IPSA (Ecole d'Ingénieurs de l'Air et de l'Espace)
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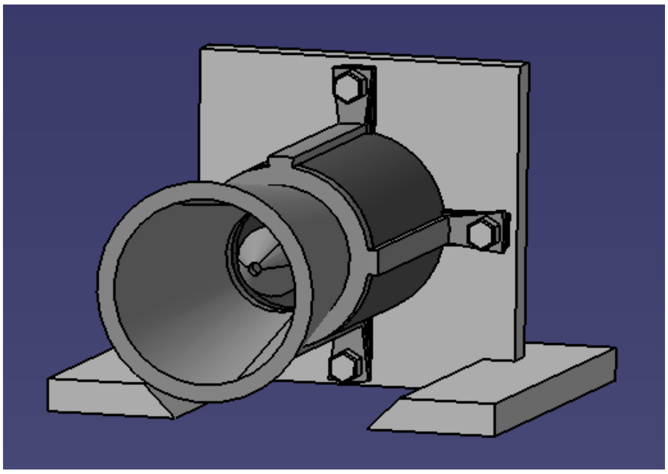
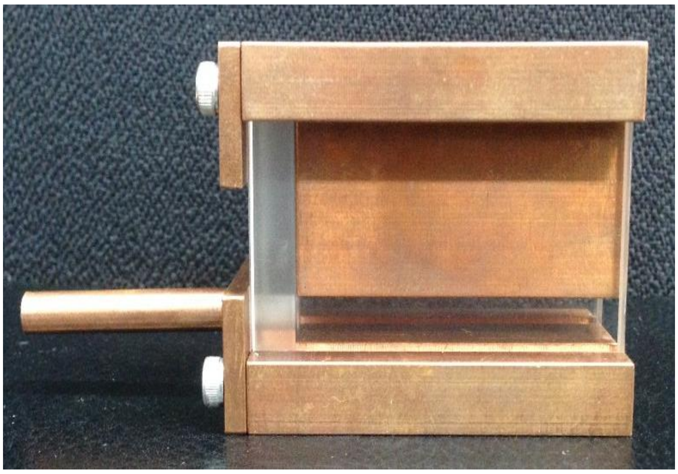
Tainan, TAIWAN

# DEVELOPMENT OF LORENTZ FORCE ACCELATOR AND GAS INITIATED PULSED PLASMA TRHUSTERS FOR CUBESAT

Aero4 Internship Report





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# ACKNOWLEDGEMENTS

I wish to express my sincere gratitude to my advisor Prof. Yueh-Heng Li and the doctoral student HouYi Lee from the Aeronautic and Astronautic Department (DAA) of National Cheng Kung University (NCKU) to provide me the possibility to do my internship and to help me working on my project, the Lorentz Force Accelerator, and on the Gaz-Initiated Pulsed Plasma Thruster. Without their help and advice, the design of my Lorentz Force Accelerator would not be finished and the model of my equipment necessary, to make experiments with the solenoid valve on the Gas Initiated Pulsed Plasma Thruster, would not have been manufactured.

My last sincere thanks go to the master student Pan Jun-You for helping me all my internship, and to my co-workers on the project Gaz Initiated PPT, the master students Kai and Sunil Kumar from the Aeronautic and Astronautic Department of NCKU for their help in the development. I commend them all again especially for the amount of knowledge I have the chance to acquire thank to them during this remarkable internship.

# KEY WORDS

Space propulsion

Gaz ionisation

Plasma formation

Lorentz Force Accelerator

Lithium Lorentz Force Accelerator

Vapor Water Lorentz Force Accelerator

Gaz-Initiated Pulsed Plasma thruster

Catia (V5)

National Cheng Kung University

Tainan

Taiwan

# ABOUT THIS DOCUMENT

We will see through this document, ideas and researches made among the ZAP Lab, a laboratory, specialized in combustion and propulsion researches, led by Professor Li Yueh-Heng, in the Aeronautic and Astronautic Department of the National Cheng Kung University. I had the chance to be integrated as a part of the crew during my Aero 4 internship.

The purpose of my research was about the design of a Lorentz Force Accelerator, and the improvement of the Gas Initiated Pulsed Plasma Thruster. It has been possible thanks to the software Catia V5 and with my team, on my last project, composed by Kai and the help of Sunil Kumar, who just finished this thesis on this research. Both have investigated on space propulsion and especially on the electric propulsion, to understand the gas ionisation and the plasma formation for realizing these thrusters. You will find assumptions, studies and 2D-draw (created by Catia).

# SUMMARY

# INTRODUCTION

For my internship necessary to validate my 4th year, I decided to orient myself in the field of the research. From the 16th of June to the 8th September, I worked in the Department of Aeronautics and Astronautics in the National Cheng Kung University in Tainan, Taiwan. I was under the supervision of my tutor, Professor Li Yueh-Hueng. I integrated his laboratory, Zap LAB, specialized in combustion and aerospace propulsion field. Everyone in this lab has to research, to develop and to do experiments in the optic to provide new researches and improvements for the space domain. It was a really rewarding experience both scientific and human side. Indeed, with the other master students and the professors, we all share knowledge, our experiments, our opinions and our culture.

The purpose of this internship was to study the plasma formation, the operation of micro thruster, the different type of models, their efficiency and characteristics among existing thesis and articles. Finally, I had to choose my own project after learning about this field: Lithium Lorentz Force Accelerator. After my design finished, I worked in another project, the Gas Initiated Pulsed Plasma Thruster, with Kai, master student. It was the rest of the thesis of Sunil Kumar, graduated student. The goal of this second project, it's to use a solenoid valve in order to increase the efficiency of the thruster and to be able to control the mass flow and create pulsed plasma.

In this internship report, we will begin by a presentation of Taiwan and the National Cheng Kung University, we will continue by the importance of using electric thrusters in the space domain. Finally, we will finish by the studies of my different projects, where I will bring out my different purposes, my work with Catia to design these complex systems and my experiment on the last project.

# I/ WORKPLACE CONTEXT

## 1) The National Cheng Kung University (NCKU)

In order to introduce my internship in Asia for three months, we can have an overview of Taiwan, then the city of Tainan where NCKU is located. Finally, we will sum up the University and the Department of Aeronautics and Astronautics.

Taiwan 台灣, or the Formosa Island ("Beautiful Island"), officially named Republic of China 中華民國(ROC) is basically, an island located in the eastern sea of China and under Japan and facing Hong Kong. Geographically, it is located on the Tropic of Cancer, therefore, the country climate is warm and humid during all the year. During the summer, it's the rainy season with typhoons.


*FIGURE 1: TAIWAN ISLAND WITH TAINAN'S LOCALISATION*

The capital of the country is Taipei based in the north of the island. Taiwan has a surface area of 36 191 km² for approximately 23,4 million habitants. The official language is the mandarin but thank to old traditional aboriginal populations, Taiwan has preserved some native culture and still has Hakka folk, Taiwanese people, Formosan nation or Fuzhou folk. However, Taiwanese people speak English, it was very helpful for me to improve my English talk.

The Formosa Island has been the place of different occupation before like Dutch, Portuguese, Japanese and Chinese. To be more precise, inhabited by aboriginals, Taiwan has been colonized by Dutch and Spanish during the17th century. Afterward, the island used to be colonized by Han folk and, hence, used to be led by the Qing Dynasty until they ceded the Island to Japanese in the 19th century after Sino-Japanese war. In the 60s, Taiwan has known a wide economic growth and industrialization period which has led to a stable economy situation. Nowadays, Taiwan is highly ranked in term of healthcare, freedom of press or public education. Taiwan is also well-ranked as one of the countries with the most tertiary education students thanks to many of famous universities as NCKU.

Tainan, officially named Tainan City, and commonly known as the "Capital City" 府城. It's the oldest city with over 200 years of history as the Capital of Taiwan under Koxinga and later Qing dystany rule. Nowadays, it’s one of the biggest cities of the island with a population of 750 000 people.

Thank to this old and long history, it is one of the cultural capitals of Taiwan, mainly for its local food, Taoist rites and local tradition. They are a lot of historical monuments in the “old city part” of the town as the Confucian school-temple and Tainan has more temples than any other town in Taiwan.

*FIGURE 2: TAINAN NIGHT MARKET*


*FIGURE 3: TEMPLE (WITH LAB FRIENDS AND OTHERS TAIWANESE FRIENDS)*

The National Cheng Kung University (NCKU) is a research-led and public university located in Tainan, Taiwan. It has more than 20,000 students and it is considered as one of the most prestigious universities in Taiwan and Asia (being considered as the 4th best university of the country). It was founded in 1931 under Japanese government as "Tainan Technical College" and became a national university in 1971.

- 1931: Creation of the university as *Tainan Technical College*, located in Tainan
- 1942: School renamed in Japanese during the occupation
- 1946: School renamed *Taiwan Provincial College of Engineering* with 6 departments (Mechanical, Electrical, Chemical, Electro-Chemistry, Civil and Architectural Engineering)
- 1956: School reformed as *Taiwan Provincial Cheng Kung University* with 4 different colleges gathering 10 departments
- 1962: Master's Degree program in Chemical Engineering created
- Doctor's Degree program in Electrical Engineering created
- 1971: School reformed as *National Cheng Kung University*; Master's Degree program in Physics, Hydraulics and Ocean Engineering

It is famous for having formed lots of notable Taiwanese personalities such as several ministers, highly-awarded scientists or architects and prestigious international university directors. Each year, new specializations are being created and new Departments are founded. The University also opened its formation worldwide and host several foreign students.

NCKU is a very polyvalent university, divided in 9 colleges: liberal arts, Social Science, Management, Sciences, Engineering, Medicine, Electricity & Computer Science, Planification & Design, Biology & Biotechnology. The Academics Program prepare students for Master Degree among its several departments. The Research Center has also a very strong place, with 15 different centers. Each of this colleges are separated in different departments for a total of 43 different departments.

*FIGURE 4: NCKU (BUILDING WHERE I WORKED)*

## 2) The Zap Lab framed by Professor Li

The Department of Aeronautics and Astronautics (DAA) in NCKU, is a place where I did my internship during this summer. We can find many laboratories leading various and innovative researches, spread between the four following areas:

- Fluid mechanics and Aerodynamics
- Combustion Heat Transfer and Jet Propulsion
- Structure and Materials
- Guidance and Control
- Nano-technology and Space system engineering through interdisciplinary projects

We can also have other interested fields in the Institute of Civil Aviation, which is also part of the DAA, like:

- Air Transportation Administration and Management
- Flight safety and Human factor engineering
- Avionics and navigation systems
- Aircraft maintenance

FIGURE 5: DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS

Also named Zic, Profesor Li has been my advisor during my research, as the same time he was leading all other research, master and PhD students. Mister Lee, the assistant of Professor Li, supervised me all the internship to permit me to understand and advance in the subject of the plasma and my projects.

Professor Li has graduated and made a Doctoral thesis at NCKU. He is specialized in Micro Electric Propulsion System, Laser Diagnostics, Thermo photovoltaic Power System, Micro-scale Power System, Energy System and Scenario Modelling and Clean Fuel Combustion Technology. Li Yueh-Heng is currently overseeing more than 20 master and PhD students, mainly working on Micro combustion and Propulsion, Thermo photovoltaic Power System, Clean Coal Combustion Technology, and Biomass Energy.

Normally each student has their own desk, spread between three rooms, but because we were a lot of trainers and students, sometimes we had to share the desks. We have access to some laboratories in the optic to test their conceptions and project researches, like for instance, with the vacuum chamber or with combustion equipment.

During the time I have worked among the research student in the Zap Lab, following are some projects which was under development by other master and PhD students:

- Micro ECR Ion Thruster
- Experiment and Simulation of Solar Thermal Water Heating Combi-system
- Development of Micro-Thermo Photovoltaic Platinum-Steel-Combined Tubular Reactor
- Spray Combustion Technology
- Laser Diagnostics Technique
- Cogeneration power system of Thermo Photovoltaic cell array combined with Stirling Engineering
- Vacuum cathode arc thruster (VAT)
- Characteristic of flame plasma
- Experimental and Numerical Analysis of Opposite Premixed Flames
- Liquid Propellant Pulsed Plasma Thruster

*FIGURE 7: ZAPLAB'S OFFICE*

*FIGURE 6: ZAPLAB'S LABORATORY*

Every week days, I worked between 9:00 AM and 5:00 PM. Sometimes more when I had a lot of work or a presentation to do.

Every Monday, from 4:00 PM to 8:00 – 9:00 PM, we had a meeting during which few selected students had to present a scientific paper or their progress researches and advancements. We could see when we are attended to do a presentation on the website of the ZapLab in which all of us have an account. Every student must be present to listen our mates. In this optic, we can share our research and create discussions on some of their project issues which they are stuck with. It was a good way to create a cohesion between all the members and to learn more about a lot of interesting scientific projects. Thank to this process, Professors from the lab can also follow the advancement of each student and help us if we need.

We use a Powerpoint presentation in English to accompany our speeches. Most of the time, scientific articles had to be presented in English whereas, project advancements can be explained in English or Chinese. Indeed, when it was too difficult for a Taiwanese student to present his project or answer the questions, he could continue in Chinese to improve in fluidity. So, me, I presented my project every time in English with a Powerpoint I tried to be more visual for my Taiwanese mates who don't understand very well the language.

### 3) Economic analysis of the laboratory

ZAP Lab is a public research institute, mostly financed by the Ministry of Science and Technology (MOST). In 2018, the financial incomes provided by MOST were about 4,443,000NTD (about 125 100 euros), an amount increasing during the three last years (2,614,000NTD in 2016 and 3,558,000NTD in 2017). This evolution is partly due to the growth of the university in the research field.

Today the laboratory has 20 employees including 16 masters, 2 doctors of philosophy (PhD), 1 professor and 1 assistant, spread in the different research projects. The laboratory also welcomes many graduated or non-graduated students achieving an internship or following their studies in the university.

The spending of the laboratory mostly concerns the acquisition of consumables, necessary to lead experiments (gas, materials), and of new equipment. The salary of employees is also considered and is distributed this way:

- Master: 6,000 NTD (about 169 euros)
- PhD: 10,000 NTD (about 281 euros)
- Assistant: 20,000 NTD (about 560 euros)

The laboratory must also provide the cost of foreign travels or project related expenses. To fulfil this budget, the laboratory receives funding from National Chung-Shan Institute of Science & Technology (NCSIST) and Metal Industries Research & Development Centre (MIRDC), other research units belonging to the government.

Today, the policy of ZAP Lab is to develop its image worldwide, opening its door to foreign students or participating to international conferences and to give a better image of the research field to young engineers or students.

# II/ INTRODUCTION TO THE PLASMA IN SPACE PROPULSION

## 1) Space propulsion systems

In the optics to generate an acceleration for spacecraft and artificial satellites, we use the space propulsion. There are different methods that we can group in three categories: chemical propulsion, electric propulsion and nuclear propulsion.

In this part, I will talk about the two most controlled and used in the space world., by highlighting their uses, advantages and disadvantages.

### A) Chemical propulsion

All spacecraft use chemical rocket to launch. It's the same for the satellite. Before gravitating around the Earth, other planets or to explore the space, we must use a rocket which the systems use the principle of the chemical propulsion for permitting to the satellites to leave the attraction of the Earth.

This type of propulsion generates thrust by chemical reactions to create a hot gas that is expanded to produce thrust.

FIGURE 8: LAUNCH OF SATURN V

In this configuration, we mix fuel and oxidizer together to get high pressure and high temperature, and by this way, to create a big propulsion permitting the launch.

