An overview of electric propulsion activities at CNES

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Abstract: The paper presents an overview of the works led on the electric propulsion 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 mainly concerns activities on Hall Effect Thruster (HET) technology.

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 since 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 achievements (SMART-1, Alphasat), allow perspectives which have not been possible before. Therefore, the Hall Effect thruster (HET) technology, developed in France for about twenty years, is not only envisaged for the operations of stations keeping but also for the orbit raising of geostationary satellites, that opens a considerable market. This turning point requires important R&T activities:

- on the short term, the development of propulsion subsystem must be better adapted to these new applications and have to win in competitiveness,
- on the middle term, the new product line will have to meet the needs of futures missions (LEO transfer, thruster cluster).
- on the long term, breakthrough has to be performed for more ambitious missions (far-off explorations, space tug…).

Current on-going activities are discussed including research activities as well as technology development and in-flight applications.

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II. Flight programs and novel mission designs

The CNES program covers earth observation, defense and security, scientific and telecommunications missions. The main drivers of the electric propulsion activities in France are the preparation or future telecommunications platforms that requires 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, allows it also to be used for low earth observation and ambitious scientific missions.

A. ALPHABUS program

ALPHABUS is a generic family of platforms issued from the Large Platform Program jointly undertaken by CNES and ESA to address the upper range of telecom satellites payloads[1]. The goal was to develop a telecommunication product line with a payload in the nominal range 12 – 18 kW and 800 – 2000 kg up to 22 kW in the extended range (called ALPHABUS extension). Alphasat is the first high-power communications satellite of this family platform, intended for extending the existing worldwide network of Inmarsat mobile telecommunications. It was launched in July 2013 on the Ariane 5 launcher. North-South station keeping is ensured by a set of four PPS®1350[2,3] thrusters accommodated by pair on two orientations mechanisms (on North and South side of the spacecraft) performing inclination and eccentricity controls, 2-axis wheel off-loading and electric top-up (end of orbit raising phase) if need. Chemical propulsion is used for drift station keeping, transfer, and attitude control during transfer, emergency controls.

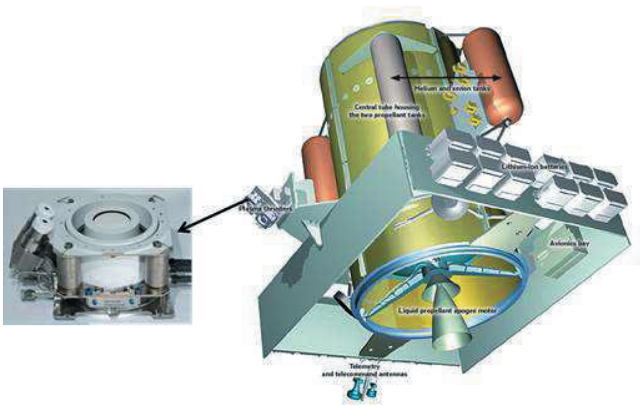

Figure 1. ALPHABUS generic platform configuration. Credits: ESA - CNES. On left side, PPS®1350-G thruster. Credits : SNECMA

B. NEOSAT program

The NEOSAT platform should represent, before 2020, the European response to the demand for new generation platforms for satellites between 3 to 6 tons, i.e. 80% of the communications satellites market[4]. The project is conducted both by Airbus Defence & Space (ADS) and Thales Alenia Space (TAS). The aim of this program, supported by CNES as part of the Investment for the future program and by ESA under the ARTES 14 program, is to obtain a 30% increase in competitiveness, for the whole satellite. As well as 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 the satellite in its position in geostationary orbit, or to correct drifts out of the orbital position. However, up until 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 even more powerful satellites can be launched. One of the major issues expected for the future NEOSAT platform, in terms of technological progress and increased competitiveness, will be to reduce the electrical orbit raising to three months.

