

AN OVERVIEW OF THE CNES ELECTRIC PROPULSION PROGRAM

Anne Cadiou, Franck Darnon, Laurent Jolivet
CNES

18 Avenue Edouard Belin
31401 TOULOUSE CEDEX 4
phone 33 5 61 28 26 32 fax 33 5 61 28 29 92
email anne.cadiou@cnes.fr

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This paper presents an overview of the CNES electric propulsion activities. The main existing and future projects are described. The field of application of electric propulsion is the station keeping and the orbit raising of geostationary telecommunication satellites (EUROSTAR,SPACEBUS, @BUS) and the fine attitude control for specific microsattellites (Microscope).

The preparation of the future with the associated Research and Technology program is described.

The future developments are mainly dedicated to the electric propulsion for large telecommunications satellites which leads to the development of thrusters with higher thrust (orbit raising) and higher specific impulse (North/South orbit control) than those existing today. Works are also performed to improve and validate the tools necessary to evaluate the plume effects of electric thrusters.

The scientific activity supporting the development of Hall thrusters is going on in the frame of the GDR (Groupement de Recherche) CNRS/CNES/SNECMA/ONERA on Plasma Propulsion.

Introduction

The main CNES projects that require an electrical propulsion sub-system to control the attitude and the orbit of the vehicle are the telecommunication geostationary satellite STENTOR, the future large platform @BUS and the microsatellite MICROSCOPE for scientific missions.

For the preparation of the future projects a Research and Technology program is updated every year. Its main axis are the following : scientific activities to improve our knowledge of Hall effect thrusters, the development of plasma thrusters with higher thrust and higher specific impulse than those existing today and the plume effect evaluation.

These different R & T activities are described in detail after a presentation of the projects.

Projects

Telecommunications

STENTOR

The first in flight validation of the use of plasma propulsion for the North/South control of an occidental geostationary telecommunication satellite was planned on STENTOR, a French Technological Telecommunication Satellite of 2210 kg of launching mass and 2,5 kW of electric power.

Unfortunately, this satellite was destroyed the 11th of December because of the Ariane 5 failure.



Figure 1 : STENTOR on Ariane 5 Adaptator

The STENTOR program was designed to improve the competitiveness of French industry in the highly competitive area of telecommunication satellites.

The program was led by a joint committee representing France Telecom, CNES and the General Delegation for Armaments (DGA - *Délégation Générale pour l'Armement*). The State project team (France Telecom, CNES and the DGA) was in charge of all technical and financial aspects, with CNES as project manager.

An integrated industrial project team bringing together Astrium and Alcatel Space Industry acted as joint prime contractor, under the authority of an industrial steering committee.

A SPT100 manufactured by Fakel and a PPS[®]1350 (figure 2) by SNECMA, was set on a Thruster Orientation Mechanism manufactured by Alcatel.

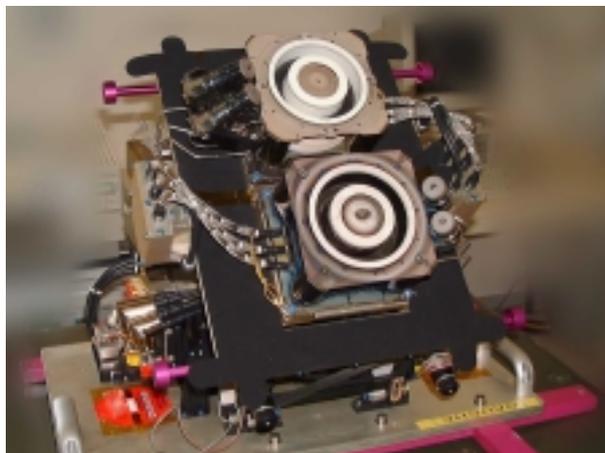


Figure 2 : SPT100 and PPS[®]1350 on the TOM

The PPS[®] 1350 has been qualified for STENTOR lifetime with margins (3500 hours of operation).

For large telecommunication satellites (EUROSTAR and SPACEBUS platforms) a new version of the thruster, called PPS[®]1350-G has been designed and manufactured with the objective to reduce the manufacturing cost of the thruster. The environmental qualification of this thruster has been performed and its lifetime is in progress with an objective of 11000 hours.

