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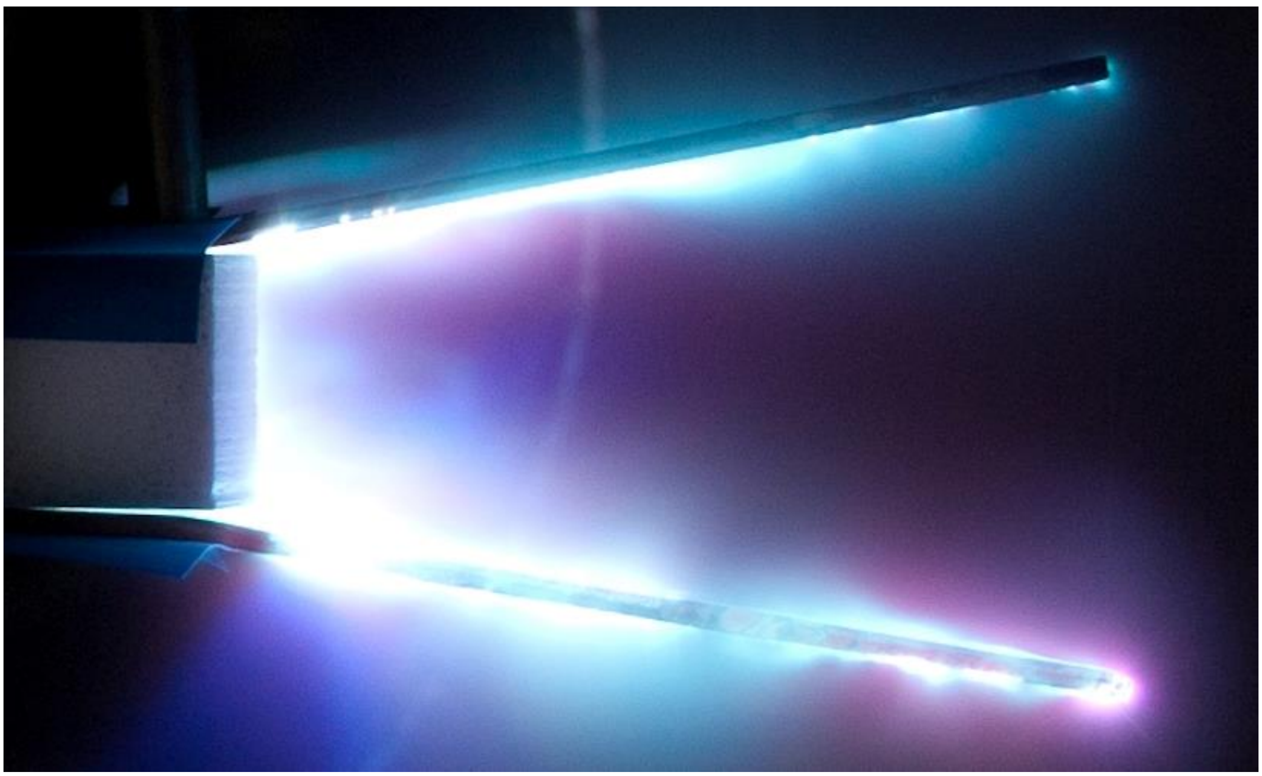
National Cheng Kung University

Zap Lab, Tainan, Taiwan

“Design and improvement of a double stage pulsed plasma thruster for micro Cube Sat”



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Tainan, Taiwan – August-September 2017

ACKNOWLEDGEMENT

I would like to address a special thanks to Professor Li Yueh-Heng for giving me the opportunity to work and learn about such a fascinating project as the conception of micro thruster. Thanks to his advices, availability and kindness, I was able to design and manufacture my own thruster. I would also like to acknowledge my co-worker Clémence ROYER and the master student Sunil KUMAR for sharing they knowledge about plasma and for their support throughout this project.

Finally, I would like to acknowledge the entire ZAP Lab team and wish them all the best for the future.

Key words:

Space propulsion

Pulsed plasma thruster

Double stage pulsed plasma thruster

Latest Time Ablation

Catia (V5)

Taiwan

About this document:

The present report contains researches, ideas and work done during my Master internship. Researches have been made in the Zap Lab of Professor Li Yueh-Heng, in the Department of Aeronautics and Astrophysics of the prestigious National Cheng Kung University (NCKU-Tainan-Taiwan).

This document is focused on the achievement of a design for a double stage pulsed plasma thruster with the help of Catia V5. This work was also based on the researches regarding space propulsion needed to understand and realize the micro thruster. In the next sections, a description of the existing built of PPT, all plan of the one realized and manufactured but also all documents related to the development of an additional piece imagined to improve the efficiency of this thruster will be documented.

CONTENT:

SUMMARY SHEET URBIETA Victor-INTERNSHIP-EP	
Internship subject	**Objectives**
" Design and improvement of a double stage pulsed plasma thruster for micro cube sat"	The objective of this internship is to design a prototype of a micro thruster using plasma pulsed and solid propellant
Internship location	**Used software**
Zap Lab Department of Aeronautics and Astrophysics National Cheng Kung University Tainan, Taiwan	CatiaV5, Excel, PowerPoint
Achieved study	
-Study, researches and state of the art of the existing propulsion system used for small spacecraft - Software assisted design of a prototype of micro thruster - Manufacture - Creation and manufacture of an additional piece to increase exit velocity of the late-time ablation	
Results	**Explanations**
- The size of the thruster is less than 10cm - The cost of the thruster is under 100 euros - Unfortunately, the experiment haven't been done before my departure	- All pieces have been optimized to be the lighter possible - The use of copper instead of silver or polythene instead of Teflon to design some pieces mainly participate to reduce the final price
Future work	**Obstacles**
- The experiment should be done - Analyze the result and conclude about the advantages of the second stage of electrode and about the additional nozzle - Reduce the reduction ratio of the nozzle to increase efficiency - Optimization of the prototype to produce the final design	- Manufacture times - Internship length

INTRODUCTION

Space field always was a fascination for Humanity, we try to go further, faster and we still small in comparison to the Space immensity. Today with the Ariane6 or the creativity of SpaceX, Space Industry is in good progression. Each new spacecraft have the last technologies on board, thanks to many years of work and studies from best minds in the word.

In the continuity of my engineering studies, I have the opportunity to perform an internship at the end of my first year of Master degree. Following that, I decided to link one of my study goal and one of my future work ambition which are: to participate at some university research program on laboratory and become an Aerospace propulsion expert. According to the previous fact, I decided to come to the National Cheng Kung University and join the Zap Lab (Zic and partners laboratory), student laboratory of Professor Yueh-Heng Li, part of the Department of Aeronautics and Astrophysics (DAA) from NCKU in Taiwan. This internship lasted one month since the August28^{TH}. During this time I joined the Zap lab, with the project to design a double stage pulsed plasma micro thruster for micro Cube Sat.

The goal was to design a micro thruster using pulsed plasma and a solid propellant that is able to create a small thrust with the first stage of electrodes, but also to improve its efficiency thanks to the second stage of electrodes. My internship length was very short, so the initial goal was to understand plasma physics and how pulsed plasma thrusters works. Then designing on CATIAV5 a suitable prototype for laboratory experiments. But I was able, thanks to Professor Li and Mister Lee, to also manufacture the micro thruster.

In this document, we will describe my work environment in the DAA, then we will focus on each task I accomplish during my researches and develop the technical aspect of my micro thruster.

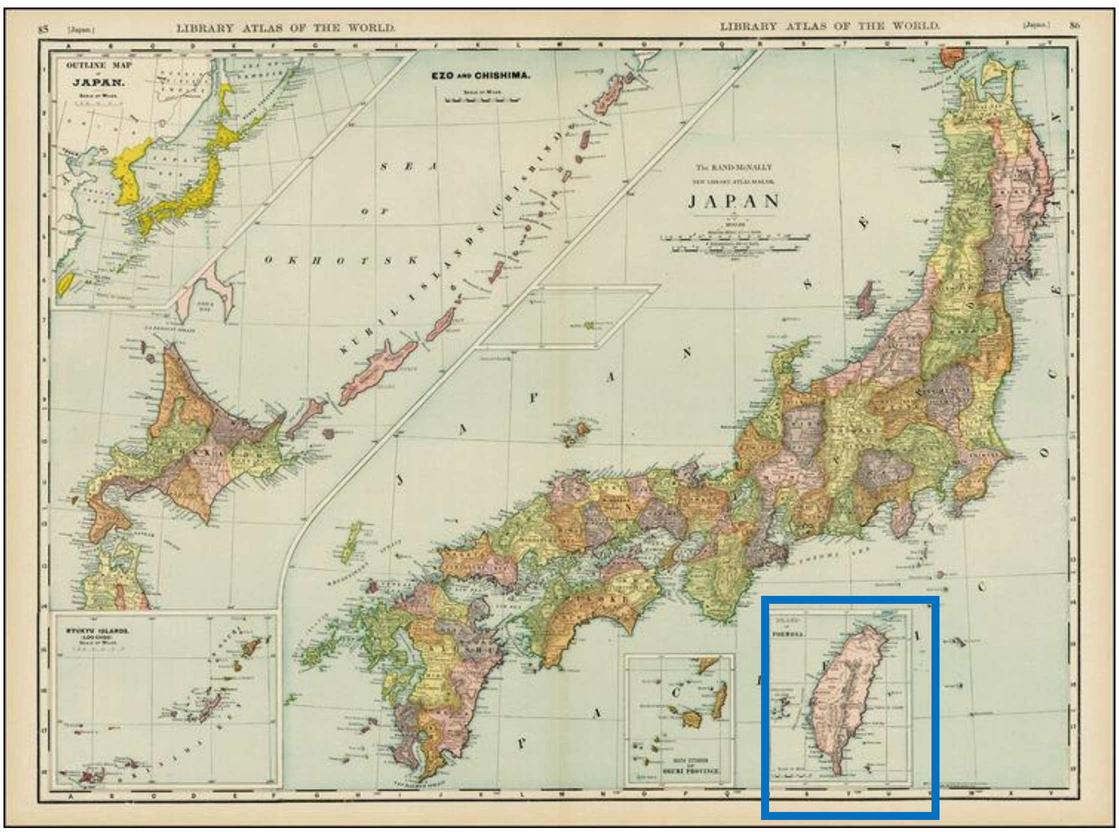
I. Taiwan, an isle with a lot of unknown resources.

I.I) Formosa Island

Taiwan, or by is official name Republic of China (ROC), is the most populous state and the largest economy that is not part of the United Nations. Located in the East of Asia, this island is surrounded by Japan, China and the Philippines islands. Due to its location, Taiwan have been under many different dominations, originally inhabited by aboriginals, the island have been colonized by Dutch and Spanish at the 17th century. From this point, Taiwan become massively colonized by Han peoples (Chinese people) and goes to the Qing dynasty (Last dynasty of China) until they ceded the Island to Japanese in the 19th century after Sino-Japanese war.

During the 60s, Taiwan has been under a rapid economic growth and industrialization period witch create a stable economy based on a strong industry. By the time Taiwan reach to the 22nd largest economy in the world and its high-tech industry is very important in the global economy. Today, Taiwan is highly ranked in term of healthcare, freedom of press or public education.

In fact, Formosa Island is one of the most highly educated countries in the world with a very high percentage of Taiwanese people whose hold a tertiary education degree.

