An overview of electric propulsion activities at CNES

IEPC-2017-102

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

Claude Boniface[1] , Jean-Marc Charbonnier[2], Luc Lefebvre[3], Vaitua Leroi[4] and Thomas Lienart[5]
Centre National d'Etudes Spatiale (CNES), 18 avenue Edouard Belin, F-31401 Toulouse, France

Abstract: The paper presents an overview of the activities carried out on electric propulsion (EP) in France, with the strong support of the French Space Agency CNES, including research activities as well as technology development and in-flight applications. This concerns mainly activities on Hall Effect Thruster (HET) technology. In addition, some interesting initiatives in the field of µpropulsion in France are also briefly presented.

Nomenclature

CNES	=	Centre National d'Etudes Spatiales
HET	=	Hall Effect Thruster
EP	=	Electric Propulsion
NSSK	=	North South Station Keeping
EWSK	=	East West Station Keeping
EOR	=	Electric Orbit Raising
R&T	=	Research and Technology
GEO	=	Geostationary Earth Orbit
LEO	=	Low Earth Orbit
GTO	=	Geostationary Transfer Orbit
ADS	=	Airbus Defence & Space
TAS	=	Thales Alenia Space
DGA	=	Direction Générale de l'Armement
SAE	=	Safran Aircraft Engine
AL-AT	=	Air Liquid Advanced Technologies

[1] Electric propulsion R&T manager, Propulsion, Pyrotechnics and Aerothermodynamics department, CNES Orbital Systems directorate, claude.boniface@cnes.fr.
[2] R&T program manager, CNES Innovation, Applications and Science directorate, jean-marc.charbonnier@cnes.fr.
[3] On-board/Ground and Platform R&T program manager, CNES Innovation, Applications and Science directorate, luc.lefebvre@cnes.fr.
[4] Electric propulsion subsystem manager, Pyrotechnics and Aerothermodynamics department, CNES Orbital Systems directorate, vaitua.leroi@cnes.fr.
[5] Head of CNES Propulsion, Pyrotechnics and Aerothermodynamics department, CNES Orbital Systems directorate thomas.lienart@cnes.fr.

I. Introduction

CNES (Centre National d'Etudes Spatiales – French Space Agency) is an historical well-known player in the field of electric propulsion. Indeed, this technology has been investigated in France for more than 40 years (FEEP, mercury ion bombardment thrusters and Hall Effect thruster). Now, the electric propulsion is at a crossroad of its history. Indeed, it is now widely used on commercial satellites for North-South Station Keeping (NSSK) maneuvers. But the significant mass savings, associated with recent in-flight achievement, allow perspectives which were not possible before. Thus, the Hall Effect thruster (HET) technology, developed in France for about twenty years, is not only foreseen for operations of station keeping but also for orbit raising of geostationary/navigation satellites, which opens a considerable market.
Moreover, Nano-satellites are new comers for space applications which can benefit from electric propulsion systems. Besides, guiding and controlling very small satellite trajectories as well as their orbital drift requires compact and robust electric propulsive systems. This is why new innovative and efficient propulsion systems are needed, and new paths have to be explored.

This turning point requires important R&T activities:

- in the short term, propulsion subsystems shall be suited to these new applications and shall increase their competitiveness,
- in the middle term, the new product line will have to meet the needs of futures missions (LEO missions, space tug).
- in the long term, breakthrough has to be performed for more ambitious missions (far-off explorations, …).

In the following sections, current on-going activities are discussed including research activities as well as technology development and in-flight applications.

II. Flight programs and new mission designs

CNES program covers Earth observation, defence and security, scientific and telecommunications missions. The main driver of the electric propulsion activities in France is the preparation of future telecommunication platforms that require high power thruster for orbit transfer as well as orbit control. Nonetheless, the new paradigm, offered by electric propulsion system in term of orbital maneuvers, opens its use for low Earth orbit observation, navigation/telecom and ambitious scientific missions.

A. French Investment Plan for Future (PIA :"Plan d'Investissement d'Avenir")

By 2020, it was estimated that more than half of all sold satellites will be all-electric or hybrid technology (both chemical and electric systems). French industry excels in the domain of commercial telecommunication satellites. To maintain its strong position in this market and to prepare the transition to the new platforms NEOSAT, industry must adapt quickly to evolving requirements, in particular due to the recent emergence of lighter and cheaper all-electric satellite buses. The space component of the national initiative PIA plan led by CNES offers support to Airbus Defence & Space (ADS) and Thales Alenia Space (TAS) to design, develop and validate their standard electric satellite platforms (respectively Eurostar and Spacebus buses) in orbit, and to Safran Aircraft Engine (SAE) in developing and qualifying its high-power electric thruster (PPS®5000) [1]. It is the case of the satellite EUTELSAT 172B based on a Full Electric platform Eurostar E3000 of ADS. This development, in particular the sub-system plasma propulsion, was supported by the PIA investment. EUTELSAT 172B satellite was launched on Ariane 5 in June 2017. The satellite will reach soon successfully the GEO orbit using electric propulsion.

B. NEOSAT program

The NEOSAT platform is the European answer to the demand for new generation platforms for satellites between 3 to 6 tons, i.e. 80% of the communications satellites market[2]. The aim of this program, supported by CNES as part of the Investment for the future program and by ESA under ARTES 14, is to obtain a 30% increase in competitiveness, for the whole satellite. In addition to the technological innovations and increased competitiveness of the equipment and the sub-systems, part of the enhanced competitiveness will also come from the shorter development time for the satellites. The key element of these new telecommunications satellites will be the electric propulsion system. Electric propulsion is not new, since it is already commonly used to maintain satellites at their position in geostationary orbit, or to correct drifts of the orbital position. However, up to now, chemical propellant has remained the nominal solution for reaching orbital location following launch. Using electric propulsion for transferring satellites to their final orbit allows saving propellant mass and the associated structures. This propulsion method means that either lighter satellites with equal payload capacity can be launched, gaining on launch costs, or more powerful satellites can be launched for an equivalent cost. One of the major issues expected for the future NEOSAT platform, in terms of technological progress and increased competitiveness, will be to reduce the orbit raising duration to three months or less.

Figure 1. Artist view of NEOSAT platform. Credit ESA.

C. SYRACUSE IV program

CNES is preparing a new generation of military communications satellite. Two satellites (X-band and military Ka-band) will be built with a strong anti-jamming capability by ADS and TAS. CNES will be in charge of the pre-development of dual use projects while the development will be done by an integrated DGA/CNES team. One the key element of these new military satellites will be the high power electric propulsion system PPS developed by SAE.

