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A "PLUG & THRUST" SYSTEM COMBINING VAT AND MPDT TECHNOLOGIES

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ABSTRACT:

In this paper, a "plug & thrust" system combining vacuum arc and MagnetoPlasmaDynamic technologies is presented as a new modular approach able to achieve a larger list of in-orbit missions for small and nanosatellites. After the qualification of Comat's vacuum arc thruster (VAT), the Plasma Jet Pack (PJP) and its power and control unit (PPSCU), the next step is to develop, with the help of European partners, a low power MagnetoPlasmaDynamic thruster (MPDT) which will be the last building block of the Modular Pulsed Propulsion System (MP2S). As matching the gas and electric discharge times is crucial for energy conversion, a fluidic benchmark has been developed to characterize the behavior of a fast valve.

1. INTRODUCTION

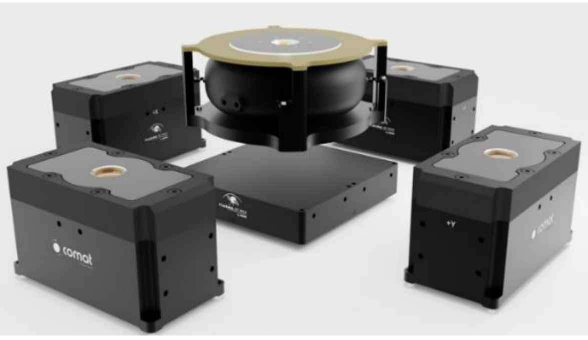

Figure 1. Modular propulsion system combining 4 PJP and 1 P-MPDT, controlled by one PPSCU

Comat has been developing a vacuum arc thruster (VAT) since 2014. Called Plasma Jet Pack (PJP), this low-power thruster has already been qualified and has flight heritage as it is already flying on two satellites, with a third launch planned for 2025. The latest iterations of the PJP have led to a modular design separating the energy storage/plasma part (nozzle) from the power generation/control part (PPSCU).

The two sub-elements are housed in separate boxes that are connected by a harness. Up to 4 nozzles can be connected to a single PPSCU. This allows better integration at satellite level and improved vectoring, as the nozzles can be oriented on different sides of the satellite.

Since the end of 2023, Comat has been developing a pulsed MPD thruster that will be integrated into the existing modular system. The aim is to combine several VAT and MPD propulsion units on a single power adapted PPSCU.

2. PROJECT PRESENTATION

2.1. Horizon Europe project

MP²S, for Modular Pulsed Propulsion System, is a European 3-year project led by Comat and part of the Horizon Europe program under the Grant Agreement n°101135440. It is in partnership with the Institut für Raumfahrtsysteme (IRS) in Germany, the Centre National de la Recherche Scientifique (CNRS) in France, Plasmasolve in the Czech Republic, and Endurosat in Bulgaria. The aim for this consortium is to develop a low-power pulsed MagnetoPlasmaDynamic thruster (P-MPDT).

2.2. Partners presentation

Figure 2. Partners' location

Comat, created in 1977, has been working on electric propulsion for 10 years. The company

develops thrusters and can master the entire development chain, from design to manufacturing, assembly, integration, and testing.
Laplace and Icare are two French laboratories specializing in plasma propulsion and the study of plasmas in general. With several decades of experience in propulsion, they developed plasma diagnostic tools: Langmuir probes, mass spectrometry, LIF, etc., which they have been able to adapt to pulsed operation with the thrusters developed by Comat.
The IRS is a laboratory attached to the University of Stuttgart. Specializing in space systems, the plasma propulsion section has been working for several decades on technologies as diverse as MPDTs, PPTs (Pulsed Plasma Thrusters), whether gas or solid, or even ABIEs (Air-Breathing Ion Engines), for example.
PlasmaSolve is a Czech company specializing in plasma modeling, with expertise in modeling PECVD-type deposition plasmas. The company also works on propulsion, having already collaborated with Comat on the development of the PJP.
Endurosat is a supplier of cubesat and space systems. They have a global, satellite-scale vision of thruster development.

3. VAT TECHNOLOGY

The principle is to generate an arc between two electrodes, eroding one and accelerating the ejected particles to create the thrust. To generate this vacuum arc, an ignition system is required. It consists of a very high-voltage, short-duration arc that is produced on the surface of a ceramic. The PJP is a low-power thruster (0-30W) that operates in a pulse mode. By adjusting the operating frequency of the thruster, it is possible to modulate the power consumption of the PJP.

