# Micro-Cathode Matrix Arc Thrusters for Small Satellites

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## Introduction and Objectives

The space community is designing small satellites to reduce cost and improve mission redundancy. Challenges on these satellites include low volume and low power restrictions that limit their options for propulsion systems. The MPNL group has been designing micro-cathode arc thrusters (μCATs), which are vacuum arc plasma thrusters that have a cathode and an anode in a coaxial configuration. These thrusters form plasmas from arc discharges that eject material from the cathode to produce thrust in the uN range. A triggerless ignition system with a DC booster circuit is used to generate the arc discharge with a thin film of carbon between the anode and the cathode. After a short number of thruster pulses, the carbon is replaced with small amounts of backscattered cathode particles. This process allows the triggerless ignition to continue.

The lifetimes of these thrusters have been between $10^3$ pulses to $1.3*10^6$ pulses. The thrust values have been between 1 to 10 micro newtons. When no magnetic field is applied, these thrusters will typically have thrust near 1 to 3 uN. The goal of this project is to make a new thruster that will improve the lifetime and thrust values while staying within the volume requirements of the μCATs.

**Objectives :**

- Develop a new thruster that has a similar size but a set of multiple cathodes in a matrix configurations to see if thrust and lifetime can be improved
- Run thrust experiments
- Run lifetime experiments

## Matrix Thruster Face Details

### Hardware

- Vacuum arc plasma thruster
- 4 separate titanium wires, average wire diameter of 0.0253 inches,
- Copper plate, 1/8 inch depth, length and width of 0.75 inches.
- Central insulator, non porous alumina ceramic tube, .25 inches long with 4 bores, 0.188 inch outer diameter, and 0.031 inch inner diameters.

### Two Modes of Firing:

- Passive mode: 1 cathode spot formed and 1 to 4 wires connected in parallel.
- Copper mode: 4 cathode spots formed on the copper plate across from the wires.

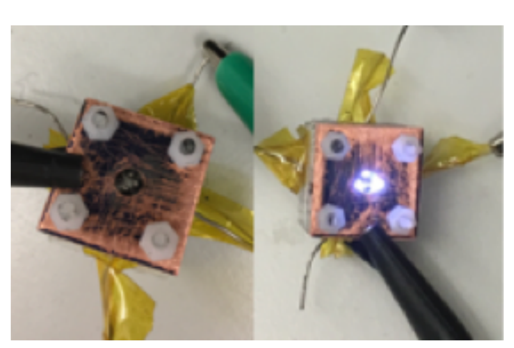

Figure 1. Matrix Thruster Head Non-firing and Firing with 4 Cathodes Energized

## Matrix Thruster Power Processing Unit (PPU) and Capacitive Storage PPU (CPPU)

**20 to 25 volts supplied to all PPUs**

### Original PPUs

1. PPU for passive modes use insulated-gate bipolar transistor (IGBT) to charge up a 550 uH inductor for preset short times

2. PPU for the copper mode uses 4 of the passive PPUs in parallel to generate a cathode spot at across from each anode

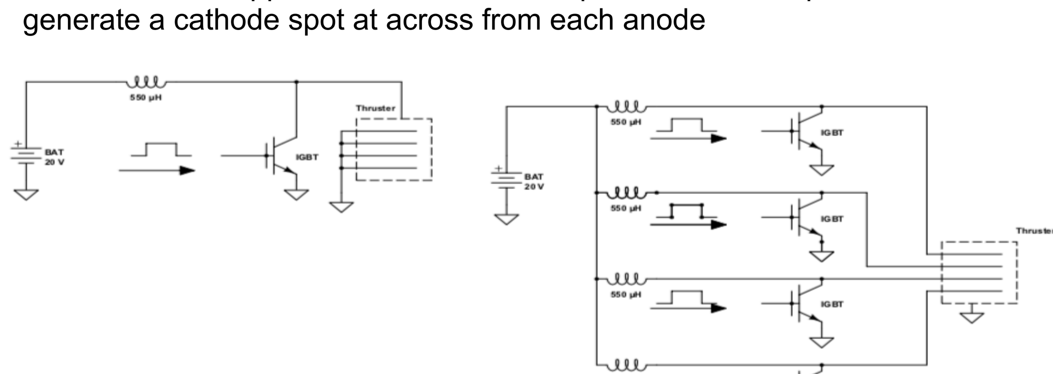

Figure 2. Passive Mode (Left) and Copper Mode PPU (Right)

### CPPU- modified version of the PPU

Used to Generate 4 cathode spots. Contains two units.

