Applied Ion Systems
AIS-TR-022

AIS ADAMANT Series Development
Preliminary Sublimation and Ionization Test #1 of Adamantane Fuel for Ultra-Low Power Micro-Ion Thruster Systems - 01/11/2021

Test Report and Summary
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I. BACKGROUND

The increasing demand of more complex and capable nano and pico satellites has spurred significant developments in micro electric propulsion systems over the past couple of decades. As such, the field has seen a boom in new EP companies developing small-scale plasma and ion thrusters catered towards these smaller satellites. Some of the main challenges associated with EP development at the nano and picosat scales however are the very low power availability of such satellites, as well as the extremely limited volume. In addition to power and volume budgets, satellites such as PocketQubes and many Cubesats flying as secondary payloads cannot fly with pressurized fuel systems.

EP technologies such as PPTs, VATs, ILIS, and FEEP scale very readily an effectively in terms of both volume and power, in addition to operating with unpressurized fuel feeds, meeting many criteria of nano and pico satellites. However, more mainstream and conventional propulsion systems such as Hall thrusters, RF plasma, and gridded ion seen at much larger and higher power satellite classes all share significant challenges in system and power scaling. In addition, these systems traditionally run using inert pressurized propellants such as Xenon, precluding them from the above mentioned classes of the smallest satellites and those flown as secondary payloads.

Recent developments have been strongly trending towards alternative fuels such as Iodine in these more conventionally higher-power EP systems, which has many advantages such as very high fuel density, solid storage for unpressurized fuel feed, high molecular weight, large ionization cross section, and low-temperature sublimation, with similar performance to conventional fuels like Xenon and Krypton. Despite this, Iodine in particular is extremely corrosive to most materials, and is relatively toxic, making testing and development a significant challenge. While other solid fuels have been tested, such as Bismuth, these often require significantly higher power for sublimation, and special considerations for fuel feeding.

New, yet limited interest has been very recently expressed in alternative molecular propellants. These propellants, while more chemically complex and far less understood in plasma and ion beam conditions, exhibit many appealing properties as alternative fuels. Such properties also include solid storage, low temperature direct sublimation, and high ionization cross section. Among these, diamandoid hydrocarbons such as Adamantane and Diamantane, as well as fullerenes such as C60 have been tested on higher power ion thrusters. In particular, Adamantane shows very interesting potential as a safer and corrosive-free alternative to Iodine.

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 AIS ADAMANT Series, which aims to leverage the unique properties of Adamantane to overcome conventional scaling limitations in EP technology such as Hall thrusters.

II. OVERVIEW

The goal of this first test at AIS was to explore the ability to sublimate and ionize Adamantane fuel at very low power levels in vacuum, using only a few watts total for both sublimation and ionization. While Adamantane has been successfully tested a couple of times in the field, 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. As such, 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

Fuel used for testing was >99% pure Adamantane. Upon delivery, the Adamantane was caked together in large clumps. Pieces of Adamantane were put into a plastic Ziploc bag and gently pounded with a hammer to break it up. The final fuel appeared as coarse table salt, which could be easily poured into the prototype sublimation cell.

