Applied Ion Systems

AIS-TR-020

10/25/2020 – 12/01/2020

AIS-gPPT3/EPPT1 Hybrid Micro Pulsed Plasma Thruster

Test Campaign Report and Summary

Michael Bretti – 12/22/2020

I. OVERVIEW

Over the past year and a half, AIS has produced several prototype pulsed plasma thruster systems. The most recent developments, the AIS-gPPT3-1C, and the later AIS-EPPT1, both featured fully integrated systems with the thruster, fuel, and electronics packaged into modules small enough in size and power draw to be compatible with PocketQube class satellites. The first of these two systems, the gPPT3, remains the most successful in firing and qualification, consisting of a coaxial design with a static Teflon fuel bore and a flat-stacked plate geometry. The EPPT1 features a larger, diverging plate design with spring-fed Teflon fuel and a 3D printed Ultem 1010 body. After initial testing was complete on the systems, several key issues were identified with both. Namely, lifetime was limited on the gPPT3 by the electronics, and limited by the thruster on the EPPT1. It was decided to combine the gPPT3 thruster head and the EPPT1 thruster electronics to continue exploring further improvements on micro sub-Joule PPTs with the systems already developed at AIS.

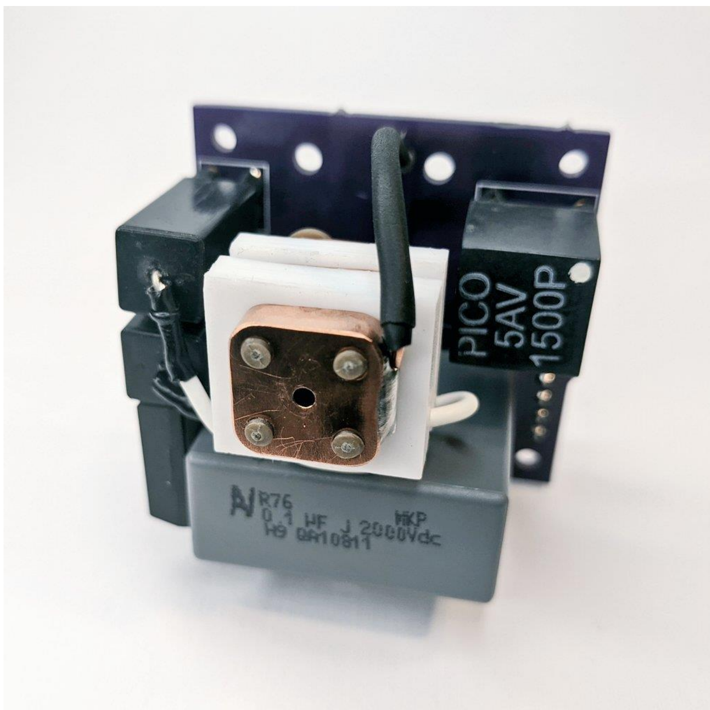

FIGURE 1: *Completed gPPT3/EPPT1 prototype hybrid micro pulsed plasma thruster assembly*

This test report reviews the testing and findings from six separate tests that were conducted on the hybrid gPPT3/EPPT1 system, which will be used for future improvements moving forward to refine PPT development at AIS.

II. PRIOR SYSTEM DEVELOPMENTS

A.) THE AIS-GPPT3-1C MICRO PULSED PLASMA THRUSTER

The AIS-gPPT3-1C micro pulsed plasma thruster was the first ever fully integrated electric propulsion system developed at AIS, and the most successful system to date. Two gPPT3 systems have been sent off for integration on the AMSAT-Spain GENESIS N and L PocketQubes in October 2019, passing TVAC and vibration testing in 2020, and have been successfully integrated onboard the satellites, currently awaiting launch. The entire thruster measures only 40x38x24mm in size, with a power draw of only a couple hundred mW max. Current measured impulse bit is around 0.65uNs, and at a nominal rep rate of 0.3Hz, gives about 0.22uN of thrust.

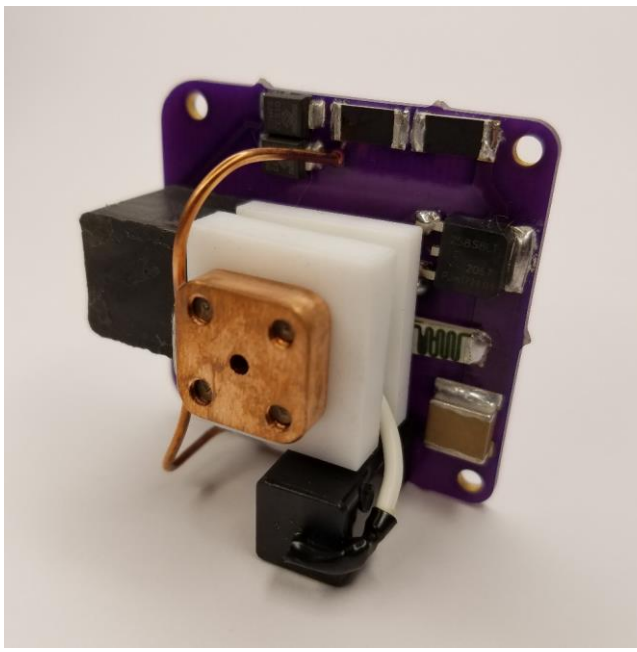

FIGURE 2: *Original AIS-gPPT3-1C micro pulsed plasma thruster module*

The gPPT3 utilizes an unconventional flat-stacked plate geometry, resulting in a coaxial-style PPT topology. The bottom plate, with central pin machined into the plate is the cathode, followed by a Teflon insulator plate, the trigger plate, which the cathode pin protrudes up into the bore of, the Teflon fuel plate, and the anode plate. Embedded inside the anode plate is a permanent magnet nozzle.