The low thrust produced by this engine and its "on-demand" operation make it possible to carry out missions requiring precise maneuvers such as docking or attitude control, thanks to its remote configuration. The PJP is also capable of orbit maintenance and deorbiting.

The principle of acceleration of the particles lies in the cathode sheath, in the cathode spot region. This mechanism is not well described in the literature, especially with the characteristics of the PJP. Indeed, the discharge is high current/short duration, which creates explosive effects at the surface of the cathode.

4. MPDT TECHNOLOGY

The acceleration mechanism of MPD technologies lies on Lorentz's forces $\vec{j} \times \vec{B}$. This force allows the plasma to reach a higher speed and therefore to increase the efficiency of the thruster.
Most of the MPDTs have a coaxial geometry with cylindrical electrodes, matching the induced azimuthal magnetic field shape to avoid edge effects [1]. Indeed, the main discharge is created radially, which then leads the plasma to get a main axial thrust component called "*blowing*" [2]. Because of the anti-axial current component present when the cathode is shorter than the anode, the plasma gets also a "*pinching*" or "*pumping*" thrust component, focusing the plasma on the exit axis, improving its vectorization. This configuration is a "*Self-field MPDT*".

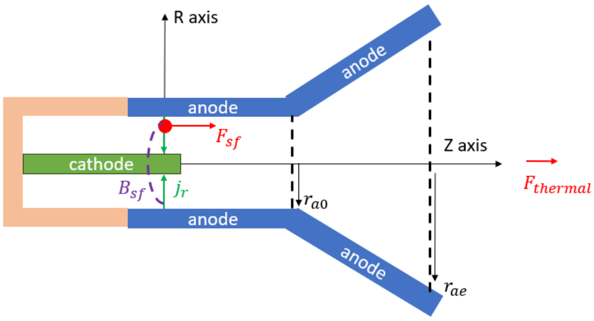

Figure 3. SF-MPDT thrust components

By applying an external magnetic field in the axial direction with magnets or coils, the plasma swirls and gets a bonus angular momentum. At the anode's end, this rotation energy is converted into axial speed which increases efficiency. Moreover, the diverging magnetic field lines induce an azimuthal hall current which, combined with the applied field, adds another axial thrust component. This configuration is called an "*Applied-field MPDT*".

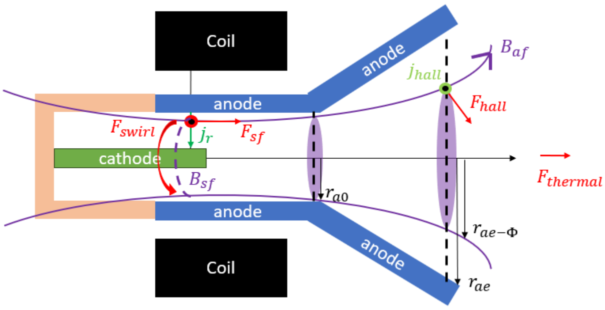

Figure 4. AF-MPDT thrust components

5. PERFORMANCES

5.1. Performances definition

First, let remind us of some usual quantities which are used to describe the performances of a thruster such as the specific impulse (I_{sp}) and the thrust-to-power ratio (T/P):

$$I_{sp} = \frac{I_{bit}}{m_p g_0} = \frac{v_e}{g_0} \qquad \text{Eq.1}$$

$$T/P = \frac{\langle \dot{m} v_e \rangle}{P_e} = f \frac{m_p v_e}{P_e} \qquad \text{Eq.2}$$

With I_{bit} the impulsion per pulse, m_p the mass ejected per pulse, g_0 is the standard gravity, v_e is the ejection velocity, f the thruster operating frequency and P_e the input electric power.

Contrary to most of the MPDTs, which are high-powered (from 100 kW to several MW) [3]. The presented P-MPDT operates at a power between 0 and 200W, depending on the operating frequency. The MP²S aims to have performances such as an I_{sp}~$2000\ s$ and a T/P ~$20\ \mu N/W$. The total impulse target is >20kNs in order to cover a wide range of missions, even at low power and in a small volume.

Considering a full conversion of the energy stored in the capacitors during the time of a pulse τ_p , the efficiency is deduced according to the I_{sp} and the T/P:

$$\eta = \frac{g_0}{2} I_{sp}(T/P) \qquad \text{Eq.3}$$

Computing with the performances above: $\eta = 20\%$. Then, by working at a reasonable frequency of 10 Hz, the mass per pulse needed is deduced from Eq.1 and Eq.2 and finally $m_p = 20\ \mu g$. A whole fluidic system must be then qualified to control as accurately as possible the mass ejected.

