Applied Ion Systems

AIS-TR-027

AIS-GDN1 Glow-Discharge Hollow Cathode Neutralizer

Ignition Test 1 - 02/20/2021

Testing 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.

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 leading developer of Adamantane research for micro-EP, and the first and only company in the world to exclusively develop Adamantane for use with micro ion and plasma thrusters.

II. OVERVIEW

The GDN1 utilizes glow-discharge cold hollow cathode technology used in the particle physics and experimental manufacturing fields. Unlike typical hollow cathodes in EP, the GDN1 operates in a cold-cathode glow-discharge mode at high voltage, low current, eliminating heaters, inserts, or RF. Such a neutralizer has yet to be employed in EP systems, however such cathodes have demonstrated power scaling from less than 1W to MW class systems for the largest pulsed sources, and can range from sub-mm to tens of cm in diameter. Because of the plasma cathode formation inside the hollow cathode, such cathodes are also capable of the highest electron beam densities of any electron source, demonstrated up to 10kA/cm2. Because of their simple and robust design, they can be manufactured very low cost with common materials (such as stainless steel), and are compatible with any gas.

FIGURE 1: *Fully assembled GDN1 hollow cathode.*

These properties allow for operation of the GDN1 at only a few watts of input power, requiring no complex or costly dispenser cathode inserts or RF power, operated at high DC voltages, can be run with any gas, and allowing for extreme miniaturization of conventional hollow-cathode technology while being incredibly simple and low-cost to manufacture, using simple stainless steel components and a 3D printed housing using ceramic embedded Somos PerFORM SLA resin. This was the first instance of such a cathode being employed for Hall thruster technology, and at such extreme power and size miniaturization, using only Adamantane fuel to operate on. As far as the author is aware, the GDN1 is the only neutralizer of its kind in the field, and the first reported instance of such a cathode, or any hollow cathode, running with Adamantane fuel.

This test builds off of the prior four preliminary ionization and sublimation tests performed using Adamantane fuel and a simple test cell in vacuum (*see AIS-TR-22, AIS-TR-23, AIS-TR-24, and AIS-TR-25 for further details.)* Throughout these first four preliminary tests, AIS demonstrated the ability of Adamantane to be sublimated at extremely low background temperatures in vacuum, as low as 11C. Adamantane was also successfully sublimated with very low heater power of 3.5W and less for these tests. In addition, the first instances of ultra-low power ionization of Adamantane for propulsion use was demonstrated, with successful glow-discharge ionization of both passively and actively sublimated fuel from less than 1W to 2W. In these ionization tests, the ionization test cell was configured and successfully operated for a variety of conditions, most notably in regards to the GDN1 development, the ability to extract a neutralizer plasma was demonstrated with the test *cell (see AIS-TR-24).*

The goal of this test was to verify the design principles of the GDN1 in a cold-cathode high-voltage DC glow discharge mode, and demonstrate operation of this cathode on sublimated Adamantane fuel at very low power levels of only a few Watts in preparation of subsequent full system ignition tests of the EHT1. This test would also verify the ability of the cathode housing material to be suitable for high vacuum compatibility, high dielectric strength, high thermal capacity, and the ability to potentially withstand direct plasma bombardment during operation of the cathode.

III. PRELIMINARY TEST SETUP

The entire cathode assembly measures 20x20x24mm. The housing is made from Somos PerFORM ceramic-embedded SLA resin. This resin is a high-performance SLA material which boasts high dielectric strength, high heat capacity, and high dimensional tolerances. Although outgassing data is not available for this material, it is expected to perform well due to the ceramic particulate content embedded into the binder material. Despite being a high performance SLA material, Somos PerFORM is readily available and offered at a low-cost from 3D printing manufacturing service providers, allowing for substantial reduction in cost compared to if the housing were made from custom machined ceramics or sintered ceramic. The ability to 3D print the housing also has allowed to keep the design incredibly compact, and include features like the integrated fuel feed channel directly into the structure itself.

