RESEARCH AND DEVELOPMENT ON PLASMA THRUSTERS IN FRANCE

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Abstract

The main objectives of the French program in the field of electric propulsion are to qualify (ground and in flight qualification) a French production of plasma thruster (Stationary Plasma Thruster) and to prepare the future of this technology through a scientific and a technological program.

The status of this program is the following:
- Scientific activities on Hall thrusters carried out by CNRS (Centre National de la Recherche Scientifique) and ONERA (Office National d’Etudes et de Recherches Aérospatiales) in the frame of a Research Group on Plasma Propulsion CNRS/CNES/SEP/ONERA are improving our knowledge of the physical phenomena involved in a SPT. The theoretical models reproduce the oscillations experimentally observed. On the experimental point of view, the analysis of these results will help us to find way of improvement of the thruster performances (efficiency, divergence). On the GDR laboratory model several studies are and will be performed: effect of different gases and channel material on the thruster performances, LIF velocity measurements, ...-
- The PPS1350 manufactured by SNECMA, division SEP, and the Russian manufacturer FAKEL (2 product lines), with the collaboration of the MIREA (Moscow Institute of Radioelectronics and Automatics), of the RIAME MAI (Research Institute of Applied Mechanics and Electrodynamics - Moscow Aviation Institute) and of the SPT « father » Professor MOROZOV has been developed with requirements corresponding to geostationary telecommunication satellites,
- An electric propulsion system with PPS1350 and SPT100 for North/South and eccentricity control will fly in 2000 on the STENTOR satellite and an electric propulsion system with a PPS1350 will perform the earth-moon transfer of SMART1 (ESA project, launch 2002).

This paper presents the development status and plan of these activities.

Introduction

Since 1991 CNES and SEP have decided to develop plasma thrusters in France because of the interesting performances of these thrusters for orbit control of geostationary telecommunications satellites. These thrusters are also very efficient to perform orbit raising of low earth orbit telecommunications constellations.

In 1993, the French plasma scientific community joined this activity.

In this paper the status of the following activities on plasma thrusters is presented:
- the scientific activities dedicated to the understanding of the physical phenomena involved in the operation of a SPT,
- the qualification of the PPS1350 manufactured by SEP, division of SNECMA,
- the in-orbit use of the PPS1350 and SPT100 on STENTOR for the North/South and eccentricity control and of the PPS1350 for the earth-moon transfer on the ESA probe SMART1.

Scientific activities

Since 1978, electric propulsion was not studied anymore in French research laboratories. The activities initiated in 1993 were therefore aiming at rebuilding a French competence on electric propulsion, particularly in the field of SPT, so as to support any future development of this technology by a comprehensive approach.

The following activities are currently being pursued in parallel:
- an experimental global approach consisting in the test of different laboratory models of SPT,
- the development of diagnostic techniques to characterise the plasma inside and outside the thruster,
- the measurement of the sputtering rate and secondary electron emission of different materials in order to evaluate the thruster erosion and to understand the plasma/thruster interactions.
- the development of different models to calculate the plasma characteristics, an hybrid model, a P.I.C. model and a fluid model.

Since 1998, the test facility PIVOINE is operational to test thrusters in the range of the SPT100. This test facility dedicated to scientific studies is described in [1].

Experimental activities

SPT Experimental Characterisation

Five laboratories are involved in these activities, the LPMI (Laboratoire de Physique des Milieux Ionisés, CNRS, Ecole Polytechnique), ONERA (Office National d'Etudes Aérospatiales), the LPGP (Laboratoire de Physique des Gaz et des Plasmas of the University of Paris-Sud, Orsay), the GREMI (Groupement de Recherche sur l'Energetique des Milieux Ionises) and the LAMO (Laboratoire d’Aéothermique de Meudon, CNRS).

Results obtained with three small Hall thrusters (SPT-20, SPT-50, ATON60) have been presented in previous papers [2].

