Applied Ion Systems
AIS-TR-024

AIS ADAMANT Series Development
Preliminary Sublimation and Ionization Test #3 of Adamantane Fuel for Ultra-Low Power Micro-Ion Thruster Systems - 01/17/2021

Test Report and Summary
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I. BACKGROUND

The AIS ADAMANT Series thrusters leverages Adamantane, a diamandoid hydrocarbon which exhibits many unique properties allowing for the potential of extreme power and size miniaturization of conventional gas-fed electric propulsion systems, with significantly reduced toxicity and no known corrosion issues like its similar and highly explored cousin Iodine. Currently, the ADAMANT Series is focusing on the development of highly integrated and modular micro-Hall thrusters run purely on sublimated Adamantane fuel. Total system power depending on the thruster is currently aimed from 5W up to 20W for the smallest class systems, with the ability to scale up to more conventional 50W class systems. Despite its unique potential as an alternative molecular propellant for conventional gas-fed EP, little work has been done on Adamantane for use as a fuel in the field.

While Adamantane has been tested a couple of times in literature, this has only been done at much higher power levels in larger gridded ion thrusters at hundreds of watts to kW class systems. Despite successful operation at higher power levels, with performance similar to Xenon, Krypton, and Iodine, Adamantane has been largely dismissed in literature without custom modifications to the chemical composition to overcome some of the inefficiencies inherent to the fuel, and overall testing in the field has been practically non-existent otherwise. Due to its many attractive properties however, such as solid storage, ease of sublimation, high ionization cross-section, high molecular weight, low cost, non-corrosiveness, and low-toxicity, Adamantane has been identified as a key technical enabler in meeting the unique challenges being addressed and inherent limitations in funding and infrastructure at AIS, and fully embraced as the central focus of new development efforts at AIS through the ADAMANT Series, which leveraging the unique properties of Adamantane to overcome conventional scaling limitations in EP technology such as Hall thrusters.

II. OVERVIEW

The goal of the third preliminary sublimation and ionization test was to explore the use of Adamantane fuel for use in a novel ultra-low power glow-discharge hollow-cathode neutralizer in development at AIS.

One of the key challenges in scaling technologies such as Hall thrusters down in both size and power is that of the neutralizer. Conventional neutralizers operate at tens of watts or more of power. While significant effort has gone into the extreme miniaturization of the Hall thruster head itself, comparatively less effort has gone into ultra-miniature neutralizers. The most commonly employed technologies for hollow cathode neutralizers include heated insert, heater-less, and RF cathodes. Heater and heater-less cathodes rely on low work function emitting inserts such as LaB6, which must be operated with inert gases. RF neutralizers can be run with any gas, and in theory very high frequencies in the hundreds of MHz to GHz range can allow for reduced power required for ionization, reducing total neutralizer size in the case of microwave frequency excitation. However, such systems are generally more inefficient than their lower-frequency counterparts, requiring still higher power than aimed for in the AIS neutralizer development effort. In addition, RF systems add increased complexity and cost in the design, and such circuitry would also increase total system size and cost more than allotted for the systems AIS is aiming to develop.

One of the ultimate goals of the AIS ADAMANT Series development is to scale conventional Hall thruster technology in size and power to be compatible from 3U Cubesats down to 3P PocketQube-class satellites. This requires extremely compact and tightly integrated propulsion, and a neutralizer that takes up bare-minimal volume at only a few watts total max power. To date, no hollow cathode on the market has been made suitable to meet these criteria for ultra-compact and low-power Hall thruster systems, and there are currently no commercial Hall thruster systems compatible at this scale. To address these unique scaling issues, AIS proposes the development of a highly unorthodox neutralizer not found in EP currently, but used in particle beam physics and experimental e-beam processing. This type of cathode is based off of glow-discharge hollow-cathode e-beam sources.

