Applied Ion Systems

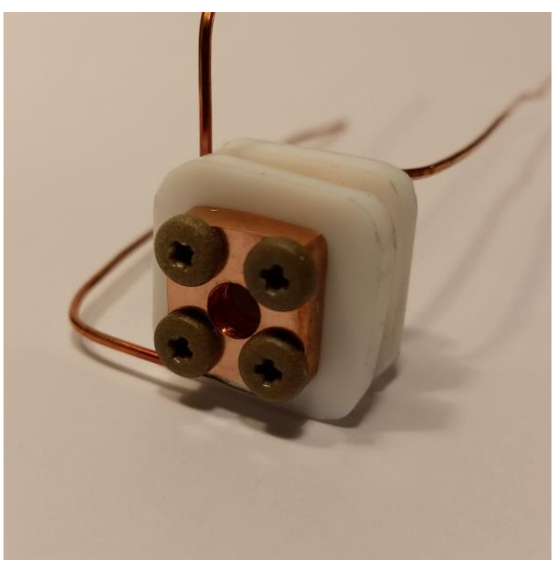
AIS-TR-003
AIS-gPPT2-1C Gridded Pulsed Plasma Thruster
Phase I - Ignition Testing - 05/26/2019
Testing Report and Summary
Michael Bretti – 06/07/2019

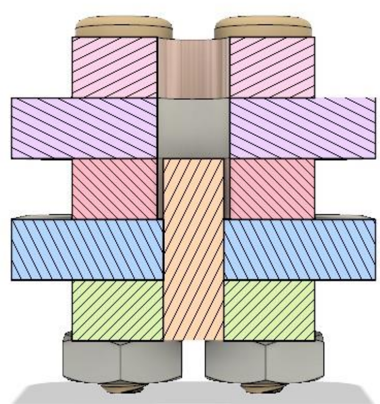
I. TEST PARAMETERS

- **Main Bank Capacitor:** 1uF polypropylene film capacitor
- **Main Bank Charging Voltage:** 680V-2300V
- **Ignition Circuit:** hydrogen thyratron pulser
- **Ignition Capacitor:** 0.01uF plastic capacitor
- **Ignition Voltage:** 4kV
- **Pulse Repetition Rate:** 0.33-2Hz
- **Maximum Chamber Pressure During Testing:** 1 x 10^-5 Torr
- **Testing Status:** SUCCESFUL

II. TEST SUMMARY

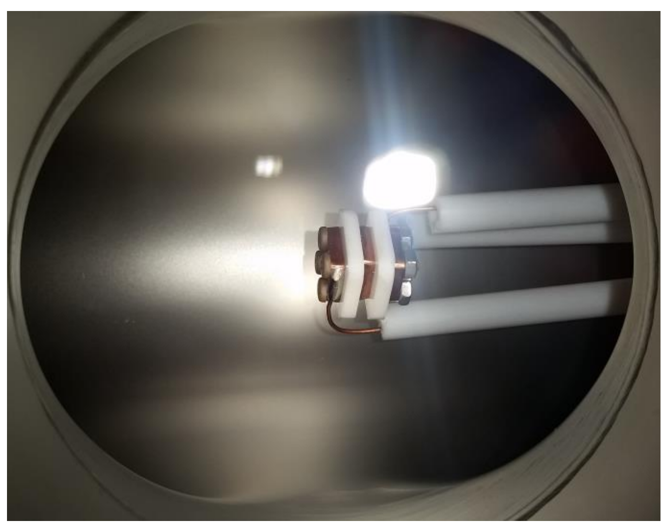
This test represents Phase I of testing and development for the AIS-gPPT2-1C Single-Channel Gridded Pulsed Plasma Thruster. The purpose of the test was to verify successful and reliable ignition of the thruster utilizing an unconventional flat-stacked plate electrode assembly with improved ignition topology for the development of sub-Joule micro-PPTs for PocketQube-class satellites.