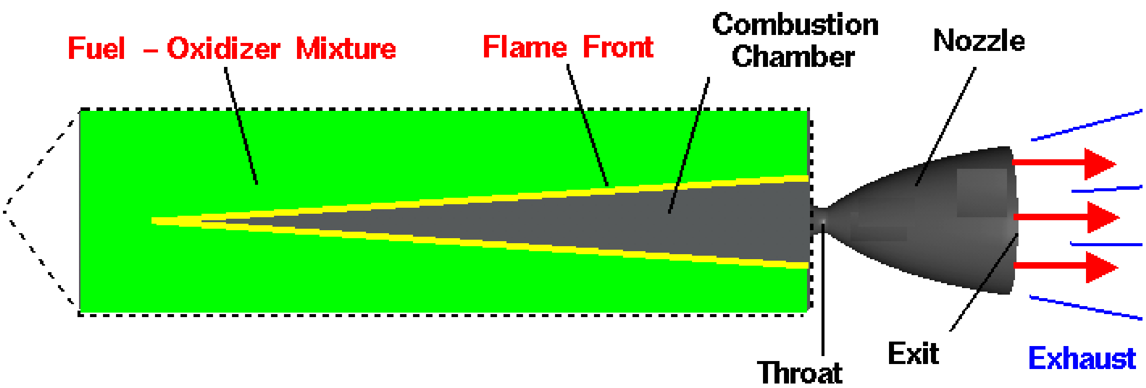



FIGURE 9: SOLID PROPELLANT FOR CHEMICAL PROPULSION OF A ROCKET [1]

In fact, it exists three types of chemical propulsion. We have solid propellant motors, liquid propellant engines and hybrid propellant motors. This category of propulsion is used for launching the satellites by the rockets, and spacecrafts (with the boosters), to realize orbit transfer and for keeping the station in the good orbit. We can realize high or low thrusts, with an exhaust speed between of 2 and 5 km/s [1].

### B) Electric propulsion

*FIGURE 10: ELECTRIC PROPULSION FOR FUTURES SATELLITES*

An electrically-powered spacecraft propulsion system makes use of electrical power to accelerate a propellant by different possible electrical and/or magnetic means, that we will see later.

The propellant used in electric propulsion (EP) systems varies with the type of thruster and can be a rare gas (like xenon or argon, in my last project I use argon) or natural gas (like vapor water), a liquid, a metal or a conventional propellant.

Nowadays, EP is use for very little satellites named CubeSat, to permit to correct orbits and do slight maneuvers. Scientists try to develop this system for more bigger satellites and spacecrafts because the use of electrical power enhances the propulsive performances of the EP thrusters compared with conventional chemical thrusters.

This interesting system will can be used in other missions like the exploration of the space and the futures travels to Mars.

### C) Comparison between the two systems

The EP is a good alternative for the space propulsion because of a lot of advantages compared the chemical propulsion

Electric thrusters typically require very little mass to accelerate spacecraft, they use much less propellant than chemical rockets because they have a higher exhaust speed than chemical rockets. With the electric system, the propellant is ejected up to twenty times faster than from a classical chemical thruster. In this fact, the overall system is many times more mass efficient.

Due to limited electric power the thrust is much weaker compared to chemical rockets, but electric propulsion can provide a small thrust for a long time because it’s not limited in energy, just by the available electrical power present in the spacecraft. Electric propulsion can achieve high speeds over long periods and thus can work better than chemical rockets for some deep space missions, like the futures missions to explore the space.

Moreover, we can compare these systems by the different specific impulse (Isp) associated.

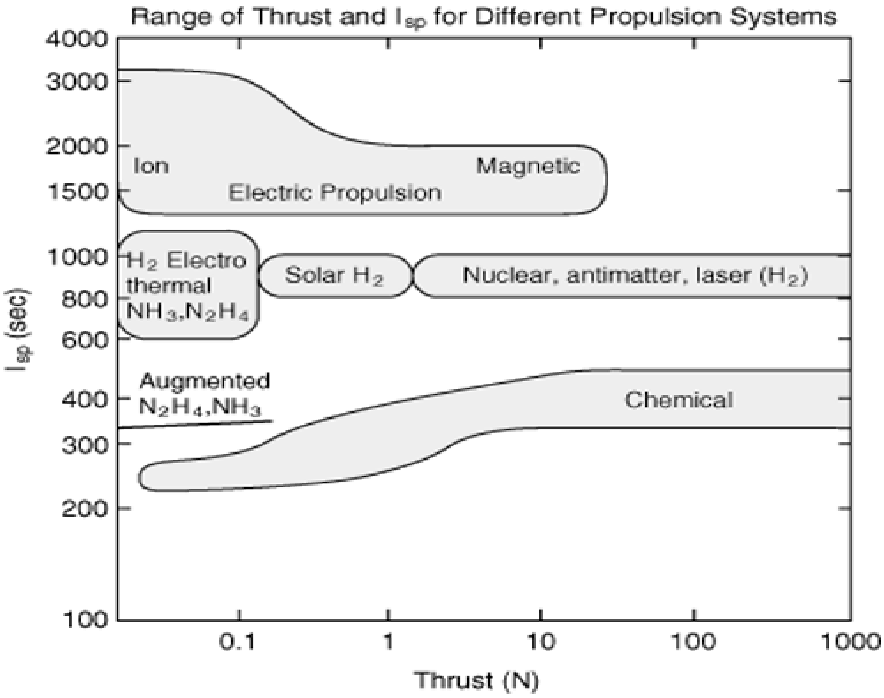



*FIGURE 11: COMPARISON OF DIFFERENT TYPE OF PROPULSION IN FUNCTION OF THE ISP AND THE POWER BROUGHT*

The Specific Impulse (Isp) is a measure to know if a rocket uses propellant in the optic of efficiency. Indeed, a propulsion system which have a higher specific impulse significate that it uses the mass of the propellant more effectively in creating forward thrust.

This equation defines the specific impulse:

$$I_{sp} = \frac{V_e}{g_0}$$

- $I_{sp}$: the specific impulse measured in seconds
- $V_e$ : the average exhaust speed along the axis of the engine (m/s)
- $g_0$: the standard gravity (m/s$^2$)

We can see in the Fig.11 that, the chemical propulsion needs a lot of power, so a big force, and it happens that this type of propulsion obtains a low Isp. The propellant is not very effectively used, we need a big weight to produce the thrust.

With the electric propulsion, we have a high Isp. It significates that we don't need a lot of power and propellant to create a thrust. This option seems very useful in term of weight and price.

## 2) CubeSat

A CubeSat is a type of miniature satellite that are commonly used in low earth orbit for application such as remote sensing or communication. The design was first proposed in the late 1990s Prof. Jordi Puing-Suari of California Polytechnic State University and Prof. Bob

Twiggs of Stanford University. The project aimed to develop a miniature satellite with small cost and manufacturing time. Indeed, Space field has limited access for many research organizations because of different problems, to use CubeSat present some important advantages, which can dodge these problems:

- The cost of production is cheaper
- The cost of launch too (because they are very small, we can put many CubeSat in one rocket)
- the risk of failure is reduced and less important (less damage in case of impact)
- Accessibility to many types of research group

| Category | Mass range (kg) |
|---|---|
| Large satellite | > 1,000 |
| Medium-sized satellite | 500-1,000 |
| Minisatellite | 100-500 |
| Microsatellite | 10-100 |
| **Nanosatellite** | **1-10** |
| Picosatellite | 0.1-1 |
| Femtosatellite | <0.1 |

*FIGURE 12: CATEGORIES OF SATELLITES*

SmallSats are all microsatellites and part of the minisatellite, in the range of 10g to 180 kg.

Basic CubeSats are always under 10kg, like the nanosatellites, picosatellites and femtosatellites, they are made up of multiple 10×10×10cm cubic units with mass no more than 1.33kilograms per unit.

There is one limitation for CubeSat namely power. CubeSats use solar cells to convert solar light to electrical energy stored in rechargeable lithium-ion batteries. The stored energy will be released when required. But due to less surface area they can store limited amount of electrical energy and as electric thruster uses electrical energy to accelerate plasma. While developing a thruster for CubeSats, power requirement is taken into consideration principally. Commonly CubeSats are used in low earth orbit but as the engineers became more familiar with the technology. Over 800 CubeSats have been launched as of April 2018. CubeSat are mainly used for communication, but too for observation and exploration like the futures projects for deep space mission to Mars and Jupiter.

We can see different projects realized or they will be realized in the future [2]:

- QB50: this was an international project which have for goal to send 50 CubeSats for multi-points in the lower thermosphere, at 90-350 km of altitude. 22 countries in the world participated like US, China, France, Australia and South Korea. These CubeSats launched in April 2017 aboard Cygnus CRS OA-7, thereafter to be deployed from the ISS.

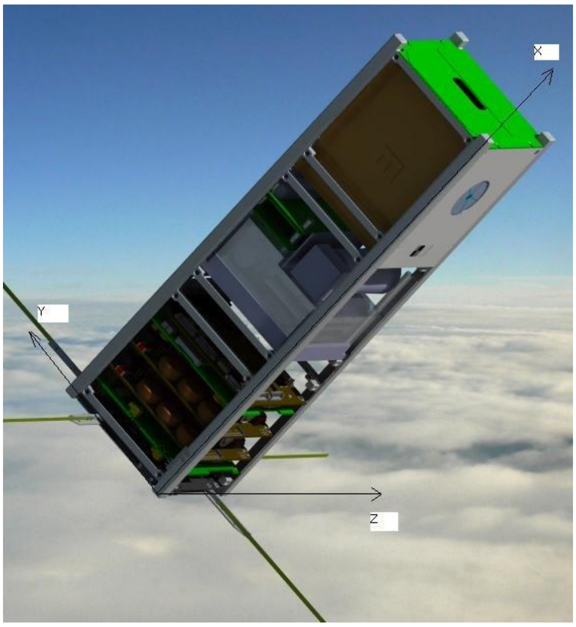



FIGURE 14: SIMBA CUBESAT (LAUNCHED DURING THE QB50)

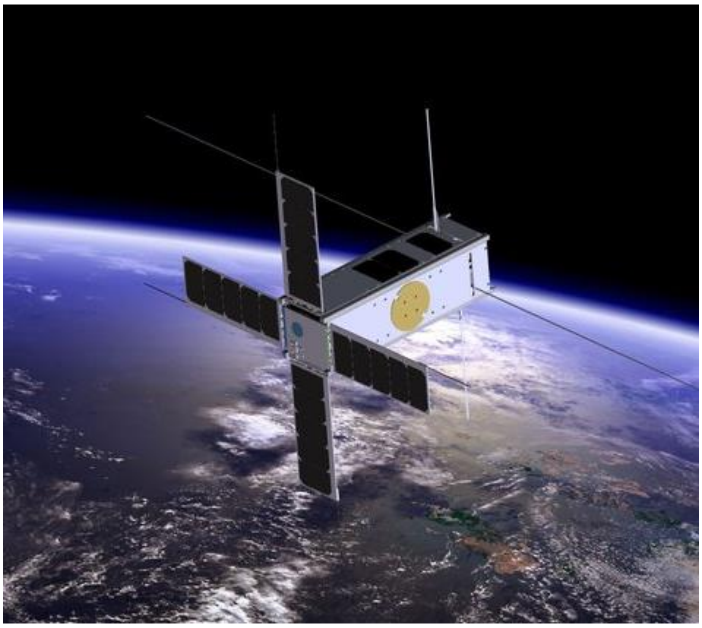


FIGURE 13: PICASSO CUBESAT (LAUNCHED DURING THE QB50)

- Mars Cube One: CubeSats send to Mars with mission of serving as a realay satellite to send data back to Earth during inSight's entry, descent and landing operations

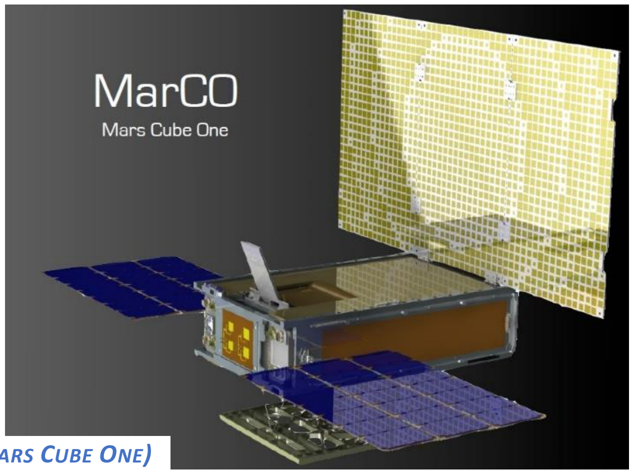



FIGURE 15: MARCO 1 CUBESAT (MARS CUBE ONE)

- Flock-3r: Constellation of CubeSats for optical Earth observation with equipment that permit 3-5m resolution. These satellites will be sending the November 31th.

*FIGURE 17: FLOCKI-3R CUBESAT*


*FIGURE 16: GROUPING OF THE FLOCKI-3R CUBESATS BEFORE THE BEGINNING OF THE MISSION*

## 3) Introduction of the plasma

Basically, we can easily define a plasma as a set of charged particles. The bulk of plasma is considerate as electrically neutral, which means that the whole contains positive particles as much negative ones. Between them-self, the particles interact thanks to the Colombian law. Contrary to a gas, where the interaction is short, the plasma particles interact with more distances. The interaction between two particles is attractive if the particle charges are opposite or repulsive if the particle charges are similar.

The following equation give us the value of this interaction between two particles:

$$F_{A/B} = F_{B/A} = k * \frac{|q_A| * |q_B|}{AB^2}$$

- $|q_A|$ and $|q_B|$ : the particles charges
- AB: the distance between the two particles
- k: a constant given in function of the middle

This general notion allows us to study plasma in a collective way and to model the behaviour as two charged fluids in interaction.

Plasma exists in various types, as more or less: dense, warm and ionized. Hence, every corps is likely able to become a plasma if its temperature and density are enough high.

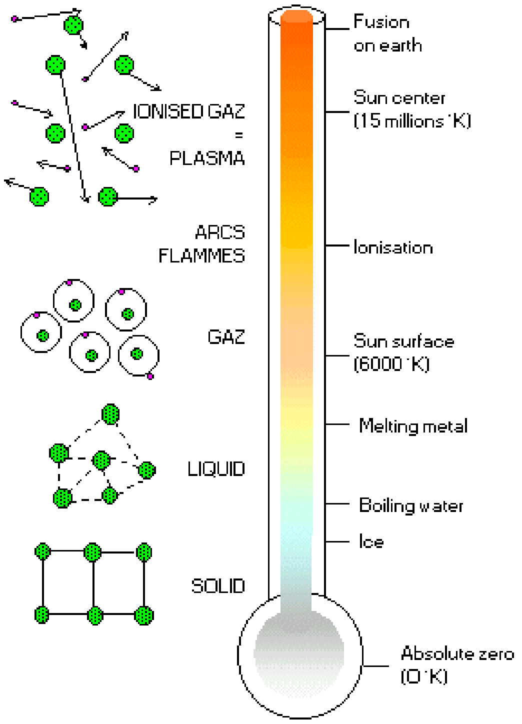



FIGURE 19: DIFFERENT STATES OF THE MATERIAL IN FUNCTION OF THE TEMPERATURE

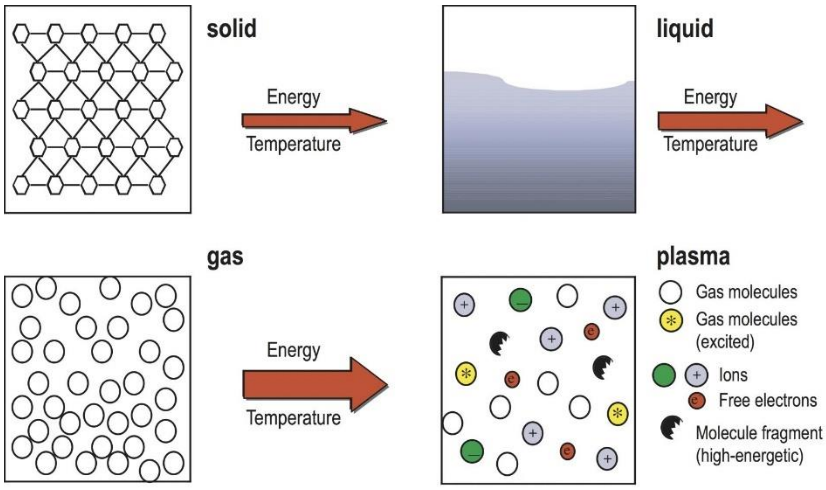



FIGURE 20: CHANGES OF THE MATERIAL UNTIL THE PLASMA

In order to get a better idea, we can observe "natural" created plasma as the Earth's Sun, the solar corona boreal auroras, flames, thunder, and nebula. We can also create artificial plasma like thrusters and fusion reactor.