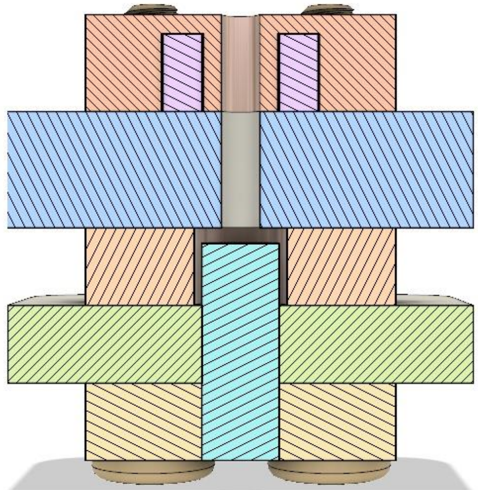

FIGURE 3: *gPPT3 thruster head cross-sectional view*

Currently, the gPPT3 thruster head has been fired at over 4000 shots. However, the electronics only survive about 1300 shots before the primary capacitor bank, consisting of two 2kV, 0.068uF, pulse-rated MLCC ceramic capacitors in parallel, catastrophically fails from pulse-related stresses. Despite this short lifetime, the gPPT3 has served as the core of micro sub-Joule PPT developments at AIS, and provides an ultra-low cost, easy to build, and simple thruster system for testing and demo purposes.

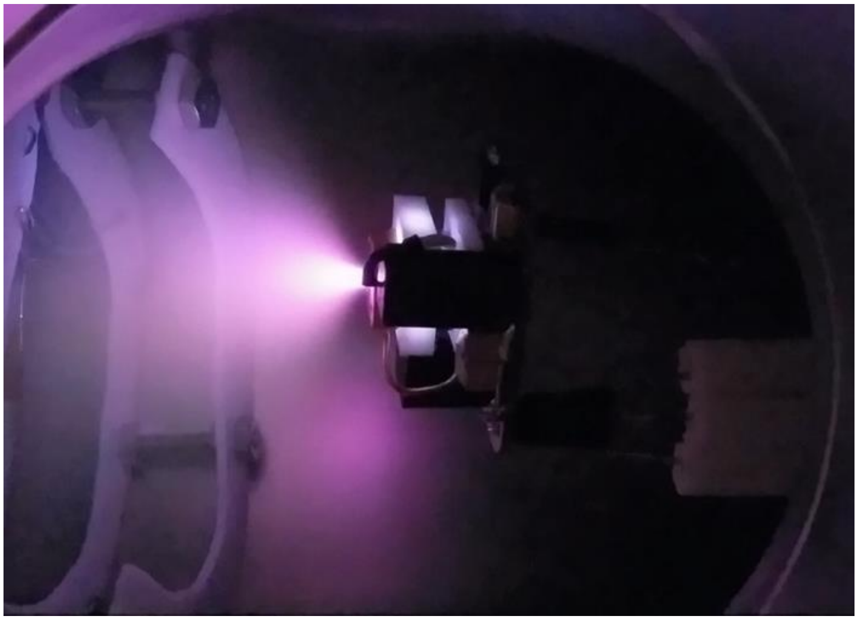

Figure 4: *AIS-gPPT3-1C plasma plume*

B.) THE AIS-EPPT1 MICRO PULSED PLASMA THRUSTER

The AIS-EPPT1 micro pulsed plasma thruster represented the next series of developments of micro-PPTs at AIS. Taking lessons learned from the prior gPPT3 development, attempts to improve performance and reliability were made with this new thruster series. The EPPT1 features more standard diverging rail electrodes and spring-fed Teflon fuel. A 0-80 stainless steel bolt serves as the fuel stop as well as the ignition pin. In order to make everything more compact and modular, the electrodes, electrical connections, spring-fed fuel, and mechanical mounting were integrated into a custom designed 3D printed Ultem 1010 housing.

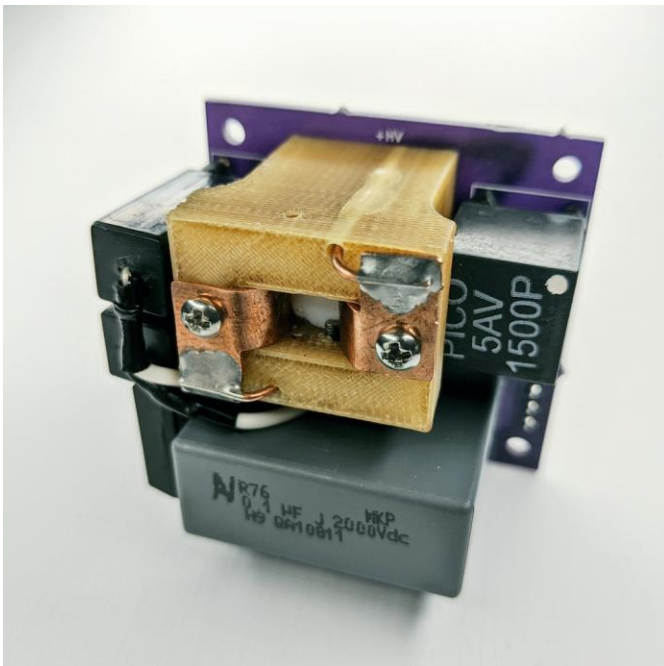

FIGURE 5: *Completed AIS-EPPT1 micro pulsed plasma thruster assembly*

In addition to mechanical design changes, several changes were incorporated into the electronics. The major change includes using a standard HV polypropylene film capacitor as the main bank rather than the ceramic MLCCs. Two ignition transformers are paralleled to increase igniter arc current, and a much larger and higher voltage thyristor is used for triggering. The original 2kV Emco supply was also switched out for a higher power and higher efficiency 1.5kV Pico supply in the same form factor. The entire thruster in the standard configuration is around 45x45x28mm in size, with the ability to easily increase fuel capacity as much as required by printing a taller housing and using a longer fuel block. In addition, several mounting holes were incorporated for a variety of off-the-shelf polypropylene capacitors, ranging from 0.1uF to 0.47uF at 2kV to increase pulse energy as required.

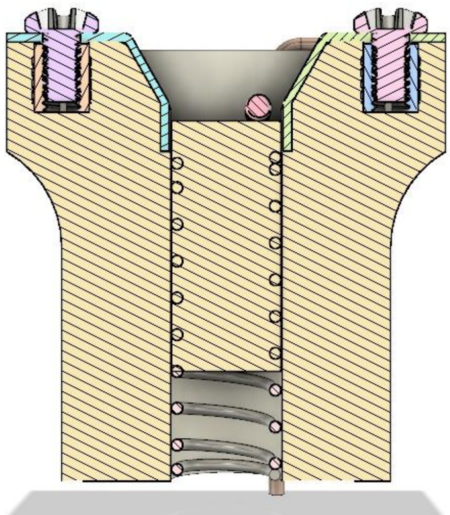

FIGURE 6: *EPPT1 thruster housing assembly cross-sectional view*

While the thruster was fired successfully during several tests, and tried in both conventional triggering as well as unconventional anode-side triggering, the design suffered from significant setbacks due to issues with arcing and failures through the layers of the 3D printed housing. As a result, the use of 3D printed housing was retired for PPT developments. However, the design showed significantly increased output at the same energy levels as the gPPT3, with both much larger plumes as well as a higher degree of ionization of the plasma.