The AIS-gPPT2-1C is the newest generation of thrusters from the Applied Ion Systems gPPT Gridded Pulsed Plasma Thruster line. This thruster represents the smallest configuration for Gridded PPTs, with a single channel, to fully qualify ignition reliability, thrust performance, and lifetime of a plasma channel in the thruster, for both single-sized as well as larger multi-channel thrusters. This topology also allows for very low-cost and rapid prototyping of thruster concepts and geometries, allowing for development and testing to progress much faster than qualification of a larger version. The thruster utilizes a cathode plate with electrode pin extending into the second plate, which serves as the ignition electrode to generate an ignition arc between the cathode pin and igniter surface. This is reversed from prior thruster iteration, where the middle plate served as the cathode, and the back plate with the pin served as the igniter electrode, with the 0.125" diameter pin extending up only 0.0625" away from the bore, as opposed to completely in the bore with the new configuration. This allows for extremely close spacing of the electrodes, as well as increases total surface area available to increase igniter lifetime. The anode has remained as the upper plate. A 0.125" thick Teflon spacer is used between the cathode and igniter plates, as well as an additional plate for fuel between the anode and igniter plates. Electrode plates are also 0.125" thick, manufactured from oxygen-free copper. The bore size was increased to 0.15" for the Teflon fuel bore, anode, and igniter plates from the prior iteration, keeping the 0.125" diameter pin for the cathode. 4-40 PEEK bolts with 316 stainless steel nuts were used for assembly the thruster plate stack together.

The AIS-gPPT2-1C thruster was mounted to the conflat feedthrough adapter utilizing a simplified direct feedthrough connection from the high voltage conflat feedthrough to a zero-clearance reducer on the micro propulsion testing chamber. 0.25"OD x 0.1875"ID Teflon tubes were used to secure and support the thruster to the feedthrough, as well as provide insulation for the high voltage lines. 18 AWG bare copper wire was used for the cathode, igniter, and anode connections. Thruster mounting lengths were determined based on the length required to center the thruster in the adjacent 6" conflat viewport.

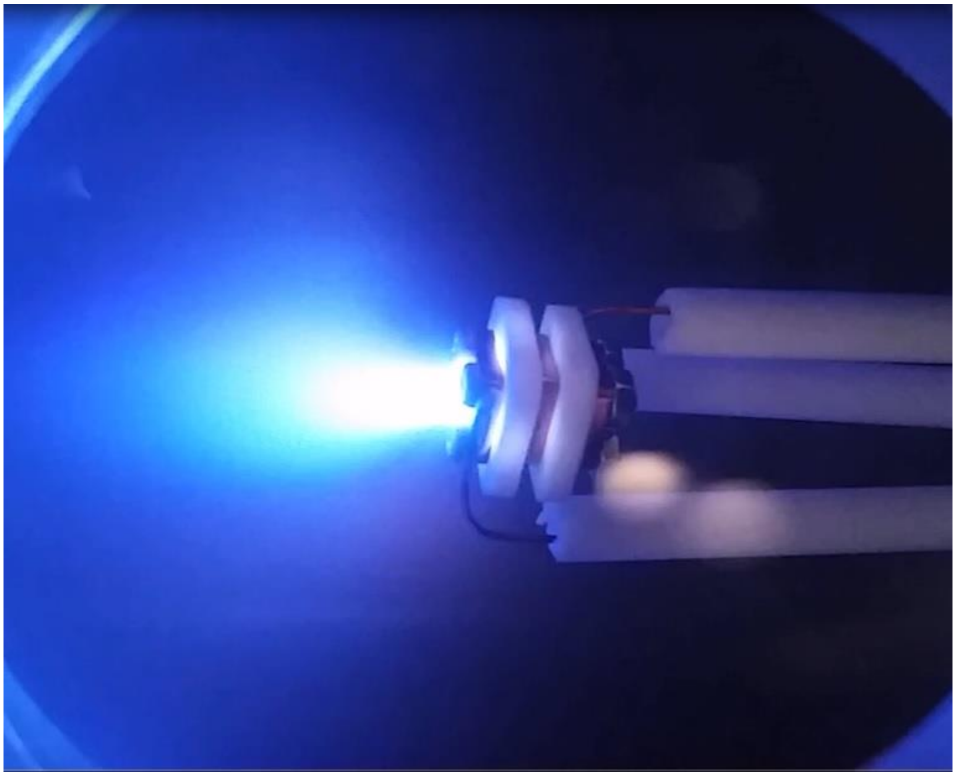


Testing was performed in the Micro Propulsion Testing Chamber using the Integrated High Vacuum Test Stand. Pumpdown conditioning of the system was achieved from atmosphere due to breaking vacuum of the chamber to mount the thruster. Ignition testing vacuum levels were first verified at 1 x 10^-5 Torr maximum before attempting ignition. Ignition voltage was set to 4kV, while the main bank voltage was set to a maximum value of 2.3kV. Depending on the repetition rate, and hence time to charge the capacitor between shots, this corresponds to a stored energy of several hundred Joules up to 2.65J for the 1uF capacitor. The chamber was grounded during the test.

