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The IPSA-ONE Low Power Gridded Ion Thruster and Testing Facility

IEPC-2024-863

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IPSA-Orbital Nano Experiments (IPSA-ONE) is a student association at Institut Polytechnique des Sciences Avancées (IPSA), an aerospace engineering school. Its mission is to design an ion thruster to counter the atmospheric experienced by saellites in Low Earth Orbit (LEO) and also to introduce students to the field of electric propulsion (EP) and space research. The association has created a partnership with the EP-team of Dr. S. Mazouffre at the CNRS-ICARE laboratory, ONE benefits high value advice and was able to develop and test the first prototype of its low power thruster called Nano Gridded Ion Thruster - 0 (NGIT-0). Through internships, discussions with researchers and self-thought skills, students were able to build the evolution of their prototype: NGIT-1. With this second version, the association aims to optimize the thruster design through series of tests performed in the association's vacuum chamber: Observation and Bench Infrastructure for Orbital Nano Experiments (OBI-ONE). The present article aims to present the association and the work conducted by its student members throughout the last few years.

I. Introduction

Over the last few decades, plasma propulsion has played an increasing role in space propulsion. Various thruster concepts have been developed over the years, and innovation continues in this cutting-edge domain. IPSA ONE is proud of working on such complex and yet exciting technologies by developing their own gridded ion thruster.

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A. Gridded Ion Thrusters (GITs)

A Gridded Ion Thruster (GIT) also called ion thruster is a type of electric thruster that produces thrust by accelerating ions - charged particles - through a set of electrically charged grids (usually two or three). Ionization occurs inside a cavity located before the grids. Neutral gas atoms get ionized and the plasma is confined by a magnetic field just before ions - much heavier than electrons - are accelerated through the grids on which we apply a great difference of potential. GITs are divided in a few main types that differ on their ionization method or magnetic topology, but all, use grids to accelerate ions and produce thrust:

- *Kaufman*: First ion thruster concept, designed by Harold R. Kaufman in the 1960s. A discharge is created between a cathode (heating element) and an cylindrical anode. The anode is shielded by an axial magnetic field and electrons, extracted from the cathode, collide with neutral gas atoms to produce plasma. Then ions are accelerated to produce thrust [1];
- *Ring Cusp*: Differs from the Kaufman concept mainly through its magnetic field topology. Using magnetic rings, magnetic field lines make up a diverging field from the cathode and are strong at the wall of the thruster, where they form magnetic cusps. Electrons are entangled where the magnetic field lines recombine, this reduces electron losses and increases discharge chamber performance compared to thrusters with Kaufman type magnetic topology [2];
- *Radio-Frequency (RF)*: Plasma is ionized through oscillating magnetic fields that are produced by applying a RF voltage to an antenna. This heats the plasma electrons that then ionize incoming neutral propellant atoms. [3];
- *Microwave*: Another type of ion thruster that uses electromagnetic fields at microwave frequency (highly energetic) to ionize the injected gas [3].

The IPSA ONE low power ion thruster is based on the ring cusp concept.

B. Electric Propulsion Testing Facilities

EP thrusters are designed to work in the vacuum of space, therefore testing such system requires a vacuum facility to simulate the extremely low-pressure environment. A vacuum chamber is thus one of the most important tools in an EP laboratory and allows to evaluate operation, performance lifetime and many more characteristics of electric thrusters by recreating environmental conditions similar to real in-space missions. Recreating a space grade vacuum is technically challenging. With a succession of different types of vacuum pumps, it is possible to achieve sufficient vacuum and especially maintain it during thruster operation. Depending on the power of the thruster, which often dictates gas propellant output, vacuum testing facilities and pumps need to be correctly dimensioned to maintain sufficiently low backpressure.

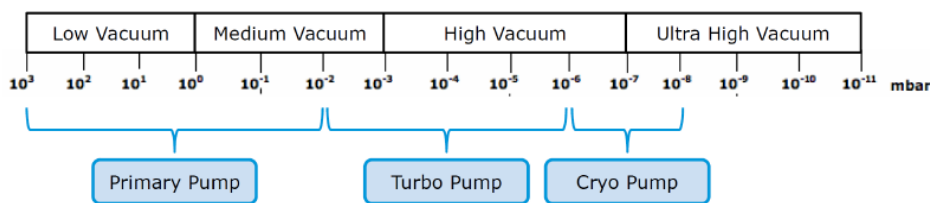


Figure 1: Vacuum pump performances [4]