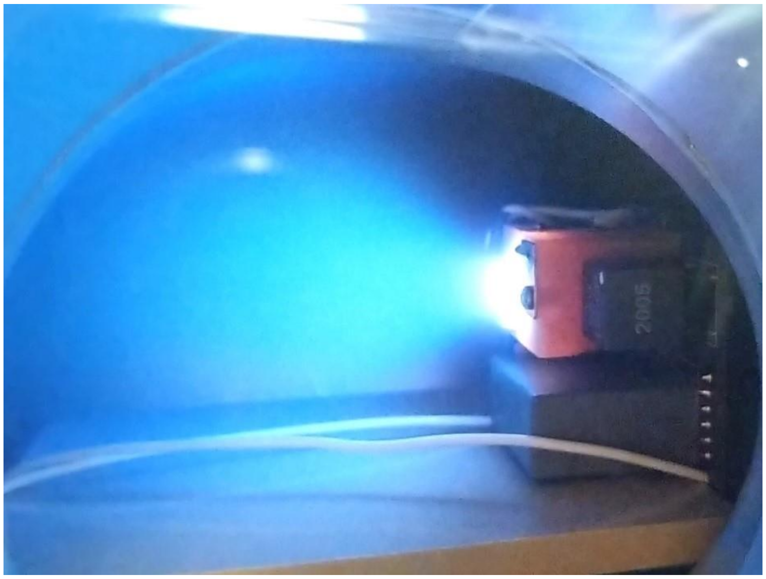

FIGURE 7: *AIS-EPPT1 plasma plume*

III. IGNITION TEST 1 – 10/25/2020

For the first ignition test of the hybrid system, the original unmodified gPPT3 head was directly soldered to the original EPPT1 thruster board in standard polarity (bottom plate cathode, center plate igniter, top plate anode).

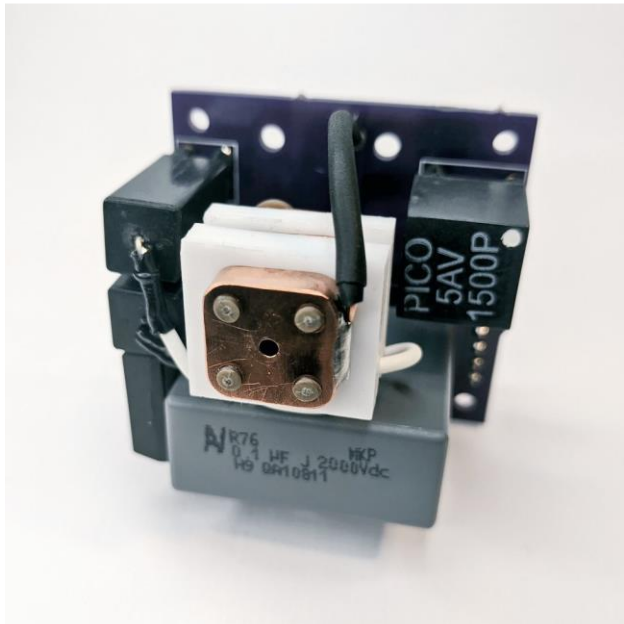

FIGURE 8: *gPPT3/EPPT1 prototype assembly for ignition test 1*

The thruster was loaded into the chamber, which was pumped down to a vacuum level of 6.5x10^-6 Torr before starting the test. During the first attempt, the thruster was started up at a nominal 5V input. The thruster began to fire, however the system appeared to latch up after only a few shots, indicating glitching of the onboard load switch that enables power to the HV Pico supply. Because of this, reliable testing could not be continued. As a result, the thruster was taken out of the chamber, and the load switch was removed, with power bypassed directly from the input connector to the Pico supply. The thruster was loaded up, and the system pumped down again.

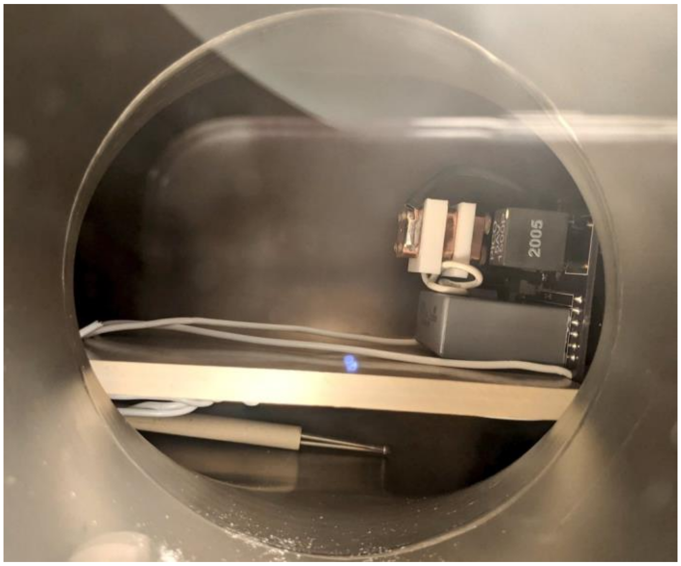

FIGURE 9: *Thruster mounting inside high vacuum chamber*

Upon powering on the thruster, the system fired, however with extremely low reliability, with the majority of shots misfiring. In an effort to increase ignition reliability, the thruster input was slowly throttled up far higher than the nominal rated voltage of 5V. At about 9.5V in, the thruster was firing extremely reliably with almost no misfires. Output voltage was measured to be 3.5kV on the readout, up from the nominal rated max of 1.5kV of the Pico supply. The repetition rate was increased to 3Hz, then eventually 4Hz, where the thruster fired reliably for several minutes before onboard failure occurred. The failure was later traced to the trigger thyristor.