- Unit 1: The original booster circuit
- Unit 2: Capacitive storage segment , 4 capacitors and diodes.
- Booster circuit charges 4 capacitors after 8 shorting cycles of the IGBT. Diodes prevent current back flow. Each capacitor supplies one cathode spot.

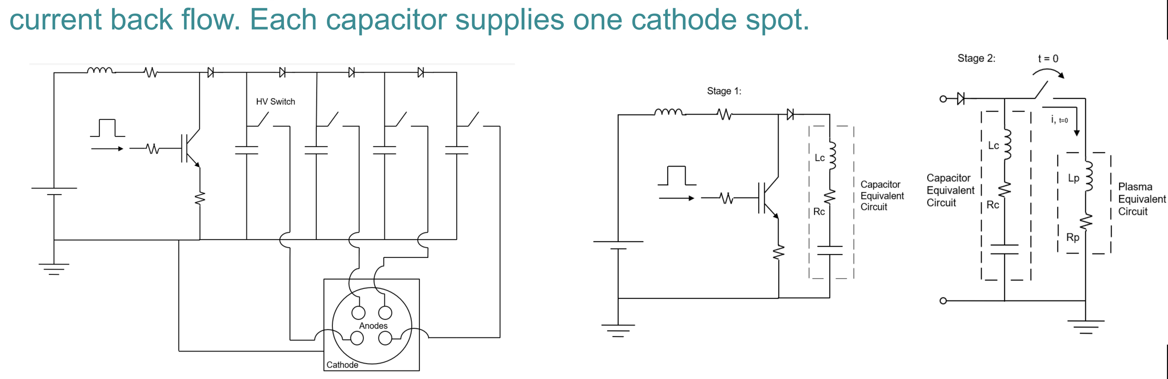

Figure 3. CPPU, Stage 1, and Stage 2

## Methods and Results

### Thrust Experiment Method with Original PPUs

The torsional stand contains a two comb calibrator and a thruster at opposite ends. A light sensor measures the deflection distances created when an external force rotates the stand. Torsional springs provide the restoring force at center of mass. The Calibrator forms a known force to distance curve. The thruster distance data is compared to calibration data to estimate the force.

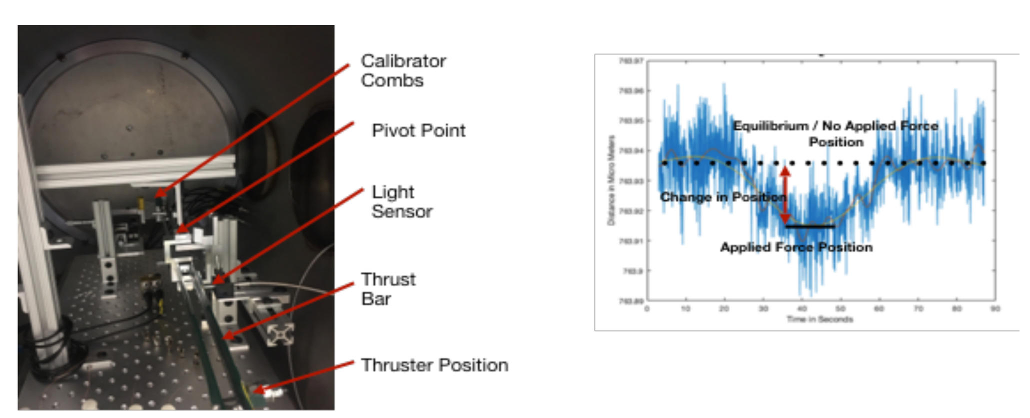


Figure 4. Stand (Left) and Measured Step Data (Right)

### Thrust Experiment Continued

- With a pressure of $10^{-5}$ torr, the thruster is run for 30 seconds to collect the average distance
- Two thruster modes are fired with the following circuit parameters.
  - To test the dependency on the firing/pulsing frequency, the circuit is commanded to have the IGBT short for 200 us, and thruster pulsing is set to 10 hz, 20 hz ,or 40 hz
  - To test the dependency on the IGBT short times, the thruster pulsing was set to 10 hz, and the IGBT short times were 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 time

### Thrust Results

#### Raw Data Observations

- Large 1sd error bars, some over the 0 point
- Copper mode: Average thrust of 1.9 to 2.6 μN. No clear trends based on circuit parameters
- Passive mode: Average thrusts 1 to 5.5 μN of thrust. Trend of increasing thrust for both increases in the pulse frequency and IGBT shorting times

#### Adjusted Data Observations

- Outliers Removed
- Copper mode: average thrust of 1.6 to 2 μN. No clear trends based on the different circuit parameters
- Passive mode: Showed thrust values in the range of 1 to 3.7 μN. Trend shifted from the raw data. Increasing the pulse frequency changes the thrust from only 1 to 1.5 μN, which is smaller than the raw data. The trend of increasing thrust with increasing shorting times remained