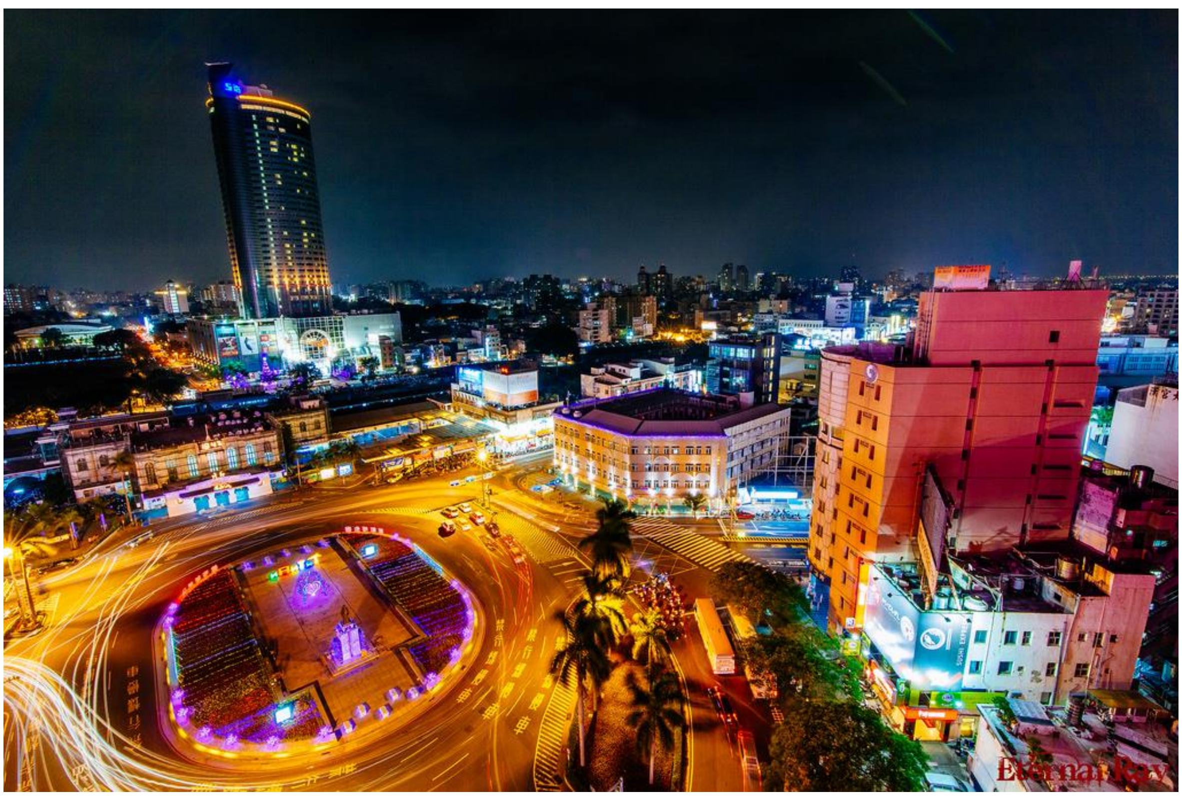


Map representing Japan and its territories after Sino-Japanese war

Satellite picture of the Island and some tea culture made in Alishan Mountain

I.II) The old Capital and the prestigious National Cheng Kung University.

Since 1949, Tainan was the capital city instead of Taipei, it still one of the biggest city of the island with a population of 750 000 people. Tainan retain a major part of the Taiwanese cultural capital, in fact, this city has more temples than any other town and lot of historical monuments.



City center of Tainan with the Main train Station

For a better understanding of the place of NCKU in Taiwan's tertiary education, it is important to remind that The National Cheng Kung University was founded during Japanese domination in 1931.

Today NCKU figures as part of the best public university in Taiwan (ranked as 4^{th} according to QS world best university), and is worldwide well known for its results in Engineering, Medicine, Computer Science or many other subject studied through the 40 different departments. The campus is located in the city center of Tainan, divided in 9 different colleges, where more than 22 000 students are living and improving their knowledge.

I.III) Working on the ZAPLab in the center of the Aeronautics and Astrophysics Department.

Initially, in 1972, the Mechanical Engineering Department of NCKU had a small division called "division of Aeronautics". From this foundation and with the help of the institute of Aeronautics and Astronautics, the DAA was created in 1985.

Research is the major component of every day's activities done in the DAA. Inside it doors, more than 26 laboratories composed by master and Phd students, are sharing high technologies facilities for completing successfully their researches. To have a better understanding of the potential research resources of the laboratories, I will list some of them:

- A combustion and jet propulsion laboratory, including several fluid visualization and analysis device as high speed photography optical systems
- An Aerodynamic and hydrodynamic laboratory equipped with wind and water tunnels, shock wave tube and many other useful devices
- A structural and material lab, for studying crack and hole interaction, stress or vibrations propagations on systems
- A navigation and control facility where microcontrollers, drones or signal processing equipment are created
- A photoelectric laboratory where sustainable energies are studied

Also, in each lab, many tools are available for manufacturing needs or for experiment preparations.

Moreover, the DAA works with the Aerospace center of Tainan which is located outside the city center, which allow the university to access to many other materials like Aircraft engines or Drones like you can see on the following picture I took during my month there.

Picture of some facilities of the DAA

The Department of Aeronautics and Astrophysics is one of the most active department on the university, more than eight hundred thesis and publications have already been done and each lab try to always work on renew subjects or field according to the one available (around more than 20 per years).

Past year, I already spent my abroad semester in the DAA and it was very rewarding on many fields. So this year, I got the opportunity to join the ZAP lab of Professor LI Yueh-Heng to work on designing a double stage pulsed plasma thruster for micro Cube Sat.

For this internship, I got the opportunity to work and exchange with Professor Li. He owns a Phd from NCKU and is area of expertise are clean fuel combustion, laser diagnostic, micro-scale power system and energy system and thermo-photovoltaic power system. His laboratory, the ZAP lab is composed by more than 16 postgraduate and master students, all working on subjects such as micro combustion and propulsion (the subject of my internship), clean fuel combustion, biomass energy or again thermo-photovoltaic energy.

The Zap lab students are very active, like Chien-chun Kao which win this year the grant best innovation award from National Industrial Energy Saving competition for is work on Cogeneration power system of thermo-photovoltaic cell array combined with Stirling Engineering.

From the time I spent in this lab, I have been working principally with the help of two master students: the first one is my co-worker on this project Royer Clémence, French student whose research field concern micro thrusters and physic of plasma. She is currently doing her master degree in the ZAP lab and she is now working on the development and the manufacturing of a device able to detect and measure micro thrust about one or less Newton. The work I achieve during this internship was in collaboration with her and decisions about the design have been take after long reflection and discussion together. The second student I worked with is Sunil Kumar from India. Sunil who is actually finishing his master degree in the ZAP Lab, and has been a very relevant advisor because of its previous work on single stage micro pulsed plasma thruster using gas and solid propellant.

During this internship and as intern student of the ZAP Lab, I was invited to join every Monday evening, a laboratory meeting which starts at seven post meridiem and usually finishes around eleven. These meetings were an opportunity for students to present their work advancement on researches to professor Li and every other students. Presenting to all students of the laboratory, even if there are not working on the same field, allows questions to come from an external point of view and maybe put in advance point we didn't think about before. If students don't have results or progression to present from a week to another, they are allow to present scientific article or journals linked to the research field. Joining this meeting has been for me a great opportunity to learn about topics I didn't know, like flame comportment and I was able to understand most of the presentation because they were mainly presented in English.

Even if my internship was very short, only one month, I was allowed to present my work after asking to Professor Li and it was really benefit for the advancement of my researches.

Zic and Partners Laboratory Logo

II. Design of the double stage pulsed plasma thruster for micro Cube sat

II.I) What is actually existing in term of micro thrusters for spacecraft?

First of all, before trying to do anything, I was asked to understand how Space Propulsion work. According to that goal, a document analysis and review was needed to understand all different propulsion systems used and figure all benefits or disadvantages of each.

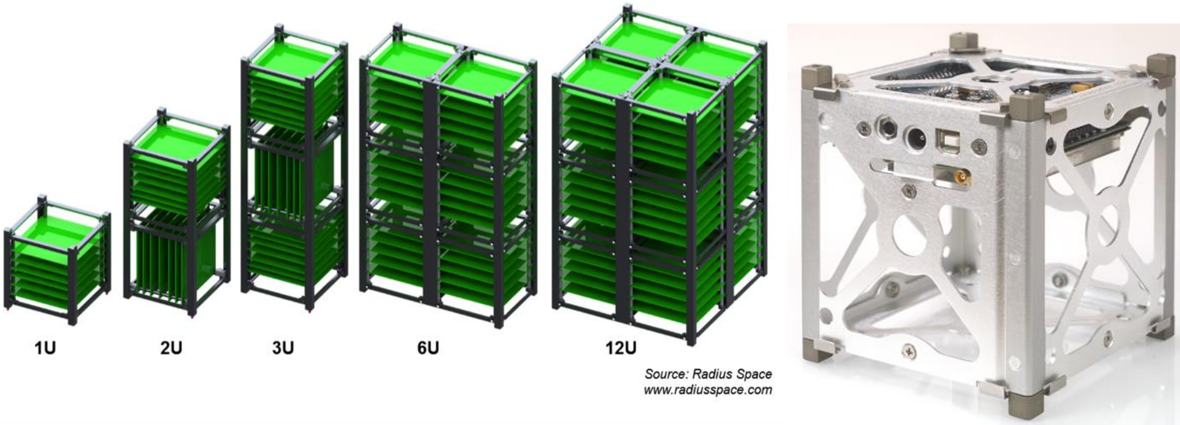
I really would like to become a propulsion expert, so it was for me the opportunity to learn a lot about a subject I didn't know before. Anyway, because of my internship length, it was very important not to waste any time, so in this part, I will only develop information about small spacecraft propulsion.

Today in the most of industries, saving cost is very important, this is why space system trends to become smaller and smaller. In the past few years, the development of miniaturized satellites become a growing trend and new designations like nano-satellites or cube sats appears. But it is important to understand what does it mean and what are the differences between all little satellites. Earlier in this report, we was talking about small-satellites, this terminology is used for spacecraft with a mass less than 180 kg and with a size about a big kitchen refrigerator. But we have to know that in small satellites, you can find five more categories to classify, by size and weight, satellites:

The first category is Mini-satellites, they used to designate spacecraft from 100 to 180 kg of total mass. After, if we continue to reduce the size, it becomes a Micro-satellite if the mass is comprised between 10 to 100 kg. For us, this is the most important category, because all the work done during this internship was for create a micro thruster for that kind of satellites (10 kg). Following the mass reduction it becomes a Nano-satellite if the total mass is 1 to 10 kg. At least it is possible to reduce again the weight to finally reach at 0.01 to 1 for Pico-satellites or at 0.001 to 0.01 kg for Femto-satellites.

The use of small satellites for space exploration has begun more than forty years ago with the launch of Pioneer 10 and 11 in March 1972 and April 1973, and it also play an important role with lunar exploration using Lunar Prospector (launch in 1998).

Another terminology we have used previously was "Cube sat" and this one is particularly important to define: Cube Sats are a class of small satellites with a standardized shape, size and weight. This standardization is using a "one unit" or "1U" which correspond to 10*10*10 cm cube and 1.33kg, and this "one unit" can be extendable from 1 to 12U. Originally developed by universities in 1999 to provide a platform for education and space exploration, Cube Sats own now his proper industry supported by government and the capabilities of this small device isn't ready to decrease.



Representation of the U scale on left and one U Cube Sat on right fig (1)

If Cube Sats or more generally, small satellites, meet with success in today's industry, it is mainly because three reasons:

-Production and launch cost are significantly reduced

- Flexibility is increased by creating constellation of Micro Sats

- Risk of losses or impact decreased

Furthermore, the miniaturization of satellites have been possible only by the technology improvement about Micro-Electro-Mechanical Systems which allow the creation of micro systems like micro fuel cells, actuators or again micro gyroscopes. Improvement of this kind, are responsible to the amelioration of spacecraft abilities, longevity and loses weight. However, miniaturization isn't always the better thing for components, some of them like high pressure fuel tanks are very difficult to miniaturize relevantly and for small cost. The last point developed is one of the reasons we chose to create a thruster using solid propellant and not gas propellant.

Following my documentation researches, it was important now to focus on the existing micro thrusters using plasma to be able to create the most relevant and economical prototype.

By present time, space industry is using two major propulsion systems and each of them presents his set of advantages and disadvantages. Number of different spacecraft propulsions systems have been integrated and tested on small spacecraft, but it was always using chemical or electrical propulsion. In our case, we will work on a device using electrical propulsion, so this part will be more detailed than the chemical one.

About **chemical propulsion,** this technology is used since 90 years and it is known as the "rocket propulsion system". Chemical rockets are using a chemical reaction to heat gas and win in enthalpy. This thermal energy is after converted in thrust.

To have a better understanding of the operating way of chemical propulsion, we will take the example of a solid propellant engine:

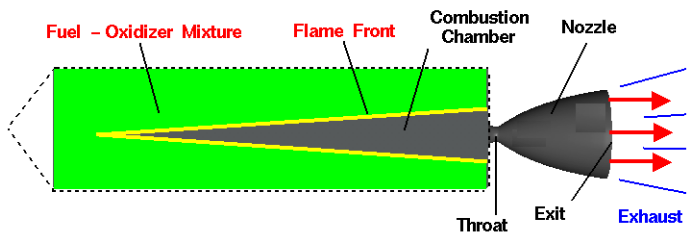


Figure representing a solid propellant engine using chemical propulsion fig (2)

The first step of the chemical reaction is the mixture of the fuel and oxidizer. Once the first step is done, ignitors will be used to initiate the combustion in order to increase gas temperature. The burning step obviously takes place on the combustion chamber. After burned gas are full of thermal energy, they will expand to a nozzle and this expansion will be the source of the thrust created.