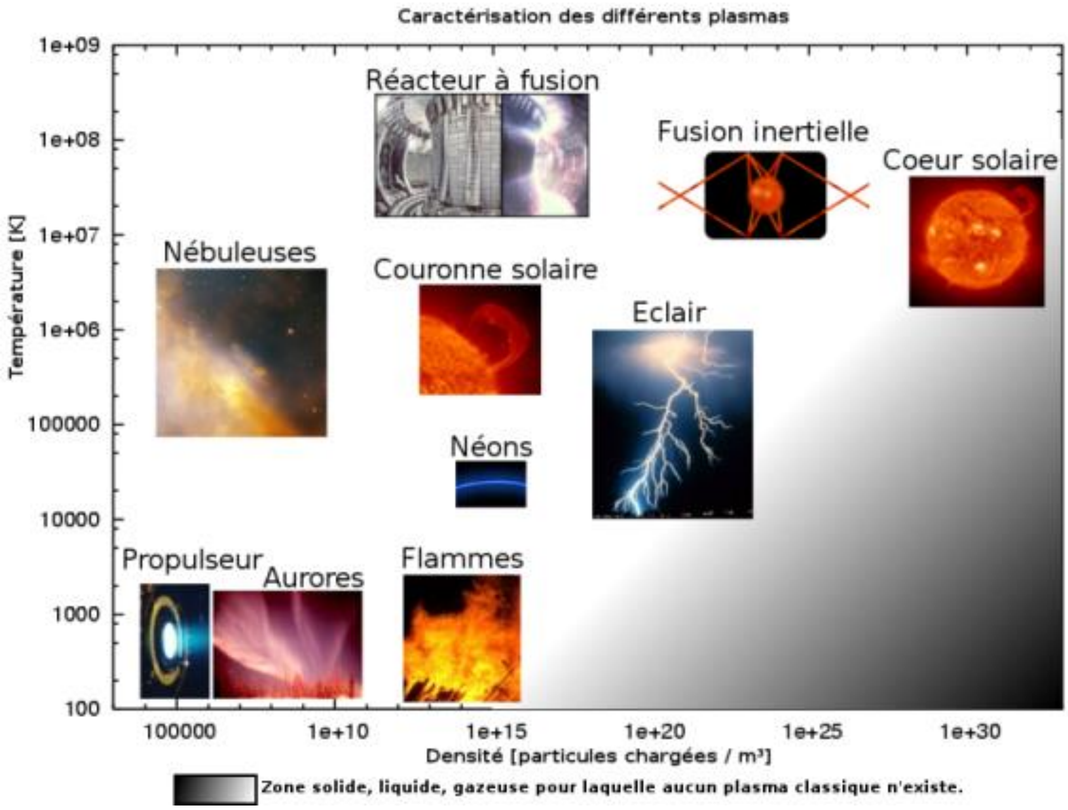



FIGURE 18: DIFFERENT PLASMA THAT WE CAN OBSERVE

To create a plasma artificially, there are some different way: we can heat a gas, for instance, or submit a solid or gas propellant to a strong electromagnetic field applied with an arc, laser or microwave generator. There are some basic aspects which have to be considered as particle distribution, density, temperature, pressure, velocity and flux.

The gas is ionized to create the plasma and accelerating with electromagnetic field:

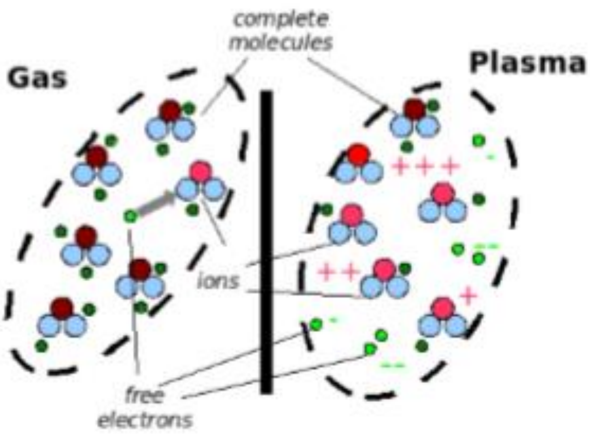



*FIGURE 21: CREATION AND COMPOSITION OF PLASMA*

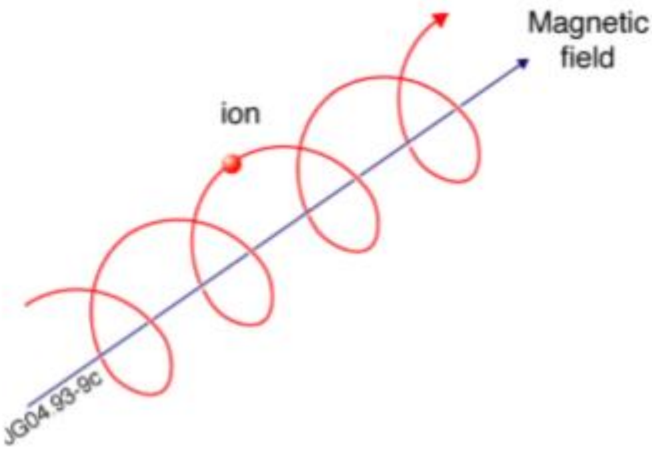



*FIGURE 22: PARTICLE BEHAVIOUR WITH A MAGNETIC FIELD*

## 4) Categories of Electric Thruster

Electric Propulsion uses wide variety of strategies to achieve this high exit velocity, and those techniques are basically divided into three types: electrothermal, electrostatic and electromagnetic propulsion.

### A) Electrothermal propulsion

Electrothermal propulsion is a form of electric propulsion in which electrical energy is used to heat the suitable propellant causing it to expand thermodynamically through a supersonic nozzle and generate thrust. Based on propellant heating it is divided into three subclasses: resisto-jet, arc-jet and microwave devices.

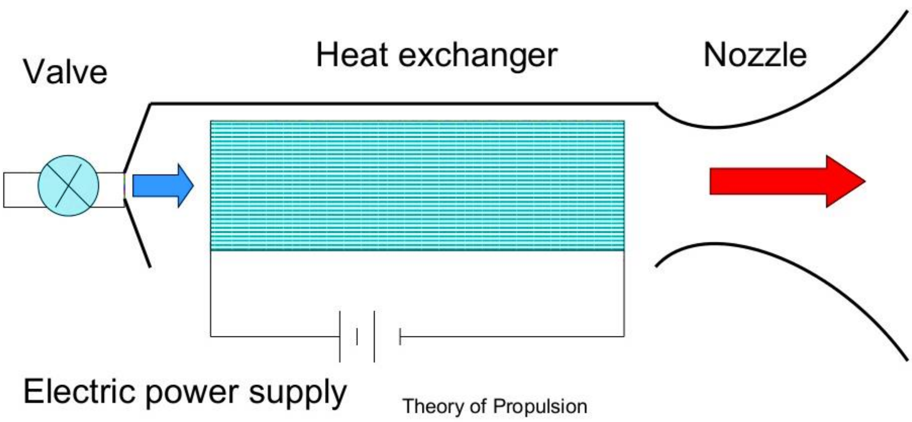



*FIGURE 23:SCHEMATIC DIAGRAM OF RESISTO-JET*

A resisto-jet works by heating a propellant fluid over an electrically heated element such as the chamber wall or heater coil and allowing the resultant hot gas to escape through a convergent and divergent nozzle as shown in Fig. 23. Typical resisto-jet uses catalytically decomposed hydrazine as its propellant. Hydrazine resisto-jets were used on iridium satellites for orbit-raising maneuvers [3].

An arc-jet is a simple and reliable form of electrothermal thruster that heats the propellant by passing it through a high current arc in line with the nozzle as shown in Fig. 24. While there is an electrical discharge in propellant path it ionizes the propellant and increase its exhaust velocity. 30kW powered arc jet using ammonia as propellant was flown on ARGOS in February 1999[4].

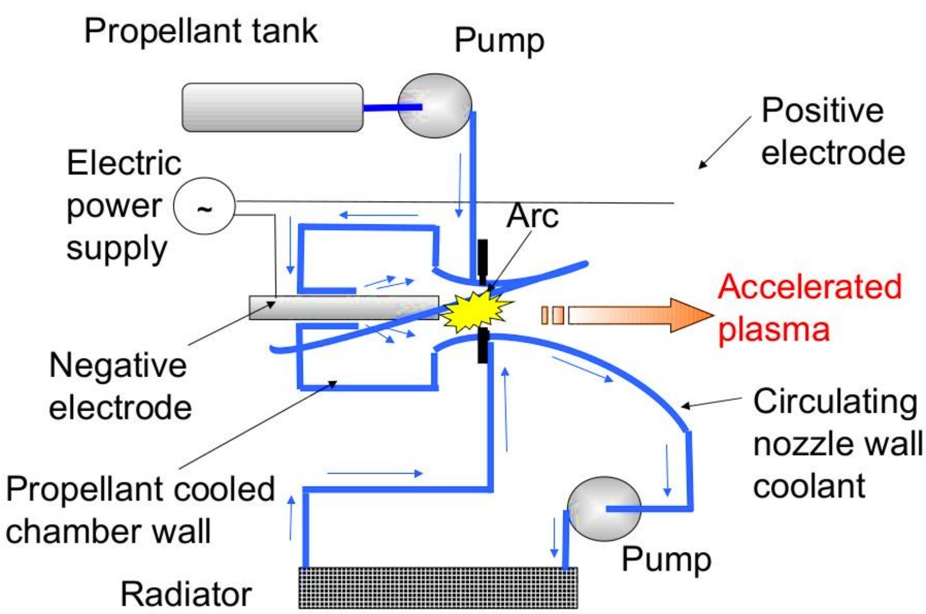



*FIGURE 24: SCHEMATIC DIAGRAM OF ARC-JET*

Microwave electrothermal (MET), standing microwave is fed from a waveguide into a plenum chamber through a dielectric window. The microwave radiation accelerates electrons which collide with the propellant. Those collisions heat the propellant which is expelled with high speed through the nozzle.

### B) Electrostatic propulsion

In electrostatic propulsion, initially the propellant is ionized and then accelerated by direct application of electrostatic forces to ionized particles. Accelerating the propellant by electrical body forces overcomes the thermal limitations (effect of heat and expansion process like in electro thermal) on attainable exit speed and life time of a thruster. Ionizing of propellant can be done in many ways: ion contact, electron bombardment, field emission, radio frequency and microwave. There are several types of thrusters in electrostatic type such as Hall-Effect Thruster, Field Emission EP, Gridded Ion Thruster and others Ion Thrusters.

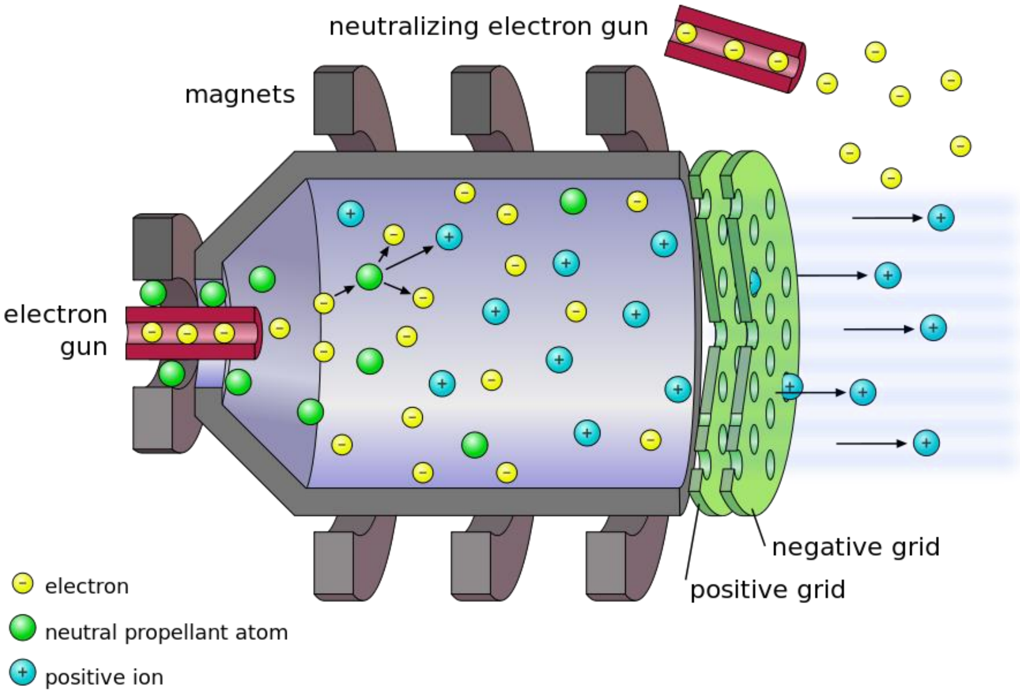



*FIGURE 25: SCHEMATIC DIAGRAM OF GRIDDED ION THRUSTER*

Gridded ion thruster is a highly efficient space craft propulsion running on electric power. Initially an electron gun releases some electrons which collide with propellant (mostly argon or xenon) and induces the ionization, then the voltage grid electrodes are used to accelerate those ionized particles at very high speeds as shown in Fig. 25. A neutralizer is used to neutralize the ionized particles in order to prevent back effect.

A Hall Effect thruster makes use of Hall Effect to generate a cross field discharge that cross fields creates plasma. Electrons are generated by a cathode at the downstream of thruster and these are attracted towards anode due to potential difference, as electrons move towards anode it encounters strong magnetic fields and gets trapped in that field spinning called Hall Effect. These trapped electrons are used to ionize the propellant to create plasma and then the plasma is accelerated to high speed using cross fields.

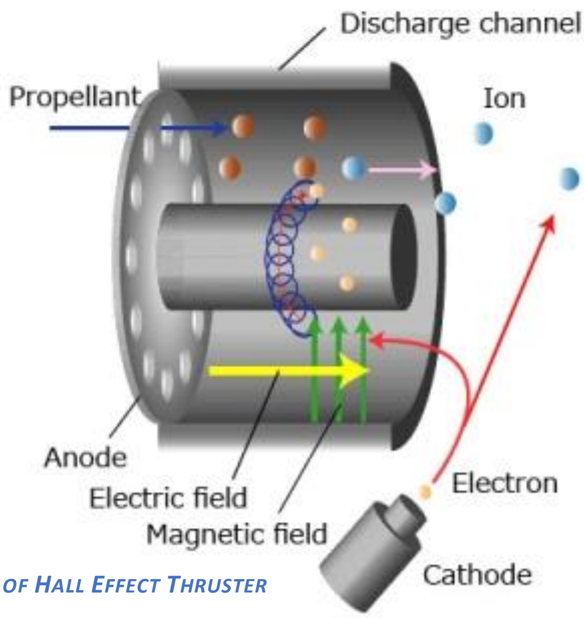



*FIGURE 26: SCHEMATIC DIAGRAM OF HALL EFFECT THRUSTER*

## C) Electromagnetic propulsion

An electromagnetic propulsion is third type of electric propulsion which relies on interaction of electric and magnetic field to provide accelerating body force, known as Lorentz force. This type can produce high specific impulse compared to electro thermal and high electron density compared to electrostatic. Pulsed Plasma Thruster and Magneto Plasma Dynamic Thruster come under electromagnetic propulsion.

A Pulsed Plasma Thruster uses electrical discharge to ionize the propellant and form plasma and this plasma is accelerated by Lorentz force (which is created by interaction of electrical and magnetic fields). This study centers on the development of pulsed plasma thruster, Hence PPT is explained in detailed in coming chapters.

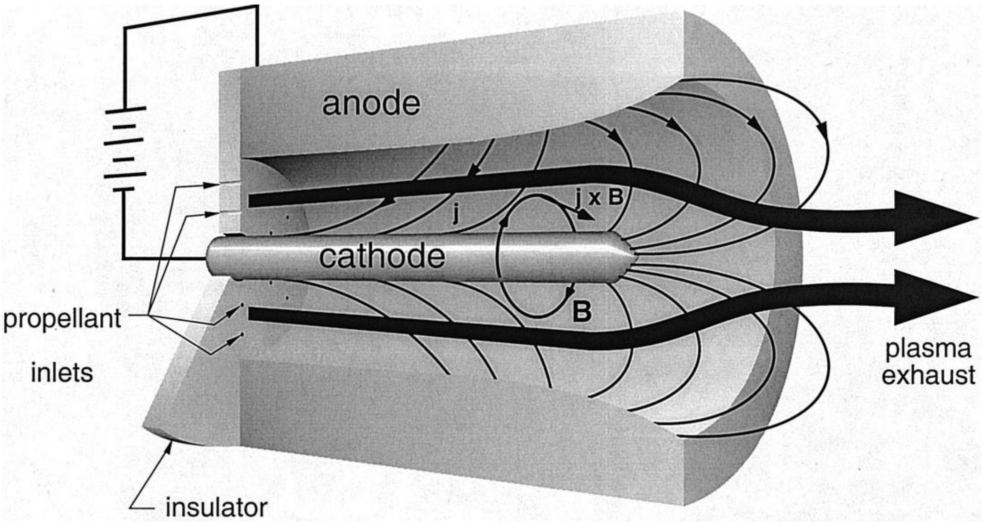



*FIGURE 27: SCHEMATIC DIAGRAM OF MPD THRUSTER*

A Magneto Plasma Dynamic (MPD) thruster is a coaxial geometry constituted by a central cathode, annular anode and an insulator. A Propellant is allowed from backside of the thruster and then there is a uniform electric arc on the way of the propellant which ionizes it and creates plasma. Furthermore, if the current is high enough, its associated magnetic field is also high. These high current and magnetic field impose force on propellant, directly accelerating it towards downstream and compressing it to hot plasma beyond cathode tip. These compression leads to expansion of plasma and that gives high exit velocity.