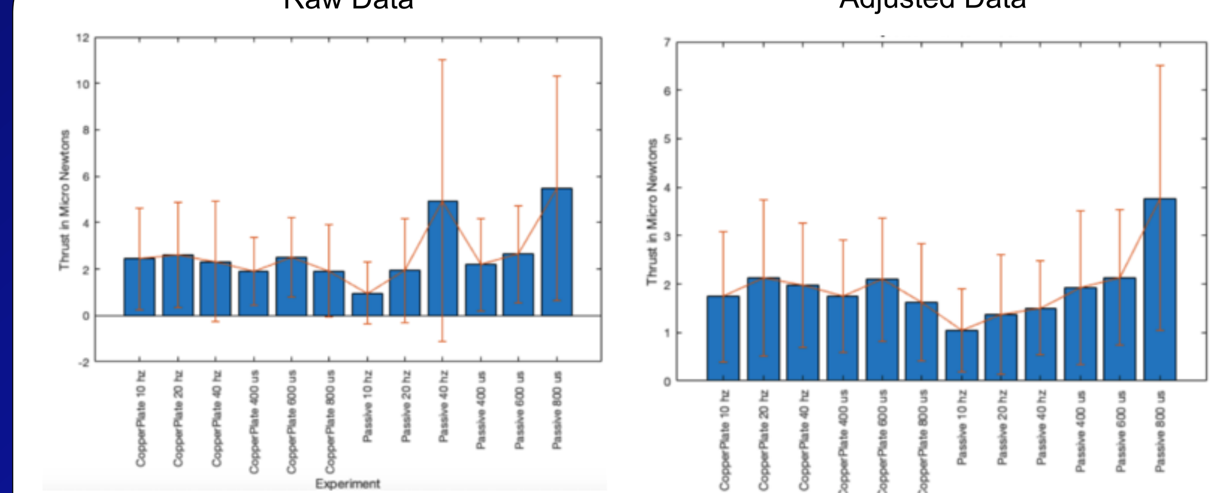


Figure 5. Raw (Left) and Adjusted Thrust Measurements (Right)

**Other observations:**
An average of 0.13 to 0.82 Watts used. Passive mode usually used less power than the copper mode. Thrust to power ratio was 3.3 to 11 μN/ Watts. Best ratio is the passive mode with IGBT short time of 400 μs and 800 μs
**Thrust data adjustments**:
Usually between 8 to 16% of data removed, one had 30% of the data removed. Current readings supported removing the outliers as the trends were similar, except they suggest that there should have been a increase in thrust with pulse shorting time for the copper mode

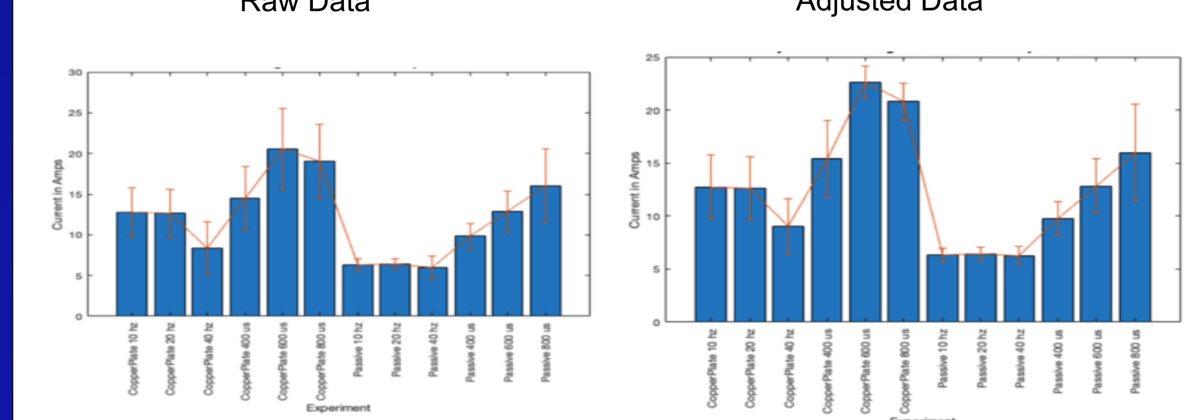


Figure 6. Raw (Left) and Adjusted Current Measurements (Right)

### Lifetime Method

Run with a discharge frequency of 10 or 40 hz, and the IGBT shorting time is pegged at 200 us or gradually stepped-up in 50 to 150 us intervals between 200 to 800 us. The thruster is run with pulsed and cooled down cycles that last for similar time spans. Thruster death is observed when no more pulsing is visible and is confirmed with resistance and current measurements. Each step takes place until thruster death. If the thruster does not start again with a step-up or the adding more cathodes, then the experiment is completed. The thruster remains inside the vacuum chamber and the above adjustments are made outside of the vacuum chamber on the circuit. At the end of the experiment, the cause of the thruster death will be determined to be due to low resistance (shorting) or to high resistance. Shorts are caused by to much cathode material falling on to the face of the thruster and high resistance is caused by not enough of the cathode material falling on the face of the thruster.