Glow-discharge hollow cathodes operate off the principles of direct breakdown and ionization of the working gas through high applied voltages between the hollow cathode and the anode. In this case, the hollow cathode consists of a simple metal cylindrical cup structure out of standard metals, such as stainless steel, copper, and molybdenum. Because ionization of the gas is based on high voltage ionization and breakdown of the working gas, no low work function inserts are utilized. Instead, the resulting plasma that forms inside the hollow cathode creates a plasma cathode, which itself has zero work function, allowing significant current densities for electron extraction. Hollow plasma cathodes have demonstrated current densities in excess of 10kA/cm^2, and are of the highest current density type e-beam cathodes. Such sources have also been demonstrated at power levels from a few watts to MW-class systems, run both in DC and pulsed modes. While such cathodes operate at similar gas pressure levels of conventional cathodes in EP, glow discharge hollow cathodes operate at significantly higher voltages, and have been demonstrated anywhere from 500V to hundreds of kV for the largest pulsed systems. Cathode bore diameters can range from several mm to tens of cm, however there has also been work on micro-sized cathodes operating at extremely high pressures and micron-level bores. Despite this incredibly wide operating range in terms of power, gases, and high electron extraction current densities, such cathode technology has not yet be employed in electric propulsion systems.

In order to test the ability of Adamantane to be run with such a cathode, the original test cell was modified to simulate the operation of the glow discharge neutralizer. Because there were significant unknowns associated with this test, it was decided to first simulate a glow-discharge hollow cathode in principle with the modified test cell, and if successful, resources could be fully committed to production of the first prototype neutralizer design.

The first two preliminary tests have successfully validated that Adamantane can be sublimated at very low temperatures and heater power levels, as well as very easy to ionize at moderate voltages and very low discharge power levels, demonstrated from 0.75W to 2W. With low power sublimation and ionization verified of the fuel, the next steps will be developing and running this new neutralizer with Adamantane. To date, there have been no published studies on the use of Adamantane fuel exclusively with hollow-cathode neutralizers for ion thrusters. While

Adamantane has been successfully tested a couple of times in the field prior, this has been only conducted at high power levels of hundreds of watts to several kW in conventional gridded ion thrusters.

Looking at currently available limited data, and drawing extrapolations from these test results and basic principles of related EP systems and other alternative fuels, AIS proposes that Adamantane can allow for unprecedented scaling of conventional gas-fed EP technologies, allowing for low-power operation and unpressurized feed for the smallest class of satellites in the field. With significantly less toxicity, and no corrosion issues like Iodine, Adamantane has further potential for much greater total system cost reduction using conventional materials in the design of the Hall thruster, neutralizer, and propellant feed system. AIS is also taking a radically unconventional approach towards cathode design to leverage these advantages to create the smallest fully integrated Hall thruster systems ever developed in the field. AIS is currently the first and only EP company in the world specifically developing Adamantane-fueled EP systems through its AIS ADAMANT Series development initiative.

III. PRELIMINARY SETUP

In order to simulate the glow-discharge hollow-cathode topology, the original ionization test cell used in the two prior studies was slightly modified. First, the bottom electrode was wired to a -3.5kV, 2W power supply, and the top electrode on the cell was wired to ground. In the prior two tests, the bottom electrode was at ground potential, and the top electrode at 3.5kV. In this case, the bottom electrode serves as the mock hollow-cathode, while the upper electrode held at ground serves as the anode. The anode aperture was selected to be 1mm.

An extractor electrode was then added to the top of the anode, spaced with 1/16” Teflon spacers. The extractor was wired to a 3.5kV, 2W supply, and the ground connection also commoned to the anode. The aperture on the extractor was larger at 1.6mm in diameter.

