INTERNSHIP REPORT: VACUUM ARC THRUSTER

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Abstract

This report presents work that had been done during the internship period between 19 November 2018 and 31 January 2019 at ZAP Lab, National Cheng Kung University (NCKU), Tainan, Taiwan. The report composes of 7 main topics. Introduction summarizes VAT's importance and its basic information. Then, in background topic will explain the deeper information of VAT and circuit used in the thruster system. The VAT and circuit design concept includes 3 VAT and 2 circuit which were designed as only a concept. On the other hand, the other 3 VAT that were designed and manufactured were shown in VAT part. After that, experimental setup and results of all 3 VAT were described. The small, ring and plate VAT can discharge continuously 20 times, 200 times and 1,200 times, respectively and the maximum total discharging times among these three is around 3,000 times for the plate VAT. In the end of the report, discussion was given and divided into 5 subjects that stopped VAT discharging.

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1. Introduction

In the present world, exploring space has become increasingly popular which leads to the development of numerous technologies that has lower cost, better performances, and longer lift time. Therefore, microsatellites become one of the fastest-growing development and it is used in many space missions. One of the main reasons of increasing of advancement in microsatellites is the cost of launching, it is lower than ordinary satellites or space rocket because of weight and dimension. The prime example is CubeSat which had the cubic geometry with small dimension about 10 cm × 10 cm × 10 cm. According to limited energy in space flights, electric propulsion comes in because the electric power can be recharged by the solar power which makes the power source of microsatellites has never run out as long as there is sunlight. Additionally, the electric propulsion has smaller size of the propellant compared with chemical propellant, both liquid and solid type; the propellant used in electric propulsion varies with the type of thruster and can be a rare gas, liquid metal, solid metal, and conventional propellant. Moreover, the propellant is ejected up to twenty times faster than from a classical chemical thruster and therefore the overall system is many times more mass efficient. Meanwhile, the electric propulsion produced a tiny amount of power compared with other propulsion systems, but it can provide a small thrust for a long time. For instance, the thrust produced by EP is in micro to milli Newton. However, this value is enough to drive the microsatellites through the space missions for long-duration applications.

Figure 1.1 *Cubesat [1]*

Moreover, Most of the Electric Propulsion System (EPS) used the electric power to transform a propellant into a plasma state and accelerated it by electric field, magnetic field, or pressure gradient. The plasma state is one of the four fundamental states of matter, distinct from solid, liquid, and gaseous states. Plasma contains a cloud of protons, neutrons, and electrons. The uniqueness of the plasma state is due to the importance of electric and magnetic forces that act on a plasma in addition to such forces as gravity that affect all forms of matter. As a result, electric propulsion system combined these properties of plasma and specific forces such as magnetic field, electric field, or pressure gradient to produce thrust for the system.

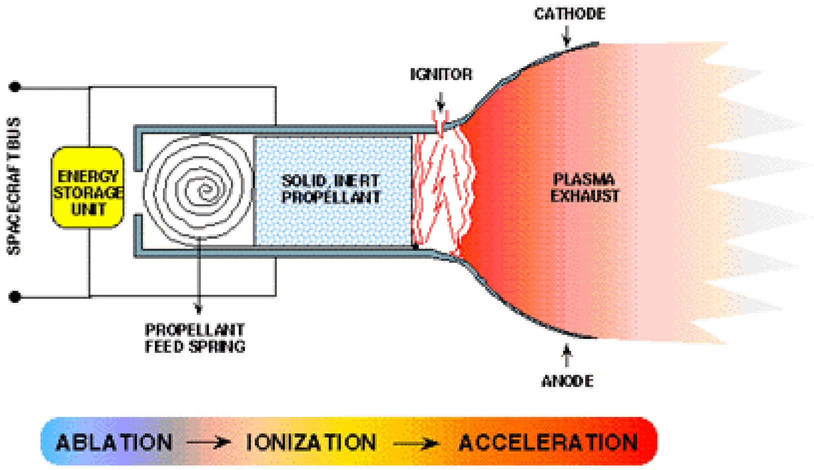


Figure 1.2 *Schematic of a Pulsed Plasma Thruster (PPT) [2]*

The schematic of a Pulsed Plasma Thruster (PPT) – the operation of this system is that the high voltage across propellant causing ablation and sublimation of the propellant. The heat generated to this arc causes the resultant gas into a plasma, thereby created a charged gas cloud. Due to the force of the ablation, the plasma is propelled at low speed between two charged plates (an anode and cathode). Since the plasma is charged, the fuel effectively completes the circuit between the two plates, allowing a current to flow through the plasma. This flow of electrons generates a strong electromagnetic field which then exerts a Lorentz Force on the plasma, accelerating the plasma out of the PPT exhaust at high velocity.

2. Background

2.1 VAT

To achieve high efficiency orbiting or travelling, the electric propulsion is introduced due to its size and energy required [3] unlike the conventional combustion propulsive systems that consume distinctively higher energy to travel the same distance. The electric propulsion provides several choices of the propulsive systems [3, 4]. One of interesting systems is Vacuum Arc Thruster (VAT). The VAT is based on the idea of using the impulse of vaporized solid propellant which, in the VAT, normally is the metal electrode that will be accelerated to very high velocity - to create the momentum thus the thrust to the micro-satellite.

The VAT composes of three main-components; cathode, anode, and insulator. The cathode and anode have main role as the electric powerplant for the VAT while the insulator acts as the tiny wall to prevent the cathode and anode accidentally electrified yet keeps them close to be easily ignited when needed. The options of the VAT design depend on the researchers' perspective. It could be briefly categorized in three aspects – the material used, the geometry, and the alignment.

Beginning with the material, the material of the VAT is crucial, especially in the cathode and anode, because the difference of the electric, plasma, and thermal properties in each material. Some combination of the cathode-anode materials might result in a distinctive change in performance or limits, as shown in the Table 2.1.

PREDICTED PERFORMANCE OF VATS AND VAITS

Species	Mass Flow Rate, $\dot{m}_t$ (mg/s)	Vacuum Arc Thruster: Thrust T (mN)	I_{sp} (s)	Total Efficiency η	Thrust-to-Power T/P (μN/W)	Vacuum Arc Ion Thruster: Thrust T (mN)	I_{sp} (s)	Propellant Efficiency η_u	Ion Production Cost ϵ_B (eV/ion)	Total Efficiency η	Thrust-to-Power T/P (μN/W)
Li		1.14			4.85	7.68			367		8.77
C	0.17	1.43	859	0.020	4.84	10.09	5949	0.468	463	0.320	10.78
Mg	0.31	2.16	709	0.040	11.47	11.42	3689	0.338	294	0.254	13.79
Al	0.28	1.66	604	0.021	7.03	11.30	4044	0.370	369	0.260	12.90
Si		2.15			7.81	11.11			430		12.14
Ca		1.99			8.48	9.56			367		10.92
Sc						10.92			298		13.14
Ti	0.3	2.70	924	0.058	12.77	14.04	4689	0.522	333	0.385	16.46
V		3.17			14.10	9.72			352		11.24
Cr	0.2	3.27	1666	0.117	14.28	14.26	7143	0.810	358	0.585	16.41
Mn		2.69			12.25	14.21			344		16.52
Fe	0.48	2.50	531	0.029	11.01	15.95	3329	0.424	355	0.306	18.40
Co	0.44	2.77	643	0.038	12.17	16.75	3815	0.514	356	0.367	19.30
Ni	0.47	2.51	544	0.033	12.24	16.61	3540	0.471	320	0.347	19.65
Cu	0.35	2.73	794	0.045	11.65	15.98	4575	0.585	366	0.418	18.29
Zn	3.2	3.91	125	0.015	25.24	21.26	666	0.113	242	0.089	26.74
Ge		3.78			21.62	17.38			273		21.33
Sr						13.78			281		16.80
Y	0.45	3.85	872	0.091	21.27	18.06	4020	0.575	283	0.441	21.99
Zr	0.53	3.83	737	0.059	16.38	17.20	3251	0.443	366	0.319	19.68
Nb		3.31			12.27	9.36			422		10.29
Mo	0.36	3.77	1066	0.067	12.85	16.16	4498	0.578	458	0.389	17.32
Pd		6.13			28.80	15.99			333		18.74
Ag	1.4	4.30	317	0.029	18.43	20.45	1463	0.239	369	0.170	23.34
Cd	6.2	4.00	66	0.008	24.99	26.51	428	0.091	250	0.071	33.13
In		3.25			18.59	23.30			273		28.59
Sn	2.95	4.02	139	0.016	22.95	25.30	859	0.174	273	0.133	31.05
Ba		3.18			17.36	17.07			286		20.75
La		3.02			17.58	15.47			269		19.05
Ce		3.21			17.93	16.35			280		19.96
Pr		3.76			18.81	15.37			313		18.30
Nd						16.13			308		19.27
Sm		3.61			24.71	16.78			228		21.35
Gd	0.55	3.65	677	0.056	16.90	24.51	4466	0.862	338	0.638	28.64
Dy		3.61			18.23	16.15			309		19.27
Ho		4.11			20.54	16.27			313		19.37
Er		4.01			21.12	15.97			297		19.24
Yb						18.69			225		23.84
Hf		3.87			15.92	13.29			380		15.05
Ta	0.56	4.70	861	0.070	16.49	22.64	4050	0.732	448	0.493	24.42
W	0.55	5.80	1078	0.096	18.24	22.12	4029	0.711	498	0.464	23.06
Ir						15.19			383		17.16
Pt		4.40			19.57	19.57			352		22.62
Au		4.00			20.32	20.76			308		24.80
Pb	5.1	4.71	94	0.014	30.39	32.36	636	0.164	242	0.129	40.70
Bi		5.18			33.20	36.00			244		45.23
Th		2.62			11.27	7.35			364		8.42
U		5.72			24.33	13.93			367		15.92

Table 2.1 *Predicted performance of VATs and VAITs in each material [3]*

Since the thrust will be generated from the ionization of the electric reaction between cathode and anode, the electrical parameters will involve significantly in the systems. The most important parameter of cathode ionization in this system is the input voltage. Different material requires different voltage to initiate the ionization state which results in the thrust generation from plasma plume - 700 V for the copper-copper electrode for example. In summary, the choices of electrode material preference directly affect related components in the circuit and might result in the size of circuit in use.

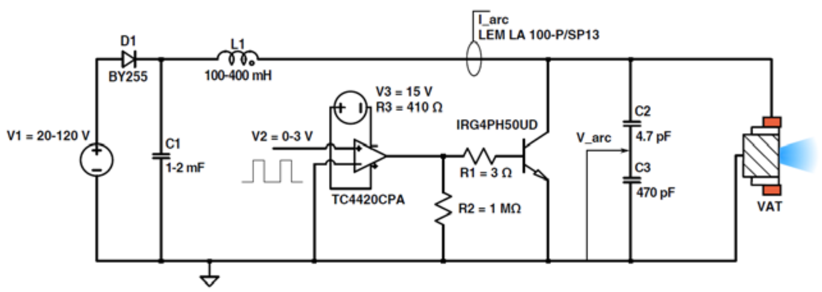


Figure 2.1 *An example of VAT circuit used in the experiment system [3]*

Next, the geometries of the VAT, which mainly has 3 shape being commonly used, are coaxial, plate, and hollow as follows:

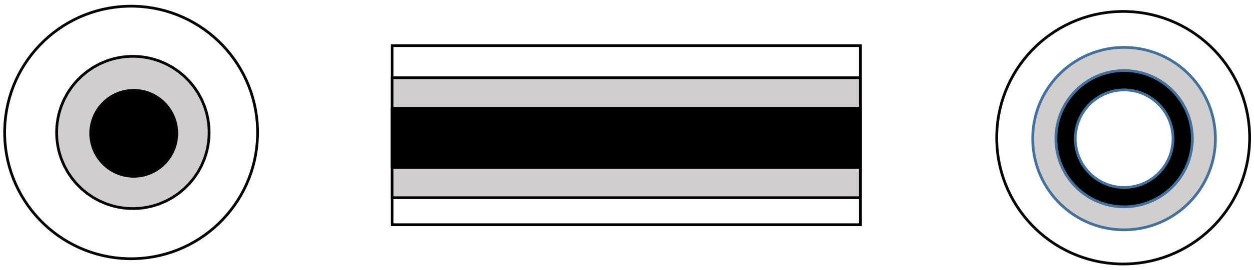


Figure 2.2 *Common shape of VAT from left to right – Coaxial, plate, and hollow (white and black for electrode, grey for insulator) [3]*

Each geometry of the VAT gives different advantages to the user such as ease of manufacturing and also might create different result of thrust created when in operation. However, some configurations of the VATs are rarely published and insufficient information was given out which leads us to the further investigation in our research.

Last but not least, the alignment of the electrodes. One coaxial VAT research [3] has shown that there is an alteration of the cathode-anode alignment, which will be called ***"Inverse VAT configuration"*** for our research. The researchers made the anode to be installed in the inner tube while the cathode was changed to be as the outer tube, unlike the common coaxial VAT setup. This configuration showed that the idea in design of cathode feeder, in purpose of continuous thrust generation, is more feasible. Unfortunately, the detailed results were not published which leads us to the study of how the alignment of the cathode and anode will result the performance or plasma plume characteristic.

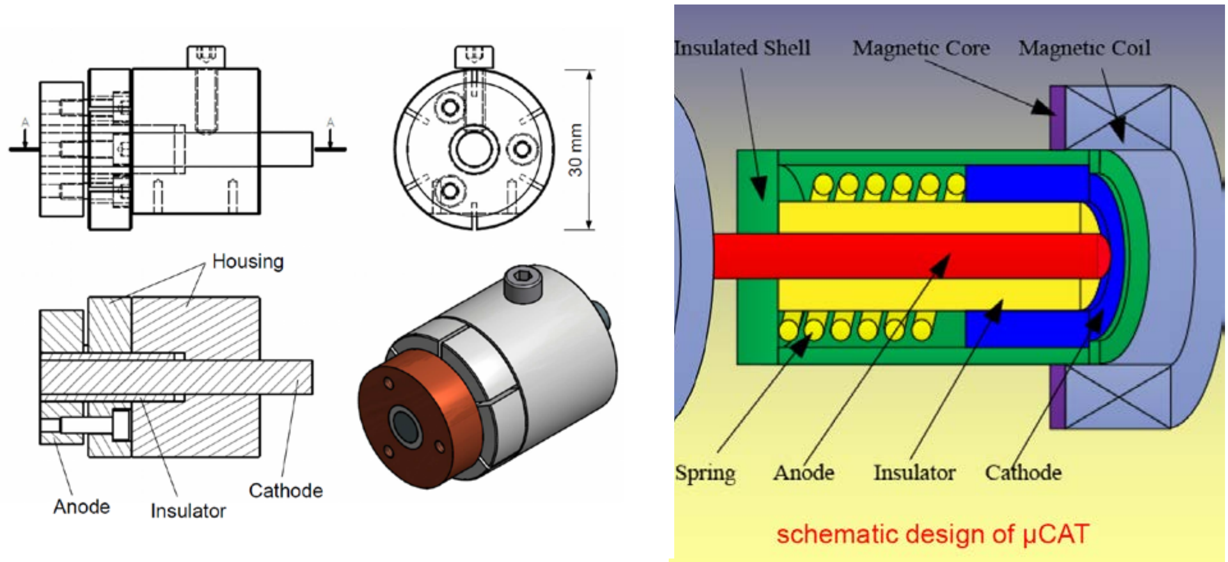


Figure 2.3 *Common coaxial VAT's electrode alignment (Left) [3] and Inverse coaxial VAT's electrode alignment (Right) [5]*

2.2 Circuit

Another importance part in order to drive the thruster is a circuit. The main components in the thruster circuit composes of DC supply, inductor and IGBT. A DC power supply is the device that is a power source of circuit and provides direct current. However, in space, the normal DC supply is impractical to be used due to its size, weight and energy source. Solar panel is then applied instead since the methodology behind this is a conversion from the power source which is sun to electricity.

Figure 2.4 *DC power supply (Left) [6] and Solar panel (Right) [7]*

As the VAT requires an extremely high voltages to generate arc, a power processing unit (PPU) plays this major role. According to the ability of inductor which can generate large amount of voltages, it is applied to be a PPU for this circuit.

The next component is an insulated-gate bipolar transistors (IGBT) which is a high voltage switch with fast switching. Considering the IGBT structure, there are 3 terminals, namely collector, emitter and gate. The collector and emitter are an input and output from the primary circuit, respectively. For the IGBT gate, it needs an extra circuit to conduct it. A function generator which is one of an equipment in the additional circuit acts as square wave producer with a wide range of frequencies. Moreover, the open and closed time of the IGBT gate is a consequence from charging and discharging time of inductor and the period of time for current to flow.

