Overview of Electric Propulsion Activities in France

IEPC-2005-162

Presented at the 29th International Electric Propulsion Conference, Princeton University,
October 31 – November 4, 2005

Franck Darnon*, Denis Arrat†, Enrico Chesta‡, Stéphane d'Escrivan§ and Nicolas Pillet**
Centre National d'Etudes Spatiales, 18 av. E. Belin ,31401 Toulouse, France

This paper reports the Electric Propulsion activities performed in France. This mainly concerns research on Hall Effect Thruster (HET) physics, the development of thrusters up to a power of 5 kW and flight applications. Since 2003, some major achievements have been obtained with the flight validation of the PPS-1350-G thruster on board the ESA SMART-1 lunar probe and the first in orbit utilization of Electric propulsion modules on board European telecommunication satellites.

I. Introduction

ELECTRIC propulsion has been investigated in France since more than 30 years. In the 70s, FEEP thrusters and mercury ion bombardment thrusters were evaluated at SNECMA (formerly SEP). In the late 80s a wide review of applications and technologies was conducted which resulted in 1991 by the settlement by SNECMA of a cooperative program with Russian teams focussed on Hall effect technology. In 1994, this initiative received a support from the national space agency CNES, resulting in the STENTOR program which purpose was to develop and qualify a Hall thruster and its associated equipments (tank and gimbals mechanism) and to offer a flight opportunity on the STENTOR technological geostationary satellite. The thruster developments were carried out in partnership with Russian teams and with the support a Research program involving scientific labs. This results in a ground qualified Electric propulsion module suited for geostationary satellites. After the loss of the 2 first applications due to launcher failures (STENTOR and the Alcatel built ASTRA-1K satellite), the flight validation was finally achieved through other spacecrafts : in a first time for the thruster on board the ESA SMART-1 lunar probe, then in a second time for the whole propulsion module on board several EADS Astrium built geostationary telecommunication satellites. Beside the analysis of flight data, the current activities are oriented toward technology improvements, new thruster developments, still supported by a strong research program. Other flight applications are also being addressed, for large geostationary bus (@bus program) and also for scientific applications, such as the MICROSCOPE program.

* Propulsion Engineer, Franck.Darnon@cnes.fr
† Head of pyrotechnics and spacecraft propulsion section, Denis Arrat@cnes.fr
‡ Propulsion Engineer, Enrico.Chesta@cnes.fr
§ Propulsion Engineer, Stephane.d-Escrivan@cnes.fr
** Propulsion Engineer, Nicolas.Pillet@cnes.fr

II. Research activities

A. Research Group on Electric Propulsion

Hall Effect Thrusters (HET) have been studied in the frame of a Research Group on Plasma Propulsion involving several organisations: CNRS/CNES/SNECMA/Universities since 1996[1,2]. These research activities are currently focussed on three main topics: 1.electron transport; 2. ceramics erosion; 3.predictivity of codes. Some recently obtained results are reported hereafter.

1. Experimental characterizations of HET

Most of the experimental activities are performed in the "Pivoine" test facility located in Orléans, which is dedicated to scientific experiments. In 2006, this facility will be upgraded for testing electric thrusters with a larger power and/or flow rate (typically above 20 mg/s).

The experimental characterisations have been performed on thrusters in the class of 1 to 5 kW as well as on a double stage device and an ATON type thruster. As an example, the following diagnostics have been recently implemented :

- Xe ion velocity at the thruster exhaust using Fabry-Pérot interferometry. The respective ratio of potential drop occurring inside and outside the thrusters channel is evaluated as a function of thruster parameters[3].
- High frequency instabilities (in the 1-10MHz range), using dedicated antennas introduced around the thruster discharge channel. Such instabilities are non linearly coupled with electrostatic waves propagating azimuthally. Spatio-temporal properties near the channel exit, axial propagation phenomena and thruster scale impacts have been analysed[4].
- Infrared thermography. Measurements are performed either during thruster ignition or for stationary thermal state for various operating power. Time-resolved acquisition give valuable information about the way and where the energy is released on the discharge chamber.[5]
- Ceramics erosion diagnostic using Optical Emission Spectroscopy. Optical lines emitted by the xenon plasma (Xe and Xe+) and by the BN-SiO_2 ceramic (B and Si) are used in conjunction with coronal model and actinometric hypothesis in order to obtain the relative (semi-quantitative) ceramic sputtering density[6].
- Other experiments are in progress, such as the time resolved Laser Induced Fluorescence for the neutral and ion velocity measurement. This powerful diagnostic has already been validated on lower scale thruster and facility.

