

# PLASMA PROPULSION FOR GEOSTATIONARY SATELLITES AND INTERPLANETARY SPACECRAFT\*

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The interest of electric propulsion for the orbit maintenance of geostationary telecommunication satellites is explained. The performances of different plasma sources are presented. Hall effect thrusters are described in detail and the Smart1 mission in space using a Hall thruster is briefly described.

Key word: electric propulsion, plasma propulsion, satellites.

## 1. INTRODUCTION

Geostationary telecommunication satellites require propulsion systems from its separation from the third stage of the launcher to the de-orbiting operation. At this separation with the third stage, the satellite is injected on a transfer orbit with an apogee at 36000 km from Earth surface. At the apogee of this orbit an applied thrust of 1-3 N gives an increment of velocity of  $\sim 1,9$  m/s and moves the satellite to a quasi-circular and quasi-equatorial orbit. One or two supplementary months are necessary to make the orbit circular and equatorial, to open solar panels, to verify the instruments, to modify the satellite attitude and to set the satellite at its working longitude.

The satellite has to be maintained at this working position throughout the mission (15 to 20 years). However the satellite moves in accordance with Lunar and Sun trajectories, inhomogeneity of the Earth and radiative Sun pressure. At the altitude of the geostationary orbit (GEO) the drag effect is negligible. The predominant effect is the Lunar-Solar interactions which are greater than the Earth inhomogeneity and the Sun radiation effects. Consequently, thrusters are required

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to bring the satellite back to its initial working place and to perform daily North-South and East-West corrections. The thrusters run during one hour each day and deliver a thrust in the range 80-100 mN. The variation of velocity is 50 m/s (North-South) and 5 m/s (East-West) per year. Sometimes, it is necessary to move the satellite during the mission to avoid a collision with an object moving in space. Because of human activities, more than 13000 objects larger than 10 cm are in space, more than 200000 from 1 to 10 cm [1]. When a risk arises, a thruster is switched on to move the satellite and avoid a destructive collision.

Finally, the geostationary satellite is de-orbited at the end of its mission to make way to another satellite (approximately 400 satellites can stay on the GEO orbit). The de-orbitation with an increment of velocity  $\Delta V=3\text{m/s}$  is realized to send the satellite on a higher orbit (of 300 km). The de-orbitation is not realized by a return in the low Earth atmosphere in order not to generate more fragments close to the Earth.

## 2. CHEMICAL AND ELECTRIC THRUSTERS

For the different space missions, the required thrusts are in a large range: 200-400 N for elliptic-circular orbit transfer, 80-100 mN for station keeping of a GEO satellite and a few micro-N for precise positioning of scientific probes.

The thrust  $T$  is defined as the product of the mass flow rate by the exhaust velocity of the propellant. It is not the only parameter that needs to be taken into account when choosing the best thruster: another significant parameter is the specific impulse  $I_{sp}$  defined as the ratio of the thrust to the mass flow and to the intensity of gravity at the surface of Earth. The specific impulse is related to the mass consumption for a defined mission associated to a required velocity variation of the spacecraft. A high specific impulse allows to decrease the mass of propellant and consequently to decrease the mass of the satellite or, for the same mass, to have more on-board scientific instruments. On the other hand, a high thrust allows a faster change of orbit.

The main parameters are:

$$\text{axial thrust } T(N) = \dot{m}V_e \quad (1)$$

$$\text{specific impulse } I_{sp}(s) = \frac{T}{\dot{m}g_0} \quad (2)$$

$$\text{mass consumption } \Delta M = M_0 \left[ 1 - e^{-\frac{\Delta V}{g_0 I_{sp}}} \right] \quad (3)$$

$$\text{power per mN } p(\text{W} / \text{mN}) = \frac{P}{T} \quad (4)$$

$$\text{efficiency } \eta = \frac{T^2}{2\dot{m}P} \quad (5)$$

Plume half angle  $\theta$  containing 90% (sometimes 95%) of the propulsive flux:

$$\int_0^\theta j(\theta') \sin \theta' d\theta' / \int_0^{\pi/2} j(\theta') \sin \theta' d\theta' = 0.9 \quad (6)$$

where  $j(\theta')$  is the density of flux.