The experimental research is now mainly performed with a specific laboratory model of SPT (dimensions close to a SPT100). This model named SPT100-ML has been designed and manufactured by the SEP and CNRS teams. It has been designed in order to allow the implementation of diagnostics to analyse the plasma discharge inside the thruster. Different geometries, magnetic profiles and materials can be tested.

A first serie of test has been performed in the PIVOINE facility in order to characterise the general operation of the nominal configuration of the thruster. Four main modes of oscillations are appearing as a function of the discharge voltage.

Fig.1 : Discharge currents as a function of time at four discharge voltages [2].

$\frac{m(Xe)}{l_{c}} = 3.5 \text{mg/s, } l_{c} = 4.5 \text{A}$

For a 3.5mg/s xenon flow the identified modes are: an irregular mode (I) for a weak voltage - 100V, a fluctuating mode (II) at 300V, an oscillating mode (III) at 400V and a pulsed mode (IV) at 600V. These modes are characterised by different levels of current fluctuations and by a main frequency increasing from 10-15 kHz (mode I) to 25-30kHz mode III and then decreasing to 25 kHz for the mode IV. In the range 100-400V and for a magnetic coil current $I_{c}=4.5A$, the thrust is varying between 20mN and 86mN then the specific impulse $I_{sp}$ is in the range 450s-1740s and the thrust efficiency $\eta$ is varying from 8% to 38%. For $I_{c}=6.3A$ the thrust reaches 105mN (due to a better electron focusing in the channel) with $I_{sp}=1985s$ and $\eta=58%$. In order to analyse the properties of the mode II and III, six Langmuir probes have been inserted in the external ceramic for the measurement of the plasma potential oscillations and a slit in the external ceramic permits the scan of the discharge by sixteen optical fibers (intervals: 0.5mm to 2mm). A spectrometer with a CCD camera is used in accumulation mode with a time resolution of 1μs and 0.4 as spectral resolution. 16 PM are also used to integrate the light of three spectral ranges (244-253nm for excited states of XeI; 460-468nm for XeII; 821-829 nm for neutral boron). After a time reconstruction [3], the space-time evolution of the emission intensities of XeI (462.4nm) and XeII (460.3nm) are obtained for the two modes I and III. For the mode I, the XeII line is observed with a maximum of intensity near the exhaust of the channel (at 4.5mm) thus the maximum for XeI is at 5mm. For
the mode II (Fig.2), the plasma is almost extinguished when the current discharge is minimum and the emission of excited neutral and ions is appearing before the maximum value of the current. This effect is due to the depletion of neutral species involving oscillations well described by an hybrid model [4]. For the mode III, the time resolution of excited boron line Bl 249.7nm shows a space correlation with the \textit{Xe}^{*} emission with a maximum at 6mm and an amplitude greater than for the mode I.

![Current intensity (A)](image)

**Fig.2**: Space-time evolution in a.u. of a) \textit{Xe}^{*} 462.4 nm, b), \textit{Xe}^{*} 460.3nm, \textit{B}^{*} 249.7nm for the mode III. Dashed line : \textit{Id}(t).

To increase the analysis of the ionisation and excitation processes in the channel, a second CCD camera (1μs exposure time) is used with a 45° axis channel observation from outside the vacuum chamber. \textit{XeI} and \textit{XeII} emissions are separated by filters and a time analysis permits to reconstruct the 2D-image of the emissive region at the edge of the channel. The Fig.3 shows the radial neutral dynamic during the oscillations of the mode III. For this mode, neutral oscillations are more important near the inner insulating surface, the maximum of luminosity from neutral is near the outer surface and the maximum of \textit{Id} is corresponding to a focussing effect of the emissive zone with also an extension out of the channel.

