

Applied Ion Systems

AIS-VAT0-DEMO

Educational DIY Micro Vacuum Arc Thruster Learning Kit

User Manual V1

Michael Bretti - 2022



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PREFACE

If you have purchased this kit or are reading this manual, you are probably familiar to some extent of my work at AIS. My journey started as a simple DIY effort in my free time (and still is today!), tinkering in a crappy, unfinished basement with wood planks and dirt floors, working under a single lightbulb, splitting power between my basement and the kitchen upstairs to run experiments. While I had a lot of background in many relevant areas of high voltage, plasmas, beams systems, and electronics prior, when I first started out developing my own thrusters, I still had no idea what I was doing. My first thruster attempts completely failed (often destroying a lot of equipment in the process.) Over time, with many, many tests and iterations, and embracing a radical, completely open DIY approach to development in the field, I worked my way up through a number of propulsion technologies, shaping AIS into something more than just a side hobby, and creating a rather unique name for myself and AIS in the field. Over the years since I started, I have run hundreds of tests, posting thousands of pictures and hundreds of videos along the way, detailing every step of every development. My journey has taken me an incredibly long way from where I first started, pushing new and exciting frontiers, and trying things that even in such a well-funded field, have not been attempted before, and accomplishing many firsts in the field, working completely independently at home in my free time and funded only through generous donations from supporters around the world. And I am still learning as I go now.

It has long been a goal of mine at AIS to develop a low-cost, off-the-shelf, DIY electric propulsion system, to greatly broaden engagement, outreach, and accessibility for electric propulsion technologies in the field. While there are countless resources and publications in the field, there have not been any true, open, independent research and DIY efforts as of yet, and there is nothing really to show how to build and operate a fully functional thruster system yourself, with simple and accessible components, and really go from the academic research level to something tangible and practical for even someone with relatively little prior experience in the field can pick up and understand. There has also never been an off-the-shelf EP kit before until now, where anyone can pick it up and build your very own fully functional space thruster!

Speaking with many people across the world from all backgrounds, I know there are a lot of people out there, from students, to researchers, to DIYers, who want to get into electric propulsion, but do not know where to start, or maybe lack the resources and facilities or guidance to get involved, or want to continue working on propulsion on their own but do not know where to begin. As someone who started on my own with no guidance, and still operates completely independently, I know how challenging it can be. There is a lot of talk all the time in the electric propulsion field about accessibility, but in my experience, just lowering the price of EP from hundreds of thousands of dollars to \$50k for a thruster, or embracing automotive manufacturing techniques, or developing more propulsion for Cubesats, is not enough. Real accessibility, really lowering the barriers of entry, should go much further. Real accessibility is when the at-home maker can build, test, and explore these technologies themselves. Real accessibility should share knowledge and results, rather than the all too common mentality in the field of absolute secrecy and stealth.

In working with this kit, you will find that electric propulsion can be done incredibly simply and cheaply with minimal resources. The electronics for the VAT0-DEMO is only a few

components, and the thruster head itself is quite simple. While triggerless vacuum arc thrusters are by far the simplest and cheapest type of electric propulsion you can build (which is one of the reasons why my first kit was developed around this tech), you can find that the same principles can be applied to literally any type of electric propulsion out there, and indeed this is exactly how I approach all forms of EP technologies.

Through all of my efforts, I want to show that there is fundamentally nothing that special about electric propulsion. It is not sci-fi magic, it is not some far out ultra-futuristic tech out of reach from everyday life, it is not something that only NASA or prestigious institutes can develop, it is not something you need millions of dollars in funding, or huge facilities, dedicated teams of top-level researchers, or advanced degrees to explore yourself or even innovate in. Electric propulsion itself is incredibly old, and all of the technologies you see used in the field are shared across many other fields and industries.

Whether you are a student, educator, researcher, developer in industry, or a DIY maker working out of a lab in the basement or garage just like AIS, more than anything, have fun with it. Experiment, hack, try new ideas, make changes, and don't be afraid to fail, think way outside of the box, and look beyond convention. It is only through countless failed experiments that we can really learn and become experts, and discover new ways to further advance what we work on.

Michael Bretti
Founder
Applied Ion Systems, LLC

I. INTRODUCTION

The AIS-VAT0-DEMO is the first ever off-the-shelf DIY educational electric propulsion learning kit in the field and on the market, allowing for electric propulsion to truly be accessible to the masses. Taking advantage of the extreme simplicity, low-cost, and wide operating range of micro vacuum arc thruster technology and leveraging the significant developments from the original AIS-VAT1-PQ Micro Vacuum Arc Thruster, the VAT0-DEMO opens the doors for anyone to start exploring electric propulsion technology and get hands on experience building and firing your very own, fully operation thruster based off of real flight-module technology.

One of the most powerful features of the VAT0-DEMO kit is the ability to leverage the wide operating range of pulsed vacuum arc sources. Because these sources can be run at both low and high vacuum, the DEMO kit allows anyone to begin experimenting with electric propulsion without the need for high vacuum pumping infrastructure, radically lowering the cost of the major barrier of entry into the field. The VAT0-DEMO has been fully vetted from 10^{-6} Torr all the way up to 200mTorr, and because of this wide operating range, only a basic rotary vane mechanical pump is required for backing the system if access to full high vacuum is not possible. At an operating pressure of 50mTorr, the VAT0-DEMO has been tested to over 300,000 shots from a single build at max rep rate (10 hours straight operation at 8Hz), with lifetime potential significantly higher due to the ability to reliably trigger and operate in a gas-enhanced mode using residual background gases in the chamber.

The VAT0-DEMO also uses the same exact thruster head and control architecture of the original VAT1 Series orbital-class thrusters, meaning that operation of the DEMO is exactly the same, and can be easily controlled with basic microcontrollers like the Arduino. The DEMO only requires 5V input with two logic commands, making for a simple and compact fully functional thruster perfect for demonstrating the fundamental principles of electric propulsion and opening up plasma thruster testing for the classroom and home use.

II. SPECIFICATIONS

- Type: Micro Triggerless Vacuum Arc Thruster
- Power: 2.5W
- Shot Lifetime (5×10^{-2} Torr): >300,000
- Shot Lifetime (10^{-6} Torr): 60,000
- Rep Rate: Single Shot to 8Hz
- Size: 50x50x21mm
- Fuel: Bismuth
- Inputs: 5V, GND, x2 Logic Pulses
- Mounting Holes: #2-56 or M2 bolts

III. KIT CONTENTS

A.) Electronics

- (x1) 5A48S Pico Electronics Power Supply
- (x2) Logic Level 450V IGBTs (*Digikey # FGB3245G2-F085CT-ND*)
- (x1) 220uF 100V aluminum electrolytic capacitor (*Digikey # 56-MAL202129221E3CT-ND*)
- (x1) Standard recovery 2000V 1A diode (*Digikey # S1V-13-FDICT-ND*)
- (x1) 1mH 3.915ohm inductor (*Digikey # 553-3607-1-ND*)
- (x1) JST B04B-XASK 4-pin connector (*Digikey # 455-1994-ND*)
- (x1) JST 0XAF-2S 12" jumper cable (*Digikey # 455-3066-ND*)
- (x1) AIS-VAT0-DEMO PCB
- (x1) Teflon coated wire

B.) Hardware

- (x5) alumina ceramic #8 0.188"ID x 0.5"OD washers
- (x4) Blue-anodized aluminum socket head screw #4-40 0.625"L
- (x2) 302 stainless steel compression springs 0.25"L x 0.25"OD x 0.21"ID
- (x2) graphite rods 0.125"D x 3"L

C.) Custom Thruster Components

- (x1) copper anode
- (x3) 99.9% Bismuth cathodes 0.25"D x 0.2"L
- (x1) Somos PerFORM 3D printed housing

D.) Cases

- (x1) Lykus mini hard case foam lined
- (x1) hard plastic vial (graphite rod storage)

IV. REPLACEMENT HARDWARE

- **Bolts:** McMaster-Carr # 98511A253
- **Ceramic Washers:** McMaster-Carr # 94610A225
- **Springs:** McMaster-Carr # 1986K65
- **Graphite Rods:** McMaster-Carr # 9121K111
- **Cable:** Digikey # 455-3066-ND
- **Bismuth Cathodes:** *Contact AIS for ordering spare cathodes*

V. TOOLS REQUIRED FOR ASSEMBLY

- Soldering iron
- Multimeter
- Wire stripper
- 3/32" hex wrench

- Helping hands (recommended)
- Cotton cue-tips (recommended)

VI. EQUIPMENT REQUIRED FOR TESTING

- Computer
- Arduino (or equivalent microcontroller)
- Adjustable 0-5V power supply (3W or higher)
- Vacuum system

VII. THRUSTER LAYOUT AND CONNECTIONS

The core circuit of the AIS-VAT Series thrusters, including the VAT0-DEMO, is fundamentally very simple with only a few components – a 5V to 48V DC/DC converter, protection diode, capacitor, inductor, and two IGBTs. While standard triggerless VATs in the field use just a single IGBT in parallel with the thruster head for triggering, AIS has developed and utilizes a unique dual IGBT topology for advanced triggering control. Due to the resistive graphite layer between the anode and cathode when power is applied, for normal triggerless VATs the thruster is always conducting power through the head, significantly increasing power losses. In addition, this provides poor repeatability and control across the thruster lifetime. In addition, performance is highly variable based on the resistive trigger layer, making repeatability and reliability of the thruster poor.