All operations are currently performed in space with chemical propulsion engines or electric propulsion engines. Electric propulsion using ion ejection by an electromagnetic field was suggested in 1906 by R.H. Goddard as a future possibility of moving in space [2, 3, 4]. The field of electric thrusters is very large and the suggested plasma sources are numerous. However, only a few have been tested, validated and used in space. Other propulsion systems are futuristic concepts. The following non exhaustive list of electric thrusters gives an idea of the large variety of electric thruster concepts.

In the ablative *Pulsed Plasma Thrusters* (PPT), the ions are produced by successive sparks with a frequency of a few Hz between two high voltage electrodes set in front of a solid propellant (Teflon). PPT delivers a high specific impulse (800-1200 s), a thrust around 1m N and operates with an electric power lower than 100 W [5,6,7]. The PPT are used for attitude control, micro-satellites and low thrust manoeuvres. Zond2 was the first spacecraft launched in space with a PPT (Soviet Union – 1964).

A *Field Emission Electric Plasma* thruster (FEEP) uses the flow of a liquid metal (caesium or indium) through a slit limited by two metal surfaces. The extracted positive ions  $\text{Cs}^+$  are accelerated by an electric field (potential ~10 kV). The very low thrust (micro-N to a few milli-N) of FEEP engines is used to compensate the drag effect, for attitude control (ESA/NASA LISA Pathfinder [8] and Microscope missions) or for formation flying. A high specific impulse is obtained by this micro-propulsion engine: more than 10 000 s. Alta SpA (Italy) [9] and Space propulsion (Austria) [10] are developing FEEP.

In a *Gridded Ion Engine* (GIE), also called *Gridded Ion Thruster* (GIT), the positive ions (Xenon) are obtained by electron impacts (Kaufman or radiofrequency ion thrusters), then extracted and accelerated by a set of 2 or 3 multi-aperture grids. This electrostatic ion engine delivers a thrust up to 670 mN, and an Isp up to 9620 s for a power of 39.3 kW, Glenn Research Center, NASA [11]. GIE is used for satellite station keeping and also for deep space trips. For the successful exploration of the Borrelly Comet (NASA Deep Space 1 mission; 1998-2001) the NEXT thrusters (90 mN at a power 2,3 kW) from the Jet Propulsion laboratory were used [12]. The Hayabusa spacecraft (JAXA, Japan) reached the asteroid Itokawa in 2005 and came back to Earth in June 2010 perhaps with samples from the asteroid [13]. Its propulsion engine was a GIE. One can also note the use of a GIE thruster to replace the satellite Artemis (2001) on the GEO orbit

after a failure of the launcher [14]. The satellite Astra 2A launched in 1998 (Hughes Space and Com. – Boeing Satellites Syst.) uses 4 ions thrusters XIPS ( $T=18$  mN).

Arc-jet thrusters are electro-thermal engines. The gas (hydrogen, ammonia, hydrazine) enters in a chamber and crosses the throat of a nozzle used as anode. An arc is sustained between this anode and a cathode set in the chamber. The gas is heated and expanded through the nozzle. Arc-jets generate a thrust in the range 0.01N - 0.5N with a specific impulse between 500 and 1000 s, Busek Comp. Inc [15], Institut für Raumfahrtsystem (IRS - Stuttgart university) [16,17,18]. A 750 W ammonia arc-jet thruster has been manufactured at the IRS (AMSAT P3-D satellite, 1994 Germany) [19].

*Hall Effect Thrusters* (HET) also named “closed-drift thrusters”, *Stationary Plasma Thrusters* (SPT) or *Propulseurs par Plasma pour Satellites* (PPS) use a partially magnetized plasma discharge in a cross-electromagnetic field. To maintain the satellites in geostationary orbit with North-South and East-West corrections, Hall Effect Thruster is now recognized as one of the most interesting concepts because of its performances mainly in the economy in propellant mass (saving about 400 kg for a 4t-class satellite for a mission of 15 years – see formulae 3).

