Micro-Cathode Matrix Arc Thrusters- A Modified Approach to Micro-Cathode Arc Thrusters

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Abstract: This research investigates the thrust and lifetime of the matrix thruster, which is a new version of the micro-cathode arc thruster (μCAT). This thruster was tested in both passive and copper firing modes. The passive mode generates a cathode spot on one of several cathodes connected in parallel while the copper mode generates 4 cathode spots on 1 cathode. Initially, 4 power processing units (PPU) were set up in parallel with one power supply for the copper mode, but later a modified version of the PPU, referred to as the capacitive storage PPU (CPPU), was developed to reduce the mass of the system. The thrust and lifetime experiments were conducted at various frequencies and insulated-gate bipolar transistor (IGBT) short times. The passive mode generated between 1 to 3.8 micronewtons (uN) of thrust. It was observed that thrust on the passive run seemed to increase with longer IGBT short times. The copper mode generated about 2 uN of thrust, but it was expected that the thrust would have also increased with larger IGBT short times and this was not observed. Running the copper mode with the CPPU was found to generate between 2 uN and 11 uN of thrust, but the thruster's performance degraded rapidly. The thruster lifetime was maximized in the passive mode. The highest lifetime was between 1.8 to 2.5 million pulses when the thruster was running in the passive mode at a 10 hertz pulse rate with gradual increases to the IGBT short times, and about 1 million pulses when the thruster was running in the passive mode at a 40 hertz pulse rate with gradual increases to the IGBT short times.

Nomenclature

amp	=	Amper
CPPU	=	Capacitive storage PPU
DC	=	Direct Current
hz	=	hertz
I	=	Current
IGBT	=	Insulated-gate bipolar transistor
kv	=	Kilo Volts
V	=	volts
MPNL	=	Micro-Propulsion and Nanotechnology Laboratory
MT	=	matrix thruster

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P	=	power
PPU	=	Power Processing Unit
T	=	Thrust
uN	=	Micronewton
us	=	Micro Seconds
µCATs	=	Micro-cathode arc thrusters

I. Introduction

In an effort to reduce cost and improve mission redundancy, the space community is designing small satellites for a variety of missions. A challenge for these satellites is that their low volume and power restrictions limits options to fit them with propulsion systems. The George Washington University Micropropulsion and Nanotechnology Laboratory has been working to address this challenge by developing the Micro-cathode arc thrusters (µCATs) for CubeSats[1]. The µCATs, are vacuum arc plasma thrusters, which have recently been designed to have a central cathode and an outer anode in a coaxial configuration. These thrusters utilize a triggerless ignition method as described by Anders[2] and Teel[3]. The thruster will form plasmas that eject material from the cathode. A portion of this ejected or ablated material will be directed away from the thruster face, thereby producing thrust in the uN range[4]. The rest of the material will fall along the thruster face which will help to continue the triggerless ignition. These thrusters have lifetimes between a 10^3 pulses to a 1.3*10^6 pulses, and a thrust value of 1 to 10 micro newtons[5], but absent an applied magnetic field, the µCATs will have thrust near 1 to 3 uN. The micro-cathode matrix arc thruster (MT) is a new design of the µCATs that has been created to improve the lifetime and thrust without applied magnetic fields.

II. Matrix Thruster (MT) Specifications

The current version of the MT, shown in Fig. 1 (a), is made of 4 central titanium wires, 1 copper plate, and 1 ceramic insulator. The ceramic insulates the wires and is the supporting structure for the application of both the carbon paint and the deposit of back scattered ablated material. The carbon paint and the deposited material facilitate the electrical breakdown that promotes plasma formation at the cathode. There are two modes that can be employed by the matrix thruster. The first mode, referred to as the passive mode, has the central wires set to be the cathode while the copper plate is set to be the anode. Unless otherwise stated, the 4 cathode wires are connected in parallel to the power processing unit (PPU). In the passive mode, the cathode spot will be generated on the cathode with the least resistance between itself and the anode copper plate. As show in Fig. 2 (a), the PPU contains a 550uH inductor and an IGBT that runs off of a 20-25 V power supply. The IGBT, an electrical switch, is defaulted to open and is then closed briefly to short the circuit. Most of the time the circuit will have nearly 0 amps flowing in the circuit, but the closing and the opening of the IGBT creates a large current change that will lead to an electric potential spike across the inductor. This process boosts the voltage to a level that allows an arc discharge between the thruster's cathode and anode.

The copper mode is the second mode of the MT. In this mode, the roles of the central wires and the copper plate are reversed, and the central wires become the anode while the copper plate becomes the cathode. Unless it is stated, the 4 central wires are all connected as the anodes. This mode quadruples the PPU setup that was used in the passive mode and runs them in parallel with a 20-25 volt power supply as shown in Fig. 3 (b). Each PPU is connected to one of the anode central wires. Figure 2 (b) shows that this copper mode generates 4 cathode spots, which might lead to higher thrust levels.