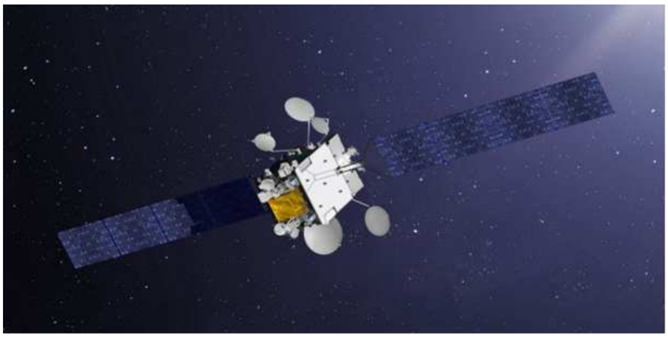


Figure 2. Artist view of SYRACUSE IV platform. Credit TAS/E. Briot.

D. Others applications and new mission designs

Servicing and Exploration

Some mission analysis exhibits multi-mission applications like space tug to perform several fast LEO/GTO to GEO transfer or in-orbit servicing (refueling, etc.). In this context, some projects are under evaluation at CNES (launcher and orbital system directories) to design a space tug that can be implemented as a passenger for launchers[3]. This implies the need of propulsion system owning a high thrust to power ratio (~ 100 mN/kW) and which can operate at very high power (20 – 100 kW).

In the long term, ambitious robotic missions like exploration of outer planets of the solar system as well as transfer of cargo vehicle to support crewed missions will require very high power electric propulsion systems (>> 20 kW).

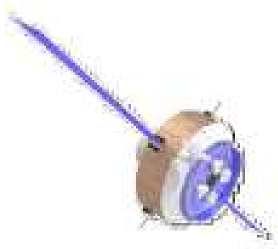


Figure 3. Space Tug design. Credit CNES.

LEO missions

Different studies have been performed in using electric propulsion for Low Earth Orbit (LEO) or constellation applications at CNES[4]. For instance, the use of electric propulsion on Myriade or Myriade Evolution platforms for missions in LEO has been analyzed. Myriade platform, developed by CNES, is a product line for micro-satellites dedicated mainly to scientific missions, but offering also flight opportunities for technological demonstrations. Numerical analysis were performed to demonstrate the high DV capability offered by electric propulsion, which can be used for orbit acquisition (typically, in the case when the satellite is launched as a co-passenger) and for end-of-life manoeuver, to ensure an atmospheric re-entry much shorter than the required 25 years.

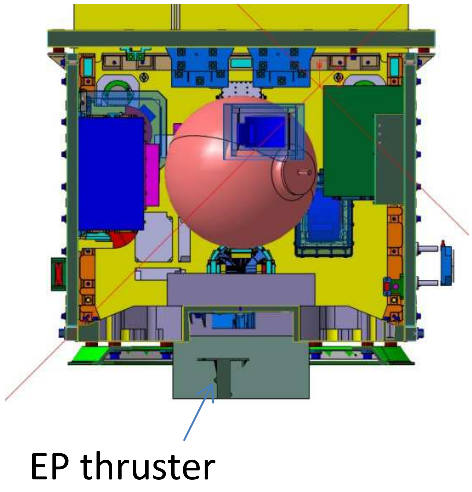


Figure 4. Myriad Platform in electrical configuration

III. Thruster development and qualification

E. PPS®1350-E thruster

The PPS®1350 thruster is a Hall effect thruster by SAFRAN, initially designed at 1.5 kW total power. The version of this thruster named PPS®1350-G was qualified for North-South Station Keeping (NSSK) of geostationary satellites. The nominal operating point of the thruster was set to a discharge voltage of 350 V and a discharge current of 4.28 A. With an average thrust of 89 mN and an average specific impulse above 1650 s, the PPS-1350-G demonstrated a total impulse of 3.36 x 10^6 Ns under various environmental conditions. A total ground qualification time of more than 10 500 hours was reached, allowing its use on the Alphasat satellite launched in 2013[5].
The operating point of the PPS®1350G at 1.5 kW was optimized to reach the NSSK requirements of the Alphabus satellites. Nevertheless it is well known that Hall thrusters offer throttling ability and can operate on a wide range of power and thrust[6]. This feature is of interest when considering other possible missions for a thruster.

That is why an extended range version of the PPS®1350 (-E version) is currently under qualification. Based on R&T activities performed with Safran & CNES co-funding and on the robustness of the PPS®1350 design, it was decided to increase the input power up to 2,5 kW[7]. One of the main advantages in the thruster development is to rely on the similarities of both thruster versions in order to reduce the development schedule and recurring costs. A preliminary 6700 hours life test campaign on an engineering model was performed in 2014 in order to mitigate the development risks. The PPS®1350-E offers higher capabilities with thrust up to 140 mN and specific impulse up to 1800 s.

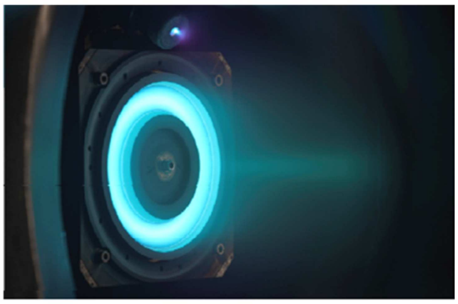


Figure 5. PPS®1350-E thruster on stage and during ground qualification test. Credit Safran Aircraft Engine.

At the same time, Safran works to increase the potential of this kind of thruster following two ways:

- To increase the lifetime capability (> 5 MN.s) of the thruster by shaping the magnetic field configuration.
- To operate at high voltage (> 500 V) and so at higher specific impulse by improving ceramics channel lifetime duration.

Work is ongoing now with the support of technical research program from ESA and an CNES R&T program.

F. PPS®5000 thruster

The introduction of electric propulsion for orbit raising of geostationary satellites, on top of the conventional NSSK mission implies several technical challenges (increase available power, total impulse capability, diversity of operating points). In addition to the technical capabilities required from the thruster, it has also to satisfy cost effectiveness requirement. This feature is mandatory in this highly challenging market. The development of the 5-kW-class PPS®5000 Hall thruster answers theses shifting needs in terms of electric propulsion[8,9].