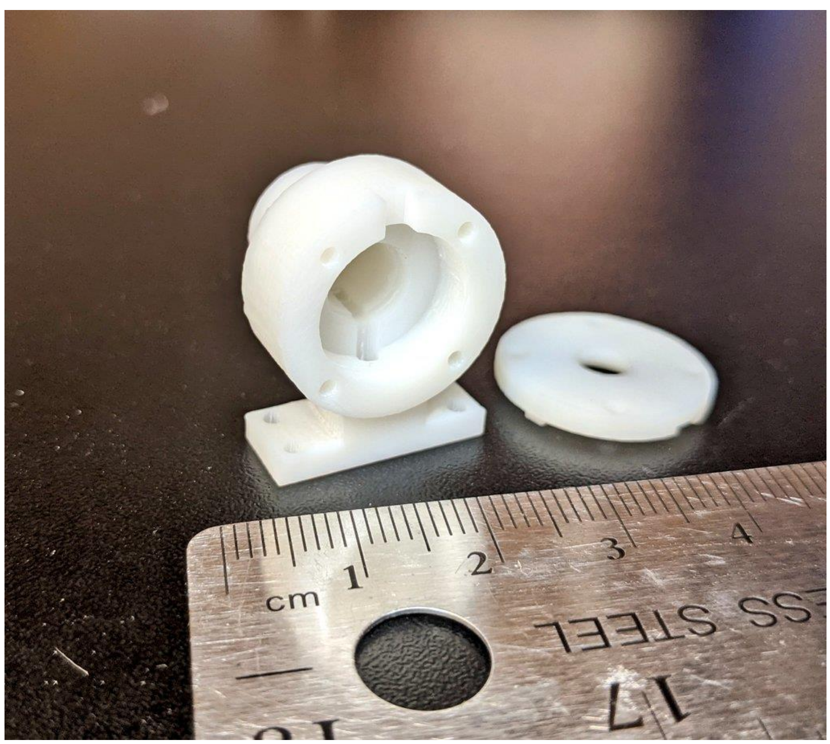

FIGURE 2: *AIS-GDN1 neutralizer 3D printed housing. Ruler shown below for reference scale.*

The hollow cathode is a simple stainless steel cup measuring 7mm in length with an internal diameter of 4.5mm. The neutralizer also uses simple laser-cut stainless steel anode and extractor electrodes with off the shelf ceramic washers as inserts for insulators. A small feedhole on the side of the cathode lines up internally with the gas feed channel in the housing, allowing for direct gas flow into the cathode, helping to eliminate external feedlines. A threaded stud is machined directly onto the cathode insert to provide the high voltage electrical connection for the discharge power.

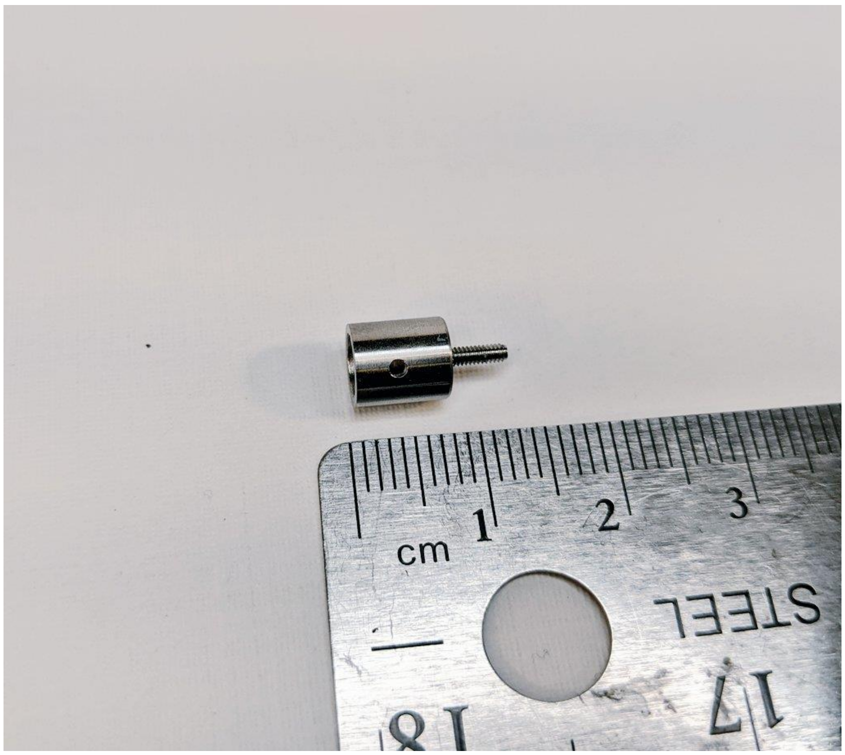

FIGURE 3: *Stainless steel hollow cathode insert for the GDN1. Ruler shown below for reference scale.*