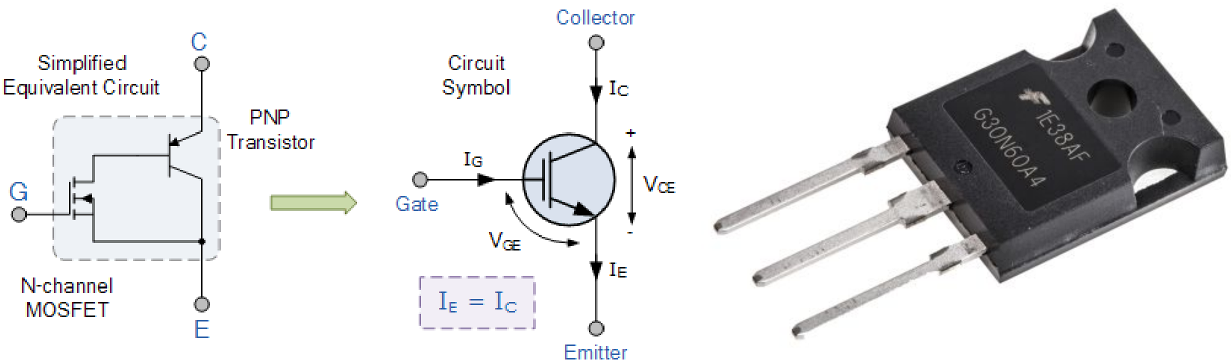


Figure 2.5 *IGBT symbol (Left) [8] and IGBT [9]*

Furthermore, some of new circuit designs offer capacitor to be part of the circuit because it is a device capable for accumulating electric charge and can temporarily perform as a power supply, thus working cooperate with the DC supply enhanced the amount of current for charging an inductor [10].

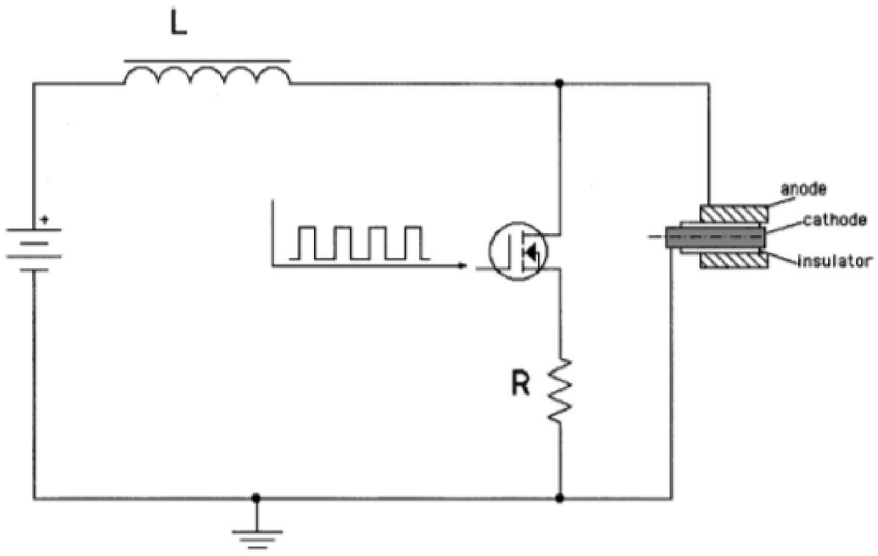


Figure 2.6 *The inductive energy storage circuit [10]*

As seen from Figure 2.6, the circuit is called an inductive energy storage circuit as it solely uses inductor. This is a two-stages circuit, alternative work which regulates by IGBT. When the IGBT is on, meaning the gate is close, the DC supply will provide electric current to charge the inductor. In this first stage, the energy will not pass through the VAT line since the voltages is not high enough for the VAT to spark, so at this moment the VAT performs like an open circuit. The other stage occurs after the inductor is fully charge and the IGBT switches off; Both DC supply and inductor will send voltages to trigger VAT [4]. During this discharging state of inductor, the input wire connects to anode and cathode is connected by the output wire. Between anode and cathode where the insulator is, there is a thin conducting coat on it, normally carbon from pencil. This coat enhances the capability of the circuit by require less voltages to vaporize the electrode which performs as a bridge, so the electric energy can finish the loop [3].

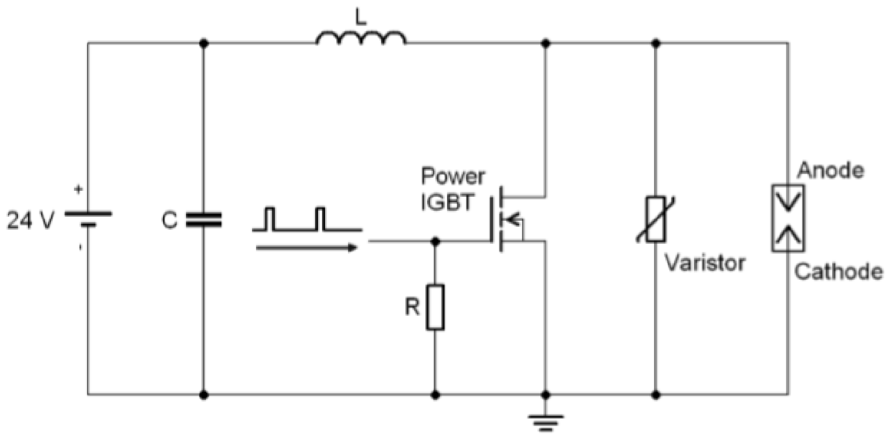


Figure 2.7 *The capacitor-inductor energy storage circuit [11]*

On the other hand, adding a capacitor into the circuit as shown in Figure 2.7 will plus one more stage into the circuit manipulation which is charging the capacitor during the off IGBT [4]. To be enlightened about this circuit, the diagram of how it works is presented in Figure 2.7. Also, in this report, this capacitor-inductor energy storage circuit will be used as a reference for other circuit designs and in experiments to test VATs.

3. VAT and Circuit Design Concept

3.1 VAT

3.1.1 Normal VAT and Feeding Mechanism Design

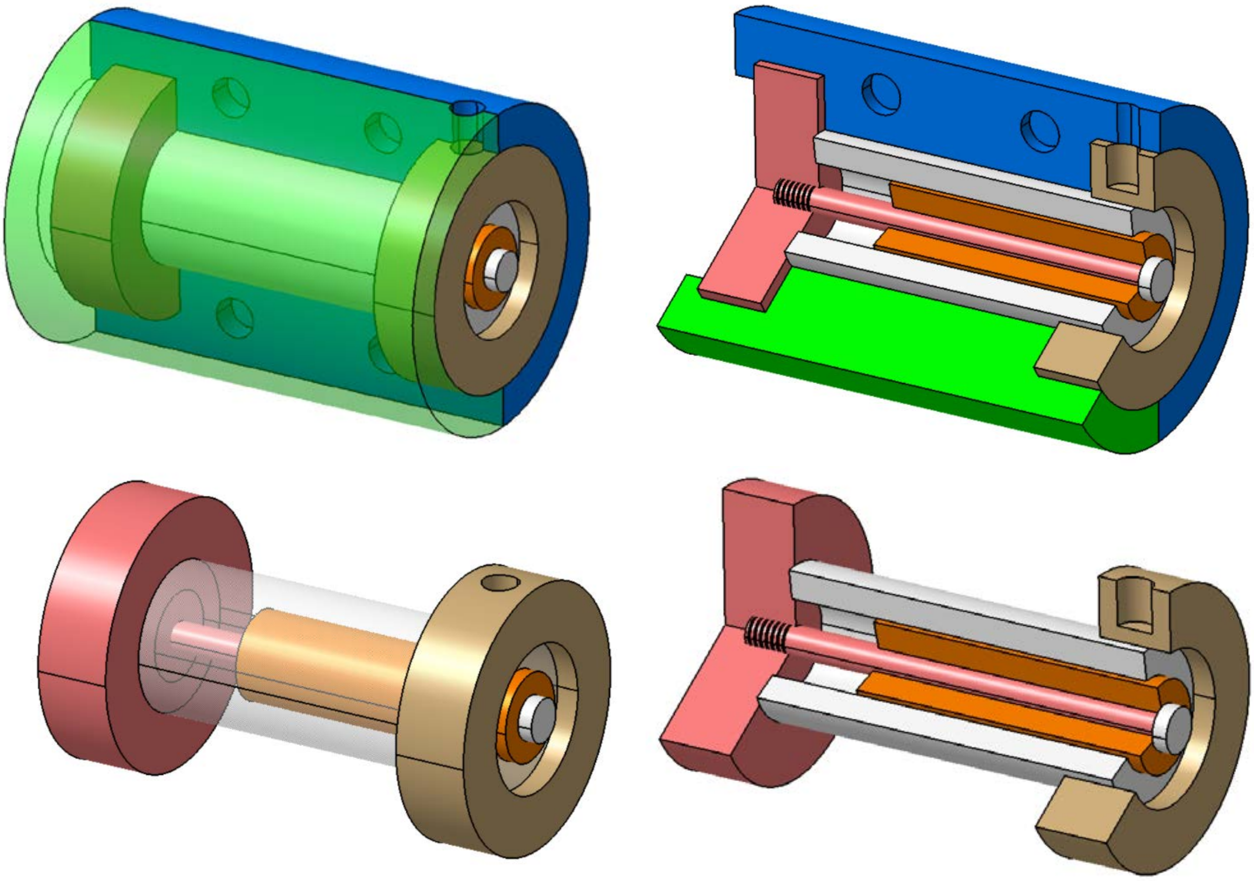


Figure 3.1 *The concept design of conventional VAT with feeding mechanism*

This is a design of normal coaxial VAT with feeding mechanism, the dimension are 24 mm and 33.5 mm for diameter and length, respectively. The aim of this concept is to design the feeding mechanism that has no moving part except cathode, so instead of connecting the wire to the cathode directly, we design to let the current pass through the cathode connector, which is located at the middle of the VAT, and then pass to cathode (Figure 3.1).

In this design, the size of VAT is a bit larger compared with other design concept because the feeding mechanism components are relatively large compared with what we expect. Moreover, the cathode connector size and cathode size are also the main factor that limit the VAT size due to the manufacturability.

To control the movement of cathode, spring is installed between the end of cathode and cathode connector base as shown in the Figure 3.1, this spring will generate the force to push the cathode moving forward. Then, cathode will be blocked by small white part at the front (blocking part) to make it moves appropriately, this blocking part is a part of the cathode connector rod coating with insulator compound such as ceramic or plaster. The reason of coating the blocking part is to prevent the occurrence of arc between anode and blocking part instead of cathode.

However, there is an issue about area around the blocking part that erosion might not occur; erosion will occur around the outer area instead (Figure 3.2). From the fact that arc will appear at the point where cathode and anode close to each other most [12]. Therefore, we believe that after the area nearby the outer radius of cathode is eroded to the point where the distance to anode is longer the distance from area behind blocking part to anode. Then, the cathode area near the blocking part start to be eroded as shown in the Figure 3.2.

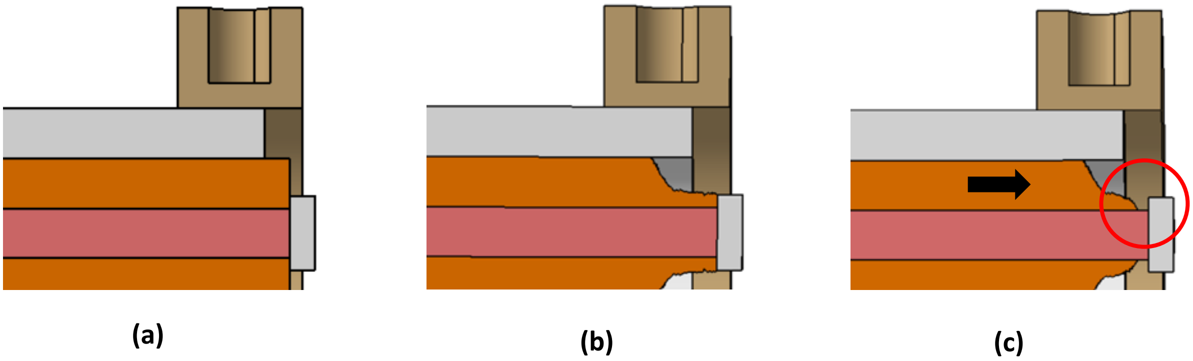


Figure 3.2 *The erosion of cathode, (a) at the beginning, (b) start to be eroded, (c) the erosion of cathode around blocking part*

3.1.2 Inverse VAT and Feeding Mechanism Design

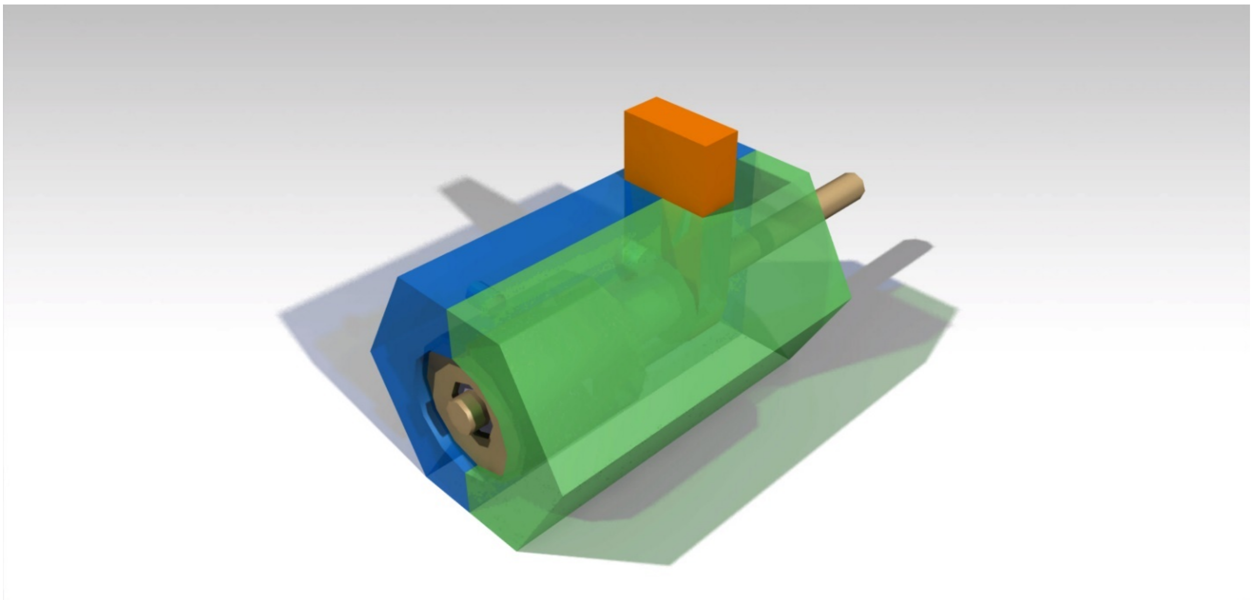


Figure 3.3 *The concept design of Inverse VAT with feeding mechanism*

The inverse VAT, as defined previously in introduction section, is based on switching the alignment of the cathode to be outside, instead. This design aims on improving the ease of feeding mechanism implementation.