2. Numerical assessments

Two laboratories are working on the simulation of the plasma inside and outside the thruster, using particular and hybrid methods. The most recent achievements obtained with these models make them of primary interest either for understanding the plasma behaviour peculiarities, (for experimental result analyses and for thruster optimisation) and for performance prediction.

As an example, the particular model is used to evaluate the conditions for apparition of micro instabilities and their contribution to the electron conduction across the B field. On another hand, the hybrid model is reproducing with a good agreement the plasma parameters inside the discharge channel and the thruster performances[8], at least for classical thruster operations. In that case, the model has shown that the role of ceramics walls in the electron conductivity is probably not significant inside the discharge channel.

B. International cooperation

The research group on propulsion is cooperating with international partners, mainly in Poland (IPPT institute), and with Russian and Ukrainian partners in the frame of INTAS programs. 2 projects are conducted together with 8 Russian and Ukrainian teams to address several electric propulsion concerns, related to the high voltage thruster operation peculiarities[7] (performances, drawbacks, physics of the discharge, optimized design for high voltage,…) and to the ceramics erosion (design and test of upgraded ceramics for increased thruster life capabilities).

III. Technological activities

C. Transverse technologies for Hall thrusters

A technological program is ongoing with SNECMA Moteurs with the general aim of improving plasma propulsion performances. Various axis are under investigation for the development of transverse technologies and the evaluation of new thrusters. This includes, as examples : methods for life test acceleration, alternative propellants, alternative cathodes, new ceramics, permanent magnets, new magnetic circuit alloys, new anode design and manufacturing process, improved thermal design, high-reliability electrical connections, and others. A technological demonstrator in the 1-2 kW power range, based on a modular and flexible design and capable of testing most of these technologies is designed and will be manufactured and tested in a short future.

In the frame of an ESA program, SNECMA Moteurs is also evaluating (by test) some thruster design modification for giving the thruster a thrust angle steering capability. Preliminary results are very encouraging.

D. Double stage Hall thruster

Beside transverse technology developments, some new thruster concepts are under evaluation by SNECMA Moteurs, such as a double stage Hall Effect thruster which has been designed in cooperation with MIREA Institute in Russia. The purpose is to get a thruster with a very flexible operating point together with improved performances in term of divergence and efficiency. The design is presented in[8]. The thruster have been extensively tested in “Pivoine” facility, and compared with the performances measured in Russia. The analysis is on going, using numerical tools for simulating the plasma properties as shown figure 1.

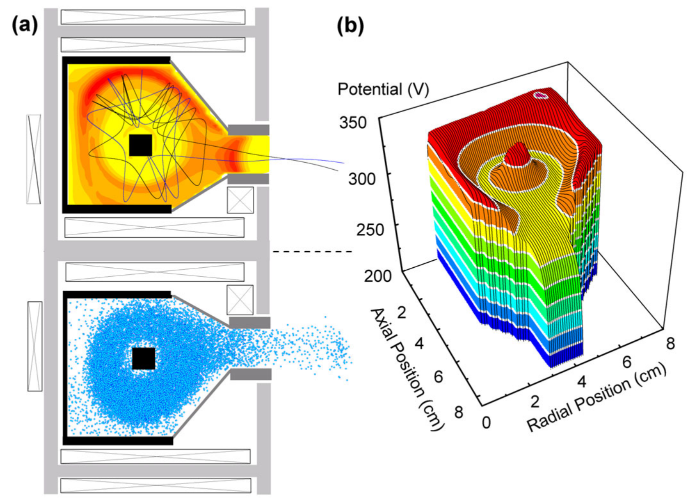

Figure 1. Numerical simulation of a double-stage plasma thruster (left: ionization rate (top) and ion location (bottom) ; right: potential)[8]

E. Pulsed Plasma Thruster evaluation

An activity dedicated to Ablative Pulsed Plasma Thruster study and development is ongoing with Russian partners (RIAME and Kurchatov institutes). An APPT thruster, typically in the 10 J to 100 J range, is going to be designed, manufactured and tested. Some characterizations of existing devices (before optimization) indicate promising characteristics as reported figure 2. The purpose is to evaluate the potential of this technology for applications on small platforms, such as the de-orbiting of a micro satellite[9].