The key objectives of the PPS®5000 development are therefore:

- Meet the technical requirements of the customers.
- Achieve a cost-competitive solution.
- Meet the stringent time-to-market constraints imposed by the new generations of SatComs.

The PPS®5000 offers higher capabilities with thrust of 100 - 300 mN and specific impulse within 1730 - 2000 s. The PPS®5000 development and qualification are on-going.

Figure 6. PPS®5000 thruster on stage and during ground test. Credit Safran Aircraft Engine.

In parallel, Safran developed several product lines to catch the different markets that can be reached by the Hall Effect Thruster technology[10]:

- Dual mode electric, propulsion subsystem for GEO applications.
- A low power thruster for LEO applications.
- A thruster higher than 20 kW for exploration applications.

G. µpropulsion in France

Nano-satellites or very small platforms tend to be strategic for spatial applications. Guiding and controlling very small satellite trajectories as well as their orbital drift ask for compact, efficient, and robust propulsion systems. However, traditional propulsion systems hardly match the required constraints for this new generation of small satellites. Most of these technologies have been optimized for operation at a range of power levels that serve the needs of usual space missions (NSSK and EOR). For example, a relatively large number of Hall Effect thrusters range from almost 200 W in power level to several tens of kilowatts. New innovative and efficient propulsion systems are then needed, and new tracks have to be explored. Several initiatives (non-exhaustive list) are undertaken in France to propose solutions to reach the requirement demanded for this kind of new platforms:

- COMAT industry – Vaccum Arc Thruster (VAT) [11]
- Start Up Thrust Me – RF-Ion thruster[12]
- Start Up Exotrail - µHET with magnetic ceramics[13]
- ONERA institute – Electron Cyclotron Resonance Thruster[14]

IV. Technology and research

Electric thruster development cycles are very long. Therefore, it becomes crucial to anticipate technological breakthroughs to make them available for new developments. That is why technological activities sponsored by CNES are focused toward an improvement of thruster performances (efficiency, ratio mass/volume, lifetime and extended operating range), reliability and competitiveness. Especially, different activities on Hall Effect Thruster are under investigation in the frame of technological program with Safran and industrials. Many studies were performed which includes (non-exhaustive list) methods for life test acceleration, new ceramics and magnetic circuit alloys, new anode composition, high-reliability electrical connections, innovative xenon regulation system. The latter is discussed in the next section.

H. High pressure xenon regulation

AL-AT has developed, with the support of CNES, a xenon flow regulator in rupture with standard systems. A very light valve, less than 10 grams, delivers a xenon mass-flow directly from the tank outlet pressure, covering the whole range of pressures from BOL to EOL : typically from 200 to 5 bar (which are the current requirements, but this range can be adapted to higher pressures). Mass flow rate covers thrusters needs from 0 mg/s to 20 mg/s and is fully flight adjustable. Electric Propulsion architecture is greatly simplified with this disruptive architecture, bringing in one component two functions: pressure regulation and mass flow rate regulation. This new approach could bring competitiveness for future product lines. This component is derived from a helium pressure regulator onboard Rosetta Philae and will be onboard ExoMars 2020 rover. The tests which have already been performed are encouraging. The valve can deliver flow rates adapted to thruster in the range 100 W-5kW. Some additional tests are under progress (xenon high pressure tests and coupled valve/thruster tests) with the aim to reach a TRL 6 by the end of the year 2017. More details are reported in the paper IEPC-2017-202[15].

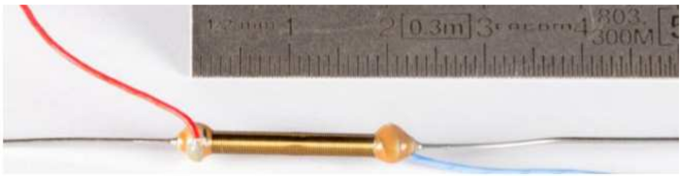


Figure 7. Air Liquide Multi Function Valve. Credit : AL-AT

Type of Valve	Normally Closed / Regulation electronically controlled micro valve (can also be used as an ON/OFF valve)
Size	Length < 25mm Diameter < 3,5mm
Weight	< 10g
Tightness	< 10^{-7} mbar.L/s
Media	Inert gas (He / N2 / Xe / Kr / Ar)
Mass flow rate range	0-20mg/s
Power Consumption	< 3W
Inlet Pressure	5- 200bar
External environment	Atmosphere down to vacuum
Thermal environment	-40°C / 110°C

Table 1 : Key feature of Air Liquide micro Multi Function valve.

I. Thruster hollow cathode

The trend in communication satellites is to perform NSSK and EOR maneuvers using electric propulsion electric propulsion (EP). Cold gas systems or chemical propulsion (CP) in general are instead used to perform fast attitude dynamics of a safe mode, additional wheel momentum management and dedicated East/West station keeping (EWSK) control or de-orbitation maneuvers.

Such maneuvers may be also performed by the well-known qualified PPS®1350 hollow cathode from Safran (without any modification of the design) by operating at different following mode: cold gas, resistojet and discharge modes.

An experimental campaign has been performed in 2016 by Safran at Aerospazio test bench, where the thrust and the discharge parameters of the cathode were measured for each mode.

The main information is the following :

- For the cold gas mode, the thrust is included between 0.11 to 0.7 mN with an Isp (Specific Impulse) at the order of 22 s for the mass flow rate range 0 to 3 mg/s.
- For the resistojet mode at 40 W, the thrust and Isp are included respectivelly between 0.2 to 1.1 mN and 40 to 80 s for the mass flow rate range 0 to 3 mg/s.
- For the discharge mode, the test has been carried out at 4.28A and 6.80 A for a mass flow rate of 0 to 1.1 mg/s. At 4.28 A, thrust and Isp are included respectivelly between 0.18 to 0.50 mN and 45 to 60 s while at 6.80 A thrust and Isp are included respectivelly between 0.30 to 0.70 mN and 65 to 110 s.

