DOI: 10.13009/EUCASS2023-358
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Activities in space electric propulsion at the French Space Agency - CNES

Ulysse Weller⋆†, *Vaitua Leroi*⋆ *and Fabien Castanet*⋆
⋆*Centre National d'Etudes Spatiales (CNES),*
18 Av. Edouard Belin 31000 Toulouse
† ulysse.weller@cnes.fr

Abstract

This paper presents an updated overview of the current electric propulsion activities carried out at CNES (Centre National d'Etudes Spatiales - French Space Agency). The agency supports the development of different types of technologies with different maturity level, from low TRL R&T (Research and Technology) activities and scientific research with the supervision of doctoral activities to expend our knowledge of the underlying physical phenomena to higher TRL up to in flight mission demonstration and operational life. Not only focused on the thruster's development, efforts are also made to sustain the progress of subsystems such as the fluidic lines (Flow control Regulators, tank...) or the power management with the Power Processing Units (PPU). This concerns not only Hall Effect Thrusters (HET) for low power, medium power and high power EP systems but also Gridded Ion Engines (GIE) and other alternative solutions for very low power applications such as micro-propulsion for LEO applications.

1. Introduction

CNES (Centre Nationale d'Etudes Spatiales - French Space Agency) is a well known actor in the development of space technologies, including EP (Electric Propulsion) technologies. Investigated for more than 40 years in France with the CNES support, several types of EP devices such as FEEP (Field Emission Electric Propulsion), GIE (Gridded Ion Engines) or HET (Hall Effect Thruster) have been developed.

EP allows satellite mass saving as it is greatly more efficient than more conventional CP (Chemical Propulsion) [1] for long duration missions and lower thrust and reactivity needs. It comes along with the improvement of thrusters' efficiency and reliability, which makes its use more attractive. GEO satellites platforms are now fully equipped with electric propulsion, even for the orbit raising phase (EOR). This implies longer transfer time than with chemical propulsion to reach the operational orbit, but is compensated by the lower propellant mass budget which reduces the overall satellite mass and cost. Furthermore, the emergence of the small and nano satellites market represents a new application for EP systems. As this satellite category is often operated in LEO, it needs propulsion systems mainly to maintain the altitude and the attitude, and help for reentry. Satellites constellations is a type of such application.

So far, conventional EP systems such as HET and GIE were operated with xenon, a noble gas perfectly suited for EP, thanks to its chemicophysical properties. However, due to industrial and geopolitical reasons, xenon price has exploded over the past years [2]. The EP community is thus constrained to look for use of alternative propellants and to adapt the EP systems including the thruster to them. It is a new and challenging subject as it needs to be fulfilled quickly to address the available market as soon as possible. Up to now, krypton seems to be one of the better options to replace xenon rapidly, as it is also a noble gas with similar properties, but ten times cheaper. However, adaptation of the design and operation of the platforms and EP systems needs to be addressed, especially with regard to the fluidic subsystems as krypton needs to be stored at higher pressure comparatively to xenon [3]. Moreover, use of krypton implies also more erosion and thus reduces the thruster lifespan. Iodine is a molecular propellant with very promising performances. Stored under its solid forms, its energetic storage density is much greater than any other gas. However, this propellant has the drawback of being corrosive [4]. It thus presents challenges, firstly to obtain and maintain the iodine under its gaseous form to feed the thruster, and secondly to adapt the EP system material for compatibility. Additionally, there is up to date, no HET cathode compatible with use of iodine, which is still a strong technological limitation.

CNES research activities financed by the R&T (Research and Technology) program are part of the PPRT (Programme Pluriannuel d'actions de Recherche & Technologie) which aims to investigate innovative technologies starting

DOI: 10.13009/EUCASS2023-358

at low TRL (2-3) and increasing their maturity. Several projects are actively explored all over the EP thematics (Thruster heads, fluidic, power, science) with all the French actors with the following objectives:

- fulfill the ongoing developments concerning the xenon related technologies,
- support the transition to krypton for short to medium term usage,
- do the spadework and trade-off for the long term technological needs.

CNES is also a major contributor to support the European Commission effort in R&I (Research and Innovation) for enabling technologies such as Electric Propulsion, in the frame of Horizon 2020 and Horizon Europe. CNES as part of the PSA (Project Support Activities) is strongly involved in roadmapping, preparation of the calls and follow on of the grants developments. Major progress on EP systems have been done in the past years since 2014 and will continue, supporting industry and scientific institutes research and developments.

In the next section, will be briefly presented the electric propulsion physics basics. Then, an overview of the French EP actors and CNES partners landscape is introduced.

2. Electric Propulsion Basics and overview

2.1 Electric Propulsion principle

The thrust principle in space oftenly relies on a momentum exchange between the spacecraft and the ejection of a mass quantity. It is derived from the Newton's second law and is proportional to the ejection velocity and the mass flow rate:

$$T = v_e \dot{m}_p, \tag{1}$$

Where v_e is the ejection velocity in [m/s] and $\dot{m}_p$ the mass flow rate in [kg/s]. While CP relies on a large mass flow rate and a relatively small ejection velocity, EP devices are known to have an important ejection velocity combined with a small mass flow rate. This leads EP systems to be very efficient in terms of propellant consumption compared to CP. This can be derived from the so-called Tsiolkovsky equation which relates the change in velocity with the propellant mass consumption and the thruster efficiency:

$$\Delta v = I_{sp} g_0 ln[1 + (m_p/m_f)], \tag{2}$$

where I_{sp} is the specific impulse in [s] and is equal to $I_{sp} = v_e/g_0$ and m_p and m_f are respectively the mass of propellant used for the maneuver and the total mass of the spacecraft after the maneuver, in [kg]. From eq.2 it comes:

$$m_p = m_f[exp(\Delta v/v_e) - 1]. \tag{3}$$

The last equation emphasize that higher the ejection velocity, the less propellant is consumed, for the same change in velocity. It makes EP more interesting compared to CP for mission profiles not requesting high thrust. Actually, EP cannot produce high thrust as it is shown in Tab1.