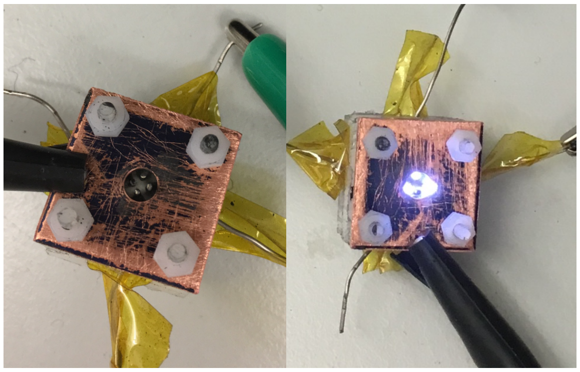

Figure 1 a) MT, b) MT with 4 cathode spot

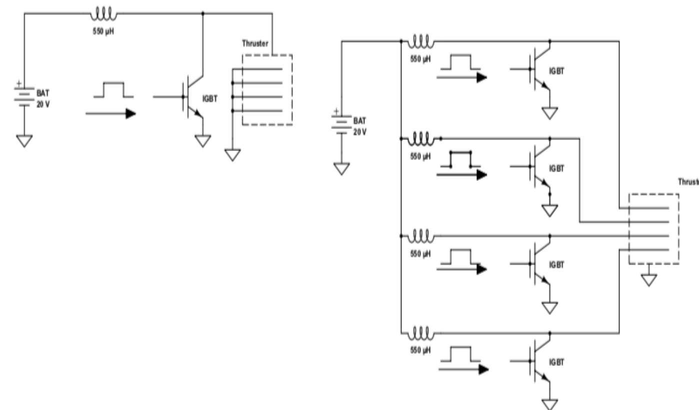

Figure. 2 a) Circuit for Passive Mode , b) Circuit for Copper Mode

Running the copper mode requires 4 inductors which leads to a significant increase in the total mass of the PPU. There was a clear need to create a circuit that could generate multiple cathode spots with fewer inductors. This can be achieved by synchronously running four separate inductive energy storage PPUs from the same 25V DC power source6. The capacitive storage PPU (CPPU) was created to generate 4 cathode spots when the cathode and anode were setup for the copper mode. The CPPU stores high-voltage pulses in high-voltage capacitors, allowing it to generate 4 cathode spots while using 1 inductor. The first iteration of the CPPU, shown in Fig 3., operates in two stages. The first stage of the CPPU is the same setup as the PPU on the passive mode. This first stage utilizes the inductive energy storage PPU, in which a microcontroller triggers a semiconductor switch, an IGBT, in order to draw a current through the inductor and store this energy in the form of a magnetic field. Once the microcontroller signal is removed and the IGBT switch is opened, a voltage spike of roughly 1.2kV is created by the inductor and stored in each of the four parallel capacitors that are in the second stage. The formula that approximates the voltage spike value is shown in Eq. 1 where V are the volts, L is the inductance, di is the infinitesimal change in current, dt is the infinitesimal change in time.

$$V = L\frac{di}{dt} \tag{1}$$

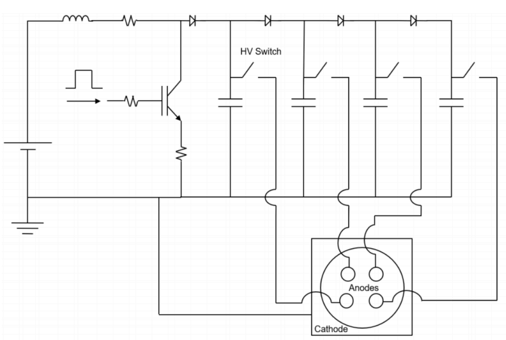

Figure 3. Capacitive PPU with Matrix Arc Thruste

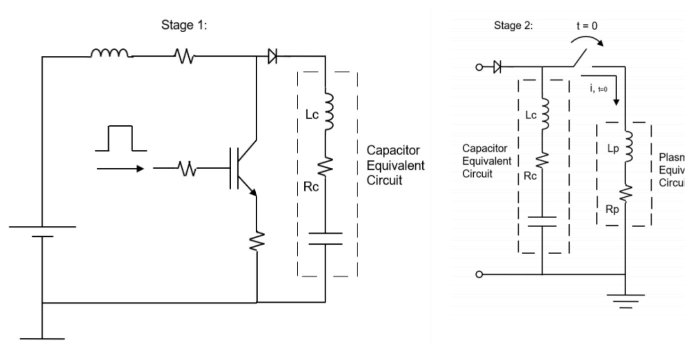

Figure 4. Stage 1 and Stage 2 of Capacitive PPU

High voltage diodes are used to prevent the capacitors from back-discharging into the inductor or IGBT. During the second the stage, the microcontroller triggers a series of high voltage switches, each of which connect an anode in series with a capacitor, creating four cathode spots and initiating an arc from the shared cathode to each anode.