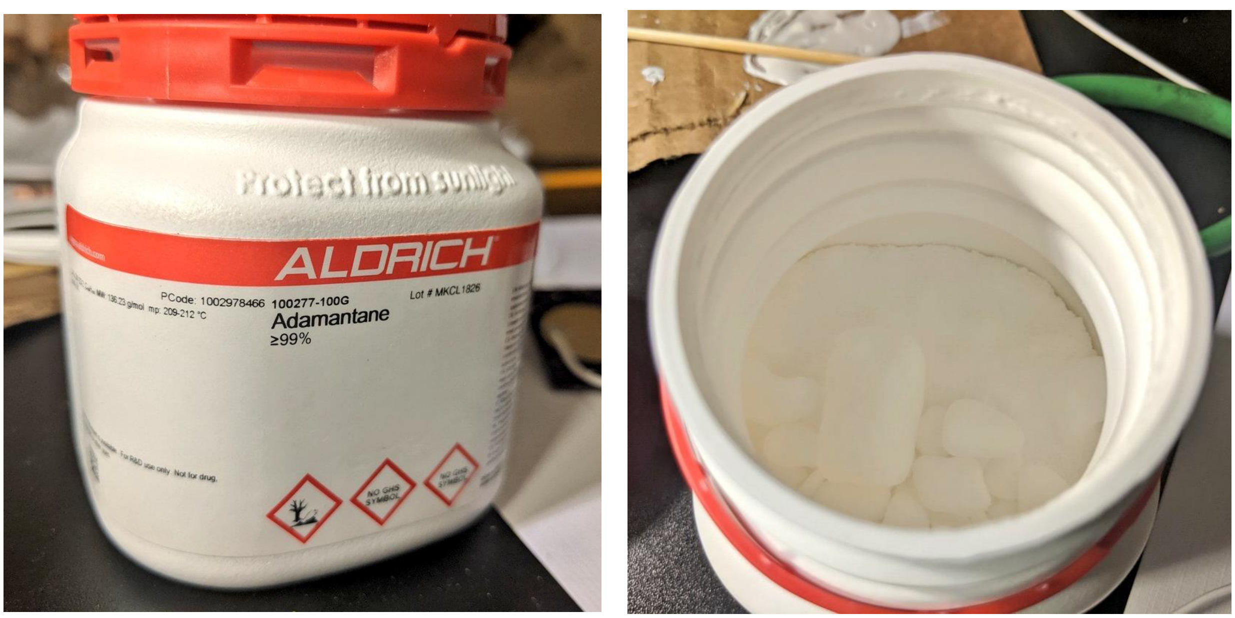

FIGURE 1: *Adamantane used for the experimental setup*

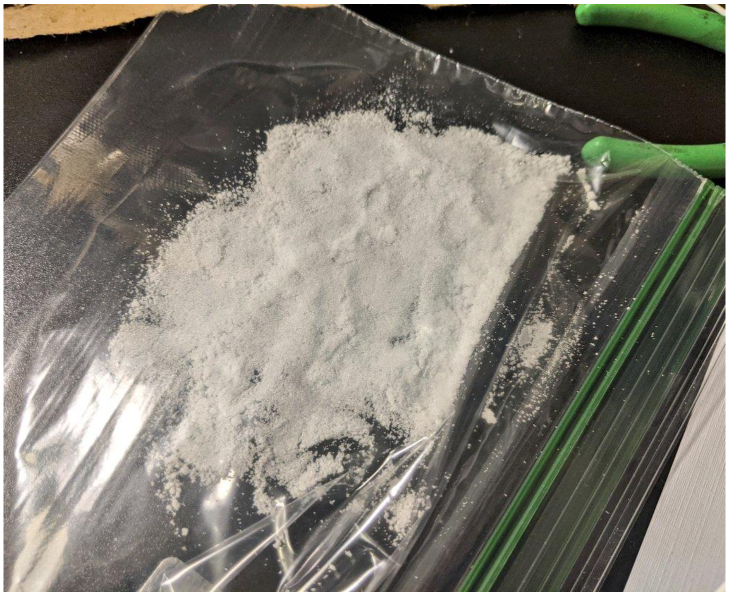

FIGURE 2: *Adamantane fuel preparation for loading into the test sublimation cell*

Due to the limited resources available to AIS, as well as the large number of unknowns in this first test, it was decided to construct a very simple sublimation and ionization test system using only components immediately available and salvaged from prior builds. This included spare boards, an Ultem 3D printed housing, and various extractor electrodes from the AIS-ILIS1 series development.