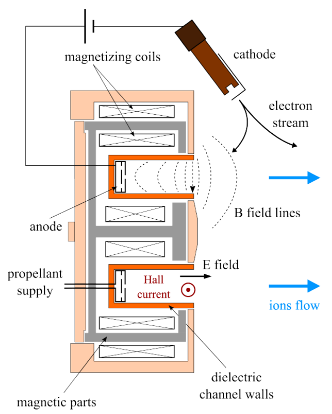

Figure 1: HET schematic, from [5].

The most common technologies are the HET and the GIE. We can briefly describe these EP systems and their working principles. The HET (Fig.1) uses a set of magnetic parts (permanents magnets or coils) which creates a radial axi-symmetric magnetic field in the discharge channel. The electrons emitted by the cathode are then magnetized

DOI: 10.13009/EUCASS2023-358

(Larmor radius much smaller than characteristic length of the thruster) and through the combined effect of the electromagnetic field, creates a current in the azimuthal direction, the Hall current. This will ionise the neutrals, generally injected from the anode. The ions are then accelerated through the anode-cathode electric potential. It is interesting to note that around 20% of the cathode emitted current is flowing into the discharge channel whilst the remaining 80% goes in the thruster plume for neutralization. The performances range are depicted in Tab.1.

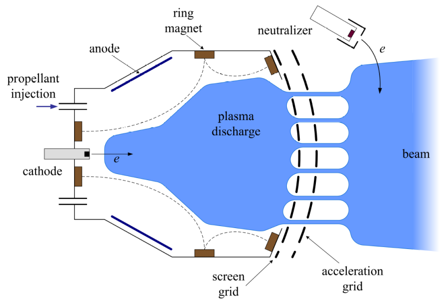

Figure 2: GIE schematic, from [5].

The GIE (Fig.2) uses a set of grids to accelerate the ions. The propellant (generally an inert gas) is ionised within the discharge chamber by inelastic collisions with the electron bombardment coming from the internal cathode. An assembly of magnets can be used in order to confine the plasma to avoid wall losses and increase the ionisation efficiency [6]. An external neutralizer is also used to inject electrons within the thruster plume and compensate the positive charges. While this device allows for very high specific impulse depending on the applied potential between the accelerator grids, it is therefore limited in thrust. The amount of current passing through a plasma sheath (due to the high grids potential) is limited by the space charge effects [6, 7] which limits the amount of charged particles ejected passing through the grids, thus the mass flow rate, and finally the thrust. Moreover the grids are sensitive to erosion and GIE thrusters request much more volume for accommodation on satellite platforms than HET for the same power range

Thruster	**Thrust range (mN)**	**Isp range (s)**	**Power range (kW)**
HET	1 - 10^3	1500 - 2500	5.10^{-2} - 50
GIE	1 - 2.10^2	2000 - 7000	0.1 - 40

Table 1: Recap of HET and GIE characteristics.

2.2 French EP ecosystem overview

The french EP ecosystem is a very diversified environment in which a large panel of technologies are investigated over a large power range. Electric Propulsion has been investigated for more than 40 years in France, especially with researches related to HET. The medium power market in the range of 3 to 7 kW is dominated by SAFRAN with the 5kW HET PPS®5000. This thruster is mainly used for GEO telecommunication satellites and enables the possibility to have full electric platforms (EOR (Electric Orbit Raising) + NSSK (North-South Station Keeping)). As an example, it meets the needs of the Eurostar Neo platform of Airbus Defense and Space and of the Spacebus Neo platform of Thales Alenia Space. Evolution toward development of a dual mode EP system is supported by supported by the European Commission R&I in the frame of the CHEOPS Medium Power (CHEOPS MP) grant in the frame of the Horizon 2020 EPIC program. The low power is also in the market target range of SAFRAN with the TRL 9 PPS®1350, declined in two power versions:

1. The PPS®1350-S with a nominal power of 1.5 kW,
2. The PPS®1350-E with a nominal power of 2.5 kW.

All the previous thrusters are currently working and have been qualified with xenon as propellant. SAFRAN addresses also the 200 W to 1000 W power range with the development of the low cost PPS®X00 to adapt to the market needs. This thruster, optimised for xenon is currently at qualification level for krypton applications, and intends to address the LEO market through the constellations needs. This Low Power EP system is supported by the European Commission R&I in the frame of the CHEOPS Low Power (CHEOPS LP) grant in the frame of Horizon 2020. The French new space

DOI: 10.13009/EUCASS2023-358

start-ups also enrich the technologies and power diversity of EP systems. Exotrail develops as well HET products, for the VLP (Very Low Power) from 50 W with the Spaceware™-nano, up to 150 W with the Spaceware™-micro. The Low Power is also addressed through the Spaceware™-mini and Spaceware™-small, addressing the market from 300 W to 1.5 kW.