The EHT1 thruster head, which the GDN1 will ultimately be used with, is directly machined into an adapter flange, which allows it to be directly bolted to the fuel delivery system, eliminating any fuel lines. In addition, the adapter flange has mounting and a fuel feed port for the GDN1, located right next to the thruster head. This allows simultaneous feeding of both the thruster head and hollow cathode from a single fuel vapor source, further eliminating the need for additional feed lines, and keeps the total system volume highly compact. The proportion of fuel flow between the thruster head and the cathode is adjusted via physical dimensions of the fuel feed holes for each. In the event the hollow cathode is not used, the cathode feed port can be blanked off. The adapter flange measures only 50mm in diameter, with the thruster head offset to one side, measuring only 20mm in diameter and 10mm in height fully assembled.

FIGURE 4: *Fully assembled EHT1 thruster head.*

The fully assembled GDN1 is bolted directly to the EHT1 adapter flange. This arrangement puts the cathode at a direct 90 degrees from the Hall thruster, and is positioned as close as possible to the output of the thruster. While an unusual setup for traditional Hall thruster systems, this allows the full thruster and neutralizer combination to be as small volume as possible, and is expected to help with plasma bridging and ignition at the very low total discharge power and relatively low fuel flow rates the EHT1 is operated at.

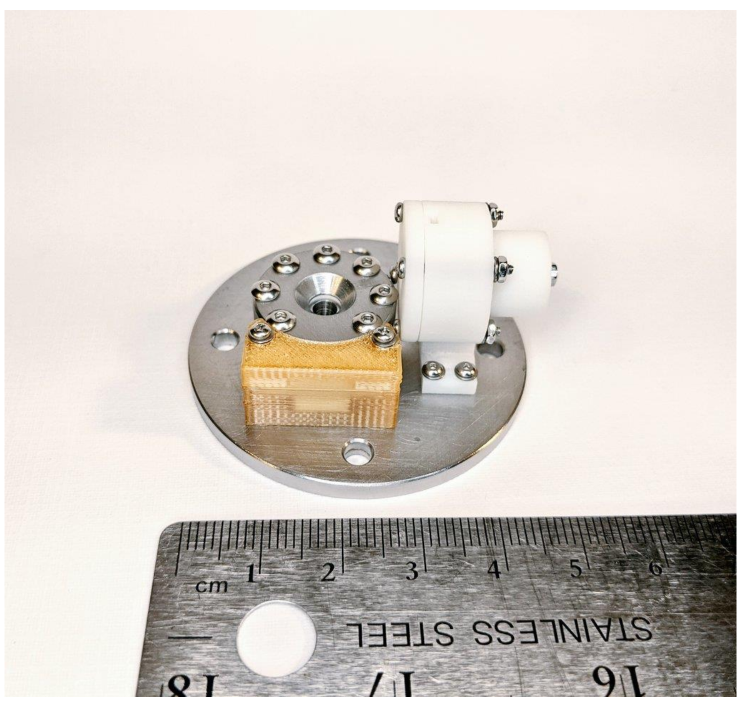

FIGURE 5: *Fully assembled EHT1 Hall thruster head with GDN1 neutralizer bolted on. Ruler shown below for reference scale.*

Prior to final assembly, the thruster must be fueled with Adamantane. Adamantane has the consistency of coarse table salt, which is poured directly into the fuel heater cartridge and packed down. A presser plate is placed over the fuel charge, preventing fuel from escaping, while allowing vapors to rise up from sublimation through holes drilled around the plate.