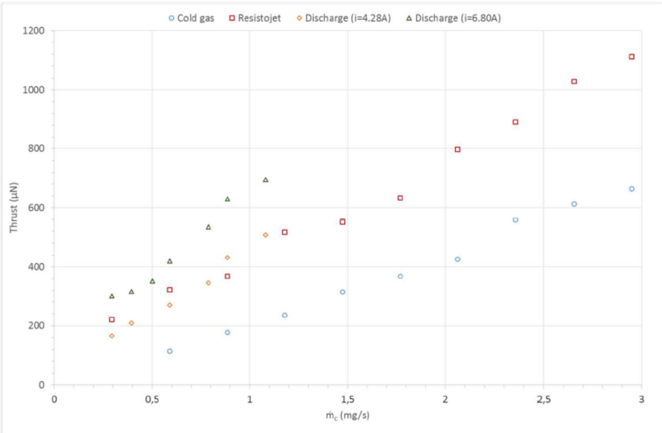


Figure 8. Comparison of the thrust as a function of the mass flow rate for the discharge mode (Id = 4.28 A and Id = 6.8 A), resistojet (Ih = 8 A) and cold gas. Credit Safran Aircraft Engine.

The results show that the thrusts obtained in the cold gas and resistojet mode are comparable with the literature and the simulation carried out. This experimental campaign gives a mapping (especially in resistojet and cold gas mode) of capability of the 10 500 hours ground qualified and flight proven hollow cathode from SAE. It suggests some interesting performance in case of thruster failure in flight or de-orbitation maneuvers.

V. Scientific Research activities

A. Research group on electric propulsion

Hall Effect thruster has been studied in the frame of French research Group on plasma propulsion since 1996 in order to maintain a deep expertise of complex physical phenomena occurring in HET. This research group coordinated by CNES involves many partners (CNES, several laboratories from CNRS and universities, Safran and ONERA) specialized in all fields required in Hall Effect Thruster physics (plasma physics, optical diagnostics, laser, magnetism, matter physics, numerical simulation…). These research activities are currently focused on three main topics:

- improvement of thrust lifetime (ceramics development, plasma-wall interaction studies),
- improvement of performances and thruster physical understanding (magnetic field – plasma coupling, micro-turbulence),
- improvement and optimization on Hall Effect Thruster design.

In parallel of this research group, CNES supports transversal activities, dedicated to diagnostics development (plasmas probes, Thomson scattering), numerical tools (magnetized plasma propulsion modeling) and new concepts of EP thruster technologies.

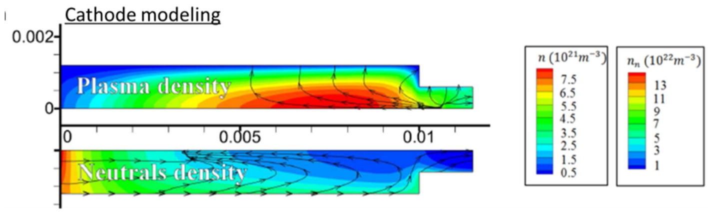
Some new results are reported hereafter.

B. EP Modeling

EP and for instance HET are now often used in station keeping and soon for orbit raising or long-term scientific missions. They are required to operate for many thousands of hours. However, interaction of plasma-facing surfaces inside the thruster, such as the dielectric walls, and transient phenomena result in erosion which can degrade the thruster performance or cause complete failure. Therefore qualification of newly designed thrusters is an important process, but one which typically requires many months or years of continual testing in high-vacuum space simulation chambers. This testing is expensive and time consuming, and highlights the need for accurate models and simulations to help predict erosion rates and lifetimes without needing such long-term experimental work. In addition, these different models are needed to help design and develop new thrusters to meet future performance requirements, while minimizing costly experimental optimization campaigns.

Hollow cathode modeling

A two dimensional quasi-neutral fluid model of a hollow cathode for Hall Effect Thrusters taking into account consistently both the plasma discharge in the interior region of the cathode and the temperature profile of the electron emitter has been developed at LAPLACE/GREPHE laboratory[16]. It has been coupled with a thermal model into a self-consistent generic model applicable to any hollow cathode design. One of interesting results show the global behavior of the LaB_6 cathode differs radically from that of the BaO cathode in the same operating conditions: the plasma repartition is more spread inside the cathode and the equivalent electron current produced in the ionization of xenon amounts to a large fraction of the total discharge current. Works are ongoing to validate experimentally this model and to design an experimental prototype of high current cathode (> 50 A). More details are reported in the paper IEPC-2017-486[17].



-

Figure 9. 2D Simulation results for a LaB6 hollow cathode: plasma density and neutrals density,

Magnetic circuit modeling

An efficient method and a robust tool for designing optimal electromagnetic circuits have been developed at LAPLACE/GREM3 laboratory. It consists in a hybrid source code (ATOP) which is built as a topological (ATOPTO) and a parametric (ATOPPO) optimization method. The method allows to change global dimensions in order to reach the given magnetic cartography. The topology (number of holes, boundaries) of design domain can change during the optimization process[18]. Such tool is nowadays used to design and improve the classical magnetic circuit of Hall Effect thrusters.

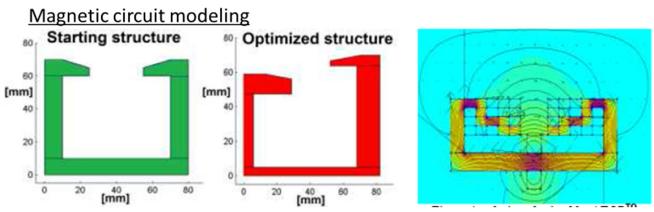


Figure 10. Optimization of magnetic circuit using ATOP algorithm.

Anomalous Electron transport modeling

Despite being a mature technology that has seen almost 60 years of development, there is a number of aspects of Hall-effect thrusters operation that are still not understood. Anomalous electron transport across the thruster magnetic field is one the most famous unresolved issues and still identified as poorly understood. Recently, a CNES post doc fellow researcher at LPP laboratory proposed an interesting theory of anomalous transport. According to his work[19,20] , the anomalous electron transport occurs because of an enhanced electron-ion frictional drag force associated with an electron cyclotron instability in the azimuthal direction due to the large azimuthal electron drift velocity. This instability grows rapidly before nonlinear effects associated with ion-wave trapping set in to limit the amplitude. This convection (due to the large ion drift velocities in the axial direction) carries the instability downstream, and leads to a strong increase in the electron cross-field mobility that agrees qualitatively and quantitatively with what is seen experimentally. This mobility is a strong function of almost all plasma parameters, and consequently does not scale with simple $1/B^2$ 0 or 1/B laws. These results are also in very good agreement with particle in-cell (PIC) simulations.