The French new space start-ups enrich the technologies and power diversity. Exotrail develops as well HET products, for the VLP (Very Low Power) from 50 W with the Spaceware™-nano, up to 150 W with the Spaceware™-micro. The LP is also address through the Spaceware™-mini and Spaceware™-small, addressing the market from 300 W to 1.5 kW. Several electric propulsion alternatives to HET are currently developed in France. ThrustMe is also addresses the VLP market with the NPT30-I2 product (35 - 65 W). This GIE solution offers high specific impulse performances and is specifically designed to operate with iodine [8]. Another thruster developed by ThrustMe is the I2T5, a cold gas thruster, also working with iodine. The latest is a compact product designed for collisions avoidance or deorbiting. ThrustMe also intends to address higher power market with the NPT300, a 300 W class thruster under development.
Ion-X is a new player in the EP ecosystem, developing an ionic liquid based electrospray. Offering compact and high Isp solution, it is an innovative solution on the VLP market (50 W power consumption). Created in 2021, Ion-X is the results of an R&T activity jointly led between CNES and the C2N laboratory for the development of an EHD (Electro-Hydro Dynamic) thruster resulting in the publication of a shared patent.
COMAT is also a disruptive actor developing a compact thruster for the VLP market, based on the VAT (Vacuum Arc Thruster) technology. It is a pulsed thruster working with solid metal as propellant. This allows for very high energetic density storability. The COMAT VAT developed with the support of the European Commission through the PJP grant under the Horizon 2020 EPIC program is a 30 W class thruster [9]. All the products depicted above are resumed in Tab.2

EP constructor	Technology	Product	Power class (W)
Safran	HET	PPS®5000 PPS®1350-E PPS®1350-S PPS®X00	5000 2500 1500 800
Exotrail	HET	Spaceware™-small Spaceware™-mini Spaceware™-micro Spaceware™-nano	1000 400 150 60
ThrustMe	GIE RF & Cold gas	NPT300 NPT30-I2 I2T5	300 50 5
Ion-X	Electrospray	HALO-100X	50
COMAT	VAT	PJP30	30

Table 2: Recap of EP thrusters products of French constructors.

This industrial environment is sustained by many French research laboratories, from modeling to experiment. The laboratories involvement is fundamental for technological transfer to industry. In addition, creating new physical models in order to better understand the underlying physics, they are the ground for the product development by de-risking the technologies and consolidating the first and crucial TRL steps.
The ICARE-CNRS laboratory based in Orleans, is specialized in electric propulsion experiments with a strong knowledge in all types of plasma diagnostics, especially with non-intrusive diagnostics such as LIF (Laser Induced Fluorescence) and ITS (Incoherent Thomson Scattering) [10, 11]. The national high power facility PIVOINE-2G is based there [12] and it is used by all compatible French EP products, mainly for research applications. Simulations also has a crucial role, especially for plasma modelling. Several research institute and laboratories are specialized in this field. The LAPLACE-CNRS laboratory, based at Paul Sabatier University in Toulouse, is conducting researches in HET and hollow cathodes modelling, through Particle in Cell (PIC) simulations. CERFACS (Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique) is a research institute with competences in simulations and modeling. They are developing 3D codes to simulate the HET plasma discharge. The LPP (Laboratoire de Physique des Plasmas) is a laboratory in plasma physics where experimental and simulation work is done. Efforts have been carried out on the Iodine compatibility for EP devices [13, 14]. ONERA own a few labs dedicated to electric propulsion research, in both experimental and simulations research fields. Some work is ongoing on the development of an ECR (Electron Cyclotron Resonance) plasma thruster [15, 16]. These innovative promising technology has also been supported by the European Commission in the frame of the MINOTOR grant in the frame of Horizon 2020 in the EPIC project.

DOI: 10.13009/EUCASS2023-358

3. Thrusters and equipment development and qualification

3.1 Thruster PPS®5000 and associated sub-systems

The 5kW class HET PPS®5000 has reached its qualification in xenon in July 2021. With more than 19 000 hours of functioning, the thruster has reached a world record of longevity with a total impulse of more than 17 MNs. Moreover, during its on ground qualification, the thruster has demonstrated an amazing stability in terms of performance all over its lifetime. This performance has been today confirmed in flight with more than 18 PPS®5000 in orbit until now.

During its on ground qualification, the thruster has not only demonstrated an amazing stability all over the lifetime, it has also shown some margins in term of thermal, mechanical and functional design. In that framework, SAFRAN Spacecraft Propulsion (SSP) and CNES have decided to launch a study in order to extend the qualification domain of the thruster: The goal will be to have the thruster ready for future needs in term of voltage, Isp and thrust by extending the domain from 350 V up to 400V 5kW. With the increase of voltage, the thruster will gain in terms of specific impulse that will save xenon.

In parallel of that qualification domain extension, with the war in Ukraine and the price increase of the xenon (see section 1 and Ref.[2]), a study is lead in order to use krypton instead of xenon. This study identifies all the points to be checked on the thruster and to build a delta-qualification file in krypton. Thanks to the margins on the thruster, the impact in terms of thermal and thermomechanical behavior seems compliant with the use of krypton. Several other major topics have been identified and SSP is working on those specific points in order to demonstrate the feasibility to use the PPS®5000 with krypton. One major uncertainty is the total impulse that the thruster could achieve. Indeed, as krypton is lighter than xenon, the erosion rate should theoretically be increased [3, 17] and consequently the total impulse in krypton will be lower of several percent to the one demonstrated with xenon. An experimental study will be done in order to compare the erosion rate with both krypton and xenon, and to assess the total impulse reachable with the thruster in krypton and the associated performance. Then, a delta-qualification plan will be discussed in order to propose a PPS®5000 qualified for both krypton and xenon, taking into account the coordination of activities with the CHEOPS Medium Power grant at subsystem level.