Energy (J)	30
MIB (mNs)	1.0
Specific impulse (s)	1150
Frequency (Hz)	2
Thrust (mN) @2Hz	2
Power (W) @ 2Hz	60
Mass (Thruster + PPU) (kg)	7 (without Teflon)
Total Impulse (kN.s)	> 20 (≈1.7 kg Teflon)
Size of the thruster, mm (HxLxD)	100x160x160
Size of the PPU, mm (HxLxD)	< 55x80x160

Figure 2. 30J APPT Performances (RIAME)[9]

IV. Industrial developments

F. High pressure Xenon tank

High pressure tanks are developed by EADS-ST for the storage and distribution of Xenon[10]. The high pressure tank is made of a titanium liner over wrapped with carbon fibers. In order to optimize the sizing of the high pressure vessels, a demonstration of the LBB (Leak Before Burst) capacity is now required. The LBB test was recently successfully performed on a 70 liter tank, with a diameter of 338mm and a weight of 10Kg. The Maximum Expected Operating pressure is 19MPa. The minimum burst pressure is 28,5MPa.

G. PPS-1350 Thruster

The PPS-1350 thruster has been initially developed and qualified in the frame of the STENTOR program. Then, a derived version of thruster : PPS-1350-G has been designed by SNECMA Moteurs in order to be specially suited for geostationary telecommunication satellite applications, i.e. with a large total impulse capability, a reduced production cost and an improve mechanical behavior[11,12]. The qualification of this thruster is currently in progress[13]. After environmental tests successfully performed, the thruster is now running a highly cycled life test (7500 h achieved in Sept. 2005) coupled to a flight representative PPU.

The thruster reference characteristics and performances are:

Thrust	90 mN
Specific impulse	1700 s
Discharge power	1500 W
Discharge voltage	350 V
Divergence (90%)	< 42 °

Life time > 9000 h, expected to exceed 11500 h.

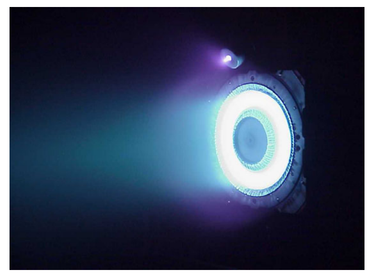

Figure 3. PPS-1350-G thruster in operation

Beside the ground qualification, almost 5000h of operation in orbit have been performed on the PPS-1350-G thrusting SMART-1 lunar probe. This demonstrates a high level of reliability, and prove the capability of this thruster to maintain good performances over a very long operating time and for various operating conditions (in Power). Consequently, the thruster is a very good candidate for a wide range of applications, from telecommunication spacecrafts to scientific probes.

H. PPS 5000 Thruster

The growth in mass and power of geostationary telecommunication satellites, associated to an extension of the electric propulsion utilization field like orbit raising, require new thrusters with improved performances. The main requirements are: a higher total impulse, a high specific impulse operating mode (driven by the on station needs) and a high thrust operating mode to perform an efficient orbit transfer. To face these new requirements, a high power Hall effect thruster (PPS-5000) is under development by SMECMA Moteurs. In order to validate the new technologies and the thruster configuration, two thruster demonstrators, "PPS-X000" have been designed, manufactured and tested in QinetiQ (UK) and Pivoine (F) facilities up to a power of 6 kW and a discharge voltage of 1000 V[14]. These demonstrators are designed to allow an easy change in geometric and magnetic configurations. The purpose is to characterize the thruster, to determine the optimized configuration and operating point, as well as to validate the new technologies. Following an extensive