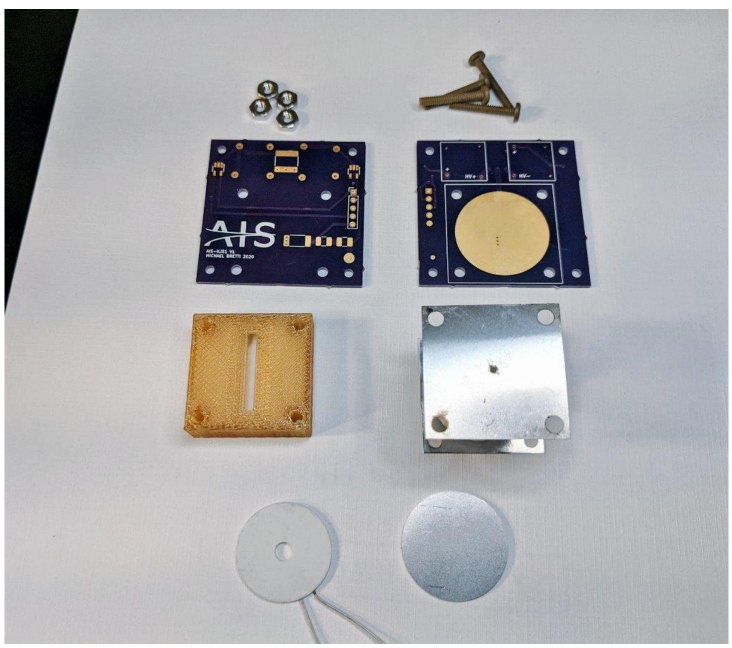

FIGURE 3: *Parts used for the sublimation and ionization test cell*

To create the fuel sublimator, two older version ILIS1 boards were used to create the heater surface and fuel storage. A 25mm diameter, 19W ceramic-metal heater element was sandwiched between two boards, with the top board having the large HV contactor disc facing up. An ILIS1 presser plate was used between the heater element and the upper board to create both a thermal buffer and increase the thermal mass of the heater assembly. When power is applied to the heater, the boards also heat up, providing a heated surface to sublimate Adamantane.

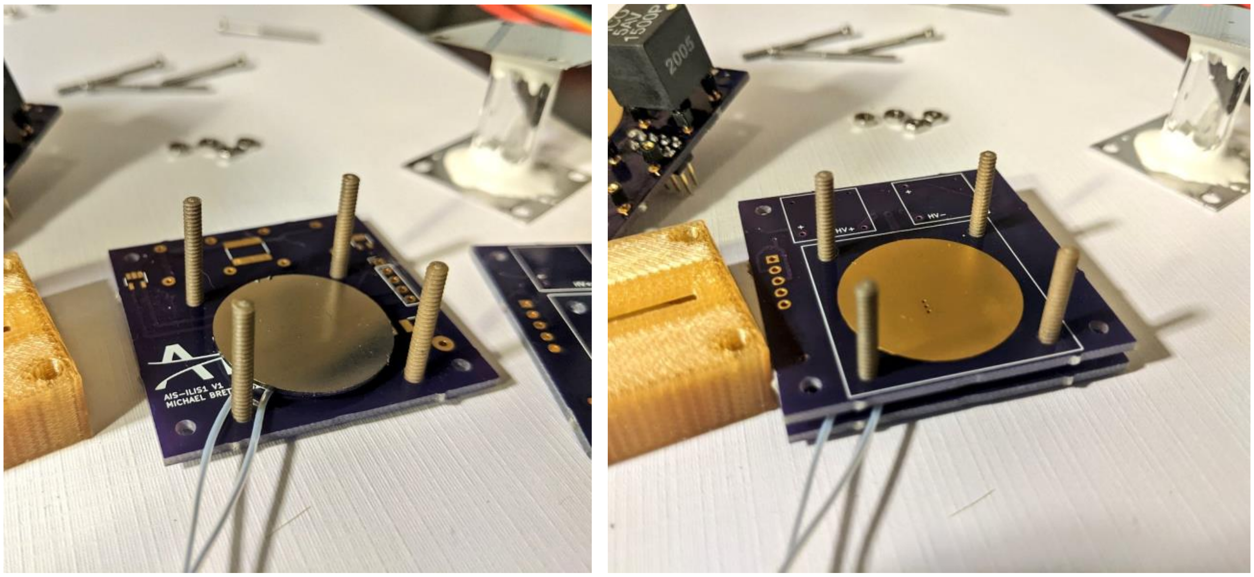

FIGURE 4: *Heater assembly using ILIS1 boards, a ceramic-metal disc heater, and nickel contact plate*