Figure 2. Artist's view of NEOSAT platform. Credits : ESA

C. French national PIA ("Plan d'Investissement d'Avenir") program

By 2020, it was estimated that more than half of all satellites sold will be all-electric or hybrid technology (both chemical and electric system). Commercial telecommunications satellites are a domain where French industry excels and most of these satellites are built in France. To maintain its strong position in this market and to prepare the transition to the NEOSAT new platforms, industry must adapt quickly to evolving requirements, in particular due to the recent emergence of lighter and cheaper all-electric satellite buses. The plan laid out under the national initiative, which CNES has been tasked to lead, seeks to help ADS and TAS to design, develop and validate their standard electric satellite platforms (respectively Eurostar 3000 and Spacebus 4000 buses) in orbit, and to assist SNECMA in developing its high-power electric thruster (PPS®5000), which would be a key component of these platforms. The development phase (2014-2016) is underway, with contracts awarded by CNES under the French government's PIA future investment program[5]. The next phase (2017-2018) will cover in-orbit validation to demonstrate product performance. The PIA will also fund part of in-orbit validation activities. Three of these activities are for all-electric satellites covering the full spectrum of power requirements, demonstrating the utility and commercial potential of the products developed through this project.

D. Others applications and novel mission designs

Very high power Hall Effect thruster

Ambitious robotic missions like exploration of outer planets of the solar system as well as transfer of cargo vehicle to support crewed missions require very high power electric propulsion systems (>> 20 kW). Such range of thrusters could be also used for multi-mission applications like re-usable space tug to perform several fast LEO/GTO to GEO transfer. In this context, some projects are under evaluation at CNES (launcher directory) to design a space tug that can be implemented as a kick-stage for launchers[6]. This implies the need of propulsion system owning a high thrust to power ratio (~ 100 mN/kW) and can operate at very high power (20 – 100 kW). The PPS®20K (Thrust ~ 1N), developed by SNECMA with the support of CNRS in the frame of the European Commission FP7 HiPER project, could be one of them[7].

Phase 0/A studies

Various pre-projects are currently under evaluation by CNES (orbital vehicle directory) and by satellites primes. In 2012, different studies have been performed in using electric propulsion for Low Earth Orbit (LEO) or constellation applications at CNES[8]. For instance, The CNES have analyzed the use of electric propulsion on a Myriade or

Myriade Evolution platforms for missions in LEO. Myriade, developed by CNES, is a product line for micro-satellites dedicated mainly for scientific missions, but offering also flight opportunities for technological demonstrations. Numerical analysis have been performed to demonstrate the high DV capacity, that 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. Among different options, the low power Hall Effect thruster EPS-500 (see section IV) from SNECMA has been identified as one of a good candidate to ensure such a mission.

III. Thruster development and qualification

E. PPS®1350-E thruster

The PPS®1350 thruster is a Hall thruster of SNECMA, initially designed at a 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 90 mN and an average specific impulse above 1650 s, the PPS®1350-G demonstrated a total impulse of 3.36 10^6 Ns under various environmental conditions. A total ground qualification time of more than 10 500 hours was reached, which allowed it to be manufactured for the Alphasat satellite launched in 2013.
The operating point of the PPS®1350-G 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[9]. This feature is of interest when considering other possible missions for a thruster. As discussed previously, the shift to ‘all electric” telecommunications satellites needs to widen the missions devoted to electric propulsion and to cover the orbit transfer requirements of GEO satellites. For NSSK, the total electrical power is limited for propulsion by the payload needs and the lifetime of the propulsion system is linked to the lifetime of the satellite, i.e. 15 years. When considering orbit transfer, the propulsion specifications are totally different and the main constraint is to minimize the transfer time by using the maximum available electrical power for the propulsion in order to maximize the thrust. A possible option is then to implement dedicated PPS®1350 thrusters at a higher power in order to perform the orbit transfer for a minimum duration, typically about 4 – 5 months.