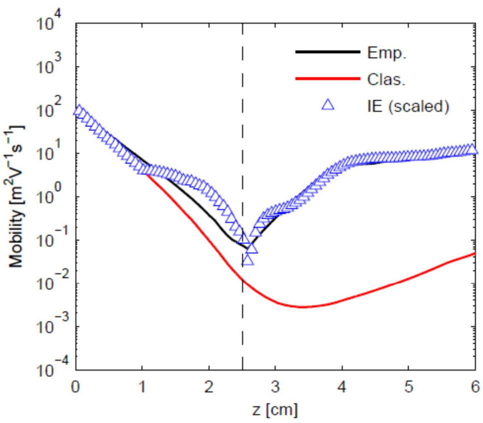


Figure 11. Electron cross-field mobility as a function of axial position within a classical Hall Effect thruster. The solid black line is an empirical mobility which is needed in fluid simulations in order to get agreement with experimental results, the red line is the mobility based on classical diffusion across a magnetic field, while the open blue triangles show the scaled mobility due to the saturated instability-enhanced electron-ion friction force. Curve is issued from paper[19].

Plasma-Wall interaction modeling

It is known that electron emission (EE) has a non-negligible impact on HET plasma behavior (and thus, on HET performances). It has been shown through measurement and modelling that EE varies with numerous parameters (e.g. incident electron energy, incident electron angle, wall material, etc.). However EE models used in particle-in-cell (PIC) and fluid modelling are generally very simple and empirical parameters are chosen to describe it. For example, it is common in PIC models to consider only one type of electron, with one emission energy and isotropic angular distribution. However, EE phenomenon is more complex and it is necessary to consider different types of emitted electrons (secondary and backscattered) with specific angular and energy distributions to describe it physically.

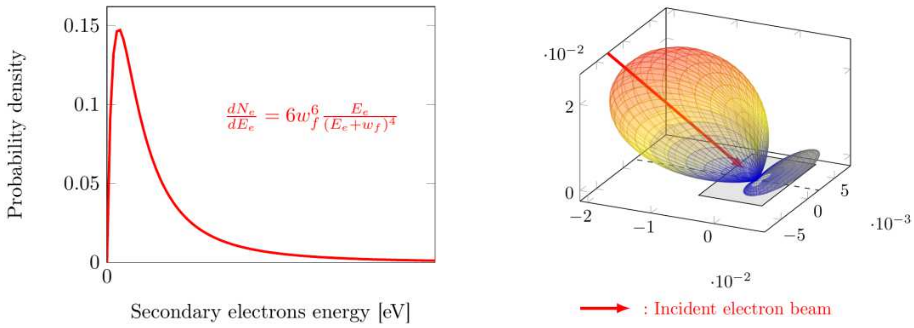


Figure 12. (left) Secondary electrons energy distribution according to Chung and Everheart model. (Right) Elastically backscattered electrons angular distribution according to SLAB model.

This model - developed at ONERA with CNES support - considers two types of electrons: secondary and elastically backscattered electrons (inelastically backscattered electrons are neglected). They are described in term of emission yield, angular and energy distribution.

This model presents several advantages. First of all, it is based on a physical description. This allows a physical understanding of EE phenomenon as well as extrapolation to values which cannot be reached experimentally (razing incident and emission angle, high temperature, numerous materials, etc.). Besides, as it depends on several physical parameters (incident angle and energy, material type, material density, etc.), it will allow observing the influence of these parameters on HET performances. Finally, it is an analytical model, which ensures calculation over a wide range of parametrical values in a reduced computing time (from some minutes to some hours).

In further studies, this EE model will be implemented in a PIC simulation in order to evaluate more precisely the influence of EE on HET plasma behavior. On a wider range of time, it will be attempted to extract general law of the influence of plasma/wall interaction in order to implement them in a HET plasma fluid modelling. Detailed of the modeling are described in the paper IEPC-2017-366[21]

C. EP diagnostic

Qualification of EP system must be tested in high vacuum environments for long period that increases drastically the cost of such systems. Adapted diagnostics (ex situ or in situ) are needed to follow carefully the thruster behavior during the development phase.
Besides, the design of accurate diagnostics to measure the main properties of the electric propulsion discharge is a great of importance to improve our understanding of the main features of the propulsive system but also to provide relevant database to improve the modeling of the propulsive equipment.

Incoherent Thomson Scattering

The accurate determination of electron properties – density, temperature (or the electron energy distribution function, or EEDF) – is a long-standing challenge for magnetized plasmas. Invasive tools such as Langmuir probes must be used with care, due to their perturbative effects on the plasma under study, and the shortcomings of existing probe theory when applied to magnetized plasmas. The most advanced non-invasive diagnostic available for the measurement of electron properties is incoherent Thomson scattering (ITS), used since the 1960s in fusion plasmas.

The application of this tool to the study of electron properties in the Hall thruster is motivated by the lack of reliable measurements for the electron density, temperature and distribution functions inside the channel and near-field magnetized plasma regions. In the channel and near-field regions, electron temperatures are expected to be a few tens of eV, dropping to a few eV in the far-field plume. Accurate knowledge of the electron properties is critical for the construction of reliable codes and theories and for an improved understanding of phenomena such as anomalous transport.

The application of ITS to such plasmas poses an important challenge: the low electron densities encountered in comparison to fusion plasmas (3 or 4 orders of magnitude lower) result in proportionally-lower scattered signal intensities. This requires the development of much more sensitive diagnostics. In recent years, efforts have been made to apply this diagnostic to a number of low-density sources, and this project extends these efforts.

An initial feasibility study with partial support from CNES was carried out to determine the possibility of ITS measurements in a Hall thruster plasma. This feasibility study involved the design and construction of a new diagnostic prototype known as THETIS (S. Tsikata, B. Vincent) at ICARE, with important contributions from collaborating groups at the LPGP laboratory in Orsay (T. Minea) and CEA Saclay (SACM). The initial feasibility study was carried out using a hollow cathode.