With the AIS dual IGBT topology, the first IGBT operates as the standard trigger switch, while the second IGBT sits in series with the thruster head between the cathode and ground. This prevents power from flowing through the thruster head when not firing, essentially completely disconnecting the thruster head between pulses. For operation, the second IGBT, known as the GATE, is first switched on, starting the charging cycle for the inductor. Once a pre-determined charge time has been reached, the trigger command for the first IGBT, known as the TRIGGER, fires the thruster, creating a high voltage inductive spike across the graphite trigger layer to initiate discharge. After a set discharge time, both IGBTs are switched off in sequence, and the process repeats for the desired repetition rate. Using this more advanced triggering method, significantly greater shot-to-shot repeatability and control can be achieved. In addition, power draw is significantly less, and conduction only occurs during inductive charging and capacitive discharge. In this topology, the capacitor always remains charged regardless in the thruster head is connected or not, ensuring stable voltage between shots.

Thruster power and control is simple, and the thruster itself consists of four inputs – 5V power, ground, TRIGGER, and GATE. These pins can be accessed on the rear of the thruster with the 4-pin JST B04B-XASK connector.

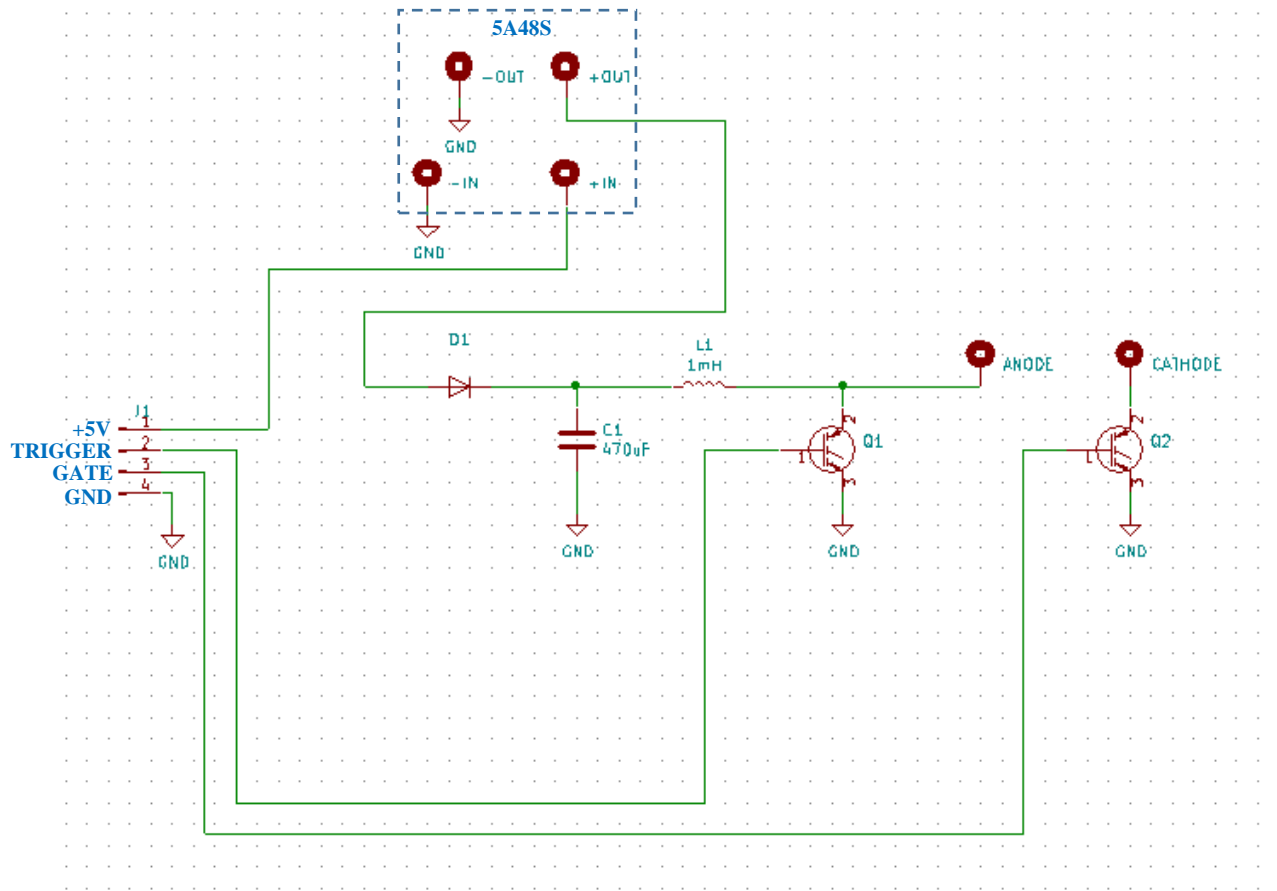


Figure 1: AIS-VAT0-DEMO thruster driver schematic.

CONNECTION	INPUT
PIN 1	+5V
PIN 2	TRIGGER
PIN 3	GATE
PIN 4	GND

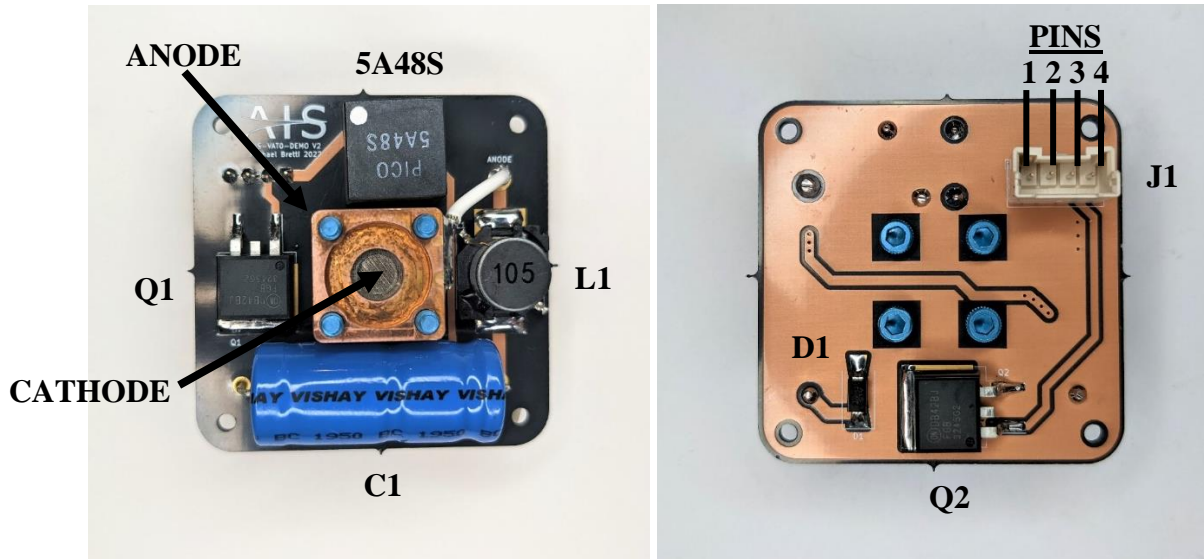


Figure 2: Front and back of a completed VAT0-DEMO assembly. Looking at the back of the thruster in the correct orientation, input pins on the connector correspond from 1-4 going from left to right.

Like the electronics, the thruster head is very simple, consisting only of a few components. The head of the VAT0 is actually exactly the same as the VAT1 Series orbital class thrusters, including a copper anode, graphite coated alumina ceramic washer, bismuth fuel cathode, contact spring, and Somos PerFORM 3D printed housing. The components are stacked together in order, bolted directly to the PCB, with a wire soldered to the anode for connection to the board, and a spring to make contact with the cathode to the board.