Here we have talk about solid propellant and it is one of the three existing categories for chemical propulsion. The two others categories are: liquid propulsion which include Mono and Bi-propellant and finally hybrid propulsion using solid and liquid propellant.

Chemical propulsion presents many advantages like, for solid propellant, a very simple design for high thrust and many years of development. Anyway, the major issue of chemical propulsion is its fuel consumption with low specific impulse (I_{sp} =100 to 500s, it is used to measure the efficiency of thrusters). Also for that kind of propulsion you will need a lot of fuel, which will gives extremely high cost of launches.

About **Electrical propulsion**, it has been created to do exactly the same work as chemical propulsion but with some noteworthy differences. If we look closer to the technical aspect of electrical propulsion, we can say that it use onboard chemical power to create and accelerate a plasma in order to create thrust. Comparing to chemical propulsion, we notice that electrical propulsion have very low thrust, acceleration take time and it can have potential lifetime issues. But in the other side, chemical propulsion have a higher exhaust velocity, higher propellant efficiency so a higher specific impulse (about 700 to more than 10 000s). Also, electric propulsion can provide small thrust for very long time and achieve very high speeds over long period (because constant acceleration), which is more relevant, if you need to achieve deep space mission that doesn't need fast maneuver.

As chemical propulsion, electrical one, can be separated in three major types:

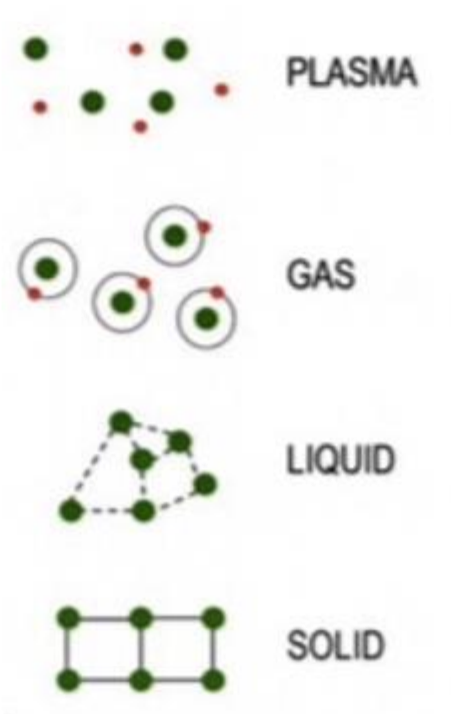
Electro-thermal: it uses electricity to heat neutral gas, a small amount of gas will be ionized to create an arc and the rest of the gas will pass through the arc and be accelerated. This kind of electrical propulsion is useful because it have a simple design and an efficiency of 30 to 50 per cent. This technology is often used on “Arcjet”.

Electro-static: it uses a static electric field and sometime a static magnetic field to accelerate the plasma created. Anyway the magnetic field, is not always used and it only serves to confine the plasma. This technology finds an application on “Gridded Ion thrusters”.

Electro-magnetic: it use electric and magnetic field to create plasma from the propellant and accelerate it between two electrodes. We will use this technology on our prototype of micro thruster, so we will spend a bit more time on it to understand well the mechanisms of pulsed plasma thrusters.

Nowadays, is it possible to create PPT using gas propellant but, because its design is simpler and cheaper we chose to design a PPT using Teflon as solid propellant.

It is important at this point, to give a definition of what is a plasma and the simplest definition is: Plasma is a form of matter in which the electron shift freely and in any direction among the nuclei of atoms. Plasma is only created at very high temperature (about 10000K) and it has been called the fourth state of matter.

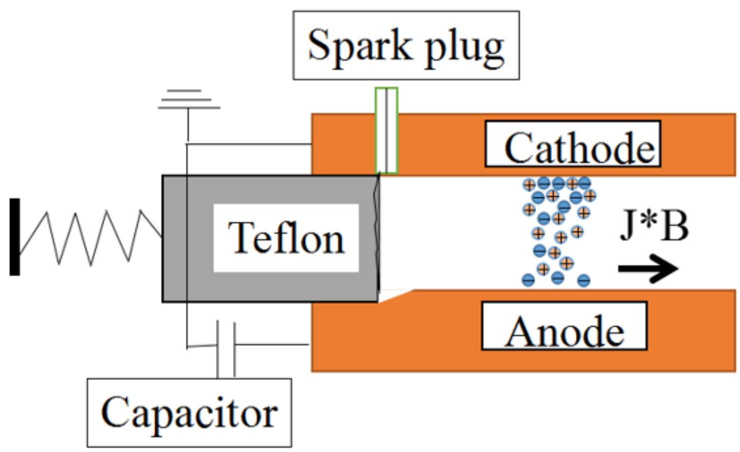


Here it is an illustration of the electron (in red and nuclei in green), behavior for each state of matter fig (3)

Moreover, a volume of plasma is considered as neutral, there is an equal number of positive and negative particles. For plasma particles, interactions can be made with more distance than for gas, thanks to Colombian law. This kind of interactions vary as function of the charge of particles. If two particles charges are similar, they will be repulsive and attractive if they are opposites. We can found Natural plasma in the Wild for instance in thunder or flames.

At this point, we have a more precise idea of what a plasma is, we should now be able to understand how it is used to create thrust for Cube Sats.

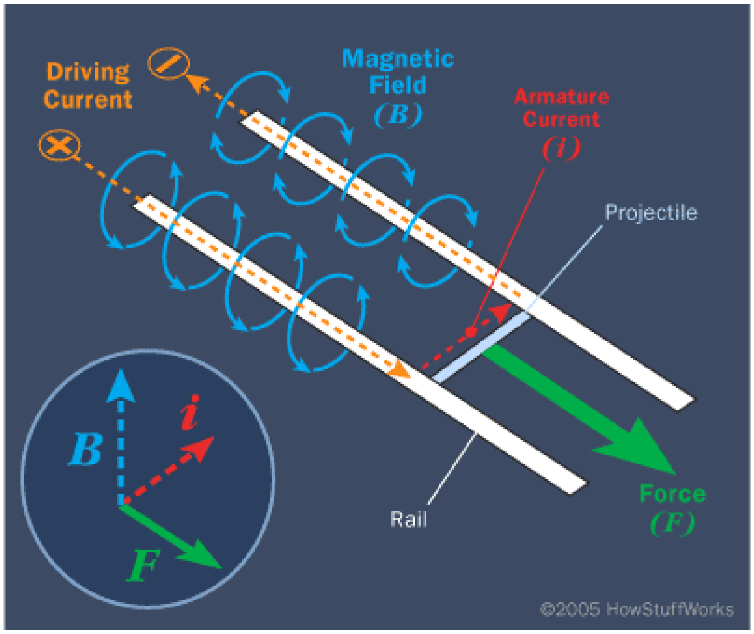
Pulsed plasma thruster have one of the simplest architecture compared to other thrusters, it is composed of two electrodes (a cathode and an anode), an ignitor, a scare of Teflon as propellant, and finally a spring to contentiously feed the transformation. The creation of thrust with a PPT use an electrical current between two electrodes. To create this current, a high voltage capacitor is used. This device is able to be charged, with the help of a power supply and to release this energy quickly.



Single stage pulsed plasma thruster illustrating the plasma acceleration fig (4)

The next step of the total mechanism is the ignition. The spark plug creates a discharge, this reaction initiate an arc and some electrons are release. The electrons will now hit the propellant in order to create more electrons. After, all the released electrons will create a link between the cathode and the anode, initially loaded by high voltage, to enable the current flow in the system.

Finally, due to the magnetic field and the Lorentz force, the plasma created by the link of electrons, will be accelerate and expulsed at very high velocity from the electrode, creating at the same time a small thrust.



Representation of the Current and magnetic field application to create thrust from Lorentz force fig (5)

Single stage pulsed plasma thruster like the one presented just before are working very well, anyway it doesn't take into account one parameter called "late-time ablation" composed by gas and macro particles.

LTA is a phenomena created by the sublimation of the propellant and it take place after the main discharge. LTA is created because the temperature inside the PPT reach close to the sublimation temperature of the Teflon or Polytetrafluoroethylene and this phenomena is mainly responsible of the poor propellant efficiency. So we decided to add a second stage of electrodes, in order to accelerate this LTA and increase significantly the efficiency of our PPT. We will develop in the next part, every choices and decisions takes to create a relevant design of double stage pulsed plasma thruster.

II.II) Technical review of all calculations and design choices made to create a prototype:

For the following part of this report, some data or assumption have been made using a paper about the work made by searchers of the University of Southampton, United Kingdom.

"Design of a Two-Stage PPT for Cubesat Application" is a paper presented at the 31st International Electric Propulsion Conference by M. Coletti, R. Intini Marques and S. B. Gabriel in 2009. The following paper was a really good base to understand the basis information needed to be able to design our prototype on only one month. In such a way, we decide to use two parameters from this previous work, as starting point of our study, we will use a **voltage of 1 kV** and a **capacitor of 3 micro Farads**. Also, we have fix the power of our **power supply at 1 W** because NCKU already had this one. This is important to determine many parameters as current needed or charging time of the capacitor because we try to realize a prototype able to be tested in the laboratories of the DAA.

Now we will calculate all important parameters needed to realize our double stage PPT.

We start by determining the energy supplied to the capacitor:

$$E = \frac{1}{2} C V^2 = \mathbf{1,5\, J}$$

From the last equation we are now able to determine the resistance intensity and the electrical current:

$$R = \frac{V^2}{P} = \mathbf{1\, M\Omega}$$

$$I = \frac{P}{U} = 1.10^{-3} A = \mathbf{1\, mA}$$

Now we focus on the time needed by the capacitor to be charged, this time will represent the time interval between each discharges during the experiment. Using the following chart, we can determine the time and frequency:

$$T = 5\, RC = \mathbf{15 s}$$

$$f = \frac{1}{T} = \mathbf{0,067\, Hz}$$

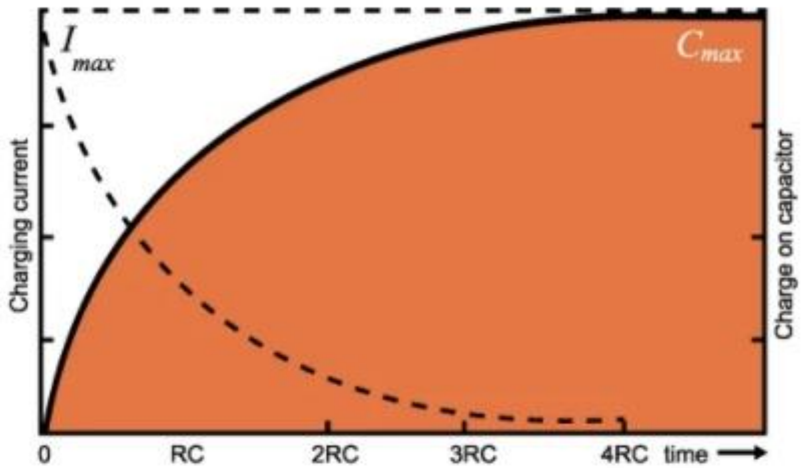


Chart used to determine the Charging time of the capacitor fig (6)

In addition to that, it is important now to determine the dimension of our set of electrode in order to create the most efficient prototype. We are limited at a power unit of 1W, we should focus on the resistivity of each components and try to make this resistivity as less as possible.

Each material are resistant to current and the general induced resistance of a material is represented by the following formula:

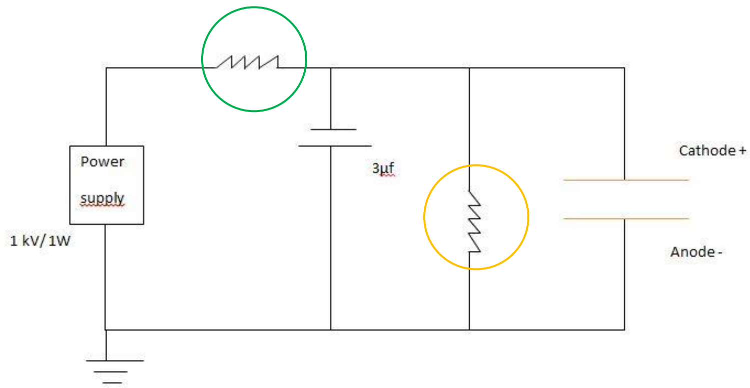
$$R_w = \frac{\rho\, l}{A}$$

A is the area of the wire in mm^2

ρ is the resistivity of the wire material in nΩm

l is the lenght of the wire in m

For the need of our PPT, we have also created the following electrical circuit. The use of two identical circuits, one for the first set and one for the second set is important. Also the ignition module will have its own circuit.