Different technologies of pumps are made to operate at different pressure levels. First to initiate vacuum, centrifugal pumps are used. For the test of EP devices such pumps are limited, only able to reach a pressure of 10^{-2} mbar. They need to be assisted by more powerful technologies. With turbomolecular pumps, it is possible to achieve a high vacuum, usually down to 10^{-6} mbar. For small vacuum vessels designed to test low power thrusters – with low gas output – a combination of a centrifugal (primary) and a turbomolecular pump can be sufficient. To achieve ultra-high vacuum and for vacuum facilities designed to test thrusters with high gas output, cryogenic pumps, that can reach 10^{-8} mbar, are needed. To achieve even higher

vacuum, ion pumps can be added to the pumping system. But as cryogenic pumps, or a combination of several cryogenic pumps is able to maintain sufficient vacuum for test EP devices, ion pumps are not most often used in EP laboratories.

C. The IPSA-ONE Association

IPSA-ONE is a student association at IPSA, an engineering school specialized in aeronautics and space, located in Ivry-sur-Seine near Paris, France. The association is dedicated to two primary objectives: first, introduce undergraduate students to space activities and especially electric propulsion for space in complement of what they learn in class, and second, designing a student CubeSat with a focus on developing a low power thruster for nsatellites. Students reunite at least every Thursday afternoons – a time dedicated to student’s associations, in the French school system - to work on their ongoing project: developing an electric thruster. Through their endeavor students learn new skills, that will be very valuable in their academic life as numerical tools of theoretical knowledge or soft skills, but also in their next professional career. Very recently, students build a test facility that permitted them to get almost full independence regarding the test of their young thruster under vacuum conditions. Supported by professors of IPSA and the EP team of the ICARE Laboratory, currently, the team is actively engaged in testing the thruster and improving its design.

D. Organization

Section 2 will give a detailed description of the IPSA ONE student association, first through a brief history, then by explaining the functioning of the associations, its scientific and educational ambitions. The firsts theoretical and experimental works that led to the prototype NGIT-0 and the first lab version NGIT-1 of IPSA ONE’s GIT are presented in section 3.1 et 3.2. We will then move on to the small vacuum bench test – OBI ONE - built by the students for the students in section 4. And finally, results and an overview of the perspectives of the associations are discussed in section 5 and 6.

II. IPSA-ONE

The association has now been founded for 7 years to develop a student CubeSat equipped with a student-built low power (30W) electric thruster. In the early moments of the project, it already was focused on the propulsion technology that the student would develop. Wanting to build a CubeSat for LEO or VLEO the thruster has been selected as the main payload with the goal to extend the satellite’s life by countering the atmospheric drag expericened at such low altitudes. The project has experienced many evolutions during the last few years. Among them, members have had the opportunity to participate in numerous contests such as the Capgemini’s Pitch Contest and Concours Lépine. After a few years of development and on the advice of the ICARE laboratory, the association decided to change thruster technology. So, during the covid-19 crisis, from the initial idea of an RF Helicon concept (which would have too low efficiency and is much more complex) students switched to a better-known technology: Gridded Ion Thrusters. Currently, the design of the CubeSat has been put on hold because of the lack of means of the association and especially to focus on the thruster’s design, but it remains our guideline.

IPSA-ONE is composed of around 30 members and is organized in four distinct division specialized in a certain aspect of the project, among them:

- *Mechanic and Structure*: students work on a CAD software to model useful parts of the project, as parts for the thruster, that they will later print with 3D printers (if possible) or have machined;
- *Testing and Facility*: students get a practical knowledge on how to operate the vacuum chamber and essential EP concepts to successfully test the thruster;
- *Physics*: students get a deeper theoretical knowledge about plasma physics, EP and GITs, to improve the thruster’s design and analyze tests data;
- *Electronics and programming*: the team seeks to optimize the power inputs in order to be able to properly power the thruster and develop it’s PPU.

All these divisions allow us to diversify and develop our abilities with direct application on a space thruster project, they allow students to deepen their learning and train them on various softwares that will undoubtedly be very valuable in their classes and in their future career in EP or other fields. Another objective of ONE is to educate students about the space industry but also unite students around a common project allowing them to learn from each other's and learn important soft skills essential to the future engineers that they will become.