## D) Comparison between these different types of thruster

We can compare these different kinds of thrusters with the power and force necessary to create a thrust, with the $I_{sp}$ and the Total Impulse ($I_T$) to show the efficiency to which they use the propellant.

The Total Impulse is linked to the Specific Impulse. Indeed, we can write:

$$I_T = m_p * I_{sp} * g_0$$

- $m_p$: the total propellant mass
- $I_{sp}$ : Specific Impulse
- $g_0$ : the standard gravity

It delivered per unit of propellant consumed.

| Propulsion type | Thrust (mN) | $I_{sp}$ (sec) | Total Impulse (N-sec) |
|---|---|---|---|
| Arc-jet | 100-2000 | 480-810 | 12,000 |
| Resisto-jet | 180-500 | 280-305 | $3\times10^5$ |
| Hall effect | 11-512 | 950-1,950 | $2.3\times10^6$ |
| Ion bombardment | 10-160 | 2,500-3,310 | $>3\times10^6$ |
| PPT | 0.3-0.75 | 830-1,200 | 15,000-20,000 |
| MPD | 23 | 600 | >1,000 |

*FIGURE 28: PERFORMANCE PARAMETERS OF VARIOUS PROPULSION SYSTEMS [3]*

The Electrothermal thrusters (Arc-jet and Resisto-Jet) need more energy than the others and they have a weak $I_{sp}$.

The Electrostatic thrusters (Hall effect and Ion bombardment) need less energy than the Electrothermal propulsion, they have a very good $I_{sp}$ but they use a lot of fuel (we can see with the very big $I_T$).

The Electromagnetic thrusters (PPT and MPD) need very low power, so it's very interesting for the future. They have an $I_{sp}$ and an $I_T$ very correct. This family of thruster seems have a lot of advantages in comparison with the others.

# III/ DEVELOPMENT OF THE VAPOR WATER LORENTZ FORCE ACCELERATOR (VwLFA)

This part is my beginning in the laboratories of the ZapLAB. My work consists to find a new thruster, never realized in these laboratories. I choose to take the Lithium Lorentz Force Accelerator (LiLFA) and make improvements on it to create something new. I worked on this complex project during half of my internship, to understand all the principles of the plasma and make my Catia design the best as possible.

I will present the LiLFA to introduce my project, and we will continue with the improvements brought to arrive at the Vapor water Lorentz Force Accelerator (VwLFA), after we will have the presentation of the electrical and gas system, for finishing by my Catia design of this thruster.

## 1) Characteristics of the Lithium Lorentz Force Accelerator (LiLFA)

The LiLFA belongs to the family of Magneto Plasma Dynamic Thruster (MPDT), and the big family of the electromagnetic thrusters.

A MPDT is a form of electrically powered spacecraft propulsion which uses the Lorentz force (the force on a charged particle by an electromagnetic field) to generate thrust.

The lorentz force is the combination of electric and magnetic force on a point charge due to electromagnetic fields. A particle of charge *q* moving with velocity v in the presence of an electric field E and a magnetic field B experiences a force. This equation characterizes this force:

$$F = qE + qV * B$$

Generally, a gaseous material is ionized and fed into an acceleration chamber, where the magnetic and electrical fields are created using a power source. The particles are then propelled by the Lorentz force resulting from the interaction between the current flowing through the plasma and the magnetic field (which is either externally applied or induced by the current) out through the exhaust chamber. Unlike chemical propulsion, there is no combustion of fuel. As with other electric propulsion variations, both specific impulse and thrust increase with power input, while thrust per watt drops.

The LiLFA uses lithium as propellant and a multi-channel cathode. There are two types of thrusters, applied-field and self-field. Applied-field thrusters have magnetic rings surrounding the exhaust chamber to produce the magnetic field, while self-field thrusters have a cathode extending through the middle of the chamber. Applied fields are necessary at lower power levels, where self-field configurations are too weak. My thruster is an applied-field with a coil to make an electromagnetic field. It works with a continuous flow, so we can have a wonderful homogeneous plasma.

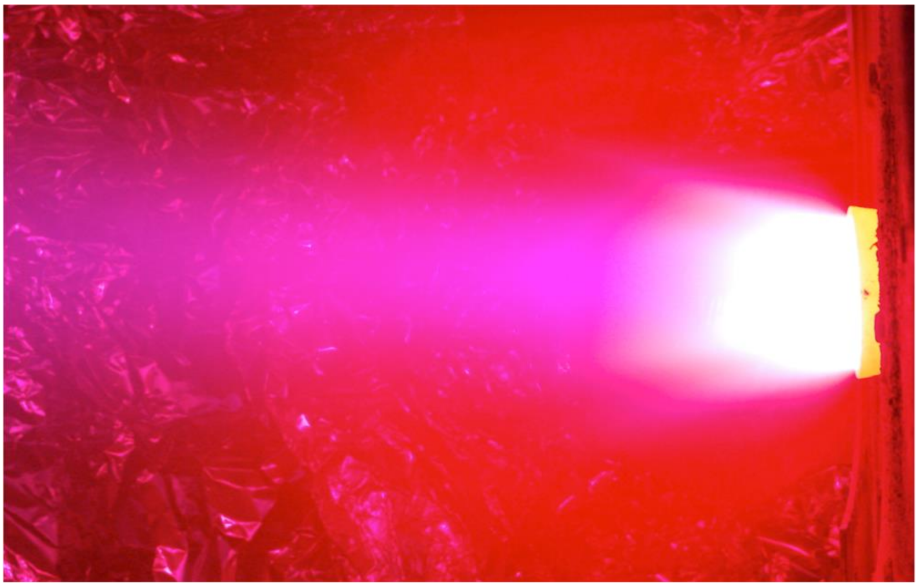


*FIGURE 29: PLASMA CREATED BY THE LILFA*

Recently, a thrust efficiency of 43% at an Isp of 3460 s was measured in Moscow [5] for a low-erosion LiLFA operating at 130 kW. The thrust-to-power ratio of these devices is typically about 25 N/MW. The extension of the lifetime of such thrusters to above 1000 hours has been recently shown to be within reach with the demonstration of 500 hours of practically erosion-free operation of a 50%-efficient Li-LFA at 0.5 MW [6].

## 2) Improvements resulting of the new thruster (VwLFA)

Firstly, my project and my design rely on this schema:

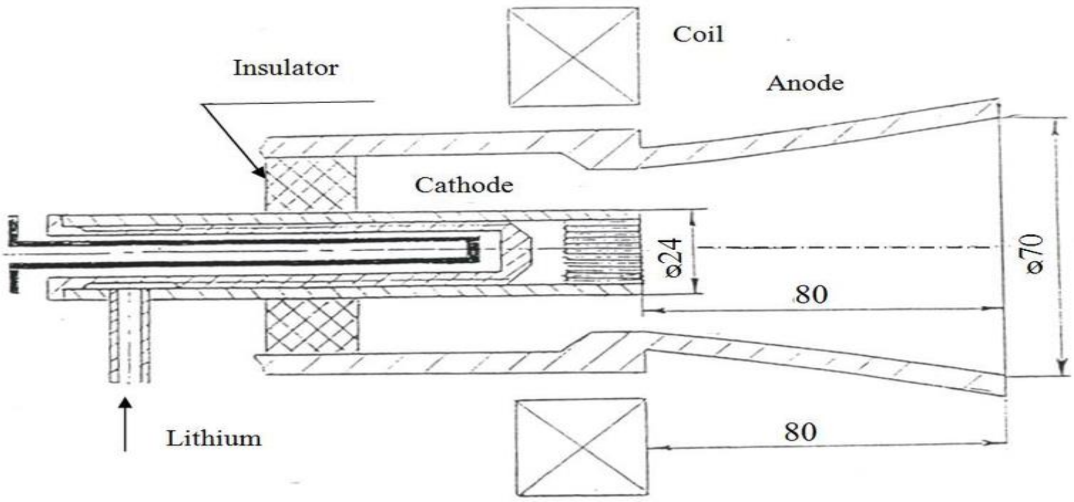



*FIGURE 30: SCHEMA OF LILFA*

Lithium was too dangerous to use in NCKU's labs. So, I thought about using water vapor. The thruster name becomes Vapor water Lorentz Force Accelerator (VwLFA).

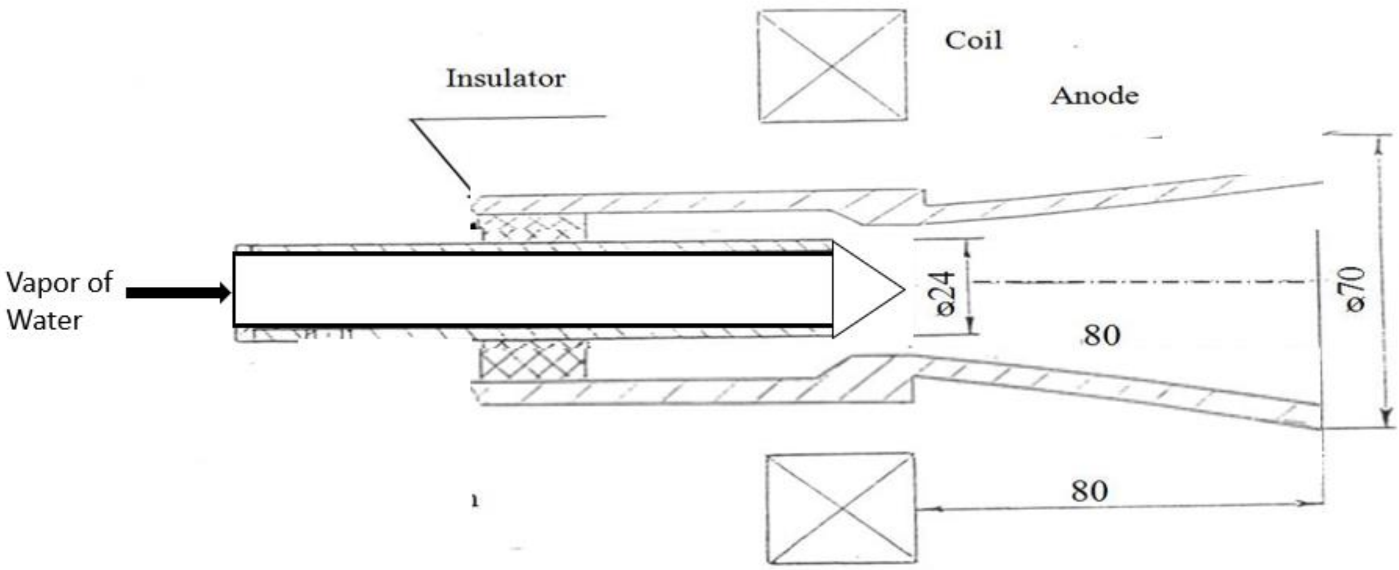



*FIGURE 31: SCHEMA OF VWLFA*

This system had several advantages:

- It was very inexpensive
- not dangerous

Moreover, I could remove the heating of my cathode because in the vacuum chamber there is very little pressure, so we have that water molecules with the force of pressure that makes sure to retain it liquid state, without this pressure force, my water molecules will escape to form the gaseous state and thus the water vapor. Then I changed the end of my cathode in a point with a small hole, to allow the arc to remain stable is continuous, because if the area was too large, the arc would become discontinuous and I would quickly have problems to create my electric field. In this same perspective of stability of the arc and therefore of the electric field, I reduced the distance between my cathode and my anode, so that the arc will can be more shorter and therefore more stable.

## 3) Electrical and gas system

My electrical is very simple, thank to the use of a continuous flow. I need just to have a power source coupled with an amplifier, because of the high voltage necessary for good operation and effective of my thruster.

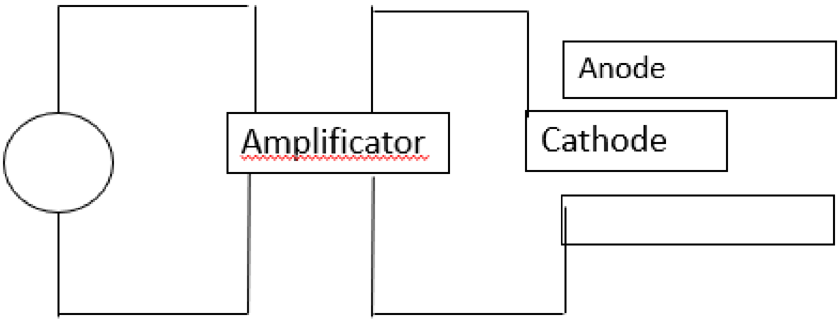



FIGURE 32: ELECTRICAL SCHEMA FOR MY VWLFA

The thruster can work with minimum power of 3 kW. To determine the voltage and current necessary, I use the formula of electrical power:

$$P = U * I$$

- P: Power in Watts
- U: Potential difference (voltage) in Volts
- I: Current in Amperes

A low current is necessary for the security during the experiences, but because of the big power that my thruster needs, the risk have to be a bit high.

I choose to take a voltage of 3 kV and a current of 1 A.

$$U * I = 3000\ V * 1\ A = 3000\ W = P$$

## 4) Catia Design

Firstly, for my design, it was essential to make a base solid in the optic to put and connect all my components (Appendix 1).

After, all the components must be perfectly measured to permit that the assembly doesn’t have any inconsistency. These components are relied to the base with screw and nuts and they have the holes.

So, with the help of Catia, it was able to make the Anode (Appendix 2), the anode Insulator (Appendix 3), the Cathode (Appendix 4) and the cathode Insulator (Appendix 5). You can find all the measures relied to pieces on these Appendices.

It misses just to create the coil, but I really didn’t understand the use of it, so I didn’t make it before changing of project.

You can see all the components in exploded view in the Appendix 6.

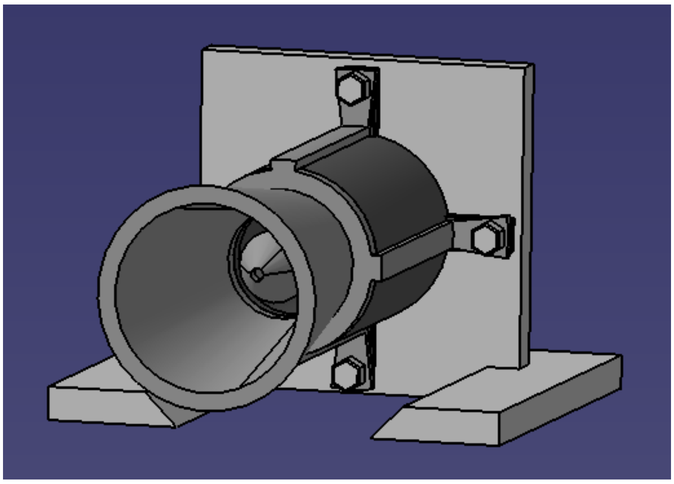


FIGURE 34: VIEW 1 OF THE ASSEMBLY CATIA DESIGN OF THE VWLFA

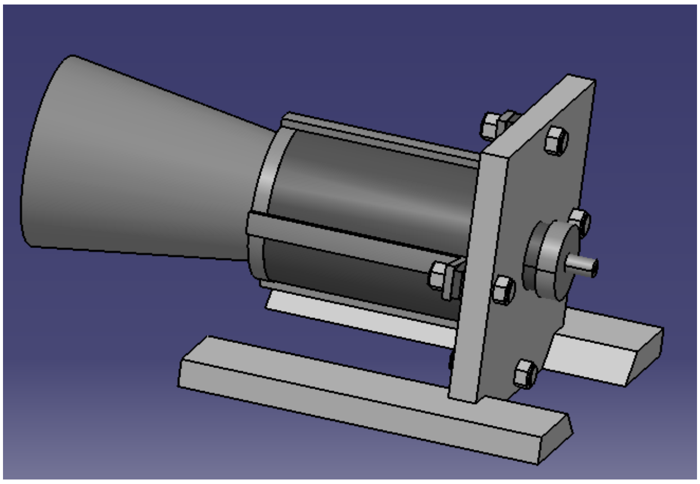


FIGURE 33: VIEW 2 OF THE ASSEMBLY CATIA DESIGN OF THE VWLFA

The thruster has a total length of 196 mm and a width of 100 mm (width of the base).

