Plasma Jet Pack Technology for Nano-Microsatellites

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Abstract: The vacuum arc thruster (VAT) appears to be a credible alternative to gas feed propulsion systems for nanosatellites and microsatellites. With solid metal propellant and high specific impulse, it significantly simplifies the propulsion unit architecture and offers new missions possibilities. Since 2015, Comat develops the Plasma Jet Pack (PJP). This paper presents the PJP advantages and the key points of this development.

I. Introduction

COMAT[1] designs, manufactures, qualifies and commercializes equipment for space industry since 1977. This company initially developed its activity in the microgravity field, designing and building science equipment for manned flight. Some years ago, COMAT expanded its expertise to satellite markets and particularly to space equipment such as mechanism and propulsion. COMAT is an integrated company with the ability to deliver a global offer for space equipment.

With the emergence of the "New Space" COMAT reinforced its R&D team in order to develop equipment for Small Sat, one of them is a propulsion module named "Plasma Jet Pack".

Since 2015, Comat develops several tools and collaborates with different research centers in order to improve the understanding of the vacuum arc physics. Comat engaged an experimental strategy based on iterative Bread Board Models (BBMs) characterization. The final objective is to commercialize two types of propulsion modules:

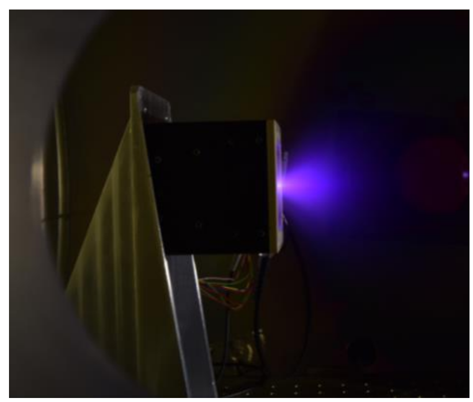

Figure 1. BBM6 prototype firing at COMAT propulsion laboratory

- Plasma Jet Pack 0-30W for nanosatellites in 2021
- Plasma Jet Pack 0-150W for small satellites in 2022

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II. PJP's development and achievements

A. PJP physics

The vacuum arc thruster (VAT) physics allows eroding solid metal propellant thanks to electrical discharge in vacuum between two electrodes: the cathode (solid propellant) and the anode (passive electrode). The VAT is classified in pulsed electromagnetic thruster's category. The PJP uses capacitive storage: capacitors banks are connected to the terminals of the electrodes and are waiting for the High Voltage Trigger System (HVTS - © under patents) to begin the main discharge. Because the vacuum is one of the best isolator (around 30kV/mm), the role of

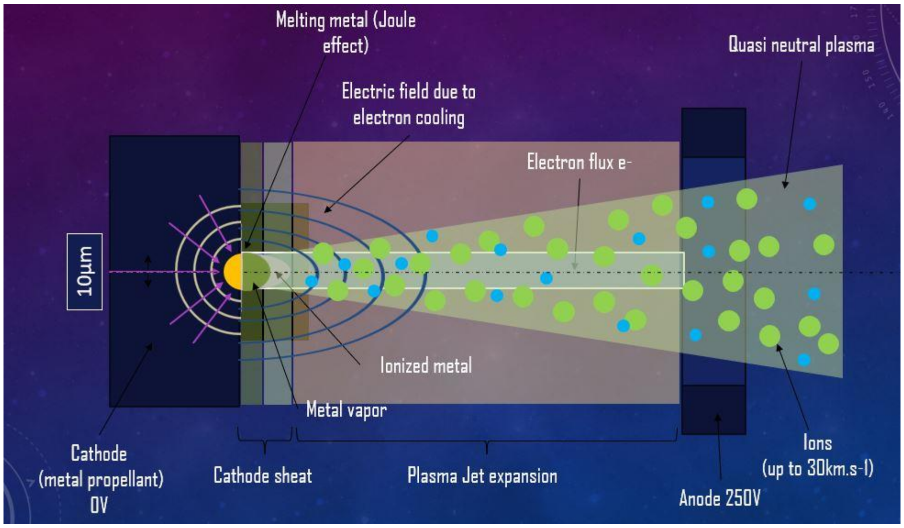


Figure 2. Vacuum arc physic.

the HVTS is to provide matter in the inter-electrodes region in order to ignite the arc in vacuum at lower voltage (~ 200V). Therefore, the frequency of the plasma pulses is dictates by the frequency of the HVTS.