FIGURE 6: *Fueling of the fuel heater cartidge with Adamantane.*

After filling the heater cartridge with about 3 grams of Adamantane, the cartridge is inserted into the 3D printed Ultem housing. A conical spring presses the plate into the Adamantane, providing continuous contact with the bottom heated portion of the cartridge, which is heated by a ceramic-metal heater in direct contact with it. A top fuel plate completes the assembly, locking the cartridge into the fuel tank housing and compressing the spring into the fuel presser plate.

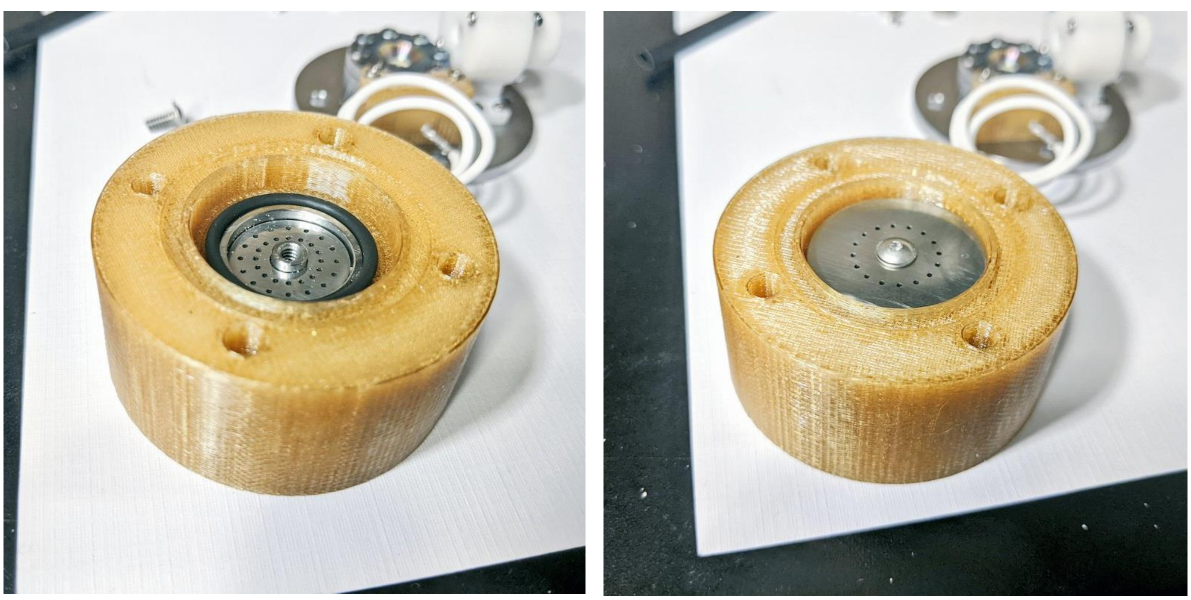

FIGURE 7: *Assembly and sealing of the fuel cartirdge inside the fuel system housing.*

The EHT1 head, along with the fully assembled and attached GDN1 neutralizer, is then bolted to the Sublimation Fuel Delivery System, or SFDS. Like the prior ignition test of the EHT1 with a tungsten filament neutralizer, the valve was not finalized prior to the test, and was therefore not included, so Adamantane would directly sublimate and flow into the Hall thruster and neutralizer upon reaching vacuum, however only power will be applied to the neutralizer.