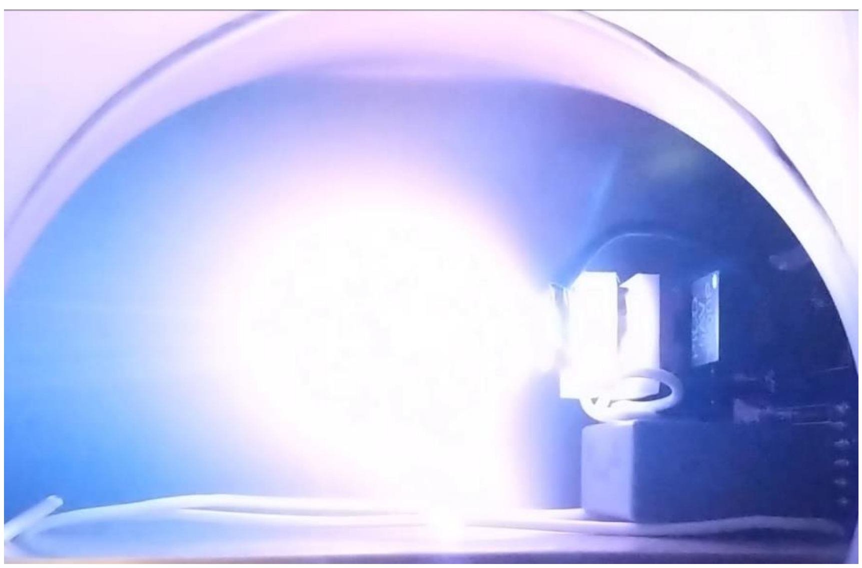

FIGURE 10: *gPPT3/EPPT1 firing in high vacuum at 3 Hz*

During this first initial test, it was shown that given high enough input voltage, the thruster could fire very reliably at significant repetition rates for a pulsed plasma thruster. Despite being overdriven by nearly 100%, the Pico HV supply proved extremely reliable and rugged, handling the extreme overvoltage during testing without issue. The polypropylene capacitor used for the main pulse bank on the EPPT1 electronics also has shown a significant improvement in lifetime and durability over the HV pulse rated MLCCs used for the original gPPT3 bank, which have repeatedly failed catastrophically after ~1300 shots. The polypropylene capacitors, while significantly larger, are 10x cheaper than the ceramic MLCCs, and as one of the critical components of the system, is worth the tradeoff of size for lifetime.

Several key issues during the test were also identified. The first major issue was that at high enough pulse intensity, the onboard load switch appears to glitch, causing issues with operation. Future iterations will eliminate this load switch and just power the thruster directly with input voltage to the Pico supply. In addition, at nominal input levels, thruster operation has still shown to be sporadic, requiring some redesign of the gPPT3 thruster head. Finally, additional circuit protection must be placed around the thyristor to improve its lifetime.

IV. IGNITION TEST 2 – 11/10/2020

After the first test run, the EPPT1 thruster electronics were rebuilt from scratch, this time incorporating a larger 0.22uF bank, as opposed to the original 0.1uF bank. The gPPT3 thruster head was mounted the same as the prior test.

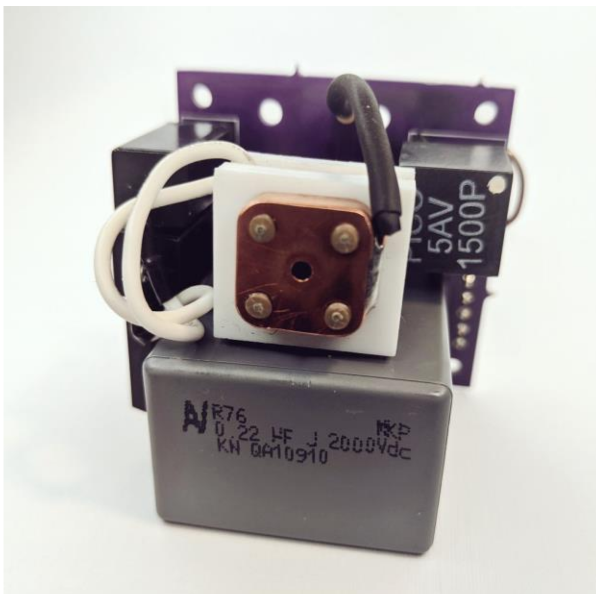

FIGURE 11: *gPPT3/EPPT1 thruster assembly for ignition test 2*

The thruster was mounted into the chamber, which was pumped down to a level of 8x10^-6 Torr before starting the test. Unfortunately, immediately at the start of the test, the thruster experienced failure.

FIGURE 12: *Thruster mounting inside high vacuum chamber*

Troubleshooting the thruster, it was again found that the thyristor had immediately failed. The damaged thyristor was removed, and no further testing on this iteration was performed.

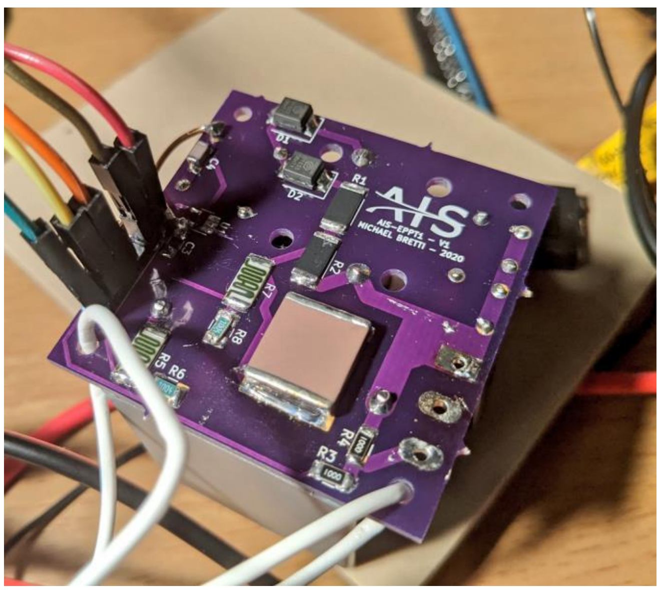

FIGURE 13: *Troubleshooting thruster electronics after ignition test 2*

V. IGNITION TEST 3 – 11/19/2020

After the second ignition test, the thruster was repaired, with some additional upgrades to help improve performance. The major upgrade included switching to a much larger -25kV trigger transformer, as opposed to the dual parallel -10kV transformers used in the original EPPT1 design. The larger pulse transformer is still rated to around 400V on the primary as the two smaller ones, but with over double the output voltage, it can be driven at lower levels to reduce stresses on the trigger thyristor.

The thyristor was also upgraded from a 1600V, 45A one to a 1600V, 75A version. Two 300V varistors were placed in series across the thyristor for transient suppression. A reverse polarity protect diode was placed on the gate, and the gate drive resistors were increased from 0.25W to 2W versions.