When the arc is initiated, the voltage between cathode and anode falls to the so called "burning voltage"[2,3] (20-50V depending on the cathode material) extended on small cathode sheath region with a typical length lower than 1µm.This vacuum arc phenomena implies the creation of high electric field (~0.1 - 1GV/m) responsible of strong thermo-ionic emission on the cathode area.

At the same time, erosion craters called "cathode spots" are created by Joule effect due to main discharge current. The number of spots per pulse varies depending on the arc current (0.1-10kA). During the discharge, the spots temperature increases over the boiling point and the spots grow up from 1 to 30µm (see Figure 3.). Vaporization takes place until the arc moves on another spot or extinguishes. Finally, electrons emitted from the cathode by thermo-ionic emission collide with neutral. Then, all the neutral atoms are due to an avalanche mechanism and quasi-neutral plasma is created.

The ions close to the border of the cathode sheath are strongly directed to the cathode spot due to the high electric field in this region. This ion bombardment allows maintaining cathode erosion and vaporization. Among the total ion population, one part is used to ensure the arc stability and the other part is used to generate thrust.

The plasma formed is a collisional cold plasma[4] with a Debye length around 1µm. Plasma expansion from the quasi-neutral region leads to the formation of complex potential structures due to the electron cooling phenomenon. In fact, the rapid thermal expansion of the light electrons compared to the slow expansion of the massive ions leads to the formation of an electric field which strives to maintain quasi-neutrality in the plasma by accelerating the ions. Thanks to this ambipolar acceleration, the ions velocity increases from thermal velocity (1-4km/s) to supersonic velocity (10-40km/s).

Finally, by doing a discharge between two electrodes, the vacuum arc physic enables sublimation, ionization and acceleration of quasi neutral plasma from solid metallic propellant. Consequently, the PJP hasn't the disadvantages of other gaz feed technologies (storage tank, valves, debit controller, grid erosion, neutralizer, etc.) but has the main advantage to get solid propellant with high specific impulse (1000-4000s). These benefits allow this *Plug & Thrust* technology to target the Small Sat market by offering high total impulse in very small volume without any pre-heating process or safety integration constraints.