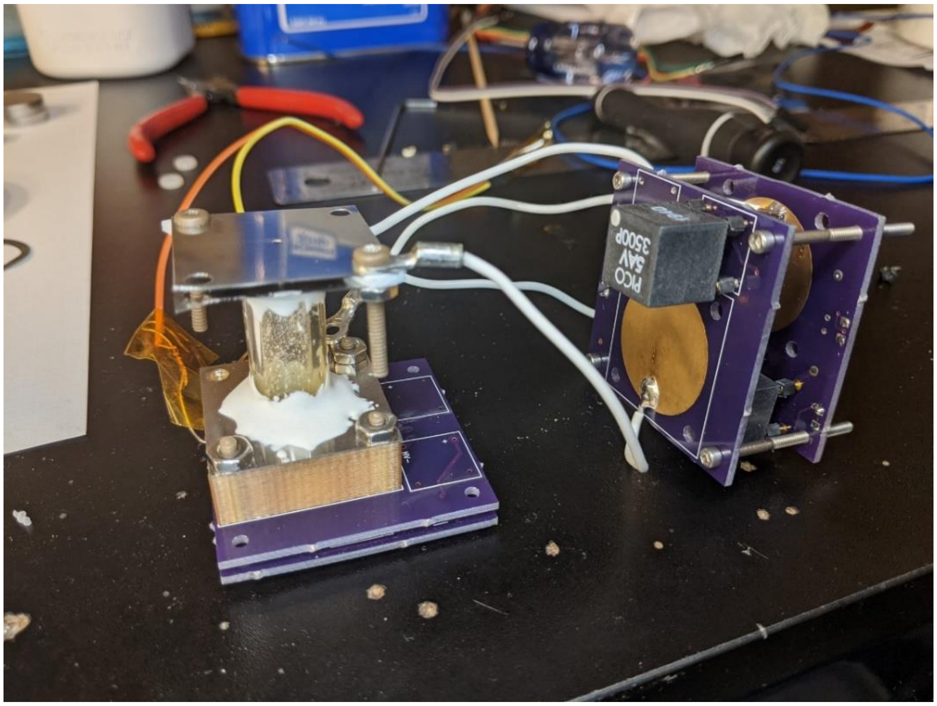

FIGURE 1: *Completed and assembled modified test cell for simulating glow-discharge hollow cathode operation*

The assembly was fueled and bolted together like in the prior two tests (see *AIS-TR-022* and/or *AIS-TR-023* for reference.) The entire assembly was wired up and mounted in the vacuum chamber.

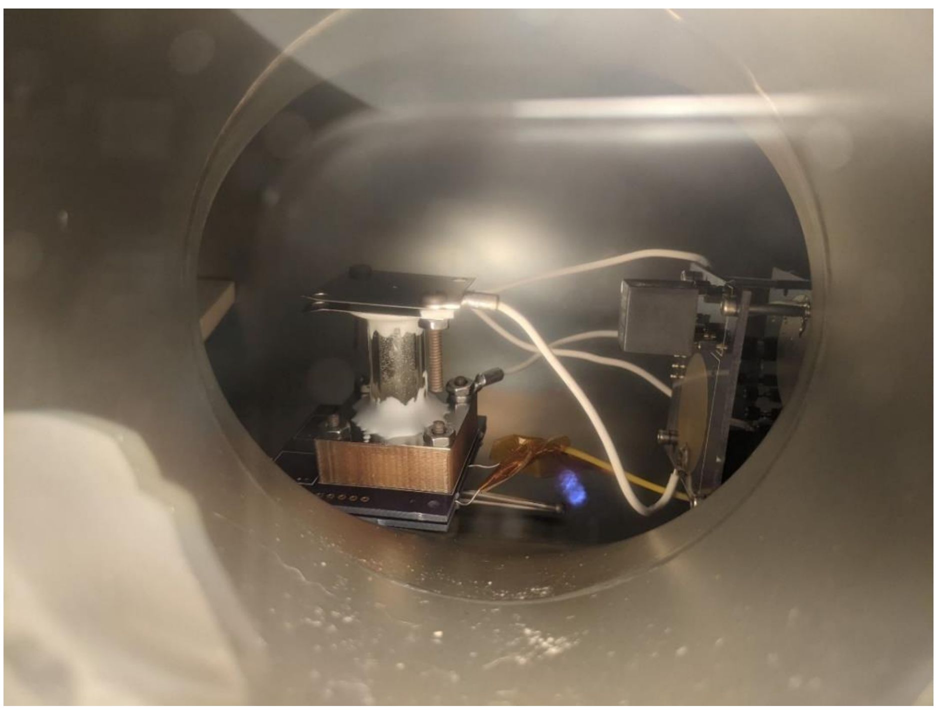

FIGURE 2: *Mounting of the test cell in the high vacuum chamber for testing*

IV. TESTING

Pumpdown behavior was the same as the prior two tests, slowly reaching an ultimate vacuum level in the mid-10^-4 Torr range prior to ignition attempts. First, the -HV supply was turned on, easily achieving a stable glow discharge at low power levels. Like in the prior second test, no heater power was used, and discharge was sustained purely on passively sublimated Adamantane vapors at 14.5C ambient.