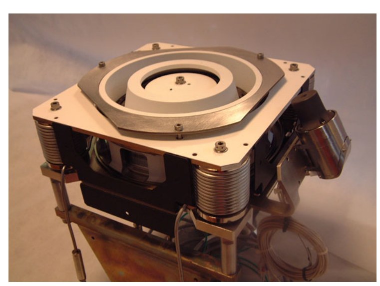

Figure 4. PPS-X000 technological demonstrator

thruster characterization, two preliminary life tests have been performed, including one lasting more than 1000h with a single thruster configuration and operating point[15]. Then, based on PPS-X000 demonstrator test results, a "flight version" has been derived: the PPS-5000, whose design is fully based on SNECMA Moteurs's patent and will be a fully independent European Design and Product. The PPS-5000 design has been reviewed and confirmed during a PDR which took place in dec. 2004 with the involvement of CNES, ESA and European Primes. In parallel, a high power processing unit (HPPU) development is in progress at Alcatel-ETCA (Belgium). The power processing unit anode module has been already tested end 2004 coupled to the thruster with successful results.

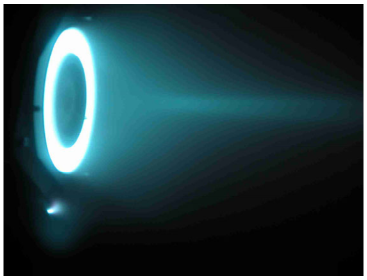

Figure 5. PPS-X000 technological demonstrator in operation

V. Flight applications

I. In support to flight applications : Plume effects assessments

A general program is conducted to evaluate the interactions between the plume ejected by a Hall Effect thruster and a spacecraft[16]**.** The different steps of this program are the following:

- Plume modeling, performed with dedicated numerical tools and validated with flight results (e.g. the data recorded on SMART-1).

- Plume/surface interactions evaluation: dedicated experiments are performed at ONERA[17]**.** The purpose is to evaluate the sputtering yield of various materials impinged by Xenon ions, the characteristics of sputtering product (direction of re-emission, composition for organic materials,…) and the effect of erosion and contamination on the material properties.

In parallel, a study dedicated to micro-propulsion (FEEP) plume effects evaluation is ongoing in collaboration with ONERA. In this case, the variation of physical parameters (electrical conductivity and optical properties) of sensitive spacecraft components (solar cells, thermal covers and paints), caused by the contamination (controlled deposition) of specific propellants (like cesium) will be characterized and analyzed.

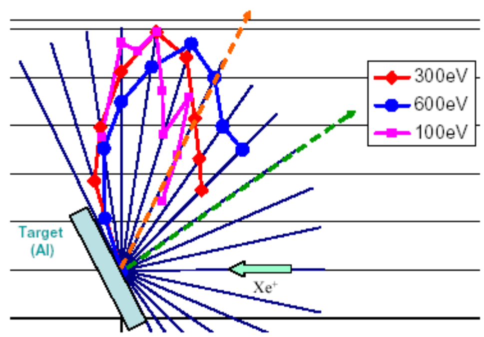

Figure 6. Example of an emission profile of Aluminum sputtered by a Xenon ion flux[17]

J. Current Geostationary telecommunication satellite

In order to improve the competitiveness of the French primes in the field of telecommunication satellites, the technological satellite STENTOR has been developed, including various technological innovations, such as the utilization of electric propulsion for orbit control. In this frame, an Electric propulsion module (including SPT-100 and PPS-1350 thrusters, electric supplies, gimbals mechanism and fluidic equipments) has been developed and ground qualified[23]. After the loss of the STENTOR satellite due to a launcher failure in December 2002, the flight validation of the electric propulsion module has been finally obtained on board commercial telecommunication satellites which are using modules directly derived from the STENTOR one, except the thrusters which are replaced by Russian SPT-100. Two EADS-Astrium built telecommunication satellites (INTELSAT-10-02 and INMARSAT-4F1) are currently using electric propulsion for orbit control since June 2004. Some others are to be launched in the coming months. All the equipment are operating satisfactorily[18].