Thrust (BOL)	>85 mN	nominal point	88 mN
Thrust (EOL)	>83 mN		
Specific impulse (BOL)	1650 s	nominal point	1720 s
Specific impulse (EOL)	1570 s		
Discharge power	1500 W		
Discharge voltage	350 V		
Discharge current	4.28 A		
Divergence (90%)	< 42 °		
Total Impulse	qualification requirement including 50% of margin $3,5 \cdot 10^6$ Ns 9127 cycles		

Table 5- Qualification random vibrations

20-70 Hz	+6 dB/Oct
70-165 Hz	1.0 g ² /Hz
165-175 Hz	-104 dB/Oct
175-300 Hz	0.13 g ² /Hz
300-560 Hz	-9 dB/Oct
560-2000 Hz	0.02 g ² /Hz
2 oct/min	

Table 6- Qualification sinus vibrations

5-29.5 Hz	10 mm
29.5-100 Hz	35 g
3 min. per axis	

Table 7- Qualification shock

//		⊥	
500 Hz	150 g	500 Hz	140 g
700 Hz	210 g	1400 Hz	700 g
4200 Hz	2000 g	4000 Hz	3000 g
10000 Hz	2000 g	10000 Hz	3000 g

The PPS[®] 1350-G will also be used on the ESA mission SMART1 to reach the moon. This satellite will be ready for launch as an Ariane 5 auxiliary payload in April 2003.

In addition to the ISTI qualification, a SPT 100 connected to a PPU from ETCA and to a mechanical pressure regulator from Muspace has also performed a life test at SNECMA after an environmental qualification (6900 hours).

The STENTOR programme allowed the ground qualification of a complete plasma propulsion sub-system [1] including, in addition to the previously mentioned pieces of equipment, a wound carbon/titanium liner tank from EADS-LV and a Power Processing Unit from ETCA.

But, with the launch failure, there will be a lack of in-orbit data on the interactions between the plasma ejected from the thruster and the satellite. These interactions are difficult to evaluate in ground test facilities because of the pressure and of the interactions with the vacuum chamber.

@BUS

Alcatel Space Industry and Astrium are jointly developing the next generation of large platform for telecommunications satellites. In a first step, the payload accommodation capability will extend from 12 to 20 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 electrical propulsion including for station acquisition. Electrical engines are then a key element for the satellite payload capacity performances.

Thrusters performances required to cover such a satellite, especially in term of total impulse, correspond to a power range extending typically from 3 to 5 kW.

This requirements are beyond the European equipment suppliers present capabilities. Consequently, some activities have been initiated in Europe to develop gridded-ion and Hall-effect engines meeting these requirements.

Microsatellites

In 1996 CNES decided to develop another product line for microsatellites mainly dedicated to scientific missions and technological demonstrations. The objectives of this product line are to offer frequent flight opportunities with a low cost.

Propulsion is not required for all the microsatellites. Nowadays 2 missions requiring hydrazine propulsion have been decided, DEMETER and PARASOL and one mission requiring electric propulsion, MICROSCOPE.

Microscope (MICROSatellite à traînée Compensée pour l'Observation du Principe d'Equivalence) is the fourth CNES project based on the Microsatellites line of products. The project is presently in phase A. Microscope will be a three-axis 170 kg stabilized spacecraft compatible with a low cost launch like ASAP ARIANE V and will be launched into a near-polar, quasi circular orbit at about 700 km altitude. Microscope is a space fundamental physics mission proposed by ONERA and CERGA institutes whose aims at testing the Equivalence Principle expressed by Einstein in 1911 to a high level of precision, namely 10^{-15} . This level represents a gain of 2 to 3 orders of magnitude compared to what exists presently on the earth and an instrument composed of two differential accelerometers will be used for the measurement. For such accurate experiment, it is necessary to actively control the attitude as well as the atmospheric and thermal drag in such a way that the satellite follows the test masses of the accelerometers in their pure gravitational motion. In order to obtain such a control, Microscope needs a propulsion system able to provide thrusts in the 1 to 150 micronewtons range with a near instantaneous switch on/switch off capability and a high-resolution throttleability. Field Emission Electric Propulsion (FEEP) technology is particularly suited to obtain such features. ESA, which is involved in the development of this technology for many years, collaborates to the project by providing the Field Emission Electric Propulsion (FEEP) thrusters and the associated hardware.

Four clusters of thrusters will be implemented on Microscope for a total of 8 or 12 FEEP thrusters, depending on the final choice for the configuration. These clusters are located at four corners of the satellite as shown in figure 5. That will be the first time that the FEEP technology will be used in flight as a propulsion system and the thrusters have to be able to operate during one year in a continuous mode.