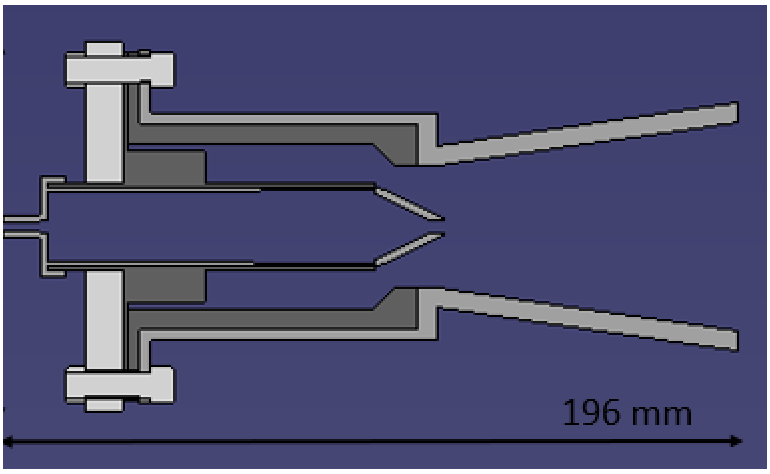



FIGURE 35: CUT OF THE VWLFA

For the material of my Anode and Cathode, at the beginning, to use Tungsten seems me a very good solution. Indeed, the fusion point of the tungsten is 3422 °C (Supports the high temperature of an arc very well), the tungsten is very resistant to corrosion (Perfect for the cathode where the vapor water pass through it) and it has an electrical conductivity equal to $8{,}9.10^6 S.m^{-1}$

The use of a tungsten has a problem. The tungsten is a heavy and very hard stone, so very complicated to work for the manufacturer.

Now, my cathode and anode will be in copper. The copper has a fusion point of 1083 °C, an electrical conductivity of $59{,}6.10^6 S.m^{-1}$. Moreover, in space or vacuum chamber, there is no air so no oxidation. Just, the little problem maybe will be the corrosion of my pieces and maybe with the high temperatures.

My insulators will be in boron nitride. This material is very resistant to the high temperature with a fusion point of 2800 °C.

# IV/ EXPERIMENT OF THE GAZ-INITIATED PULSED PLASMA THRUSTER (PPT)

In this part, I continue the thesis of Sunil Kumar with my co-worker the master student Kai in the optic to develop the Gaz-initiated PPT in adding a solenoid valve in the system. I worked on this complex project during half of my internship

I will present the general PPT to introduce my project, and I will continue with the concept, the electrical and gas system for finishing by the experiment realized in the laboratories of Zaplab.

## 1) Introduction to the PPT

Pulsed Plasma Thruster is one of the most promising electric propulsion devices for micro- and nano-satellites as it is low cost, simple in design, light weight and low power consumption. It can generate very high specific impulse with less power consumption, Therefore PPT has great advantage in altitude control and station keeping. PPT were the first form of electric propulsion that flown to space on two soviet probes Zond 2 and Zond 3 in 1964. Since then there has been a lot of interests in developing PPT. This thruster pertains third type of electric propulsion system that is electromagnetic propulsion. It is made up of several constitutional parts: Power supply to charge the capacitor, capacitor is used to store the energy, propellant mainly Teflon, electrodes which accelerates the forming plasma. Propellant in PPT is accelerated as shown in Fig. 36.

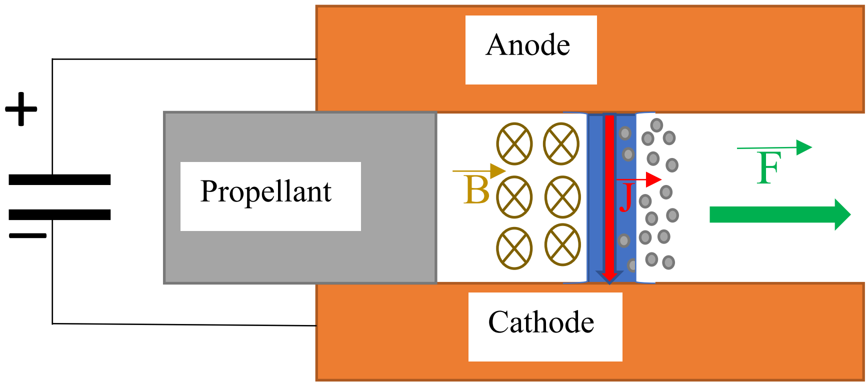



*FIGURE 36: ELECTROMAGNETIC ACCELERATION OF PLASMA*

The accelerating mechanism is defined as rapidly discharging finite electrical energy source that transfers energy to a self-created magnetic field around an induced current flow, in which part of the current flow is through a self-generated plasma. In which exploitable thrust is created from Lorentz force which is produced by interaction of the magnetic field with the flowing current through the plasma [7]. Currently exists five types of PPT geometry configurations, these types are basically defined by the combination of two types propellant feeding systems (breech feed and side feed) and electrode configuration (rectangular, coaxial and z-pinch) [8].

## 2) Gaz Initiated PPT (GPPT)

### A) Concept and operational process

Operation of gas initiated pulsed plasma thruster (G-PPT) is similar to electrical break down. Operational process of G-PPT is divided into four stages: Capacitor charging, Release of gas, Electrical breakdown and Acceleration as shown in Fig. 37.

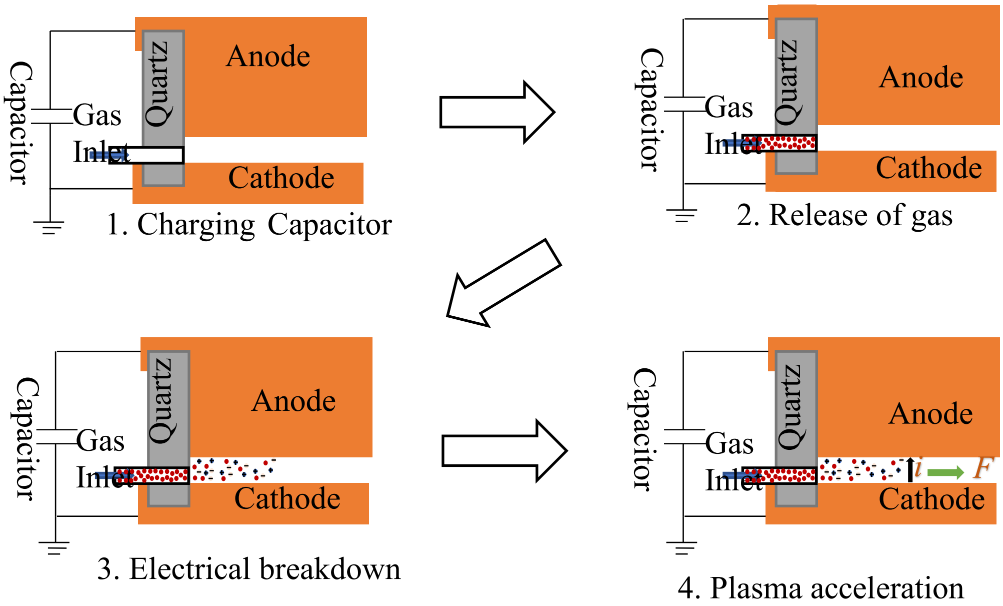



*FIGURE 37: OPERATIONAL PROCESS OF G-PPT*

1. *Charging Capacitor:* The process starts with power unit supplying electrical energy to the capacitor. This stage is same as pre-ignition stage in solid fed pulsed plasma thruster. The charging time depends on the resistor and capacitance of the capacitor. This charging time plays an important role in repetition rate of discharge. Once the required amount of energy is stored in capacitor then it is ready for second stage. Charged voltage acts as a potential difference between anode and cathode.

2. *Release of gas:* After charging the capacitor. The gas is released in between the electrodes in such a way that the pressure between the electrodes becomes sufficient enough to create electrical breakdown. Low pressure can be obtained by releasing micro grams of gas per second. When the pressure is sufficient enough and there is a potential difference between the electrodes, it is ready for third stage.

3. *Electrical Breakdown:* There is always a background radiation coming from cosmic rays, these rays can cause photoemission from the cathode. These release the electron that travel from cathode to anode. The electron, while moving towards anode collides with

neutral gas particle to create charged particles and slowly all the gas in between the electrodes gets ionized and plasma source is formed between the electrodes. Plasma source acts as a conductive path between electrodes and allows the discharge to happen thus creating current loop. As the discharge time is very less (in the range of Microsecond) it leads to produce very high instantaneous current (in the range of kA).

4. *Acceleration:* The large current in the plasma plume induce a strong magnetic field. Current in the presence of magnetic field experiences a Lorentz (J×B) force. This force accelerates the plasma plume out of the thruster with certainly high speed and non-ionized particles are expanded from the thruster with low speed. This stage is same as fourth stage of solid pulsed plasma thruster.

#### B) Prototype

A prototype has been designed to test, which constitutes of two electrodes with width 10mm, which acts as anode and cathode. Gas is allowed from backside through cathode as shown in Fig. 38. Quartz is used as insulating material to separate anode and cathode. Two more plates made from quartz is used as side walls of the prototype so that the gas cannot escape but flows to exit between the electrodes and screws are placed to electrodes which helps in connecting cables from the capacitor.

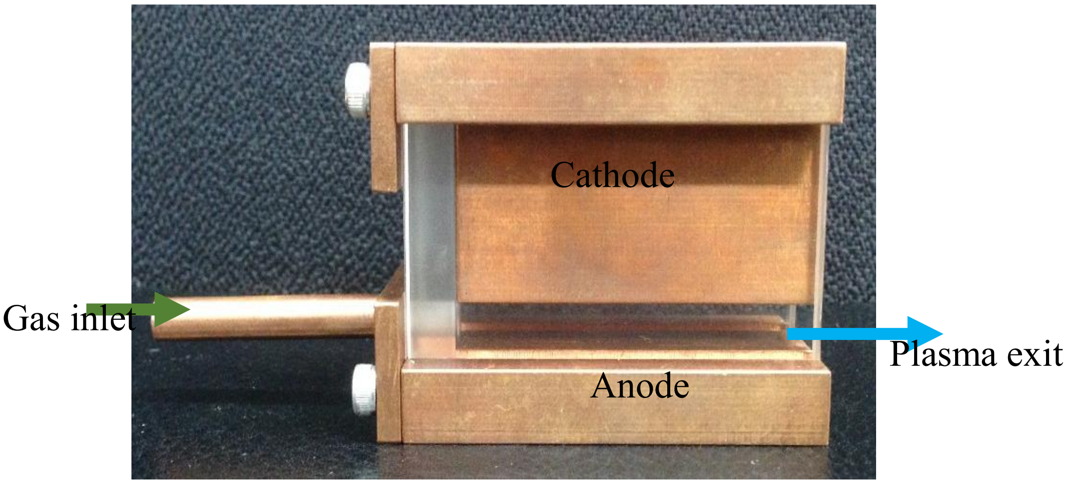



*FIGURE 38: PROTOTYPE OF G-PPT*

### 3) Preparation of the system with the Solenoid Valve

#### A) Gas system

Firstly, for the G-PPT I use Argon gas as propellant. We need a tank which contains this specific gas.

My solenoid valve permit to stop and open the entry of gas to create a pulsed plasma. It has two entry, one to the tank and another for the gas inlet on my prototype.

FIGURE 39: SOLENOID VALVE WITHOUT CONNECTOR

To permit the connexion between the gas inlet and the solenoid valve, our crew manufactured a connector with my Catia Design (Appendix 7). We just change at the last moment the length of the extremity, 6mm to 20 mm, to permit that the pipe has enough place. In fact, my solenoid valve is in a first time connected to a material on the vacuum chamber, and this material connected to the gas inlet of my G-PPT.

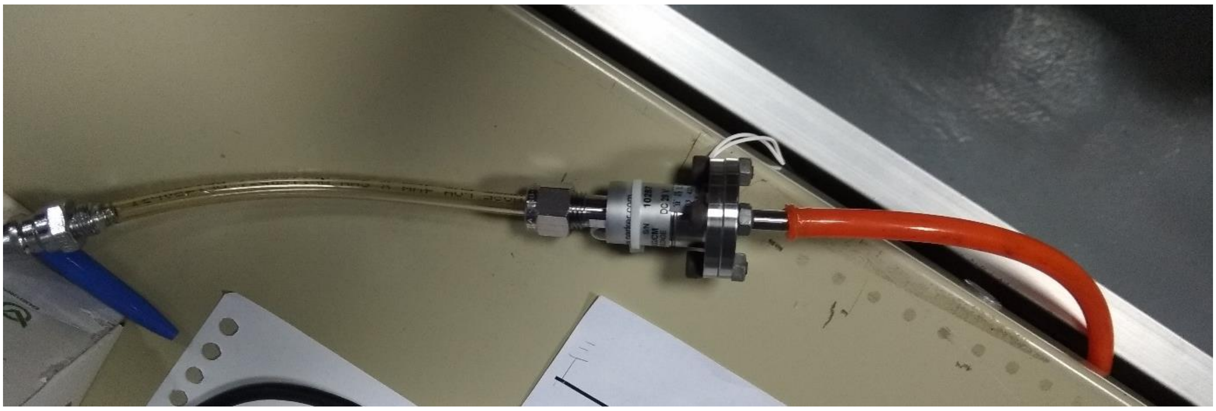


FIGURE 40: SOLENOID VALVE WITH CONNECTOR AND PIPES

Moreover, the mass flow controller was not necessary because the solenoid valve with the pulse can control the entry of gas. We still tried with this equipment too.

## B) Electrical system

I have two different systems:

- Power for my anode and cathode with capacitor

- Power for my solenoid valve with IGBT and Pulse generator (or function generator)

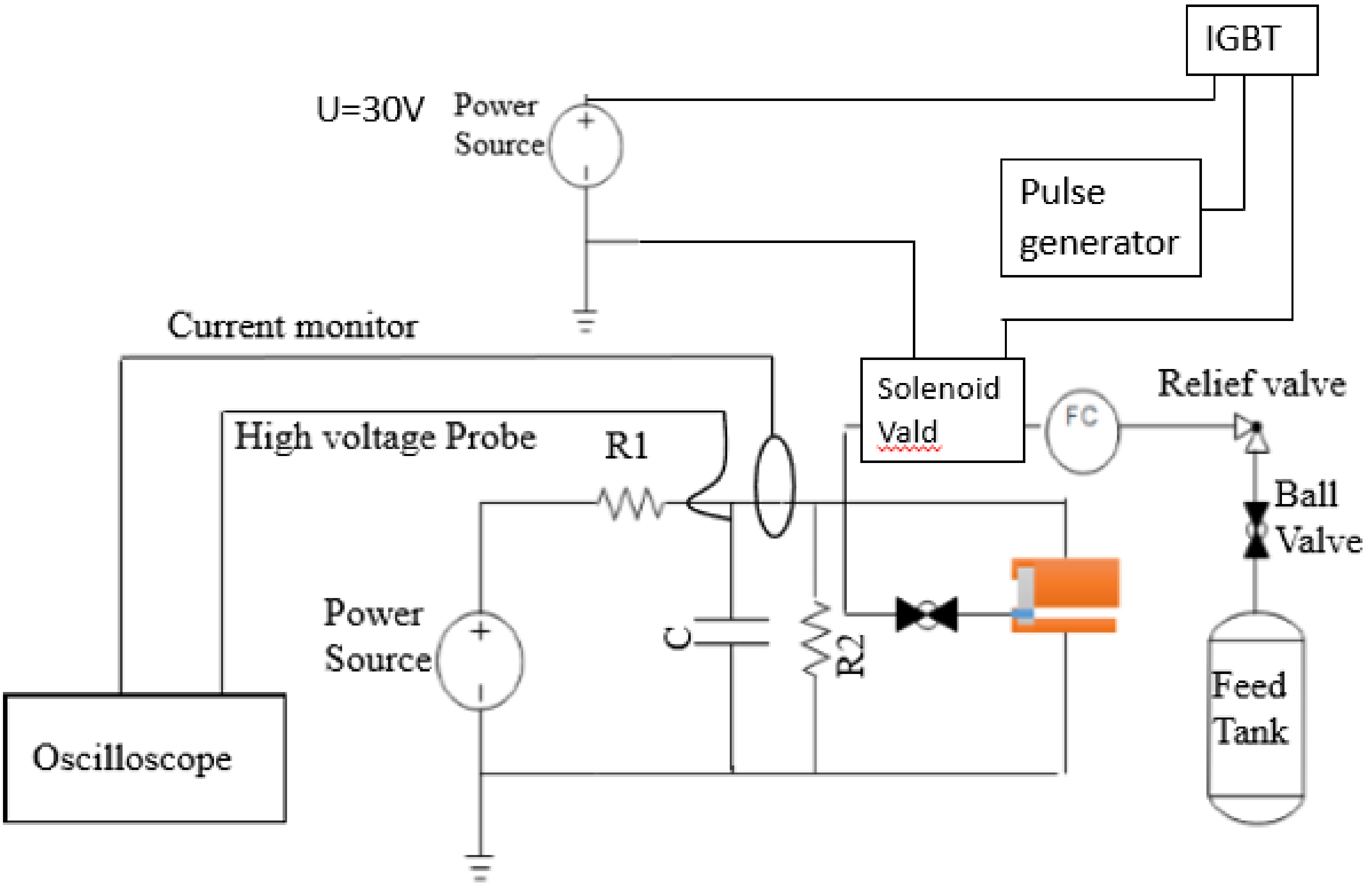



FIGURE 41: ELECTRICAL SYSTEM (AND GAS SYSTEM) OF MY G-PPT

For my first power source (anode and cathode), the range is between 0 and 4 kV and we must try and fluctuate the values to find the best voltage in the optic to create an arc with the most efficiency. The capacitor is very important because it permits the first step ("Charging Capacitor") in order to stop the arriving of electricity, essential for the creation of the pulsed plasma.