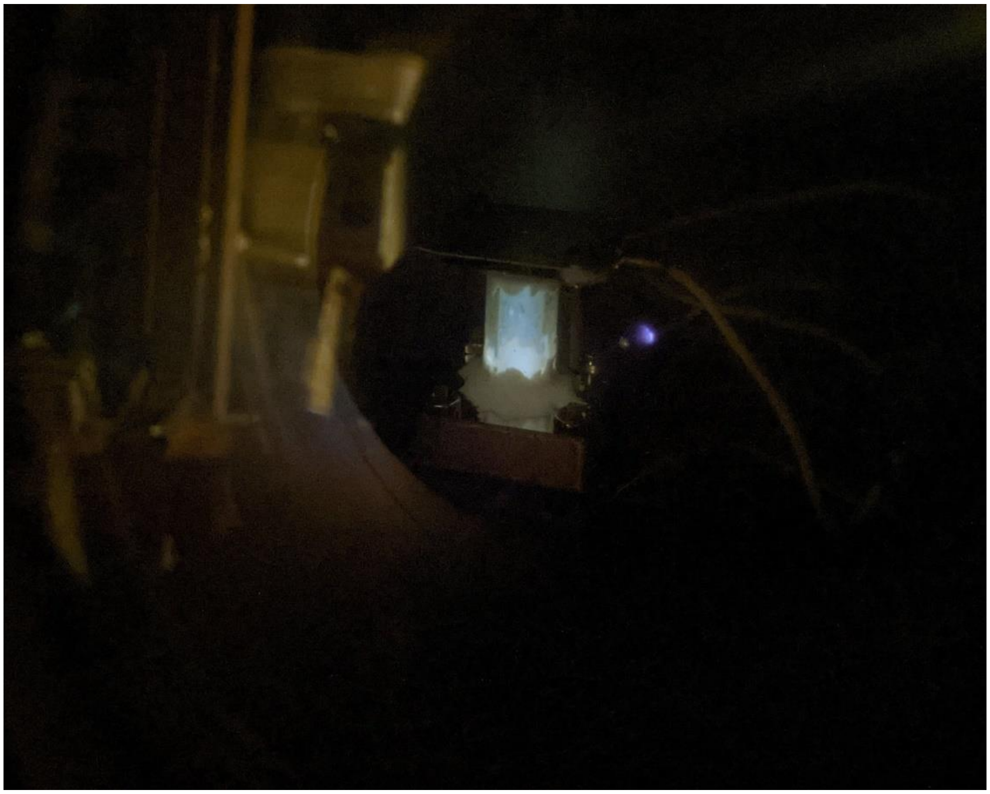

FIGURE 3: *Initial Adamantane plasma glow-discharge on purely passively sublimated Adamantane vapors from ambient background of 14.5C*

Once the discharge was established, the +HV supply on the extractor electrode was turned on and slowly increased. Immediately, a noticeable plume emerged from the aperture of the extractor plate.