![Internal wall](image) ![External wall](image)

**Fig.3**: 2D imaging for \textit{XeII} for the mode III. a) \textit{Id} minimum, b) \textit{Id} maximum

The different discharge modes in the channel induce different behaviours of the plasma plume. In order to perform a space-time analysis of the plume and then to correlate the results with the time-resolved measurements in the channel, Langmuir Probes (LP) and a Retarding Potential Analyser (RPA) have been used. Along the plasma axis and from \textit{z}=100mm to \textit{z}=300mm, the plasma potential is decreasing from \textit{32V} to \textit{23V}, the electron temperature from \textit{4.4eV} to \textit{3eV} and the density from \textit{3.5} to \textit{1.10^{17} m^{-3}} for a discharge voltage of 300V. For the mode III, a time reconstruction (Fig.4) shows the oscillations of the map of the current density collected by the single LP [5].

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Fig. 4: Current density measured by Langmuir probe in the plume as a function of time.

The mean value of the IEDF indicates for the mode I, a low dispersion for the energy (lower than 15eV) that assumes a uniform potential for the ion source region (separated to the accelerated zone). For the mode III, the dispersion is more important but the mean ion energy is nearly the same. The time evolution of the ion energy distribution function (IEDF) has been obtained in the plume by RPA measurements for the modes I and II and for two plume cross sections (located at z=430mm and z=860mm). Interesting results have been deduced by RPA measurements as the increase of the plume divergence with the discharge current, suggested correlation between IEDF and time and range variations of anode potential, ions created further into the channel than in the mode I (verified by optical measurements).

Fig. 5: Time evolution of ions energy distribution function. RPA at z=860mm. a) mode I, b) mode II

Laser induced fluorescence (LIF) is a fruitfully diagnostics to perform a local measurement of the ion velocity [6]. Experiments have been carried out in order to measure the axial and radial ion velocities of Xe+*(5d⁷D₁/₂) with a laser excitation at 605.1nm. The velocity is deduced from Doppler-shifted spectra and a comparison with a model introducing the spectra line structure (isotopic and hyperfine structures). The ion velocity has been measured in the plume of a SPT-50 (Ud=300V) set in the ONERA-B61 chamber. A linear profile (450m/s/mm) has been obtained for the radial velocity at z=30mm and the axial velocity is 2.5km/s at z=3mm (measurement through the ceramic), 15.0km/s at z=+2mm and 18.74km/s at z=+30mm. Low energy ions are observed in the plume at r=30mm.

The feasibility of a time resolved LIF measurement has been proved by the GREMI and the LSP (Laboratoire de Spectrométrie Physique of the University Joseph Fourier at Grenoble) by testes with a 30kHz pulsed Helicon plasma source.

LIF measurements will be performed to analyse the ion velocity inside and outside the SPT100-ML.
Krypton is a propellant alternative for SPT due to its high mass, inert properties and low cost compared to xenon one. For the same operating conditions including magnetic profile and gas flow, the length of the ionization layer with krypton is greater than xenon one and for a discharge voltage \( V_d = 300 \text{V} \) the thrust is 11% lower (Fig.7) and the efficiency 26% lower (Fig.8) [9].

The optimisation with krypton should also include a new SPT design.

### Plasma/wall interactions

The erosion of the acceleration channel is one of the life limiting factor of a SPT. The sputtering rate of different material as a function of the Xenon ion energy and incidence has been measured at CERT (Centre d'Etudes et de Recherches de ToulouseONERA). The secondary electron emission of the ceramic can modify the electron conductivity and the performances of the thruster. This emission is measured at CERT-ONERA for different incident electron energies and for different materials. In the frame of the Research Group on Plasma Propulsion activities, the RIAME/MAI is performing calculations inside the thruster to evaluate the erosion of the thruster and also to know the trajectories of the sputtered particles inside the thruster. These calculations are under experimental validation by the use of quartz micro balances. The LPGP is carrying out the research on the correlations between Boron line BI emission for different operating thruster conditions (Fig.2).