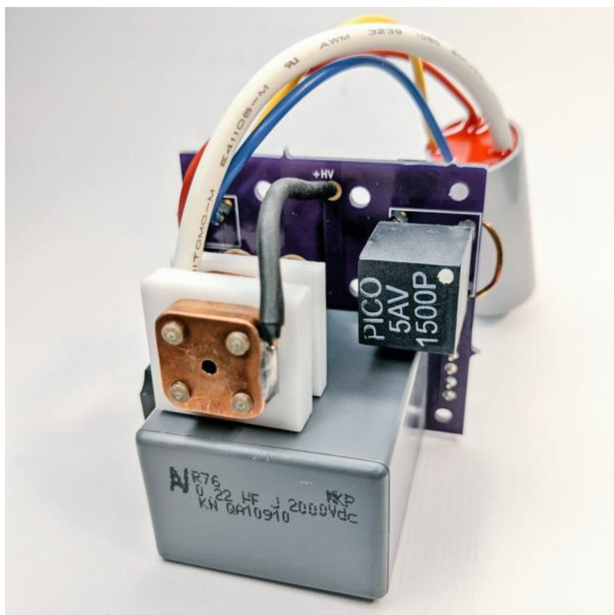

FIGURE 14: *Front view of the gPPT3/EPPT1 modified prototype assembly for ignition test 3*

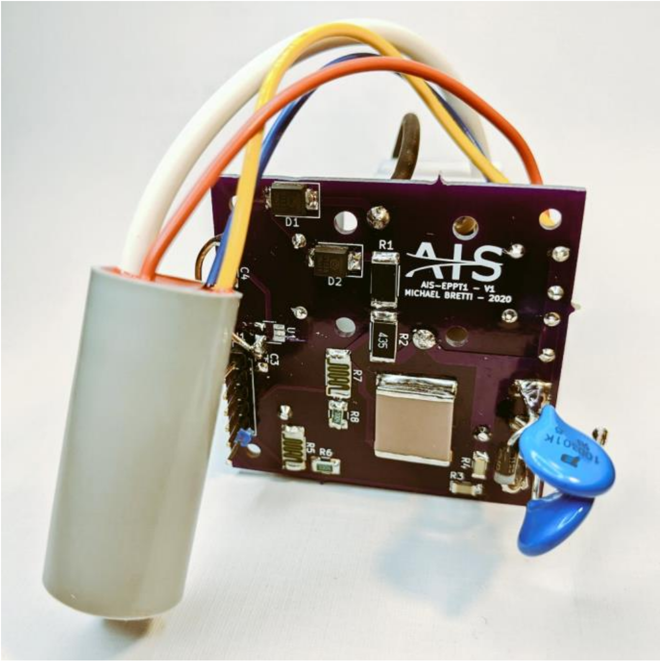

FIGURE 15: *Back view of the gPPT3/EPPT1 modified prototype assembly for ignition test 3*

The system was pumped down to the 5x10^-6 Torr level before starting the test. Starting up at 5V proved difficult, and the system was slightly overdriven at 5.5V in to achieve an initial firing rate of 0.5Hz. During this phase of the test, the number of misfires were manually counted. 22 shots were recorded in in 60 seconds with 4 misfires, giving a firing rate of slightly under 0.5Hz, with a misfire rate of about 15%.

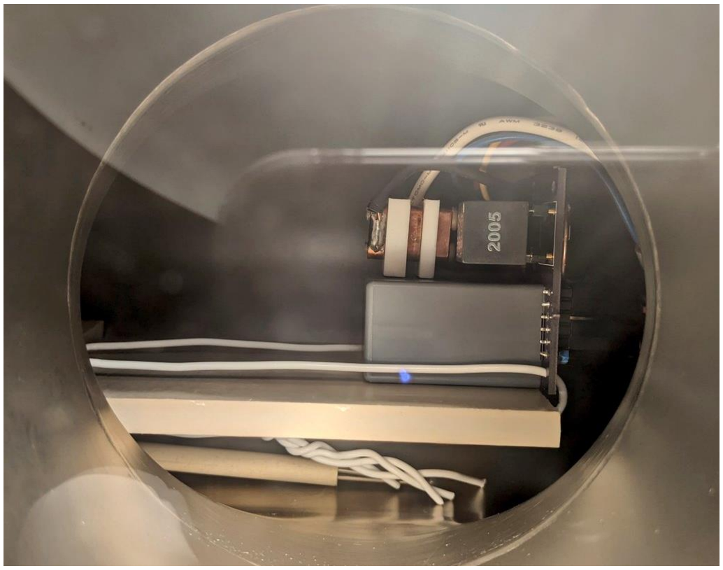

FIGURE 16: *Thruster mounting inside high vacuum chamber*

After about 10 minutes, the repetition rate was increased to 1Hz, and the system continued to fire reasonably well. During this phase, an average of 56 out of 66 shots in 60 seconds was recorded, still giving about a 15% misfire rate. Test parameters at this point were 5.5V in, 1.6kV peak out, and 0.825W power draw.

FIGURE 17: *Plasma plume during thruster operation*

During testing, waveforms from the pulse were also captured on the oscilloscope from the Faraday cup. Although the Faraday cup was not directly measuring ion currents from the plasma, it was found that during prior tests of the pulse igniter, the Faraday cup would reproduce the pulse noise from measured noise. It can be seen that a unique double-peak was present during a successful ignition of the thruster.

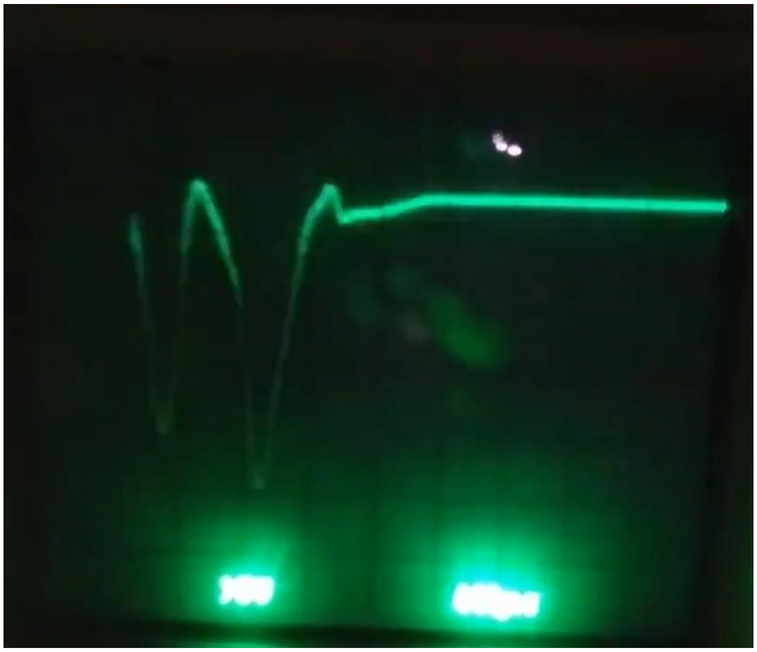

FIGURE 18: *Captured pulse during firing with double peak during the discharge*

Eventually, the system became significantly unreliable, barely firing with only spurious pulses. The system was overdriven to up to 6V in, which did not further improve performance, forcing the end of the test. While nothing onboard the thruster broke, reliability was too poor to continue.