III. Thrust Experiment

A. Experimental Setup

To measure thrust at the micronewton level, a torsional thrust stand, shown in Fig. 5, is used at the Micro-Propulsion and Nanotechnology Laboratory. This thrust stand is a long bar with a calibrator attached to one end and a thruster is attached to the opposite lengthwise end. The thrust bar's center of mass is positioned at the pivot point, where torsional springs provide a restoring force that respects Hooke's law. An applied external force will cause the stand to rotate perpendicular to earth's gravity field. This thrust bar's calibrator contains two metal combs. One comb is attached to the thrust bar and the other is attached to an immobile platform positioned a short distance away. During the calibration, the two metal combs are charged up to create specific levels of electrical force that will cause the gap between the combs to decrease. This electrical force rotates the thrust bar against the gradually increasing restoring force of the torsional springs until the net force is 0. The distance the thrust bar rotates away from the equilibrium position, a position where the thrust bar stays when no force is applied, is recorded for each value of incremental applied force. Figure 6 shows a distance change from equilibrium, which is measured by a Philtec DMS light sensor. Similar to the dynamics of the electric force applied at the calibrator, when a thruster is discharged it rotates the thrust bar against the torsional springs until the net force is zero. The thrust is then estimated by comparing the distance the thrust bar rotates to distance and force values recorded during the calibration to estimate the applied thrust [7-8].

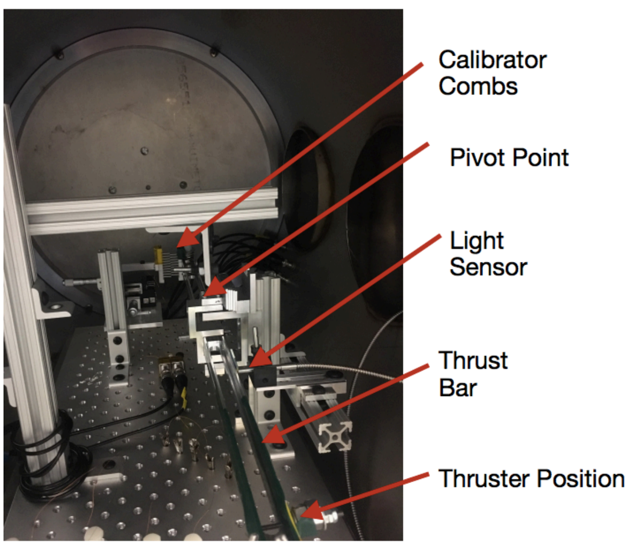

Figure 5. Thrust stand apparatus with calibrator and distance sensor

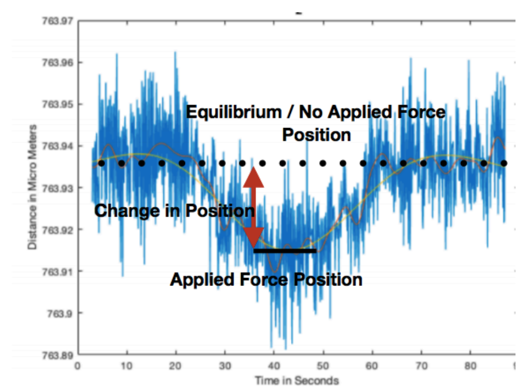

Figure 6. Thrust Distance Steps

For each thrust trial, the thruster is run for 30 seconds to collect the average distance the thrust bar rotated. The two thruster modes are fired with the following circuit parameters. To test the thrust values dependency on the thruster's firing/pulsing frequency, the DC power supply is set to 20 volts, the circuit is commanded to have the IGBT short for 200 us, and thruster pulsing is set to a frequency of 10 hz, 20 hz ,or 40 hz. To test the thrust values dependency on the IGBT short times, the DC power supply is set to 20 V, the thruster pulsing was set to a frequency of 10 hz, and the IGBT short times are set to 400 us, 600 us, or 800 us. Each experiment is run for 5 to 10 trials on each of these circuit parameters and the experiments are repeated 5 times. The power data is collected with an oscilloscope and analyzed in a similar manner as Zhuang described[9]. The average power is calculated by finding the total power in the discharge and this value is then multiplied by the thruster pulsing frequency. Post data collection modifications of the data are made by removing the initial outliers calculated as values greater than 1.5 * the inter quartile range of the data grouped by thruster mode and circuit parameter on both the experiment and the trial level. The experiment are all completed in a vacuum chamber at a pressure on the order of 10^-5 Torr. In addition to performing the thrust experiments, a null test is completed to confirm that the distance measurements are not being caused by other factors such as resonance or interactions with an external magnetic field. This null test is completed by running the thruster in the same modes described above, but the thrust head is covered to prevent the ablated material from completing leaving the thrust system.