### Plasma modelisation

Two laboratories are working on the modelisation of the plasma inside a Stationary Plasma Thruster, the CPHT (Centre de Physique Théorique, Ecole Polytechnique) and the CPAT (Centre de Physique des Plasmas et Applications de Toulouse).

After works on an hybrid 2D stationary model and experimental observations on the SPT operation, the development of a one-dimensional transient quasi-neutral hybrid model has been decided because the SPT is operating mainly in a pulse mode (frequencies close to 20, 30kHz).

The primary components of the model include the continuity equation for neutrals with a constant velocity and ionisation loss term, a microscopic description of the ion transport and a fluid description of electrons. Charged neutrality is assumed, and the axial distribution of the radial magnetic field profile is given. The model successfully predicts the plasma oscillations observed in this device as described in detail in [10]. Recently, this model has been used to calculate the performance of a laboratory model of SPT100 as a function of discharge voltage, mass flow rate and for 2 different gases Xenon and Krypton. The model predicts correctly the trends observed experimentally [9].

The future of this hybrid model is the development of a 2 dimensional version using the same general hypothesis than the 1D version. This evolution will allow to include a real magnetic configuration and to take into account more accurately the plasma/wall interactions. Work is also continued to better understand the electron transport in Hall thrusters with comparison of Electron Energy Distribution Function with two different approaches (Monte Carlo
Simulation and kinetic models of electron transport [11]).

Another 1D model using a full kinetic description of the plasma and fully time dependent is being developed. The use of the so called direct implicit method with a predictor corrector method allows to work with time steps larger than the plasma frequency. The time step is limited by the electron gyro frequency. A completely consistent method describes electron-neutral collisions and ionisation. The main advantage of a fully kinetic description is that it gives the exact distribution function of the electrons. Collisions with the wall as well as the existence of a Debye sheath are also modelled. The code is now fully operational and in the preliminary test runs it has been able to reproduce low frequency oscillations very similar to the ones observed in an SPT50.

Comparisons between the hybrid and the PIC models have been performed [12]. They provide very similar (qualitative) predictions of the space and time variations of the plasma properties. One of the conclusion is that the low frequency oscillations in the SPT are associated with the depletion of neutral atom density in the exhaust region due to strong ionisation.

The steady state and the oscillations of the discharge is also described by an 1D fluid description at the IPPT-PAN (Institute of Fundamental Technological Research at Warsaw – Poland) with the Research Group on Plasma Propulsion. In the model, electrons, ions and neutral atoms are described by fluid equations assuming an electric neutrality, an azimuthal electron velocity and an electric field deduced from generalized Ohm’s law. An electron-wall collision frequency is introduced. In the most simplified version of the fluid model with a constant electron temperature, the electric field has a singularity and the set of equations gives two solutions. By introducing a jump discontinuity ion velocity, ion density, electric field and electric potential have been calculated.

**PPS1350 Development and Qualification**

The development of a plasma thruster by the manufacturer SNECMA division SEP, with the collaboration of Russian companies and research centers has begun in 1993.

The design of the PPS1350 uses a patent from FAKEL and a patent from SEP. The main differences with the SPT100 are the magnetic configuration, the mechanical design and the discharge voltage of the nominal operating conditions. Two product lines are developed, a Russian one, FAKEL, using Russian materials and FAKEL processes and an occidental one, SEP, using occidental materials and SEP processes.

The nominal performances of the thruster are the followings:
- thrust 88 mN
- specific impulse 1720 s
- electric power 1500 W
- discharge voltage 350 V
- total impulse 1,4410⁵ Ns
- operating cycles 5200
- divergence 42°

The environmental specifications are summarised below.