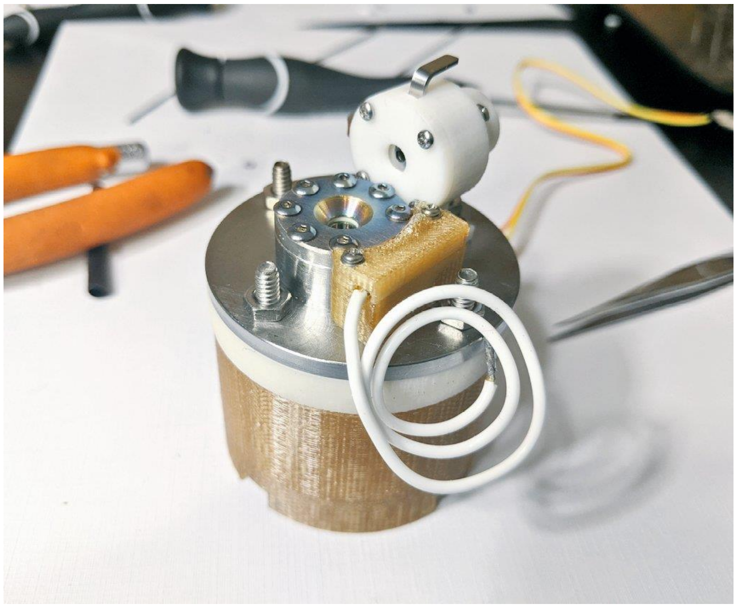

FIGURE 8: *GDN1 mounted to the EHT1 hall thruster plate, with the fuel tank bolted and fueled.*

Since only the neutralizer would be tested, the anode power supply was not connected. A makeshift power supply using a 2W 3.5kV and a 2W -3.5kV Pico power supply were used to power the cathode. This was the same supply used in the third preliminary sublimation and ionization test using the makeshift test cell (*see AIS-TR-24 for further details*.)

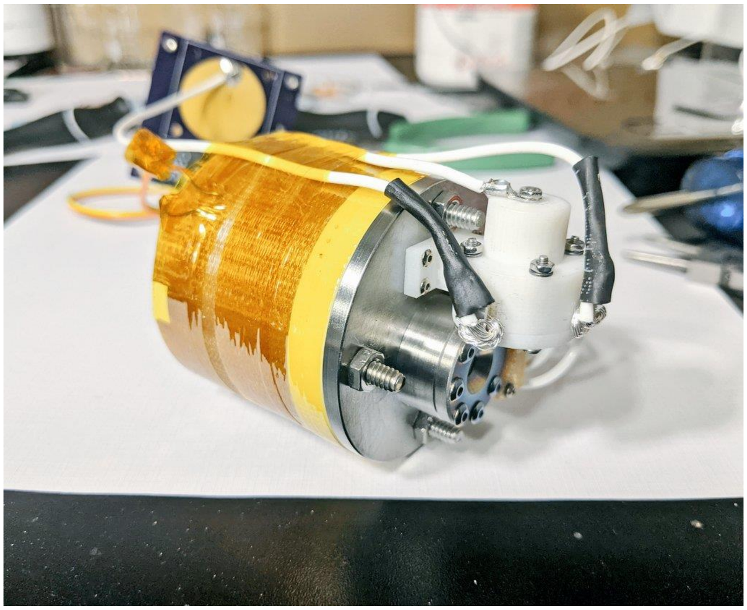

FIGURE 9: *GDN1 fully wired to the discharge supply.*

IV. TESTING

After assembly, the full system was wired up and mounted into the chamber for testing. The thruster was rotated facing towards the chamber viewport, so the resulting plume from the neutralizer, which is located at 90 degrees to the thruster, could be better observed.