B. Results

Based on the raw data, which contains the initial unadjusted measurements, the copper plate mode showed average thrust values from 1.9 to 2.6 μN. This data does not exhibit a clear trend based on the different settings of the circuit parameters. In contrast, the passive mode shows a trend of increasing thrust for both increases in the pulse frequency and an increases in the IGBT shorting time. The average thrusts values on the passive mode measure from 1 to 5.5 μN of thrust. Reviewing Fig. 7 (a), it can be seen that this initial data has large standard error bars with some points that spread over the 0 value mark. Figure 7 (b) shows the adjusted data, which is the raw data adjusted by post data collection modification methodology described in the preceding section. The number of trials and the percent of data removed for both the thrust and the power measurements can be reviewed at the bottom of table. 1. For the thrust data, generally between 8 to 16 percent of the data is removed, but there was one that has 30% of the data removed. Most of the power data has between 0 to 18% of the data removed, but there were a couple of experiments that have more than 22% of the data removed. After making these adjustments, the standard deviation bars for all of the experiments are above the 0 μN thrust level.

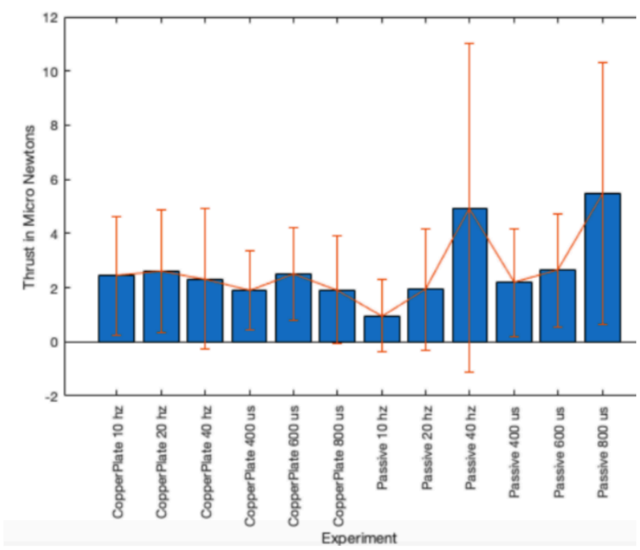

Figure 7. a) Raw thrust data for each experiment

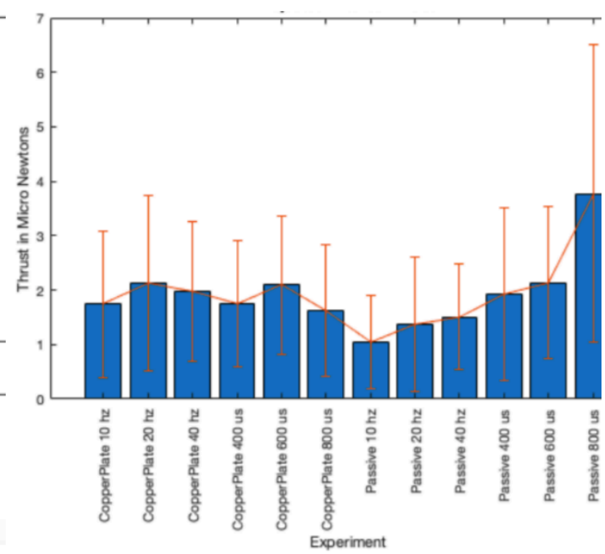

Figure 7. b) Adjusted thrust data for each experiment

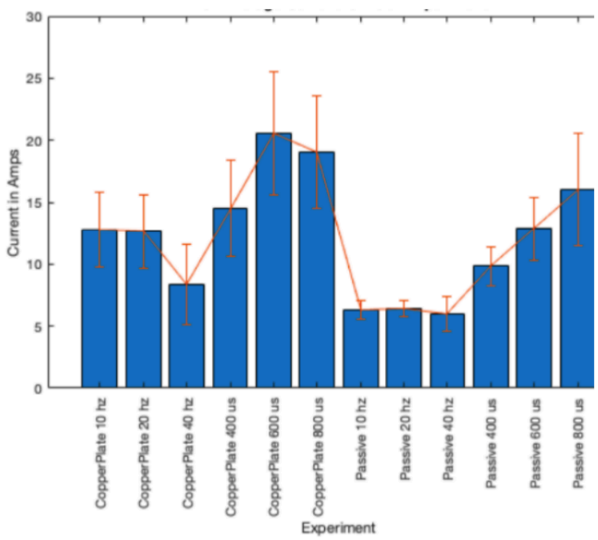

Figure 8. a) Average max current on raw data

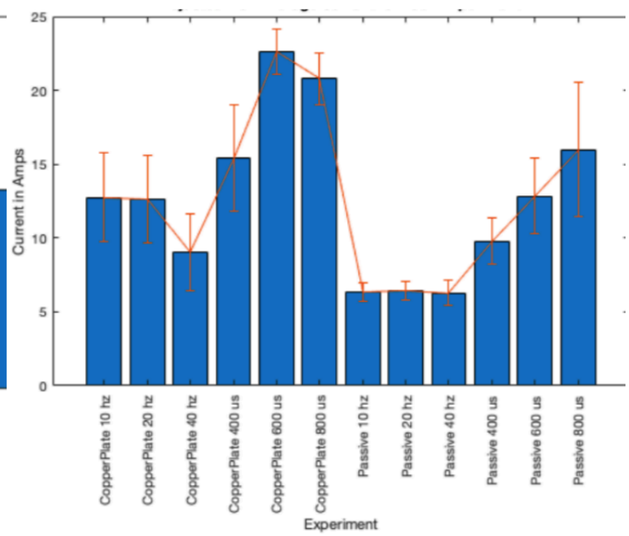

Figure 8. b) Average max current on adjusted data

After the data adjustment, the copper plate data has average thrust values in the range of 1.6 to 2 µN of thrust with no real trend in relation to the the circuit parameters. The current, which can be viewed in table 1, remains near 3.5 to 4.3 Amps when the frequency was changed. This supports our observation that average thrust would remain fairly static. In contrast, the current moved from 4.3 to 7 amps when the IGBT shorting time was increased so we would have expected to see an increase in thrust, but this was not observed.

The passive mode adjusted data has an average thrust values in the range of 1 to 3.7 µN, but the trend in the data shifted from the raw data. Increasing the pulse frequency only changes the thrust from 1 to 1.5 micro newton which was a smaller shift than was observed in the raw data. When the pulse frequency is increased, the average current stays close to 2 amps. The average max current in Fig 8 show similar current behavior in both the raw and the adjusted data. This supports the removal of the outliers since the thrust data and the current data show similar non-increasing trends relative to changes in the pulsing frequency. Increases in the passive mode's IGBT shorting time does show an increase in thrust from 1 to 3.8 µN which also corresponds to an increase in current values.

Table 1. Summary Of Experimental Data

	Copper Mode						Passive Mode					
	10 hz	20 hz	40 hz	400 us	600 us	800 us	10 hz	20 hz	40 hz	400 us	600 us	800 us
Mean of Raw Thrust Data in Micro Newtons	2.44	2.61	2.31	1.89	2.52	1.91	0.96	1.93	4.94	2.18	2.63	5.50