FIGURE 43: CAPACITOR (WITH TWO CAPACITORS CONNECTED BETWEEN US)

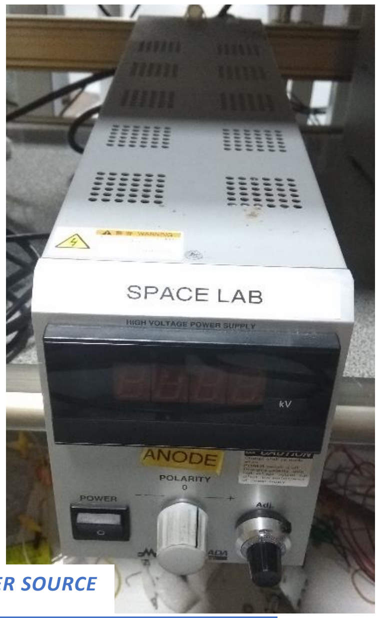



FIGURE 42: FIRST POWER SOURCE

For my second power source (solenoid valve), the voltage necessary depends of my solenoid valve. This one can work with 28,7 V. So, we take a little battery (3,7V) and a DC-DC Converter (an amplifier) to have a voltage of 30V. There are two resistors of 10 Megaohm one between the power source and the capacitor, and another between the capacitor and the ground.


**FIGURE 45: BATTERY OF 3.7V**

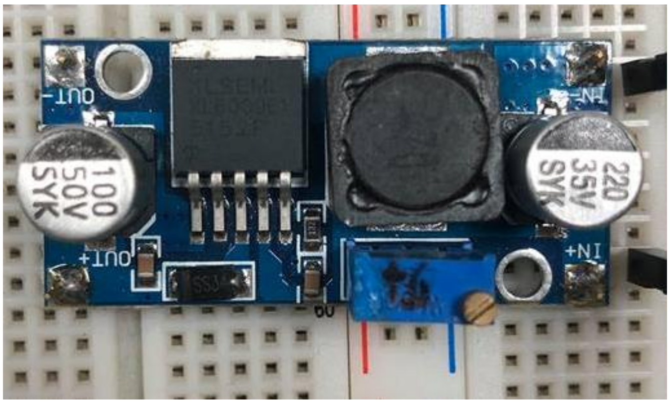


**FIGURE 44: DC-DC CONVERTER (AMPLIFIER TO 30V)**

An IGBT (Insulated-Gate Bipolar Transistor) is a three-terminal power semiconductor device primarily used as an electronic switch which, as it was developed, came to combine high efficiency and fast switching.

Therefor, IGBT coupled to the pulse generator permit to open the solenoid vald to let the gas through, and then closed to block the gas inlet, so on to generate the pulses, part essential of this project in terms of efficiency

**FIGURE 46: IGBT**

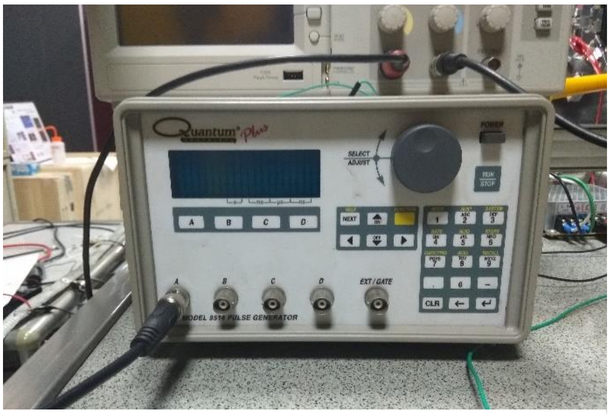


**FIGURE 47: FUNCTION GENERATOR**

We went a lot of times in the electric shop, to buy resistors, connectors, batteries. NCKU reimburse any cost useful for experiments, the students just have to take a bill, take a pictures of the components and show to the office. I am grateful for the help of the students of the ZapLab for, every time, coming with me and help to find the good component for this experiment.

## 4) Experiment and future work

With Kai, we did the experiment less time before I leave Taiwan, because it took time to find all the pipes and electric connectors, and to prepare all the gas and electrical system.

Firstly, we have to make the same conditions than in the space to test the thruster. It' necessary to use a Vacuum chamber, present in the laboratories of the ZapLab. It takes approximately 40 minutes, to put out the air of the vacuum chamber, in order to have almost no pressure for bringing closer of the space conditions.

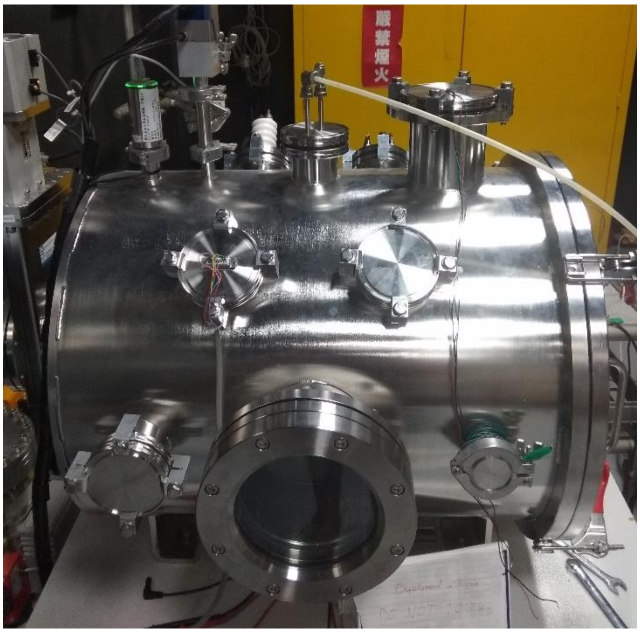


*Figure 49: Vacuum chamber*


*Figure 48: Pressure Control Panel*

Finally, we tried the experiment, but it didn't work. Perhaps, it's because we didn't think before to put a nodal valve on the tank, to permit to stop directly the gas, which go out of the tank. So, the biggest trouble was on the pipes, because when the solenoid valve works, and it closes for example, the gas, so the pressure is more important in the pipe. In the optic to go over this trouble, we tried to put the mass flow controller, but the experiment doesn't work too.

Another problem was on the connexion between the IGBT and the function generator, we didn't find this electrical connector in the lab, and the student, who uses this, was in Thailand for a meeting.

My co-worker will have to try again this experiment with the nodal valve and the connector between the IGBT and function generator. The electrical and gas system are finished and installed (like you can see on the pictures).

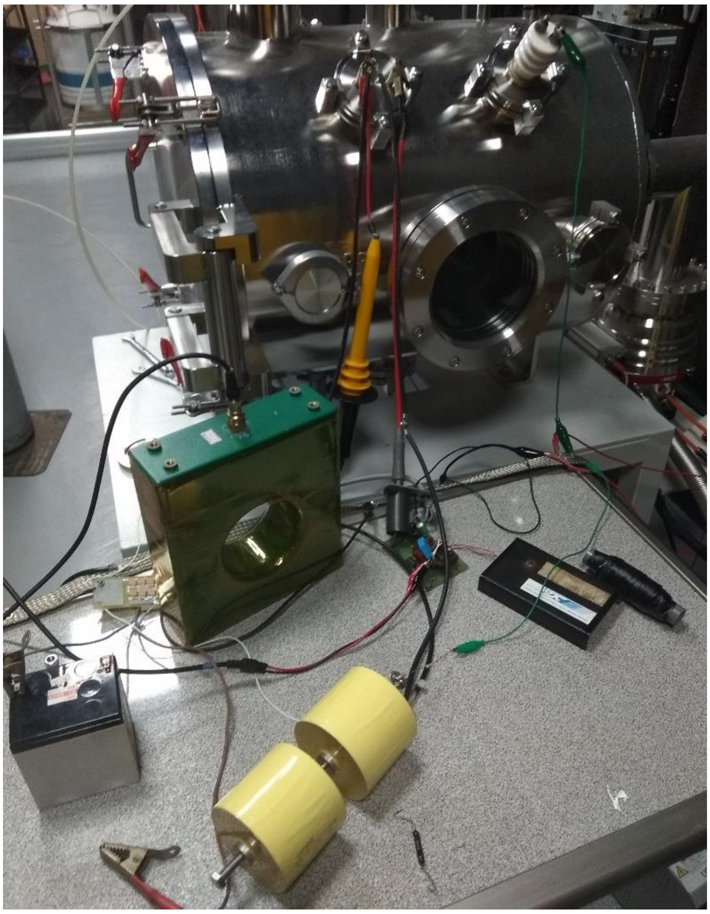


*Figure 52: First electrical system with capacitor (yellow), connector to the anode (black) and to the ground (green)*

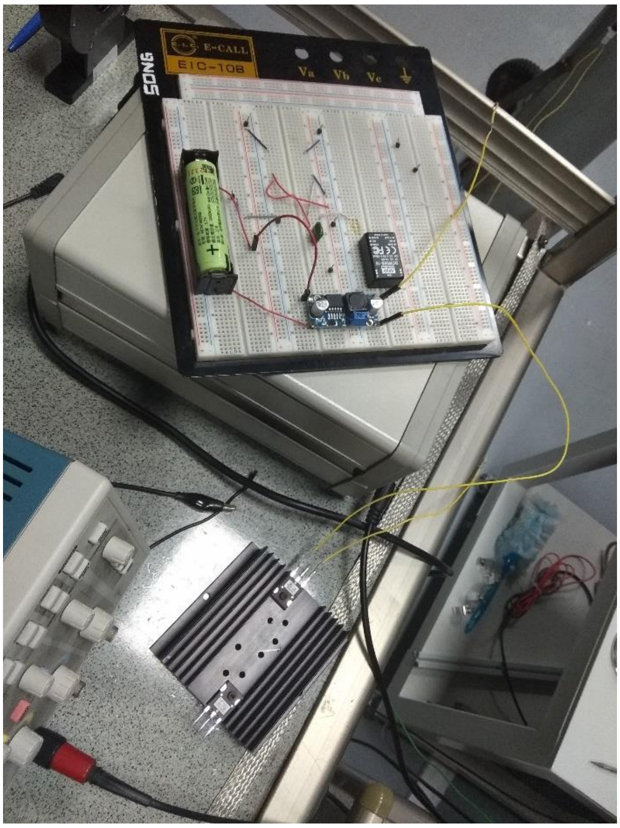


*Figure 51: Second electrical system with battery (green), amplifier, IGBT (black with the yellow connectors)*

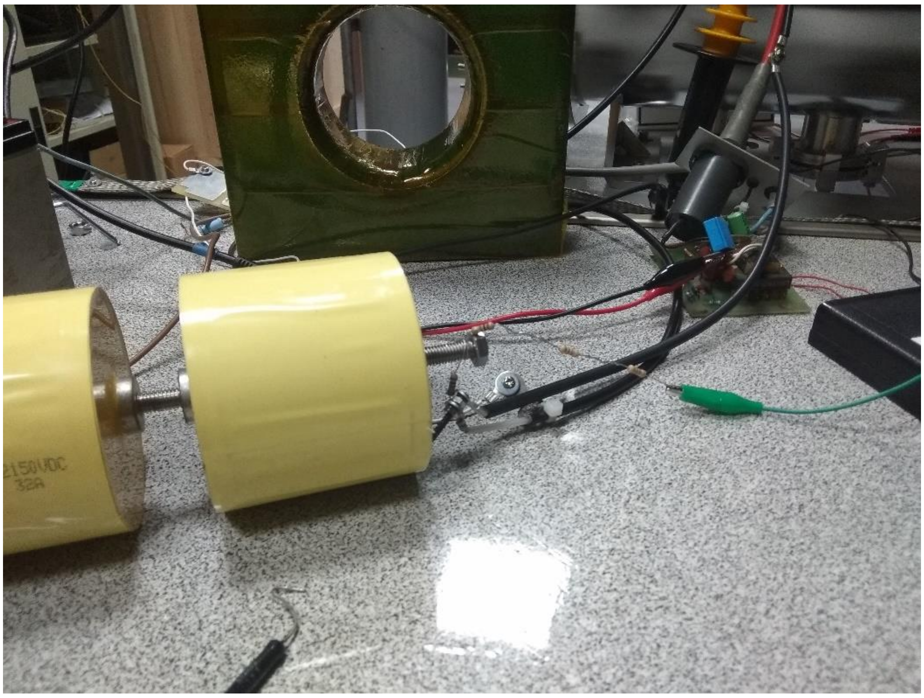


*Figure 50: zoom on the first electrical system with capacitor, resistors, connectors*

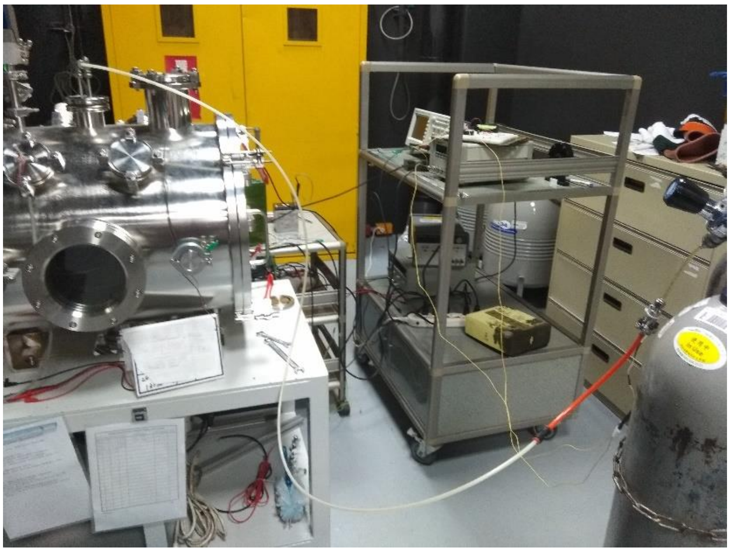


FIGURE 53: GAS SYSTEM WITHOUT MASS FLOW CONTROLLER (TANK, SOLENOID VALVE, PIPES)

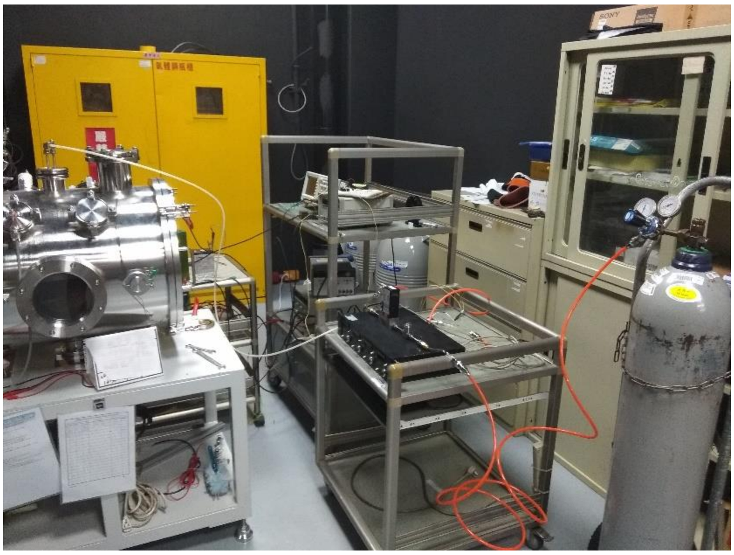


FIGURE 54: GAS SYSTEM SECOND TEST (MASS FLOW CONTROLLER, TANK, SOLENOID VALVE, PIPES)

In terms of security, every time after experiments, it's necessary to discharge the capacitor with the use of cable connected to the ground like we can see in Fig. 42, but without touch the capacitor or with protective gloves.