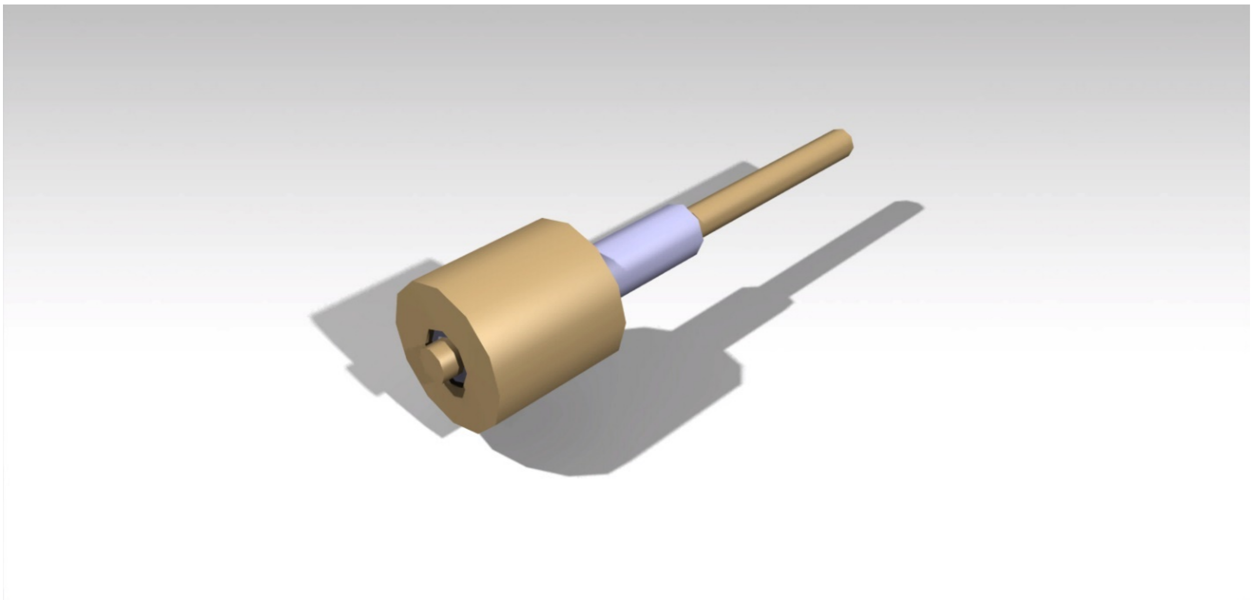


Figure 3.4 *The Inverse VAT without housing and connection part*

The cathode (**Figure 3.4**, bronze, outer tube) is made from copper with 4 mm and 10 mm inner and outer diameter, respectively. The length is 10 mm. The designer decided to use the insulator that is ready to use to reduce the time waiting for manufacturing. The insulator (**Figure 3.4**, taro, middle tube) has dimension of 2.4 mm for inner diameter and 4 mm for outer diameter. The length is 20 mm with offset from the front tip of cathode for 0.5 mm behind to coat the graphite. The material is ceramic. The anode (**Figure 3.4**, bronze, inner tube) was chosen to be made of copper and have 2.4 mm diameter to fit with an insulator we have with the length of 40 mm for circuit connection, clipped directly from behind. The anode has an offset from the cathode 1 mm forward.

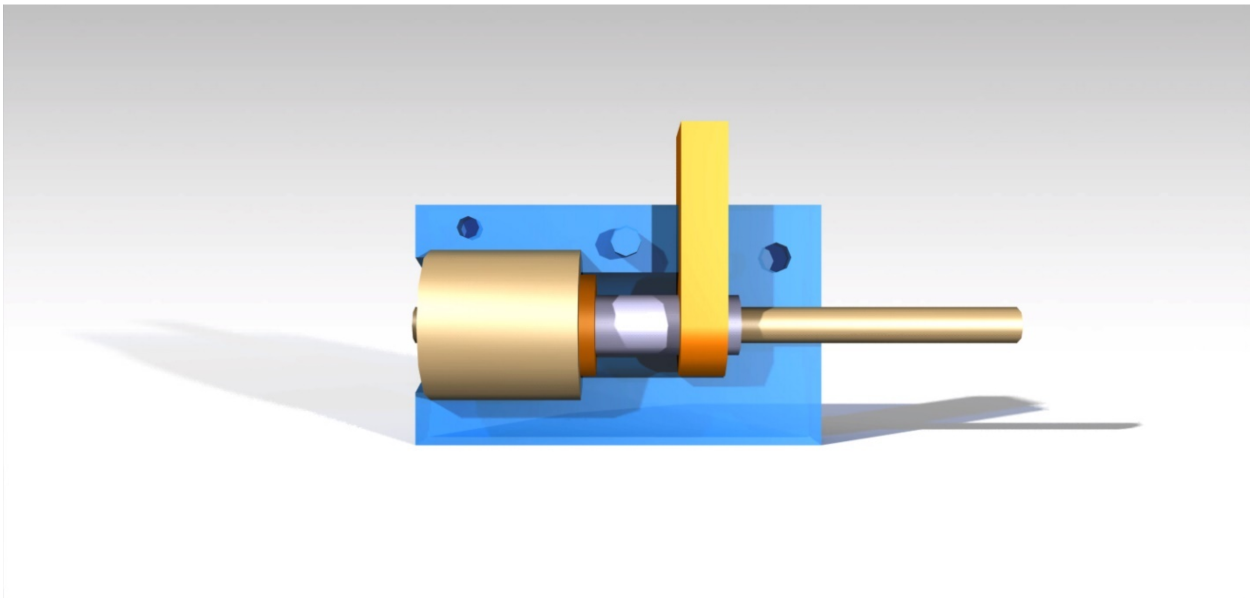


Figure 3.5 *The half-sectioned of assembled Inverse VAT showing the components inside*

The metal plate (**Figure 3.5**, right, orange) purposes to give the circuit connection accessibility from outside the housing by crocodile clip and conduct the electricity to the metal spring (not included in the picture). The plate can be made with any material that has ability to transfer the electricity such as aluminum or copper. The plate has outer radius 7 mm and has a 4 mm hole. The total height of the plate is 16.5 mm which will give an access above the housing for 5 mm after assembled. The thickness is 3 mm which will be enough for the clipper to clip on.

The ring metal plate (**Figure 3.5**, left, orange) was designed to transfer the electricity conducted through the metal spring and pass it to the cathode next to it. The ring plate has same circular dimension as the metal plate which is 7 mm and 4 mm for outer and inner diameter with thickness of 1 mm, made of aluminum or copper.

The spring that the designer chose is from the pen spring since it is easy to find a replacement and have enough force to push the cathode forward when needed.

The housing consists of two parts, left (**Figure 3.3**, green) and right (**Figure 3.3**, blue), with the hexagonal geometry. The advantage of hexagonal shape is that it can hold the VAT position firmly and provides an accessibility from different angle or position at the same time. The two housing will be connected by the holes and sticks as shown in the picture. The slots in housing providing supports to the VAT and other component to be fixed in place before completely secure the thruster with another housing. In addition, there is a hinge around the front cross-section of the thruster to block it from moving forward accidentally. The housing is made of non-electric conducting material such as plastic (UHMWPE).

3.1.3 Inverse VAT with Magnet and Feeding Mechanism Design

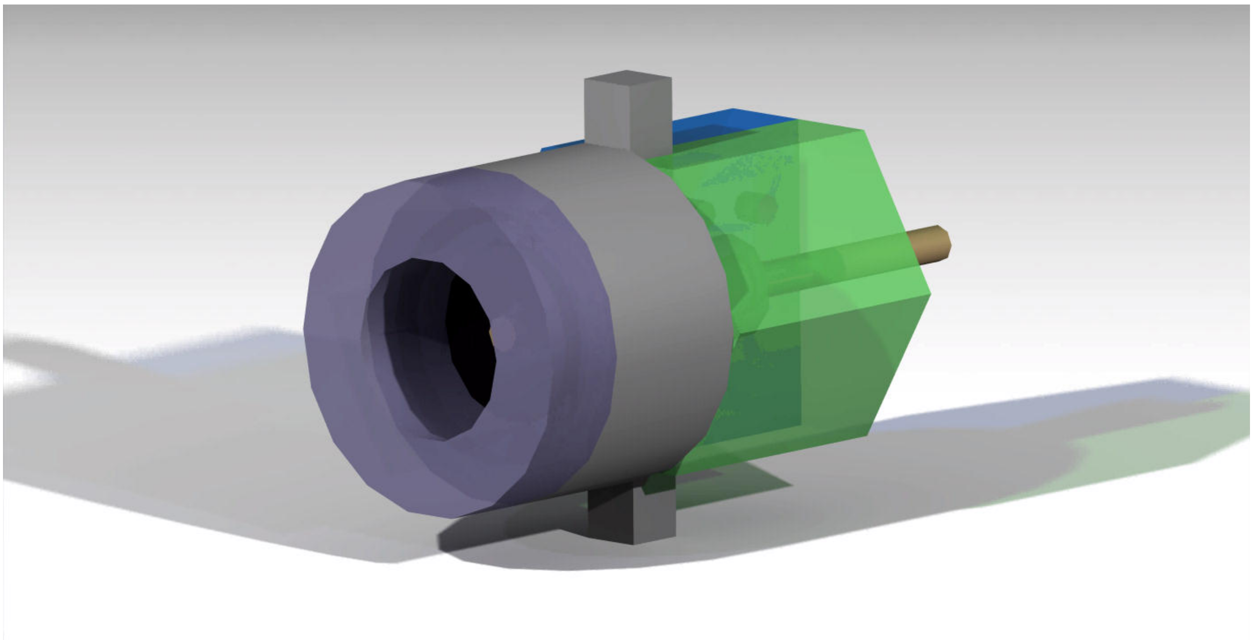


Figure 3.6 *The fully-assembled Inverse VAT with magnet and feeding mechanism*

Similar to *Inverse VAT*, the *Inverse VAT with Magnet* is the improvement of its previous design. According to some research [5, 14, 15, 16], applying the magnet to create the magnetic field can improve the uniformity of the cathode erosion and also accelerate the plasma ion coming out after ionization. With this, the designer adapted, made some adjustments, and added some improvements to the *Inverse VAT* which results in the design as follows.

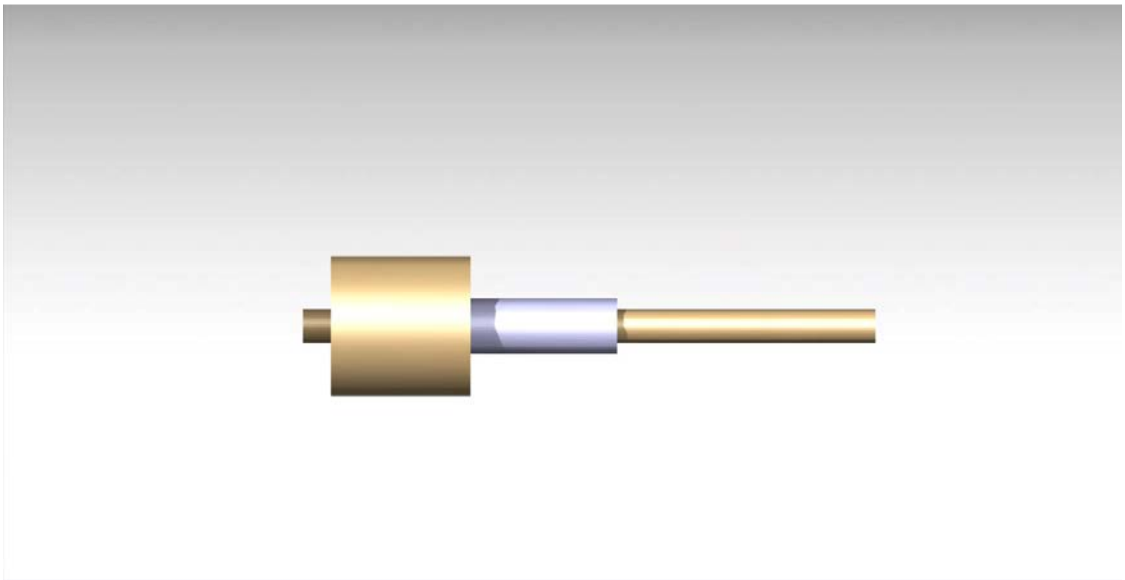


Figure 3.7 *The side view of the VAT alone*

Cathode and insulator have the same aspects. Anode length was extended to 41 mm with other aspects remain the same.

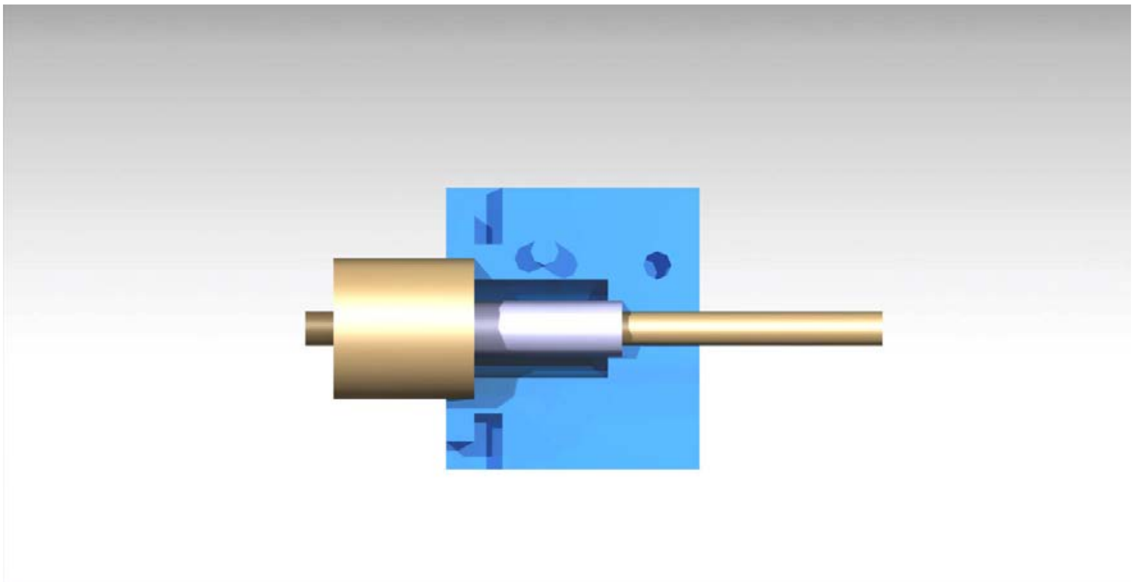


Figure 3.8 *The side view of the VAT with its housing*

Similar to the previous design, the housing was shortened to 18 mm and the number of hole and stick was decreased to 2 pairs. Two new slots (**Figure 3.8,** blue, upper and lower part) were created to hold the metal conductor from upper and lower part, each side of the housing. The material also uses UHMWPE.

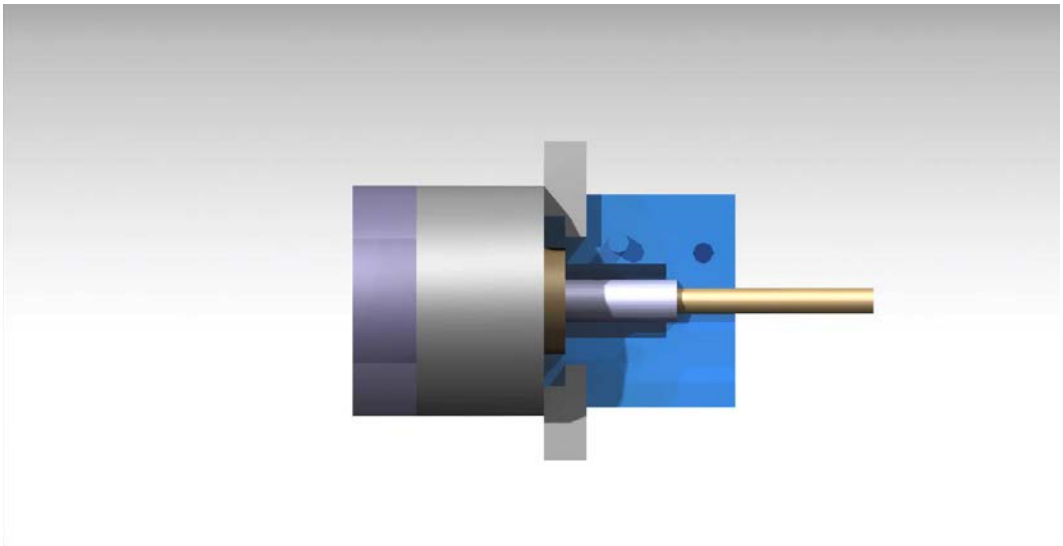


Figure 3.9 *The half-sectioned side view of assembled Inverse VAT with magnet*

The metal conductor (**Figure 3.9,** grey) replaces the metal plate and ring plate in the previous design. Instead of multiple stages of electricity transfer, the crocodile clipper will clip on the stick that extends from the tube metal conductor and conduct the electricity directly to the cathode surface being covered by the metal conductor.

As mentioned previously about the advantages of applying magnet to the thruster, the magnet (**Figure 3.**9, pale purple) that designer would like to examine its application is the Neodymium magnet which is one of the strongest magnets on earth at the time of report being written. The magnet will help improving the electrode erosion to be uniform and accelerate the plasma plume thus higher thrust due to higher ion velocity. The magnet also acts as the ceramic mesh holder to lock the mesh in place.