To hold the Adamantane fuel on the topmost board, an ILIS1 housing would be used over the heated contact pad. Adamantane would be poured into the top slit, and the assembly bolted together with a HV discharge cell on top with a small feed hole for sublimated gas to flow into.

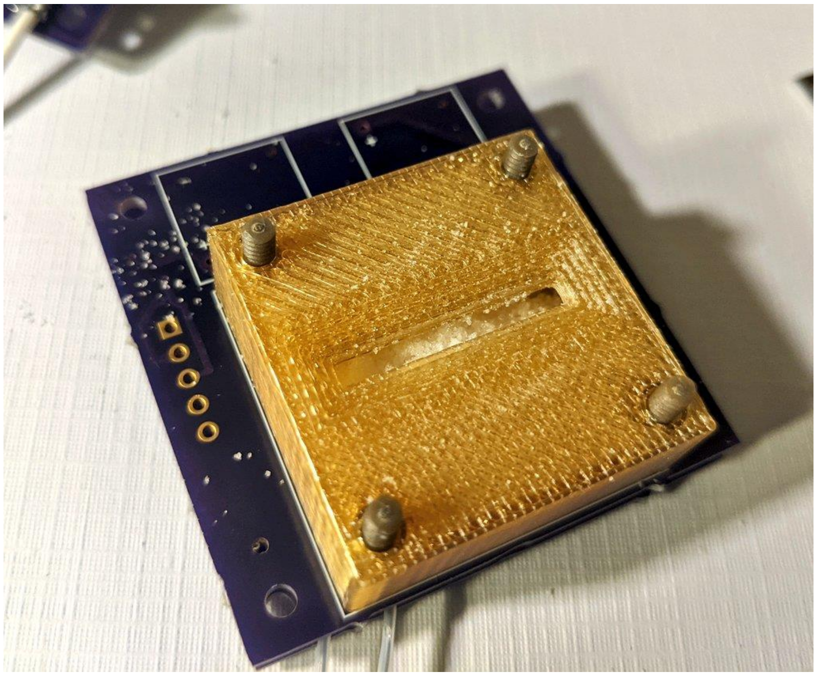

FIGURE 5: *Loading of Adamantane fuel into the test sublimation cell housing*

To create the discharge cell, a 3cm length of 0.375″ diameter borosilicate glass tubing was epoxied spare ILIS1 extractor plates on the top and bottom using vacuum compatible Hysol-1C epoxy. The bottom plate had a 1.4mm diameter hole, while the top plate has a 1mm diameter hole. The test cell was then bolted in place over the makeshift fuel chamber.

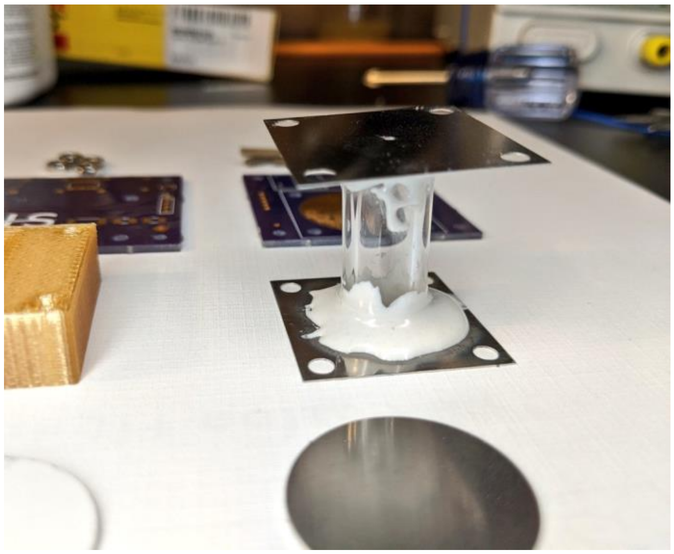

FIGURE 6: *Ionization test cell made from stainless steel, borosilicate glass, and Hysol-1C epoxy*

Prior to final assembly, both the Ultem housing and the epoxied test cell were baked and degassed in vacuum for several hours to mitigate any extraneous and unwanted gas loads during testing.