In addition, CNES is also supporting PPU NG2 (Propulsion Power Unit) and electric propulsion system activities, coupled with the PPS®5000 from SAFRAN, and performed by Airbus Defense and Space (ADS) through different contracts. The PPU NG2 development up to PDR has been successfully achieved in the frame of a French national contract, PEGASE. The PPS MkII development (including PPU NG2) is currently in progress, under ARTES contract, aiming to bring PPU NG2 / PPS Mk-II from CDR up to QR. Such phases also includes PPU NG2 EM2 manufacturing and coupling qualification tests.

3.2 SAFRAN Propulsion Thruster PPS®X00

The second thruster under development with SAFRAN is the sub-kilowatt class PPS®X00. This thruster inherits of the return of experience of the PPS®1350, and has been studied at EP system level in the frame of CHEOPS grant and is developed jointly with the CHEOPS LP grants. Indeed, the main goal was to produce at high rate and low cost a thruster in a quicker way, with less parts and a production cost that could afford the telecommunication constellation targets. With CNES, SSP has worked on the building blocks of the thruster. Efforts have been done on the maturation of new technologies that would enable to create a breakthrough in the usual way to produce these thrusters, and to have an optimized propulsion system in terms of cost and manufacturing time. Part of the development is done under a CNES - ESA GSTP contract covering several aspects such as the CDR and the Kr qualification of the thruster.

Moreover, like for the PPS®5000, the change of propellant has also been discussed. With the dedicated market to which this thruster is oriented (constellation principally), the need of bi-compatibility for both xenon and krypton becomes mandatory. As the thruster is dedicated to the small satellite market, and in particular to small, medium and large constellations, multi-propellant compatibility is essential. The development tests validated the thruster's operation with xenon and krypton, enabling the tuning parameters for both propellants to be defined. Qualification, scheduled for 2024, will be carried out using krypton.

In parallel, a CNES R&T (Research and Technology) activity is ongoing with the aiming at answering the following question: does an optimized krypton chamber would give better performance?

3.3 Air-Liquide Multi Function Valve

The Multi Function Valve (MFV), is a very lightweight valve ($m < 10$ g) and is currently under development at Air Liquid Advanced Technologies (ALAT) with CNES support. This bi-compatible valve (Xe / Kr) is based on thermal

DOI: 10.13009/EUCASS2023-358

expansion to regulate both the mass flow rate and the pressure. Usually, these two functions are dissociated on actual platforms. This new design approach allows for efficient mass and cost saving. Linked directly to the tank outlet, the regulation is efficient from 300 bars (krypton storage pressure) to 3 bars which is the classical requirement, thus applicable from BOL (Beginning Of Life) to EOL (End Of Life). Work has been done in several R&T activities in order to characterise the MFV and verify its relevant use for EP systems. The mass flow rate can vary from 1 to 20 mg/s such that a large power range can be addressed (from 100 W to 5 kW). Leak test has shown satisfying performance with a leak rate < 10^{-7} mbar.L/s at 180 bars He. The valve was initially designed to be an Helium regulator for scientific instruments, especially for gas phase chromatographs. It will be onboard the Dragonfly mission for the DraMS instrument.

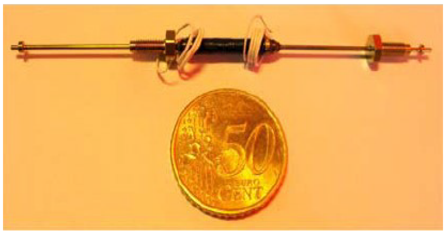

Figure 3: ALAT valve.

The development is still ongoing through a technological development. This project called PEGASE, supports R&D activities for telecommunications platforms applications. The targets are twofold. Firstly the MFV delta-design will be defined. Meanwhile, the FMS (Flow Management System) development will be brought up to the PDR (Preliminary Design Review) level in which the valve is integrated. Finally, the objective is to use this product for the regulation of Safran PPS®.

4. Research and Development

4.1 2D axis thrust balance

The needs for accurate thruster diagnostic is very important to have reliable data. Thrust balance is a well known diagnostic to measure the thrust. Several designs can be chosen regarding parameters such as the thruster performances or the vacuum chamber available volume [18].
A vectorised thrust allows to answer for several needs such as reaction wheels desaturation or alignment of the thrust vector with the center of mass. Several strategies can be adopted to adjust the thrust vector. Either with a mechanism that moves the entire thruster or, for thruster with discharge guided by a magnetic field, the adjustment of the latest can dealign the thrust vector with the normal of the exit plane. Furthermore, while the thrust vector is supposed to be collinear with the normal of the exit plane, it might not always be time the case. Such misalignment needs to be reliably characterized and quantified.
In this context, a 2D thrust balance is developed within the CNES R&T program framework with Dactem International. The objectives are to design, develop and test a thrust balance in order to measure the thrust in simultaneously two perpendicular directions. The final aim is to pave the way for a 3D balance. The main challenge is to measure the thrust in the axis colinear to the gravity $\vec{g}$ as the mass of the thruster implies high equivalent thrust, and the vectorisation implies high precision measurements.

4.2 Innovative Cathode

Cathodes are key components of HET devices. The reliability of this element is crucial and is one of the most important failure source. Electrons are extracted from the emitter, generally made of Lanthanum Hexaboride (LaB6), a thermionic ceramic. Efficient cathodes could work in a self-heated mode, meaning that the energy deposited after igntition by the plasma close to the emissive surface is sufficient to maintain the discharge without additional power from the heater. This is particularly challenging for cathodes associated to low power HET, such as 50 W or 150 W class. Reducing the ignition power and time to ignite a HET is a milestone as the power budget on micro to small satellites is limited, which will reduce the thermal stress of the cathode and increase the thruster head reliability.