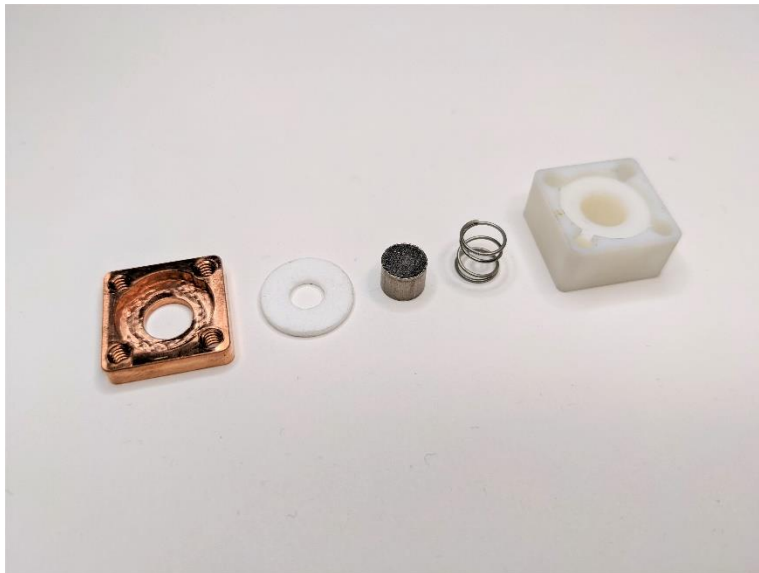


Figure 3: Components used for both the VAT0-DEMO and VAT1 Series thrusters. From left to right – copper anode, alumina washer, bismuth fuel cathode, contact spring, and Somos PerFORM 3D printed housing.

VIII. SOLDERING

Starting with the back of the board, solder the GATE Q2 IGBT and D1 diode.

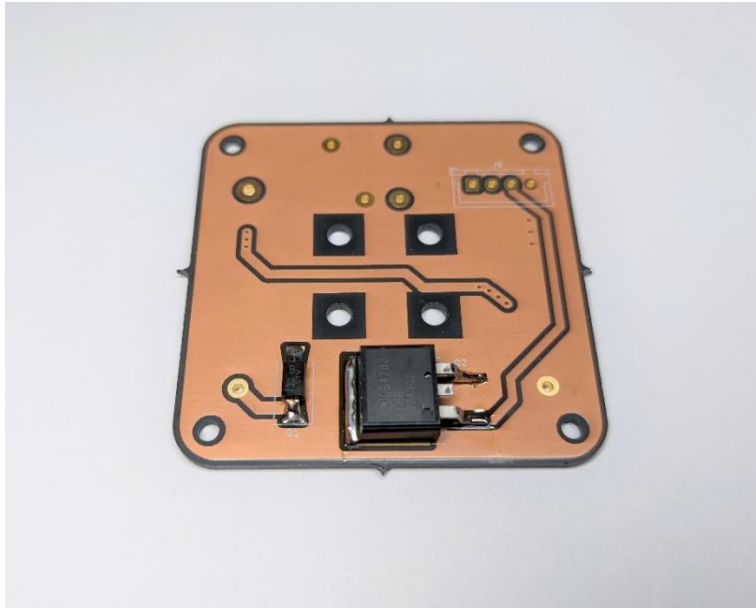


Figure 4: Soldering Q2 and D1 on the back of the board.

Next, flip the board over to the front and solder the Q1 TRIGGER IGBT, L1 inductor, C1 capacitor, and 5A48S Pico power supply.



Figure 5: Soldering Q1, L1, C1, and 5A48S on the front of the board.

****TIP:** It is often cited that standard electrolytic capacitors are not recommended for use in space applications or in a vacuum environment. However, for this kit, and general prototyping, experience at AIS has shown that these low-cost and ubiquitous capacitors are perfectly acceptable. Early prototypes for the VATI Series development used a wide range of standard electrolytic capacitors, and between the VAT0 and VAT1, AIS has not experienced a single electrolytic capacitor failure yet to date, even for extended operating times at full rep rate under high stresses of repetitive pulsed operation.

After, insert the J1 connector in the back of the board and solder the connections on the front. Note the orientation of the connector when soldering.

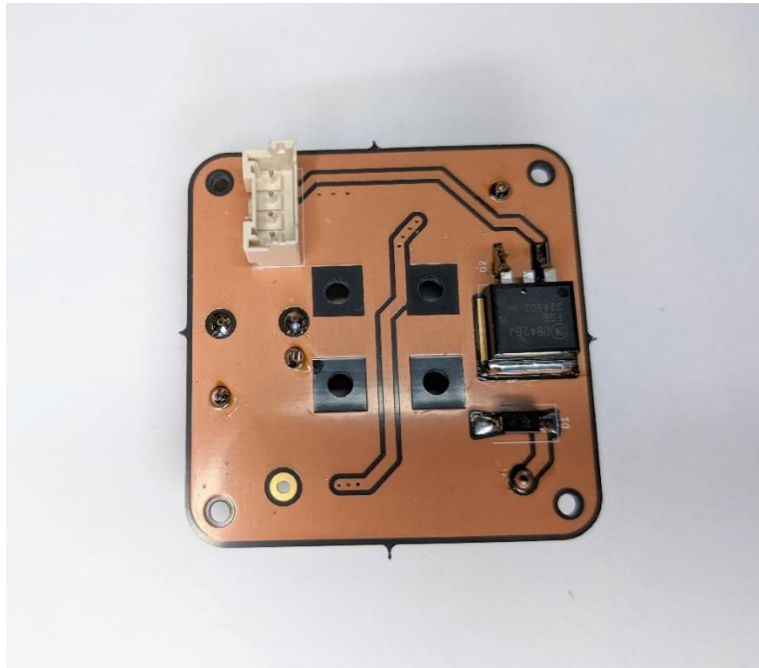


Figure 6: Soldering J1 on the back of the board.

Next, it is time to solder the copper anode. Take the provided section of Teflon coated wire, and strip one end. Place the copper anode vertically in a helping hands solder holder or similar tool, with one edge horizontal, and the machined face of the anode facing towards the left. Place the stripped wire in the other clip, and position the wire directly above the anode face to be soldered.



Figure 7: *Prepping the anode and anode connection wire for soldering.*

Tin the exposed wire, then tin the flat side face of the copper anode. With the copper anode tinned and still hot, bring the wire and anode together and finalize the solder joint.

****TIP:** *Be sure that excess solder does not drip onto the flat rear side of the copper anode, which must remain perfectly flat for proper contact with the graphite coated trigger washer underneath during assembly.*



Figure 8: *Soldering the anode and anode connection wire.*

After the copper anode is soldered and cooled down enough to handle, take the soldered board, 3D printed housing, and copper anode, and mount them together with two of the bolts, one on each corner. Make sure the wire is on the right side of the thruster facing towards the inductor.

****TIP:** Only two bolts are needed along with the anode and housing without the internal contact spring, cathode, or washer for this step.

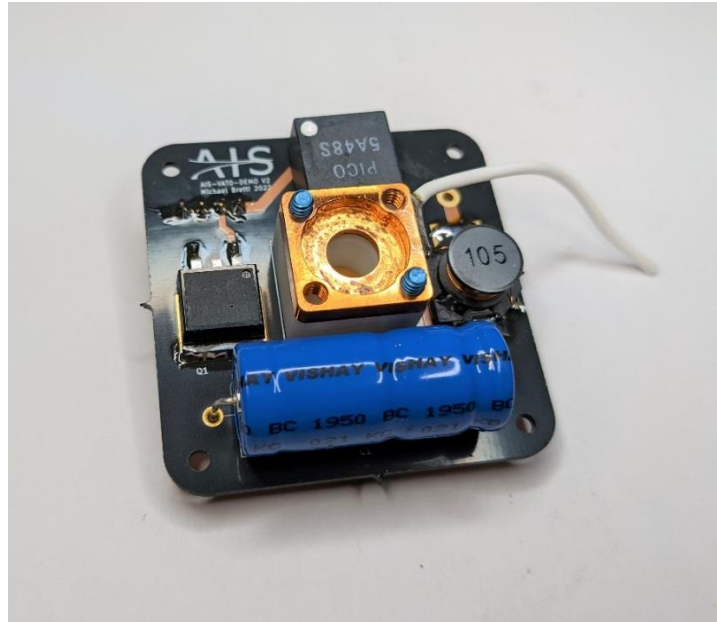


Figure 9: Bolting the anode and housing onto the board for wire length fit.