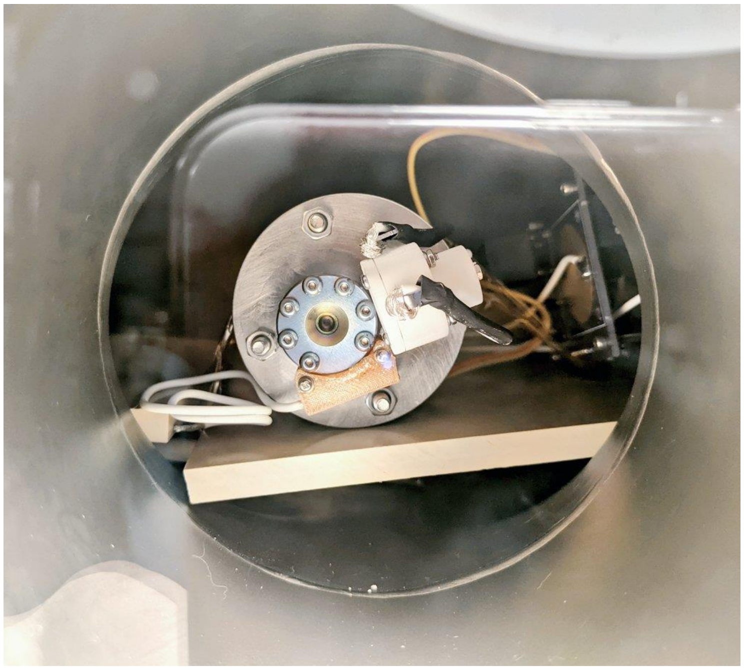

FIGURE 10: *Full system assembly mounted inside the high vacuum chamber.*

After an ultimate pressure of mid 10^-4 Torr was achieved, ignition was attempted. First, the sublimation heater power was turned on to a nominal power of 3.5W. The hollow cathode discharge supply was turned on to about -1kV, and the extractor power was turned on to +1kV. Discharge and extractor power were both adjusted without successful ignition. As a result, fuel flow was increased by increasing sublimation power to 6.5W. Despite this, no discharge was observed.

At that point, the extractor supply was shut down, and the discharge power was reduced. At a very low voltage of only a couple hundred volts, a glow was visible from the hollow cathode. Extractor power was then turned back on, and slowly increased. Eventually, a bright glow was emanating from the cathode, as a successful neutralizer plume was established.

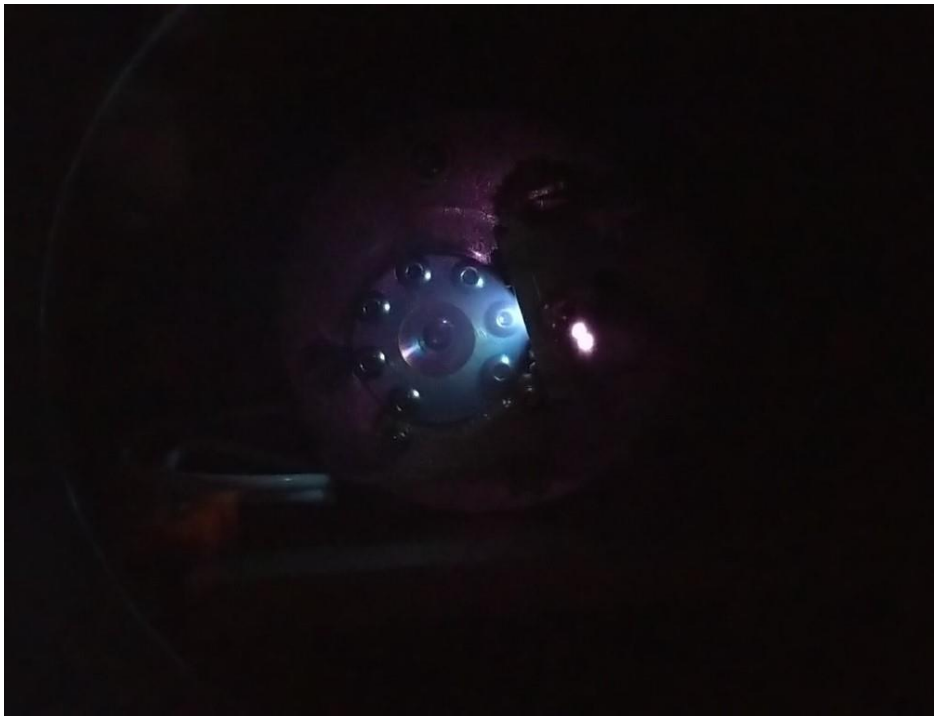

FIGURE 11: *Ignition of the GDN1 in vacuum at reduced power.*

As extractor power was then raised to maximum power, with the discharge supply operated at minimal voltage, the output plume grew larger. The neutralizer plume was operated until evidence of fuel depletion, indicated by flickering of the neutralizer plume and eventual decrease in output.