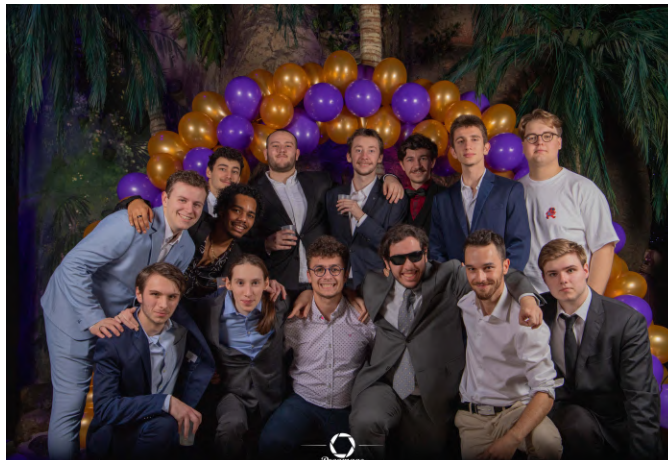


Figure 2: IPSA-ONE Students

III. NGIT

A. NGIT-0

NGIT-0 (Nano Gridded Ion Thruster) represents the initial phase of the IPSA ONE project that aims to develop a small-scale ion thruster suitable for CubeSats. This prototype was developed through a collaboration with the ICARE Laboratory – CNRS Orléans – during initial internships, where elementary theoretical work and early prototyping were carried out by the students of the association. The main objective of NGIT-0 was to validate the design architecture and functioning of the ion thruster. This plasma thruster prototype was the first try of our team to build a demonstrator for a 20 to 30 watts device, equipped with a thoriated tungsten wire as mean of ionization. This first prototype was able to generate plasma, marking a significant milestone for the students. This initial success was achieved by successfully ionizing gas (argon or krypton) using electronic bombardment between a cathode and an anode, was followed by test on the electrostatic acceleration through high voltage grids that was unfortunately not conclusive. Although, This first plasma was characterized using a Langmuir probe, which provided valuable insights on the ionization process and plasma characteristics. The primary components of NGIT-0 included a cylindrical anode positioned within an alumina cavity, a thoriated tungsten filament as the cathode. During the internship at ICARE, students went through different phases, from first, testing cathode electron emission, to step by step build the prototype around it, until being able to produce plasma (Fig. 3).

B. NGIT-1

Following the successful testing of NGIT-0, the IPSA ONE team moved on to the development of NGIT-1. This second version, modelled and built by the students as a laboratory version of the thruster aims to build upon the lessons learned from NGIT-0. It was designed to be easily modified through testing and different design changes, with an emphasis on optimizing ion production and acceleration (see fig. 4). Key improvements in NGIT-1 included the use of more complex grid designs and the incorporation of advanced materials to enhance performance and durability. In fact, one of the main obstacles for ionic propulsion is linked to the erosion of certain component located in the cavity, where the plasma is formed, as well as the

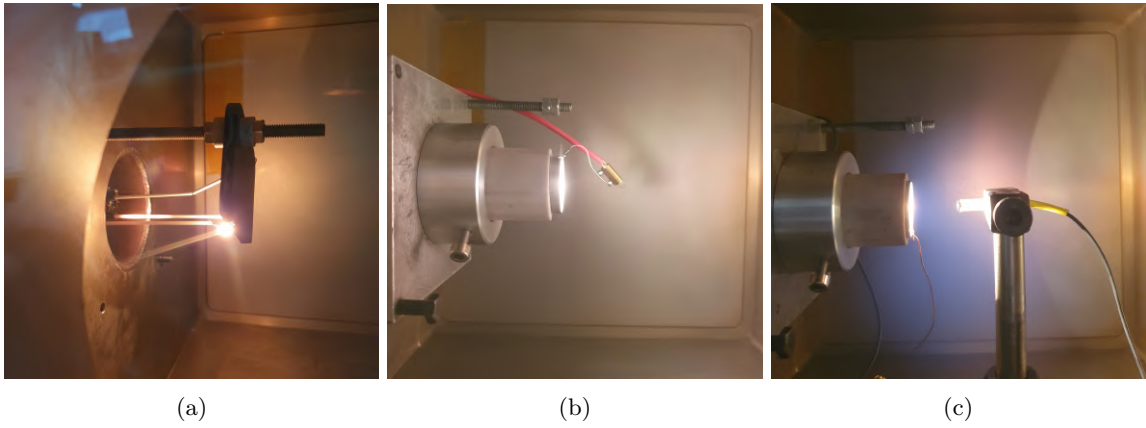
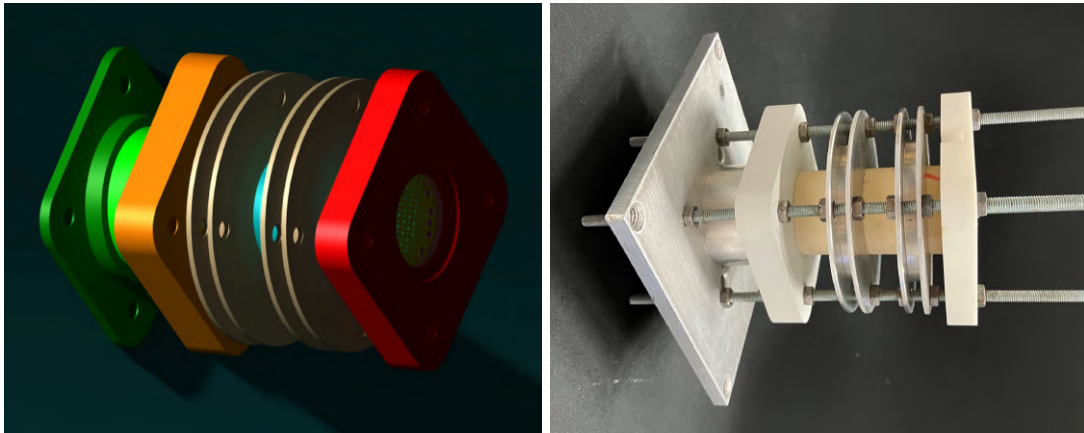