Trim and strip the other unsoldered side of the wire to prepare it for soldering to the board.

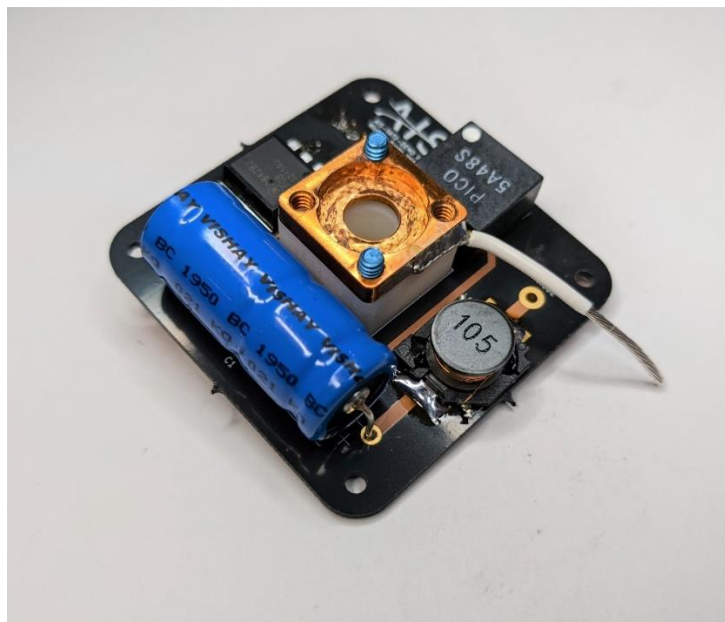


Figure 10: Trimming and stripping the anode wire for soldering.

Bend and insert the wire into the labeled ANODE hole. Be sure to leave enough wire that the wire length is minimized, but not so short that it is excessively tight. This step insures the anode is properly set and makes reassembly and rebuilds easier down the road.

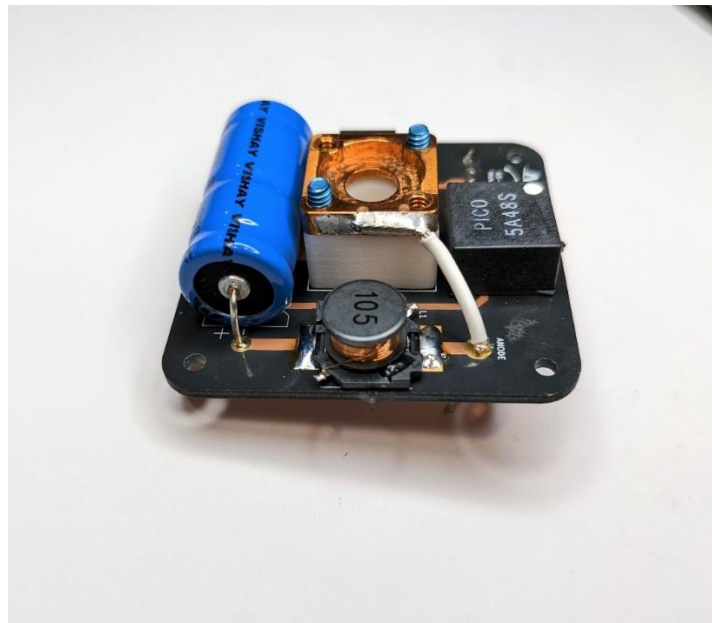


Figure 11: *Final anode wire length adjustment.*

Solder the wire and trim the excess.

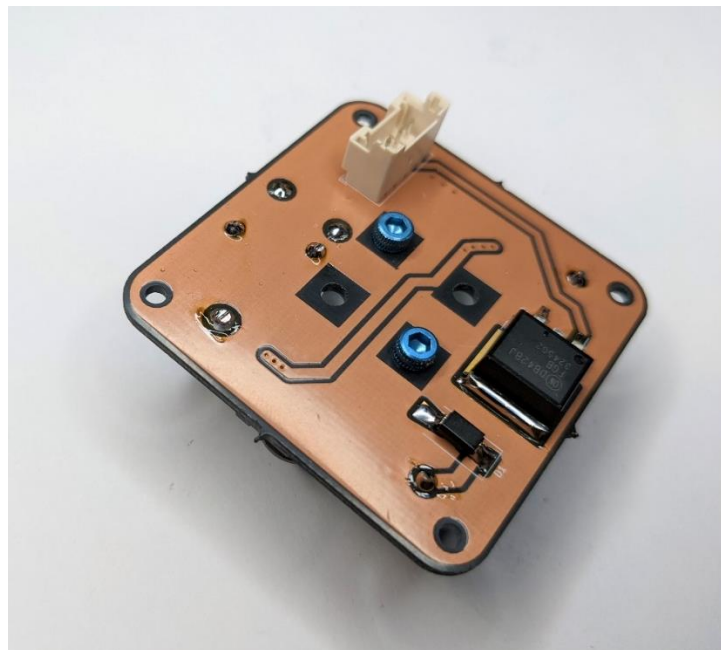


Figure 12: *Soldering the anode wire in place.*

After soldering the anode connection wire, remove the two bolts and the housing underneath the anode, and bend the anode up. This will help with assembly in the next steps. Make sure to clean

any flux residue from soldering after you are done. Congratulations, your VAT0-DEMO thruster is fully soldered and ready for final assembly!



Figure 13: Soldered anode with the housing removed, ready for final assembly.

IX. SETTING THE GRAPHITE TRIGGER LAYER

After the thruster has been fully soldered, it is time to set the graphite trigger layer on the ceramic washer. This is the single most important and crucial step, and ultimately decides thruster operation. The techniques used for setting the washer trigger layer are simple, but are the result of significant trial and error at AIS to determine the optimal method to ensure the best operation of the thruster.

First, take one of the provided graphite rods, and slightly sharpen on end. This will help for coating the washer bore more easily and precisely.

****TIP:** Only use pure graphite for coating the trigger layer. Other substances like carbon paint or pencil lead will result in significantly inferior performance, or may not work at all. Especially for pencil lead, which has clay and other binders in it, this will result in severely reduced lifetime and poor operation.



Figure 14: Prepping the graphite rod for trigger layer coating.

First, take one of the provided ceramic washers, and using the sharpened graphite rod, apply a solid, uniform coat around the inner bore of the washer. This provides the bridging contact across the washer surface between the anode contact layer and the cathode contact layer.

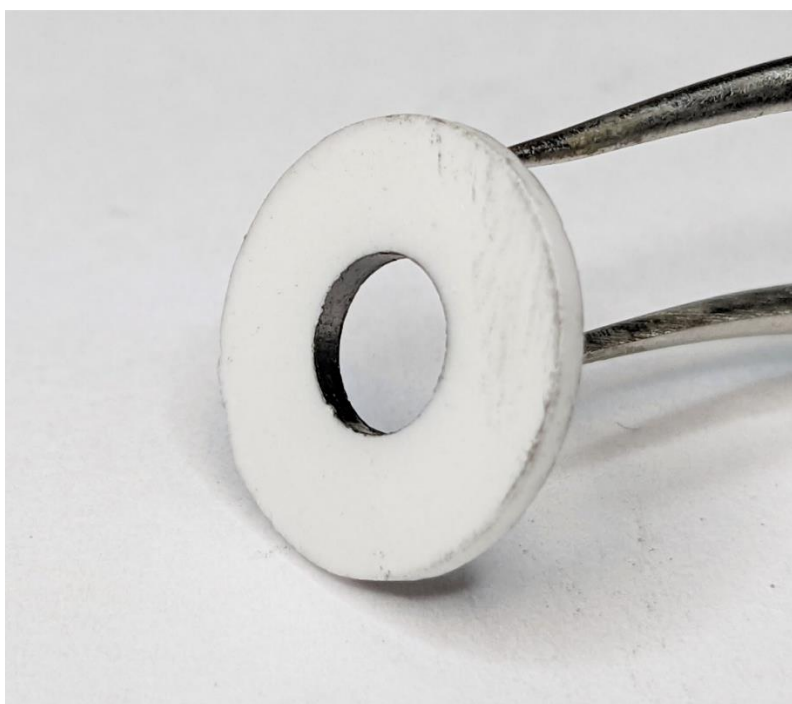


Figure 15: Coating the inner bore of the washer with graphite.

Next, flip the washer over to one side and apply a solid, uniform coat on the face around the inner bore, extending out ~3mm. Make sure to apply graphite at the corner where the bore and washer face meet to ensure continuity. This provides contact for the bismuth fuel cathode.