Median of Raw Thrust Data in Micro Newtons	1.93	1.98	2.06	1.84	1.85	1.63	0.76	1.77	2.00	2.07	2.25	3.04
Adjusted Data (Outliers Removed)												
Mean Thrust in Micro Newtons	1.74	2.12	1.97	1.76	2.09	1.62	1.05	1.37	1.50	1.92	2.13	3.77

(Current value of Thrust)/ (Thrust at 10 hz and 200 us short on IGBT)	1.00	1.22	1.13	1.01	1.20	0.93	1.00	1.31	1.43	1.83	2.03	3.58
Mean Current in Amps	4.27	3.95	3.48	5.33	7.26	6.98	2.19	1.99	2.12	3.55	4.51	5.50
Mean Pulse width in Micro Seconds	82	70	53	127	137	100	96	68	64	168	213	241
Mean Power during Thrust Run in Watts	0.21	0.40	0.67	0.48	0.79	0.62	0.13	0.22	0.46	0.32	0.55	0.82
Mean Thrust to Power in (Watts /Micro Newtons)	9.76	6.87	3.63	4.41	3.29	3.43	7.15	6.47	3.73	10.32	8.27	10.94
Raw Thrust Trials	60	60	60	55	45	45	45	45	45	45	45	45
Thrust Trials left after Outlier Adjustment	52	55	51	51	40	41	38	39	31	43	38	38
Percent of Thrust Trials Removed (similar to 2x of trimmed mean)	**13**	**8**	**15**	**7**	**11**	**9**	**16**	**13**	**31**	**4**	**16**	**16**
Raw Power Trials	48	49	49	44	41	45	42	44	45	43	44	44
Power Trials left after Outlier Adjustment	48	49	42	36	23	38	29	43	35	41	44	44
Percent of Power Trials Removed (similar to 2x of trimmed mean)	**0**	**0**	**14**	**18**	**44**	**16**	**31**	**2**	**22**	**5**	**0**	**0**

Table 1 also shows the thruster uses an average of 0.13 to 0.82 Watts. With the exception of setting the IGBT shorting to 800 us, the passive mode consistently used less power than the copper mode. The pulse width, with is the time span of the discharge, decreases for both modes as the frequency increases, but the pulse width generally increases when the IGBT shorting time is increased. The thrust to power ratio is observed in the range of 3.3 to 11 uN/Watts. The best power to thrust ratio is observed in the passive mode when the IGBT is shorted for 400 us and 800 us.

IV. Lifetime Experiment

A. Experimental Setup

The lifetime experiment is designed to approximate the maximum number of pulses that a thruster can achieve, a value which can be used to estimate how long a thruster will survive based on a mission's requirements. The thruster is placed into a vacuum chamber and the chamber is pumped down to 10^-5 Torr, as is the case with the thrust experiments. Before each thruster run, the resistance is collected by connecting a standard ohm meter across the cathode and anode. When the thruster is running, an oscilloscope is used to measure the discharge's voltage and current waveforms. The lifetime experiment run cycle runs through periods of thruster pulsing and cooling. The cool down period helps to prevent thermal damage on the thruster. These run cycles are repeated until the thruster dies, a point that is determined via extremely high or low resistance measurements, and inconsistent arcing or degrading current readings. Typically the thruster death will be the result one two possible cases. In one case, the ablative material builds up on the thruster head and causes a short circuit. The second case has the opposite issue because not enough ablative material is deposited. This leads to a high resistance which is equivalent to a permanently open circuit between the anode and cathode.