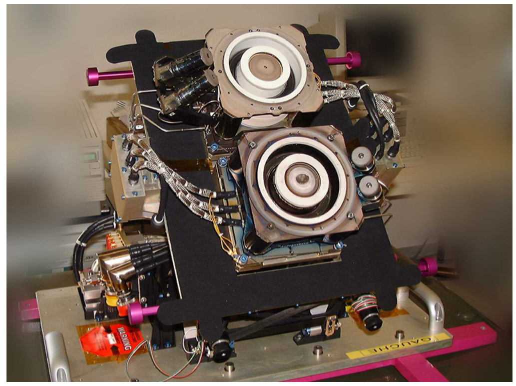

Figure 7. STENTOR electric propulsion module made of one SPT-100 and one PPS-1350 thrusters mounted on an ALCATEL gimbals mechanism.

K. Future Geostationary telecommunication satellite

Alcatel Alenia Space and EADS-Astrium are jointly developing the next European generation of large platform for telecommunication satellites. In a first step, the payload accommodation capability will extend from 12 to 18 kW corresponding to 800 kg to 2000 kg payload mass. Built in growth potential to accommodate market evolutions and availability of improved technologies will be considered from the beginning to allow payload up to 25 kW. This satellite range requires an extensive use of electric propulsion including for station acquisition. Electric propulsion is one of the key element for the satellite payload capacity performances.

Different electric thrusters are considered for @bus. The baseline electric propulsion module is the direct heritage from STENTOR design and is based on the PPS-1350-G thruster. In order to cope with the upper range of the satellite bus, new thrusters offering a large total impulse capability (i.e. a large power) may be subsequently implemented.

L. SMART-1

Since 2003, an electric propulsion sub system developed by SNECMA Moteur and based on a PPS1350-G thruster is used on board the ESA *SMART1* mission[19]. The thruster is used for primary propulsion of the probe to reach a lunar orbit. Due to mission constraints, the thruster is used in different operating conditions of electric power and operating points as reported figure 9, and generally for long duration burns (up to 240 h). Almost 5000 h of operation have been cumulated on one single thruster in orbit, demonstrating the reliability and in-orbit performances of the PPS-1350-G thruster[13]. On SMART-1, a diagnostic package is implemented to measure ion energy distribution and plasma potential in the plume backflow. A lot of valuable experience has been gained thanks to this technological program, such as the verification of flight behavior and performances of the thruster in comparison with tests in ground conditions. As an example, the discharge current oscillations are found much lower than those measured during ground life testing. Moreover, this mission allows a better understanding on the electrical coupling between the thruster, the plume, the spacecraft and the environment, resulting, for instance in a positive cathode reference potential compared to spacecraft electrical ground.

Figure 8. SMART-1 PPS-1350 thruster in operation on the spacecraft during end-to-end tests[19]

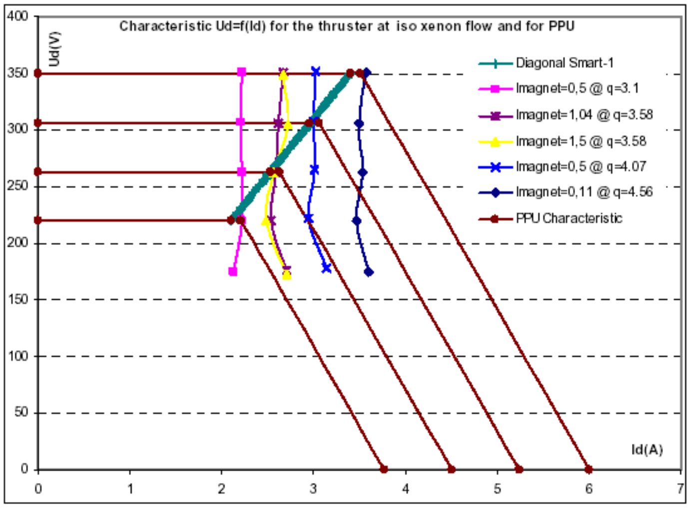

Figure 9. SMART-1 : PPS-1350 Operating points[19]