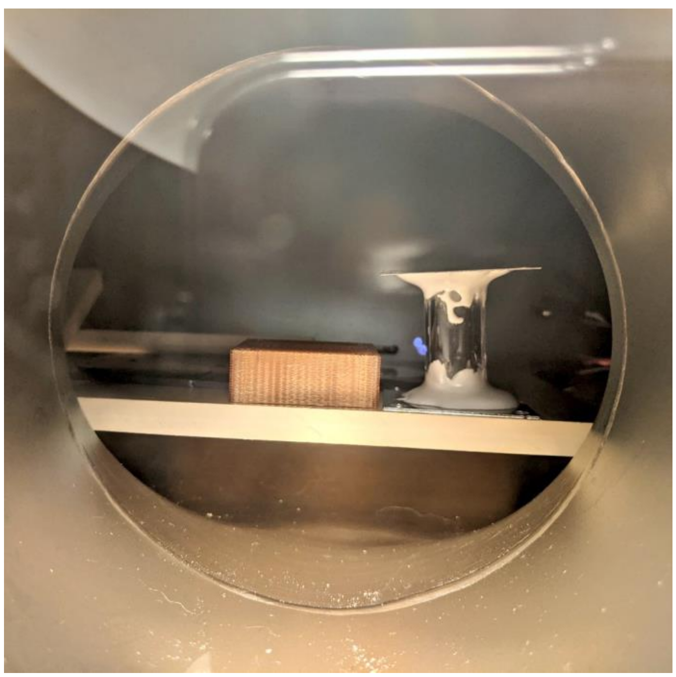

FIGURE 7: *Vacuum baking and degassing of the Ultem fuel housing and ionization cell*

The test cell was then wired up to a small 2W, 1.5kV Pico supply, with the bottom plate at ground and the top plate at HV. The system was loaded up into the vacuum chamber and pumped down.

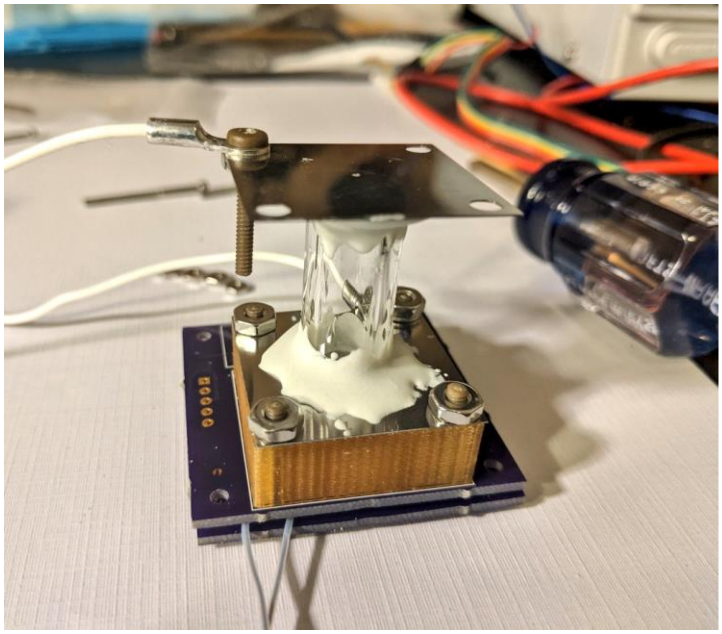

FIGURE 8: *Completed and assembled prototype sublimation and ionization test cell*

IV. TESTING

Pumpdown was unusually difficult, reaching a final vacuum level of only around 5.8×10^{-4} Torr. This was most likely due to the passive sublimation of the fuel into the chamber during pumpdown, and the relatively low pumping speed of the system (400L/s effective speed for air), given the overall heavier molecular weight of the gas. However, the chamber temperature was only 12.5C, indicating that the gas load from the sublimation of Adamantane in vacuum was still significant even at very low ambient temperatures.