Consequently, there is no feedback from previous flights concerning the plume effects on the spacecraft and the eventual damaging effects that could appear before the end of the mission due to the intensive use of the thrusters. Therefore, CNES has started a study on the sputtering, contamination and electrical effects at the spacecraft level in view to estimate the impacts of such effects on Microscope over the mission life. First results are presented in [2].

The launch of Microscope is expected in 2006.

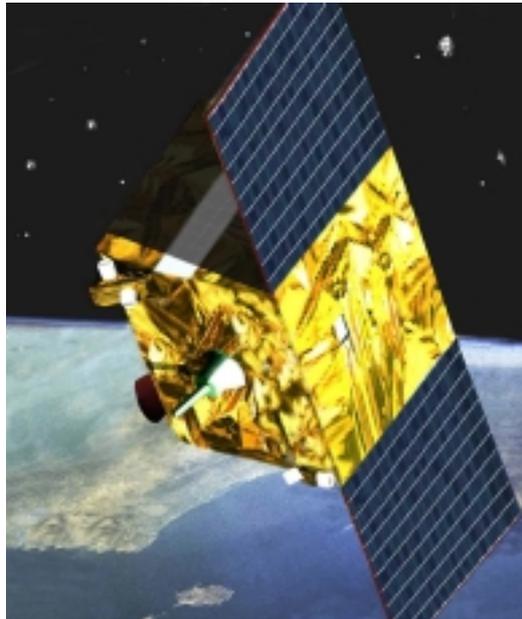


Figure 3: schematic view of Microscope. The Electric Propulsion Subsystem Assemblies (EPSA) are located at the corners

Research and Technology Program

The main activities in electric propulsion are the scientific works on Hall effect thrusters including improvements in our knowledge of the physical phenomena involved in these thrusters but also the modifications to improve their performances such as specific impulse, the studies on a high power thruster PPS[®]X000 and the plume effects evaluation.

Scientific activities

Scientific activities performed in 2002, in the frame of the Research Group (GDR 2232 “Plasma Propulsion for Space Systems”) CNRS/CNES/SNECMA/ONERA, have been mainly focussed on :

- the high frequency instabilities and their relationship with the electron mobility,
- the influence of the Xenon distribution on the thruster operation,
- the interaction between the cathode and the main discharge,
- the study of different magnetic circuits including permanent magnet
- time resolved measurements of Xenon ions velocity with Laser Induced Fluorescence technique,
- study of a method to measure the temperature of neutral Xenon atoms inside a SPT using a Fabry-Pérot interferometer [3]. First measurements of Xe* spectrum has been performed at the outlet of the thruster,
- study of the influence of the ceramic temperature on the secondary electron emission [4],
- systematic use of the 2D hybrid model to compare with experimental results,
- improvements in the Collisional-Radiative Modeling [5],
- design and manufacture of a laboratory model of high thrust thruster.

High frequency instabilities and their relationship with the electron mobility [6] [7]

Instabilities in the 5-10MHz range have been measured on the electron Hall current of the SPT100ML. In order to understand the physics associated to these instabilities, 2 wide band antennas have been set on the external ceramic of the discharge chamber. A detailed comparison between the signal of these 2 antennas revealed some space-time features of these instabilities such as propagation azimuthal velocity, close to the expected electron drift velocity.

The 2D PIC models of the discharge show that high frequency instabilities appear close to the discharge channel exit and have a strong impact on the longitudinal electron mobility.

Complementary experiments are prepared in order to verify that the high frequency instabilities measured experimentally and calculated correspond to the same physical phenomena.

Influence of the Xenon distribution on the thruster operation [8]

In order to study the influence of the Xenon distribution on the thruster operation, a new distributor with different configurations of injection has been designed and manufactured.

The Xenon density without plasma has been measured with an electron gun for these different configurations.

Tests with the plasma are in progress in order to find correlations between the thruster performances and the injection characteristics.

In parallel to this experimental activity, modeling with the 2D hybrid model is performed.

Interaction between the cathode and the main discharge [9]

Different hollow cathodes from the MIREA (Moscow Institute of Radioelectronics and Automatics), KhAI (Kharkov Aviation Institute) and Laben Proel have been tested on the SPT100 ML. The influence of the cathode mass flow-rate, anode mass flow-rate, discharge voltage and of the heating current (MIREA cathode) have been studied.