Overall, an estimated 1200 shots were counted, bringing the gPPT3 thruster head lifetime to over 4000 shots on the same electrodes and fuel, and the new electronics to 1200.

VI. IGNITION TEST 4 – 11/22/2020

For this next round of testing, the gPPT3 connections were modified for anode-side triggering, which was found to improve ignition reliability during the second ignition test of the original EPPT1 thruster. In this configuration, the anode and cathode connections were swapped, resulting in the anode as the bottom plate, and the cathode as the top plate, with the trigger plate providing the initial trigger pulse to the anode. During prior tests with anode-side triggering, it was found that the -10kV pulse from the EPPT1 would naturally arc easier to the +1.5kV charged anode. As a result, some of the charge from the main bank would pass through the ignition arc and through the secondary of the trigger transformer to ground, dumping extra energy into the ignition pulse, making the ignition pulse more intense.

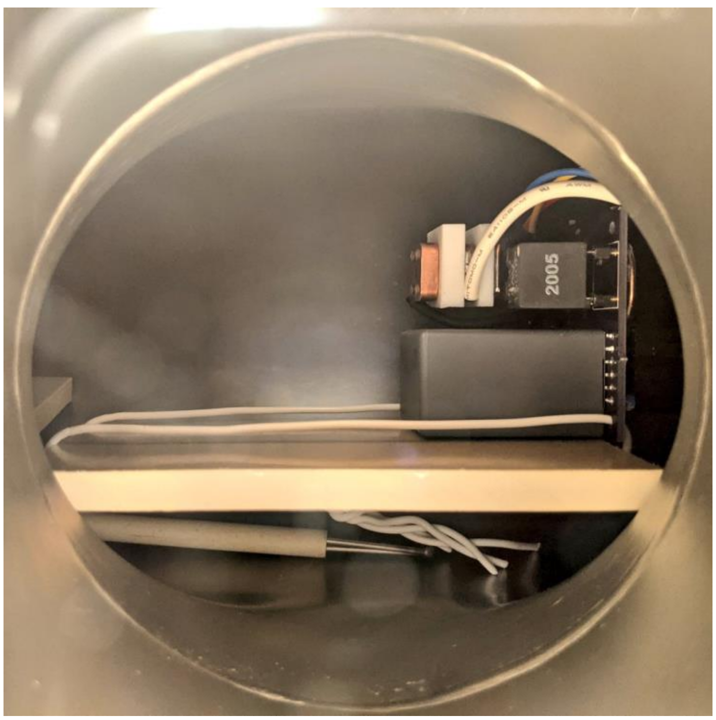

FIGURE 19: *Thruster mounting inside high vacuum chamber*

The system was pumped down to 7x10^-6 Torr before testing. During the test, it was found that the physical plume was significantly reduced in size, appearing as a very small focused burst rather than the typical large expanding plume. Thruster operation appeared erratic with difficulty starting and mostly misfires.

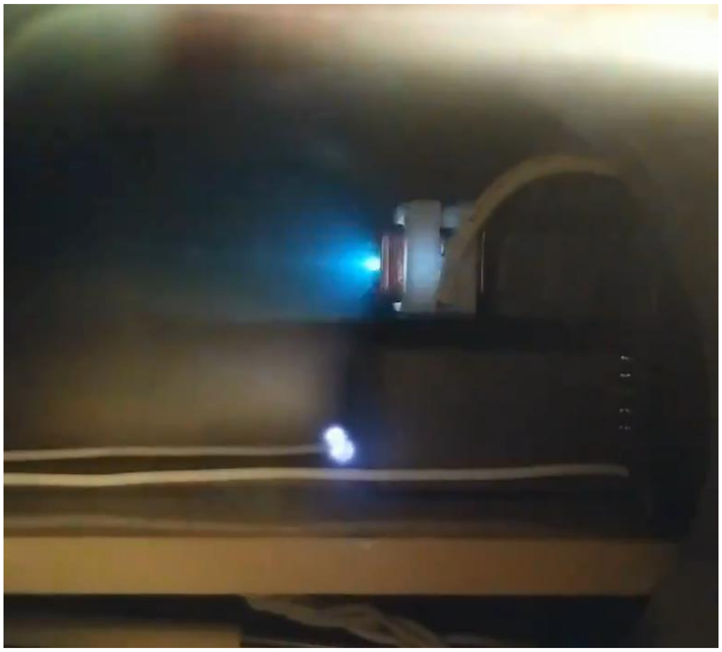

FIGURE 20: *Plasma plume during thruster operation with anode-side triggering*

On the oscilloscope, it was also observed that instead of the typical 300ns pulse seen during standard operation of the gPPT3, the pulse width was significantly widened to 100uS. Despite the incredibly small plume, the width appeared massively changed in length during anode-side triggering operation.