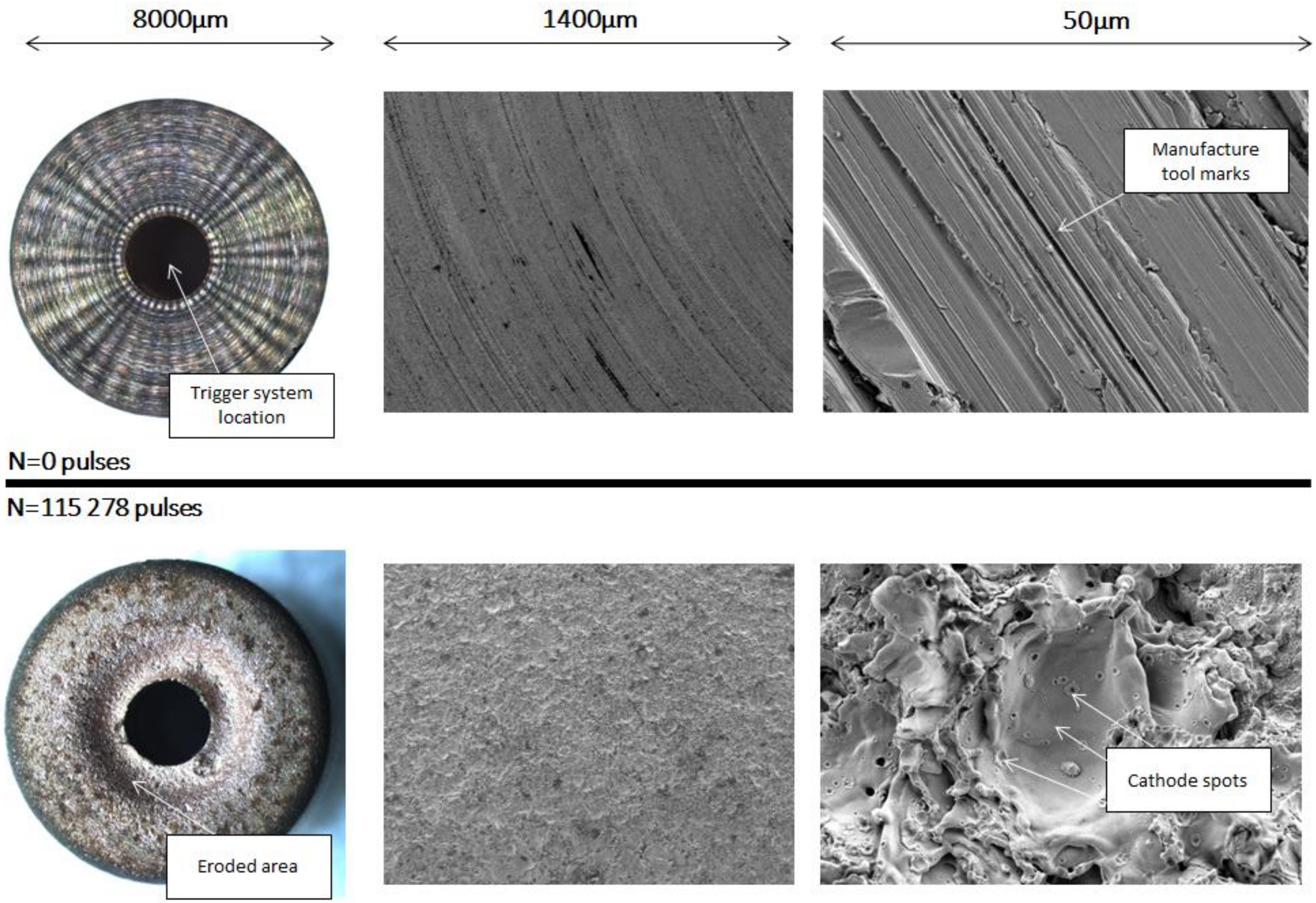


Figure 3. Copper cathode MEB pictures © CNES - ELEMCA. Top : Clean cathode. Bottom : Eroded cathode (N=115 278 pulses at 2J/pulse) with cathode spots.

B. BBMs's development

The vacuum arc has been extensively studied by Boxman et al among others[2,3], and has applications in metallic coating deposition, ion source, high current interrupters, etc.

However, in spite of numerous scientific researches on vacuum arc physics, VAT suffers from a lack of experimental feedbacks and theoretical studies to better understand the physics phenomena, especially the acceleration mechanism. Indeed, the plasma density is so high that it cannot be simulated easily with PIC or fluid models. Therefore, Comat decided to initiate an experimental approach by designing, manufacturing and testing Bread Board Models.