Lifetime test are conducted at a discharge frequency of 10 or 40 hz, while the IGBT shorting time is either pegged at 200 us or gradually stepped up. The step up of IGBT short times is done in 50 to 150 us intervals in the range of 200 to 800 us. When experiments are run with step ups, each step is implemented when the thruster appears to be on the verge of dying. During the 10 hz run, the thruster is initially setup in passive mode with only one cathode connected. Once the thruster starts to die, the other 3 cathodes are connected in parallel with the initial cathode and then the thruster runs in this configuration until the thruster starts to die again. At this point, the IGBT short step time is increased between 50 and 150 us. The thruster is then run until the thruster starts to die again. This process is repeated until either the thruster dies or the IGBT short time rises above 800 us. The running cycle is set so the thruster will pulse for about 8 minutes and will cool down for 8 to 16 minutes. The pulse counts are estimated through the number of commanded pulses that were sent during the experiment.

For the 40 hz run, the pulse counts are collected by setting up a Siglent SDS 1104X-E oscilloscope to count the number of times the current wave shows a discharge. Based on preliminary experiments that used the oscilloscope to count the number of pulses, it was determined that the difference between the number of counts commanded verses what was registered by the oscilloscope during the run cycle was less than 10 pulses per run or a percent error of 0.4%. The run cycle on the 40 hz runs is set to pulse the thruster for about 1 to 1.5 minutes, which is equal to 2,500 to 3,600 pulses. The thruster is then cooled for 1 to 1.5 minutes. Two of the four experiments at 40 hz, are conducted with the passive mode having 4 cathodes and 1 anode connected and the copper mode having 1 cathode and 4 anodes connected. These two experiments also have the IGBT short time increased as described previously. The other two experiments of the 40 hz run have only 1 cathode and 1 anode connected for both the passive and the copper run. There is no step up of the IGBT short time in these other two experiments.

B. Results

As was described above, there are a total of 6 experiments conducted on 5 thrusters. In the passive mode at 10 hz, table 2 shows the thruster runs with one cathode for 695,000 pulses. The same thruster then ran for an additional 1,870,360 pulses when 4 cathodes were connected in parallel and the IGBT short times are stepped up. This means that this one thruster generated 2,565,420 pulses, which is a noticeable improvement from the 1 million pulses that had been recorded for the MPNL uCATs. It should be noted that the addition of the cathodes were enabled at the circuit so the thruster itself was never adjusted. The overall death of thruster in this experiment was due to a short caused by the anode plate shifting when the Teflon support screw melted. It is likely that the thruster would have continued to fire for a longer period, because Fig. 8 shows that two of the 4 cathodes were completely ablated while two of the other cathodes still had leftover material. On later MT models, the Teflon screws were replaced with metal screws.

For the 40 hz passive mode run, 1,152,793 pulses were observed when 4 cathodes were connected and the IGBT short times were stepped up. In contrast, for the 40 hz passive run with only one cathode connected and no IGBT short step ups, the thruster died at 101,309 pulses. When the 40 hz copper mode was run with 4 anodes, one cathode, and the IBGT short time were stepped up, the thruster generated 101,309 pulses. During the 40 hz copper mode when 1 anode, 1 cathode, and no IGBT short step ups were enabled, the thruster generated 94,553 pulses. In all of the 40 hz runs, the thruster death was determined to be caused by a level of high resistance.

	Passive mode with one cathode at 10 hz and <u>No</u> IGBT short step ups	**Passive mode with 4 cathodes at 10 hz and IGBT short step ups**	**Combined pulses for the 10 hz run passive mode**	**Passive mode with 4 cathodes at 40 hz and IGBT short step ups**	**Passive mode with 1 cathode at 40 hz and <u>No</u> IGBT short step up**	**Copper mode with 4 anodes at 40 hz and IGBT short step ups**	**Copper mode with 1 anode at 40 hz and <u>No</u> IGBT short step ups**
Pulse Count	695,060	1,870,360	2,565,420	1,152,793	101,309	109,352	94,553

Cause of Death (Short or High Resistance)	High Resistance	Short	Short	High Resistance	High Resistance	High Resistance	High Resistance