Electrical circuit of the thruster (need two identical to lead the prototype) fig (7)

The first resistance, in green, is here to protect all the system of the high voltage and the second one in orange is here to protect us during the experiment time (but it is "optional" so the following calculation will only speak about the green one).

According to electrical rule, we find the expression of the equivalent resistance induced by electrode and wire as:

$$R_{eq} = \frac{R_w R_e}{R_w + R_e} \ (1)$$

And we know, that electrode induced resistance can be express as $R_e = 2 * \frac{\rho\, t}{w\, h}$ and wire induced resistance as $R_w = \frac{\rho\, l}{\frac{\pi\, \emptyset^2}{4}}$.

By integrating the two last equations in (1) we are able to find:

$$R_{eq} = \frac{\left(\frac{\rho\, l}{\frac{\pi\, \emptyset^2}{4}}\right) * \left(2 * \frac{\rho\, t}{w\, h}\right)}{\frac{\rho\, l}{\frac{\pi\, \emptyset^2}{4}} + \left(2 * \frac{\rho\, t}{w\, h}\right)}$$

$$R_{eq} = \frac{4\, \rho\, l}{2l\, w\, h + t\, \emptyset^2\, \pi}$$

Fixing the following data:

-wire diameter $\emptyset = \mathbf{2,5}\boldsymbol{mm}$

-Maximum wire length between the capacitor and electrodes $\boldsymbol{l} = \mathbf{1}\boldsymbol{m}$; this value have to be the smallest as possible to reduce losses in the wires

- Electrodes thickness t = **2 mm**

We can do the numerical application to get the value of our equivalent resistance:

$$R_{eq} = \frac{4*1,68\ .10^{-8}*1}{2*1*\ w\ h+0,002*\ 0,0025^2\ \pi} = \mathbf{8,4.10^{-5}}\boldsymbol{\Omega} \text{ for a } w*h = \ 4.10^{-4}m^2$$

Moreover, it is very important to choose the material of our electrodes. For that we compare different material resistivity value for an ambient temperature of 20 $°C$.

Material	Resistivity ρ
Aluminium	$2,65\,.10^{-8}\Omega m$
Silver	$1,59\ .10^{-8}\Omega m$
Copper	$1,68\ .10^{-8}\Omega m$
Iron	$9,71\ .10^{-8}\Omega m$

If we look closer to the tab, we can easily deduce that the best material for or prototype is Silver because it have the smallest resistivity. However, due to the cost of Silver, we choose to use copper because it presents the better compromise between low cost and low resistivity. Thus, the electrodes of our prototype will be made of copper.

We are now focusing the sizing of our electrodes, we choose to consider the width of our electrode as $w = 0{,}015m = \mathbf{1{,}5}\boldsymbol{cm}$.

Helping by the following chart, we deduce h the height of our electrode.

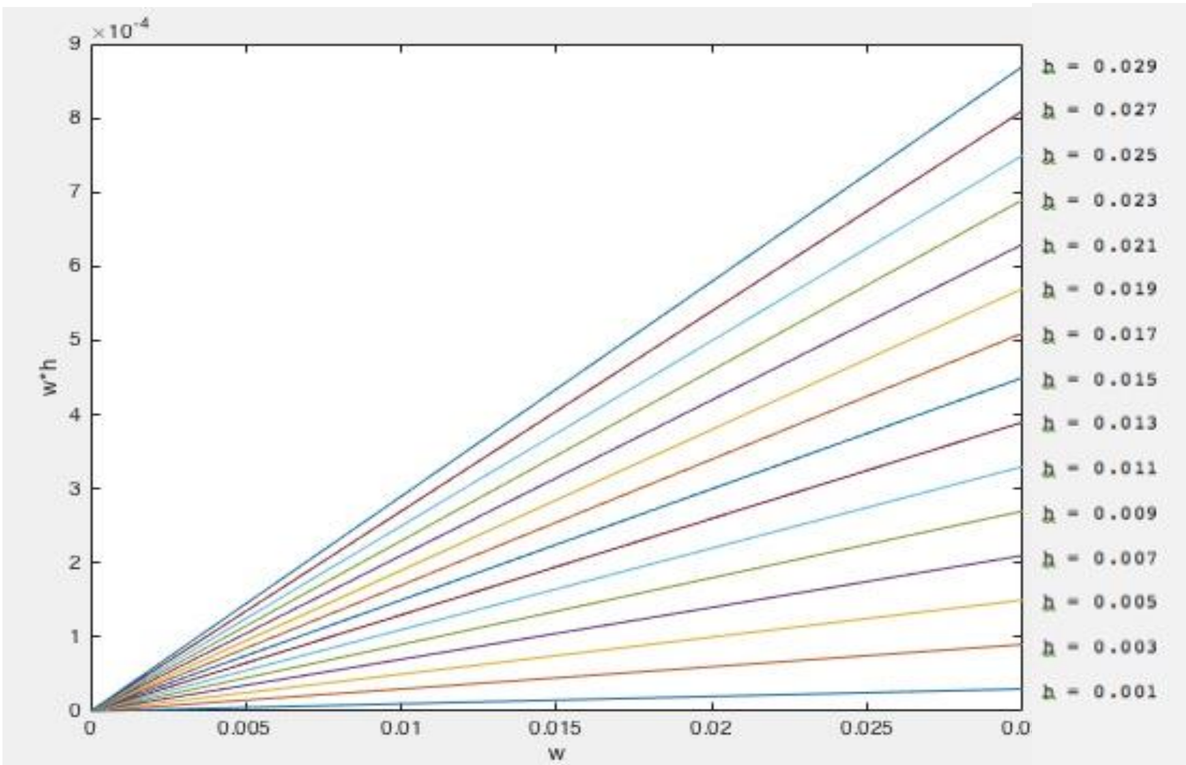


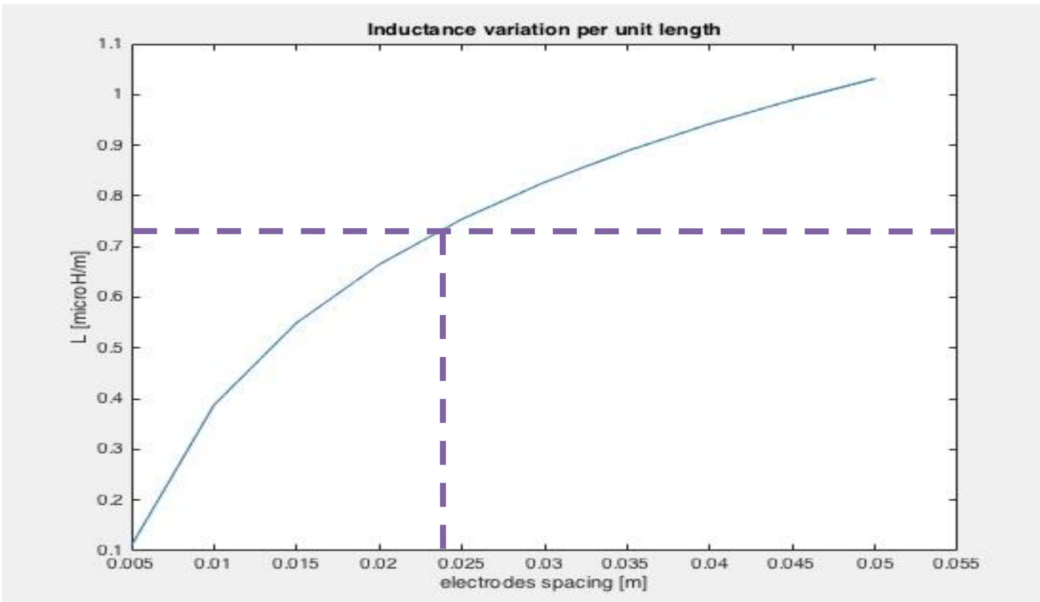
Chart presenting the width and the width by the height of electrode fig (8)

Indeed, it gave us an height of 0.027m or **2.7 cm**. We have already the height, the thickness and the width but we still need to determine the spacing between the cathode and the anode which will produce more thrust. At the point, we have use once again the data from the scientific paper and we are able to determine the inductance variation per unit of length:

With $L' = 0,6 + 0,4\ \ln(\frac{spacing}{w+t})$

But in this paper, we can also find a ratio which is very useful: $spacing/width = 2$

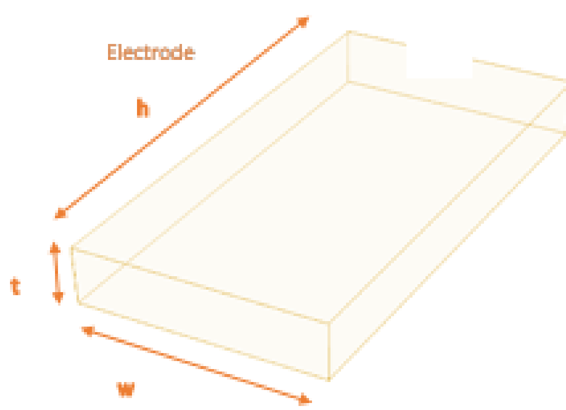
And we had already fix the width at 1.5cm so we found using the following chart$L' = 0{,}743 \mu H/m$.



Inductance variation per unit length fig (9)

Finally following the dots in purple we found by graphic lecture the spacing between our two electrodes would be equal to 0.024m or **2.4cm**.

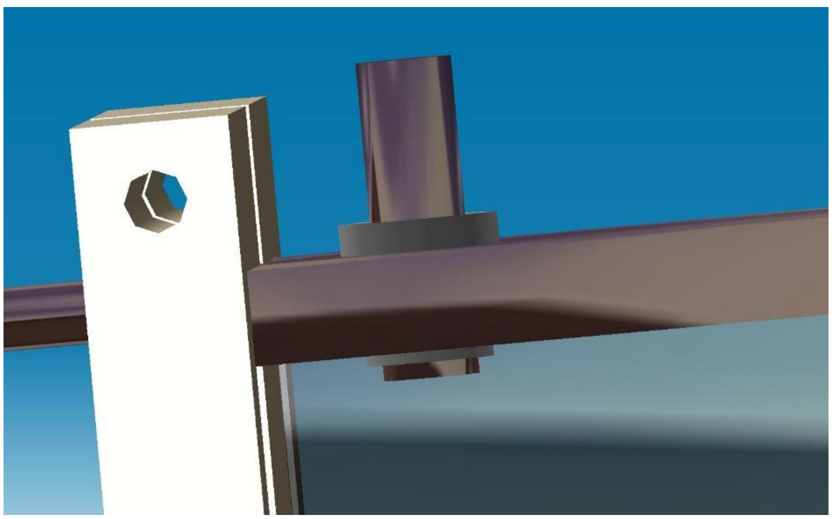
To summarize about electrode dimensions, we will have a height of 2.7cm, a width of 1.5cm, a thickness of 2 mm and finally a spacing of 2.4 cm.



II.III) 3D design presentation of the double stage pulsed plasma thruster

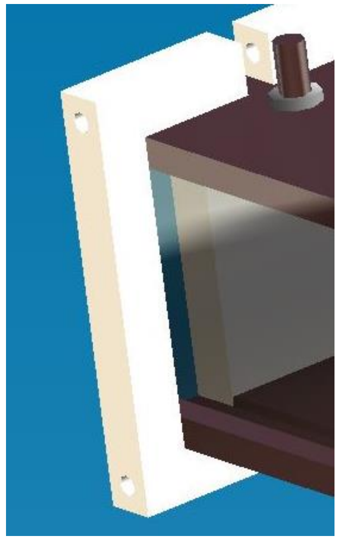
I this part, I will be presenting the 3D design highlight on the software CatiaV5 by my co-worker and myself. I will start by detailing some of the major components of the double stage PPT and I will finish by presenting the entire model.

First of all, I will talk about the ignitor. The main role of the ignitor is to give a small discharge or spark, which will initiate the transformation. This spark can be created by existing spark plug used on motorcycle or car engine. It is cheap and work really well. Anyway, we decide to create and use our spark plug instead of existing one because if we used an existing one we would have to design a hole of more than 0.5cm of diameter. It wouldn't be relevant according to the size of our electrode (only 1.5cm of w and 2.7cm of h). Our spark plug is smaller and lighter which is a very important detail to consider when you are designing cube sat thruster.