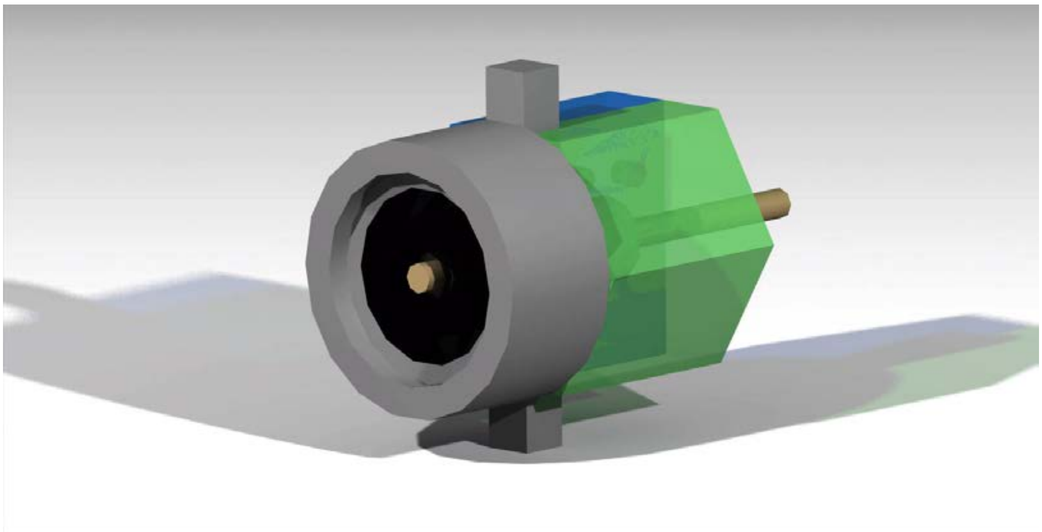


Figure 3.*10 The fully-assembled without magnet attached Inverse VAT showing the ceramic mesh*

The ceramic mesh (**Figure 3.**10, black) was added to solve the problem of the conventional hinge that might prevent the cathode to get eroded thus the feeding mechanism will not work as it should be. The mesh will provide enough space between each spot on the cathode surface to be ionized equally without blocking the sparking. On the other hand, it will also perform as a hinge to hold the cathode to stay at the desired limit for feeding mechanism purpose.

3.2 Circuit

3.2.1 Circuit Design 1

Most of the vacuum arc thruster (VAT) circuit use only one inductor and one capacitor with IGBT switch as shown in the figure below (Figure 3.11).

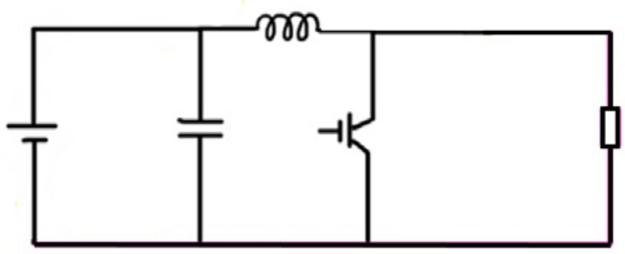


Figure 3.11 *The ordinary VAT circuit*

As the circuit information and principle are explained in the introduction that the circuit has to provide high voltage to the VAT and the pulse rate mainly depends on the IGBT frequency. Thus, this means increase the pulse rate of the VAT can be done only by increase the frequency of the IGBT switch. The IGBT frequency is the parameter which indicates when the high voltage will be released to the VAT and amount of time that current pass through the inductor, so this parameter must be set at appropriate value in order to provide enough time for inductor to be fully charged.

Another important parameter is thrust, the amount of thrust depends on many values such as ion mass, ion velocity, or thrust correction factor and discharge current as shown in the following equation [12].

$$T = \frac{M_i f_i J_d u_i}{e} \langle Z^{-1} \rangle C_t(\bar{L}, \bar{r}_a)$$

M_i	is the mass of ion
f_i	is the constant fraction of the discharge current
J_d	is the arc discharge current
u_i	is the ion velocity
$\langle Z^{-1} \rangle$	is the mean inverse charge state
$C_t(\bar{L}, \bar{r}_a)$	is the thrust correction factor

Therefore, the higher discharge current, the higher thrust from VAT [12]. However, in some case, the required charging time is relatively large when the current is increased; which means the inductor needs more time to be fully charged. As a consequence, this become the essential limitation of the increase VAT pulse rate because when the pulse rate rise, there is less time for current to pass through the inductor. Hence, to overcome this problem, we design to place another inductor to generate high voltage when the first inductor discharges the energy to VAT; in short, they will work alternately. In addition, the power of VAT also two time higher due to increase of the number of plasma occurrence with equal amount of time.

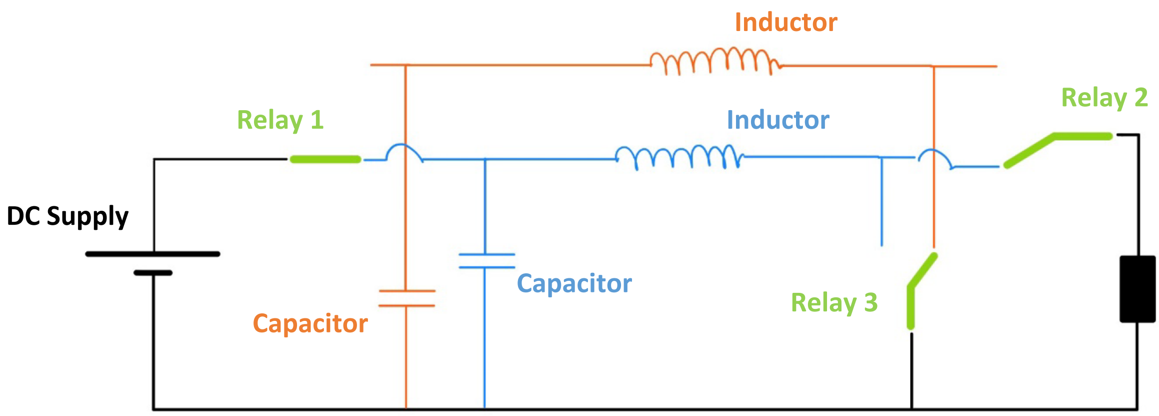


Figure 3.12 *The first design concept of the VAT circuit*

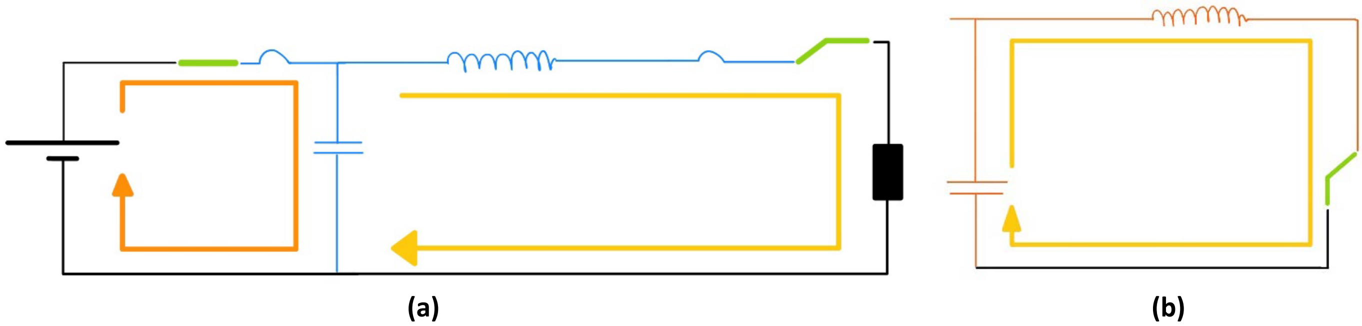


Figure 3.13 *The sub circuit (a) sub circuit 1, (b) sub circuit 2*

This design concept uses solid state-relay instead of IGBT to operate and switch between each loop. The reason is IGBT is the transistor type, so it means that it can only open and close, it has no capability to switch from one loop to another loop as we want to design. Additionally, in this design circuit concept, all of the solid-state relay works at the same time, so it is easy to be controlled.

From the Figure 3.13, there are two sub circuit (orange and blue loops) in the main circuit, these two sub circuit will operate alternatively. For instance, when relay 1 and 2 are connected to the sub circuit 1 but relay 3 is connected to sub circuit 2, the inductor in the sub circuit 2 are allowed to be charged while in the sub circuit 1, the inductor discharging the high current and voltage to the VAT to produce thrust and capacitor is also charged. In the next stage, relay 1 and 2 are connected to sub circuit 2 and relay 3 is connected to sub circuit 1, the sub circuit 1 and 2 will work as same as the other sub circuit in previous stage.

However, from researching about solid state relays, we found that the dimension of solid-state relay which its specification match to the design circuit is quite large, about 45.7 x 58.4 x 23mm [13]. This is because relays have to be able to hold high voltage and current that are discharged from the inductor.

3.2.2 Circuit Design 2

This circuit design based on the first design by combining two circuit together and every procedure is the same as the original one, except the relays. As the circuit design 1 has a problem about the relays' size and number, this circuit needs only one relays and two IGBT that can share the same additional circuit to control them. However, this circuit requires two DC supplies which are not an issue since in the space solar panel will be adopted.

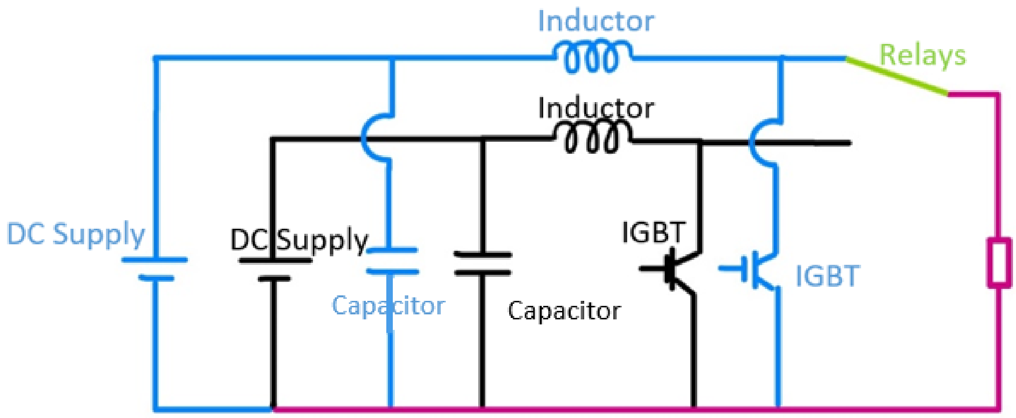
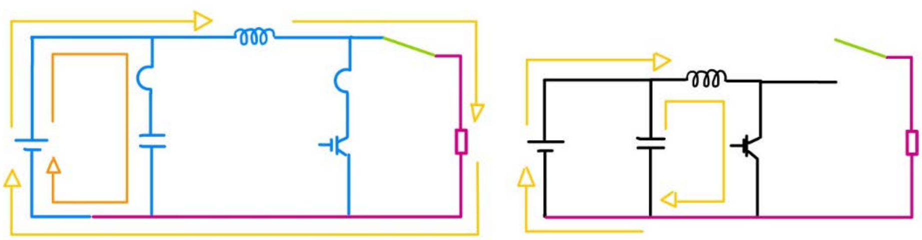


Figure 3.14 *The second design concept of the VAT circuit*

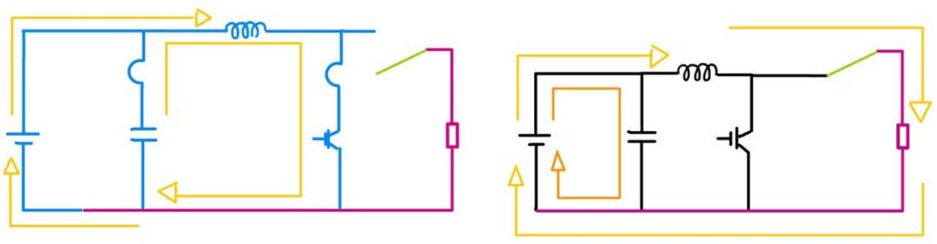
As illustrated in Figure 3.14, it shows steps how the circuit works. For clarity, it can be divided into two main stages, by on and off of the IGBT and relays switches. During the first stage when the IGBT is off and relays connect to sub circuit 1 (blue), the inductor will discharge its energy to VAT and thrust is produced. This process follows the yellow line in Figure 3.15 (1a). After the inductor is fully discharged, the capacitor is then charged and the current will flow through only capacitor wire, respecting to the orange line in Figure 3.15 (1a). The reason is the voltages are not enough to initiate the VAT, so it acts as an open circuit. While the IGBT of sub circuit 2 (black) is on, the inductor is charged by both DC supply and capacitor as shown in Figure. 3.15 (1b) In contrast, for stage 2, sub circuit 1 (Figure 3.15 (2a)) and 2 (Figure 3.15 (2b)) work conversely from their first stage.

Stage 1



(1a) **(1b)**

Stage 2



(2a) (2b)

Figure 3.15 *Stage 1: sub circuit 1 (1a), Stage 1: sub circuit 2 (1b), Stage 2: sub circuit 1 (2a), Stage 2: sub circuit 2 (2b)*

4. VAT

All of the following VAT applied similar materials in manufacturing due to the simplicity in comparison their efficiency. Copper is used as an anode and cathode for the VAT since it has a good conductivity, low cost and easy to machine. While other conducting parts such as feeding mechanism and part that is connected to wire and circuit are made of Aluminium because of its low weight and fine conductivity characteristic. The insulator between the electrodes is ceramic as it does not affect the arc performance and has a great thermal-resistance. However, the ceramic is hard to manufacture, so the insulators adopted in this report are ready to purchase and the size are fixed. On account of facilitate the handle, housing is designed and Teflon is then employed as housing material because it is easy to construct to any shape and vacuum friendly.

When assembly the VAT, there is an offset between anode and cathode. Because cathode will erode and some of them will contaminate anode and make anode has less efficiency [12]. Nevertheless, when anode and cathode are on the same plane, the maximum thrust is achieved because there is no part that shield plasma. This cathode's recess length from anode is decided to be 0.5 mm for every design.

4.1 Small VAT

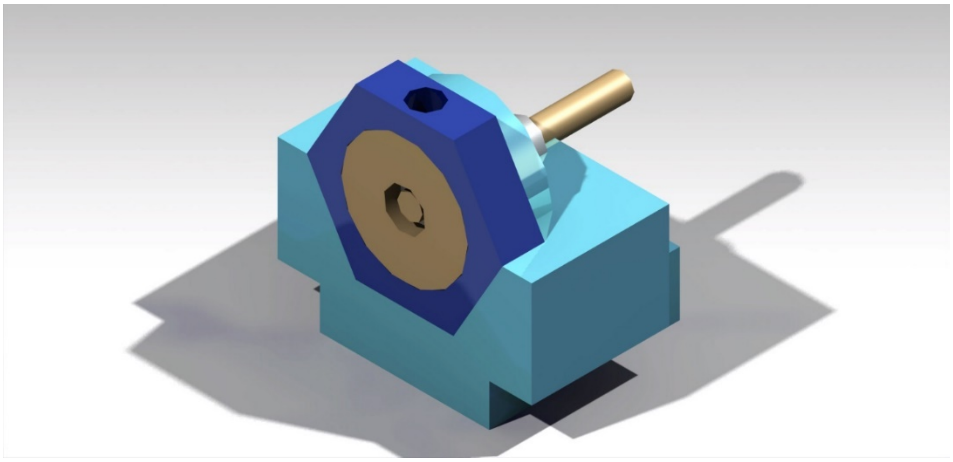


Figure 4.1 *The fully-assembled of small VAT together with its Lego-base housing*

The VATs mostly use the coaxial configuration that the cathode being in innermost while the anode being the outermost part with the insulator between them. From now on, we will call this setup as “conventional VAT” configuration. The VAT that we are designing was inspired from a conventional VAT that has been successfully developed in Taiwan (**Figure 4.2**). The VAT has cathode diameter of 6 mm, 50 long and 10 mm and 30 mm for the anode inner- and outer- diameter, respectively.

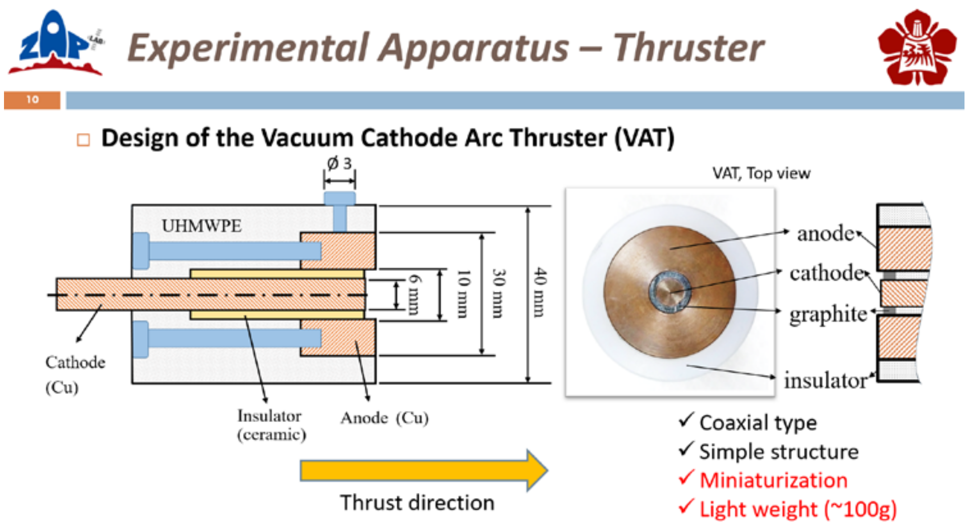


Figure 4.2 *The dimension of referenced VAT*

Although this VAT has already proved that it can perform satisfyingly, we believe that the size of this VAT can be more compact yet perform similar performance in term of efficiency and life span.