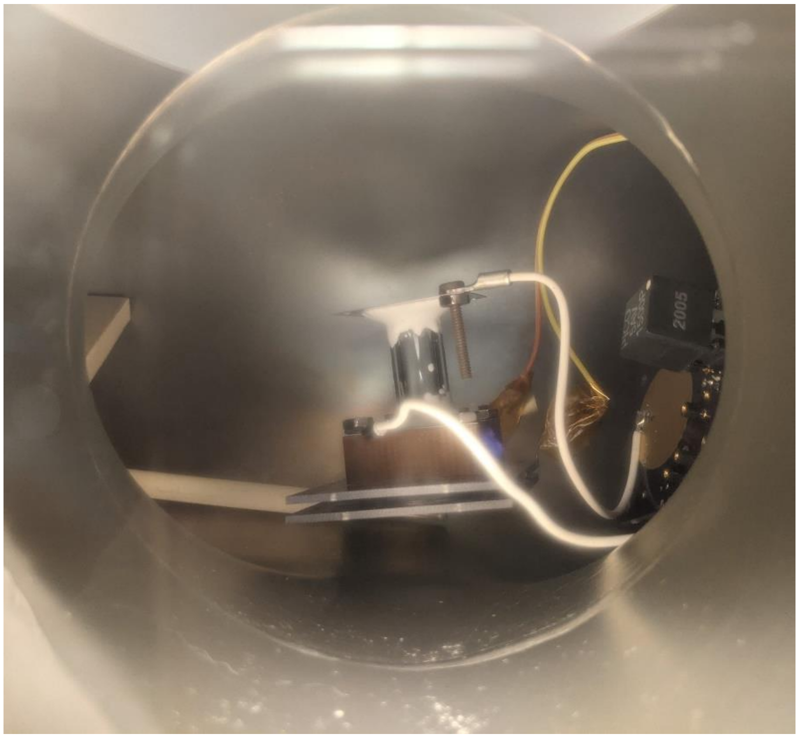

FIGURE 9: *Mounting of the test cell in the high vacuum chamber for testing*

High voltage was first applied to the test cell, starting out from only a few hundred volts, and raised to a maximum of 1.5kV. During this period, no discharge was observed. Heater power was then brought up to 3.5W, where vacuum loading on the chamber increased. After a period of several minutes warm-up, a clear discharge was ignited and observed in the test cell. Discharge voltage sagged down to 1kV, with total input power to the discharge supply at 2W. Heater power was turned off, in which the glow discharge eventually faded.

After this initial lionization verification, the test cell was cycled on and off several times with heater power still on, each time with very easy and immediate ignition of the Adamantane plasma. The discharge was then allowed to run until fuel depletion, evident by a decrease in vacuum levels in the chamber, as well as extinction of the plasma. During the run, the plasma discharge was very stable. At the top aperture plate where the positive HV was applied for the plasma discharge, a very small plasma plume was observed. Video of operation of the test cell and successful ionization can be viewed on the AIS website and AIS YouTube page.