CNES is thus supporting low power cathode (LPC) development with Exotrail, with the objective of reducing power consumption for low power HET applications. Two aspects are considered, the thermal confinement associated

DOI: 10.13009/EUCASS2023-358

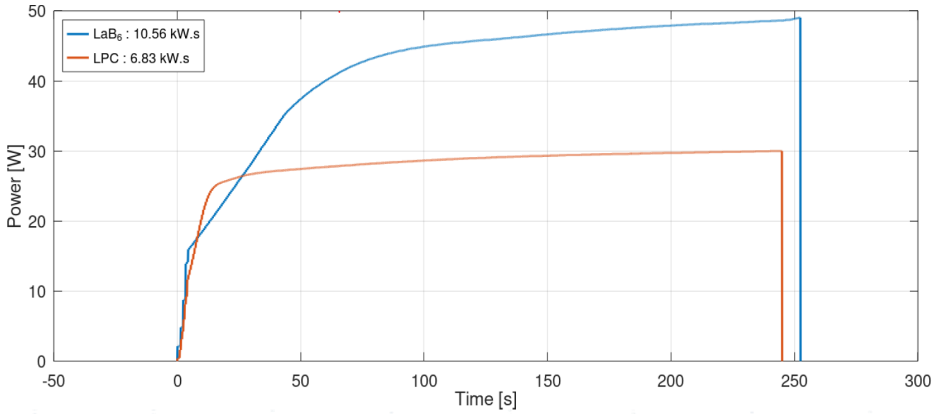

Figure 4: Ignition power consumption for the LPC (in orange) compared to a standard cathode (in blue) in function of time. Credits: Exotrail.

to the cathode design and the nature of the thermionic material. By using a better emissive material compared to LaB6, with a lower work function, the temperature required for a same emission current density is reduced (see section 6.3 of Ref.[6]). Furthermore, a better thermal confinement can reduce the ignition time and favored the self-sustained capacity. In order to ignite a cathode, the low power consumption of the cathode has been well demonstrated and thermally characterized with a total energy reduction of more than 35%, from 10.56 kW.s to 6.83 kW.s (see Fig.4). Work is now ongoing to characterize the cathode in lifespan over more than 3000 cycles, either in terms of stability or reliability. Other material like ceramic electride C12A7:e- from the Spanish ATD company have also been investigated with Exotrail in the frame of the NEMESIS project, a H2020 disruptive grant supported by the European Commission R&I funding, to find a European alternative to non-European produced LaB6.

4.3 Iodine activities

CNES is actively supporting alternative propellants activities in order to pave the way for xenon replacement. Activities concerning Iodine (I_2) are discussed in this section.
Iodine is classified as a molecular propellant. It is made of two iodine atoms and its formula is I_2. The physical properties of this species are very interesting and makes it a privileged propellant for EP devices. Its mass of 253.8 amu is similar to xenon when dissociated. Moreover, this molecule has a low ionization energy, 10.4 eV. Under ISO conditions, iodine has a density of 4.9 g/cm3 and is stored under its solid forms which is particularly interesting for its storage density. However, it is toxic and corrosive. Manipulations needs to be carried carefully and specific protection protocols are addressed for experiments and operations. Before being ionized, solid propellant needs to be heated in order to sublimate. The sublimation temperature of the iodine is quite low, 358 K (85 deg C). Furthermore, it has a dissociation energy of 1.54 eV, largely lower than the ionization energy [19]. Thus, a significant part of the positive charges will be I^+ atomic ions (97%) for only 3% of molecular ions (I_2^+). This feature is very important when studying the efficiency of the thruster using this propellant. However, as shown in Ref.[20], the ionization cross section of iodine, in both its molecular and atomic forms, is about twice as large as xenon during electron impacts of energy equal to 50 eV [21].
CNES is supporting iodine compatibility products developments through different programs such as R&T activities and a TRL 6-7 demonstrator.

ThrustMe has a development and flight heritage in terms of Iodine use for electric propulsion applications. Several R&D projects are to be launched in 2023 in order to master some key technological building blocks. One of the main challenges in the xenon to iodine transition is the propellant mass measurement. Thermodynamics analysis allows to measure the remaining mass in a gaseous propellant tank. This strategy is not possible as iodine is stored under its solid state. A new system thus needs to be developed. The principle, patented earlier by ThrustMe, is to use an acoustic wave generator, and while the propellant mass is decreasing during the mission, the frequency response will change in consequence. A relationship can be established between the remaining mass and the frequency response. ThrustMe is developing with the CNES support a mass measurement system and its associated algorithm. The solution should then be embedded in their propulsion system NPT30-I2 and NPT30-Maxi.

The NPT30-Maxi thruster is the evolution of the NPT30-I2 GIE and is developed in the CNES Demonstrator framework. The objective is to create a new product with the following guidelines:

DOI: 10.13009/EUCASS2023-358

- increase the thrust,
- increase the propellant storage capacity,
- improve the neutralizer design in order to increase its lifetime.

The CNES accompanies the thruster development up to TRL 6 level of maturity through the manufacturing, the assembly and the integration of an EM (Engineering Model).

4.4 Electromagnetic Characterization and Compatibility

Most of EP devices are based on the acceleration of charged particles (see section 2.1), thus producing electromagnetic emissions from the dielectric plasma plume [22, 23]. HET can be subject to several types of instabilities and oscillations in the kHz to GHz range [24], leading to potential interferences with onboard subsystems, especially antennas. In order to better characterize and understand the impact of such interactions, activities are ongoing at CNES on this topic.
An R&T has been launched in 2022 for the preliminary study of a facility dedicated to the characterisation of radiated electromagnetic emission of electric thrusters. Three configurations are evaluated (Fig.5):

- Configuration 1 : Vacuum chamber with a dielectric excrescence surrounded by an anechoic chamber, similar to the Aerospace Corporation facility [25].
- Configuration 2 : A dielectric vacuum chamber is placed within an anechoic chamber.
- Configuration 3 : An anechoic chamber is placed within a vacuum facility.