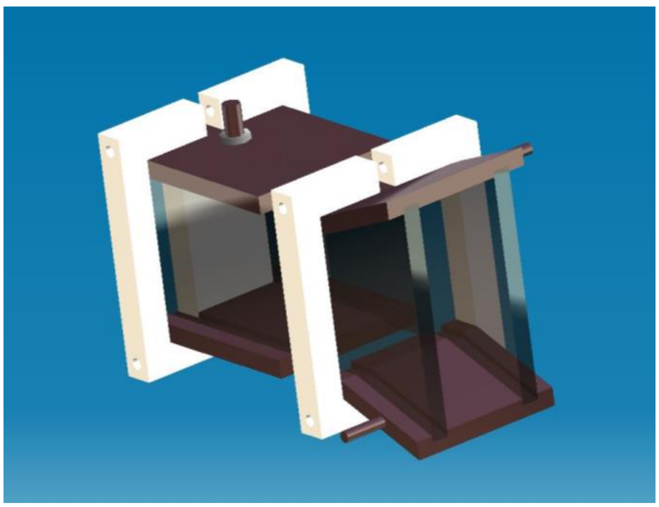
Catia picture of the spark plug designed fig (10)

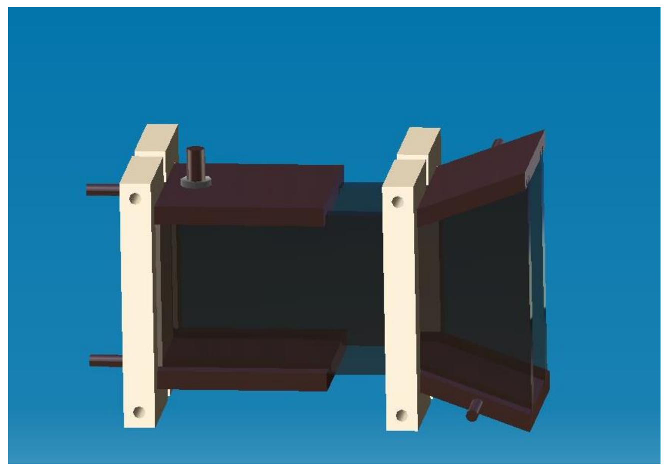
About the other components, like said before, we will use electrode made by copper. We will also need to use a material to contain the plasma inside the electrode, for that we will use quartz. A scare of Teflon will be our solid propellant. And finally, we have designed kind of "link" to hold the entire structure together. Here it was very important to once again choose a material which can be placed in a vacuum chamber, according to advice from other students, we choose to use polythene.



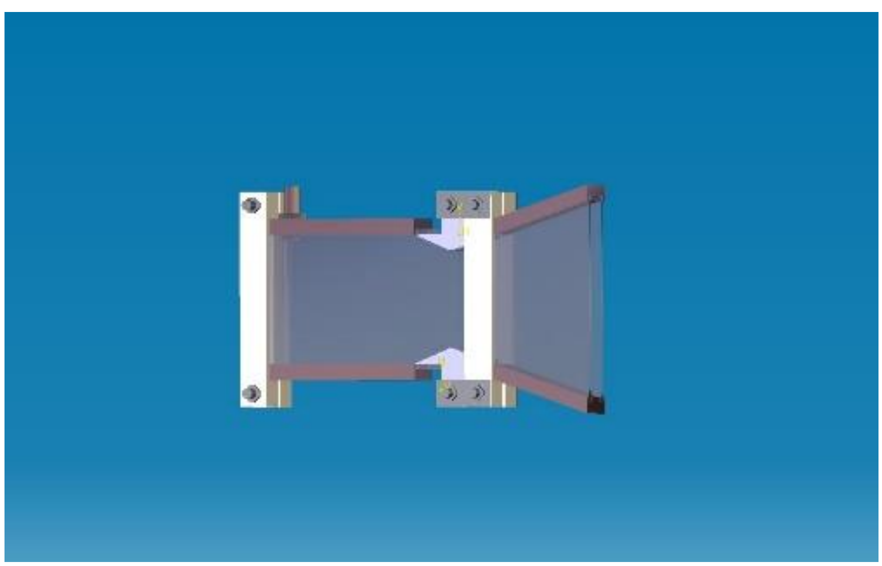
Attach created to maintain the two stages of electrodes together fig (11)

Now when main detail have been told, it is time to present the entire model designed.





Some screen shot of the Double stage Pulsed Plasma Thruster created fig (12,13,14)



Regarding to the pictures, we can see that the two set of electrodes doesn't have the same shape. The second set has an angle of 20 degree in order to increase the efficiency and the acceleration of the plasma.

If you look closer to the figure number 14, you may have notice an additional piece between the two sets of electrodes. This additional piece is the realization of an idea I got to improve the efficiency of our PPT.

As my first day as intern, I got the luck to assist at the experimentation of a single stage PPT designed by the master Student Sunil Kumar. During the experimentation, I see a picture of a double stage PPT and the "tongue" shape of the second set, as propulsion engineer, immediately make me think about an exhaust nozzle. After some discussions with my co-worker and with Professor Li, I have been allowed to design an additional piece.

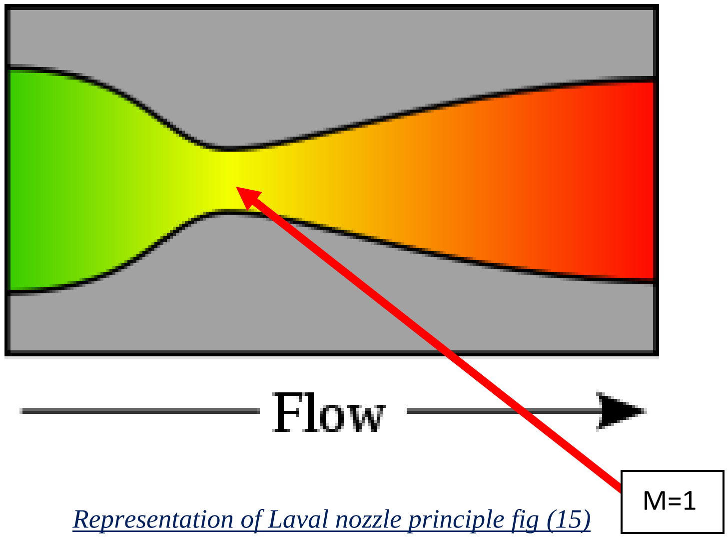
The purpose of the piece, is to improve the efficiency of the double stage PPT by creating a nozzle which will use Bernoulli equations, Venturi effect and flow conservation to create an additional acceleration.

The principle is mainly use in Rocket propulsion.

By reducing strongly and after increasing the area of a nozzle, it is possible to increase the flow velocity until Mach equal one at the neck of the nozzle. After the neck, flow velocity continue to increase until supersonic velocities.

This kind of nozzles, are called *Laval nozzle* in memory of its creator and are taking advantage to the heat increase of the gas to convert this energy in kinetic energy.

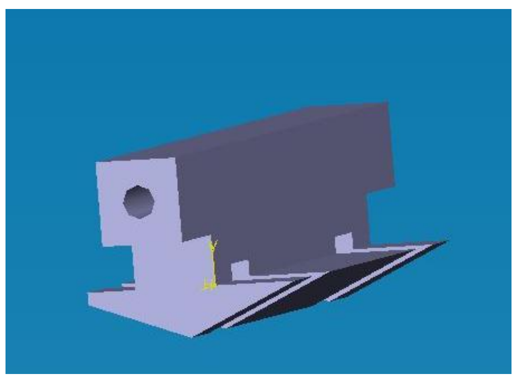
Actual rocket booster using the Laval Nozzle principle



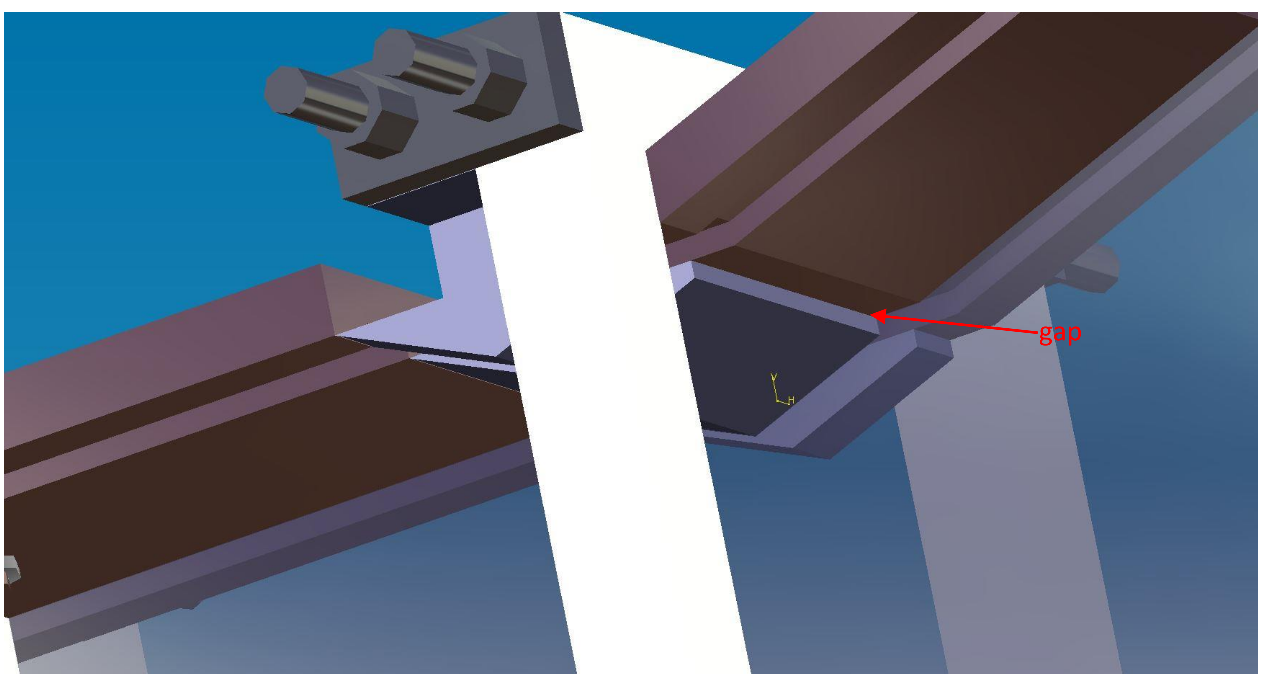
Representation of Laval nozzle principle fig (15)

Anyway, Laval nozzle only work for subsonic flow and the exhaust velocity of the plasma is between supersonic and hypersonic. So it is important to understand that this additional piece is here not to accelerate plasma but LTA.

The "nozzle" created fig(16)



Nozzle integrated on PPT fig(17)

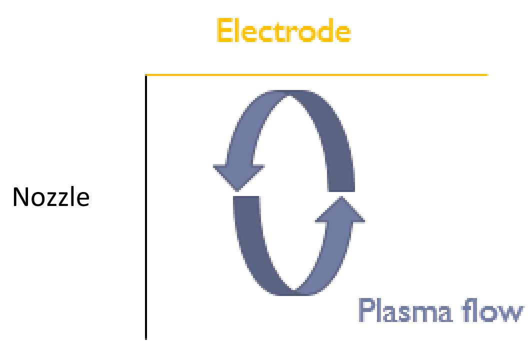


II.IV) Potential issues, manufacturing result and future work

Designing an additional piece was not a simple task. First of all because all the dimensions or design have been think in order to obtain the best efficiency for this PPT and add some weight could be disadvantageous. This is one of the reasons why the nozzle will be made in polythene to be light, cheap and easy to manufacture.

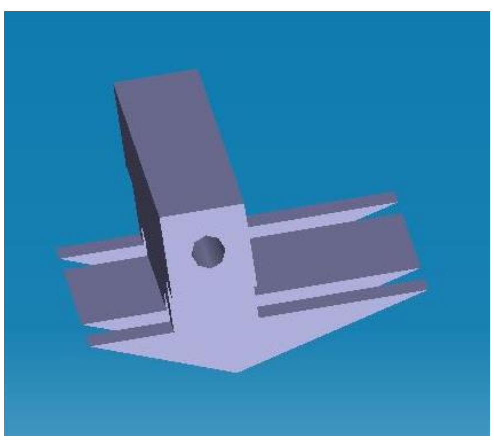
Another issue we had to face with the use of this nozzle is the speed reduction of the plasma. Previously, I explained the principle of the Laval Nozzle and precise that it was designed only to accelerate LTA which is a subsonic flow. But, plasma has a supersonic ejection speed and using a convergent-divergent nozzle normally reduce the speed of supersonic flow. Anyway, with some researches and discussion with my advisors and due to the special characteristics of the plasma, we decide to put a reduction ratio of the nozzle of only ¼. Following this idea, it should not affect too much the plasma flow and simultaneously increase exhaust velocity of the LTA.