This initial feasibility study validated a new approach to the ITS diagnostic design, based on the use of a volume Bragg grating for stray light attenuation for the first time in an ITS bench. It also validated other design choices and analysis procedures. Based on the initial feasibility study, upgrades to the diagnostic were made and a range of cathode measurements were successfully obtained. The current diagnostic is notable for its compactness and sensitivity (providing measurements of electron densities down to 10^{16} /m^3), with future upgrades and thruster studies planned. Results are detailed in the paper IEPC-2017- 442[22]

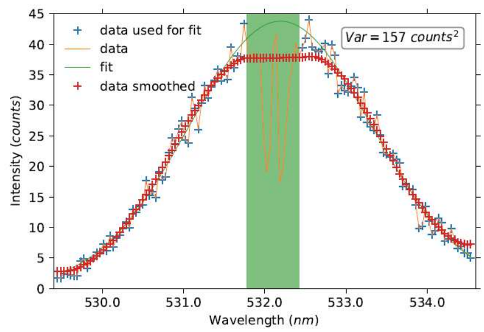


Figure 13. Example of an incoherent Thomson scattering spectrum obtained for a hollow cathode plasma. Curve is issued from paper[23]

Faraday Probes

Measurements of the ion current density angular distribution in the ion beam far-field region of EP devices give access to several quantities such as the propellant utilization, the beam efficiency and the divergence angle. An accurate estimate of those quantities is critical for the development, optimization and qualification of electric thrusters for spacecraft. A comparison between three electrostatic probes has recently been performed to define the more suited probe architecture. Experiments with a planar probe (PP), a planar probe with a guard ring (PPGR) and a Faraday cup (FC) have been carried out in the plume of the 1.5 kW-class PPS1350-ML Hall thruster fired with xenon in the PIVOINE-2G test bench.

Examination of results, in combination with previous data analysis, enables to provide a list of guidance, recommendations and good practice rules for ion current density measurements in electric thruster plumes. In particular studies reveal a Faraday cup is certainly an appropriate diagnostic tool for ion current acquisition.

This work can be considered as a first step towards the standardization of EP device plume measurements in simulated space environment, an essential phase towards improving the reliability of comparisons between different thrusters and different vacuum chambers and towards furnishing high-quality data for thruster qualification and validation of numerical simulations. Detailed description can be found in the paper IEPC-2017-336[24]

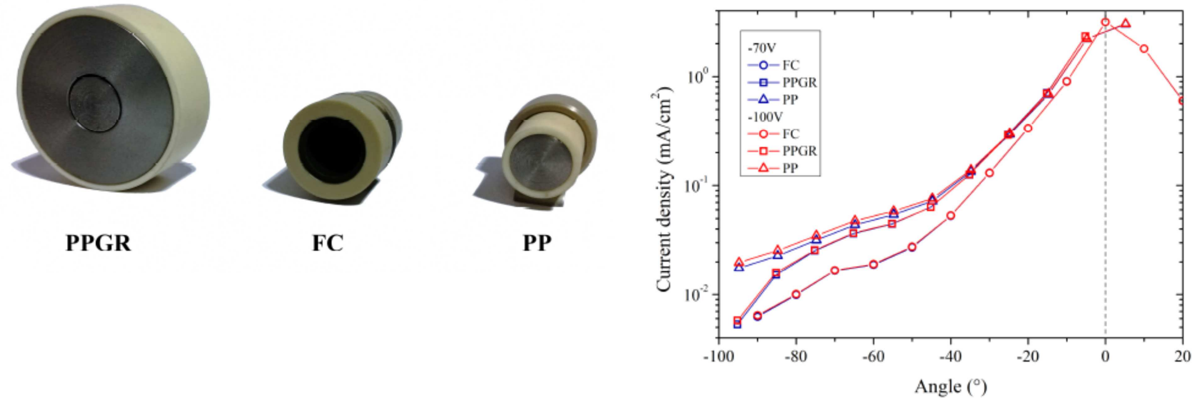


Figure 14. (left) Picture of the 3 electrostatic probes used to measure the ion current in the plume of Hall thrusters : planar probe with a guard ring (PPGR), Faraday cup (FC) and planar probe (PP) ; (right) Angular distribution of the ion current density measured with the 3 probes for two bias voltages in the plume of the PPS 1350-ML thruster (350 V, 4.8 mg/s, 4.08 A).

Secondary electron emission measurement

The energy balance measurement of electron emission at a wall submitted to electron impact at low incident energy is a topic of interest for miscellaneous technological applications and especially for Hall Effect thruster technology. Indeed, electron emission is suspected to have a non-negligible impact on Hall Thruster performance since it has been shown experimentally that changing wall materials could affect strongly the thruster operation. As a consequence, ONERA has created an experimental protocol to obtain reproducible and quantitative electron emission measurements. The measurements have been performed for incident electrons energy between 5 eV and 105 eV and for three specimen materials: silver, graphite and SiO2. These measurements show that wall absorbs more energy at high incident electrons energy and that graphite absorbs more energy than silver, than SiO2. Results are presented for mono-energetic incident electron beam and for a Lambertian energy distribution. Analytical laws fitted from experimental results and applicable for modelling issue are proposed for a Lambertian distribution of incident electrons. Detailed description of the experimental campaign are reported in the paper IEPC-2017-366[25]

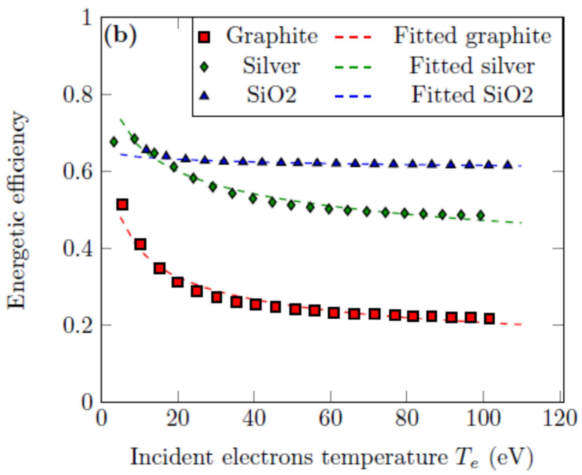


Figure 15. Measurements of Energetic efficiency as function of the incident energy for mono-energetic incident electron energy.

D. Materials and thruster lifetime

Synergic ion/electron erosion on ceramic channel

One limitation of Hall Effect thrusters is the lifetime decrease due to the erosion of the discharge chamber wall. The erosion of the ceramics has been studied since years experimentally and numerically. But these different studies have never taken the possibility of a synergic effect, ie ion/electrons, on the erosion of the thruster. In the frame of an experimental campaign performed at ONERA in the DEESSE vacuum chamber, the synergic erosion effect has been tested on two different materials used in the frame of electric propulsion. The two samples selected are BN-SiO2 M26 and HD-BN. The synergic erosion effect has clearly been demonstrated during this study on material containing oxides such as BN-Si02. No synergic effect has been shown on the HD-BN. As the conditions are representative of the exit plane of a HET thruster, this study clearly show that the presence of the electron current on the walls has to be taken into account to have an accurate assessment of erosion in HET. This study also shows that the synergic effect may be a good candidate to explain the anomalous erosion present on the exit plane of a HET. Nonetheless, more works are needed to quantify this erosion rate. Analysis are presented in the paper IEPC -2017-314[21]

Figure 16. Picture of the sample BN-SiO2 M26 after 35 hours of irradiation.