Figure 3: Evolution of NGIT-0 at the ICARE laboratory

evaporation the thoriated tungsten filament. By working on the geometry of the filament and length of the cavity as well as a shield for metallic emission from the filament, the thruster should achieve an acceptable durability. NGIT-1 was designed to operate with both argon and krypton as propellants. The choice of krypton was due to its higher atomic mass, which provides greater thrust for the same power input. However, due to different issues with suppliers, they were only able to use argon. The design also featured an improved magnetic confinement system to enhance the stability and density of the plasma generated within the thruster.



(a) 3D model of the thruster

(b) The thruster built by the IPSA-ONE students

Figure 4: NGIT-1

Dimensions were carefully chosen based on a combination of theoretical considerations, empirical data, and practical constraints. The primary goal was to create an efficient and functional ion thruster suitable for CubeSats operating in low Earth orbit (LEO). Below are the detailed reasons behind some of the chosen dimensions:

- Length of the Cavity
 - Ionization Efficiency: The length of the cavity is crucial for ensuring sufficient ionization of the propellant gas. The chosen length allows for a balanced ionization process where the electrons have enough distance to collide with the gas atoms, resulting in more efficient ion production.
 - Space Constraints: Given the compact nature of CubeSats, the thruster needed to be small. This

length provides a compact design that fits within the limited space available on a CubeSat while still providing adequate performance.

- Diameter of the Cavity
 - Ion Density: The diameter affects the volume of the cavity and hence the ion density. Our cavity diameter provides an optimal balance between maintaining a high ion density and fitting within the CubeSat’s form factor.
 - Thermal Management: A larger diameter helps in managing the heat generated within the thruster, ensuring that the components do not overheat during operation.
- Distance Between Grids
 - Acceleration Potential: The distance between the grids directly influences the electric field strength used to accelerate the ions. Our spacing ensures a strong electric field capable of accelerating ions to the desired velocity, thus providing the necessary thrust.
 - Minimizing Losses: This distance also helps in minimizing ion losses due to recombination or collisions with the grid surfaces, which can occur if the spacing is too large or too small.
- Magnetic Field Confinement
 - Configuration Choices: The magnetic field configuration was chosen to optimize electron confinement and prevent them from escaping the ionization zone too quickly. Simulations showed that a magnetic field strength of at least 149.3 Gauss was necessary to achieve a Larmor radius small enough to keep electrons within the desired path, improving ionization efficiency.
- Grid Transparency and Effective Area
 - Transparency: Grid transparency is crucial for allowing ions to pass through while maintaining structural integrity. A transparency of 70% ensures that a significant portion of the ions generated can be accelerated through the grids without structural compromise.
 - Effective Area: This area was calculated to ensure that the ion flux could be effectively managed within the given power and space constraints of the CubeSat, providing sufficient thrust to counteract atmospheric drag at LEO.

Testing of NGIT-1 began with a series of experiments conducted in the newly established vacuum chamber at IPSA, known as OBI-ONE (Observation and Bench Infrastructure for Orbital Nano Experiments). This facility allowed for regular testing and refinement of the thruster design, providing students with hands-on experience in experimental plasma physics and electric propulsion.