Similarly, if we look closer to the figure 17, we can notice a small gap between the end of the nozzle and the beginning of the curved electrode. This space has been let to enable the straight part of the second set to accelerate the LAT normally. Once more, this little gap could be a reason for decreasing the efficiency. Effectively, I was worried that this gap created a space where flow isn't moving rightly and vortex were created between the electrode and the nozzle.



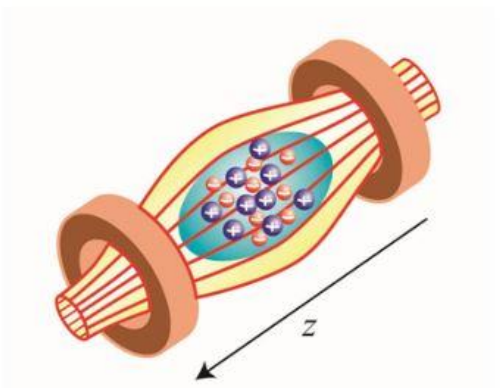
If vortex are created it will induce a very turbulent flow and the efficiency of our micro scale thruster will decrease. Thus, to avoid any risk, I have designed another piece without gap.

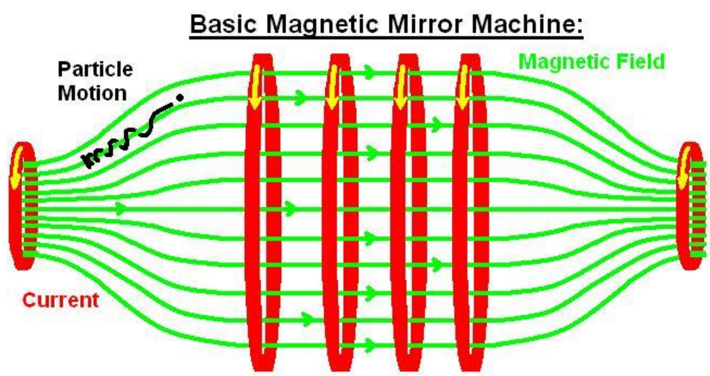
The second piece to avoid any convections issues fig (18)



Finally, during the weekly meeting, I have presented my work about this nozzle and the theacher assistant Hou-Yi Lee make me think about an important issue called “Magnetic mirror”.

A magnetic mirror, also called magnetic trap, is a device used to “trap” high temperatures plasma with magnetic field to create energy for fusion Power. In a magnetic mirror, electromagnets are used to increase the density of the magnetic field at the end of the device. That increasing force have the effect to reverse direction of particule approaching the end of the device. Our PPT is also a device using magnetic field to moove particules and adding a nozzle could be responsible of an force augmentation at the “neck” of the Nozzle. This increase of force could also trap the particules inside the first set of electrode which will have bad consequences to the efficiency of the thruster. But mirror effect occur only for particules within a limited range of velocities and angles of approach so we suppose it will not occure here.





Representation of the Magnetic field on a magnetic mirrow machine fig (20)

During this internship I had the luck, thanks to Professor Li and Mister Lee, to manufacture this prototype for laboratories testing. Unfortunately, due to manufacture length and because I was there only once month, I leave Taiwan before seen my prototype completely finished.

Despite the frustration to not be able to finish this very interesting project, I’m looking forward to see my friends from the ZAP Lab test for me the prototype in vacuum chamber. Also, when the first experiment will be made, we will be able to compare the efficiency of a single stage PPT done by Sunil Kumar to the efficiency of our prototype. In a same way, we will be fixed on the interest of the additional nozzle and if it work well we should try to improve it more by reducing the reduction ration. Also, we will know if the gap on nozzle is actually responsible of any efficiency losses.

CONCLUSION

This internship has been a wonderful experience for me on many ways. First, professor Li gave me the opportunity to join and integrate a world I didn't know before: the world of scientific researches. It was very instructive for me because I was asked to be independent in my work or in my issues. A learn a lot, about space propulsion, plasma physics, electromagnetic fields and about the methodologies of work in a laboratory but I also learn about been part of a team.

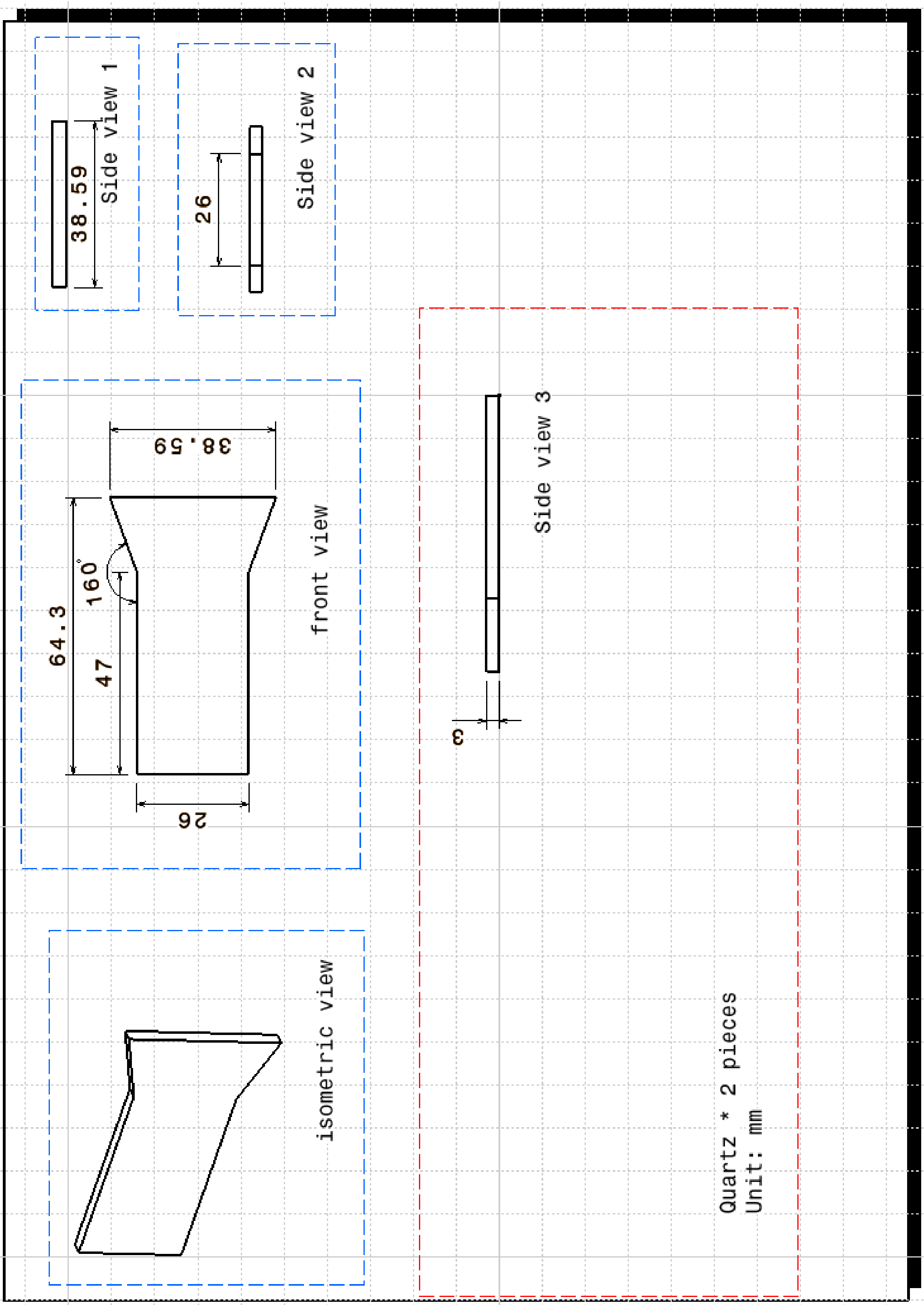
Because when you integrate the Zap Lab, even if you are not working on the same subject you are in a team. The meeting are the perfect representation of this unity about learning by each other's that Professor Li created. You learn from all and you can also teach to all.

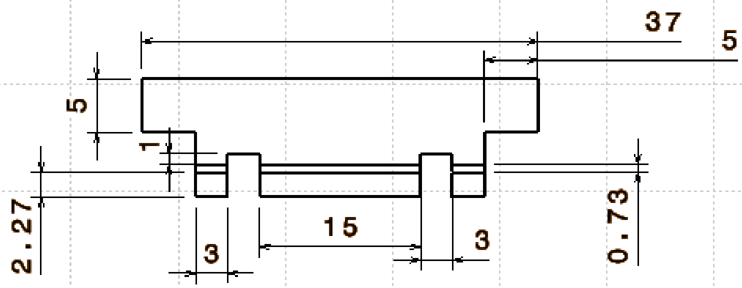
By my side, my professional ambitious is to become a propulsion expert and I'm actually doing a double degree about thermal power for aerospace propulsion. Once more, this internship has been for me the opportunity to improve my knowledge about space propulsion, a field which has always interested me but I didn't know much about before.

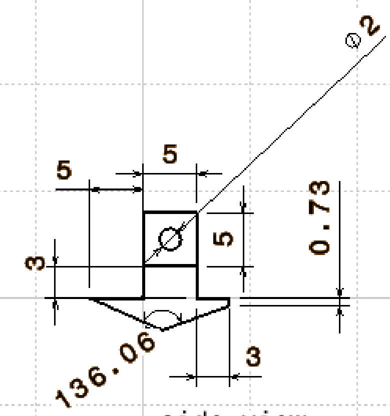
Moreover, working outside France, in an international Laboratory was a great experience. When everyone has different culture, you can share and learn a lot and it give me motivation to work at one hundred per cent in this project. Unfortunately, I leave before to have the opportunity to test my prototype but I'm sure that my co-worker will do it for me and give my feedback about the results obtained.

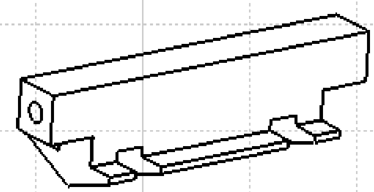
Also, even if I only spend one month on this lab, it comfort me in the idea of working outside France to still be intellectually motivated in my work. It also comforts me about the idea to become a propulsion expert as I ever wanted.

ANNEXE 1:

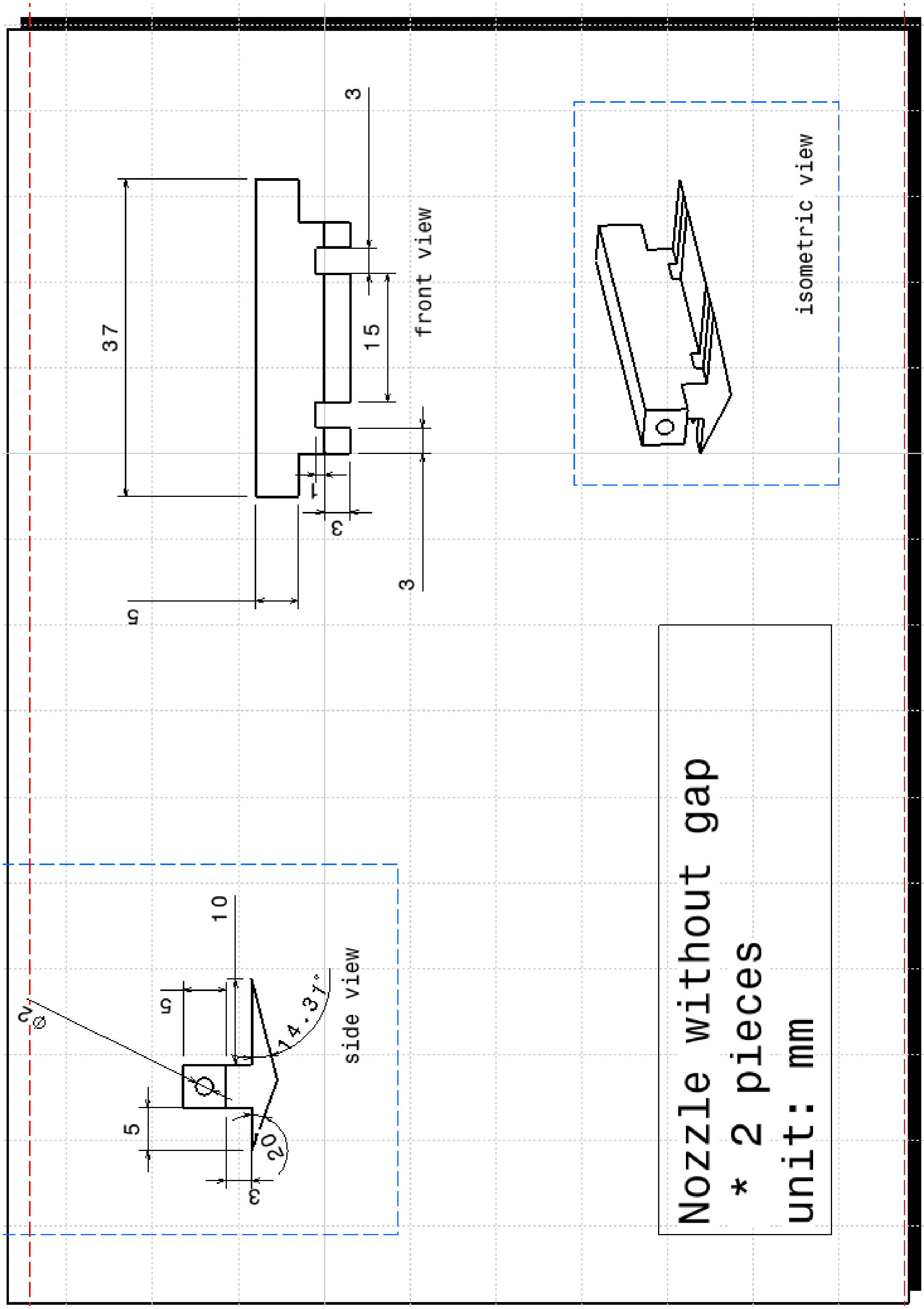

Side view 1
38.59
Side view 2
26
front view
38.59
64.3
47
160°
26
isometric view
Side view 3
3
Quartz * 2 pieces
Unit: mm