An extended range version of the PPS®1350 (-E version) is currently under development. Based on R&T activities done under SNECMA & CNES co-funding and on the robustness of the PPS®1350-G design, it was decided to increase the input power up to 2,5 kW[10]. One of the main advantages in the thruster development is to rely on the similarities of both thrusters versions in order to reduce the development delays and recurring costs. 6700 hours life test campaign on an engineering model was successfully completed 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. Development is still in progress.

Figure 3. PPS®1350-E thruster on stage and during ground qualification test. Credits : SNECMA

F. PPS®5000 thruster

The introduction of electric propulsion for orbit raising of geostationary satellites, on top of the conventional NSSK mission requires several technical challenges (increase power available, total impulse capability, diversity of operating points). Although technical skills demanded on the thruster, one key to any development remains the cost effectiveness. This feature is mandatory by the increased competition generated by this new market. The development of the 5-kW-class PPS®5000 Hall Effect thruster is in response to this shifting need in terms of electric propulsion[11,12]. 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 270 - 310 mN and specific impulse up to 1800 s. The Preliminary Design Review (PDR) and Design Review (DR) were successfully completed. The PPS®5000 qualification campaign should start at autumn 2015.

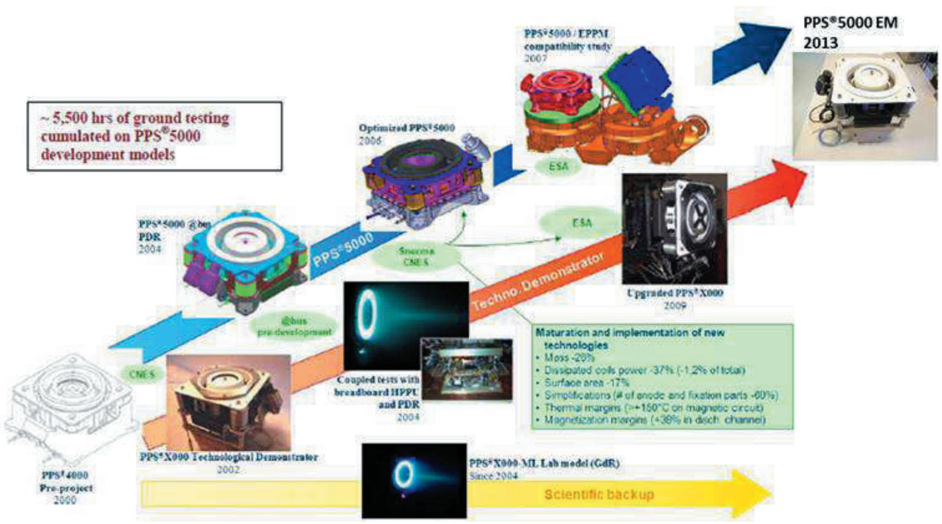

Figure 4. History of PPS®5000 pre-development activities. Credit : SNECMA

IV. Research and technology

Electric thruster development cycles are very long. Therefore, it becomes crucial to anticipate technological breakthroughs to make them available for thruster 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 a technological program with SNECMA. Many studies are made 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, low power thruster design. The latter is discussed in the next section.

G. EPS-500 thruster

EPS-500 is a propulsion subsystem concept with integrated functions gathering a thruster, a power processing unit, a fluid control device and its command electronics which, individually, are at TRL4[13]. This activity is supported by SNECMA and CNES and the current maturity level obtained for EPS-500 is a TRL3 with the test of innovative individual functions. All the functions are optimized for the available power and for low cost recurrent hardware. The overall performances are compatible with 200 - 1000 kg class mass, low power satellite, LEO missions for small or big satellites according to the requested total impulse. The 500W version is designed to perform up to 0.5 MN.s total impulse at around 30 mN thrust. Two other versions, dedicated to lower and higher input power around 300W and 700W, are under study with a minimum hardware modification. Tests results show good thruster efficiency around 40%, good electric power supply efficiency above 90%, and fluid management data within expected global performance even at supercritical Xenon temperature and pressure conditions.