IV. Testing Facility: OBI-ONE

As said beforehand, fundamental theoretical work, first prototyping and especially test of the early thruster in vacuum conditions were performed by students of the association in the ICARE Laboratory during internships within the EP Team. While being a great advantage for IPSA ONE to be supported by ICARE and being able test the thruster in their laboratory in Orléans, it limits the possibility for students to do experimental work because of the distance between IPSA and the CNRS. As IPSA ONE is located on the School’s campus it makes complicated for students to go to ICARE on a weekly basis to ensure testing of their thruster. Therefore, the project of building a small vacuum chamber in the association’s own premises has been created. Thanks to the crucial support of teachers, especially Dr Vincent Robert, in 2022, IPSA granted the association the necessary funds to build a student vacuum facility. This is a great opportunity for IPSA-ONE Students to actively develop their thruster through independent testing. Also to acquire additional knowledge on the operating principles, the assembly and qualification of an EP testing facility and practical knowledge on EP systems, as the students were independent in the dimensioning and the assembly of their vacuum chamber. The installation and the understanding of an EP test facility requires a constant workforce in order to fully and safely complete it. Starting in 2023, the installation of the facility was greatly

retarded by the heavy schedule of students and the departure of certain members as they graduated or left for an Erasmus semester. At the end of the 2022-2023 schoolyear IPISA-ONE students only ordered the facility’s main components and vacuum pumps. The testing facility was nowhere to be ready for testing.

Some students, with the support of ICARE, then proposed install the testing facility through a PMI – Projet Master IPISA – an end-of-studies project at IPISA that goes on for the first semester of Master 2 year. This allowed students to properly focus on the association’s project and deliver a fully operational vacuum chamber at the end of the PMI, in the beginning of 2024. The small team of veteran members of IPISA ONE responsible for the vacuum chamber’s installation through this Master’s project divided their work into different phases. First, in the end of august 2023, students defined the final architecture of the test facility while inventoring all the missing components. Which then led to a second phase, dedicated to contacting suppliers and ordering all necessary components needed to complete the installation project. Simultaneously students learned about the operation and assembly principles of a vacuum testing facility, that they applied later during the assembly. Being designed for the testing of an EP system, students also installed a gas feeding system, and the required electrical installation to operate the thruster. Desiring to share the experience to the rest of the association, the assembly of the vacuum chamber, the pumps and diagnostics for the pressure control where done with the help of motivated members of the association. This project provided an enriching experience for the students, serving as a practical training simulation of potential real-world scenarios in a corporate environment. Students engaged in tasks such as negotiating with suppliers and constructing test benches—activities not always encountered during internships. This collaborative venture included numerous novice members who contributed to a project genuinely dedicated to them.