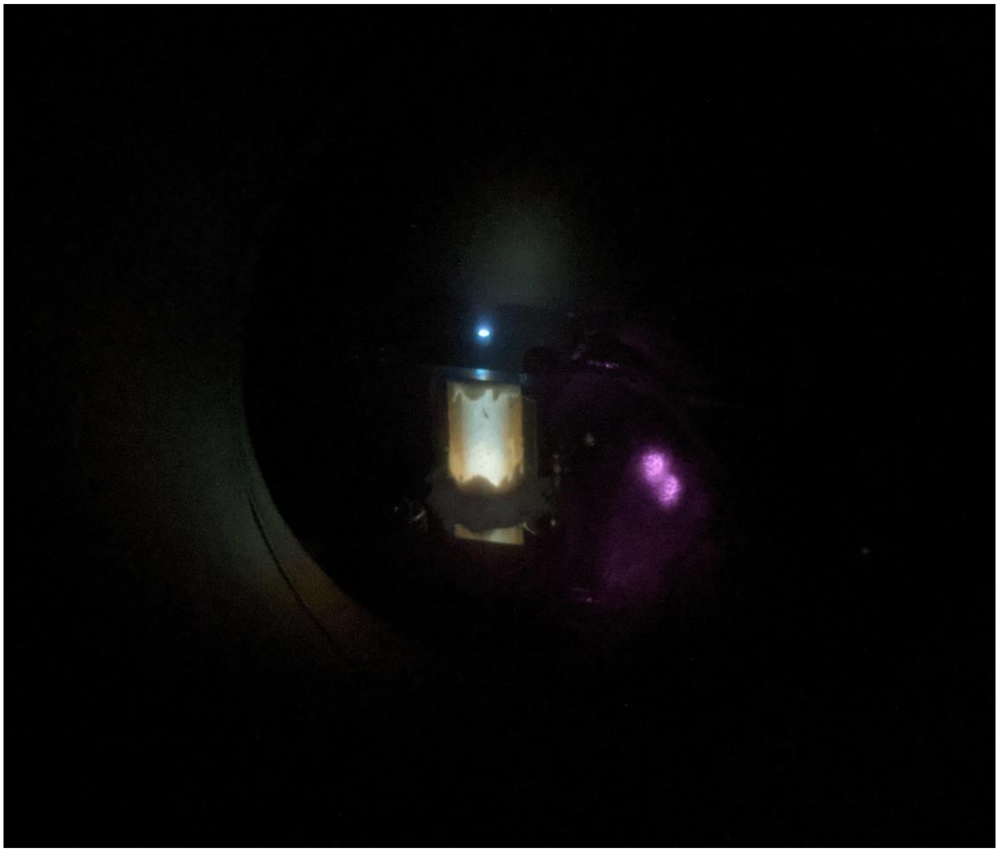

FIGURE 4: *Plume extraction from the Adamantane glow discharge on passively sublimated vapors*

Power was cycled on and off several times to verify the effect, and each time the extracted plume was reignited with ease. Next, 3.5W power was applied to the sublimation heater, increasing the sublimation rate as well as the pressure inside the discharge cell. The discharge got noticeably duller inside the cell, but the plume formation remained at the same intensity on the extractor output. Between the anode and extractor, a distinct plasma column can be seen, with a larger plume emanating from the aperture of the extractor.

FIGURE 5: *Plume extraction from the Adamantane glow with increased cell gas pressure from active fuel sublimation*

After running for several minutes with increased Adamantane pressure on the test cell, the -HV power supply was then adjusted to see the effect on the discharge. Surprisingly, when the main -HV discharge supply was reduced in voltage from -2kV to only a few hundred volts with the +HV extractor voltage on, the extracted plume intensity suddenly greatly increased. At too low levels, output extinguished, however the higher the voltage after a certain point, the less intense the output became, Adjusting the +HV extractor voltage up further, the plume output continued to increase with significant intensity, behaving linearly with increasing and decreasing voltage, appearing much more like the plasma plume output from a hollow-cathode neutralizer source. At this point, both HV supplies were operating at a combined power of only 3.2W, with 3.5W of additional power for the sublimation heater.

FIGURE 6: *Full intensity extracted neutralizer plume using a total of 3.2W discharge and extractor power at 3.5W sublimation power*

The intense output plume was notably stable for the duration of the run, which was eventually ended due to fuel depletion like prior tests. Video of operation of the test cell and successful ionization can be viewed on the AIS website and AIS YouTube page.