M. MICROSCOPE

"MICROSCOPE" project is performed in cooperation with ONERA and ESA. The principal scientific objective of this mission is to test the Equivalence Principle with an accuracy of 10^{-15}, that is almost three orders of magnitude more than what has been achieved so far on Earth. The mission will also provide an opportunity to space qualify the technology required for high-accuracy drag compensation and 6 DoF continuous control. The µScope drag-free and attitude control system is based on the technology of capacitive inertial sensors, designed for this mission as cylindrical differential accelerometers, and on electric field-emission slit geometry proportional thrusters. The Electric Propulsion System[20] is being developed and qualified by ALTA (I) under ESA contract, and will be based on four assemblies including three thruster units, two neutralizers and a PPCU (provided by Galileo Avionica). The performance requirements of the propulsion system are driven by the stringent needs of the attitude and acceleration control system (SCAA), which is being designed to provide external perturbation shielding and instrument fine calibration capability[21].

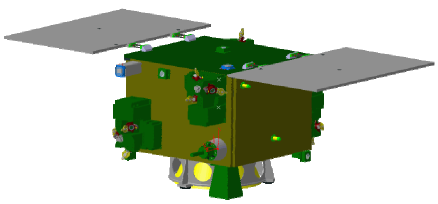

Figure 10. MICROSCOPE Spacecraft – Beginning of Phase B Configuration

The main technical specifications can be summarized as follows:

Thrust range	1 to 150 µN	command updating freq: 4Hz
Total Impulse	3100 Ns	in-orbit life: 1 year
Thrust resolution	0.1 µN	for T< 100 µN
Response time	<100ms	1 µN step
Thrust noise – Log (PSD)	<0.01 $\mu N^2/Hz$ <0.01•(0.1/f) $\mu N^2/Hz$	for 0.1 Hz < f < 1 Hz for 0.0001 Hz < f < 0.1 Hz
Beam divergence	< 15° < 40°	on slit plane perpendicular to slit plane

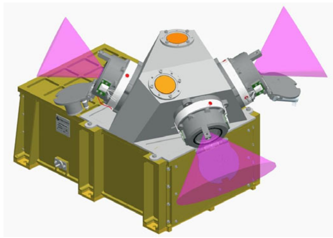

Figure 11. Electric Propulsion Subsystem Assembly – pre-PDR design

MICROSCOPE launch is currently scheduled in late 2008.

N. Other Electric Propulsion applications

3. VENµS

VENµS is a micro satellite (200 kg class) developed in the frame of a partnership between France and Israel. A technological payload provided by Israel Partners will consist in flying law power Hall effect thrusters for performing low earth orbit transfer and maintenance. This program is currently in phase B for a launch date expected end 2008.

4. Phase 0/A studies

Various pre-projects are currently under evaluation by CNES and by satellite Primes. In 2005, different studies have been performed resulting in using a formation flying concept for science applications[22]. Among other options, the FEEP propulsion option seems to be good candidate for missions requiring a fine mutual spacecraft positioning, like the PEGASE mission.

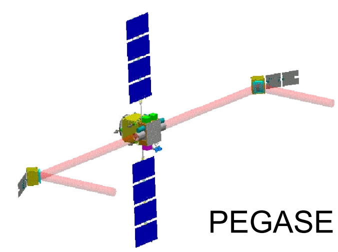

Figure 12. PEGASE mission schematic drawing

VI. Conclusion

A wide range of activities are currently performed in France on Electric Propulsion. The research group studying Hall thruster physics as provided meaningful insights on the plasma behavior, such as for instance what concerns electron conductivity. New technologies and thruster configurations are under evaluation in preparation for the next generations of Hall thrusters, in the multi kilowatt power range.

Different satellite programs using electric propulsion are running. The most significant are the MICROSCOPE program using FEEP thrusters for drag free control of a micro satellite and the @BUS program for the orbit control of very large geostationary telecommunication satellites.

Since the previous IEPC conference[1], the most significant achievements obtained in France are the first utilizations of Hall thrusters in orbit. In parallel to the ground qualification of the PPS-1350-G thruster which is almost completed, the thruster has been operated in orbit on the ESA SMART-1 probe over a very long cumulative time of 5000h. On two European commercial satellites, Electric propulsion (based on SPT-100 thrusters) is also currently used for performing the orbit control. On each spacecraft, the electric thrusters and associated equipments are operating successfully[18].

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