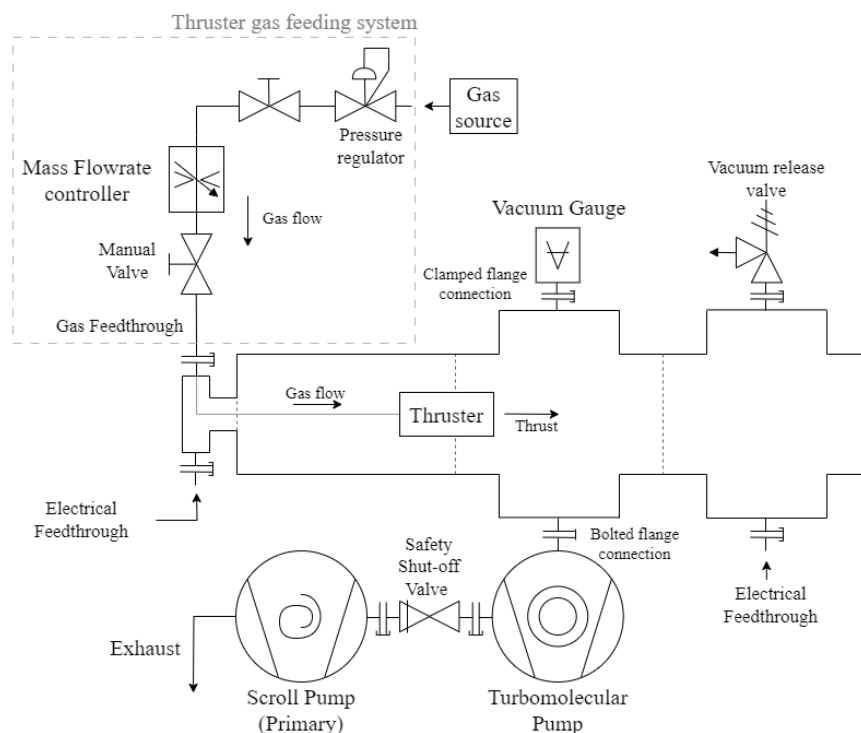


Figure 5: Diagram of OBI-ONE’s architecture and main elements

IPISA-ONE students named their vacuum chamber Observation and Bench Infrastructure for Orbital Nano Experiments: OBI-ONE. Designed for a low power thruster, the chamber is relatively small. The pumping system is able to reach 2×10^{-6} mbar and sustain a vacuum of 1×10^{-6} mbar with a 5 sccm argon gas output [5] during operation of the thruster. This is possible with first a High Scroll 12 primary pump (3.36 L/s), and then a HighPace 700 turbo-pump (685 L/s) both made by Pfeiffer Vacuum and controlled manually by Omnicontrol controllers. The vacuum chamber is also equipped with a gas feeding system for the thruster, controlled by an Alicat mass flowrate regulator, with a maximum output of 10 sccm. Two

electrical feedthroughs are also installed to electrically connect the thruster and the different diagnostics used by the students. To prevent damaging of the pump, especially the turbo pump, a safety valve has been installed on the pumping system. This valve prevents air backflow in the case of a power outage, that could cause sudden increase of pressure and severe damage on the pump's components.

Led by the veteran members that were working on the master's project, the IPSA-ONE students successfully build the vacuum chamber and qualified its operation. Figure 6 shows the OBI-ONE facility fully assembled. In addition to information on how to assemble OBI-ONE's different components in the Master's project report, a detailed manual on how to operate the vacuum chamber and electrical installation has been written [5]. This ensures knowledge acquired along this project will not be lost when veteran members of the association graduate, which is often a struggle in such projects. The chamber is fully operational for the test of NGIT-1, but improvements in its architecture are possible. As adding a bypass of the pumping system, modify the structure that holds the chamber for improved security and easy access to the pumps and controllers.



Figure 6: The OBI-ONE student vacuum testing facility

V. Preliminary results

During an internship in the ICARE laboratory ICARE, three student members of the association had the goal to develop, build and test step by step the NGIT prototype and its components. The first goal was to measure the electron collection rate on a metal anode as a function of the temperature (i.e. heating

power) of the thoriated tungsten wire. The current emitted by thermionic reaction at high temperature is collected by an anode thanks to the potential applied between the two electrodes. Multiple iterations allowed to improve the current emission rate and the current collection of the thruster firstly without the use of gas. After these analyses, students tested the ionisation process by injecting gas, and performed measurements using a Langmuir probe to observe the evolution of the collected current. The results obtained allowed to confirm the ionization of, first, argon and then krypton particles which indicates the presence of a plasma.

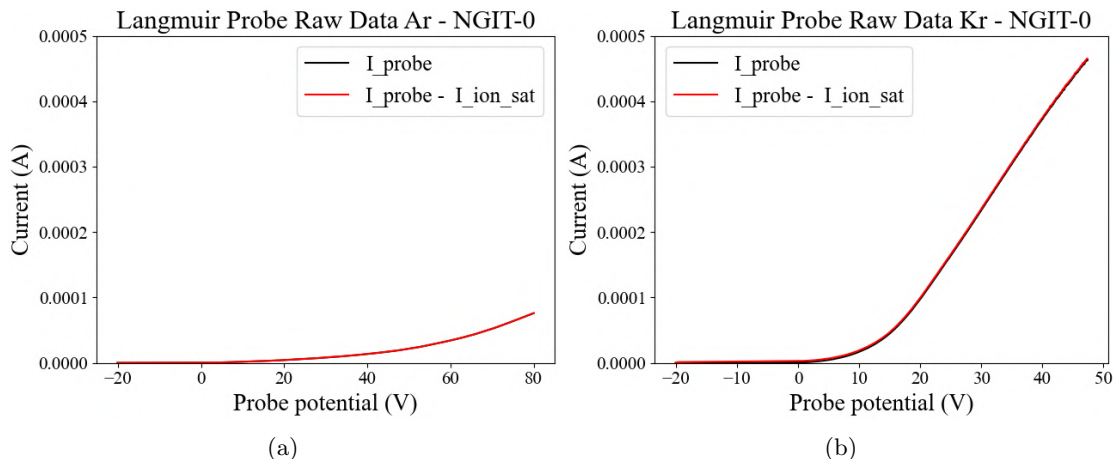


Figure 7: Argon (A) and krypton (B) Langmuir probe raw measurements

Indeed, Langmuir probe raw data plots with argon and krypton show the presence of plasma, especially for krypton with a much better ionization rate leading to a better plasma density. After post-processing the Langmuir probe data, the obtained plasma parameters can be seen in Table 1.