To achieve the goal like the predecessor, we need to re-design the VAT in every aspect. Even though most of coaxial VATs look similar, in fact, there are some design criteria for the coaxial VATs. Still, before we begin the design the dimension of anode and cathode, we need to find the insulator we would like to use. Because the insulator must have two properties in this section which are no electric conductivity to the cathode and anode and resistance to high temperature, it leads us to the only choice of cathode material which is ceramic. From this, with the complexity in manufacturing the ceramic at this very small dimension and time limitation, it is extremely difficult to make the insulator upon our request. Instead, we need to find the ceramic insulator that already have in the market which we found that the 2.4 mm in inner diameter and 4 mm in outer diameter with the length of 20 mm is the smallest available to purchase at the moment of experimental period.

Figure 4.3 *Small VAT’s insulator*

After we found the insulator that matches our specification, the process of electrodes design shall begin. One research [12] shows that the geometries of the VAT influence the performance of it. The ratio between the cathode and anode of the VAT has some relations with the momentum flux of the plasma plume expression, as depicts as follow:

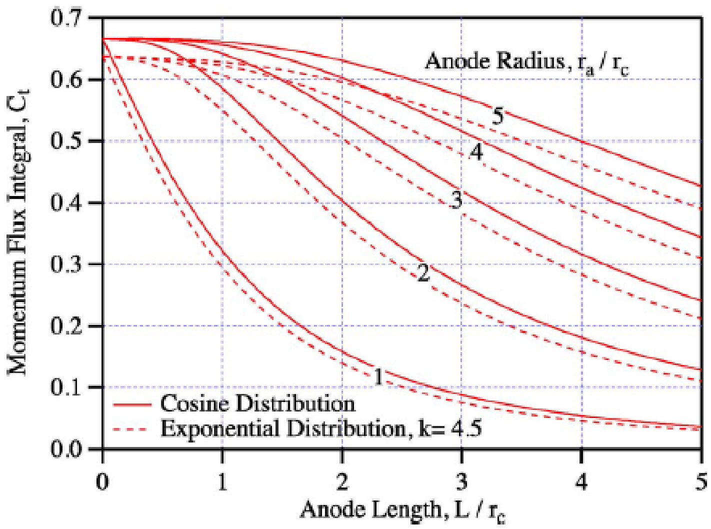


Figure 4.4 *Thrust factor which related to the geometry of anode and cathode*

As shown in the figure, the momentum flux will increase significantly when the ratio between anode and cathode change to 2 times bigger. Thus, we decided to make the anode diameter becomes 12 mm for outer diameter and 4 mm for the inner diameter. For the cathode, we chose to make it be 2.4 mm diameter rod. In conclusion, the ratio between anode and cathode radius is 5 from outer-diameter to outer-diameter.

Furthermore, the material of the electrodes also affects the performance of the VAT. Some researchs [3, 12] also indicate some parameters that predict the performance of the VAT with the use of different materials and historical data of the performance from different combination of material being used in the VATs in the past.

PREDICTED PERFORMANCE OF VATS AND VAITS

Species	Mass Flow Rate, $\dot{m}_t$ (mg/s)	Vacuum Arc Thruster				Vacuum Arc Ion Thruster					
		Thrust T (mN)	I_{sp} (s)	Total Efficiency η	Thrust-to-Power T/P (μN/W)	Thrust T (mN)	I_{sp} (s)	Propellant Efficiency η_u	Ion Production Cost ϵ_B (eV/ion)	Total Efficiency η	Thrust-to-Power T/P (μN/W)
Li		1.14			4.85	7.68			367		8.77
C	0.17	1.43	859	0.020	4.84	10.09	5949	0.468	463	0.320	10.78
Mg	0.31	2.16	709	0.040	11.47	11.42	3689	0.338	294	0.254	13.79
Al	0.28	1.66	604	0.021	7.03	11.30	4044	0.370	369	0.260	12.90
Si		2.15			7.81	11.11			430		12.14
Ca		1.99			8.48	9.56			367		10.92
Sc						10.92			298		13.14
Ti	0.3	2.70	924	0.058	12.77	14.04	4689	0.522	333	0.385	16.46
V		3.17			14.10	9.72			352		11.24
Cr	0.2	3.27	1666	0.117	14.28	14.26	7143	0.810	358	0.585	16.41
Mn		2.69			12.25	14.21			344		16.52
Fe	0.48	2.50	531	0.029	11.01	15.95	3329	0.424	355	0.306	18.40
Co	0.44	2.77	643	0.038	12.17	16.75	3815	0.514	356	0.367	19.30
Ni	0.47	2.51	544	0.033	12.24	16.61	3540	0.471	320	0.347	19.65
Cu	0.35	2.73	794	0.045	11.65	15.98	4575	0.585	366	0.418	18.29
Zn	3.2	3.91	125	0.015	25.24	21.26	666	0.113	242	0.089	26.74
Ge		3.78			21.62	17.38			273		21.33
Sr						13.78			281		16.80
Y	0.45	3.85	872	0.091	21.27	18.06	4020	0.575	283	0.441	21.99
Zr	0.53	3.83	737	0.059	16.38	17.20	3251	0.443	366	0.319	19.68
Nb		3.31			12.27	9.36			422		10.29
Mo	0.36	3.77	1066	0.067	12.85	16.16	4498	0.578	458	0.389	17.32
Pd		6.13			28.80	15.99			333		18.74
Ag	1.4	4.30	317	0.029	18.43	20.45	1463	0.239	369	0.170	23.34
Cd	6.2	4.00	66	0.008	24.99	26.51	428	0.091	250	0.071	33.13
In		3.25			18.59	23.30			273		28.59
Sn	2.95	4.02	139	0.016	22.95	25.30	859	0.174	273	0.133	31.05
Ba		3.18			17.36	17.07			286		20.75
La		3.02			17.58	15.47			269		19.05
Ce		3.21			17.93	16.35			280		19.96
Pr		3.76			18.81	15.37			313		18.30
Nd						16.13			308		19.27
Sm		3.61			24.71	16.78			228		21.35
Gd	0.55	3.65	677	0.056	16.90	24.51	4466	0.862	338	0.638	28.64
Dy		3.61			18.23	16.15			309		19.27
Ho		4.11			20.54	16.27			313		19.37
Er		4.01			21.12	15.97			297		19.24
Yb						18.69			225		23.84
Hf		3.87			15.92	13.29			380		15.05
Ta	0.56	4.70	861	0.070	16.49	22.64	4050	0.732	448	0.493	24.42
W	0.55	5.80	1078	0.096	18.24	22.12	4029	0.711	498	0.464	23.06
Ir						15.19			383		17.16
Pt		4.40			19.57	19.57			352		22.62
Au		4.00			20.32	20.76			308		24.80
Pb	5.1	4.71	94	0.014	30.39	32.36	636	0.164	242	0.129	40.70
Bi		5.18			33.20	36.00			244		45.23
Th		2.62			11.27	7.35			364		8.42
U		5.72			24.33	13.93			367		15.92

Table 4.1 *Predicted performance of VATs*

	Cathode properties			Pulse characteristics	
Ref.	**Material**	**Dia./size** (mm)	**Geometry**	**Peak arc current** (A)	**Pulse length** (μs)
a	Zn, U, Mg, Ti	3.18	Rod	200	50–500
b	W, Ti	3.18	Rod	10	100
c	Cr, Y		Rod	10–25	250–500
d	Ti	3.18	Rod	14, 510	1500, 100
e			Multi-rods	25	600
f	Ti	50	Cylinder	1500–2000	400–500
g	Cu, Al	30	Rod	50–250	20000–DC
h	Al	10 × 2 (face)	Planar	200–800	0.4
i	Ti	6.35 (outer)	Annular tube	40	400
j	Cu	~ 4 (outer)	Rod, tube	10–50	250–400

[a]Gilmour & Lockwood (1972), [b]Schein et al. (2002a), [c]Schein et al. (2002b), [d]Sekerak (2005), [e]Tang et al. (2005), [f]Neumann et al. (2009), [g]Marks et al. (2009), [h]Lun (2009), [i]Zhuang et al. (2009), [j]Pietzka et al. (2013) and Kronhaus et al. (2013)

Table 4.2 *Historical data of the material used in the experiment of VATs*

For our design criteria, we interest in three aspects which can obtain from the table above. The I_{sp}, Total efficiency, and Thrust-to-Power ratio. It can be seen that palladium has very interesting performance that it should be taken as the electrode for our VAT. However, the cost and rarity of the material itself constraints the possiblity of using it for our experiment. Apart from palladium, aluminum and copper are other material that we were interested in it. At the end of the decision making, we decided to use copper as the electrodes for our VAT due to its price and ease of manufacturing. Nevertheless, to make the comparison of performance that we stated previously become more apprehensive, using copper will achieve our preferrences.

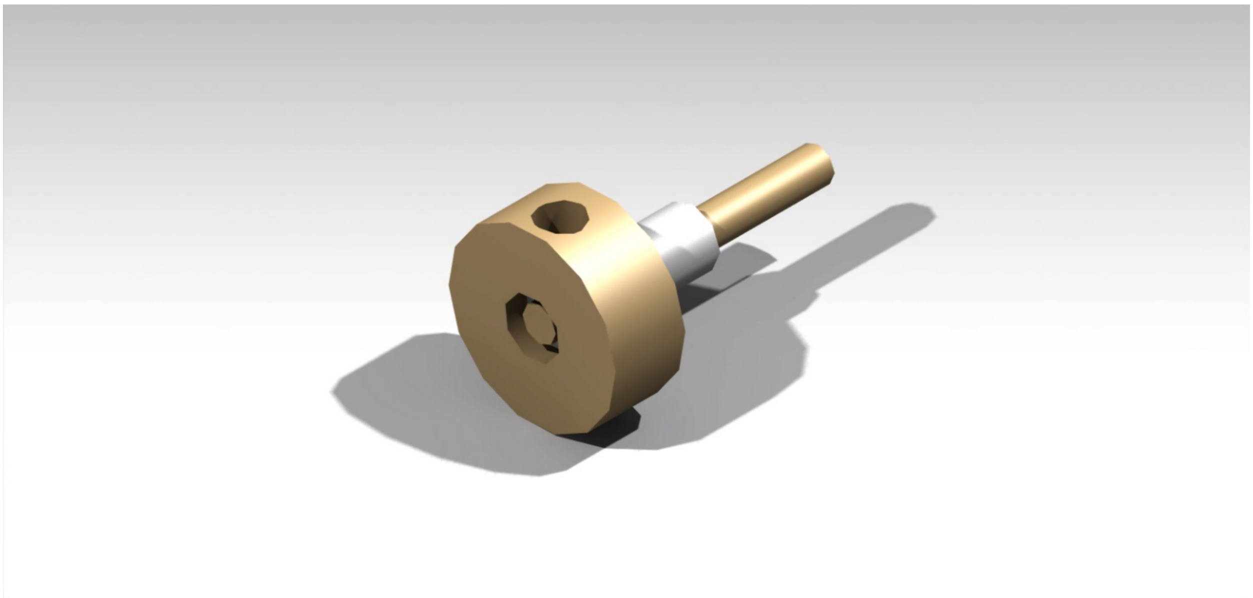


Figure 4.5 *The isometric view of the VAT*

For the wire connection, there are also two topics we conserned about. First is how to connect the VAT with the circuit properly and another is how to connect the VAT that will make it be stable during the experiment in vacuum chamber.

The first concern was solved by creating the thread on the side of anode surface to insert the M3 screw in, then, connect the crocodile clipper to the screw. The clipper also connect directly to another electrode which is the extended part of cathode at the tip of the cathode from rear-end.

For VAT stabilization, the designer of the small VAT had designed the housing that contains two seperated part of the it for ease of experiment. The first part is the hexagonal housing that will fit outside around the anode as shown in the picture below. The hexagonal housing is made of UHMWPE plastic. Because of its shape, it provides the ability to be stable when placing on the flat surface and also the reachability from three angles. Giving the experimenters more opprotunities to connect the wires upon the experiment conditions such as in limited testing space and wire connecting angle.

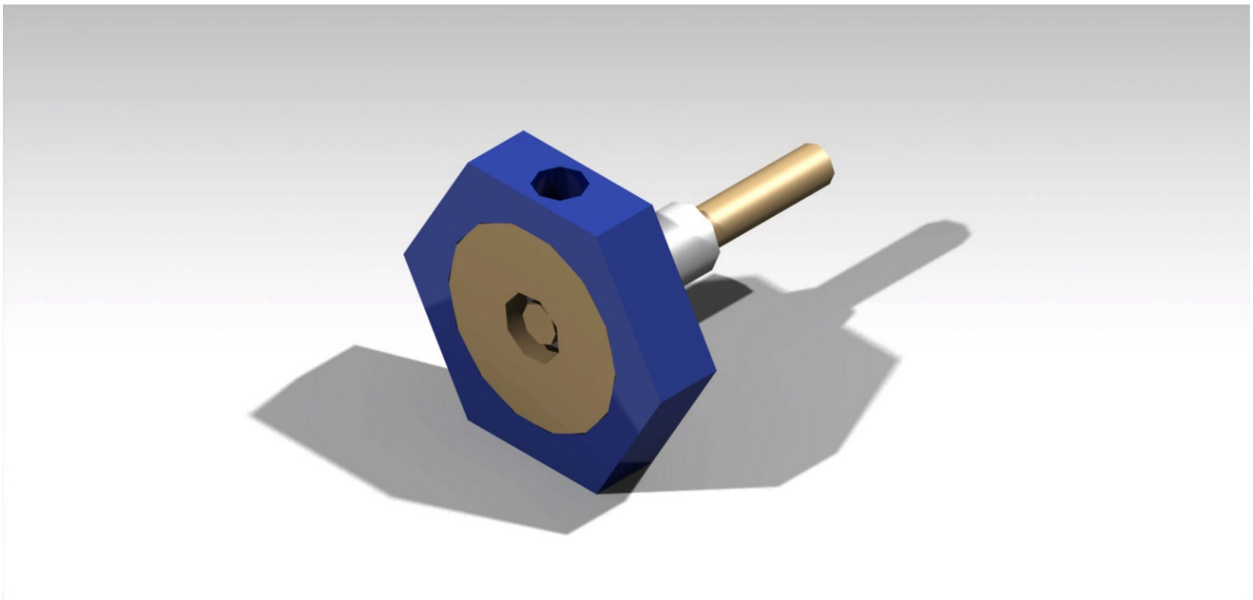


Figure 4.6 *The isometric view of the VAT with the hexagonal housing being attached*

The second part is the base of housing. The designer designed the base to have the slot that can fit perfectly on the Lego stand. The reason that we choose the stand to be made from Legos because of the ability to change the shapes upon the test environment. So, the experimenters can place the VAT housing base on the Lego stand easily and stablely when preparing the test. The housing also have other slots to hold the VAT in place which will lock and prevent the VAT from misplacing during the experiment. The material also made of UHMWPE, same as the hexagonal housing.