After the first HET on the Meteor meteorological satellite (two SPT-60, USSR, 1972), a few hundreds of SPTs were used on-board Russian satellites. A large family of HET with different input powers is currently developed: Fakel EDB, Russia: SPT 25, 35, 50, 60, 70, 100, 140, 200, 290, Snecma-Safran Group, France: PPS-1350 and PPS-5000 since 1999 for future satellites, Busek Co., USA, from BHT200, BHT400, BHT1000, BHT1500, BHT8000, BHT20k, Pratt & Whitney Space Propulsion, USA: T-40, T-140, T-220, Keldysh Research Institute in Russia: KM-32 and in collaboration with Astrium the ROS-99 and the ROS-2000, and Rafael Space Systems, Israel: IHET-300. Two IHET-300 will operate on the Rafael Venus Satellite.

The performances of these thrusters are summarized in the following Table 1.

Table 1

Performances of the HET for the nominal operating conditions for the smaller and the greater HET for each series

Thruster		Power	Thrust	Specific impulse	Efficiency
SPT 25	Fakel, Russia	58 W	2.9 mN	500 s	
SPT 290	Fakel, Russia	25 kW	1.5N	3300 s	
PPS-1350	Snecma, France	1,5 kW	88 mN	1650 s	55 %
PPS-5000	Snecma, France	5 kW	135mN	2300 s	50%
BHT200	Busek, Co., USA	200 W	12.8 mN	1390 s	43,5 %
BHT20k	Busek, Co., USA	20-25kW	1.08 N	2750 s	72 %
T-40	Pratt & Whitney Space Propulsion, USA	400 W	20 mN	1600 s	

Table 1 (continued)

T-220	Pratt & Whitney Space Propulsion, USA	20 kW	1.0 N	2500 s	
KM-32	Keldysh Research Institute, Russia	150-400W		2000 s	45 %
ROS-2000	Keldysh Research Institute, Russia Astrium	1.5-2.4 kW			
IHET-300	Rafael Space Systems, Israel	300 W	> 15mN	>1300 s	

The European technological satellite Stentor [20] was equipped with two PPS-1350 ( $T=88$  mN,  $I_{sp}=1650$  s,  $\eta=55\%$ , Snecma, France) and two SPT-100 (Fakel EDB, Russia). The ESA Smart1 Lunar mission [21] used a PPS1350G (Snecma, France). The Alphabus platform (CNES-ESA) will be equipped with the same thruster and will be able to carry a payload of up to 1500 kg. The stationkeeping of a few European satellites for telecommunication such as Inmarsat 4, Intelsat 10 is realized by SPT-100 (Fakel EDB, Russia). The first American HET in space (16 Dec. 2006) was the BHT-200 from Busek Co. United States ( $T=12.8$  mN,  $I_{sp}=1390$  s) on the TacSat-2 technological spacecraft.

Power, thrust and specific impulse above-mentioned are nominal performances.

### 3. BASIC CONCEPT OF HALL EFFECT THRUSTER

Hall effect thrusters (schematic view shown in Figure 1) are advanced electro-magnetic propulsion devices. The plasma discharge is sustained between two coaxial dielectric cylinders and between an external hollow cathode emitting electrons and an anode set at the bottom of the annular chamber. The discharge voltage is generally from 300 V to 350 V but high voltage up to 1000 V have been tested in order to increase the specific impulse. The propellant is generally injected through the anode. Xenon is most suitable thanks to its low first ionisation level (12,23 eV) and its high mass. Due to the low pressure of the channel ( $\sim 10^{-4}$  mbar at the bottom  $10^{-5}$  mbar at the exit), it is necessary to trap the electrons by a radial magnetic field ( $\sim 0.02$  T at the channel exit for a PPS100). This magnetic field is created by external magnetization coils (inner and outer coils).