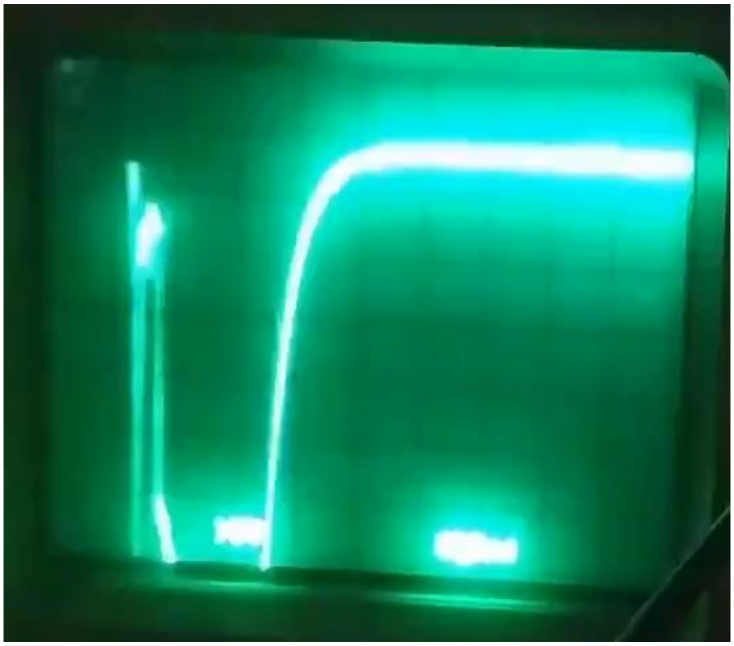

FIGURE 21: *Captured pulse during firing with extended 100uS pulse width discharge*

The system was overdriven to 5.8V with no further improvement in performance. As a result, the test was terminated.

VII. IGNITION TEST 5 – 11/28/2020

For the fifth ignition test, the thruster configuration and electronics remained the same, however the permanent magnet nozzle was removed from the anode to gauge whether or not the magnetic field was inhibiting the plume formation with the reversed polarity configuration in anode-side triggering. The system was pumped down to a level of 3.6x10^-6 Torr prior to testing.

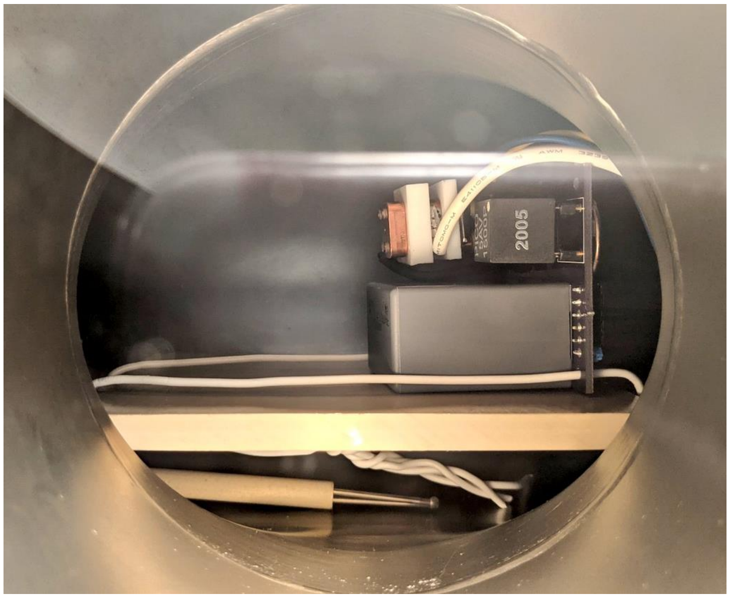

FIGURE 22: *Thruster mounting inside high vacuum chamber*

Performance was notably worse than prior tests, with almost no ignitions recorded. This however was thought to be attributed to thruster fuel depletion, as prior testing had brought the fuel bore to nearly 4000 shots, as well as general wear and carbon buildup from operation. However, a shot during successful ignition was captured. Out of all PPT testing to date at AIS, this test result was by far the most unusual. Instead of the typical blue or pink plume commonly seen with the gPPT3, and PPTs in general utilizing Teflon propellant, the resulting plume was a clean white and more focused in shape as opposed to expanding out. It is still unclear why the plume was like this, and what correlation reverse polarity configuration has on plume formation with the gPPT3 resulting in this phenomenon. However, the test did validate that the magnetic field from the permanent magnet nozzle was in fact inhibiting plume formation during operation in reverse-polarity anode-side triggering.

FIGURE 23: *Plasma plume during thruster operation with anode-side triggering and no magnetic nozzle*

VIII. IGNITION TEST 6 – 12/01/2020

For the sixth ignition test, the thruster was reverted back to the original polarity standard-triggering configuration, however without the use of the permanent magnet still, in order to compare the effects with and without the magnet on plume formation during operation in standard triggering. In addition, brand new fuel and insulator blocks were installed, and the cathode pin and igniter bore surfaces were cleaned of carbon charring deposit from prior tests.

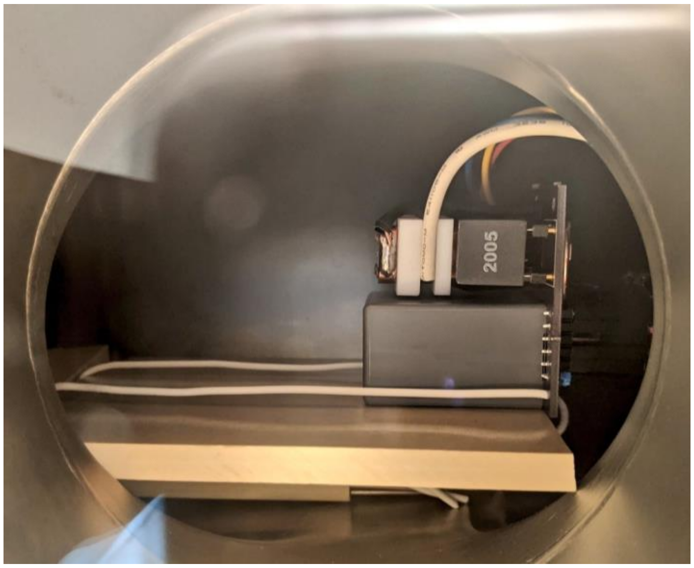

FIGURE 24: *Thruster mounting inside high vacuum chamber*

The thruster was mounted into the chamber and pumped down to 4x10^-6 Torr before testing. Although start-up was again challenging at the nominal 5V input, once the system started firing, it seemed relatively reliable in the beginning. Thruster input was increased to 5.5V to further improve ignition reliability after startup. The thruster was operated for about 5 minutes at 0.5Hz with few misfires.

After this initial warm-up, the repetition rate was increased to 1Hz. At 5.5V in, the system indicated 1.6kV out, giving a shot energy of 0.28J. The system performed reliably with few misfires during this phase.