E. New concepts

Magnetic shielding Thruster activities

Discharge channel erosion is one of the main limiting for the lifetime of Hall thrusters. One of the solutions to reduce this erosion is to use an alternative magnetic field topology called "magnetic shielding". This topology, first studied at the Jet Propulsion Laboratory and at NASA Glenn on high power thrusters (> 5 kW) [26], has been implemented at ICARE laboratory in a small 200 W permanent magnet Hall thruster called the ISCT200-MS.

Comparative studies have been conducted between this thruster and a similarly sized traditional one. The two thrusters have been shown to have similar discharge envelopes. Successful shielding of discharge channel was achieved as no erosion was seen on the walls after more than a hundred hours of firing time. Behavior of the ions in the discharge channel and near the walls was characterized through laser induced fluorescence spectroscopy. The same method was used to investigate the light erosion seen above the magnetic poles[27].

It was shown that to the contrary of traditional thrusters, one with magnetic shielding topology is not sensitive to the properties of the discharge channel material. The ISCT200-MS was fired with a graphite discharge channel and no differences were observed in either the discharge current or the plume behavior compared to BN-SiO2. The unshielded control thruster, on the other hand, saw significant increase in discharge current and plume divergence as well as a modification of the current dynamics[28].

A recent performance measurement campaign has shown that while the standard unshielded 200~W thruster could achieve as high as 40% anode efficiency, the shielded version only reached 25%. A mechanism has been proposed to explain this relatively lower performance of the magnetic shielding not observed in more powerful thrusters. More explanations are discussed in the paper IEPC-2017-172[29].

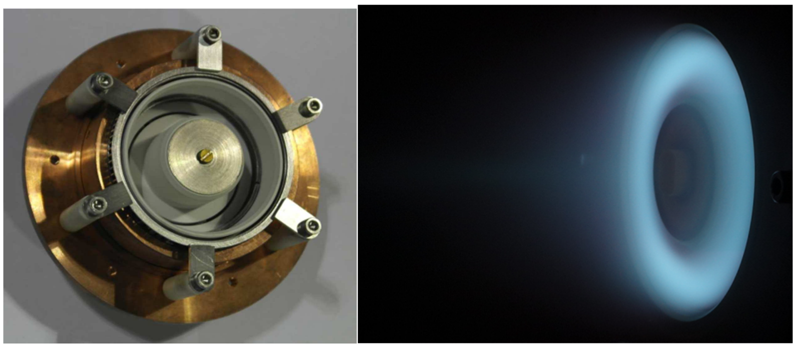


Figure 17. The 200 W magnetically shielded ISCT200-MS thruster on stage and during firing test.

New concept of Double Stage Hall effect Thruster (patent pending)

The ultimate goal of the concept of double-stage Hall thrusters (DSHT) is to decouple ionization and ion acceleration by adding a plasma source, upstream of the magnetic barrier that can be operated independently from the applied dc voltage of the acceleration stage. Although this concept is very promising and should allow wider regimes of operations with several choices of propellant, the numerous attempts at designing double-stage Hall thrusters have met limited success so far. A new design has been proposed by LAPLACE laboratories with the support of CNES, called ID-HALL (patent pending), where the ionization stage is an inductively coupled plasma source which coil is located inside the inner cylinder of the thruster. First results show that the ionization stage is a donut-shaped high density plasma (more than $2x10^{11}$ cm^{-3} for a moderate power of 125 W at pressure on the order of 1 mTorr) area around the central cylinder. The shape and location of this plasma are particularly well-suited for ion extraction through a Hall magnetic barrier. A review of DSHT thruster is presented in the paper IEPC-2017-215[30].

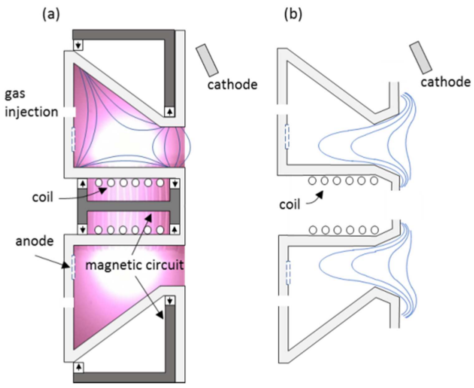


Figure 18. The ID-Hall Double-Stage Hall Truster. (a) version with internal cusps; (b), version with magnetic shielding. An image of the light emitted by the plasma (in argon) is superimposed to the diagram of the DSHT in (a)

VI. Communication and Dissemination

The COMmunities of ExperTs "COMET by CNES" are " knowledge clubs " which aim is to focus on space-based technologies and expertise[31]. Created at the initiative of the CNES in 1998, they allow:

- to promote the opening of Space technologies to other sectors
- to take account of advances in space technologies and other sectors,
- contribute to expertise and innovation ,
- produce and share knowledge,
- identify skills and expertise,
- be a privileged place of dialogue,
- to foster cooperation,

More specifically a COMET on Propulsion & Aerothermodynamics (P&A) has been recently created (July 2016) to share and exchange on the thematic linked to electric propulsion, chemical propulsion and aerothermodynamics.

In the field of electric propulsion, several topics could be addressed through seminars and workshop supported by the COMET Propulsion and Aerothermodynamics :

- µpropulsion for nanosat/cubesat,
- very high power electric propulsion,
- disruptive technologies in electric propulsion,
- low cost electric thruster,
- Interactions plasma thruster – satellites – space environment,
- …

VII. Conclusion

The Countdown of the "all electric" satellites market is on track. This new "paradigm", offered by electric propulsion system, paves the way of future ambitious space missions, demanding important R&T activities. The CNES contribution is wide and covers a large variety of research, developments and applications domains.

VIII. Acknowledgments

The authors would like to thank the CNES Telecom/Navigation project team, the CNES program R&T team and the CNES launcher directorate for our fruitful discussions. CNES thanks also the contribution of the French Research Group GIS "Propulsion à Plasma pour l'Espace", in particular ICARE, LAPLACE, LPP laboratories and ONERA institute and Safran Aircraft Engine and also recent collaborative study with AL-AT.