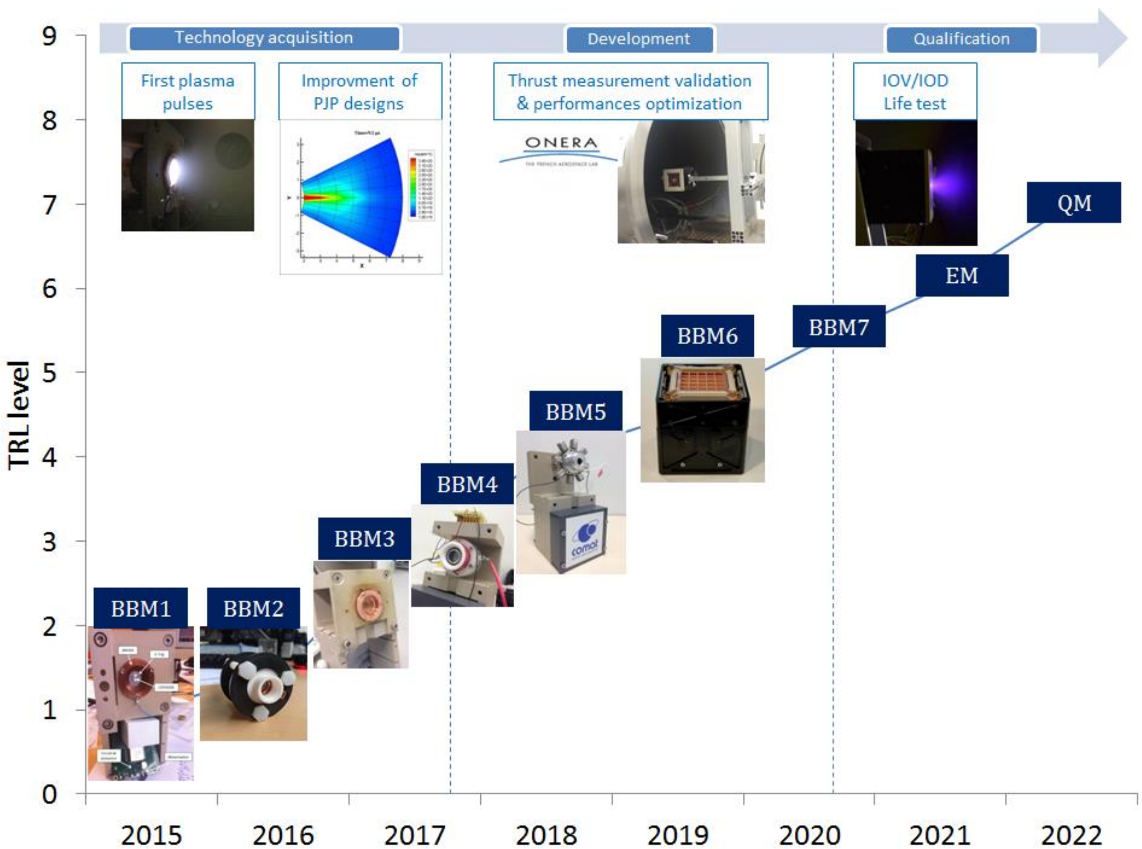


Figure 4. Road Map – PJP 0-30W.

Since 2015, the propulsion's team works on 6 axis of development in parallel:

- Cathodic material performances (atomic mass, boiling point, density, ionization level, etc.)
- Electrical discharge (voltages, currents, pulse duration, current shape, capacitors type, HVTS, etc.)
- Electronic PPU (Voltage generation, HVTS, EMC, µcontroller programming, RS 485, etc.)
- Discharge chamber (geometry, electrodes design, insulators, electromagnetic field lines topology, HVTS, etc.)
- Thermal, Thermo-elastic, Mechanical and Electronic Radiation analysis
- Facilities & Measurements tools (thrust bench, Langmuir Probes, etc.).

In four years the PJP Technology Readiness Level (TRL) increased from 0 to 5. The first BBM was tested in 2015 at TRL 1, and the BBM6 was tested at the end of 2018 at TRL 4-5. The development is now focused on life duration (total impulse) and robustness of the system. The BBM6 is a propulsion module ready to make an IOD/IOV mission with total impulse up to 200Ns. The final product will be available in 2021/2022 after the characterization of the last BBM (BBM7-2020) and the qualification process scheduled in 2021.

C. Comat facilities

Figure 5. Comat Propulsion Laboratory.

COMAT has key infrastructures for integration of space equipment and tests : 60m^2 clean room ISO 6/7 and 300m^2 clean room ISO8.

The COMAT Propulsion Lab (CPL) is located in the ISO7 room of 20m^2 and is dedicated to PJP testing. All equipment required to characterize thruster and plasma are set: pulsed current and high voltage probes, numerical high speed oscilloscope and thermal monitoring.

Additionally to the BBMs development, COMAT designs and manufactures homemade tools in order to characterize the plasma plume[4] and the thrust level.

In 2016-2017 COMAT developed a thrust balance (torsional pendulum) to characterize the performance of the PJP. Thanks to a CNES R&T funding, COMAT's thrust bench has been validated by a European reference thrust bench at ONERA Palaiseau (Paris) in 2018/2019.

Two campaigns were conducted in order to validate the thrust measurement in COMAT facilities. The first campaign took place in 2018 and concerned the BBM5.v3 prototype. The second campaign took place in 2019 and concerned the BBM6 prototype. The last campaign fully validates the thrust measurement lead by Comat. As of today, this facility can be used to measure low thrust and impulse bit with a global uncertainty lower than 5% above 5µN of thrust.