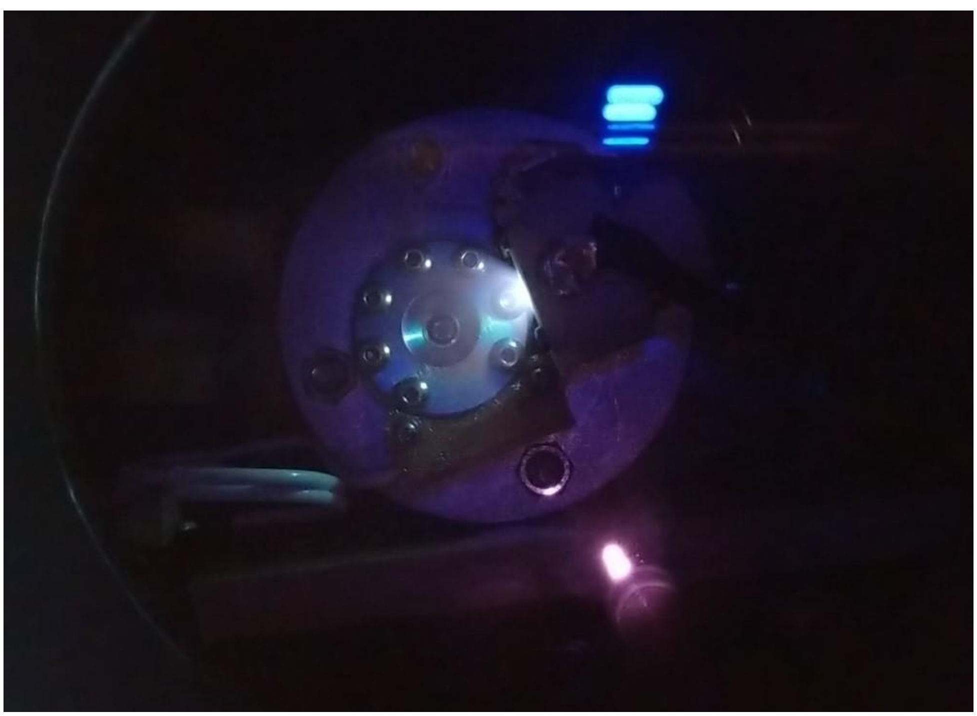

FIGURE 12: *Neutralizer plume from the GDN1 at full output power.*

V. POST TEST ANALYSIS

After the test, the neutralizer was disassembled and inspected. Discoloration was evident along the surface of the EHT1 thruster head due to the output of the hydrocarbon plasma. The outward face of the extractor electrode was also noticeably darkened, most likely as a result from direct and immediate exposure to the hydrocarbon plasma as well.