The electron Larmor radius ( $\sim 10^{-3}$  m) is small compared to the chamber dimensions ( $\sim 10^{-2}$  m) and consequently electrons are confined and magnetized.  $Xe^+$  ions are then created by inelastic electron-neutral collisions and only 10 to 15% of ion  $Xe^{++}$  is created in the discharge

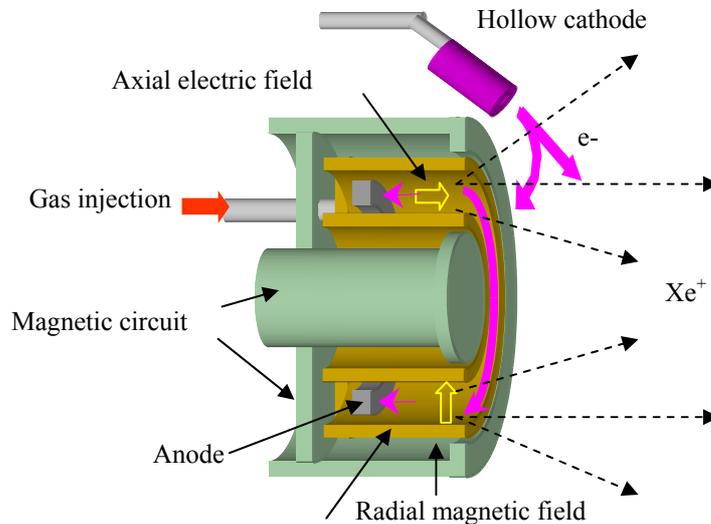


Fig. 1 – View of a Hall Effect Thruster [22].

In the channel the electrons have three origins: external hollow cathode, ionization process and wall. Typically, the plasma parameters are a density of  $10^{11}\text{cm}^{-3}$  and an electron temperature about 20 eV at the channel exit. Then the electron plasma frequency is around 3GHz and the electron cyclotron frequency is around 300 MHz (the hybrid electron frequency is close to the electron plasma frequency).

The electrons have to move toward the anode and several mechanisms have been suggested to explain the electron transverse transport through the magnetic lines. For a low pressure discharge ( $10^{-4}$ - $10^{-5}$  mbars) the electron-neutral xenon collisions frequency is insufficient to explain this transport in the channel because of the low neutral density at the channel exhaust. A.I.Morozov [23, 24] suggested a "wall" transport: electrons from the sheath scattering and secondary electrons allow transport toward the anode by successive steps along the trapping magnetic lines. The more recent explanation is given by the presence of high frequency fluctuations (1-10 MHz) of the azimuthal electric field of the plasma discharge [25, 26]. The fall of the electron mobility at the channel exhaust in reason of the increase of radial magnetic field induces an axial electric field with a maximum value (Fig. 2) around 500 V/cm (PPS-1350). This axial electric field is generated without grids: it is one of the advantages of the HET compared to the GIE.

The plasma discharge is obtained in a crossed  $\text{ExB}$  field and the electrons present an azimuthal drift velocity ( $\sim 10^6$  m/s). The Xenon ions are axially accelerated out of the thrusters with a high velocity (15–20 km/s), which implies a high specific impulse (1650 s for the PPS-100ML). Two ionic zones appear in the channel, the first one is the ionization zone inside the channel where ions are produced and the second one is the acceleration zone located inside and outside the

channel. The best efficiency (4) is obtained when these two zones are separated. There is an overlap of these two zones in a classic HET and their separation is the task [27] of the two stage thruster MAG B from MIREA institute (Moscow-Russia).

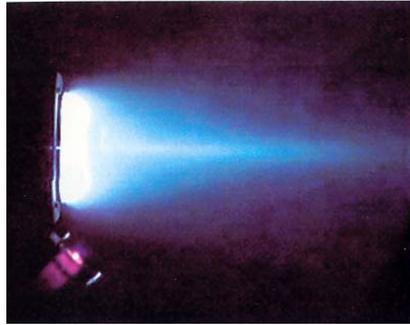


Fig. 2 – Xenon plasma plume from the PPS100-ML (laboratory model) Pivoine facility at laboratoire d'Aérothermique, CNRS Orléans, France.

The Larmor radius of the ions is around 1 m and then the ions are not magnetized inside the channel (no ion cyclotron frequency). The extraction of the ions from the channel depends on the shape of the electric potential lens which is closed to the magnetic lens. Measurements performed by laser induced fluorescence [28, 29] show that a large part of the axial acceleration of the ions takes place out of the channel (see figure 3) and that the ions present low frequency oscillations following the low frequency fluctuations of the discharge current in the range 10–30 kHz. This mode of fluctuations is named "breathing mode" and is due to the depletion of neutrals in the channel [30, 31] (see figure 4).