Parameter	Value
Electron saturation	$2.524629 \times 10^{-4} \text{ V}$
Ion saturation	$-1.187360 \times 10^{-6} \text{ V}$
Plasma potential	-5.35 V
Floating Potential	31.2 V
Temperature of the electrons	7.238 eV
Electron density	$1.419135 \times 10^{14} \text{ m}^{-3}$

Table 1: Plasma parameters (Krypton, NGIT-0)

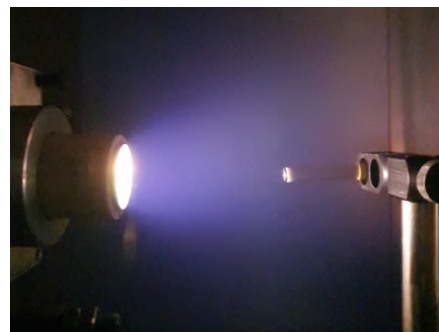


Figure 8: Krypton plasma (NGIT-0)

NGIT-0 testing has been a key milestone in the development of IPSA ONE's thruster by proving that, as students, they were able to work on such complex technologies and produce a first prototype for their future thruster. It marked the first step of the development of NGIT-1 that has been designed internally at IPSA ONE from the data obtained at ICARE and the valuable help of ICARE's EP Team. As soon as OBI-ONE became operational with all the necessary instruments in the IPSA ONE laboratory, young student members could put NGIT-1 to the test under the supervision of students with prior experience of vacuum chamber testing. Initially, the team carried out gas-free tests to confirm that the cathode and anode were working properly by observing the electron emission rate of the thoriated tungsten wire and the current collection of the aluminum anode. They then added the grids to validate the electrical circuit inside and outside the vacuum chamber with a grid potential of 500V, an anode voltage of 40V and a cathode current of 5A (Fig. 9).

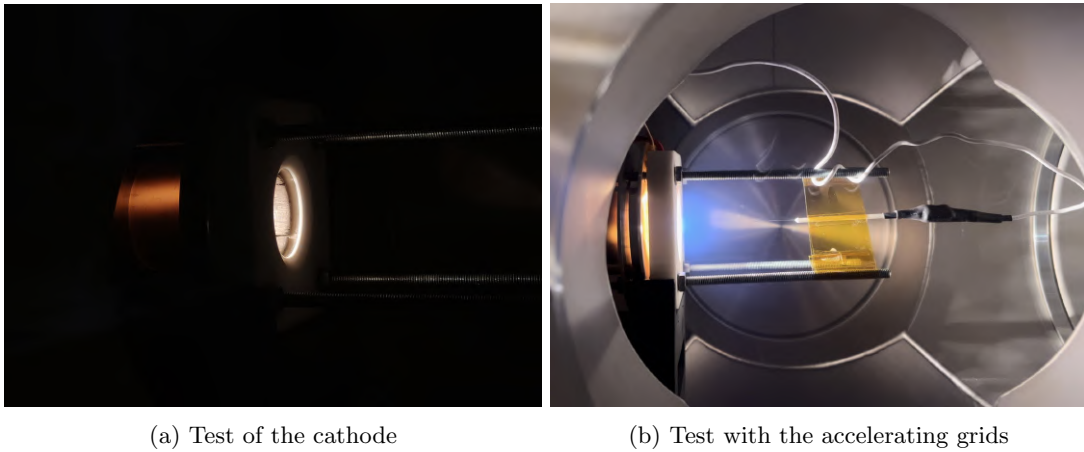


Figure 9: Frist NGIT-1 tests in the OBI-ONE facility

A first test without gas injection, allowed to validate electron emission (see Fig. 9a). Then thruster operation with the accelerating grids was tested (see Fig. 9b). The blue light observed on Fig. 9b is actually plasma, but most likely caused by electrical arcs forming across the two grids. This is due to the high voltage between the grids and the absence of ionisation in the thruster's cavity, resulting in a large number of neutral gas accumulations between the grids. We can also observe that from the Langmuir probe data in fig. 10a).