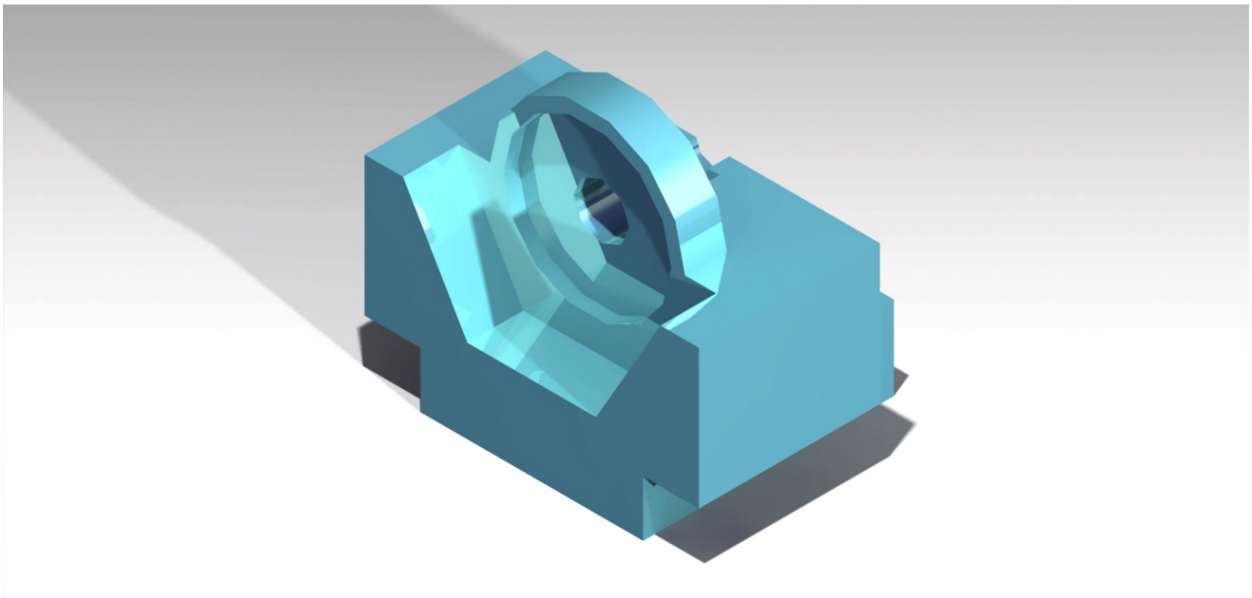


Figure 4.7 *The Lego-base housing of the VAT*

4.2 Ring VAT and Feeding Mechanism

The design of electrode both cathode and anode are in ring shape, which consist of an annular cathode and similar diameter anode. The annular insulator used in this design having a same outer diameter as electrode, while inner diameter is a bit bigger than the inner diameter of electrode to make a gap for a graphite sheet. In addition, the insulator with 1 mm thickness is used as a separator between cathode and anode. Moreover, ring VAT need a magnetic coil and magnetic core in the front of the VAT to induce the plasma plume to flow in a correct direction and make the flow more uniform. Additionally, this VAT is easy to design the feeding mechanism because anode is fix in front of cathode, so blocking part is not needed.

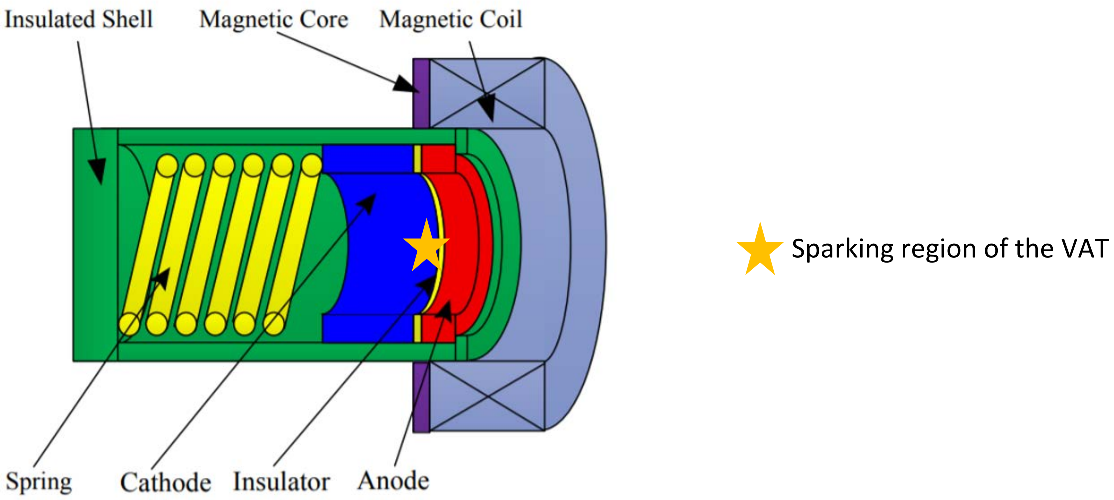


Figure 4.8 *Ring VAT's components*

However, the paper that related to this design suggested that the ring geometry VAT need a magnetic coil and magnetic core to create the magnetic field for the system. This is because the spark area of ring VAT is located inside a body. Therefore, the system is needed a magnetic field to induce the plasma plume to flow in the desired direction.

4.3 Planar VAT and Feeding Mechanism

Apart from coaxial and ring geometries, planar is the other type of the VAT geometries that has been introduced. The configuration of this design can be compares as a sandwich or a stack of plates. Although, there is not much published information about its potential and most of VAT papers prefer using coaxial and ring designed, the advantages of this design are ease of manufacture and construction on CubeSat since it is a rectangular plate [17]; hence It is interesting to be analyzed its competence and compared with the others.

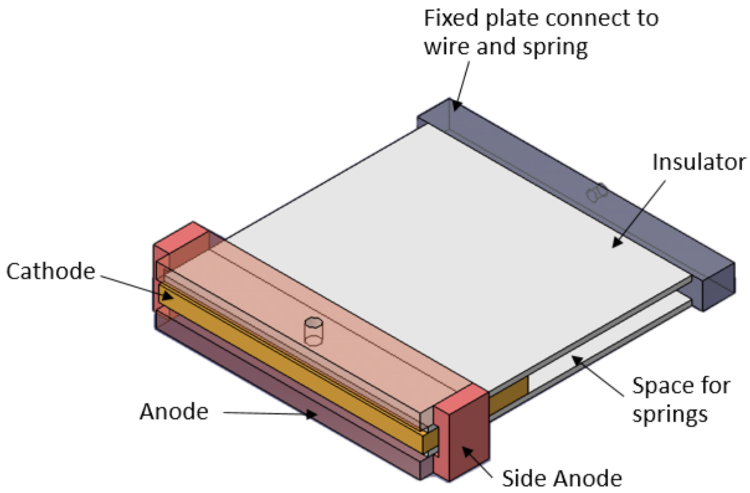


Figure 4.9 *Planar VAT excluding housing*

Nevertheless, because of the limited ceramic insulator size, the size of this designed planar VAT is big (about 11×50×50 mm), excluding housing. The design is depicted in Figure 4.9. The side anodes are responsible for connecting the upper and lower part of anode. Since the size of cathode has an effect on the lifetime because it will erode every time the ignition occurred. Respecting to the cathode diameter of the small VAT and big VAT, they use the ceramic insulator which are 0.8 mm and 2 mm thickness, respectively. For the cathode diameter, they are 2.4 mm and 6 mm, respectively, for small and bigger one. Therefore, the planar VAT applied 1 mm thickness insulator and the cathode thickness is 3 mm.

Feeding mechanism of the planar VAT design comprises a rear Aluminium plate and housings. On one side of the Aluminium plate which is connected to spring and cathode, there are two cylinder parts protruded from the plate to attach springs with it. Two springs are decided to use instead of one because the plate is long, so it is difficult for one spring to feed the cathode uniformly. The other side of the plate also has an extended cylinder part to connect wire with the circuit. The VAT and the Aluminium plate are fit with the housings which are produced as two separate pieces, making it easier to be assembled and disassembled. In the front of the lower housing, there are two segments on each side of the housings to block the cathode when the springs are feeding.

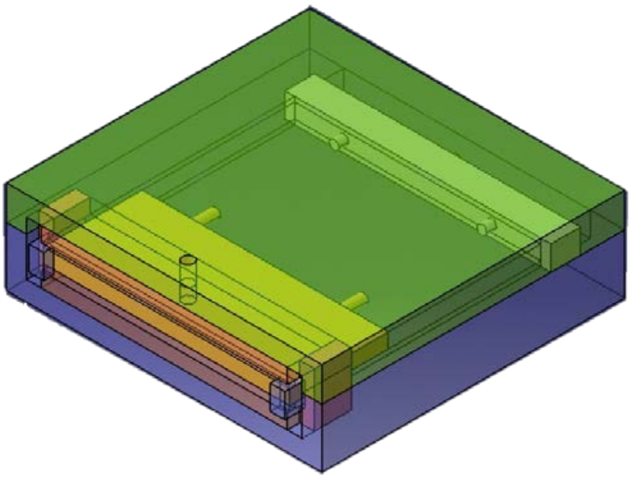


Figure 4.10 *Planar VAT with housing*

5. Experimental Setup

After finishing the design and manufacturing processes, the experiments were setup to test all VATs and the experimental apparatus were divided into two main parts. The first section (Figure 5.1) was the circuit which is outside the vacuum chamber. The second segment (Figure 5.2) was inside the vacuum chamber where the VAT is. Two parts were connected to each other via wire at vacuum chamber as can be seen from Figure 5.3.

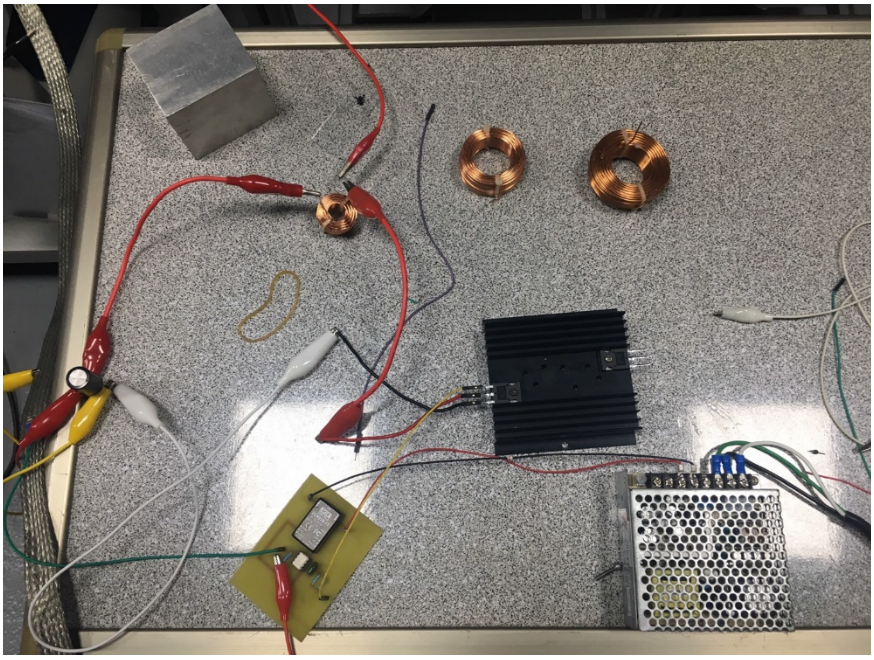


Figure 5.1 *Circuit part outside vacuum chamber*

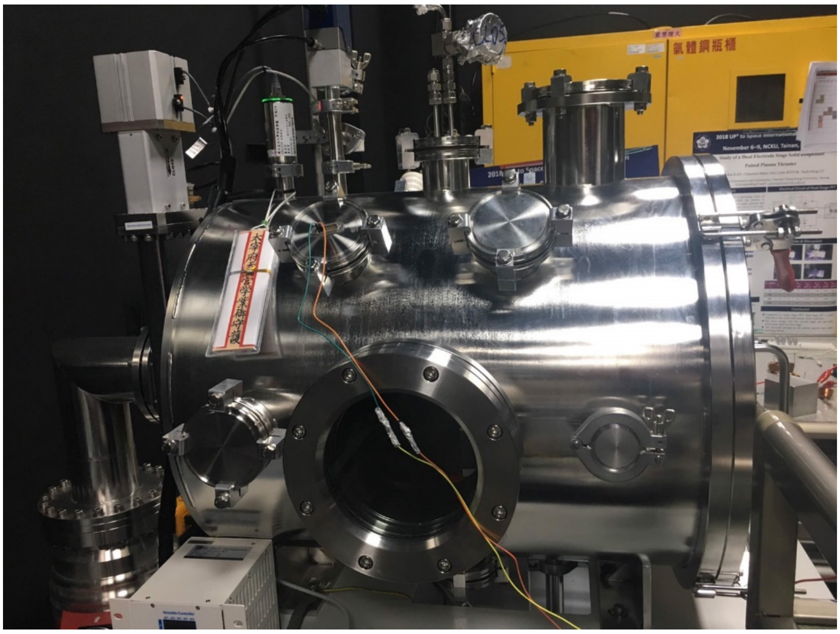


Figure 5.2 *VAT part inside vacuum chamber*

Figure 5.3 *Outside and inside vacuum chamber connector*

Focusing on the circuit part, the applied circuit was depicted in Figure 5.4. This circuit included both capacitor to store currents and inductor to increase voltages. The capacitance and inductance's value are 1800 µF and 2200 µH, respectively.

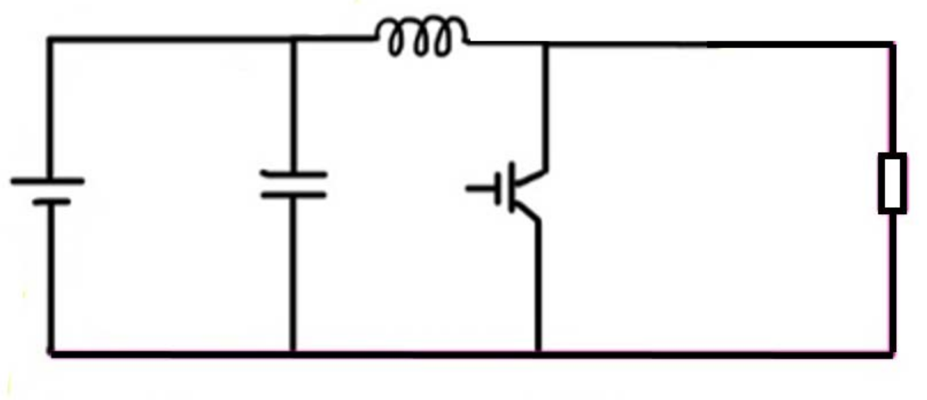


Figure 5.4 *Circuit schematic*

The tested VAT was installed inside the vacuum chamber (Figure 5.5) after coating the carbon on the insulator surface and cleaning it. Two wires needed; one was for attaching cathode to the output wire outside the vacuum chamber and the other one was for attaching anode to the input wire outside the vacuum chamber. Checking that the continuity between VAT and wires outside every time was necessary by using multimeter.

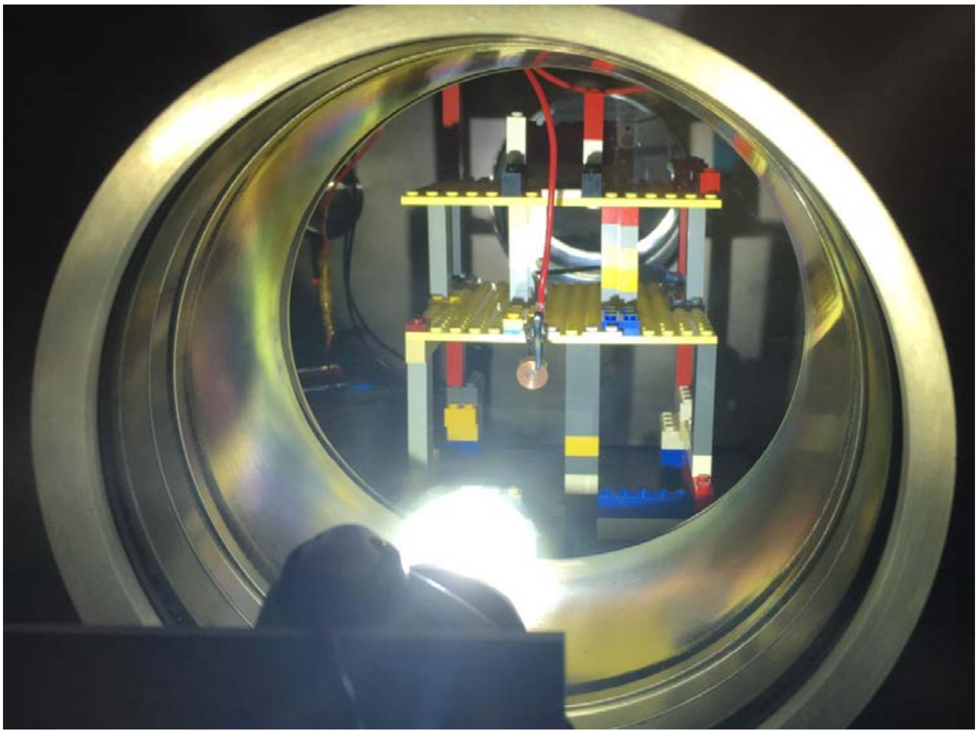


Figure 5.5 *Installing VAT inside vacuum chamber*

Turning on the vacuum chamber and waiting until pressure in the vacuum chamber went lower than 10^{-5} bar, then the experiment began. The DC power supply was utilized to provide voltages that was fixed at 30 V. Also, the function generator created waveform to circuit by setting the width of each pulse to be 8 µs and no delay. The first experiment was conducted on those three VATs to ensure that they could operate under the desired environment. For this experiment, the selected mode in function generator was ‘Single Shot’ which gives a non-continuous wave or single discharge of VAT.