**Specific Run Setups**

- **10 hz run:** The thruster is initially setup in passive mode with one cathode until the thruster dies. Then 3 cathodes are connected in parallel with the initial cathode until the thruster dies again. Finally the IGBT short times are stepped-up until the thruster no longer generates pulses.
- **40 hz runs:** 4 experiments
  - With IGBT step-ups (step-ups activated when the thruster starts to die)
    - Passive mode with 4 cathodes and 1 anode
    - Copper mode with 1 cathode and 4 anodes.
  - No IGBT step-ups (Thruster is run until it dies with no modifications)
    - Passive mode, 1 cathode and 1 anode
    - Copper mode, 1 cathode and 1 anode

### Lifetime Results

Table of Lifetime Results

| | Passive mode with one cathode at 10 hz and No 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 No 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 No 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 |

**Passive runs had the best lifetimes**
The longest run, passive at 10 hz, died due to melting plastic screws. Two of the four cathodes in this run were expelled completely as can be see in figure:

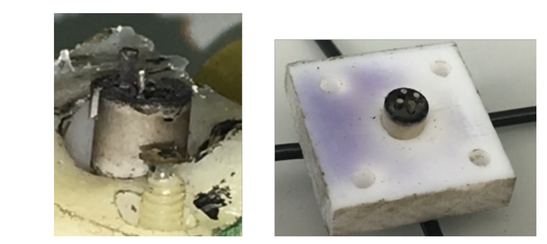

Figure 7. Thrust Death of 10 hz Run and Fresh Set of Cathodes for Passive Run

### Thrust Run with Capacitive Storage PPU (CPPU)

**Only run in copper mode with a pulsing frequencies of 5 hz, 10 hz, 15 hz, or 20 hz.**
**Observations:**

- CPPU was not able to initiate all 4 cathode spots at the same time. Time between each initiation set to be under 0.005 seconds, so ignite within 0.02 seconds
- Average maximum arc current of 70 amps and average thrust of 3μN
- Significantly degradation in thruster, resulting in the thrust decreasing from 3.6μN at 5Hz to 2.4μN at 20Hz.

Average max arc current for previous thrust experiments were between 6-22 amps This difference might explain the rapid degradation

**Another thrust experiment completed running only at 10 hz, 5 hz and then 10 hz again**

- Average thrust was 11 μN for the initial 10 hz run, 3 μN at 5 hz and then 9 μN at second 10 hz run
- The individual thrust points again showed significant degradation

The average power was observed to be about 0.815596 Watts.

## Conclusion

**Thrust Observations**
The thrust data, without the CPPU, outputs about 1 to 3.8 μN of thrust. It might be possible for the passive mode to generate 5.5 μN. No relationship between thrust and pulsing frequency was observed, but the thrust on the passive run was positively correlated with increases in the IGBT short times. The copper mode with the CPPU yielded thrust values that were between the original values and up to 11 μN., however there was a rapid degradation of performance. Thus there was a slight improvement in thrust.

**Thrust Recommendations**
Large error bars challenge our ability to state a statistical significance. This is probably caused by the thrust being near the lower bounds of the thrust stand. Increasing the sensitivity and the lower bound measurement values of thrust stand would improve this. Additional experiments need to conducted with the CPPU to test the relationship of thrust to adjustments on the CPPU's internal timing settings and the CPPU's levels of stored energy.

**Lifetime Conclusions**
The highest lifetime 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. Lower pulsing frequencies and stepping-up the IGBT short times appear to have increase the lifetime. Additionally adding cathodes in parallel appears to increase the lifetime by more than what a linear model would suggest. The copper mode lifetime experiments yielded the lowest counts, near 100,000 pulses. The passive mode showed an improvement in lifetime compared to previous thrusters

**Lifetime Recommendations**
The passive run at 10 hz must be repeated because the thruster died when the screws melted. This issue resulted in the other lifetime experiments all having MTs with metal screws. More experiments are required to estimate the model relationship between the number of added cathodes in the 10 hz passive mode to the lifetime. Lifetime experiments should also be conducted with the CPPU and more trials should be conducted on each experiment.

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