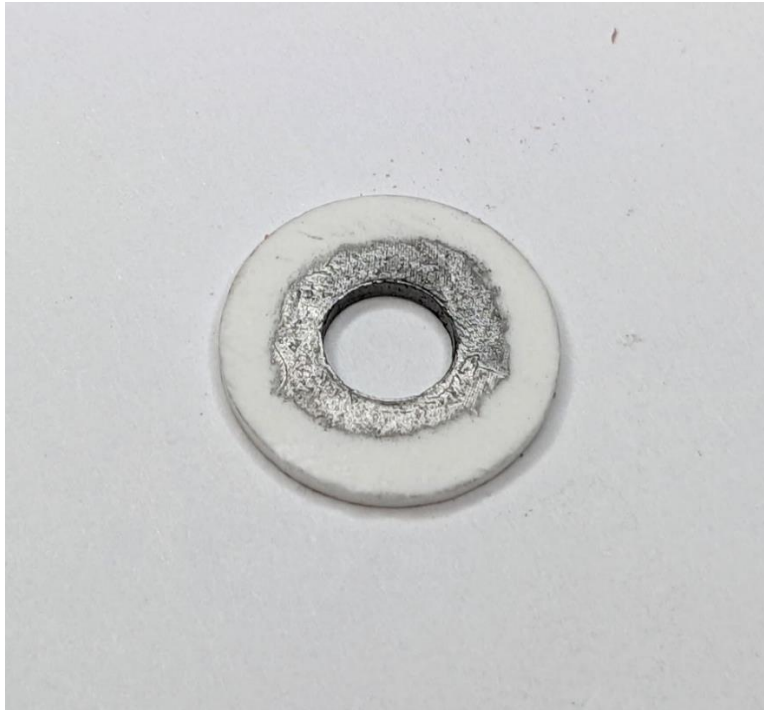
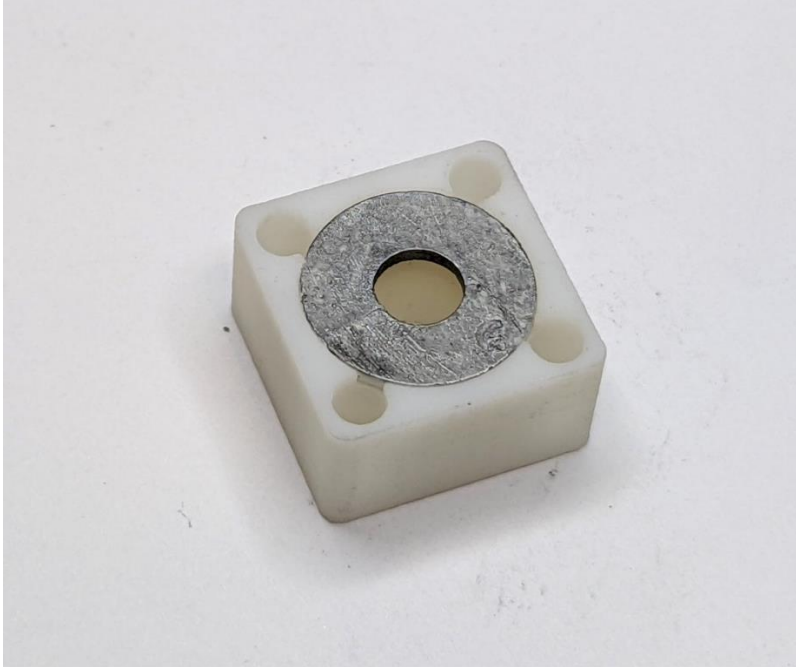


Figure 16: Applying the graphite contact layer for the cathode.

Next, place the washer in the 3D printed housing with the uncoated layer facing up to hold it and prevent rubbing off the bottom graphite layer you just applied. Apply a lighter, even coat across the surface. Make sure to apply graphite to the edge of the bore to ensure continuity from the top to bottom layers. This provides contact of the copper anode.

****TIP:** This is the most important and crucial step of the entire assembly, and largely determines thruster functionality. This layer should be even but lighter than the other layers, and serves as the bulk of the resistive surface for triggering.



***Figure 17:** Applying the anode contact layer on the top of the washer.*

Once this step is complete, you can move on to final assembly and layer adjustments for finalizing the graphite resistance to its proper value.

X. FINAL ASSEMBLY AND TRIGGER LAYER ADJUSTMENTS

To begin final assembly, first make sure the graphite coated washer is in the proper orientation in the thruster housing. Be sure not to touch the graphite, as it easily wipes off with physical contact.

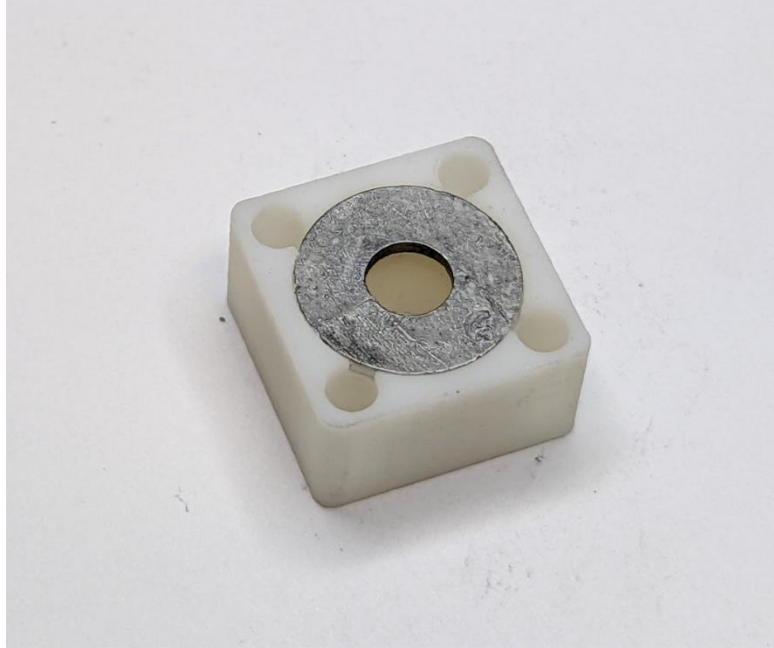


Figure 18: Place graphite coated washer into housing.

Carefully place the housing with the washer onto the copper anode, which should be already soldered to the thruster board at the proper length. Be sure the flat face of the copper anode meets with the lighter, fully coated side of the trigger washer.

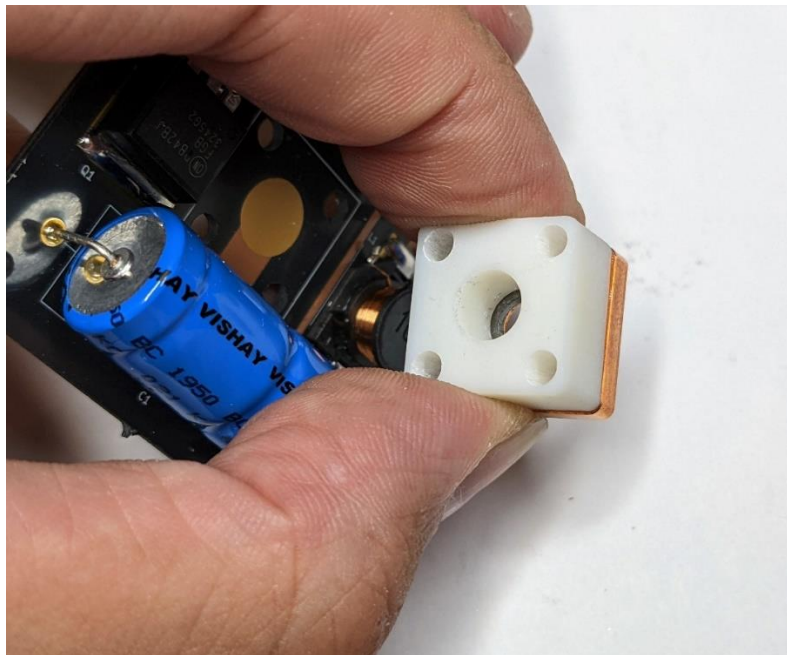


Figure 19: Pressing the housing and anode together to lock the washer in place.

Next, insert the bismuth fuel cathode into the rear of the housing. This will be pressed against the graphite contact layer with the spring in the next step.

****TIP:** Each bismuth fuel cathode can be used twice. After end of life has been reached, simply flip the cathode over to the fresh, unused side for the next rebuild.