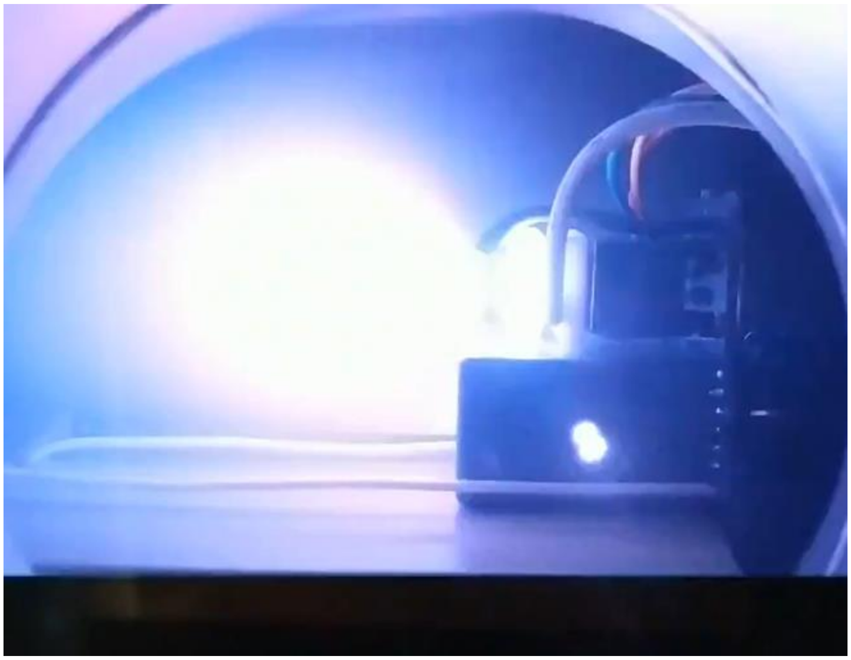

FIGURE 25: *Plasma plume during thruster operation*

Looking at the resulting pulsed waveform picked up on the Faraday cup, the typical 300ns FWHM waveform can be seen. Unlike ignition test 3 however, the distinct double peak was no longer apparent, with more of a bipolar peak during successful ignitions. This is most likely attributed to some effect of the permanent magnet nozzle, which was removed for this test but utilized in ignition test 3. However, no noticeable change in the physical plasma plume was observed during operation.

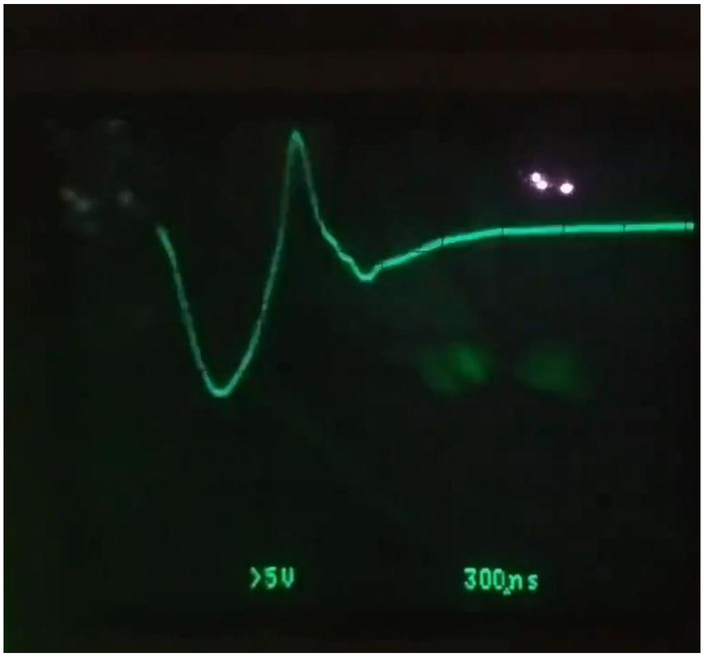

FIGURE 26: *Captured pulse during firing with typical 300ns pulse width discharge*

About 15 minutes into the test, an unusual failure mode occurred. Output suddenly dropped to 0V, however, no indication of shorting was seen. Current draw was normal, which is highly unusual, since electronics failures with this system to date have always resulted in some shorting failure, leading to excessive current draw which can be seen on the input power supply. However this time, there was no indication of shorting. After about 10 minutes, pulsing briefly resumed on its own for a few pulses, and thruster readouts returned to normal, however, the output dropped to 0V again. After waiting for additional time, operation did not return, and the test was ended.

IX. CONCLUSIONS AND FUTURE WORK

Over the course of six tests, significant operational data was collected on the gPPT3/EPPT1 prototype hybrid micro pulsed plasma thruster. Both successful ignition runs and numerous failure modes were encountered during the test. In addition, numerous configurations were tried, comparing the effects of standard and reverse polarities, as well as the effect of the magnetic nozzle on the output, and general modifications to the drive electronics.

Although it had to be severely overdriven, the system has demonstrated operation at higher repetition rates than typically encountered for Teflon fueled PPTs, especially at the low-power, sub-Joule range of micro-PPTs. The gPPT3 thruster head in particular has demonstrated it can handle these higher rep rates, and that higher rates may be possible yet. In addition, the polypropylene capacitors have proved to be a significant improvement in terms of lifetime from the prior used MLCCs. The fuel bore has also been qualified to at least 4000 shots over a wide range of shot energies, from 0.09J to 0.62J and low to high rep rates.

However, there are many key issues to still be addressed. The most significant is that modifications to the gPPT3 thruster head are needed to improve reliability. Although the gPPT3 has been successfully tested through numerous system iterations, ignition reliability remains a key challenge. This is most likely due to geometry and spacing of the current electrode configuration in the thruster. Further investigation is also needed into the exact effects of the magnetic nozzle on plume formation, and if any gains in thrust and/or efficiency can be measured with the use of such a nozzle.

The effects of reverse polarity on operation also needs to be studied further to see if any gains in performance can be quantified as well. While anode-side triggering appears to inhibit performance in the gPPT3, the unusual plume formation without the magnetic nozzle is of interest for future studies.

Finally, thruster electronics need to be significantly redesigned to provide protection of the thyristor trigger circuitry while maintaining stable operation. While the bottleneck of performance in the gPPT3 was the main pulse bank, the limit in the EPPT1 electronics appears to be the thyristor, which is the major source of faults. The load switch should also be removed with direct power to the HV supply. Future developments will most likely include dedicated supplies for the main and ignition circuitry, run at higher power but allowing for higher rep-rate operation. Higher voltage on the main bank across the anode and cathode significantly improves ignition, however this will require a much higher voltage supply, series capacitors to handle the voltage increase, and adjusting of the thruster geometry.