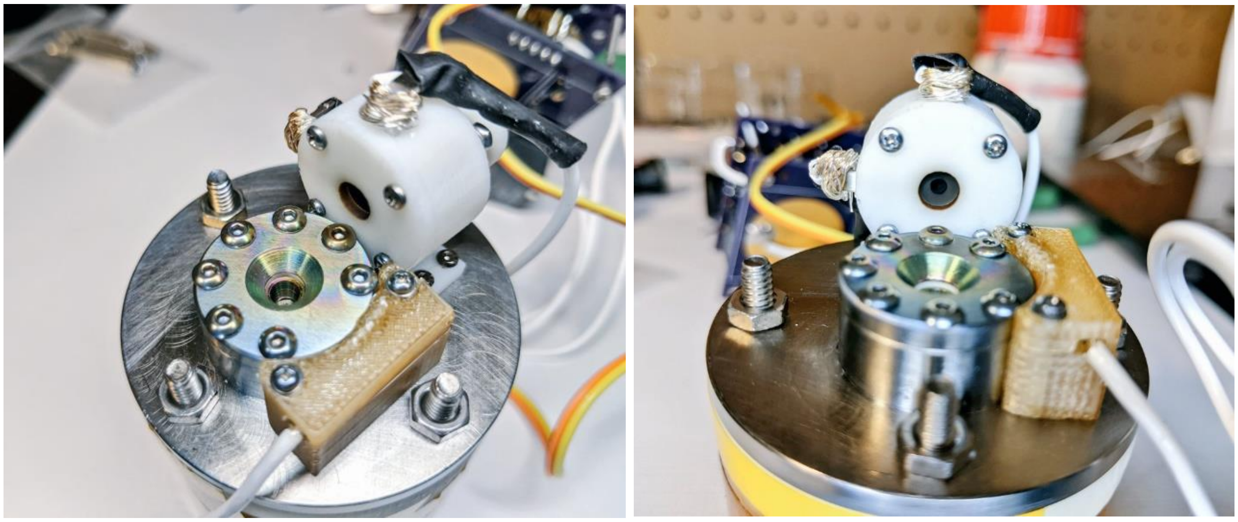

FIGURE 13: *Neutralizer inspection post-test.*

Disassembling the GDN1 for closer inspection, it was found that significant black carbon buildup was visible throughout the neutralizer. While data is limited in literature on use of Adamantane in EP, and with plasma systems in general, it can be noted that under certain conditions, there is evidence of acetylene plasma formation with Adamantane, resulting in amorphous carbon buildup, and in some cases, carbon nanotube formation. Such buildup however did not appear to cause any shorting or arcing issues during operation of the GDN1 at max neutralizer plume output. In addition despite the plasma conditions, the 3D printed Somos PerFORM housing showed no evidence of damage, melting, deformation, or stresses from operation in the plasma environment. The internal geometry of the GDN1 is specifically designed to shield the housing from as much direct exposure from the plasma as possible to minimize adverse effects on the housing, and from this test, appears to be functioning as intended.

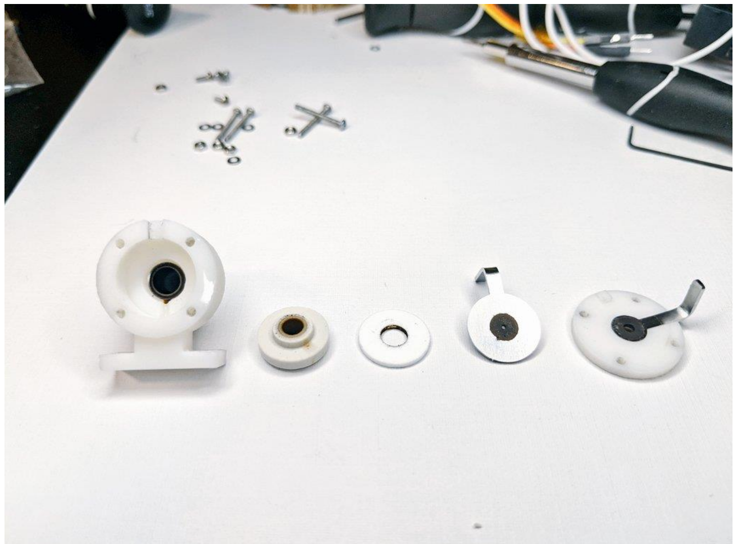

FIGURE 14: *Hollow cathode disassembly and inspection. Clear carbon buildup is present on the inside of the hollow cathode surface, as well as the anode and extractor electrodes.*

VI. CONCLUSION

The first ever ignition test of the GDN1 Glow Discharge Hollow Cathode Neutralizer was successfully conducted and completed. The GDN1 was run on purely sublimated Adamantane fuel, with 6.5W of sublimation heater power. A stable and clear neutralizer plume was successfully established at only 2W total neutralizer power, operated in the intended HV DC glow-discharge mode. Due to the topology of the neutralizer, the plume could be operated in self-sustaining mode at minimal discharge voltage and maximum extractor voltage. The GDN1 represents a new class of unique hollow cathode technology for EP, leveraging well established techniques from other fields, and demonstrating incredible potential for extreme size miniaturization and power reduction compared to standard hollow cathode neutralizers seen in the field. As far as the author is aware, this is the first time that such a hollow cathode has been employed for EP, and the first time a hollow cathode has been operated using Adamantane feed gas.

From the test, it was also verified that the Somos PerFORM housing material exceeds expectations, performing as intended with no HV breakdowns or spurious outgassing, exhibiting very high dielectric strength and negligible outgassing, and delivering the Adamantane gas directly into the cathode from the EHT1 adapter plate. No evidence of heating or plasma damage was observed. However, significant amounts of amorphous carbon buildup was discovered coating all internal components after the test. Long term effects of this buildup should be further investigated when run with Adamantane fuel, however it is expected that this cathode can be operated on virtually any feed gas at exceptionally low power levels.

Moving forward, now that beam has been established from the EHT1 Micro End Hall Thruster, and a stable neutralizer plume has been achieved with the GDN1, in both cases with purely sublimated Adamantane fuel, the next steps will be operating both the EHT1 and GDN1 together for a full system ignition test at nominal expected system power levels of 20W.