The influence of the cathode position with respect to the magnetic field lines is one axis of investigation in the future.

Study of different magnetic circuits including permanent magnet [10]

The replacement of coils by permanent magnets (SmCo) has been studied in order to simplify the design, to reduce the mass and the electrical power consumed of Hall effect thrusters. This modification of the magnetic circuit has been implemented and tested on the SPT100ML. The performances obtained with permanent magnets are slightly lower than those obtained with coils but with a magnetic field that is also slightly different. A reduction in the discharge current oscillations has also been observed.

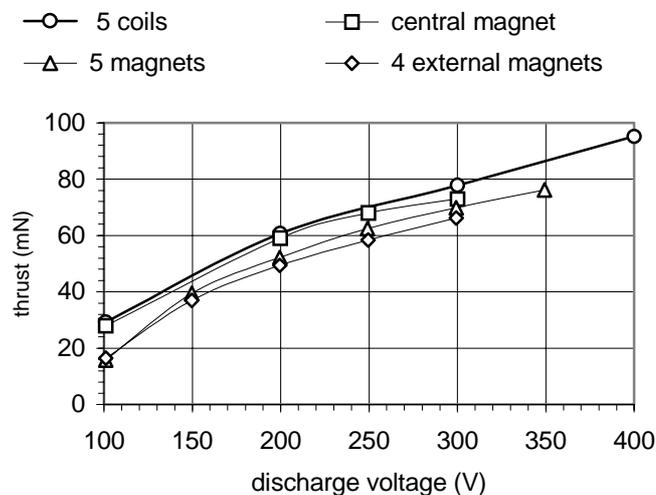


Figure 4 : Thrust as a function of discharge voltage for different magnetic configurations

A complementary program with a better optimisation of the magnets and a technological validation of the magnets is in progress.

Time resolved measurements of Xenon ions velocity with Laser Induced Fluorescence technique

2002 has been mainly dedicated to the comparison of 2 different methods to measure the ion velocity fluctuations during the discharge current oscillations :

- a “boxcar” method with a wavelength scanning for a fixed time,
- a “multichannel” method with a simultaneous acquisition of 256 channels of 1µs for a fixed wavelength.

In order to have a precise synchronisation of the SPT oscillations, a fast interruption of the discharge current was used.

Tests on the SPT50 at ONERA have demonstrated that both methods allow the measurement of the ion velocity fluctuations with a time resolution of 1 μ s. The next step will be the use of these systems on the SPT100ML in PIVOINE.

Systematic use of the 2D hybrid model to compare with experimental results [11]

The two-dimensional hybrid model of the discharge (particle method for the ions and neutrals, electrons considered as a fluid) that has been developed previously is now in a phase of intensive use in order to perform systematic comparisons between experiment and modeling. These comparisons are performed on different thrusters with different magnetic fields.

The model is semi-empirical because the electron mobility inside and outside the thruster which is difficult to quantify, can be adjusted. An electron-wall collision frequency proportional to a constant coefficient is added to the electron-atom collision frequency inside the channel. Outside the channel, electron transport is supposed proportional to the Bohm diffusion. An electron energy loss is also added to the losses due to electron-atom collisions.

The use of the model for the SPT100ML and another thruster having a different magnetic field topology (ATON) has shown that the performances and the ceramic erosion rate could be well predicted.

An example of results obtained with the hybrid model is represented below.

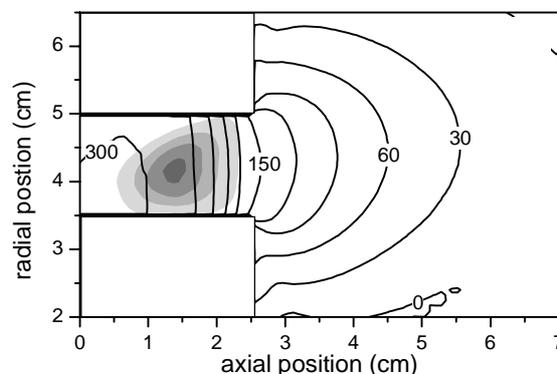


Figure 5 : Spatial profiles of the calculated electric potential (contours) and ionisation rate (gray scale, 10^{23} m^{-3}/s per interval). The applied voltage is 300 V.

Further experiments with complementary measurements such as the electric potential inside the channel and systematic comparisons with modeling are necessary to determine the validity domain of the empirical parameters, the final objective been to have an auto-coherent model.