Table 2. Pulse Counts

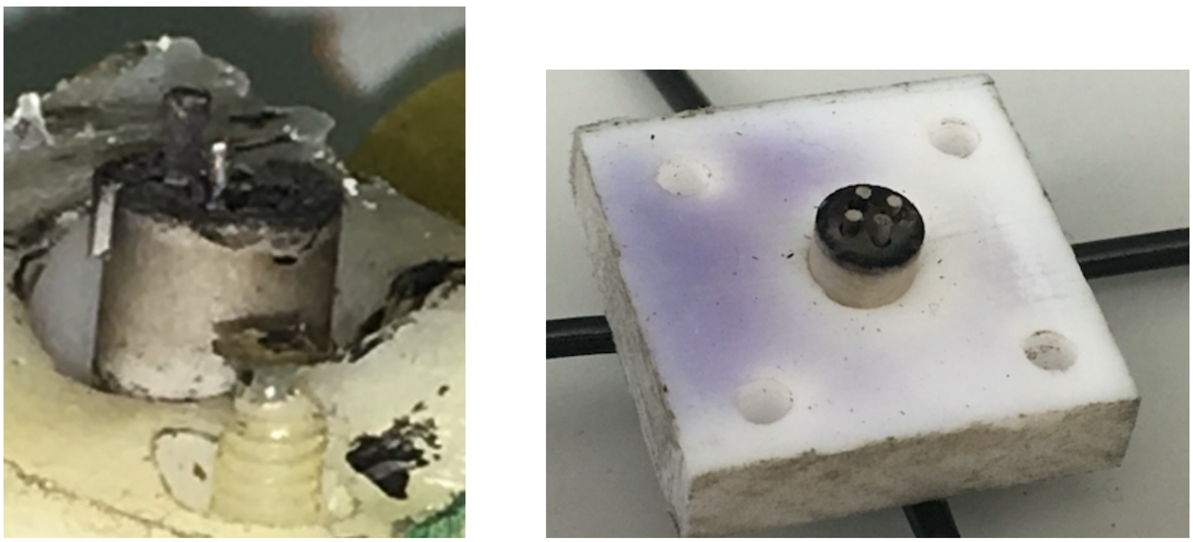

Figure 8. a) The lifetime-end 10 hz passive mode. b) A new set of cathodes for a passive mode run

V. CPPU Experiments

A. Experimental Setup

Thrust experiments are conducted with the CPPU circuit to observe the approximate thrust levels produced when this new circuit runs the thruster. The overall procedure is similar to methodology in section III of this paper, but the thruster is only run on the copper mode with 4 anodes, 1 cathode, and no IGBT short step ups. Short times of the IGBT are pegged to 600 us, which is approximately the time it takes reach the inductor's maximum energy level. Prior to each pulse of the thruster, the IGBT is shorted in 8 cycles, where a cycle is defined as a 600 us shorting period followed by a non shorting period. This process ensures the CPPU's second stage capacitors are charged to approximately 1.2 kv. During the thrust experiment, the thruster is pulsed at a frequency of 5 hz, 10 hz, 15 hz, or 20 hz. The current version of the CPPU is not able to initiate all 4 cathode spots at the same time, so the time between each cathode initiation was set to be under 0.005 seconds. This means that each pulse, consisting of all four of the cathode spots, is completed within a span of 0.02 seconds. Four trials were conducted at each frequency.

B. Results

The output current and voltage waveforms shown in Fig 9 can be found by reviewing Eq: (2) to Eq. (5) with the second stage of the capacitive PPU modeled as an underdamped RLC circuit with the initial condition of a fully charged capacitor [10]. For the following equations, V is volts, di/dt is the change in current relative to time, L is the inductance, Vo is the initial volts, I is the current, L0 is the initial inductance, e is the exponential function, Ro is the initial resistance, R is the resistance, t is the time, and C is the capacitance.

$$I = \frac{V_o}{\omega L_o} * e^{-\left(\frac{R}{2L_o}t\right)} * sin(\omega t) \tag{2}$$

$$V = \frac{V_o}{\omega\sqrt{(L_o C)}} * e^{-\left(\frac{R}{2L_o}t\right)} * sin(\omega t + \delta) \tag{3}$$

$$\omega = \left(\frac{1}{L_o C} - \frac{R_o^2}{4L_o^2}\right)^{\frac{1}{2}} \tag{4}$$