References

[1] CNES internal report, “Projet : Satellites à propulsion électrique”.

[2] J. Gonzalez del Amo, “ESA activities in electric propulsion”, *33rd International Electric Propulsion Conference*, IEPC-2013-037, 2013 Washington, USA.

[3] CNES internal report on Space Tug.

[4] CNES internal report, “Satellite micro à propulsion électrique”.

[5] F. marchandise, N. Cornu, F. Darnon and D. Estublier, “PPS®1350-G qualification status 10500h”, *30th International Electric Propulsion Conference*, IEPC-2007-164, 2007, Florence, Italy..

[6] M. Prioul *et al*, “PPS®1350-G qualification status and performances”, *4th International Spacecraft Propulsion Conference*, Cagliari, Sardinia, Italy, 2004.

[7] G. Turin, “Hall Effect thruster : the PPS1350 family”, *Electric Propulsion Innovative Competitiveness Workshop*, Bruxelles, Belgium, 2015.

[8] O. Duchemin, S. Zurbach, A. Lorand, A. Caratge and N. Cornu, “The PPS®5000 Hall Effect plasma thruster: development status and mission applications, *33rd International Electric Propulsion Conference*, 2013, Washington, USA.

[9] O. Duchemin, “The PPS®5000 : a new generation 5-kW class Hall”, *Electric Propulsion Innovative Competitiveness Workshop*, Bruxelles, Belgium, 2015.

[10] SAS CHEOPS project’s website : http://www.cheops-h2020.eu/

[11] A. Blanchet, L. Herrero L.Voisin, “2D mapping of vaccum arc thruster plume plasma thruster”, *35th International Electric Propulsion Conference*, IEPC-2017-574, 2017, Atlanta, Georgia, USA.

[12] Thrust Me’s website : http://thrustme.fr/

[13] EXotrail’s website : https://exotrail.com/

[14] ONERA MINOTOR project’s website : http://www.minotor-project.eu/

[15] Y. Fendler, S. Carpentier, P. Barbier, F. Martin, E. Guilbaud and C. Boniface, “Innovative Xenon regulation for electric propulsion”, *35th International Electric Propulsion Conference*, IEPC-2017-202, 2017, Atlanta, Georgia, USA.

[16] G. Sary, L. Garrigues and J.P Boeuf, “Hollow cathode modelling: a first approach to scaling laws”, *33th International Electric Propulsion Conference*, 2015, Kobe, Japan.

[17] R. Joussot, G. Sary, L. Grimaud, L. Garrigues, S. Mazouffre, B. Laurent, S. Oriol, F. Masson and C. Boniface, “Experimental and numerical investigations of a 5 A-class Cathode with a LaB6 Flat Disk emitter in the 2 A -20 A current range”, *35th International Electric Propulsion Conference*, IEPC-2017-486, 2017, Atlanta, Georgia, USA.

[18] A. Rossi, F. Messine, C. Henaux and S. Sanogo, “Parametric optimization of a Hall Effect Thruster magnetic circuit”, *33th International Electric Propulsion Conference*, IEPC-2015-040 2015, Kobe, Japan.

[19] T. Lafleur, S.D. Baalrud and P. Chabert, “Theory for the anomalous electron trasnport in Hall Effect Thursters. I. Insights from particle-in-cell simulations”, *Physics of Plasmas*, **23**, 053502, 2016.

[20] T. Lafleur, S.D. Baalrud and P. Chabert, “Theory for the anomalous electron trasnport in Hall Effect Thursters. II. Kinetic model”, *Physics of Plasmas*, **23**, 053503, 2016.

[21] M. Villemant, P. Sarrailh, L. Garrigues, M. Belhaj and C. Boniface, “Electron emission measurement and modeling for Stationary Plasma Thruster operation”, *35th International Electric Propulsion Conference*, IEPC-2017-366, 2017, Atlanta, Georgia, USA.

[22] B. Vincent, S. Tsikata, S. Mazouffre, T. Minea and J. Fils, *submitted to Review Scientific Instruments*.

[23] B. Vincent, S. Tsikata and S. Mazouffre, “Incoherent Scattering Diagnostic development for Plasma propulsion investigations”, *RSI*

[24] S. Mazouffre, G. Largeau, L. Garrigues, C. Boniface and K. Dannemayer, “Evaluation of various probe designs for measuring the ion current density in a Hall Thurster plume”, *35th International Electric Propulsion Conference*, IEPC-2017-336, 2017, Atlanta, Georgia, USA.

[25] P. Sarrailh, M. Belhaj, V. Inguimbert and C. Boniface, “Synergic erosionceramic by electron and ion simultaneous irradiation of the Hall Thruster Channel Walls”, *35th International Electric Propulsion Conference*, IEPC-2017-314, 2017, Atlanta, Georgia, USA.

[26] I. G. Mikellides, I. Katz, R. R. Hofer, D. M. Goebel, K. de Grys, and A. Mathers, “Magnetic shielding of the channel walls in a Hall plasma accelerator,” *Phys. Plasmas*, vol. 18, no. 3, p. 33501, 2011.

[27] L. Grimaud, J. Vaudolon, S. Mazouffre, and C. Boniface, “Design and characterization of a 200W Hall thruster in "magnetic shielding’’ configuration,” in *52nd AIAA/SAE/ASEE Joint Propulsion Conference*, 2016, pp. 1–17.

[28] L. Grimaud and S. Mazouffre, “Conducting wall Hall thrusters in magnetic shielding and standard configurations,” *J. Appl. Phys.*, vol. 122, no. 3, p. 33305, Jul. 2017.

[29] L. Grimaud, S. Mazouffre, and C. Boniface, “Performance comparison between standard and magnetically shielded 200 W Hall thrusters with BN-SiO2 and graphite channel walls,” in *35th International Electric Propulsion Conference*, IEPC-2017-172 2017, Atlanta, Georgia, USA

[30] L. Dubois, F. Gaboriau, L. Liard, D. Harribey, C. Henaux, J.P. Boeuf, S. Mazouffre and C. Boniface, "Ion acceleration through a magnetic barrier : Toward an optimized double-stage Hall thruster concept", *35th International Electric Propulsion Conference*, IEPC-2017-215, 2017, Atlanta, Georgia, USA.
[31] COMET's website : http://cct.cnes.fr/