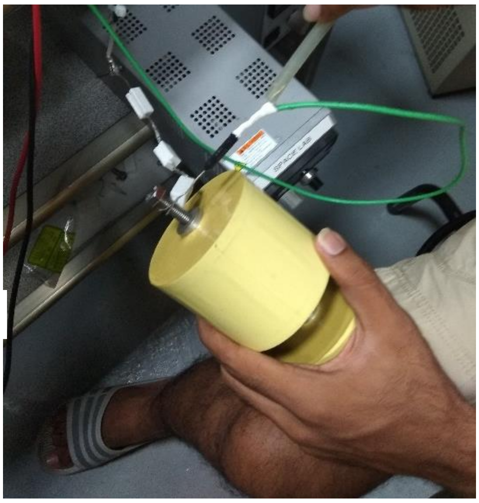


FIGURE 55: DISCHARGE OF THE CAPACITOR

# CONCLUSION

Been integrated in this kind of research internship, among the Combustion and Propulsion Laboratory of the National Cheng Kung University of Taiwan, has been more than a simple experience in my engineering studies but a real investment of all my being. It has been a real mutual exchange between other students, professors and me, about a project which I have led with passion, and this wonderful culture and traditions which have this country.

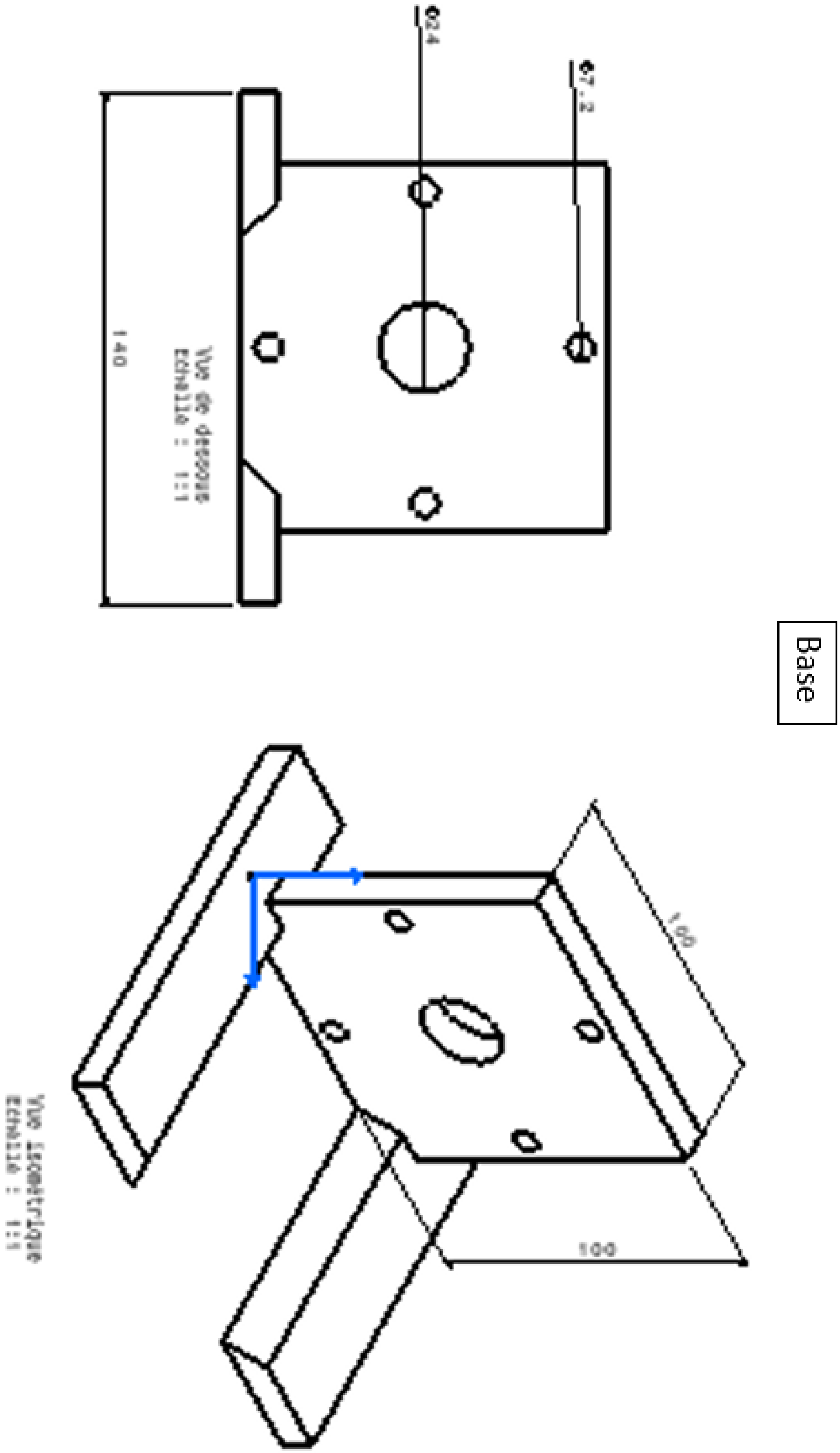
This part of the University, which I have been, is an interesting, spiritual and fascinating place, where we can pleasantly learn, discover and work. Every research represents a real step for Science. It has impressed me a lot and it has been a real satisfaction to be enrolled in these little scientific breakthroughs.

This experience has been an enrichment for my general knowledge as much for my professional rigor. It has given me the taste of working in a research laboratory. I have learnt a lot by working in team but also by working alone. This pressure in research laboratory has been a new sensation to experience and a real new challenge to take up.

The only thing I regret it’s the short duration of my internship. Indeed, my first project stops because of the delays of the manufacturers for specific pieces like this. For my second project, the experiment didn’t work at the first time and I didn’t have the time to test again the G-PPT and my gas system with the nodal valve. I hope someone will recover my VwLFA project to make it in real and to test it, and I hope that my co-worker Kai will reach to finish the G-PPT project, to make it useful and efficient.

I would like to thank again all the professors and students, for the help and enthusiasm I received. Meetings combined to my researches, have been a perfect training to face an audience and dominate a complex subject. In my mind, all of this summary is a clue to become an accomplished future engineer.

# APPENDIX 1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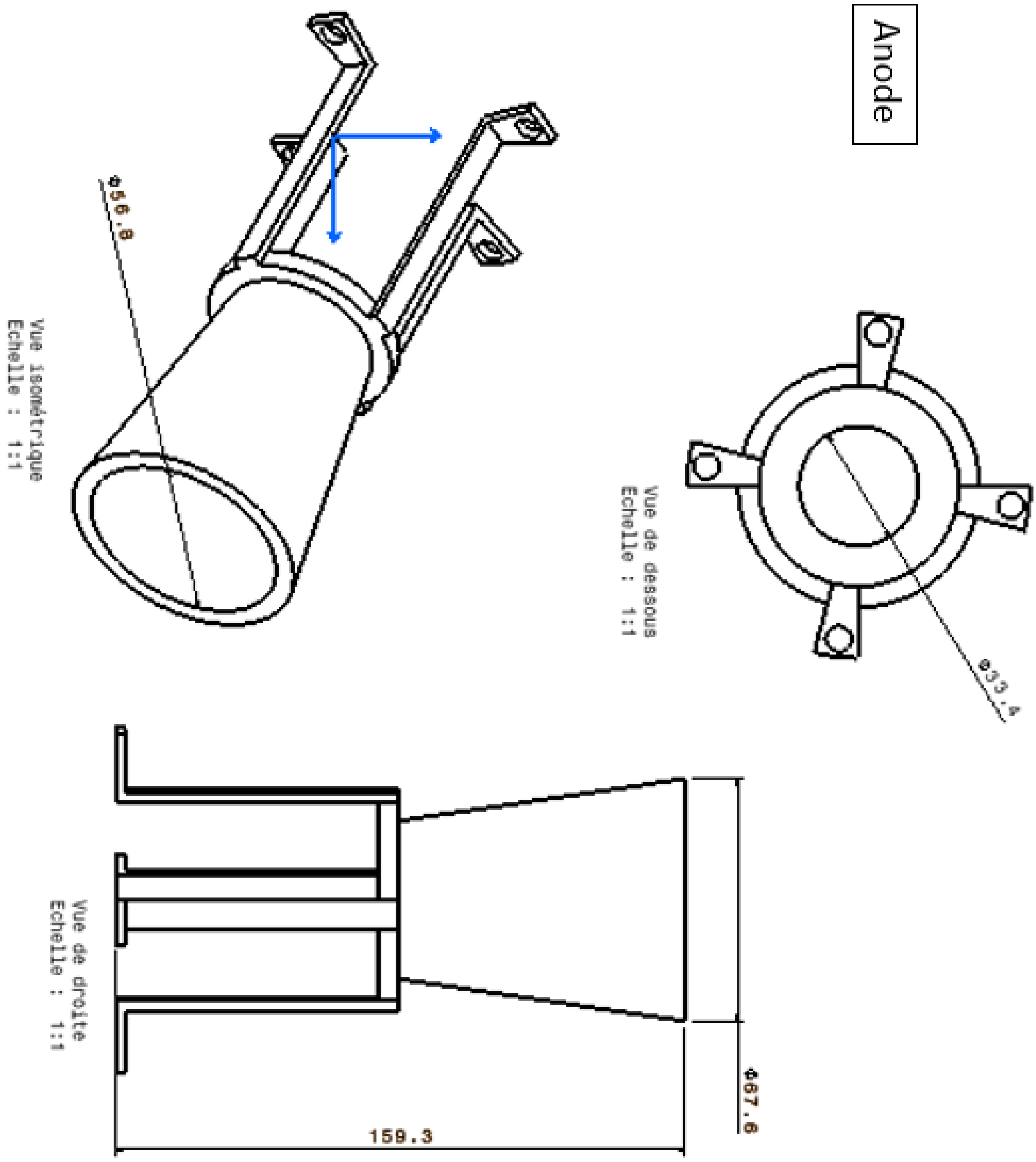
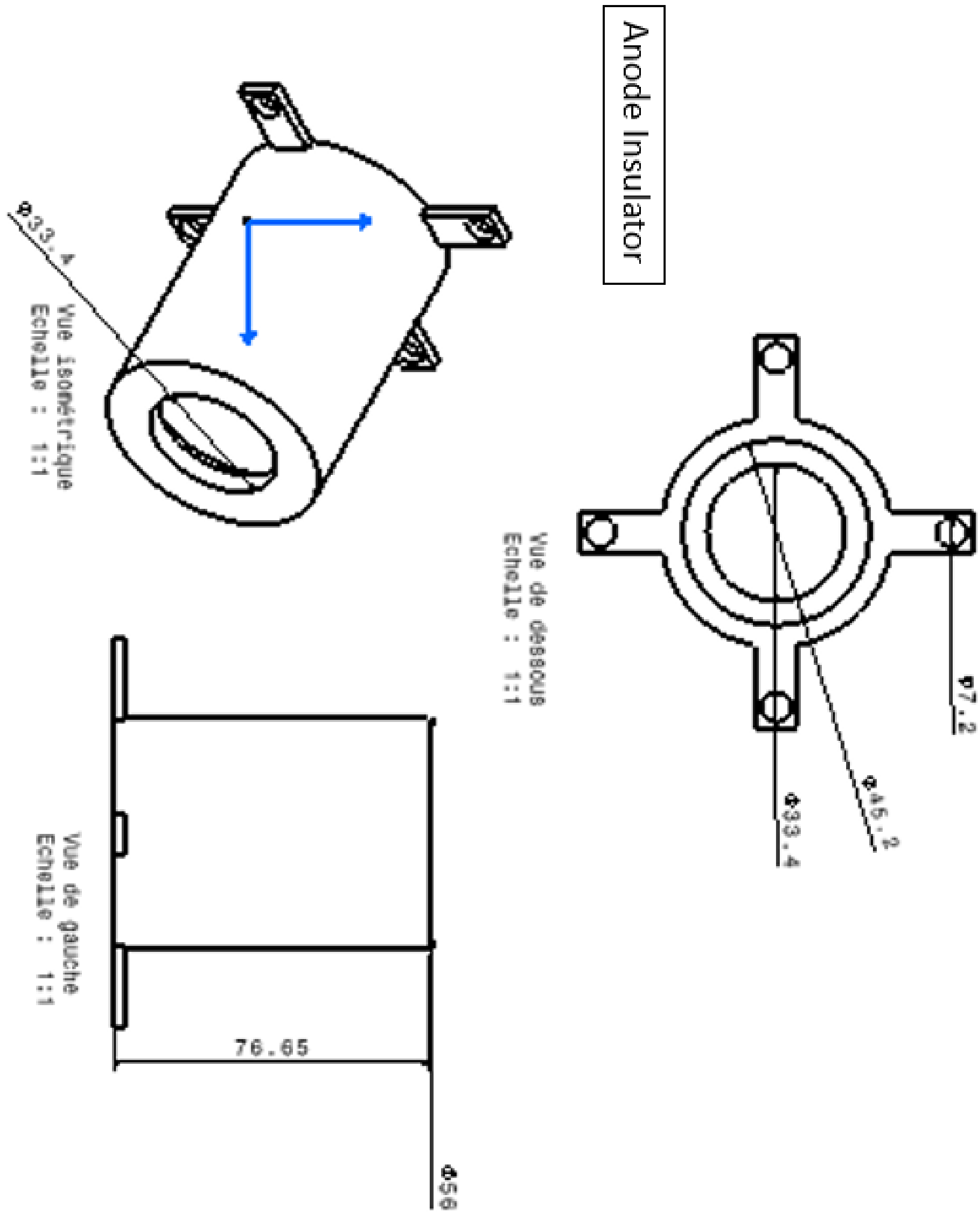
Ø7.2
140
Vue de dessous
Echelle : 1:1
Base
100
100
Vue isométrique
Echelle : 1:1