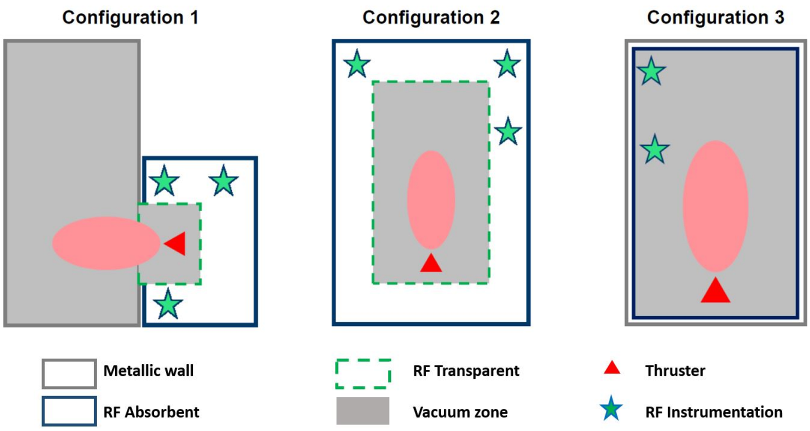

Figure 5: Configurations studied in the R&T with ONERA.

The objective is to evaluate these configurations. Once the limiting parameters are identified in terms of performances, cost, advantages and inconveniences, the most suited one is chosen according to the input specifications.
Another project is studied internally at CNES, dedicated to the study of the electromagnetic emissions of EP thrusters characterisations techniques. The aim is to design a French facility for industrial and research applications. Indeed, all facilities for electromagnetic emission studies are outside France (Italy and USA principally). CNES thus wishes to push a French solution to avoid high cost foreign test campaigns and answer to these open points for the sake of French industry and scientific laboratories. Being able to study this problematic and better understand the impacts on smallsat platforms is particularly challenging, involving in the meantime proximity between the thruster and the antennas and a large range of electromagnetic disturbance. Bringing a solution for the programmatic and commercial need is a key point for the French ecosystem.

5. Scientific Support

As mentioned in section 2.2, support to fundamental research is essential in the development of the electric propulsion field. In this section, part of the CNES support to research project is presented.

DOI: 10.13009/EUCASS2023-358

5.1 Micro-sensor for thrust measurement

Electric thrusters' characterisation and qualification require high reliability measurements. Among all the performance parameters that can be measured, thrust is one of the most important one. On ground, thrust is usually measured thanks to a thrust balance. However, such diagnostic is bulky, difficult to operate, and the comparison between different thrusters is not easy as thrust balances are specific to a each vacuum facility. In order to overcome these limitations, ONERA is developing a compact thrust sensor (Fig.6), relating the pressure on the sensor to the thrust [26, 27]. The sensor is based on a quartz MEMS accelerometer which uses a proof mass mounted on hinges. When the thruster plume hits the sensor, a pressure is applied on the proof mass. As a consequence, the tension across the vibrating beam changes. This change results in a change in the beam resonance frequency which can be linked to the plasma pressure and thus the local thrust density. Through an angular scan, the total thrust can be found.

The concept has been initiated in 2018 thanks to the CNES R&T program. The objective was to demonstrate the

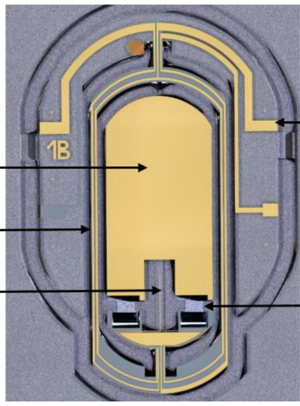

Figure 6: Thrust sensor developed at ONERA Palaiseau. Credits: ONERA.

feasibility of the concept by theoretical and simulation studies. Given the very good conclusions of this study, a thesis started in 2020 to develop the μ-sensor (the latest results can be found in Ref.[28]) and find a way to optimize the thermal loads. This point is the major concern output from this R&T activity which needs to be addressed. The performances of the sensor developed in this thesis are depicted in Tab.3. A second thesis is to start in 2023 in the continuity of the previous one. The objectives are threefold. Firstly, to focus on the measurement calibration which needs to be done within the plasma plume. Secondly to well master the sensor shift, due to several bias sources, and finally to rebuild the thrust vector.

Specification	Current Sensor value
Pressure sensitivity	0.2-0.5 Hz/μN.cm^{-2}
Beam resonance frequency	50 000 Hz
Proof mass resonance frequency	500 Hz
Acceleration sensibility	300 Hz/g

Table 3: Thrust sensor performances.

5.2 VAT Physics

Vacuum arc thruster, also known as VAT, is a micro propulsion thruster using solid metal as propellant instead of gas. It is thus a very interesting device as it does not need any feeding systems such as valves, feeding lines, tank, etc. This allows mass savings and reduced system complexity. It is composed of a cathode and an anode connected to a capacitor bank charged through a semiconductor switch. When the switch is opened, a discharge is created between the cathode and the anode, creating an arc from the cathode to the anode [29, 30]. This high current that results from the metal erosion discharge expands in vacuum creating thrust. The amount of thrust depends on the expansion direction, the eroded mass, and the energy given to the ions which can be adjusted by the signal given to the switch. Unlike more conventional devices, here the thrust is pulsed.