When the first experiment was accomplished, the second experiment which is an erosion rate or lifetime testing was conducted. The weight of cathode had to be measured before the test. The setup mode of function generator was ‘Burst’ to give multiple shot or autonomous discharge for the input number of time. Then, the VAT was taken out of the chamber and measured the weight again.

6. Results

The results of discharge tests and continuous discharge test analyses for samples associated with Conventional VAT, Ring Geometry VAT, and Plate VAT are presented in table 1 and table 2 respectively, providing the ability of discharge, the different pulse periods, and the number of generated pulses. All experiments using same electrical circuit, input voltage, and equipment.

No. of test	Conventional VAT	Ring VAT	Plate VAT
1	✓	✗	✓
2	✓	✓	✓
3	✓	✓	✓

Table 6.1 *Discharge Test*

As the result, only Ring VAT failed to discharge in the first attempt while others successfully discharge in all test.

No. of test	Input Hz	Expect No. of pulse	Actual No. of pulse
1	0.5	20	20
2	1	20	<10

Table 6.2 *Continuous Discharge Test for Conventional VAT*

By changing the input period from 0.5 second per pulse to 1 second per pulse, the VAT failed to discharge continuously and cannot reach the expect no. of pulse.

No. of test	Input Hz	Expect No. of pulses	Actual No. of pulses
1	0.5	20	20
2	1	20	20
3	1	1200	~200

Table 6.3 *Continuous Discharge Test for Ring VAT*

Ring Vat successfully discharge for 20 pulses in both 1 pulse per 2 second and 1 pulse per 1 second. However, it failed to operate to reach 1200 pulses.

No. of test	Input Hz	Expect No. of pulses	Actual No. of pulses
1	0.5	20	20
2	1	20	20
3	1	1200	1200
4	2	1200	1200
5	4	1200	~10

Table 6.4 *Continuous Discharge Test for Plate VAT*

Plate VAT successfully discharge continuously to reach 1200 pulses per 1 cycle. However, when increased the frequency to 4 Hz, the VAT failed to operate.

While the inductor discharging high current and voltage to the VAT, it caused an arc generative region between cathode and anode. Moreover, the plasma plume is produced in this region, the figure of discharging of each VAT type are shown in the figure below (Figure 6.1, 6.2, and 6.3)

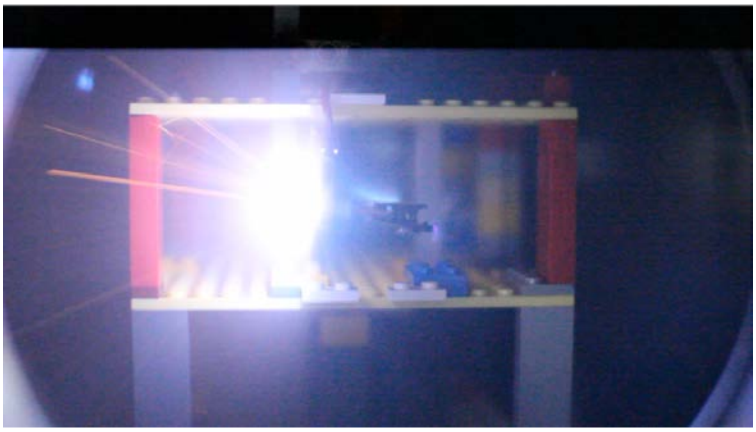


Figure 6.1 *Small VAT discharging picture*

Figure 6.2 *Ring VAT discharging picture*

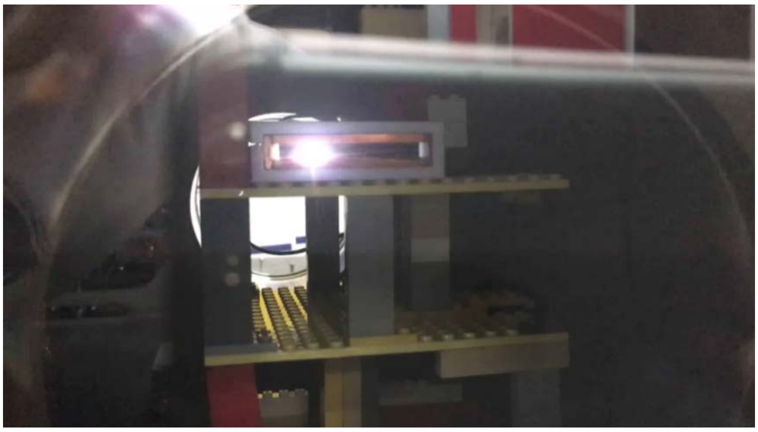


Figure 6.3 *Plate VAT discharging picture*

7. Discussion

7.1 Carbon Layer

Carbon layer is one of the most necessary part of the VAT, in this project, it is implemented on the insulator surface by pencil lead which is installed between cathode and anode as shown in the Figure 7.1. Under the vacuum environment, when the carbon layer receives energy, it will be vaporized by Ohmic heating or Joule heating [10]. The carbon ion has an ability to provide a conductive path for electron to move from cathode to anode and decrease high dielectric strength [10]. As a consequence, the required voltage of VAT becomes lower and the arc can be generated easier in the vacuum environment. In general, part of the carbon ion will come back to the insulator surface and reform back to carbon layer; therefore, this makes the arc generation process turn into cycle.

(a)

(b)

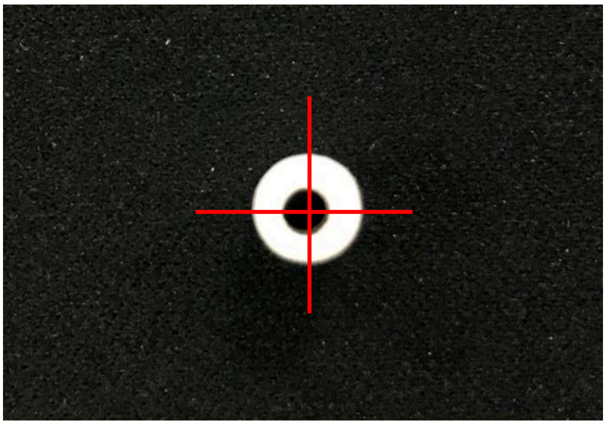
(c)

Figure 7.1 *Carbon layer on the insulator surface (a) small VAT, (b) plate VAT, and (c) ring VAT*

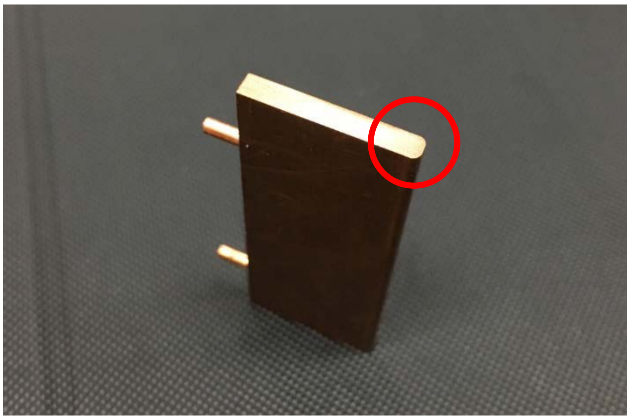
From our point of view, we think that there are three problems from carbon layer that could lead to the malfunction of the VAT after discharging for moment. The first problem is the vaporized rate and re-form rate are not balance, if the vaporized rate is higher than re-form rate, the carbon layer will slowly run out and the released voltage from inductor are no longer enough for the are generation. The quality of carbon layer is the second problem, the carbon layer of VAT in this project is created by coating the insulator surface with pencil lead, so the quality of carbon layer might not good enough for continuous discharge. The last problem is the carbon layer is finished, even the carbon ion can form back to carbon layer but it is just some portion not all of them. Hence, when the VAT is discharged long enough, there is a possibility of carbon layer running out; for instance, in the case of plate VAT, we have already discharged it for 2400 times without re-coating the carbon layer, so when we test it again, the carbon layer could be finished and make the discharge stop at around 3000 times.

7.2 Manufacturing imperfection

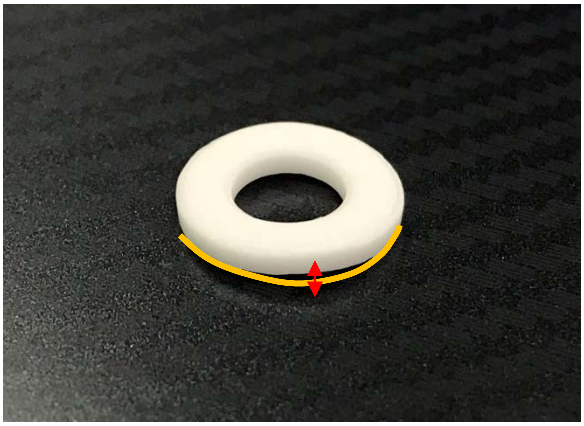
Manufacturing imperfection is one of the significant factors that could cause the failure to the VAT and effect its performance. Some components of the VAT do not have precise dimension as in the design due to manufacture process error as shown in the Figure 7.2.



(a)



(b)



(c)

Figure 7.2 *VAT component's defect (a) insulator, (b) plate VAT cathode, and (c) Small VAT cathode (from customization)*

From the Figure 7.2, the insulator dimension is not as same as it should be such as tube insulator for small VAT, the inner diameter is 1.9 mm instead of 2 mm which makes the cathode cannot be assembled, so we have to reduce the size of the cathode for small VAT. Moreover, the dimension of plate insulator is 51 and 50 mm for width and length but in the design, it should be 50 × 50 mm. Nevertheless, the cathode of plate VAT should have 90 degrees angle at the edge but it has fillet which leads to the longer distance between cathode and anode a little. As a consequence, we have to customize them which obviously cannot be as precise as it should be because of lacking of equipment and manufacture skills. Therefore, in our opinion, we think that these might be one of reasons that leads to VAT failure.

7.3 Gap between electrodes

Due to an accident that made us needed to change the insulator for the plate VAT, the substituted insulator is thinner (0.5 mm in thickness) than the previous one that we normally used (1 mm in thickness), as shown in Figure 7.3. The new insulator creates the gap between the upper anode (need to attach with the upper cover via screw) and the new insulator after assembled even though we tried to make it stay closer already (Figure 7.4).

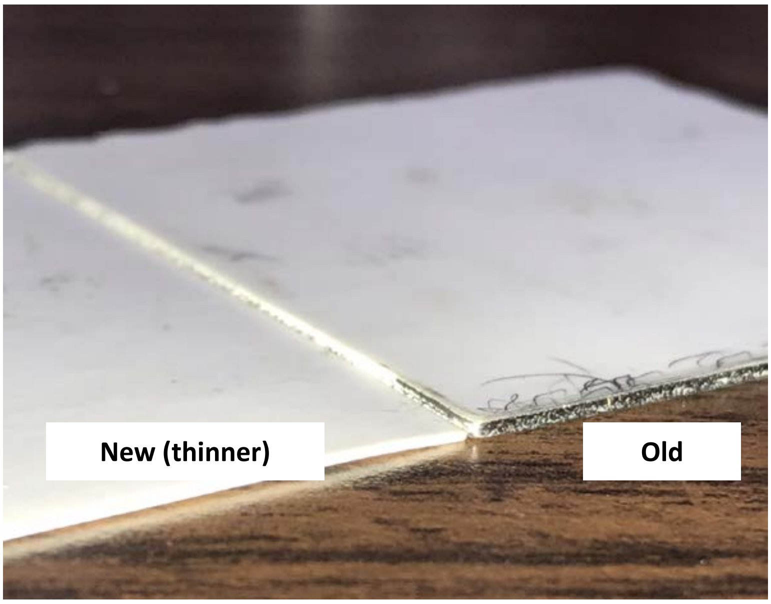


Figure 7.3 *The comparison between the new plate VAT insulator and the old one showing that there is a significant difference in the thickness*

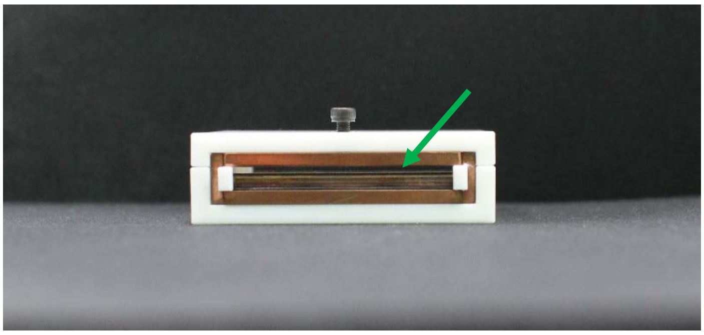


Figure 7.*4 The front view of the plate insulator showing the gap between upper anode and upper insulator (green arrow)*

When we began discharging the plate VAT, it could discharge 15 times and stopped (IGBT broke down). According to our discussion, we predict that the reason behind the VAT's discharge suspension might come from the total amount of graphite on insulator surface had been changed due to a decrease in thickness which leads to smaller area for graphite to coat on. Moreover, even the distance between the lower anode side and cathode was reduced, the upper part, however, also has bigger distance between the two electrodes, as a result of insulator thickness reduction. Because discharge spot in the VAT can occur randomly, it is possible that the discharging will occur at the upper part, which is further in distance, although it is likely to discharge between the closest spots, in theoretically. When the VAT is trying to discharge at the upper part which has longer distance, it has higher chance that the VAT will not be able to engage the ion discharge especially after a several pulses. Thus, the huge current now will go to the IGBT instead and break the components inside.

7.4 Graphite gets coated by copper

This phenomenon happens in every VAT but the Ring VAT has the most distinguish amount of copper coated over the graphite on the insulator (Figure 7.5). The graphite that being coated on the insulator helps decreasing the voltage required to discharge the VAT. The voltage delivered from the inductor in the circuit will vaporize the graphite layer on the insulator and become the carbon ion which will surround the discharge area of the VAT and results in ease of VAT discharge.

***Figure 7.5** The brownish color on the black graphite layer (red arrow) indicates that there are copper powders coated on the graphite after discharges.*

After a period of time, some parts of copper that got ionized might cover the graphite layer on the insulator. These powders may prevent the graphite layer under them from being ionized and result in insufficient carbon ion to decrease the voltage. This can lead to the failure of discharging the cathode thus the current will consequently go to the IGBT and break it down, as a result. The reason that the Ring VAT shows significant copper powders on the graphite layer because the geometry and configuration of the VAT itself that surrounding the discharge area and confine the plasma plume to be inside it. In addition, the Ring VAT has not installed the magnet at the frontal section because of the long delivery time and time limitation. Hence, we decided to not use the magnet to accelerate the plasma plume. The possible solution for this problem might be installing the magnet to induce the plasma plume forward which may result in a reduction of copper powders and might increase the performance of the Ring VAT, which need to be determined in the future work.

7.5 Anode contaminated

After discharge for several times, the anode shows a sign of other particles that have brownish color and black powder over its surface. These particles are the ionized cathode and graphite of the VAT. When these adulterants cover the discharge area of the anode, it is possible that these impurities can contaminate the discharge ability of the VAT due to the change in the electron exchange process and results in a discharge disability. When the discharge cannot be succeeded, the consequence is the overload current flow into the IGBT and break it down.