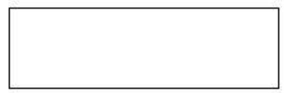




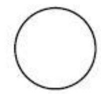


Gap nozzle
* 2 pieces
unit: mm

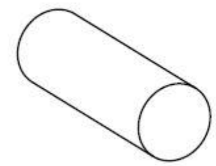

front view
side view
isometric view
Nozzle without gap
* 2 pieces
unit: mm



Vue de face
Echelle : 5:1



Vue de face
Echelle : 5:1

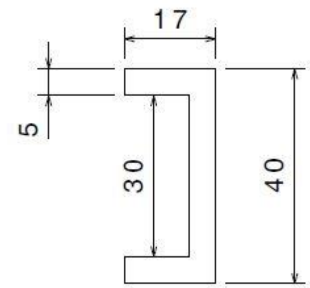


Vue isométrique
Echelle : 5:1

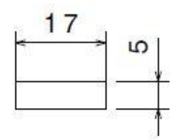
Spark plug (Copper)
Unit : mm

Isometric view 1

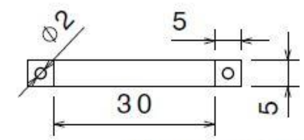
Isometric view 2



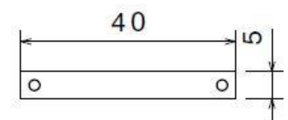
Side view



Up view

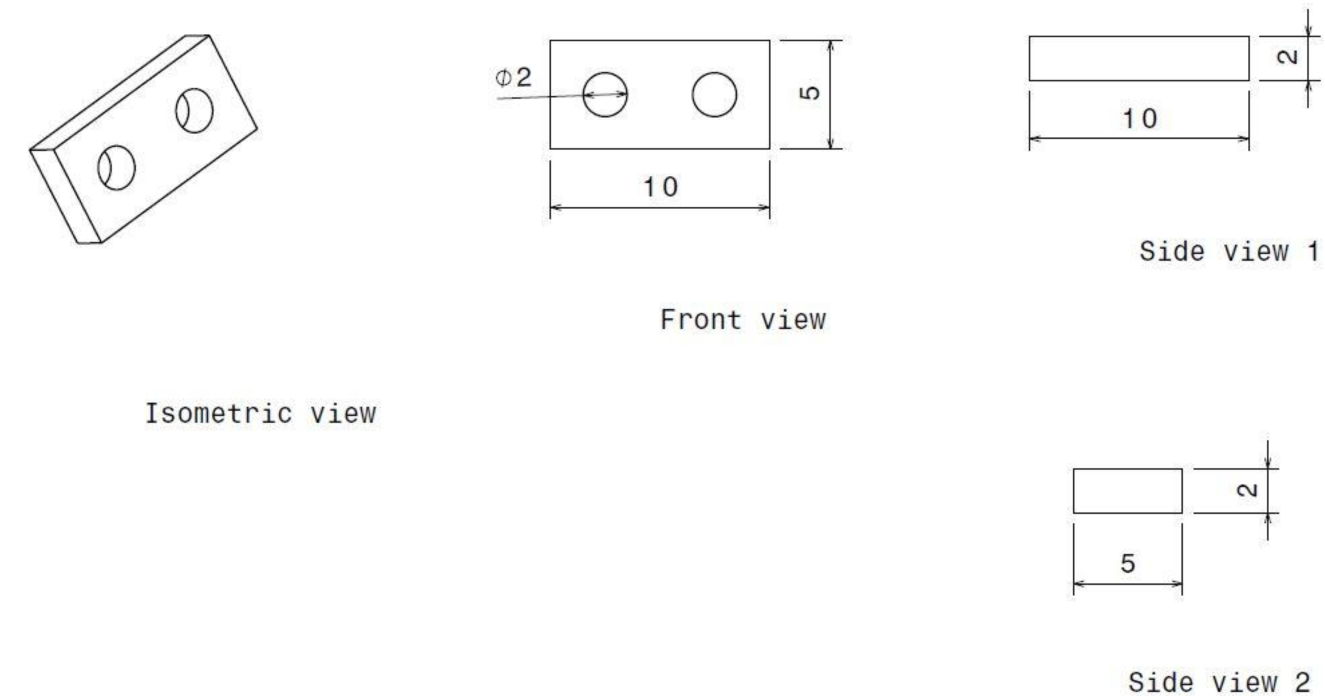


Front view 1

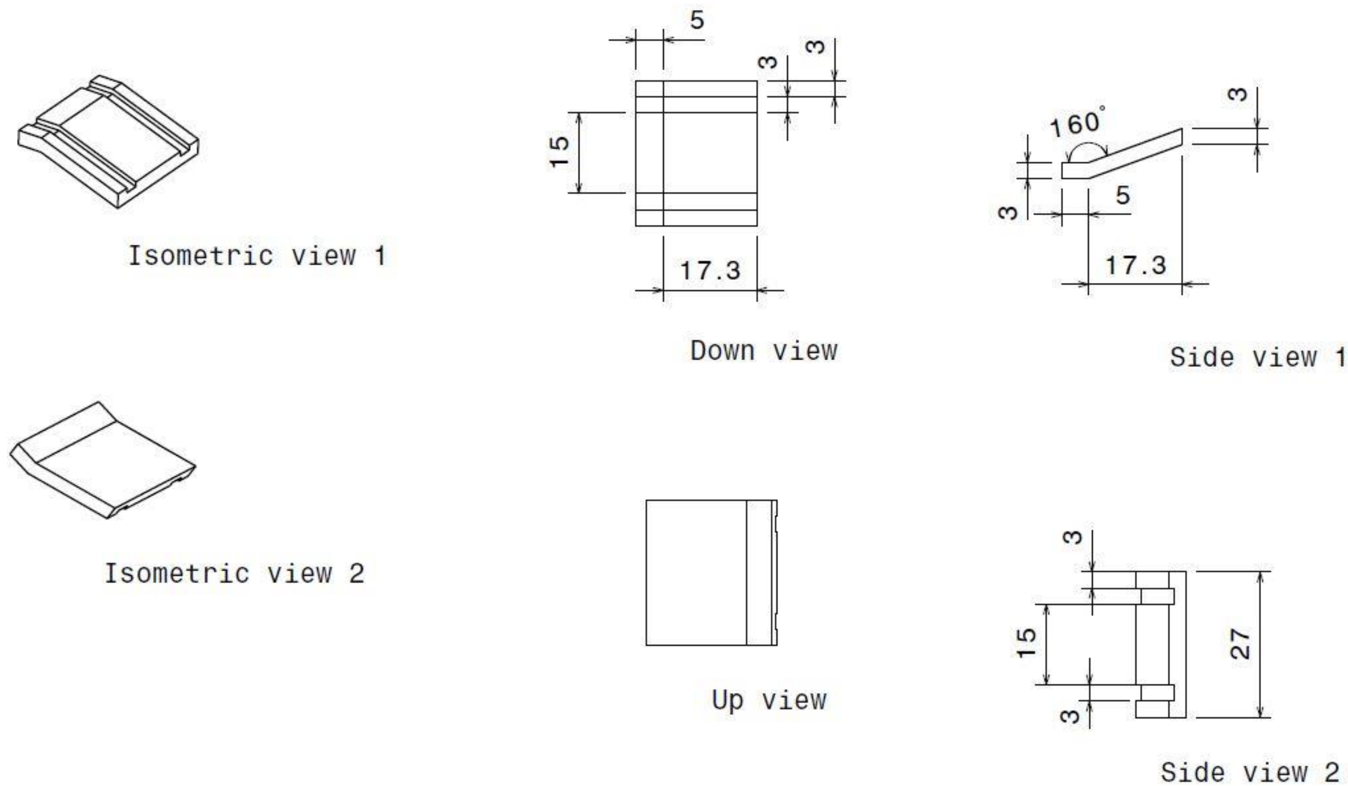


Front view 2

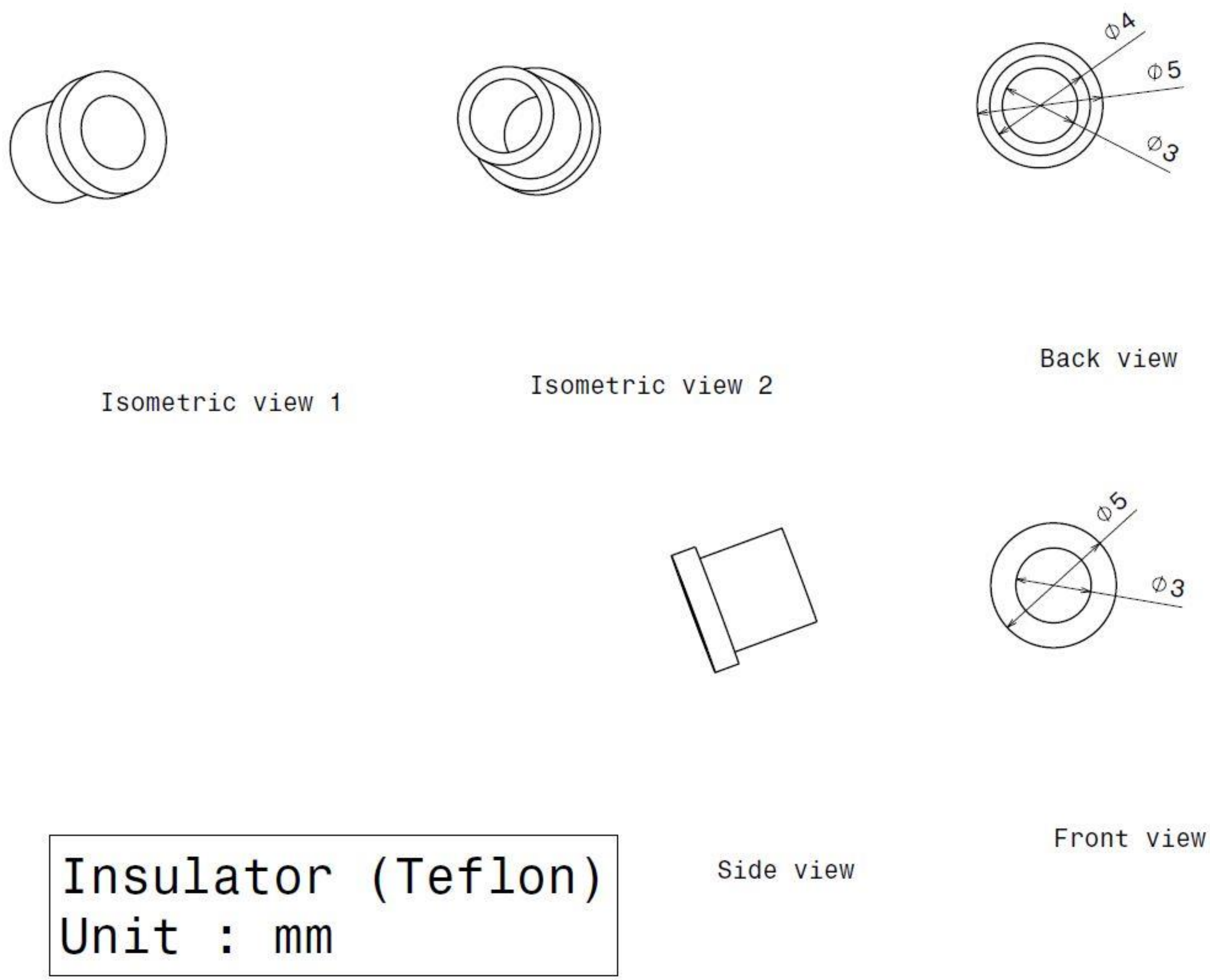
Clamp x4 (PE/PET)
Unit : mm



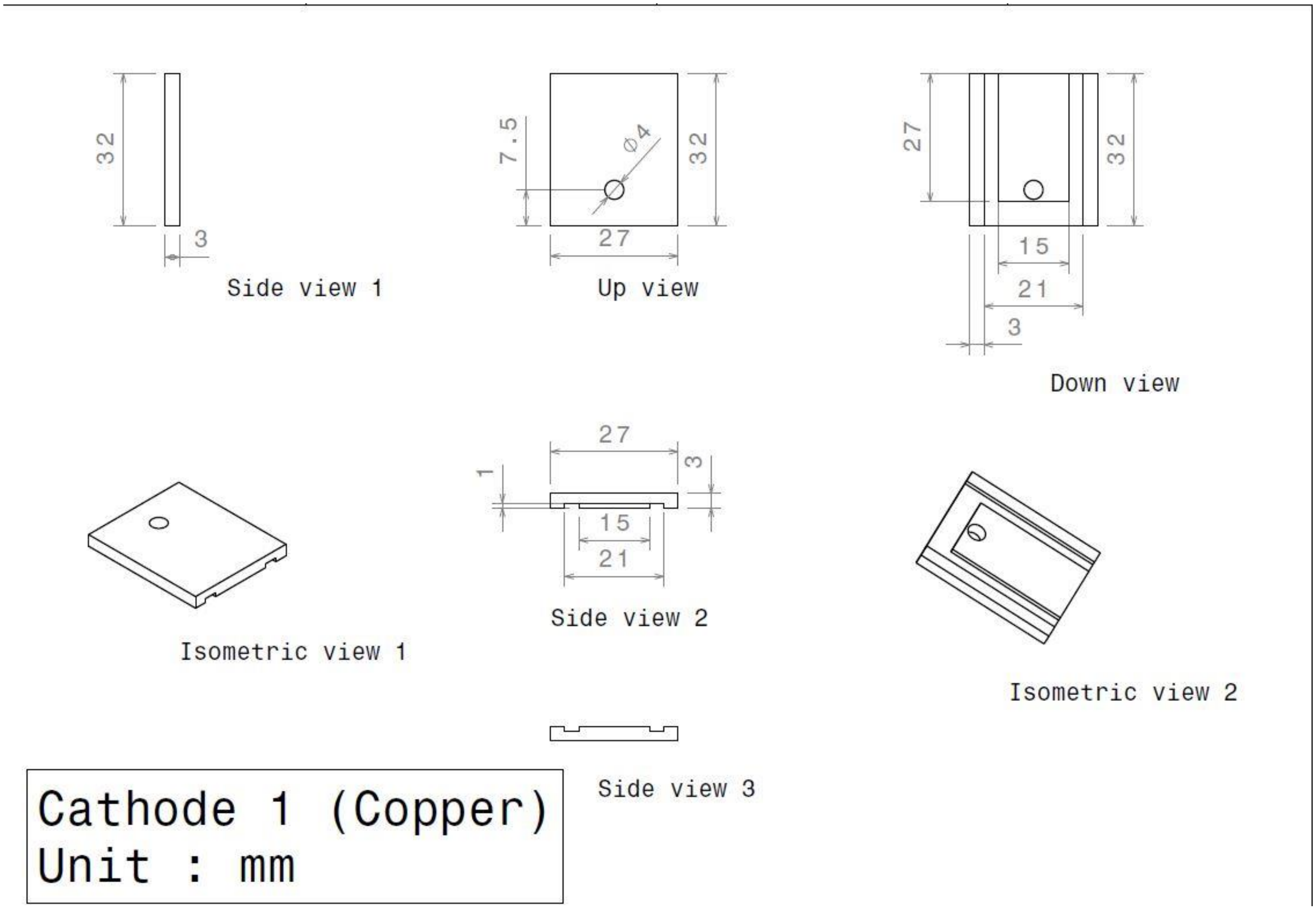
Entretoise x4 (PE/PET)
Unit : mm

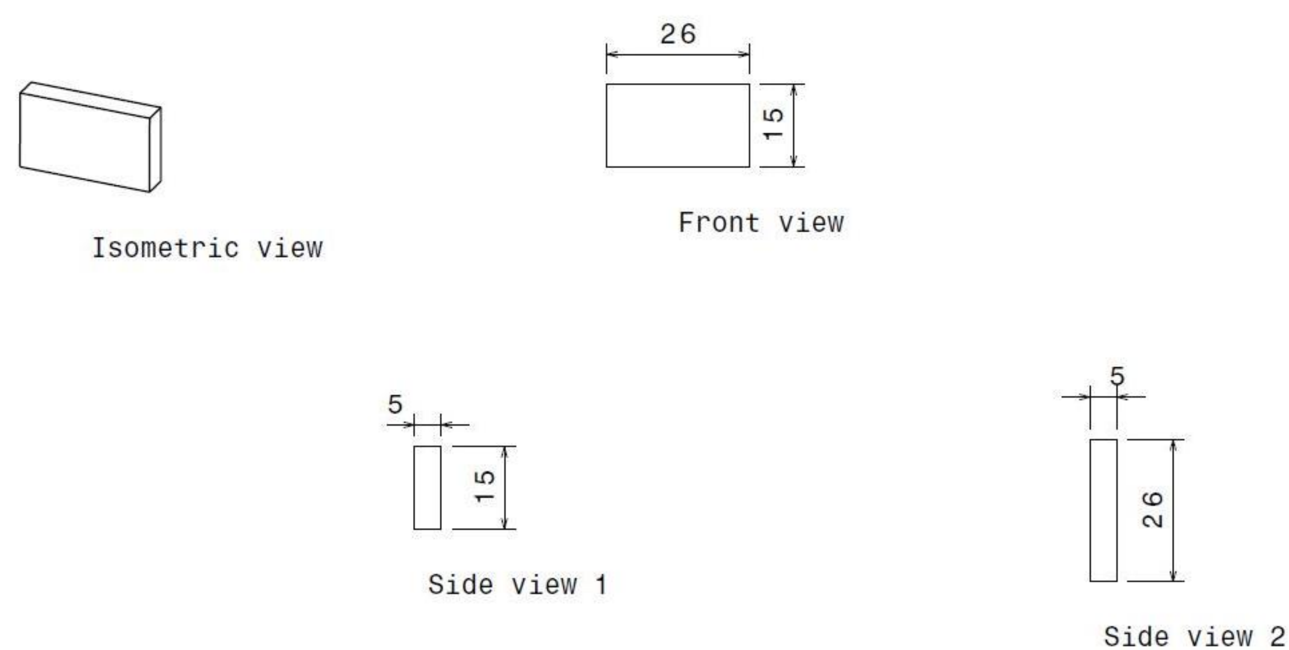


Electrode 2 x2 (Copper)
Unit : mm



Φ4
Φ5
Φ3
Isometric view 1
Isometric view 2
Back view
Φ5
Φ3
Side view
Front view
Insulator (Teflon)
Unit : mm


32
3
Side view 1
7.5
⌀4
32
27
Up view
27
32
15
21
3
Down view
Isometric view 1
27
1
3
15
21
Side view 2
Isometric view 2
Side view 3
Cathode 1 (Copper)
Unit : mm



Teflon (Teflon)
Unit : mm

ANNEXE 2:

CP201709072

報 價 單

客戶名稱：成功大學航太學系
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電話：03-3766272#14
傳真：03-3766261
Mobil : 0931-264-001
E-mail : paul@crma.com.tw

序號	品名 / 規格 / 附件圖號	數量	單價	總價
1	透明石英視窗(如附圖)	2	1650	3300
2	以 下 空 白			
3				
4				
5				
6				
7				
8				
9				
10				

營業稅 $ 165
合 計 $ 3465

附註：
交期:二周

客戶/廠商確認簽章：李後毅
2017/09/08

昇銳材料股份有限公司
Center Reach material Co.,Ltd.

承辦簽章：

審核簽章：

It correspond to 97 euros on actual court of the Taiwan dollars

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3. K.I Parker, "*State-of-the-art for small Satellite Propulsion System"*, NASA/Goddard Space Flight Center, August 24-27 2016

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5. R. Intini Marques, " *A Mechanism to Accelerate the Late Ablation in Pulsed Plasma Thrusters",* University of Southampton, PhD Thesis, 2009.

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ABBREVIATIONS

NCKU: National Cheng Kung University

DAA: Department of Aeronautics and astronautics

PPT: Pulsed Plasma Thruster

ZAP lab: Zic And Partners Laboratory

LTA: Latest Time Ablation

$\boldsymbol{I}_{sp}$: Specific Impulse

GLOSSARY

Small Sat: Space craft with a mass equal or below 180 kg.

Cube sat: Family of small sat with a standardized size and shape by a unit called U (10*10*10 cm =1U).

Thruster: Engine used for propulsive purpose abroad of Spacecraft.

Electrode: A conductor through which electricity enters or leaves an object, substance or region.

Nozzle: A round spout at the end of a pipe used to control a jet of gas or liquid.

Propellant: Substance that propels the Engine.

Thrust: Propulsive force of a jet or rocket engine.

Efficiency: The ratio of the useful work performed by a machine or in a process to the total energy expended or heat taken in.

Specific impulse: Total impulse delivered per unit of propellant consumed (measured in Second), it is mainly link to the efficiency of a thruster.

Mach: The ratio of the seed of a body to the speed of sound. Mach equal one indicate once the speed of sound.

ABSTRACT