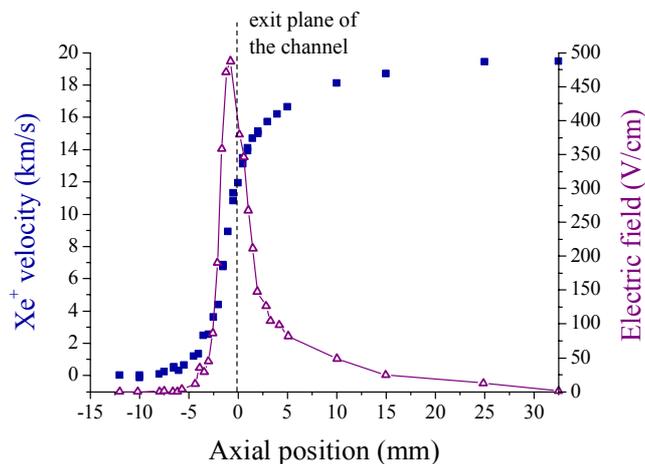


Fig. 3 –  $\text{Xe}^+$  velocity measurement by Doppler shifted laser induced fluorescence and axial electric field [28,29].

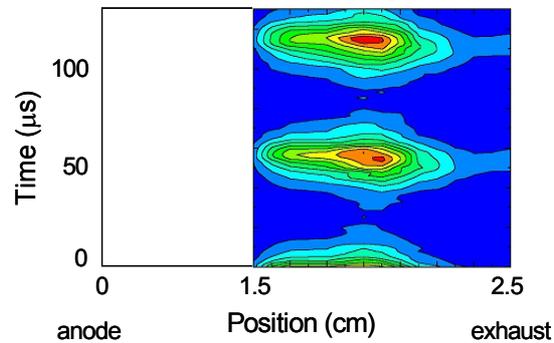


Fig. 4 – Low frequency ion fluctuations in the discharge channel from the bottom (anode) to the exhaust [30].

Another complex and fundamental point is related to the role of the plasma-surface interactions on the behaviour of the plasma discharge of Hall thrusters. A surface erosion appears in the region in contact with the acceleration zone where the ions have a divergent trajectory related to the thruster axis and impact the surface of the channel. This erosion is mainly due to ion sputtering. Moreover, a superimposed “anomalous” erosion process is observed in every Hall thruster (see figure 5). This erosion is characterized by regular visible ridges. Today, no satisfying theory is suggested to explain this “anomalous” erosion: effect of electrons? effect of electrons and ions?

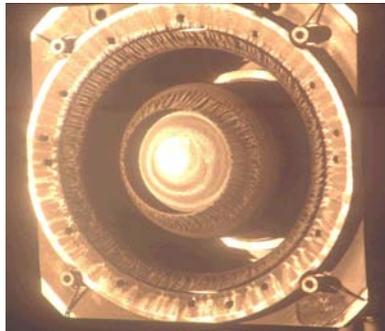


Fig. 5 – Anomalous erosion on the wall of a Hall effect thruster.

The *secondary electron emission* rate (S.E.E.) is now recognized as having a significant contribution to the plasma discharge: values of the plasma discharge current and low frequency fluctuations (amplitude and frequency) [32, 33]. It seems from various tests with different materials, shown in figure 6, that a secondary electron emission rate lower than one is required to optimize the plasma properties. A S.E.E. rate greater than one induces a potential sheath saturation effect increasing the discharge current and the electron energy deposition on the walls.