We can observe in figure 10 that the current is very low and can be considered zero, meaning that almost no charged particles are detected by the probe outside the thruster. From observation and data analyses, students were able to deduce that the thruster does not generate sufficiently dense plasma to maintain it through the cavity. They then worked on explaining the reason behind these results. The first few hypotheses pointed towards chamber backpressure during operation, the input power for ionization, potential gas leakage in the thruster's design, and the use of argon. Indeed, not having a sufficiently low pressure in the chamber can lead to difficulty regarding the ionization of the gas. With a very low gas output of 0.9 sccm, the chamber maintained vacuum with a pressure of 2×10^{-4} , low enough to avoid plasma recombination. Students later deduced that the most plausible cause for the lack of ionisation was a dimensioning problem on the cathode/anode system. Good ionization rate was most likely too low because a combination of several factors: low input power limited by the power supplies or low electron emission due to under-dimensioning of the cathode low input power. Indeed, students tested the ionization process with argon, which has a higher ionization energy than krypton, the original propellant used for the design of NGIT-1. There's a lot of room for improvement on the thruster's design and dimensioning. Thanks to the OBI-ONE facility, students will be able to implement modification and directly test to validate them and advanced on the association's goal to build a student gridded ion thruster.

VI. Conclusion and Perspectives

The first iteration of IPSA ONE's nano gridded ion thruster (NGIT-0) proved that, as a student association, they were able to develop a functional plasma source thanks to the help of the ICARE laboratory and its team. It marked a key milestone in the history of IPSA ONE and from then, the team was able to confidently start the development of NGIT-1. While students were designing and building the thruster itself, they had the opportunity to establish a testing facility inside the IPSA laboratory, enabling them to carry out experiments on NGIT-1 by themselves. The students were able to gain a wide range of skills, including 3D modelling, magnetic field simulation, practical knowledge on the operation of vacuum chambers and electrical systems, plasma physics, design and experimentation of EP engines and a variety of other skills valuable to an electric propulsion engineer. IPSA-ONE members had a lot of trouble working with argon during testing mainly because of a low ionization which made it almost impossible to generate and maintain a plasma observable with the naked eye. This allowed to test multiple arrangements inside the vacuum chamber in order to understand every aspect of the design. IPSA ONE students will keep working on the

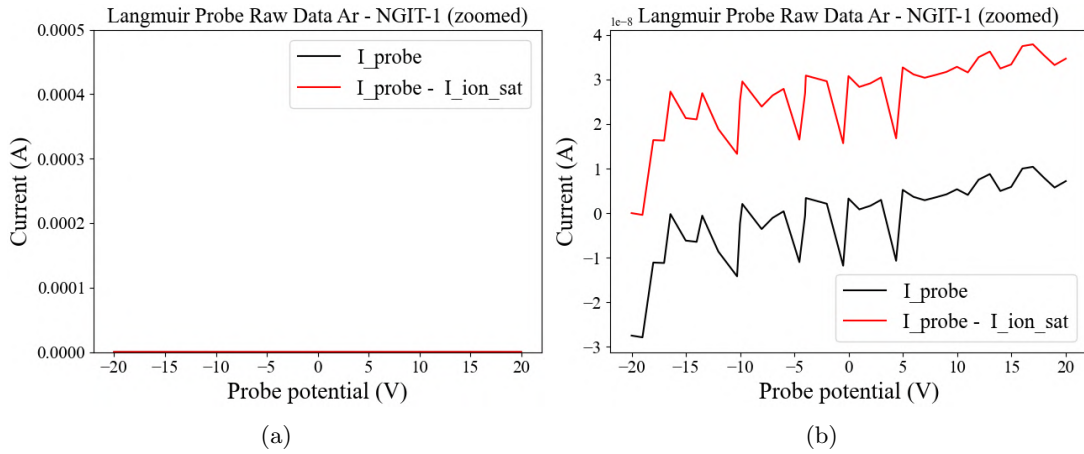


Figure 10: First Langmuir probe measurements on NGIT-1

current thruster, NGIT-1, with argon and then krypton in order to study the physics involved and try to improve its design and operation. These studies will give the team a better understanding of the different mechanisms involved in the thruster and enable them to develop a second version of NGIT that should be more efficient and reliable. Also, it will be a great opportunity for students to learn extensively about plasma physics theoretically and experimentally. IPSA ONE is aiming to generate a denser plasma by the end of the year and should be able to start the development of the new design from then. This new thruster, NGIT-2, will be based on NGIT-1 but enhanced by significant upgrades. The development of such complex technologies is a tremendous asset for students, since not many undergraduate students have the opportunity to work on actual electric propulsion systems with such an infrastructure. Indeed, the expertise acquired by members of IPSA ONE during their five years of study at IPSA is highly relevant to both companies and research institutes specialized in electric propulsion.

VII. Acknowledgments

This work has been possible thanks to our professor Dr. Vincent Robert which has accompanied the association for several years now and allowed the association to obtain the necessary financing for the project of installing a vacuum chamber in the premises of IPSA ONE.

The association also thanks Dr. Anica Lekic, who has been following its development for several years and for offering many and diverse opportunities for student members.

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