In addition to the previously mentioned activities, the future scientific program will be mainly focussed on the high power laboratory model of thruster, the PPSX000ML. The pumping capacities of PIVOINE will be increased in order to be able to perform tests of this thruster for different mass flow-rates.

New designs

2-stage Hall effect thruster (SNECMA with MIREA) [12]

2 prototypes of double stage Hall effect thruster have been designed, manufactured and tested. These thrusters, called SPT MAG have been designed with the objective to separate the ionisation and the acceleration zone. Inside a buffer zone ions are created and concentrated in the middle of the channel to avoid recombinations on the walls. In a downstream zone, these ions are accelerated. The 2 thrusters are the SPT MAG A with an internal diameter of the external ceramic of 70 mm, the length of the channel being 24mm and the SPT MAG B with an internal diameter of the external ceramic of 90 mm. The tests of these thrusters have shown the feasibility of this principle and that very low divergence can be obtained.

Multi-stage electric thruster (THALES)

An innovative High Efficient Multistage Plasma (HEMP) thruster concept has been developed by Thales Electron Devices (TED). It consists in the focussing of an ion beam in a multi-stage magnetic cusp structure. In paper [13] are presented the results of demonstration model tests. Very good performances have been obtained during evaluation tests at ONERA Palaiseau. For example, an efficiency exceeding 30 % for a 600 W typical power at 1680 s of specific impulse has been demonstrated in July 2002. The potentialities of

this concept are very promising in term of performances (especially for efficiency, plume divergence and mass) and tuning capabilities over a wide range of specific impulse. New optimized models have already been designed and will be tested soon.

PPS®X000

For upper range of geostationary telecommunication platforms, satellite primes are requiring thrusters with high total impulse capabilities. For Hall effect thrusters, the only way to increase the total impulse (without reducing efficiency) is to increase the operating power. Consequently, SNECMA is developing, with CNES support, the PPS-X000 Hall effect thruster which is designed to withstand a 6 kW power level and to deliver a total impulse exceeding $8 \cdot 10^6$ Ns. This design, which includes several technological improvements, is fully based on SNECMA patents and will result in a fully European product.

A demonstration model has been manufactured by SNECMA and tested in QinetiQ facilities in Farnborough (UK) for about 200 h of operation. A large number of thruster configurations have been evaluated, for what concern channel dimensions, anode and cathode locations, magnetic field magnitude and topology, electrical configuration and thruster operating points. Performances and behavior of the thruster have been found very satisfactory. The design seems to be robust to thermal solicitations, even at 6 kW power level. Very promising performances and a good discharge stability have been measured on a wide operating range, especially in term of power and specific impulse. For example, the following thruster characteristics have been measured:

Power	Thrust	Specific Impulse	Efficiency
6 kW (20 A x 300 V)	335 mN (+/- 10 mN)	1769 s (+/- 53 s)	47.4 %
5 kW (2.4 A x 585 V)	232 mN (+/- 10 mN)	2480 s (+/- 107 s)	55.6 %

These characteristics include losses in cathode and magnetic circuit. These points not necessary correspond to the flight operating point. This (or these) one will be chosen in order to fit as much as possible to the system requirements, thruster capabilities and qualification constraints.

After some additional characterization tests, the thruster will be fired for an endurance evaluation test (typically 1000 h) in order to anticipate its lifetime capabilities and then coupled tests with a PPU breadboard will take place. All these tests are planed to be achieved by Q3 of 2003. The detailed test results are presented in the paper [14].



Figure 9 : PPS®X000 technological demonstrator

Plume effects

A general program has been decided in order to evaluate the different interactions between the plume ejected by an Hall effect thruster and a spacecraft [15]. The different steps of this program are the following :

- the plume modeling. The CNRS (CPAT) laboratory has developed a physical model of the plume. This model is connected with the hybrid model of the discharge developed in the frame of the GDR on Plasma Propulsion.
- The plume/surface interactions evaluation. Experiments have been carried out at ONERA Toulouse, in connection with Alcatel and ASTRIUM, to measure the sputtering rates of different materials under Xenon ion bombardment. The back-contamination by erosion products have also been evaluated. The

effect of erosion or contamination on the thermo-optical properties of materials has been measured.

These tests are reported in [16].