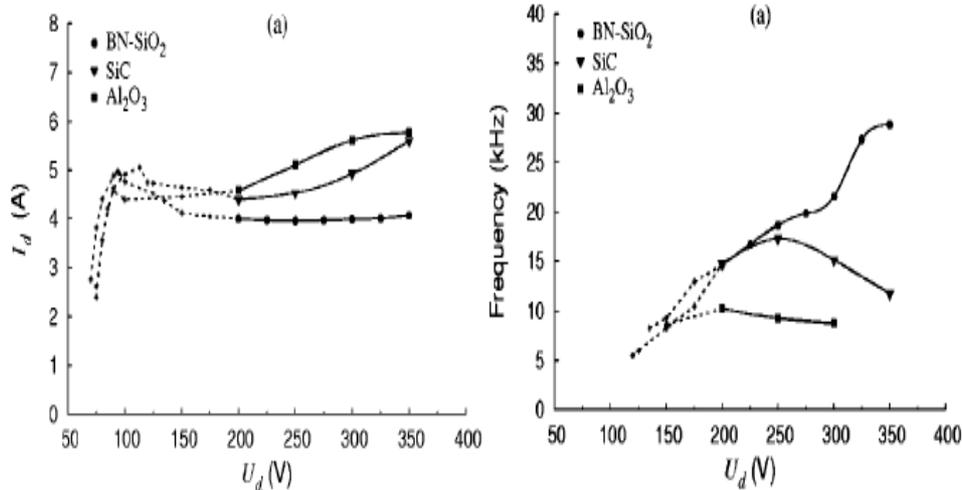


Fig. 6 – Discharge current and low frequency measurements for surfaces made of BN-SiO<sub>2</sub>, SiC, Al<sub>2</sub>O<sub>3</sub> [33].

The temperature of the inner and outer walls due to ion and electron impacts modifies the secondary electron emission rate and consequently, this temperature has an influence on the properties of the plasma flow. The temperature of the walls also changes the temperature of the neutral Xenon by thermal accommodation, but the Xe temperature has not a great influence on the plasma flow properties.

#### 4. SMART 1 EUROPEAN MISSION

Snecma has developed a range of Hall effect plasma thrusters as PPS-1350 PPS-5000. In particular, the PPS-1350 was equipped on-board the CNES/DGA/France Telecom Stentor satellite and the ESA probe SMART 1 that was successfully sent to a Lunar orbit (Sept 2003-Nov. 2004). SMART 1 for “Small Missions for Advanced Research in Technology” was launched on 27<sup>th</sup> sept. 2003 and was the first mission using Hall thrusters outside of Earth’orbit. SMART 1 is the first European mission to the Moon [34]. With an initial mass of 366.5 kg, 19kg of scientific instruments and only 82 kg of Xenon, the probe reached the Earth-Lunar Lagrange point on 15<sup>th</sup> Nov. 2004 after a trip of 84 Mkm and a Lunar orbit (3000–10000 km) after a trip of 15 months from the launch. Finally, the probe impacted the Lunar surface on 3<sup>rd</sup> Sept. 2006. This Lunar mission proved successful thanks to a PPS1350G ( $T=88$  mN,  $I_{sp}=1650$  s, Snecma – Safran Group, France). Only 80 kg of Xenon has been consumed for a total thruster run of 4600 h with a maximum of 240 h of run without interruption.

## CONCLUSION

Electric thrusters and especially Hall effect thrusters now present a great interest for space applications: for orbit maintenance of geostationary satellites for telecommunication as shown by the large number of satellites using this propulsive device ( $\sim 400$ ) and in the future for orbit transfers and interplanetary missions as already demonstrated by the success of the European Smart 1 mission. A large range of power for HET (from a few 100 W to 100k W or more) allows the use of this propulsion device for a wide domain of missions in space.

Since 1996, a large scientific effort has been made in France in the domain of Hall effect thruster to deepen the knowledge of the complex and coupled phenomena appearing in the plasma discharge, such as plasma fluctuations in a broad frequency spectrum, wall interactions, influence of the magnetic topography and electron conductivity. This work has been performed with three main objectives in mind: achieve greater lifetime, better performance, and innovation in Hall effect thrusters. This activity associates CNES, Snecma, French laboratories with scientific collaborations with foreign institutes. The research uses theoretical developments, numerical simulations and experiments. These experiments are carried out in the national ground test facility Pivoine (ICARE, Orleans, France) [35] using a large set of plasma diagnostics. The research on Hall thrusters is carried out in the frame of a collaborative national scientific research programme (*GDR Propulsion par plasma dans l'espace*).