CNES is supporting a thesis at the ICARE laboratory on this subject to study the physics of a high current VAT, using the PJP30 of the COMAT company [9, 31]. As the thruster pulses are very short ($\approx$ 30 μs for the PJP30) some

DOI: 10.13009/EUCASS2023-358

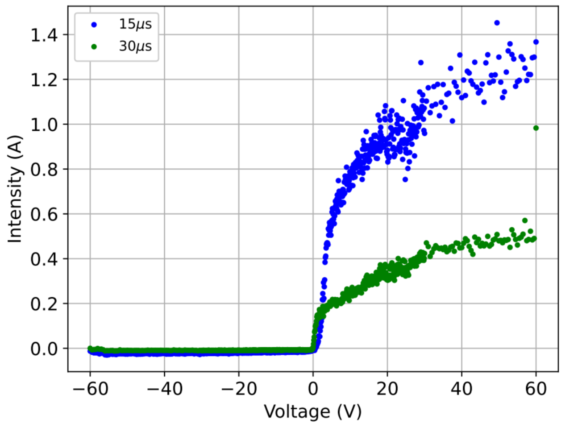

Figure 7: Reconstructed I-V curve of the VAT PJP30 through statistical analysis at two discharge time, $t = 15\mu s$ (in blue) and $t = 30\mu s$ (in green). Credits: Ref.[9].

diagnostics techniques such as the Langmuir Probe (LP) needs to be adjusted. The raw data of a LP is an I-V curve. The probe potential is swept from minus some dozens of volts to a positive voltage respective to the ground. However, the voltage sweep time is much longer than the discharge time of each pulse during which the plasma properties are not constant. Thus, I-V curve needs to be reconstructed through statistical treatment (see Fig.7 and Refs.[9, 31]). The analysis highlighted two distinct regimes during one discharge pulse, spark and arc. The first one is characterized by a high voltage for a short duration, while during the arc regime, the voltage is lower and the plasma conditions are more stable.

The ion velocity is investigated thanks to a Time of Flight (ToF) measurement technique. Two probes biased at the same electric potential are separated by a known distance. Taking the time difference between the two acquisitions, the ion velocity can be found. The results shown that several ions population are emitted, with mean velocity between 25 and 40 km/s. Velocities up to more than 100 km/s have also been observed on some pulses. Furthermore, the cathode material plays a major role on the plasma discharge properties.

5.3 Electron Dynamics in ECR Thruster

The Electron Cyclotron Resonance (ECR) technology is an electromagnetic thruster using a magnetic nozzle for plasma acceleration. The idea is to synchronise a microwave frequency source with the cyclotron frequency of electrons around the solenoid magnetic field lines [32] which leads to thermally excited electrons. This thermal energy is then converted into kinetic energy through the magnetic nozzle. The ions are accelerated by the ambipolar diffusion in order to satisfy the plasma quasi-neutrality and charge balance.

Figure 8: 30 W ECR thruster ECRA. Credits: ONERA.

ECRA is an ECR thruster developed by the ONERA - Palaiseau (Fig.8) with relatively good foreseen total efficiency, around 45%. CNES is supporting development activities both in R&T activities and in the frame of the

DOI: 10.13009/EUCASS2023-358

H2020 EPIC roadmap, in order to explore key questions that have not yet been addressed, and that would potentially increase the thruster efficiency:

- How can the microwave power be better delivered to electrons ?
- How the wall losses can be lowered through the magnetic nozzle topology optimisation ?
- Can be developed scaling laws for ECR thrusters ?

A thesis is ongoing at ONERA to study the Electron dynamics in ECR thruster. The characterisation of the plasma detachment of the magnetic nozzle is one of the investigated aspects.

6. Conclusion

The CNES support is covering a large range of activities mainly carried out with support of the R&T and demonstrator national program, the GSTP funding through ESA and the European Commission R&I funding in the frame of Horizon 2020 and Horizon Europe. Efforts are made on new thrusters concept development and maturation as well as the development of associated sub-systems and facilities. Several types of technologies are investigated and the innovation potential of the ecosystem is strongly supported. CNES makes sure of the coherence and interest of all the development and fundings ongoing under national or european funding support. With a transverse view of the different actors, their constraints and objectives, CNES aims at improving French and European sovereignty in the space sector, especially for the electric propulsion field.

7. Acknowledgements

The authors would like to thank CNES colleagues from the Telecom/Navigation and Earth Observation departments, the R&T program and the PASO (Advanced project team) departments for fruitful discussions and support. The French Space Agency CNES, through the authors, acknowledges the contribution of CNRS, French Research laboratories like ICARE, LAPLACE, LPP, CERFACS and ONERA research center. CNES also acknowledges the historical collaborative activities carried out by SAFRAN Spacecraft Propulsion (SSP), Airbus Defense and Space (ADS), Thales Alenia Space (TAS), Air Liquid Advanced Technologies (ALAT), and more recently by COMAT, ThrustMe, Exotrail and Ion-X. CNES also thanks the European Commission and the HaDEA for the funding of the EPIC roadmap established and maintained by the PSA through the Horizon 2020 and Horizon Europe R&I programs.

References

[1] Stéphane Mazouffre. *Propulsion électrique pour les systèmes spatiaux*. 2018.

[2] Business Khabar. *How rare-gas supply adapted to Russia's war*. URL: https://www.businesskhabar.com/money/finance/how-rare-gas-supply-adapted-to-russias-war/.

[3] Nathan P Brown and Mitchell LR Walker. "Review of plasma-induced Hall thruster erosion". In: *Applied Sciences* 10.11 (2020), p. 3775.