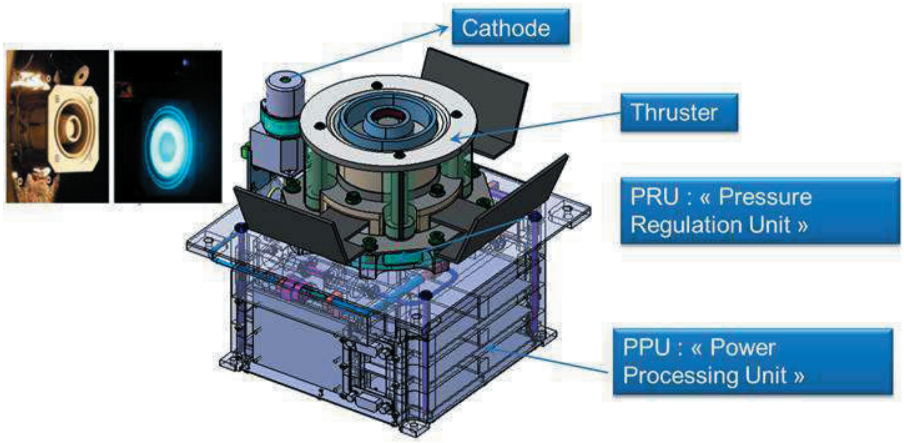

Figure 5. EPS-500 architecture with thruster, power processing unit (PPU) and pressure regulation unit (PRU) mounted on the same structure. Thruster prototype and firing during initial tests are also represented. Credits: SNECMA

V. Scientific Research activities

H. Research group on electric propulsion

Hall Effect thruster or Stationary Plasma thruster has been studied in the frame of research Group (GDR) on plasma propulsion from 1996 to 2011. In order to maintain a deep expertise of complex physical phenomena occurring in a HET, a new structure has been created in 2014, called GIS PPE (Groupement d'Intérêt Scientifique Propulsion par Plasma pour l'Espace). This research group coordinated by CNES involves 13 partners (CNES, several laboratories from CNRS and Universities, SNECMA and ONERA) specialized in all the 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 thruster lifetime (ceramics development, interaction plasma-wall studies),
- improvement of performances and thruster physical understanding (magnetic field – plasma coupling, micro-turbulence, dual mode operating),
- new concepts deriving of Hall effect thruster technology (new magnetic configurations, double stage thruster, alternative propellant).

In parallel, transversal activities, dedicated to diagnostics development (plasmas probes, Thomson scattering) and numerical tools (high computing simulation, electron fluid modeling improvements), are also planned.

Some recently results are reported hereafter:

Micro-turbulence and instability:

- Recent radial-azimuthal PIC simulations suggest that micro-turbulence is responsible for particle heating and a broadening of the electron energy distribution not only in axial and azimuthal directions but also in radial directions. Therefore, this plasma heating could increase the electron wall emission and cause a transition to a beam instability regime able to generate a jump in the electron current[14].
- To investigate this non-linear coupling between the instability and the wall emission, Thomson scattering measurements of the modes features with different wall emissivity have been performed and compared to PIC simulations. Significant difference of unstable mode amplitudes and discharge current fluctuation levels for the different materials (standard borosil and velvet carbon) has been observed[15].
- A time-resolved laser-induced fluorescence study was performed on the high frequency oscillation of the ion velocity distribution in the 100 kHz – 1 MHz frequency range. It was shown that the discharge high frequency content tended to be stabilized by the modulation of the breathing mode, which suggests that the ion transit time is correlated with ionization events[16].