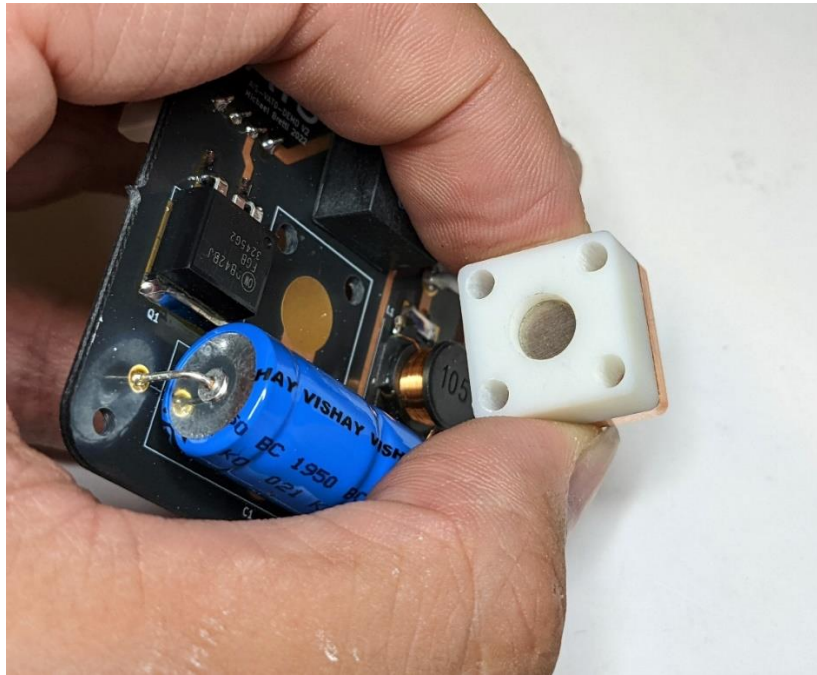


Figure 20: Inserting the bismuth fuel cathode into the rear of the housing.

Next, with the thruster head assembly still facing down, insert the contact spring after the cathode.

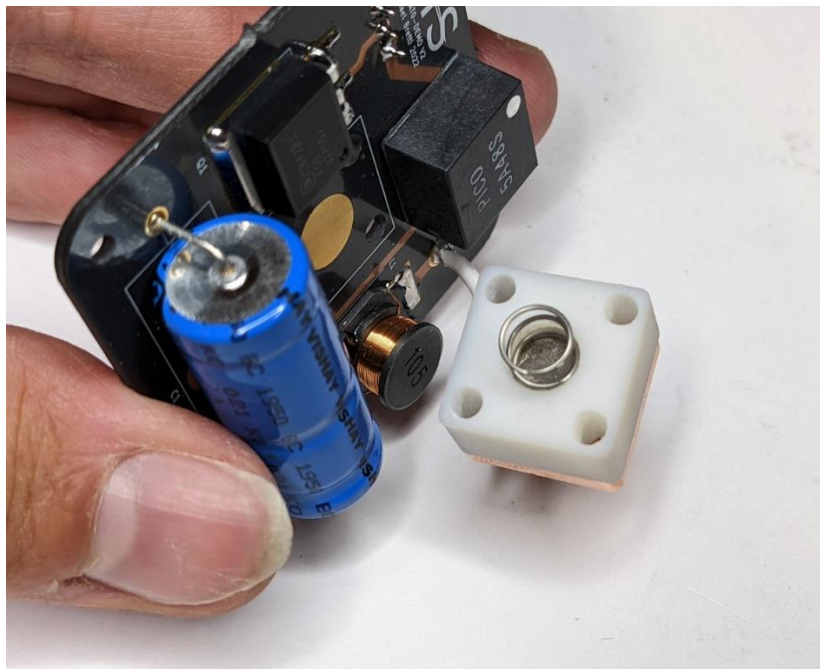


Figure 21: Inserting the contact spring into the housing after the cathode.

With the thruster assembly still facing down, very carefully press the thruster head together to the board. Make sure to keep it fully pressed evenly into the board until it is bolted down.

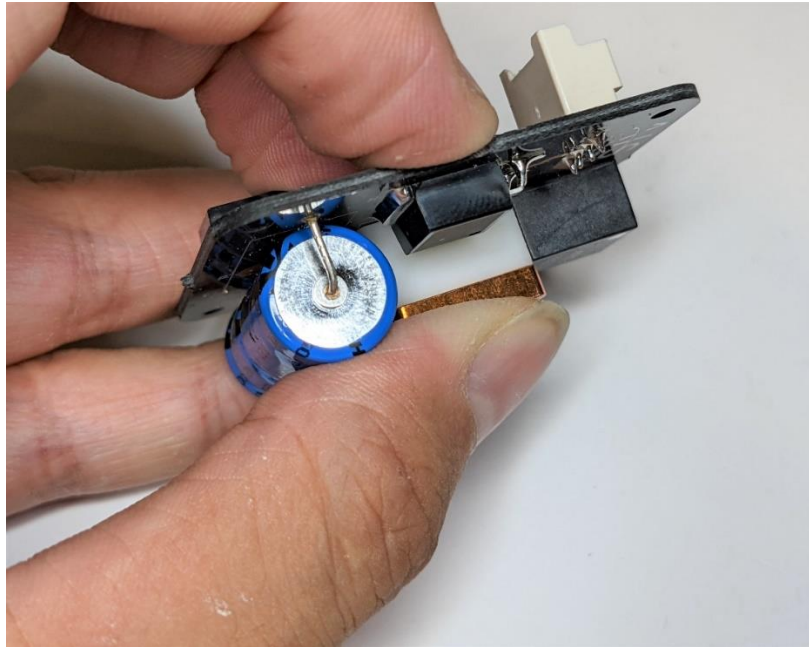


Figure 22: *Compressing the housing with spring loaded assembly together onto the board.*

Next, insert two bolts into any two opposite corners, and with the thruster head still fully pressed together, fully tighten the screws by hand. Once hand tight, very carefully tighten the bolts down with a hex wrench.

****TIP:** *Do not overtighten the bolts! The tolerances for the thruster head are very tight internally, and overtightening or uneven tightness could crack the ceramic washer. You will know this happens when you hear and feel a light “click” when tightening the bolts. For this step, only two bolts are needed until the washer resistance is finalized.*



Figure 23: Bolting the thruster head assembly onto the board with two screws for graphite resistance measurements.

Next, with your multimeter set to measure resistance, place one probe in contact with the copper anode, and the other probe in the center of the bismuth cathode. The ideal resistance should be between 1-2 kohms.

****NOTE:** Lower resistance will result in more power draw at full rep rate, but stronger initial plasma. Higher resistance will result in lower starting power draw at full rep rate. Under 1kohm, the resistance will be too low and the thruster will not fire properly. If the resistance is too high, much more than 2kohms, there will be less trigger spot formation on the graphite layer, and weaker plasma due to the increased resistance. Based on the operation of the thruster, the failure mode at the end of life is open circuit due to depletion of the exposed graphite trigger layer over time.



Figure 24: Measuring graphite layer resistance between anode and cathode.

If the resistance is between 1-2 kohms, congratulations! Your thruster is ready for final assembly and bench checks. However, setting the graphite layer is the most challenging and tedious part of the build, and takes a lot of practice to get the right feel. You will most likely need to make some adjustments based on the resulting layer resistance, and it often takes more than one try to get exactly right.

If the measured resistance between the anode and cathode is slightly too low (800-900 ohms), you can make a minor adjustment by taking a clean cotton cue tip and very lightly swabbing the exposed graphite layer to increase the resistance.