## REFERENCES

1. Ch. Bonnal, Orbital debris: What to do with the Kessler syndrome ..., Space Propulsion 2010, San Sebastian, Spain, 3–6 May 2010.
2. R.H. Goddard, The papers of Robert H.Goddard, E.C. Goddard and C.E.Pendray, Eds. New York: MacGraw-Hill, 1970.
3. P.J. Wilbur, R.G.Jahn, F.Curran, Space Electric Propulsion Plasmas, *IEEE Transactions on Plasma Science*, Vol. 19, N°6, Dec. 1991.
4. E.Y. Choueiri, A Critical History of Electric Propulsion: The First Fifty Years (1906–1956), *J. of Propulsion and Power*, Vol. 20, N°2, pp.193-203, March-April 2004.
5. R.L. Burton, P.J.Turchi, Pulsed Plasma Thruster, *J. of Spacecraft and Rockets*, Vol. 14, N°5, pp. 716–735, 1998.
6. G. Popov, N. Antropov, G. Diakonov, M. Orlov, V. Tyutin, V. Yakovlev, *Experimental Study of Plasma Parameters in High-Efficiency Pulsed Plasma Thrusters*, 26th IEPC, paper 01-163, 2001.
7. N. Pillet, B. Pouilloux, P. Pelipenko, J. Folliard, F. Darnon, E. Chesta, P. Bousquet, F. Alby, N.N. Antropov, G.A. Diakonov, V.N. Jakovlev, M.M. Orlov, P.M. Trubnikov, V.K. Tyutin, *Pulsed Plasma Thruster Option for Myriade Deorbiting*, *European Conference for Aerospace Sciences*, EUCASS, 4–7 July 2005, Moscow, Russia, 2005.
8. D. Nicolini, *LISA Pathfinder Field Emission Thruster System Development Program*, 29th International Electric Propulsion Conference, Florence, Italy, September 1720, 2007.

9. S. Marcuccio, M. Saviozzi, L. Priami, M. Andrenucci, Experimental Performance of 1 mN-class FEEP Thrusters, 28th International Electric Propulsion Conference, Toulouse, March 17–21, 2003.
10. A. Genovese, N. Budrini, M. Tajmar, W. Steiger, Experimental Performance of 1 mN-class FEEP Thrusters, 28th International Electric Propulsion Conference, Toulouse, March 17–21, 2003.
11. HIPEP NASA report, NASA/TM-2004-213194.
12. J.E. Nordholt et al, Deep Space 1 encounter with Comet 19P/Borrelly: Ion composition measurements by the PEPE mass spectrometer, *Geophysical Research letters*, Vol. 30, 1465, 2003.
13. T. Kubota et al, Guidance and Navigation Scheme for Hayabusa Asteroid Exploration and Sample Return Mission, ESA workshop on GNC for Small Body Mission, ESA/ESTEC, Noordwijk, The Netherlands, 14–15 Jan. 2009.
14. R. Killinger et al, Artemis Orbit Raising Inflight Experience with Ion Propulsion, IEPC paper 0096, 28th International Electric Propulsion Conference, Toulouse, March 17–21, 2003.
15. K. Hohman, T. Brogan, V. Hruby, K. Annen, R. Brown, Two kilowatt bipropellant arcjet developments, IEPC paper 0122, 28th International Electric Propulsion Conference, Toulouse, March 17–21, 2003.
16. J. Heiermann, M. Auweter-Kurtz, Numerical simulation of the Arthur-2 arcjet, IEPC paper 0033, 28th International Electric Propulsion Conference, Toulouse, March 17–21, 2003.
17. D. Bock, M. Auweter-Kurtz, H. Kurtz, 1kW ammonia arcjet development for a science mission to the Moon, 29th International Electric Propulsion Conference, IEPC paper 2007-075, Princeton University, Oct. 31–Nov. 4, 2005.
18. D. Bock, H.P. Roser, G. Herdrich, M. Auweter-Kurtz, Subscale lifecycle test of thermal arcjet thruster Talos for the Lunar mission BW1, 30th International Electric Propulsion Conference, IEPC paper 2007-137, Florence, Italy, 17-20 September 2007.
19. J. de Dalmou, J. Gigou, Ariane-5: Learning from Flight 501 and Preparing for 502, ESA Bulletin Nr. 89, February 1997.
20. F. Darnon, J-P. Diris, J. Hoarau, L. Torres, Th. Grassin, Plasma Propulsion on STENTOR Satellite: In Flight Acceptance Operations and Experimental Program, 27<sup>th</sup> International Electric Propulsion Conference, paper IEPC-01-167, Pasadena, CA, Oct. 14-15, 2001.
21. Smart-1, European Space Agency, BR-191, June 2002 and Smart-1: A Solar-Powered Visit to the Moon, *ESA bulletin*, number 113- February 2003.
22. N. Gascon, Etude des propulseurs plasmiques à effet Hall pour systèmes spatiaux. Performances, propriétés des décharges et modélisation hydrodynamique, Thesis, University of Provence, Marseille, France, Dec. 15, 2000.
23. A.I. Morozov, V.V. Savelyev, Fundamentals of stationary plasma thruster theory, in *Reviews of Plasma Physics*, 21, Ed. By B.B. Kadomtsev and V.D. Shafranov, Kluwer Acad/Plenum Publishers, New-York.
24. A. I. Morozov, V.V. Savelev, Theory of the near-wall conductivity, *Plasma Physics Reports*, Vol. 27, No. 7, 607 (2001).
25. S. Tsikata, Small-scale electron density fluctuations in the Hall thruster, investigated by collective light scattering, Thesis, Ecole Polytechnique, France, Nov. 19, 2009.
26. S. Tsikata, N. Lemoine, V. Pisarev, D. Grésillon, Dispersion relations of electron density fluctuations in a Hall thrusters plasma, observed by collective light scattering, *Physics of Plasmas* **16**, 033506, 2009.
27. J. Perez-Luna, G.J.M. Hagelaar, L. Garrigues, J.P. Boeuf, Model analysis of a double stage Hall effect thruster with double-peaked magnetic field and intermediate electrode, paper IEPC-2007-124, 30<sup>th</sup> International Electric Propulsion Conference, Sept. 2007, Florence, Italy, 2007.
28. N. Sadeghi, N. Dorval, J. Bonnet, D. Pigache, C. Kaldec-Philippe, A. Bouchoule, Velocity measurements of Xe<sup>+</sup> in Stationary Plasma Thruster using LIF, AIAA 99-2429, 35<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, June 20–24, Los Angeles, CA, USA, 1999.