V. POST-TEST ANALYSIS

After the test, the test cell was removed from the vacuum chamber for inspection. Erosion and discoloration around the extractor aperture was significantly more noticeable than prior tests, due to the more intense output plume.

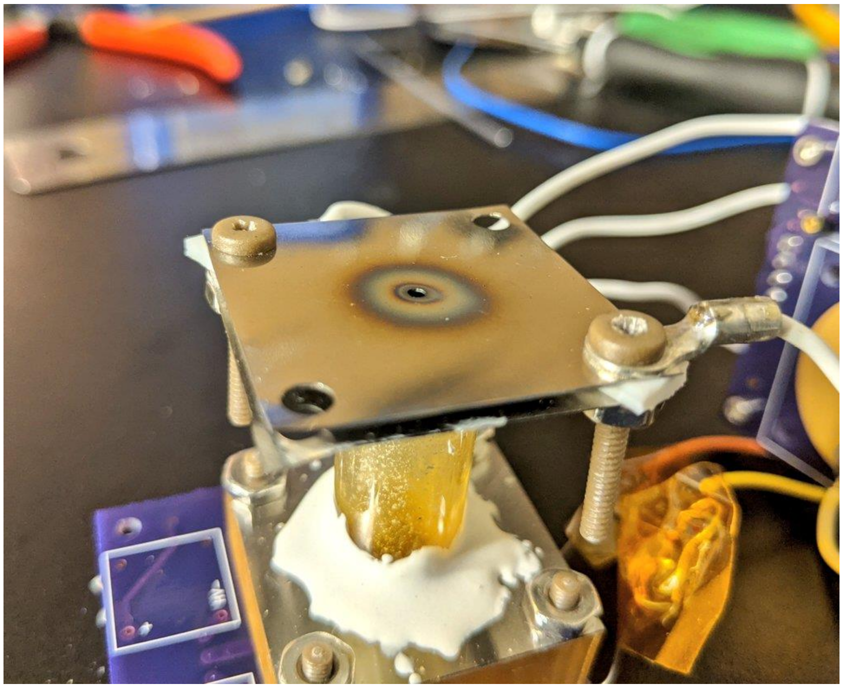

FIGURE 7: *Erosion and discoloration around the output aperture of the extractor electrode*

Removing the top extractor plate, erosion and discoloration was also visible on the bottom side of the plate

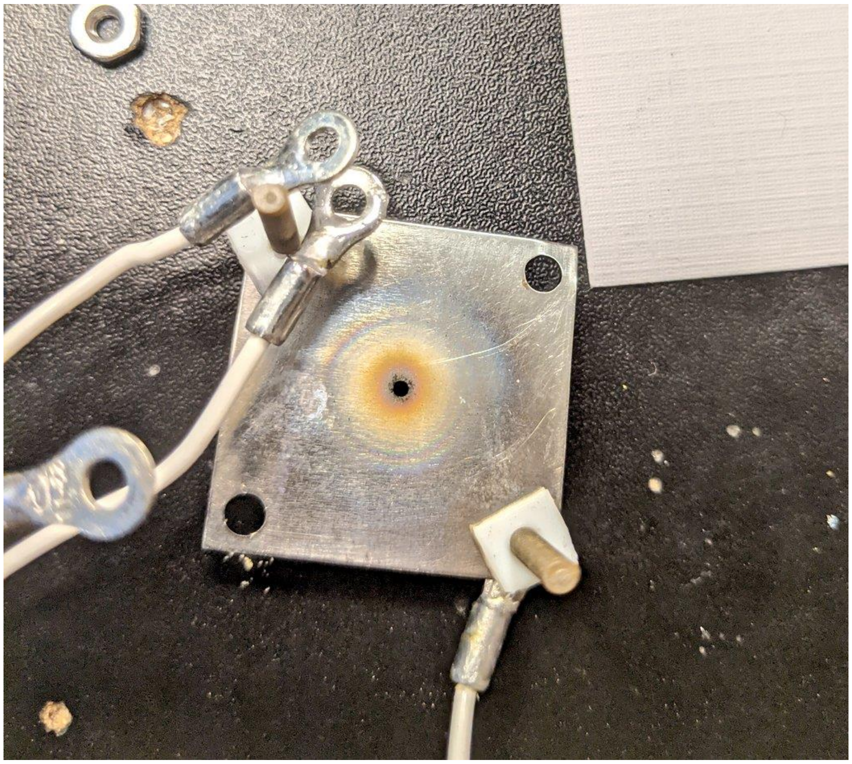

FIGURE 8: *Erosion and discoloration around the bottom of the aperture of the extractor electrode*