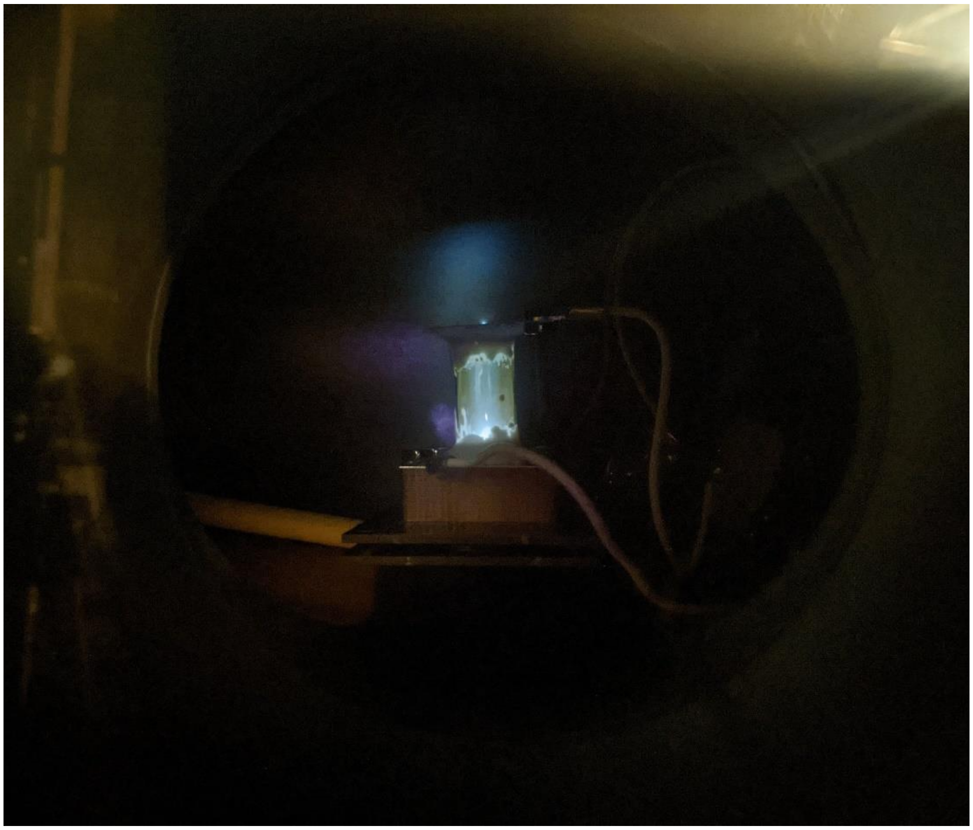

FIGURE 10: *Successful Adamantane plasma glow-discharge initiated at 2W discharge power and 3.5W sublimation heater power*

V. POST-TEST ANALYSIS

After the test, the test cell was removed from the vacuum chamber for inspection. A very clear ring of erosion could be seen on the top of the upper discharge plate around the exit hole due to the plasma. It was also clear that all of the Adamantane was successfully sublimated during the test. In addition, there appeared to be some buildup and slight charring of fuel on the bottom plate, most likely to both condensing fuel as well as plasma leakage into the fuel holding area. It was also discovered that the Pico supply was failing (as a result from intensive stress-testing during prior tests with the modified gPPT3 thruster), which could be replaced for future tests.