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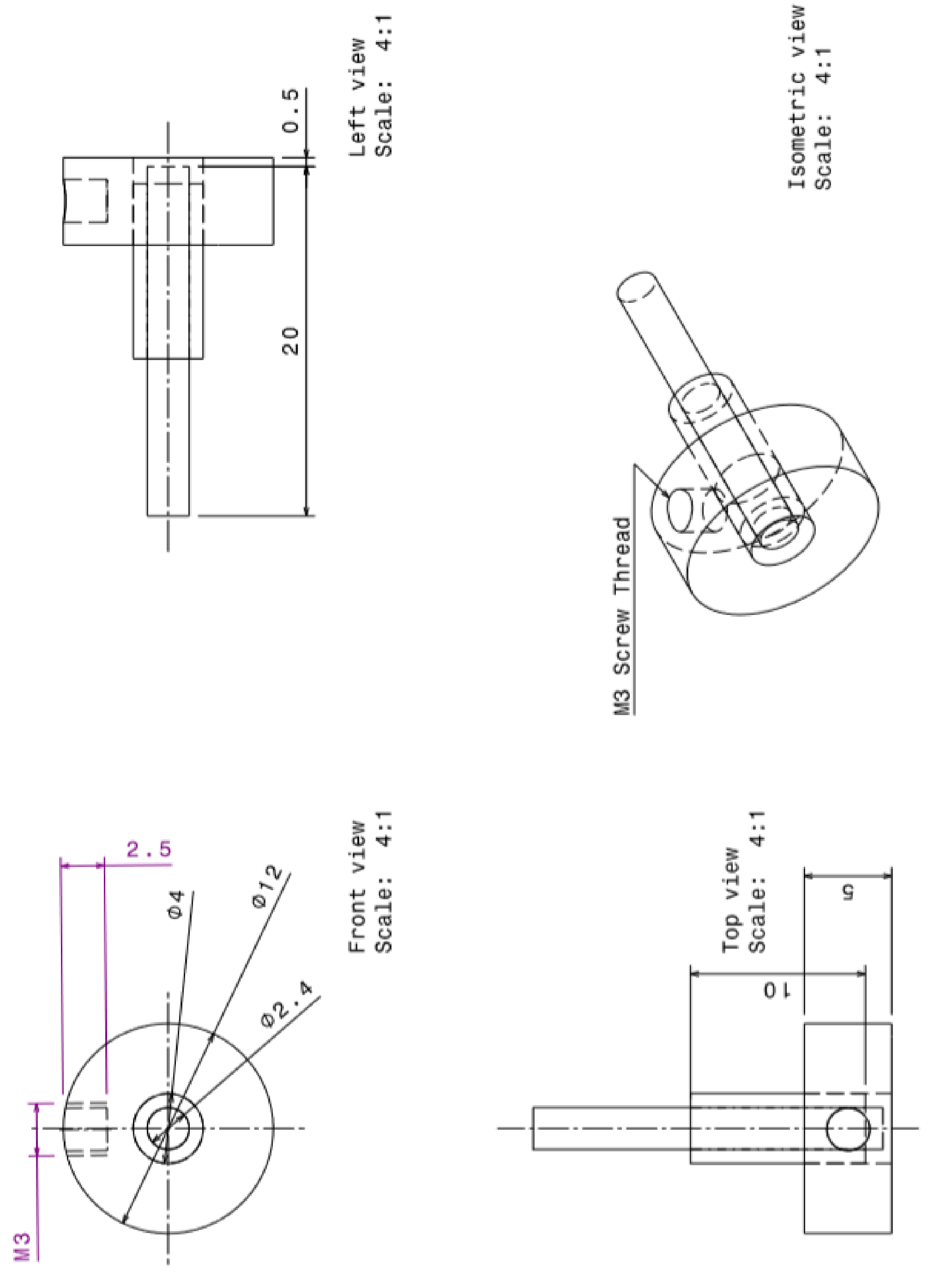
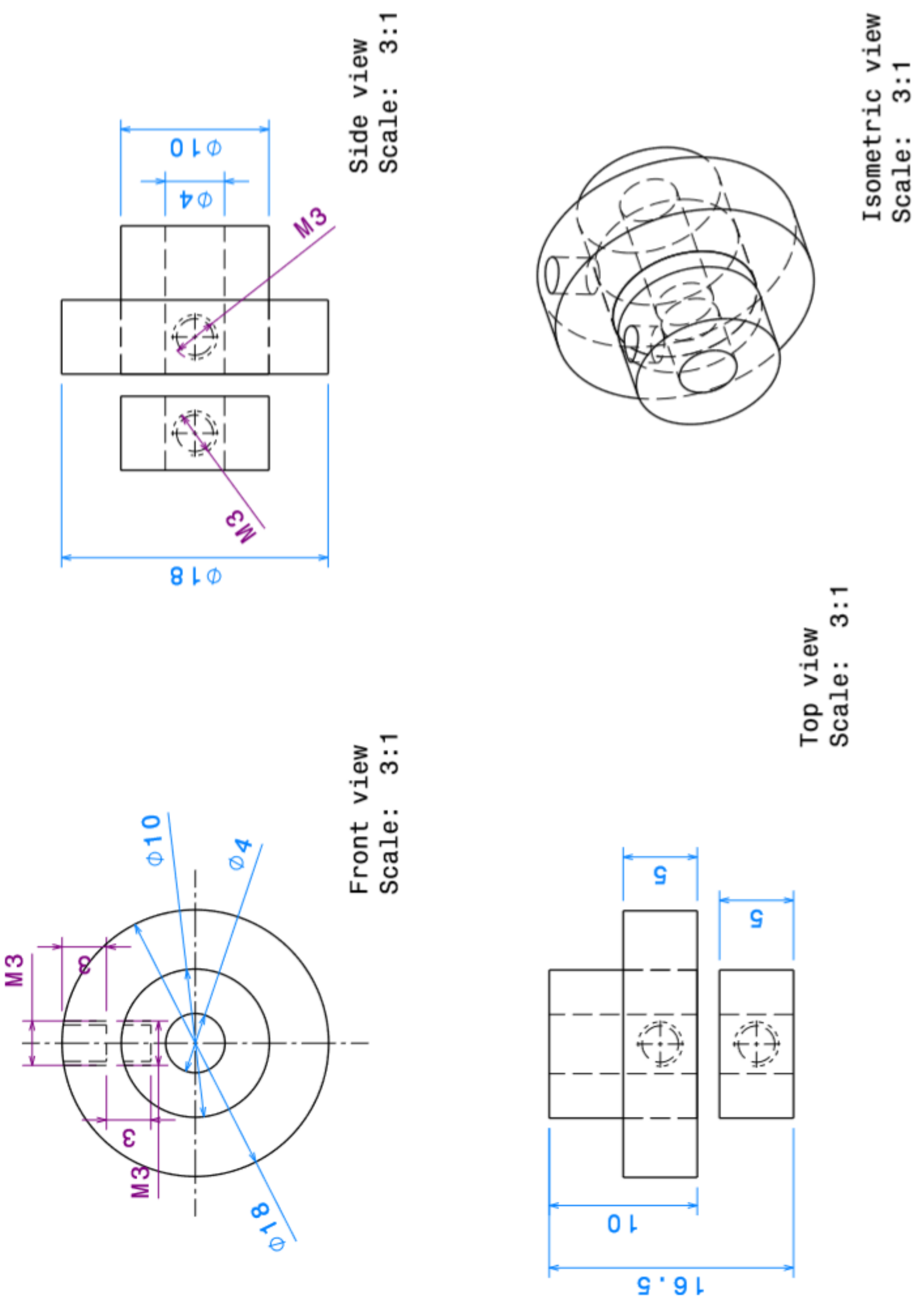
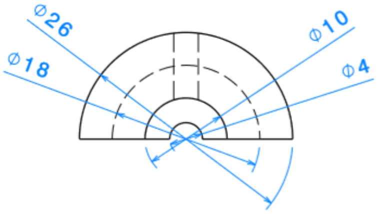
Appendix A: Small VAT Design Summary

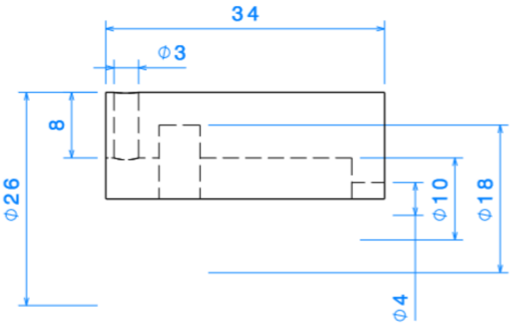


Appendix B: Ring VAT and its Feeding Mechanism Design Summary

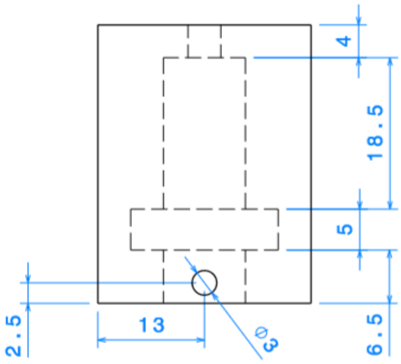




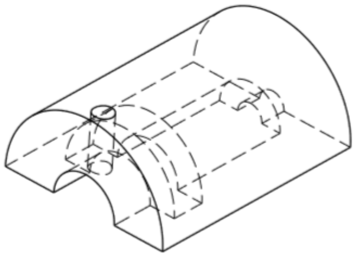
Front view
Scale: 2:1



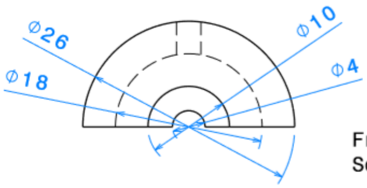
Side view
Scale: 2:1



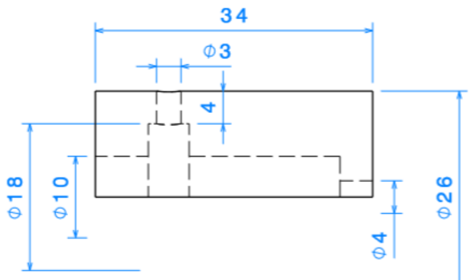
Top view
Scale: 2:1



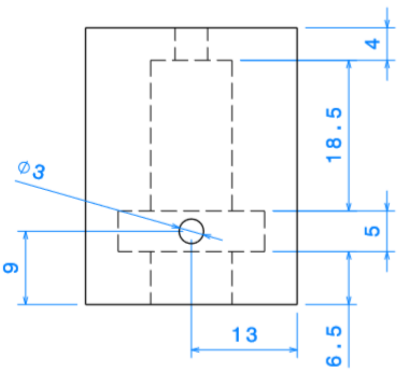
Isometric view
Scale: 2:1



Front view
Scale: 2:1



Side view
Scale: 2:1



Top view
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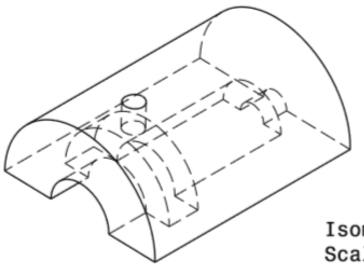
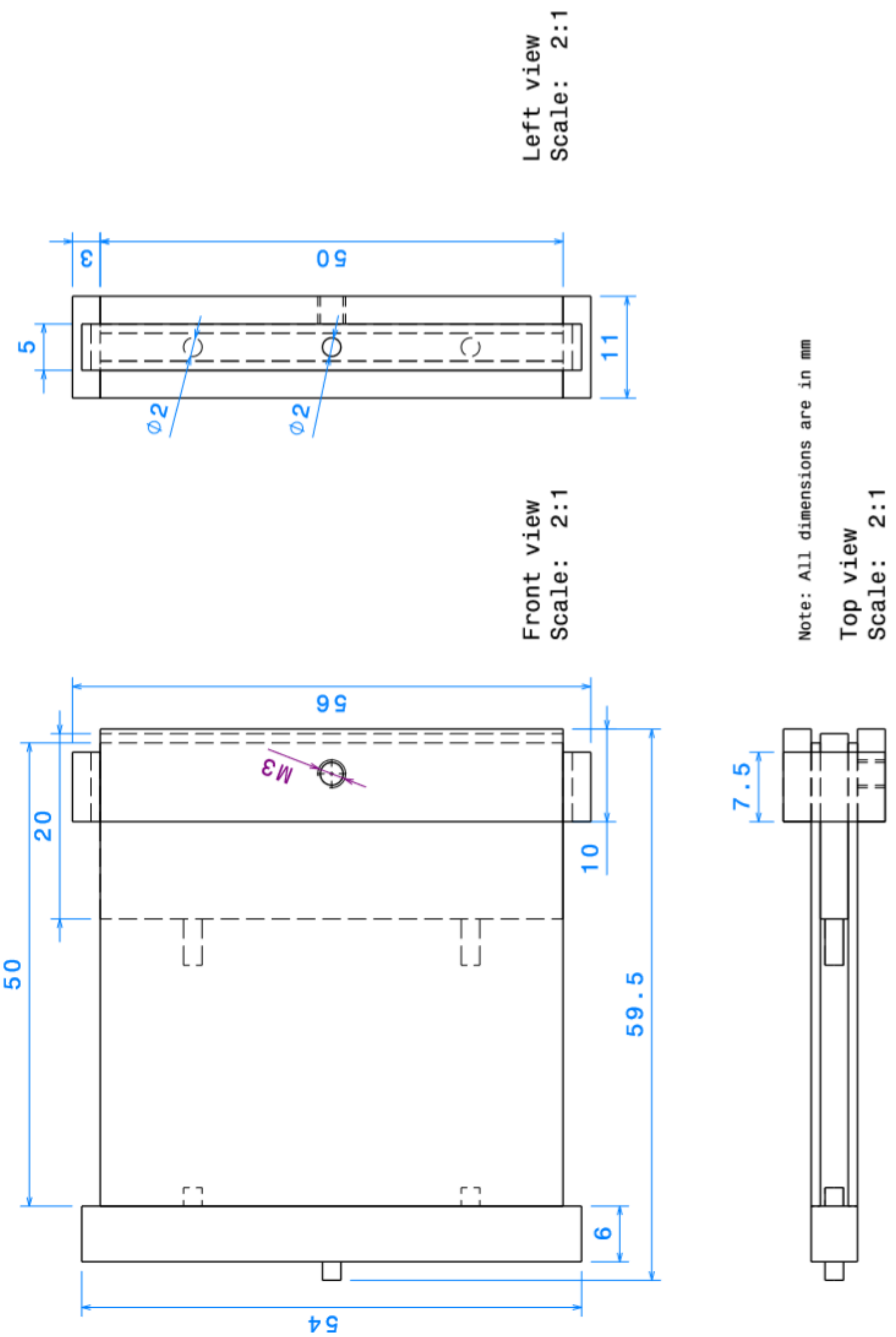
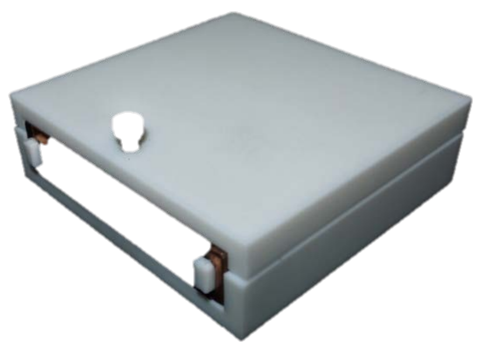


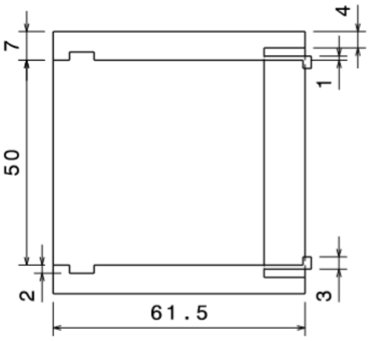
Isometric view
Scale: 2:1

e

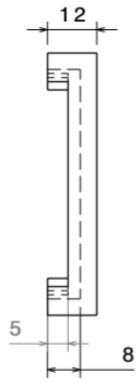
Appendix C: Plate VAT and its Feeding Mechanism Design Summary





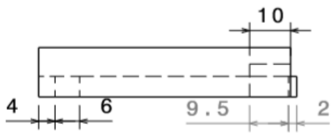


Front view
Scale: 1:1

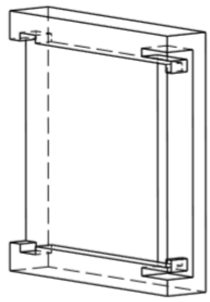


Note: All dimensions are in mm

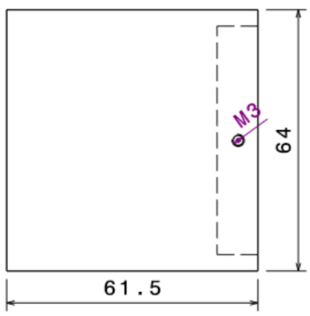
Left view
Scale: 1:1



Top view
Scale: 1:1



Isometric view
Scale: 1:1



Front view
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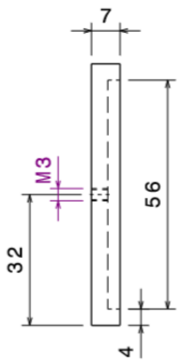
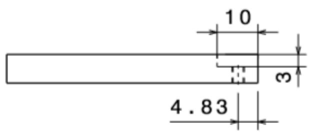


Note: All dimensions are in mm

Left view
Scale: 1:1



Top view
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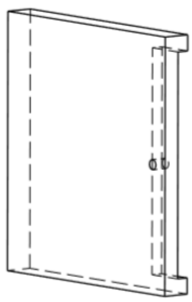

Isometric view
Scale: 1:1

Appendix D: Gantt Chart