**Temperature range**:
- Operating -43°C, +205°C
- Qualification -48°C, +210°C

**Qualification random vibrations**:
- 20 - 70 Hz 49 dB/Oct
- 70 - 175 Hz 1 g²/Hz
- 175 - 210 Hz -12 dB/Oct
- 210 - 280 Hz 0,26 g²/Hz
- 280 - 300 Hz -22 dB/Oct
- 300 - 900 Hz 0,13 g²/Hz
- 900 - 2000 Hz -6 dB/Oct

**Qualification sinus vibration**:
- 5 - 22 Hz 10 mm 2 Oct/mn
- 22 - 100 Hz 20 g

**Shock level**:
- 500 Hz 100 g
- 1200 Hz 600 g
- 3000 Hz 2000 g
- 10000 Hz 2000g

3500 hours of cumulated on-time have been performed on a breadboard model. The operation of the thruster was quasi-continuous (only one hundred cycles on/off). Two qualification models have been manufactured. One of this model has been qualified to thermal and mechanical environment and the second one is dedicated to endurance testing [13]. Nowadays, 4005 hours of operating time and 4490 cycles have been cumulated on this model. The complete qualification lifetime corresponds to 7000 hours of operation.

The lifetime requirement for the STENTOR satellite being 1500 hours, the manufacturing of the 2 flight models has been decided and performed.
STENTOR

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

The programme is 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) is in charge of all technical and financial aspects, with CNES as project manager, and awards the qualification.

An integrated industrial project team bringing together Matra Marconi Space (MMS) and Alcatel Space acts as joint prime contractor, under the authority of an industrial steering committee.

The STENTOR satellite has a mass of approximately 2000 kg. It will be placed on a geostationary orbit near the Télécom-2 satellites. Of a total power of 2500 W, at 2 years, 1000 W will be allocated to the payload, both night and day. STENTOR will fly enough fuel for positioning, followed by 2 years in orbit to ensure the redundancy of the plasma propulsion system for this same period, necessary for intense experimentation. The quantity of xenon required for plasma propulsion will be sufficient for nine years in orbit.

Ariane 5, in double launch configuration, is planned to launch the satellite before the end of 2000.

The Plasma Propulsion Subsystem controls the inclination and eccentricity for north/south station keeping. This subsystem includes in particular a wound carbon xenon tank with a titanium liner, a pressure regulator and two plates of two plasma thrusters, one SPT100 and one PPS1350. Thruster Modules and Electrical Modules are developed under SNECMA’s responsibility.

In addition, an experimentation plan is implemented, in order to monitor the performances of the Plasma Propulsion System and its interactions with the satellite (plume effects). The different in-orbit experiments that will be performed are the following:
- plasma effects on radio communications; the satellite will be oriented in order to maximise the interactions between the plasma plume and the antenna,
- plasma propulsion sub-system experiments; test of the thrusters with different operating conditions,
- measurement of the thrust and the dynamic plume effects with the attitude and orbit control system,
- additional measurements on the solar array; a Langmuir probe, an energy analyser, quartz microbalances and specific solar cells will allow the measurement of the plasma characteristics, of the erosion and of the contamination generated by the plasma.

A detailed description of the plasma propulsion subsystem and its qualification status is presented in [14].

SMART1

SMART1 is the first Small Mission for Advanced Research in Technology of the ESA’s Horizons 2000 scientific programme. This project is under approval. Its purpose is to test new technological concepts to prepare future cornerstone missions using solar electric propulsion. The 350 kg SMART1 spacecraft will be launched in late 2002 and will use PPS1350 to reach a moon orbit [15]. The PPS1350 will be used with different values of the electrical power because of the SMART1 electrical characteristics. A special procedure, already tested in the PIVOXE facility, will be used in order to master the inrush power demand well below the available satellite power. SNECMA is responsible of the plasma propulsion sub-system.
Conclusion

This paper has presented the different activities in the field of Plasma Propulsion Development.

To summarise, the objective of this program is to improve the competence of industry and scientific laboratories in Electric Propulsion and particularly in the Hall effect thrusters.

Today, this competence is unique in Western Europe and will allow the prime contractors to be competitive in the area of telecommunication satellites.

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References