****TIP:** *It is better to start too high resistance and try to add graphite than too low and reduce it.*

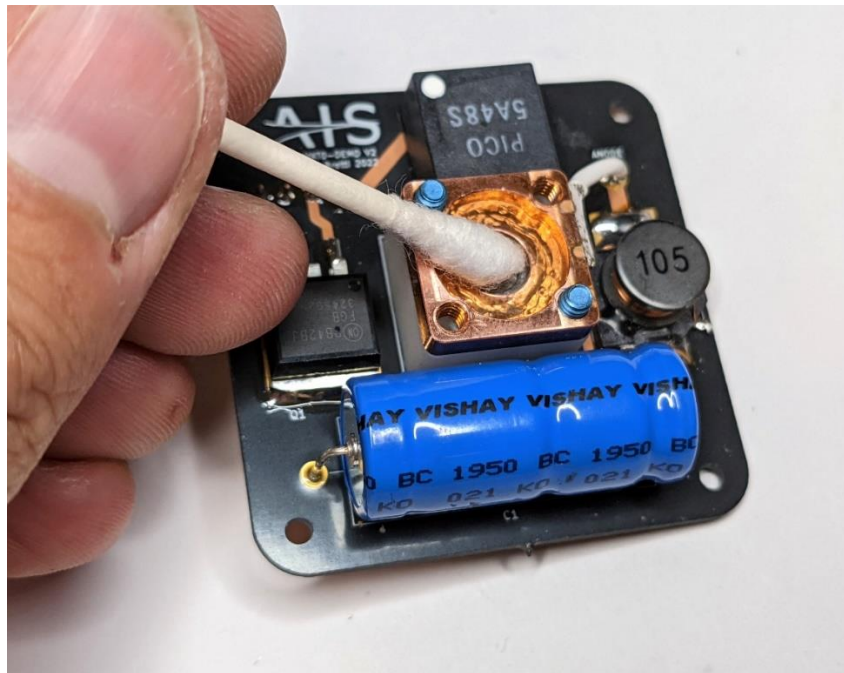


Figure 25: *Adjusting the graphite layer resistance if slightly too low by swabbing with a cue-tip.*

Conversely, if the graphite layer resistance is a bit too high (2.1-2.2 kohms), you can lower the resistance by taking the sharpened graphite rod and rub additional graphite on the exposed washer.

If the graphite resistance is too high however, you will need to disassemble it and apply more graphite to the front face of the washer. This should be done evenly across the surface.

Once you have achieved the proper resistance and are happy with the results, you can add the remaining two bolts and carefully tighten down the thruster head. Once all four bolts are tightened, perform one final measurement between the anode and cathode to ensure you are still within the target range resistance. If you are, congratulations! You have officially fully assembled your very own micro vacuum arc thruster! You can now move on to final bench checks before vacuum testing!



Figure 28: Fully assembled VATO-DEMO after final graphite layer adjustments and full tightening of the mounting bolts.

XI. BENCHTOP TESTING

Once the thruster is fully assembled with the correct graphite layer resistance, it is time to run final bench checks on the thruster to make sure everything is functional before firing it in vacuum. Connect the provided cable to the plug in the back of the thruster, making sure to wire the correct pins to the proper inputs. Clip your multimeter leads to ground and the copper anode. With an adjustable DC power supply, slowly raise the input voltage up watching the multimeter. The onboard Pico supply should turn on past 0.7V, with output voltage proportional to the input voltage. Raise the voltage up, making sure you are seeing a rise in anode voltage.

****TIP:** *since the thruster is not firing at this point, and there is light loading on the Pico supply, the output voltage can exceed more than 50V before you reach the full 5V input. It is therefore recommended to only raise the input voltage up enough until you confirm output voltage on the anode at around 35-40V.*

After you verify output voltage, it is time to run atmospheric pulse checks on the thruster. The following code is used at AIS to operate AIS VATs in single shot mode for testing. Load the

following code for your Arduino microcontroller, making sure the TRIGGER and GATE pins are wired correctly. Dim the lights, and be sure you have clear view into the thruster bore to watch for the trigger arc breakdown pulse. With the anode voltage at around 35-40V volts (high voltage is not needed at this stage), and watching into the thruster head, input a “1” command into the serial monitor input screen to initiate a trigger pulse. You should see multiple small surface sparks around the exposed graphite layer, along with an audible “click” noise. If you see the sparks and hear the click, congratulations! Your thruster is fully functional and ready for vacuum testing!

*****TIP: Do not fire the thruster too many times in air! Only a single shot in atmosphere is necessary to verify full functionality of the system. While you can do a few quick pulses, too many pulses will burn the graphite layer, severely degrading it rapidly and cause premature failure.***

```
int pulse = 14;
int gate = 15;

void setup() {
  pinMode(pulse, OUTPUT);
  digitalWrite(pulse, LOW);
  pinMode(gate, OUTPUT);
  digitalWrite(gate, LOW);
  Serial.begin(9600);
  Serial.println("INPUT 1 TO FIRE");
}

void loop() {

  if (Serial.available()){
    int state = Serial.parseInt();

    switch(state){
      case 1:
        delay(100);           //trigger delay
        digitalWrite(gate, HIGH); //gates the thruster to ground to begin inductive charging
        delayMicroseconds(4600); //sets inductor charging time
        digitalWrite(pulse, HIGH); //trigger pulse for firing
        delayMicroseconds(100); //sets trigger pulse time
        digitalWrite(pulse, LOW); //trigger off
        delayMicroseconds(3000); //sets time for main discharge
        digitalWrite(gate, LOW); //thruster gated off
        Serial.println("FIRE!"); //serial monitor confirmation of completed firing cycle
        break;
      }
    }
}
```

XII. THRUSTER OPERATION

If you have made it this far with your VAT0-DEMO system, it is finally time to see your thruster in action! Load your thruster into your vacuum chamber, making sure to properly wire the thruster to the right electrical feedthrough connections based on your chamber setup. Once the thruster is loaded up and wired, you can begin pump down for ignition testing!

Because of the extremely wide operating range of vacuum arc plasma sources, AIS has developed tested the VAT0-DEMO to operate across a wide range of pressures, making propulsion testing significantly more accessible based on what vacuum infrastructure you have available. Regardless if you can only achieve rough vacuum, or have the capabilities for full high vacuum testing, the VAT0-DEMO will fire the same. However, depending on the pressure regime you are operating at, lifetime and plume dynamics will vary dramatically.

The following code is used at AIS for testing and operation of the VAT0-DEMO at all vacuum levels. The first delay in the main loop sets the repetition rate. The VAT0-DEMO can be operated anywhere from single shot mode up to 8Hz. While the thruster can be pushed to higher rep rates, it is recommended to keep the maximum rep rate to 8Hz (set as a delay of 125ms).

```
int pulse = 14;
int gate = 15;

void setup() {
  pinMode(pulse, OUTPUT);
  digitalWrite(pulse, LOW);
  pinMode(gate, OUTPUT);
  digitalWrite(gate, LOW);
}

void loop() {
  delay(250);           //sets repetition rate (4Hz in this example with 250)
  digitalWrite(gate, HIGH); //gates the thruster to ground to begin inductive charging
  delayMicroseconds(4600); //sets inductor charging time
  digitalWrite(pulse, HIGH); //trigger pulse for firing
  delayMicroseconds(100); //sets trigger pulse time
  digitalWrite(pulse, LOW); //trigger off
  delayMicroseconds(3000); //sets time for main discharge
  digitalWrite(gate, LOW); //thruster gated off
}
```

To start up the thruster for the very first time, it is recommended to first power on the Arduino with the above loaded code and begin the trigger command sequence without main power applied to the thruster. Next, turn on your adjustable power supply, and begin slowly raising up input voltage. At some point, you should see plasma pulses coming from the thruster. Continue raising up voltage until you reach the maximum 5V input for full thruster operation.

****TIP:** For your very first operation, especially your first time building or rebuilding the thruster, it is recommended to start up the thruster at a low rep rate, maybe 1-2Hz first, slowly bringing the system up to full power. Once it is operating at the full 5V input, you can go ahead and modify the thruster control code and upload the code as it is firing. Once you get it firing at full input voltage, you can cycle power on and off, or change the rep rate during operation whenever you like, and do not need to slowly raise up power each time after. The thruster can be cycled from no power to full power whenever at this point.

In high vacuum (10^{-5} Torr or less), the thruster will behave very similarly to orbital conditions, with both plume expansion dynamics and lifetime. At this level, you can take thrust and performance measurements. For high vacuum levels of 10^{-5} Torr and lower, lifetime is around 55-60k shots.

****TIP:** Operating the thruster a number of times, and getting a feel for properly setting the graphite layer, you will begin to see patterns for operation. At the beginning of the test, power draw will be higher. When you start reaching towards the end of thruster lifetime, power will begin to drop as the graphite layer resistance increases over time. Typically, you will see power fluctuations around 30-40k shots. This is normal. When you start reaching over 50k shots, and you are running at the full 8Hz rep rate, the plume output will be much weaker, and may start to struggle to fire reliably after each shot. When you start to observe this happening, reduce the rep rate by half to 4Hz. When the thruster begins to struggle again, reduce the rep rate to 2Hz, then 1Hz, until plume output becomes too weak. This typically happens somewhere between 55-60k shots, though can vary depending on how you set the graphite layer.



Figure 29: Typical bismuth exhaust plume during standard operation at high vacuum (10^{-5} Torr or lower).