[4] Gabriel F Benavides et al. "Iodine Hall-effect electric propulsion system research, development, and system durability demonstration". In: *2018 Joint Propulsion Conference*. 2018, p. 4422.

[5] Stéphane Mazouffre. "Electric propulsion for satellites and spacecraft: established technologies and novel approaches". In: *Plasma Sources Science and Technology* 25.3 (2016), p. 033002.

[6] Dan M Goebel and Ira Katz. *Fundamentals of electric propulsion: ion and Hall thrusters*. John Wiley & Sons, 2008.

[7] Jérôme Moritz et al. "Sheath size and Child–Langmuir law in one dimensional bounded plasma system in the presence of an oblique magnetic field: PIC results". In: *Physics of Plasmas* 28.8 (2021), p. 083501.

[8] Dmytro Rafalskyi et al. "In-orbit demonstration of an iodine electric propulsion system". In: *Nature* 599.7885 (2021), pp. 411–415.

[9] E Michaux, Stéphane Mazouffre, and R Fritzsche. "Spatial and temporal evolution of ion and electron parameters in the plasma jet of a 30 W VAT". In: *37th International Electric Propulsion Conference*. 2022.

[10] Stéphane Mazouffre. "Laser-induced fluorescence diagnostics of the cross-field discharge of Hall thrusters". In: *Plasma Sources Science and Technology* 22.1 (2012), p. 013001.

DOI: 10.13009/EUCASS2023-358

[11] Benjamin Vincent, Sedina Tsikata, and Stéphane Mazouffre. "Incoherent Thomson scattering measurements of electron properties in a conventional and magnetically-shielded Hall thruster". In: *Plasma Sources Science and Technology* 29.3 (2020), p. 035015.

[12] P Lasgorceix et al. "A new French facility for ion propulsion research". In: *24th International Electric Propulsion Conference, Moscow, Russia*. 1995.

[13] Romain Lucken, Pascal Chabert, and Anne Bourdon. "Simulation and modeling of PEGASES thruster operated with iodine". In: *7th Workshop on Radio-Frequency Discharges*. 2017.

[14] Romain Lucken et al. "Global model of a magnetized ion thruster with xenon and iodine". In: *36th International Electric Propulsion Conference*. IEPC-2019-678. 2019.

[15] Jean C Porto and Paul-Quentin Elias. "Full-PIC simulation of an ECR plasma thruster with magnetic nozzle". In: *IEPC 2019*. 2019.

[16] Julien Jarrige et al. "Characterization of a coaxial ECR plasma thruster". In: *44th AIAA Plasmadynamics and Lasers Conference*. 2013, p. 2628.

[17] Alex Kieckhafer and Lyon B King. "Energetics of propellant options for high-power Hall thrusters". In: *Journal of propulsion and power* 23.1 (2007), pp. 21–26.

[18] Andreas Neumann, Julian Sinske, and Hans-Peter Harmann. "The 250mN Thrust Balance for the DLR Goettingen EP Test Facility". In: *33rd International Electric Propulsion Conference, IEPC2013*. 2013, pp. 1–10.

[19] Kristof Holste et al. "In search of alternative propellants for ion thrusters". In: *34th International Electric Propulsion Conference, At Kobe, Japan*. 2015.

[20] Patrick Dietz et al. "Molecular propellants for ion thrusters". In: *Plasma Sources Science and Technology* 28.8 (2019), p. 084001.

[21] D Mathur and C Badrinathan. "Ionization of xenon by electrons: Partial cross sections for single, double, and triple ionization". In: *Physical Review A* 35.3 (1987), p. 1033.

[22] Matteo Albani et al. "Modeling and dielectric characterization of EMI/EMC ground test for the evaluation of the electric propulsion thruster emissions". In: *2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*. IEEE. 2017, pp. 2599–2600.

[23] N de Mejanes et al. "Simulation of the microwave propagation through the plume of a Hall thruster integrated on small spacecraft". In: *Journal of Applied Physics* 131.24 (2022), p. 243303.

[24] EY Choueiri. "Plasma oscillations in Hall thrusters". In: *Physics of Plasmas* 8.4 (2001), pp. 1411–1426.

[25] Edward Beiting and Michael Garrett. "Facility for high-fidelity electromagnetic compatibility studies of electric thrusters". In: *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. 2007, p. 5329.

[26] Severin Astruc, Paul-Quentin Elias, and Raphael Levy. "Compensation of perturbative effects on a thrust measurement MEMS probe for electric propulsion". In: *2021 Symposium on Design, Test, Integration & Packaging of MEMS and MOEMS (DTIP)*. IEEE. 2021, pp. 01–06.

[27] Séverin Astruc et al. "Thrust measurement using a plasma pressure probe immersed in the plume". In: *International Electric Propulsion Conference 2022 (IEPC 2022)*. 2022.

[28] Séverin Astruc et al. "Analysis of perturbative effects of a momentum flux probe in a plasma plume". In: *EUCASS 2023*. 2023.

[29] Jochen Schein et al. "Vacuum arc thruster for cubesat propulsion". In: *IEPC-0276, 28th IEPC* 100 (2003).

[30] Jonathan Kolbeck et al. "Micro-propulsion based on vacuum arcs". In: *Journal of Applied Physics* 125.22 (2019), p. 220902.

[31] E Michaux, S Mazouffre, and R Fritzsche. "Evolution in time and space of ion and electron properties in the jet of a lowpower Vacuum Arc Thruster". In: *Space Propulsion Conference 2022*. 2022.

[32] Joel Christopher Sercel. *An experimental and theoretical study of the ECR plasma engine*. California Institute of Technology, 1993.