Looking at the top anode plate on the test cell, erosion and discoloration patterns were also observed around the output aperture similar to the top extractor plate.

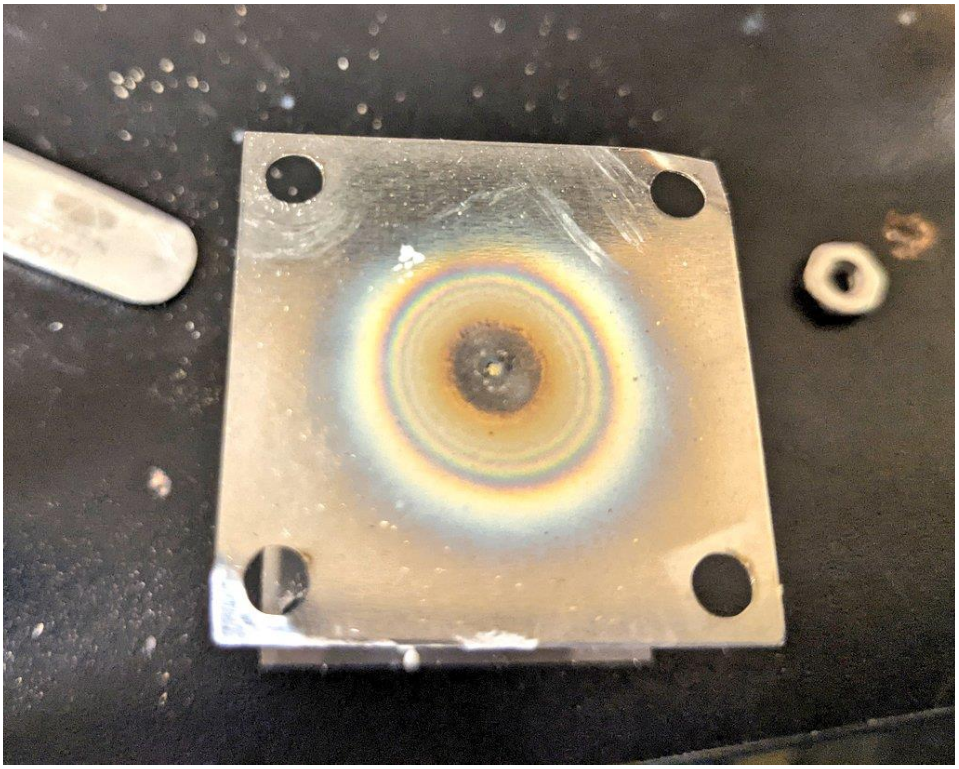

FIGURE 9: *Erosion and discoloration around the output aperture of the anode*

Finally, looking at the bottom of the cathode plate around the fuel input aperture, more noticeable fuel buildup and charring was observed than prior tests. This was most likely caused from plasma leakage into the fuel chamber from the backpressure after increasing the flow rate with sublimation power on. During the test, some dull glow observed inside the Ultem fuel housing after sublimation power was increased and during the peak of the discharge.