$$\delta = tan^{-1}\left(\frac{4L_o}{R_o^2 C} - 1\right)^{\frac{1}{2}} \tag{5}$$

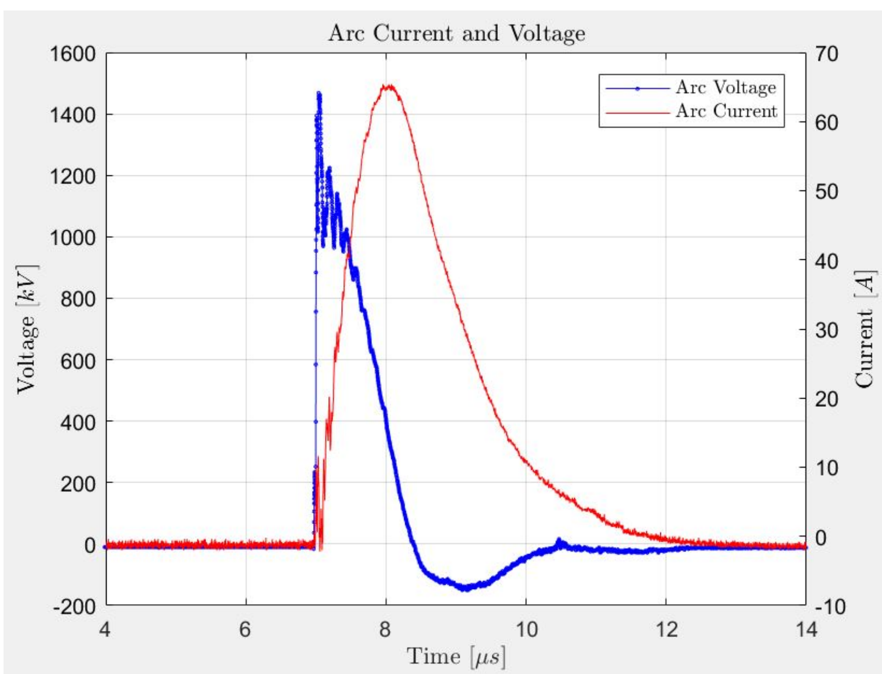

Figure 9. a) Thruster Arc Current with Capacitive

The experiments resulted in an average maximum arc current of ~70A and an average thrust of ~3µN. However, at the end of the thrust experiments, the thruster had significantly degraded, resulting in the thrust decreasing from ~ 3.6µN at 5Hz to ~ 2.4µN at 20Hz. In contrast, the average maximum arc current measurements for the previous thrust experiments in section 3 were between 6-22 amps, so this difference in max current might explain the rapid degradation. Since a large degradation was observed, it was decided to conduct another thrust experiment where the thruster was run for 10 trials at 10 hz, followed by 5 trials at 5 hz and then 5 more trials at 10 hz. The mean thrust in this experiment was measured to be 11 uN for the initial 10 hz run, followed by 3 uN at 5 hz and then 9 uN at second 10 hz run. The power observed to be about 0.815596 Watts on average.

VI. Conclusion

The thrust data, without the CPPU, suggests that the thruster outputs 1 to 3.8 uN of thrust with a power to thrust ratio of between 3.3 -11uN/W. The raw data also suggests that it might be possible for the passive mode to generate an average thrust of 5.5 uN with 600 us of IGBT shorting. Neither mode showed much of a correlation between thrust and changes to the pulsing frequency, but this observation was supported by the measurements of current. The thrust on the passive run was positively correlated with increases in the IGBT short times, but the copper mode did not display this relationship. Based on the current readings, it was expected that the thrust would be increased with longer IGBT short times, thus the copper plate thrust relationship to IGBT short times is not expected. Overall, the copper mode had a thrust value of about to 2 uN but this changed when the copper mode was used with the CPPU. The initial set of thrust experiments with the CPPU yielded thrust value that were similar to the previous set of thrust experiments, but it was also observed that there was a significant degradation of thruster. This might be caused by the high average maximum arc current being generated with the CPPU. A second set of CPPU thrust experiments yielded thrust values between 11 to 9 uN at 10 hz, but it was again observed that the thruster's performance was degrading over the trials.

The highest lifetime, consisting of 1.8 to 2.5 million pulses, was observed using the passive mode at 10 hz with a step up in the IGBT short times. Comparing the passive mode between the 10 hz and the 40 hz run while stepping up the IGBT short times, indicates that the lower pulsing frequency leads to higher lifetimes. This is an important observation since it was noted that the thrust did not appear to have a noticeable dependency on the frequency. The 40 hz passive mode experiments suggest that adding separate cathodes in parallel can increase the lifetime by more than what than what a linear model, comparing the number of cathodes to the lifetime, would suggest. This is supported by the observation that the number of pulses on the 40 hz passive run increases from 101,309 to 1,152,793 pulses. All of the copper mode lifetime experiments ended up having a pulse count that was similar to the lowest readings on the passive mode, which was near 100,000 pulses.

Based on the above review, there are several recommendations that can be offered if further research is to be continued on the MT. On the thrust experiments, the large error bars challenge our ability to state the statistical significance of these measurements. Part of the reason for the large error bars is due to the measured thrust values being near the lower measurement bounds of our thrust stand. This can be resolved by increasing the sensitivity and the lower bound measurement values of thrust stand. This would be done by replacing the current torsional springs with ones that have a lower spring constant and by isolating the external vibrations from external sources. Once these adjustments are complete, further data should be collected on the passive runs to confirm the above thrust measurements. Additionally, further experiments should be done on CPPU to test the relationship of thrust to adjustments on the CPPU's internal timing settings and the CPPU's levels of the stored energy. For the lifetime data, the lifetime passive run at 10 hz must be repeated because the thruster died when the Teflon screws melted. This issue resulted in the other lifetime experiments all having MTs with metal screws. More experiments are also required to estimate a model relationship between the number of added cathodes in the passive mode to the lifetime on the 10 hz run. Lifetime experiments should also be conducted on the MT powered by the CPPU and in general we should complete more trials on each experiment.

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