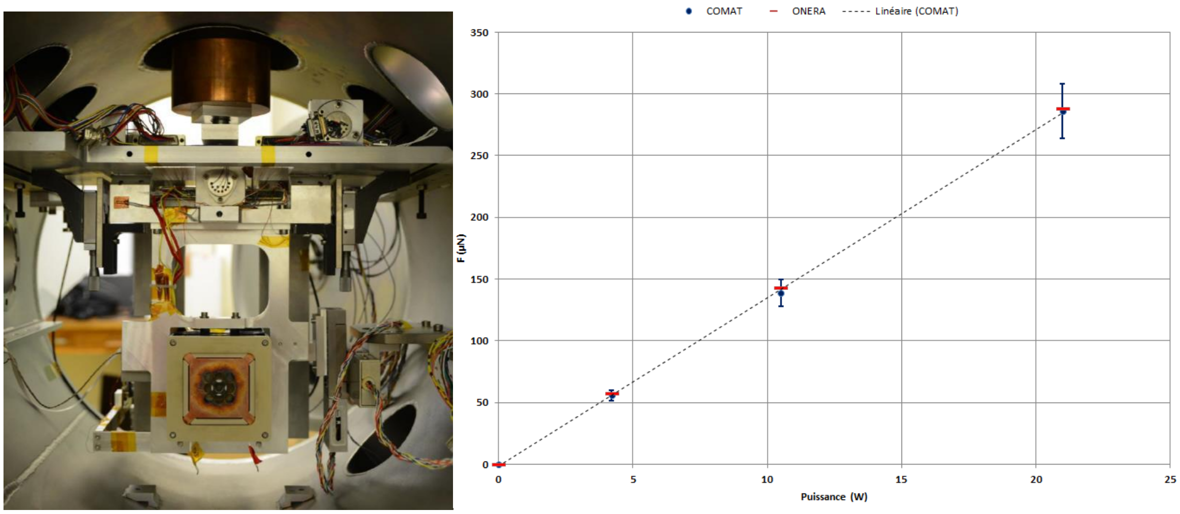


Figure 7. BBM6 thrust measurements. a) BBM6 integrated on ONERA thrust bench © ONERA picture. b) Measured mean thrust (µN) in function of PJP power (W). Blue: Comat dots with error bars at ±3σ. Red:

D. Performances reached & future works

The most challenging part was to develop a robust HVTS that can ignite the arc with a 100% probability with low power consumption. This step was reached in 2017 thanks to the BBM5. After that, plasma diagnostic and thrust measurement has been done to reach satisfactory performances. For example, with a copper cathode, the maximum thrust at 30W full power is around 270µN with a specific impulse around 2400s. At this stage of development, the maximum thrust efficiency achieved is around 10%.

By reaching 1U overall volume and 1kg overall mass (thruster + propellant + PPU), the BBM6 is one of the most compact electric thruster on the nanosatellite market. The module is able to handle 4kNs with less than 18cm^3 propellant volume. The functional specification is almost reached and the entire module takes account of all the space field constraints (thermal, thermo-elastic, mechanical, etc.).

On BBM6, the following performances have been validated:

Power	0 - 30	W
Overall Volume	1	U
Overall Mass	1	Kg
Thrust to power *	2 - 14	µN/W
Specific Impulse *	400 - 3200	s
Total impulse	196	Ns
Electronic efficiency	90	%

** depending of the metal propellant*

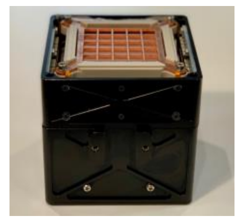
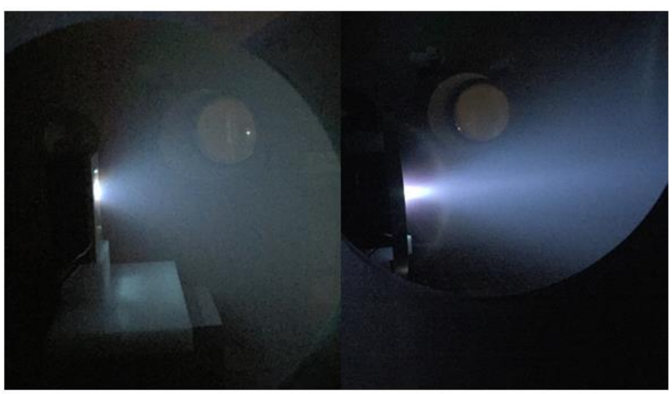


Figure 5: BBM6 validated performances.

The first life duration (200Ns) of the system showed some issues relative to plasma pollution of the insulator surface that can lead to a failure of the HVTS system. Several modifications of the geometry have been done to tackle this contamination phenomenon, especially on the external geometry of the HVTS. The new design is in manufacturing and will be tested at the beginning of august 2019 in order to reach the objective of 4kNs of total impulse.