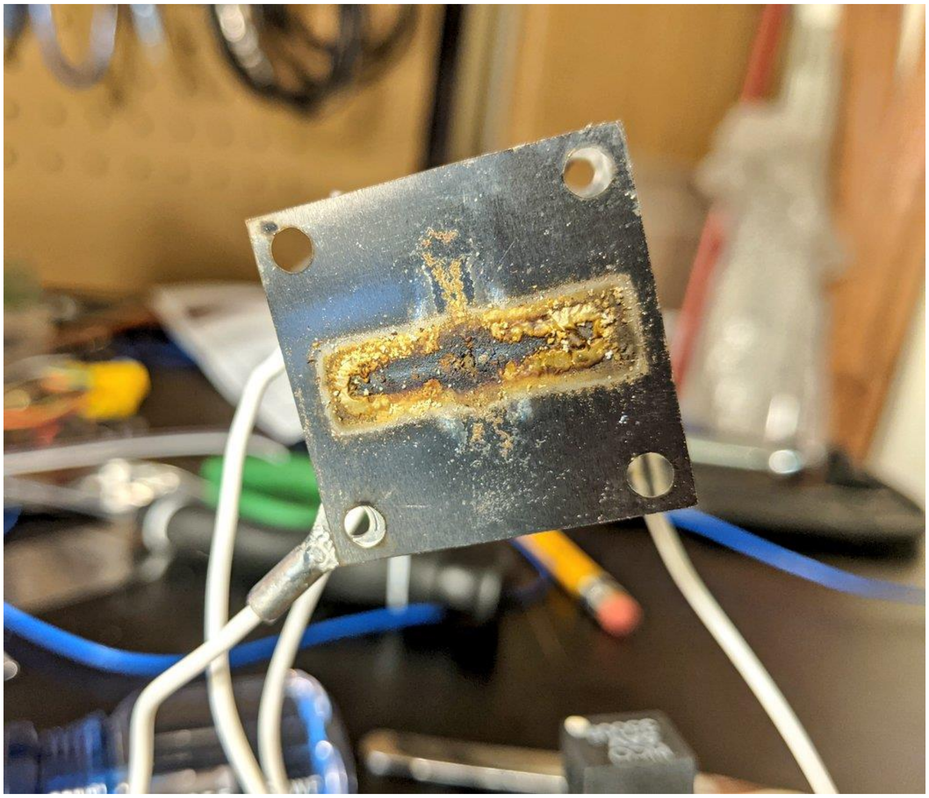

FIGURE 10: *Fuel buildup and charring around the bottom cathode plate and fuel input aperture*

VI. CONCLUSION AND FUTURE DEVELOPMENTS

The third preliminary sublimation and ionization test of Adamantane fuel in vacuum has been successfully completed. In this test, ionization was successfully demonstrated on both purely passively sublimated Adamantane vapors at chamber background temperatures at 14.5C as well as actively sublimated fuel using 3.5W of heater power. Most significantly however, this test validated the initial hypothesis of the potential for ultra-low power neutralizer operation using Adamantane fuel with the modified test cell configured to simulate glow-discharge hollow-cathode source. When both the -HV discharge supply and +HV extractor supplies were properly adjusted, with the -HV supply at a minimum and the +HV supply at a maximum with full fuel flow, the resulting plume output was significant. At peak output, total discharge and extractor power was only 3.2W. Discharge power was cycled on and off with immediate and reliable ignition. The extracted plume also remained stable during the run.

While the test cell will not operate exactly as the final neutralizer, this test represents a major breakthrough in the AIS efforts in the development of a novel low-power neutralizer that will be able to be run off Adamantane, as well as any other feed gas used for Hall thrusters, operating on only a few watts total power and being able to support the extremely compact Hall thrusters AIS is developing for nanosats and picosats ranging from 3U Cubesats down to 3P PocketQubes. Because of its uniquely diverse range of operation demonstrated in other fields, the glow-discharge hollow cathodes developed at AIS can easily be scaled up in size and power to support higher power-class Hall thrusters, and offer a unique solution for low-power, fuel agnostic, high current density neutralizers. Due to the simplified physical build of these devices, requiring simple materials for construction with no dispenser inserts or RF power, such cathodes can also be rapidly built and manufactured at a fraction of the price of conventional cathodes. Based on this and the prior test results, AIS will be moving forward with the final design and prototype build of the first low-power micro glow-discharge hollow cathode neutralizer for operation with the new EHT1 Micro End-Hall Thruster in development, a 20W class Adamantane-fueled Hall thruster.