The apparition of a new kind of small Spacecraft called **Cube Sat** is a complete revolution in the **Space industry**. Before, building a satellite was really time consuming and extremely expensive, but now, even university students are able to do it. Facing that, industrial companies are now using constellations of Cube Sat to complete simple missions. The **miniaturization** of the average size of satellite leads to the reduction of every component including thrusters. The reduction of the thruster size is a very difficult task in order to keep a good level of efficiency.

Following this trend, the study was focused on the possibility to increase the efficiency of a special case of thruster using **pulsed plasma** by using two consecutives sets of electrodes. In the present report you will find the **conception** and **development** of a **double stages pulsed plasma thrusters** and an additional nozzle created to improve the efficiency of PPT. The purpose of these researches was to imagine and build a more efficient model of thruster but with strict size, cost and weight restrictions (must be implemented in a Nano Cube Sat). Charts, diagrams and prototype design are provided in this document in addition to a guide line for the next steps. Finally, this double stages pulsed plasma thruster is the first non-tested prototype imagined and it have been created to be use in **NCKU** Laboratories so it is non- fully optimized in terms of performances and open to improvements.

RÉSUMÉ

L'apparition d'un tout nouveau type de petits engins spatiaux appelés **Cube Sat** est une révolution dans **l'industrie Spatiale.** Auparavant, construire un satellite demandait beaucoup de temps et d'argent, cependant aujourd'hui il est possible d'y arriver dans des laboratoires universitaires. Face à cela, les entreprises spatiales ont décidé d'utiliser des constellations de micro satellites pour remplir des missions dites simples. La **miniaturisation** de la taille moyenne des satellites entraine la réduction de chaque élément du satellite ainsi qu'une réduction de la taille des propulseurs. Cependant, miniaturiser un propulseur spatial est une tâche difficile si l'on souhaite garder un bon rendement propulsif.

En suivant cette idée, l'étude réalisée est centrée sur la possibilité d'améliorer le rendement propulsif d'un propulseur fonctionnant à l'aide de **plasmas pulsés,** en utilisant deux sets d'électrodes consécutifs. Dans ce document vous trouverez la **conception,** le **développement** d'un **propulseur utilisant du plasma pulsé et deux sets d'électrodes,** mais aussi une pièce supplémentaire créée pour augmenter les performances du propulseur. Le but de ces recherches était d'imaginer et de designer un propulseur performant tout en respectant des contraintes strictes en taille, poids et coût (le prototype doit respecter les contraintes pour être utiliser sur un nano-satellite). Graphiques, design final et plans de construction du prototype sont fournis dans ce document en complément d'une trame des prochaines améliorations à réaliser. En conclusion, ce propulseur a été réalisé pour être testé dans les laboratoires de **NCKU**, il n'est donc pas totalement optimisé en terme de performances et ainsi, toujours sujet à des améliorations.