29. S. Mazouffre, D. Gawron, V. Kulaev, N. Sadeghi, Xe<sup>+</sup> Ion Transport in the Crossed-Field Discharge of a 5-kW-Class Hall Effect Thruster, *IEEE Transactions on Plasma Sciences*, Vol.36, N° 5, p. 1967–1976, Oct. 2008.
30. J.P. Bœuf, L. Garrigues, Low Frequency Oscillations in a Stationary Plasma Thruster”, *Journal of Applied Physics*, 84, 3541, 1998.
31. D. Pagnon, F. Darnon, S. Roche, S. Béchu, L. Magne, T. Minea, A. Bouchoule, M. Touzeau, P. Lasgorceix Time Resolved Characterization of the Plasma and the Plume of a SPT Thruster – AIAA-99-2428, 35<sup>th</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Los Angeles, CA, USA, June 20–24, 1999.
32. N. Gascon, M. Dudeck, S. Barral, Wall material effects in stationary plasma thruster I: Parametric studies of an SPT-100, *Physics of Plasma*, vol. 10, n° 10, p. 4123-4136, Oct. 2003.
33. S. Barral, K. Makowski, Z. Peradzynski, N. Gascon, M. Dudeck, Effect of wall material in stationary plasma thrusters II – Near-wall and in-all conductivity, *Physics of Plasma*, Vol. 10, n° 10, p. 4127–4152, Oct. 2003.
34. C. Koppel, F. Marchandise, M. Prioul, D. Estublier, F. Darnon, „The SMART-1 Electric Propulsion Subsystem around the Moon: In Flight Experience” in proceedings of 41<sup>st</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Reston VA, 2005, Paper N° AIAA-2005-3671, 2005.
35. P. Lasgorceix, C. Perot and M. Dudeck, PIVOINE ground test facility for ion thrusters testing, in Proceedings of the Second European Spacecraft Propulsion Conference, 27–29 May, 1997.