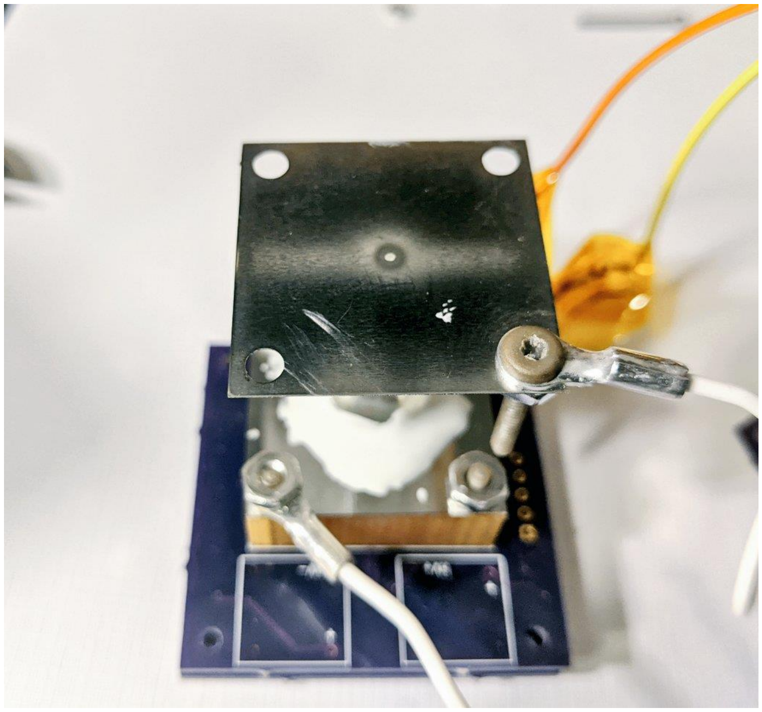

FIGURE 11: *Plasma erosion around the output aperture of the ionization test cell*

FIGURE 12: *Near complete sublimation of the Adamantane fuel charge during the test*

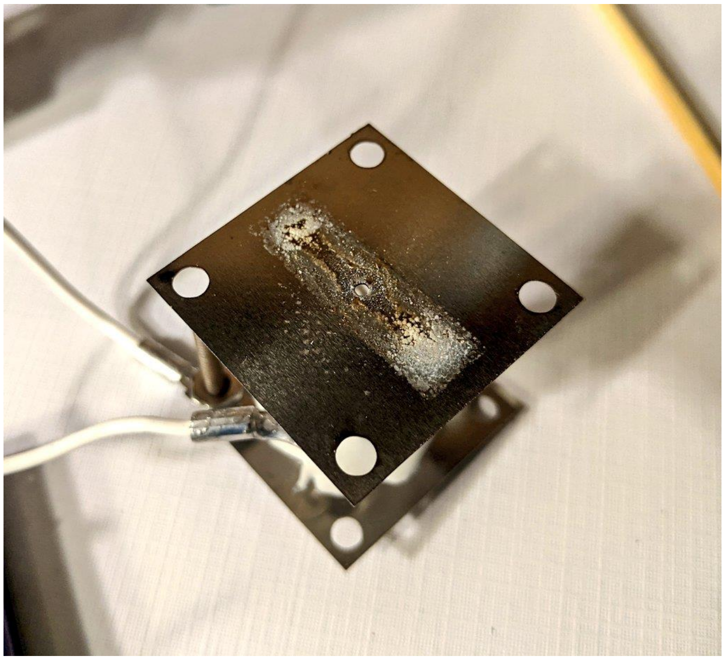

FIGURE 13: *Slight charring and buildup of Adamantane fuel on the bottom plate of the ionization test cell*

VI. CONCLUSION AND FUTURE DEVELOPMENTS

This test marked the very first steps at AIS exploring the use of highly experimental and unconventional Adamantane fuel for electric propulsion. There is currently almost no data in the EP field for this fuel, and even in the chemistry field in general there is very little on the ionization properties of Adamantane. The results of this test not only validated the initial hypothesis that low-power discharge could be sustained, with minimal heater power to create an effective gas load in a simple open-ended test cell, but also have significant implications, not only for the general use of Adamantane fuel in micro-EP, but for extreme power scaling and miniaturization of conventional gas-fed EP systems. Not only has it been demonstrated that Adamantane is incredibly easy to sublimate at low temperatures, but it can also be ionized very readily at extremely low power levels at a couple of watts or less. During the test, total applied heater power was 3.5W, and total ionization power for the discharge at 2W. High sublimation gas loading on the vacuum system was also observed even at the low ambient background temperatures before heater power was applied to increase the sublimation rate. During testing, the Adamantane plasma discharge was observed to be stable, and very easy to relight without issue. As far as the author is aware, this test also marks the first time that Adamantane fuel has been tested for extremely low sublimation and ionization power levels specifically for use in ultra-low power EP systems. Now that this first preliminary test has been successfully completed, AIS will be moving forward on additional sublimation and ionization tests, as well as completion of the design of the first ever Adamantane-fueled micro-Hall thrusters, and the first thruster of the AIS ADAMANT Series.