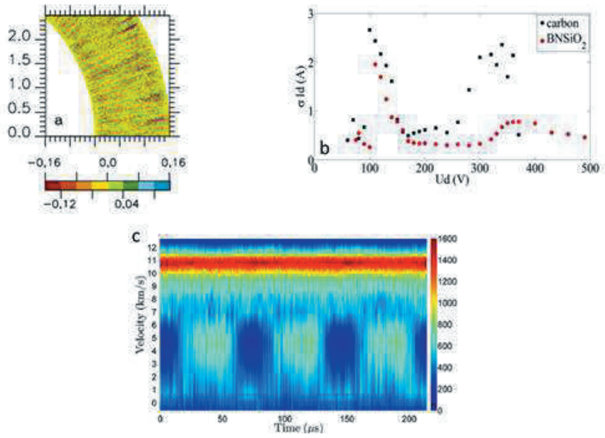

Figure 6. (a) Cartesian representation of ion density fluctuations in the (R,θ) PIC simulations, (b) Standard deviation of discharge current as a function of discharge voltage for borosil and velvet carbon materials, (c) Axial ion velocity distribution at 4 mm away from the discharge channel as a function of time. The window spans three breathing oscillations.

Modeling

- A two dimensional quasi-neutral fluid model of a hollow cathode for Hall 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. 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[17].
- An efficient method and a robust tool for designing optimal electromagnetic circuits have been developed. It consists of a hybrid source code (ATOP) which is built as a topological (ATOPTO) and a parametric (ATOPPO) optimization method. The method allows to change some 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].

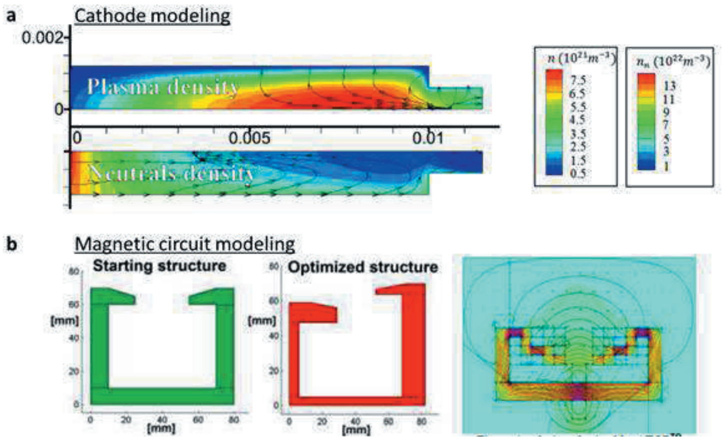

Figure 7. (a) 2D Simulation results for a LaB6 hollow cathode: plasma density and neutrals density, (b) Optimization of magnetic circuit using ATOP algorithm.

Magnetic topology

- Different magnetic topologies have been studied using our unique versatile PPS-Flex thruster and a 200-W class permanent magnet PPI hall thruster[19, 20], especially in magnetic shielding (MS) and wall less (WL) configurations [21, 22]. The expected advantages of such configurations are the following: the WL and the MS configurations have certain similarities, with their advantage over conventional thruster designs based on reduced plasma-wall interaction and so an expected increase of lifetime. Nonetheless, the questions on the ion beam divergence remains still open. In any case, a WL thruster is also a good source for examination of plasma physics (instabilities like rotating spoke, ionization, turbulence…).

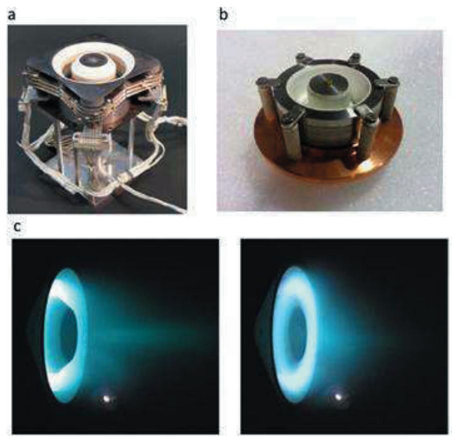

Figure 8. (a) PPS Flex thruster, (b) PPI permanent magnet thruster, (c) Photos of the PPS Flex thruster operating with Xenon at 250 V and 3.5 mg/s. (left) Standard unshielded magnetic configuration (right) magnetic shielding configuration with the lines parallel to the walls.

VI. Conclusion

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

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