Upon engaging the high voltages for the main bank and trigger, the thruster fired successfully without external arcing or unwanted discharges between connections inside or outside of the high vacuum chamber. The initial repetition rate was set to 0.5Hz. During testing, it was noted that the thruster did not always fire at the set frequency. However, it is suspected that the discharge of the engine at full capacitor charge was leading to timing issues with the function generator used for the trigger pulse, rather than failed thruster ignitions. After numerous confirmed ignitions at low repetition rate, the repletion rate was increased to up to 2Hz, which the thruster responded successfully and fired continuously at the set rep rate without issue for several minutes.

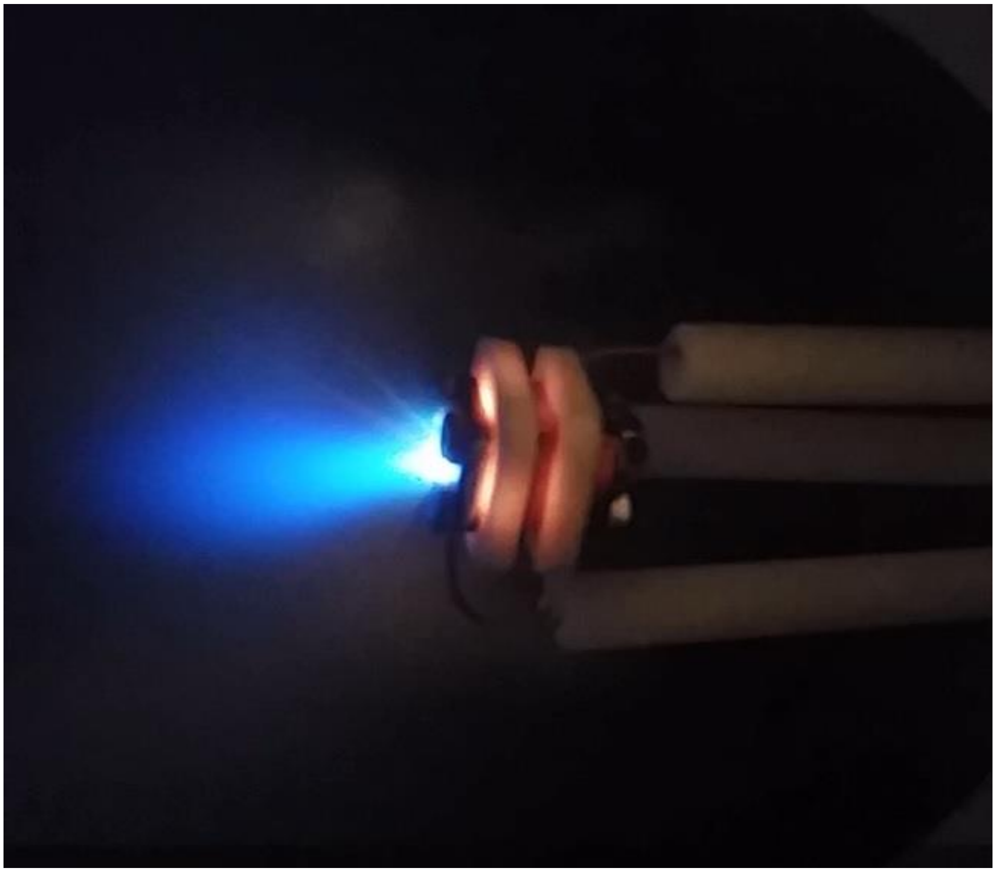
III. TEST RESULTS

For the first part of ignition testing, the repetition rate of the thruster was set to trigger at 0.5Hz. However, during this test, the thruster fired at intervals of anywhere from 1Hz down to 1/3Hz. This corresponds to a charge voltage of roughly 1.2kV, 1.8kV, and 2.3kV, with stored energy range from 0.72J, 1.62J, and 2.65J respectively, based on the time required to charge the 1uF capacitor with the main supply, which has a maximum current of 1.5mA, for a total charging power of 4.5W. The captured plasma plume from ignition can be seen below:



A significant length plume emanating from the thruster can be observed during the discharge, with the most intense region of the plasma about the same length as the thruster (0.625”), with the plasma expanding outwards more diffusely as distance increases. From initial visual observations, the resulting plasma plume from the discharge is significantly larger and more intense than initially expected, and is significantly larger and more intense than the plasma plume of the prior tested thruster iteration. Future testing and plasma diagnostics will be able to confirm characteristics of the exhaust such as ion velocities and discharge current.

For the second half of the test, the repetition rate was increased to a frequency of up to 2Hz, which corresponds to a charge voltage of 680V, and a stored energy of 0.23J. The resulting plasma plume intensity was significantly reduced due to the lower bank energy, as expected. During the discharges, some evidence of expulsion of the copper electrode material was observed, due to release of small sparks with the main plasma plume. The engine fired successfully at the increased repletion rate properly synchronized to the timed trigger pulse. Due to the lower discharge energy at 2Hz, interference with the electronics was not observed, and the thruster seemed to trigger on command at this rate. The captured plume for the higher repetition rate, lower energy shot can be seen below. Both the main plasma plume can be observed, as well as evidence of copper electrode erosion from small sparks emitted as well. The ignition of the plasma is also visible through the Teflon.



During the total duration of testing, a total of 216 full-power ignitions (0.7J and greater, at over 1kV) were recorded on video, as well as 82 reduced power ignitions at the lower energy (0.23J, 680V), 2Hz repetition rate. This correlates to a total of 298 pulses captured on video. However, the thruster fired numerous times between video recordings, and after the completion of video recording. As a result, it is expected that total ignitions to date is on the order of 350-400.

IV. DAMAGE REPORT

The testing of the AIS-gPPT2-1C was successful without any internal or external arc faults or damage to the thruster or connections. However, due to the interference from the pulses of the thruster at high power, one of the new replacement HPT-100 vacuum gauges eventually lost connection during testing, and seems to have been damaged upon testing and inspection after completion of the test. A spare gauge is currently available for continued testing.

V. FUTURE RECOMMENDATIONS

This test represents the first successful ignition testing and operation of the AIS-gPPT2-1C Single-Channel Gridded Pulsed Plasma Thruster at high vacuum under nominal operating conditions, over a range of charging voltages, capacitor energies, and repetition rates. This is also the first confirmed successful thruster developed at Applied Ion Systems. With successful ignition, and Phase I testing of this generation of thrusters complete, additional thruster qualification can begin. The next phases of testing will include impulse-bit measurements, as well as lifetime testing of the thruster.

Upon reviewing literature on micro-PPTs of the coaxial configuration in the low-energy regime, several additional improvements can be made. For thrusters in this range, plasma acceleration is dominated by electrothermal means, rather than electromagnetic means for larger and parallel-electrode configurations. It has been shown that implementing a nozzle on the output electrode can improve impulse bit, thrust, and efficiency as opposed to a straight bore. Recommended nozzle angles are around 15 degrees. Performance is also significantly dependent on thruster geometry, including electrode spacing, fuel bore size, exposed fuel area, and fuel bore length. With future impulse bit measurements, changes to the geometry should be explored for maximizing impulse bit of the thruster operating in electrothermal mode. As a general rule of thumb based on reported trends in literature, ISP and efficiency increases as the Teflon fuel channel diameter decreases, and as spacing between the anode and cathode increases. Efforts to improve thruster lifetime should also be explored, due to the extremely small amount of fuel present in the micro-thruster, as well as reducing electrode erosion when firing the thruster. Based on reports in literature, initial rough estimates for a sub-Joule micro-PPT are expected as follows: impulse bit <= 10uN-s, specific impulse between 300-400 s, and efficiency <= 5%.

For future testing, any gauges electrically connected to the chamber will have electronics powered down, disconnected, and removed during operation of the thruster, to prevent damage to the gauges. Testing has verified that for micro-PPT operation, vacuum pumping speeds are high enough that vacuum is not affected by thruster exhaust during testing.