At rough vacuum, the thruster will fire and operate the same, however there will be some very distinct and unique operating modes at this level. Between 1mTorr and 1Torr, you will observe a

wide range of variation in plume behavior and expansion, which will look very different from behavior at high vacuum. In addition, there will be several unique phases as the thruster is fired longer. For the following pictures and examples, the thruster was operated at 50mTorr, and in general, for rough vacuum operation, it is recommended to first start around the 50mTorr level.

For the first phase of operation, the thruster will fire like typically, operating solely on the bismuth cathode fuel like in high vacuum. However, depending on your operating pressure, the resulting plume will be very different. At levels around 50mTorr for example, you will see plasma glow from the thruster head itself, but there will be an expanded plasma ball about 1-2cm away from the thruster head. As pressure is further increased, this expanded and separated plume will begin moving closer and closer to the thruster head. At several hundred mTorr, the plume will be a tightly concentrated ball at the output. This significant difference in observed plume expansion is due to the accelerated plasma interacting with the residual background gas. At lower pressures, the mean free path increases, while at higher pressures, it decreases. At high vacuum, you will see a light, diffuse glow from the thruster head. At low mTorr levels, you will also see this glow, but also the separated, expanded plume interacting with the background gas away from the thruster head. As pressure increases, the mean free path will force this expanded plume closer and tighter to the head, and instead of being a diffuse plume, it will become a tighter and more concentrated ball at the output.

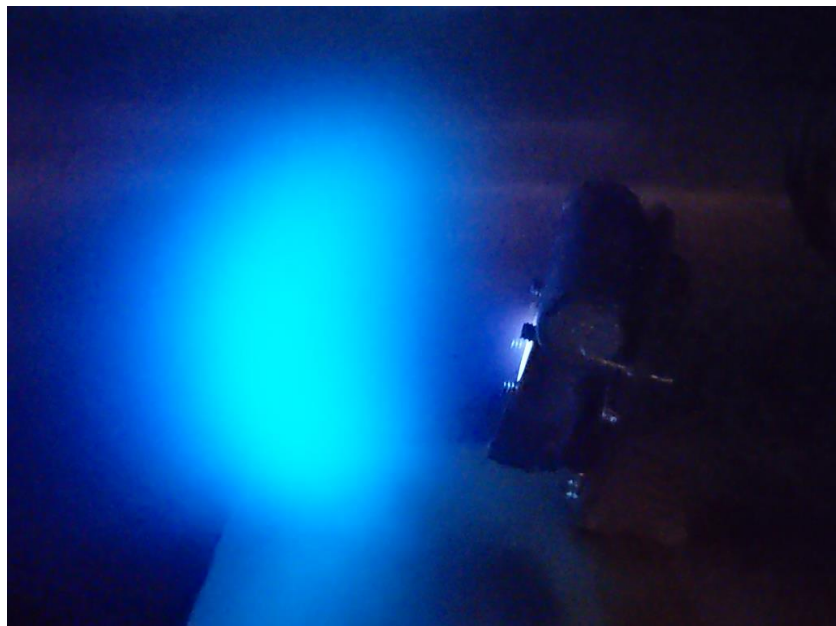


Figure 30: Typical bismuth plasma plume at rough vacuum (50mTorr) during phase 1 of lifetime at rough vacuum (0-40k shots).

At around 40-50k shots however, you will begin to see an interesting transition in operation. At high vacuum, the plume will gradually begin to grow weaker. However, at rough vacuum (tens of mTorr range), you will see residuals of the light blue expanded exhaust from the bismuth fuel, but also a bright purple-pink plasma at the thruster head simultaneously. As the graphite layer changes resistance, and gets towards the typical end of life in high vacuum, with the presence of residual gas now at the thruster head, and weaker ionization of the bismuth, you now begin to see

more ionization of the residual air in the chamber. This is a unique gas-enhanced transitional mode.



Figure 31: Typical transitional phase exhaust plume showing bismuth plasma expansion (outward crescent blue plume) and partial gas-enhanced operation with air plasma (bright inner plume) at 50mTorr at extended operating lifetimes.

As you continue to operate the thruster for longer periods of time, far in excess of the standard lifetime at high vacuum levels, the diffuse expanded blue plasma ball will disappear altogether, replaced with a very bright and intense plume more purple or pink in color (depending on the background gas composition and ionization level.) The thruster has now transitioned into what AIS refers to as a gas enhanced mode of operation. The bismuth fuel cathode and graphite layer are still breaking down and ionizing, but with the much higher resistance, bismuth ionization is significantly reduced, but as a result, can still result in significant ionization of the background air. In addition, AIS has discovered that gas enhanced operation of triggerless vacuum arc thrusters actually leads to a significantly increased operating lifetime, with radical reduction of graphite layer depletion. This special gas enhanced mode of operation allows the VAT0-DEMO to be operated well beyond its rated high vacuum “orbital” lifetime to hundreds of thousands of shots. The principle of gas enhanced operation is also currently being leveraged with the AIS-GEVAT Series orbital class thrusters.



Figure 32: Full gas enhanced mode of operation with air plasma operation (50mTorr).

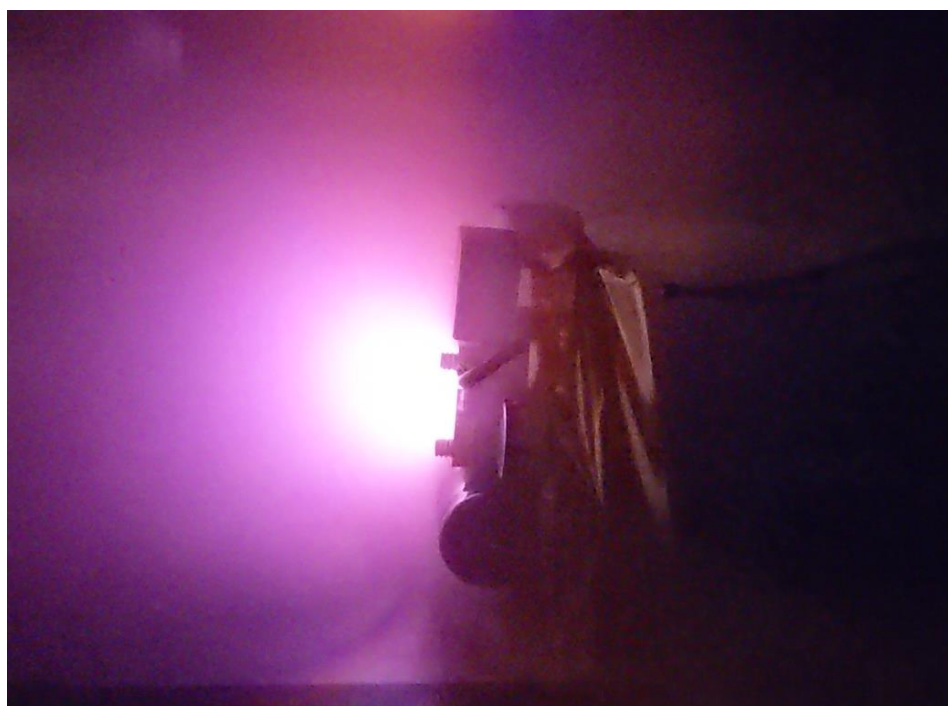


Figure 33: Example of full gas enhanced mode of operation at 50mTorr with different background air concentration.

XIII. IDEAS AND EXPERIMENTS TO EXPLORE

Once you have a fully built and functional thruster as well as a vacuum system for testing, the doors will be wide open to explore new ideas and experiments! After firing your thruster and exploring the different modes of operation, try out some different experiments! And share your results with the community!

Modifications: increased capacitance, increased inductance, changing pulse timings, different cathode materials (titanium is easy to use, aluminum can be very difficult at these low power levels)

Measurements (High Vacuum): thrust via micro ballistic pendulum, ISP, time-of flight (advanced), plume divergence

Interesting Experiments: pulsed sputter deposition (using the VAT0-DEMO as a pulsed vacuum arc sputter gun), gas enhanced operation with different background gases (low vacuum), plume spectroscopy

XIV. TROUBLESHOOTING

PROBLEM	POSSIBLE CAUSES
High power draw, no ignition	- Graphite layer resistance too low
Very low power draw, weak or no ignition	- Graphite layer resistance too high - Reaching thruster end of life
Very low or no voltage on the output of the Pico supply	- Pico power supply failure
Full anode voltage, proper graphite resistance, no triggering, excessive power draw during triggering	- TRIGGER and GATE pins swapped
Full anode voltage, proper graphite resistance, no triggering	- Damaged IGBT
Full voltage on the output of the Pico supply, no voltage on anode or capacitor	- Diode is soldered in reverse