In 2019, COMAT explores the influence of an applied magnetic field on the performances. The application of external magnetic field can improve both thrust and specific impulse. Indeed, magnetic field increases the erosion rate of the cathode material and gives additional acceleration to the ions thanks to the magnetic nozzle phenomenon[5]. Moreover, the magnetic field focalizes the plasma jet and thus decreases the contamination risk of the HVTS. These experimental campaigns lead to future evolution of the PJP's design (BBM7).



B=0 mT B=22 mT

Figure 2: BBM6. a) Without magnetic nozzle. b) With magnetic nozzle.

All the tests conducted on BBM6 will improve the understanding of physics and the performances (thrust, specific impulse, total impulse, efficiency) for the next PJP's generation. The futur improvements of the BBM7 design are the following ones:

- Increase the thrust to power and the specific impulse thanks to magnetic nozzle.
- Handle life duration up to 4000kNs of total impulse.

E. PJP's advantages and capability

Such technology will represent a key competitive asset to sustain the commercial demand for satellites (including those of large and medium constellations). Furthermore, the emerging international laws on space debris and satellite end-of-life operations, for Low Earth Orbit satellites, open additional market opportunities for the PJP technology.

PJP technology offers several advantages for nanosatellite platforms:

Small size	The first constraint of this type of platform is to get required performances for all equipment in order to perform the mission. The service module equipment should be small in order to maximize the volume of the payload.
Low power consumption	Onboard these small platforms, only a small area of solar panels can be accommodated. So, every equipment should be efficient and works at low power.
High reliability	Commercial applications require high reliability and longer duration for thermal, mechanical, radiative environments.
Low mass	This constraint is especially important for commercial applications within satellite constellations. The launch cost is one of the business drivers to build profitable in-orbit infrastructures.
Low cost	The cost target must be reduced by half, compared to the current market price.
ITAR Free	All selected components have been chosen to be ITAR-free. These products will improve European independence from the USA. All products can be sold around the world for any applications.
Ready to use	All products are ready to use after delivery. The objective is to reduce all integration constraints at the minimum level.
LOS compliant	All parts of the module can be burn in the earth atmosphere for the deorbitation. PJP avoid passivation issues because there is no presurized tank.

Table 1: PJP advantages for nanosatellite platforms.

Using Plasma Jet Pack technology removes most of the important in-flight constraints:

No preheating	This is a "Plug & Thrust" thruster, no latency time is imposed before firing. So, firing can be done on demand.
Thrust adjustable	Thrust is adjustable as function of frequency of the pulses without any variation in efficiency. There is not only one operating point, but an infinity from 0 to 30W.
Remaining propellant	The remaining propellant estimation is done by counting the number of pulses. The uncertainty is largely reduced due to the repeatability of the erosion.

Table 2: PJP in-flight advantages.

Consequently, the suppression of these constraints allows new missions in addition to the classical ones:

Continuous altitude control	Station keeping for low earth orbit satellite consists in one long maneuver each 5 to 10 orbits. With Plasma Jet Pack, the mission can continue normally. Thrust correction is done pulse by pulse when the thruster is aligned with speed vector.
Fine attitude control	Some missions need to have very accurate thrust. The PJP thrust can be adjusted with frequency and the capability to thrust without pre-heating allows to do these missions with better accuracy than with cold gas thruster.
In flight formation	These class of missions requires fine tuning of velocity increment to enable precise formation flying while thrust strategy are envisaged to assist formation flying. The PJP small impulse bit allows to have small transfer momentum.
Satellite inspection	inspection or spying of other satellites can be performed with small and accurate satellites. These satellites should be agile in order to take detailed pictures of the target.
Deep space mission	The high specific impulse combined with the high mass density opens to high delta V mission like asteroid exploration.

Table 3: Missions achievable by PJP.

III. Perspectives

All these advantages allow the PJP to open the nanosatellite market by offering new mission possibilities (e. g. synthetic aperture radar or optic) and answer to specific need in term of SCAO (e.g. in-flight formation for science mission). Comat is now ready to make an IOD/IOV in order to demonstrate the capability of the system in the space environment.

The latest BBM is scheduled in 2020; the BBM7 will be the last prototype before the qualification phase and the beginning of the PJP 0-30W commercialization. The PJP 0-150W is designed in parallel thanks to PJP 0-30W heritage by clustering the main building blocks of the module.

COMAT plans to be ready in 2021 to offer PJP module at the world wild nanosatellite market's customers.

Acknowledgments

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