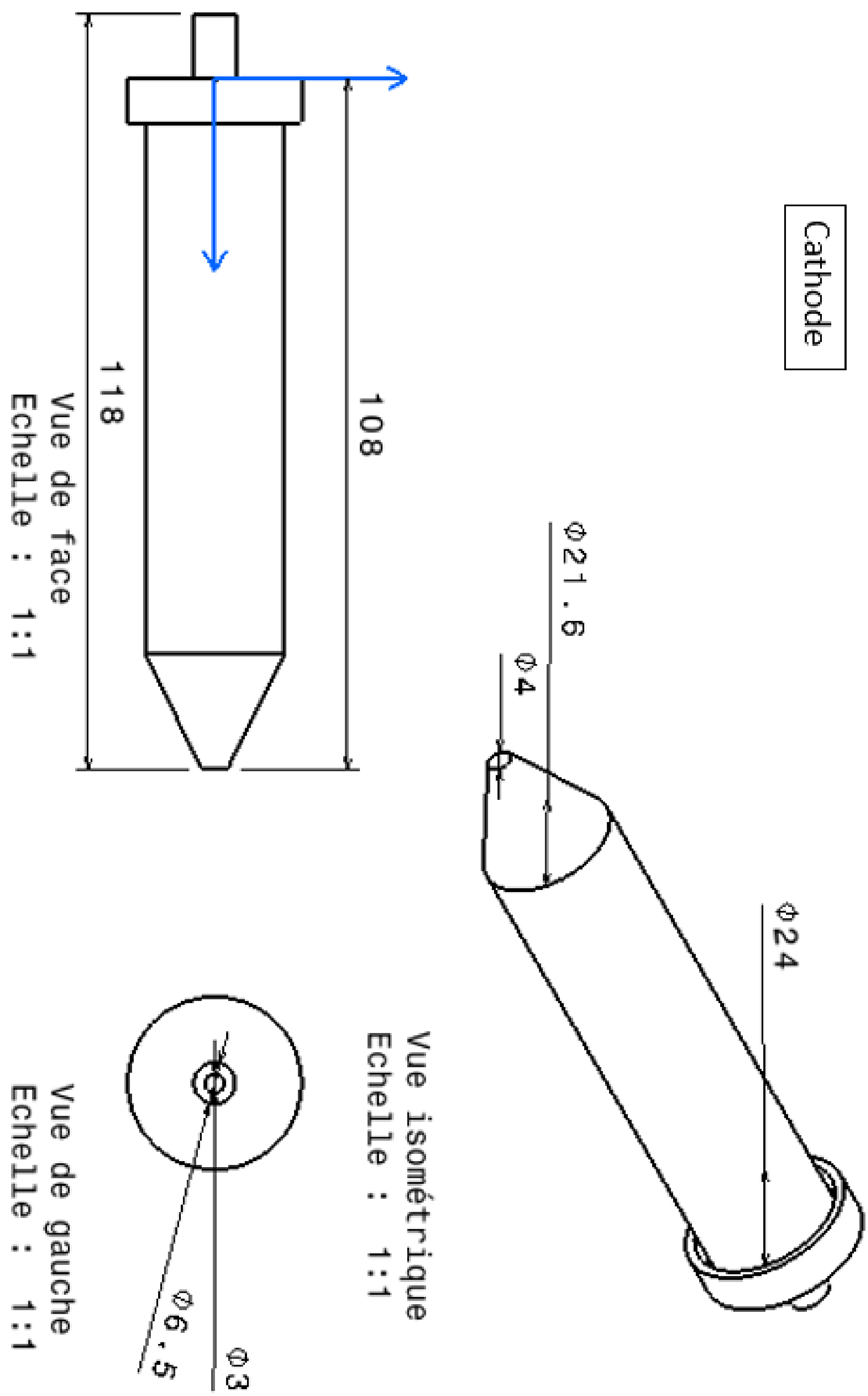
# APPENDIX 2


Anode
Vue isométrique
Echelle : 1:1
Φ56.8
Vue de dessous
Echelle : 1:1
Φ33.4
Vue de droite
Echelle : 1:1
Φ67.6
159.3

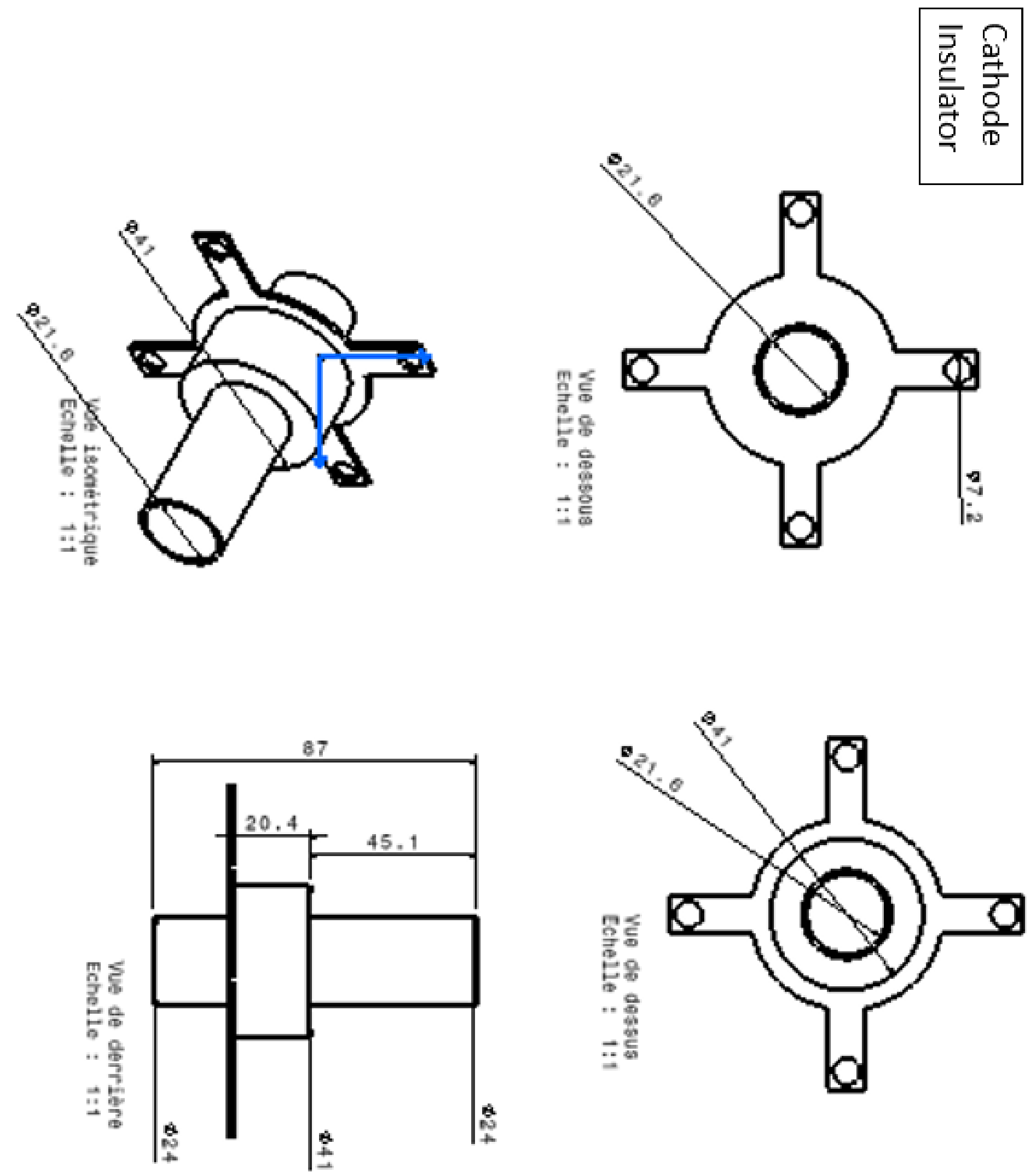
# APPENDIX 3


Anode Insulator
Φ33.4
Vue isométrique
Echelle : 1:1
Vue de dessous
Echelle : 1:1
Φ7.2
Φ45.2
Φ33.4
Vue de gauche
Echelle : 1:1
76.65
Φ56

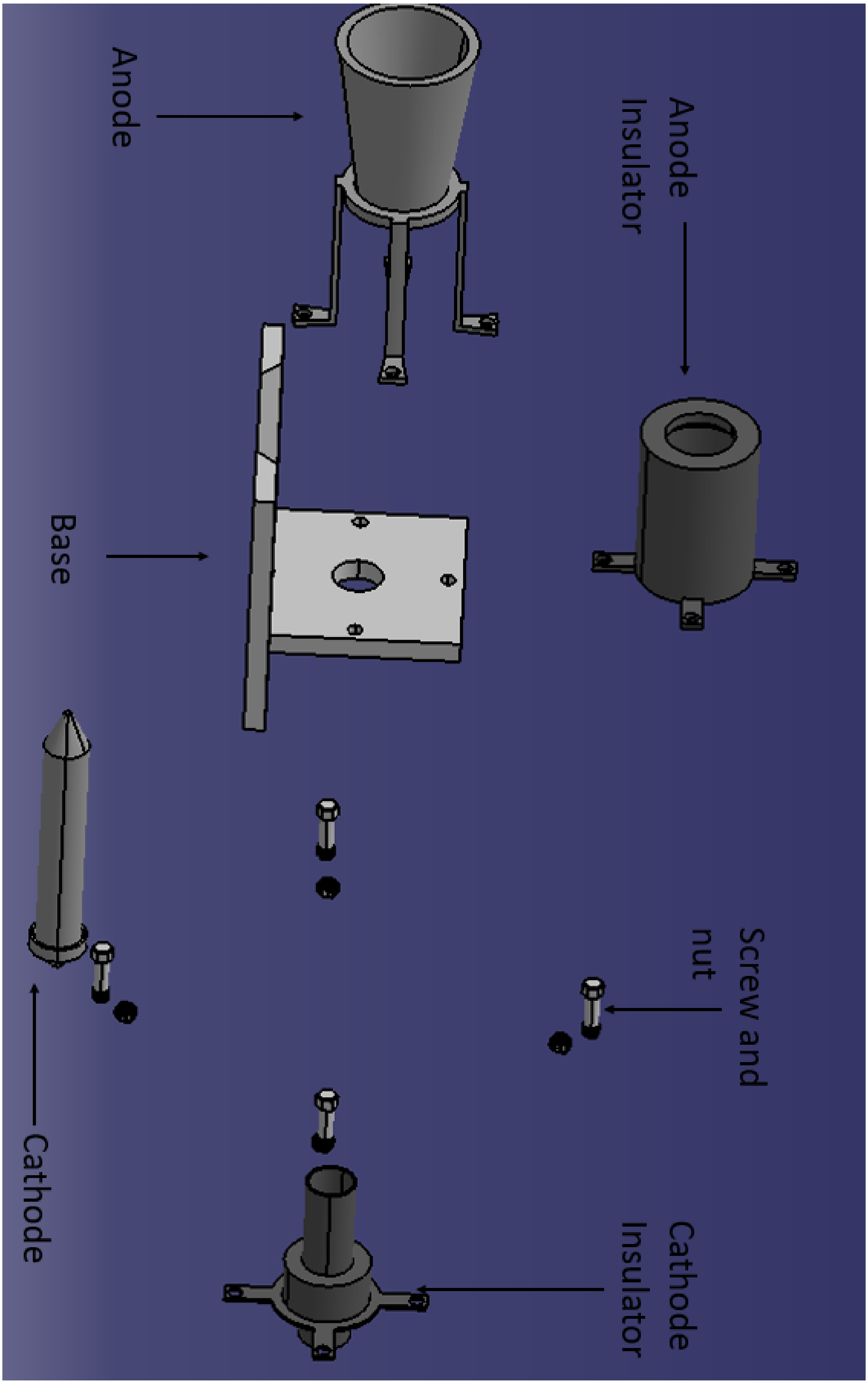
# APPENDIX 4


Cathode
118
108
Vue de face
Echelle : 1:1
Φ21.6
Φ4
Φ24
Vue isométrique
Echelle : 1:1
Vue de gauche
Echelle : 1:1
Φ6.5
Φ3

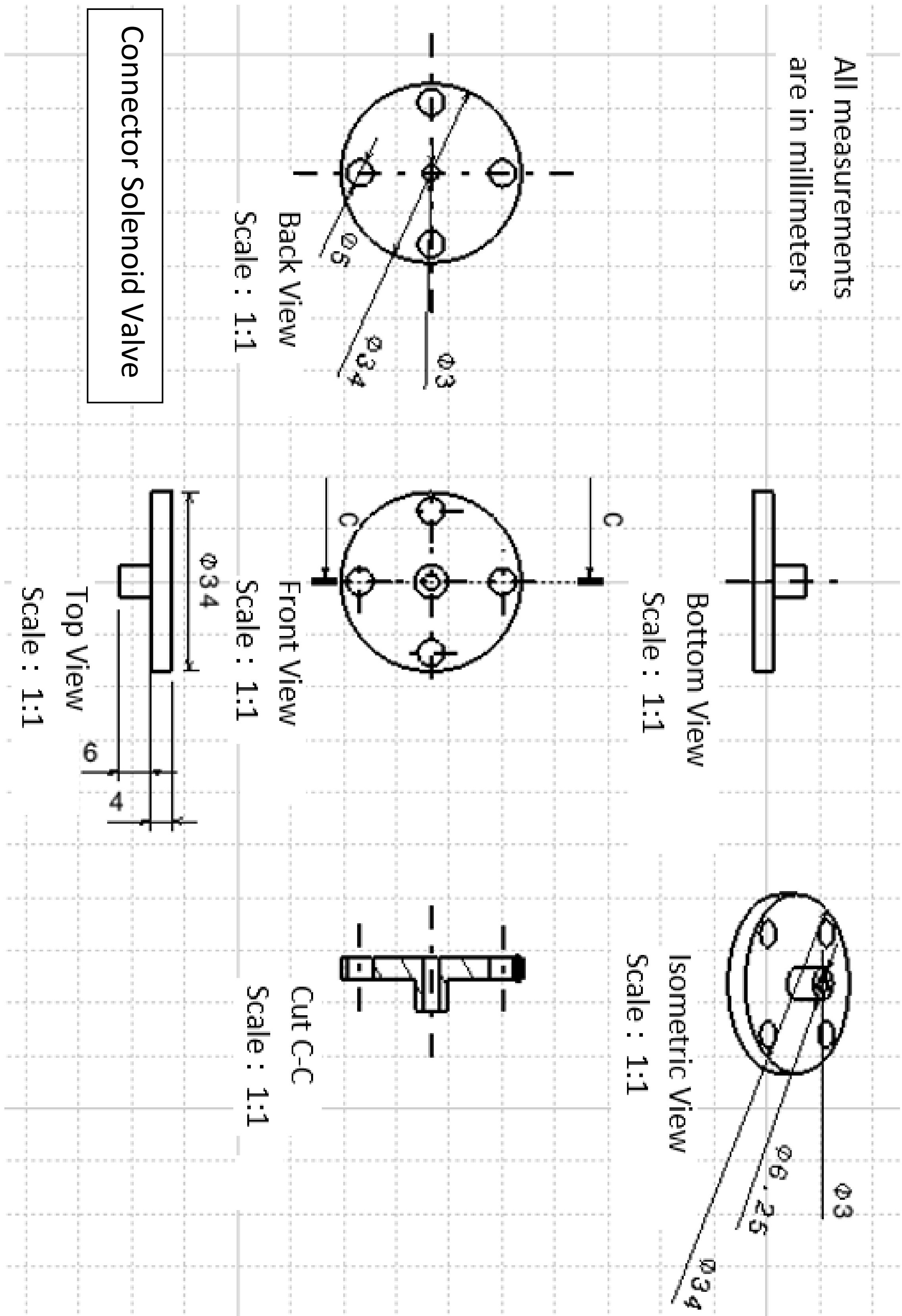
# APPENDIX 5


Cathode Insulator
Ø41
Ø21.6
Vue isométrique
Echelle : 1:1
Vue de dessous
Echelle : 1:1
Ø7.2
87
20.4
45.1
Vue de derrière
Echelle : 1:1
Ø24
Ø41
Ø24
Vue de dessous
Echelle : 1:1

# APPENDIX 6


Anode
Anode Insulator
Base
Screw and nut
Cathode
Cathode Insulator

# APPENDIX 7


Connector Solenoid Valve
All measurements
are in millimeters
Back View
Scale : 1:1
Ø5
Ø34
Ø3
Front View
Scale : 1:1
C
C
Ø34
Bottom View
Scale : 1:1
Top View
Scale : 1:1
6
4
Cut C-C
Scale : 1:1
Isometric View
Scale : 1:1
Ø6,25
Ø3
Ø34

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# ABREVIATIONS

NCKU: National Cheng Kung University

DAA: Department of Aeronautics and astronautics

ZAPlab: Zic And Partners Laboratory

LFA: Lorentz Force Accelerator

LiLFA: Lithium LFA

VwLFA: Vapor water LFA

MPD: Magneto Plasma Dynamic

MPDT: Magneto Plasma Dynamic Thruster

ZAPlab: Zic And Partners Laboratory

PPT: Pulsed Plasma Thruster

G-PPT: Gas initiated PPT

$I_{sp}$: Specific Impulse

$I_t$: Total Impulse

$F_{A/B}$: Interaction force between two particules

$k$: Constant of the middle

$AB$: Distance between the two particules

$q$: Charge of the particule

$F$: Lorentz's force

$E$: Electric field

$B$: Magnetic field

$P$: Power

U: Voltage

I: Current

# GLOSSARY

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

Cube sat: Family of smallsat 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.

Propellant: Substance that fed the thruster, by ionizing it.

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), also a witness of the thruster efficiency.

Total impulse: Change in momentum, measured in Newton second.