENDATIONS

Based on observations during testing, as well as post-testing analysis, several major recommendations are presented going forward for the next generation of thrusters in the AIS-uPPT line. The primary underlying cause of ignition failure was the inherent design of the thruster itself. Highly polished surfaces make vacuum arc formation more challenging at high vacuum. While the highly polished surface, smooth edges, and large overall surface area would greatly improve erosion uniformity and electrode lifetime, ignition arc initiation becomes a greater challenge. It is therefore recommended to first further decrease the gap between the ignition electrode and the cathode electrode. Further surface modification, such as roughing of the surface of the ignition electrode at the exposed areas where ignition is to occur may also help. Lower ignition voltages due to closer electrodes as well as increased field enhancement at the surface will improve reliability, and lower the overall high-voltage stresses on the system.

The lower conductivity of stainless steel as opposed to copper may also contribute, as well as the difference in electron avalanche at high vacuum between the two materials. Stainless steel tubing was chosen due to a wide range of off-the-shelf sizes, reducing the need for custom machining. However, ignition may be easier with the utilization of oxygen-free copper, at the expense of custom machining.

Due to the tight spacing of the boards based on small-satellite space constraints, it is highly recommended to implement additional board-to-board insulation between surfaces of adjacent-facing boards. It is in this region where the arc faults during testing occurred when pushed to higher voltages. Such insulation can include laser-cut Kapton sheets with the same board pattern, or Teflon sheets with tight fits near exposed metal surfaces. Solder mask over any unsoldered surface traces may also help mitigate arc faults between boards.

A further potential redesign suggestion includes the use of separate voltages on the anode board, and placing a direct connection to the cathode board. In the original design, the anode board includes the central anode fingerstock connection, and the cathode connection on the periphery, where the stainless steel bolts make a low-inductance and evenly-distributed contact to the upper cathode board. By eliminating this configuration, and using direct connection to the cathode board through a connecting wire, chances of main capacitor discharge failure across the board can be eliminated. PEEK hardware can also be employed for non-conductive assembly of the boards in the socket.

Finally, in terms of testing, for all future vacuum tests, pumpdown and cooling data is to be saved prior to the start of ignition testing of a thruster, in the event the Arduino Mega and/or other electronics crash or are damaged due to external supply arc faults.