The flight validation of the plume modeling was expected through STENTOR satellite experiments, especially thanks to dedicated plasma probes which were mounted on the satellite. A similar diagnostic package is on board SMART1 spacecraft, but with more limited possibilities to investigate the plume and its effects. Since the STENTOR launch failure, we are looking for some other flight opportunities to validate plume effects models.

Other activities

Studies have been performed on Pulsed Plasma Thrusters in cooperation with Russian teams from Kurchatov and RIAME, in the frame of a European program (namely INTAS). Main achievements are the development, tests and modeling of optimized devices in the ranges of 10-150 J and 100-1000 J. Results and thruster performances are published in [17].

Conclusion

The main drivers of the electric propulsion activities in France are the preparation of the future large telecommunication platforms that will require high power thrusters for orbit transfer and orbit control. The French propulsion program is mainly focussed on the thruster but a European harmonized program is in progress in order to provide complete propulsion systems.

In parallel to these developments, we investigate other thrusters concept with the objective to improve the thruster performances (divergence reduction, efficiency increase, erosion decrease, ...).

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References

- [1] P. GARNERO, T. GRASSIN, L. PETITJEAN, F. DARNON "***STENTOR Plasma Propulsion Subsystem Experience***" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/048
- [2] L. JOLIVET, B. DEBRAY "***Field Electric Emission Propulsion Plume Effects on MICROSCOPE satellite***" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/291
- [3] S. MAZOUFFRE, D. PAGNON, P. LASGORCEIX, M. TOUZEAU "***Temperature of Xenon Atoms in a Stationary Plasma Thruster***" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/283
- [4] V. VIEL "***Secondary Electron Emission of Ceramics used in the channel of a SPT***" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/258
- [5] K. KATSONIS, A. SISKOS, M. TOUZEAU "***Coronal type and Collisional-Radiative Modeling of Rare Gases Plasmas***" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/285
- [6] A. LAZURENKO, V. VIAL, A. BOUCHOULE, M. PRIOUL, J.C. ADAM, A. HERON, G. LAVAL "***Characterisation of Microinstabilities in Hall Thruster Plasma***" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/218
- [7] M. MAKOWSKI, Z. PERADZYNSKI, S. BARRAL, M. DUDECK "***The Azimuthal Beam-Plasma Instabilities in Stationary Plasma Thrusters***" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/166

- [8] V. VIAL, A. LAZURENKO, C. LAURE, A. BOUCHOULE, D. PAGNON "*Xenon Gas Injection in SPT Thrusters*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/221
- [9] M. DUDECK, L. ALBAREDE, V. LAGO, P. LASGORCEIX, K. MALIK, A. LOYAN, A. BUGROVA, G. NOCI, P.F. SICILIANO, J. BUSSOTI "*Physical Processes and Interaction of a Hollow Cathode with a Hall Thruster*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/333
- [10] P. RENAUDIN, V. CAGAN, M. GUYOT, M. DUDECK, A. CADIOU, V. VIAL, P. LASGORCEIX, P. DUMAZERT "*Magnetic Circuits for Hall Thrusters*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/284
- [11] J.P. BŒUF, J. BAREILLES, C. BONIFACE, G. HAGELAAR, L. GARRIGUES "*Parametric Study of Hall Thruster Operations based on a 2D Hybrid Model*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/183
- [12] L. JOLIVET, O. SECHERESSE, V.K. KHARCHEVNIKOV, A. BUGROVA, A.I. MOROZOV "*Development and Testing of a Two-Stage Hall Effect Thruster*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/290
- [13] G. KORNFELD, N. KOCH, G. COUSTOU "*First test results of the HEMP-thruster concept*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/212
- [14] P. DUMAZERT, O. DUCHEMIN "*Development and Testing of a High Power Hall Thruster*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/032
- [15] F. DARNON "*Plume effects in plasma propulsion, an overview of CNES activities*"
Third international Conference on Spacecraft Propulsion, Cannes, October 2000.
- [16] V. VIEL, F. DARNON, T. TONDU "*Erosion of Materials used on Satellite External Skin by Electric Propulsion*" 28th International Electric Propulsion Conference, Toulouse, March 2003 – IEPC2003/257
- [17] N. ANTROPOV, G. DIAKONOV, M. ORLOV, G. POPOV, V. TYUTIN, V. YAKOVLEV, Y. ALEXEEV, M. KEZEEV, F. DARNON "*High efficiency ablative Pulsed Plasma Thruster characteristics*"
Third international Conference on Spacecraft Propulsion, Cannes, October 2000.