5.2. Propelling gas

Regarding a wide range of existing MPDT prototypes [3], lots of propellants can be used for the discharge which represents an advantage compared to other technologies.

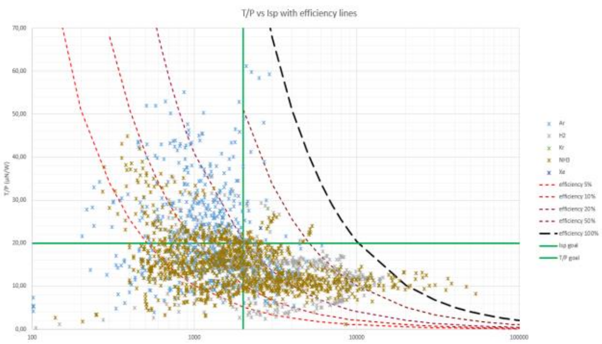

Figure 5. Isp vs. Thrust-to-power ratio with iso-efficiency lines for MPDTs, MP2S's performances are represented by the 2 green lines – Princeton university database

Argon is a very common gas, non-reactive, and easy to supply compared to Krypton and especially Xenon. For safety, it has been decided to completely avoid hydrogen because of the explosion risks and to choose Argon at first.

6. ELECTRIC DIMENSIONNING

The duration of the electric discharge depends on the duration of the gas pulse, as the aim is to maximize the ionization rate to increase performances. As a first approximation, the electric behavior of the main discharge of a pulsed MPDT can be assimilated to a simple RLC circuit critically damped [4].

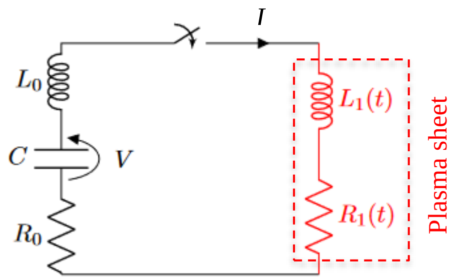

Figure 6. Equivalent Circuit of an MPDT discharge

To define the capacity, the energy stored in the capacitor bank is set as the energy defined previously in the performances:

$$E_{capacitor} = \frac{1}{2} C V^2 \qquad \text{Eq.4}$$

Therefore, as the initial voltage takes values from 250 to 500 V and the input energy is 20 J, the capacitor bank values range from 160 to 640 µF. For this circuit, Kirchhoff's laws yield:

$$V = (R_0 + R_1)I + \frac{\partial}{\partial t}(L_1 I) + L_0 \frac{\partial I}{\partial t} \qquad \text{Eq.5}$$

$$V = R_{eq} I + L_{eq} \frac{\partial I}{\partial t} \qquad \text{Eq.6}$$

Where $R_{eq} = R_0 + R_1(t) + \frac{\partial L_1}{\partial t}(t)$ and $L_{eq} = L_0 + L_1(t)$. As the final resistance is dominated by plasma inductance variations [4], it is difficult to get a clear criterion, without involving complex MHD simulations, which would yield optimized chamber dimensions. To get at least an order of magnitude of the circuit's constants, the well-known criterion for critically damped RLC circuits can be used:

$$\xi = \frac{R_0}{2}\sqrt{\frac{C}{L_0}} = 1 \qquad \text{Eq.7}$$

As the circuit's inductance is in the order of 100 nH, the resistance needed here varies from 25 to 50 mΩ. With those parameters, the discharge time, which can be estimated as 5 times the characteristic time of the RLC circuit: $\tau = 2L_0/R_{eq}$, varies from 20 to 40 µs. This is a relatively short time compared to what on-the-shelf gas valves can achieve (around 1 ms).

The main problem to overcome will be to match those times by decreasing the gas discharge duration, or by exploring more complex circuit architectures. For example, using a Pulse-forming network (PFN) to increase the stability and duration of the electric pulse [5], or using two RLCs like a waterfall which pulse multiple times creating a burst during the gas discharge.

Therefore, the goal is to develop a configurable electric discharge architecture which is as modular as possible to explore different arc discharge types.

7. VALVE CHARACTERIZATION

7.1. Valve description

For a pulsed gas-fed thruster, it is very important to know the valve's behavior to predict the mass ejection and therefore being able to guarantee a full use of the mass and a maximum of efficiency.

For this purpose, a fast valve has been chosen. Its opening time is about 2 ms, and the goal now is to characterize its opening according to the upstream pressure and the input voltage. As it has been underlined in the electric dimensioning part, the gas discharge time must be as reduced as possible, which could be achieve by pulsing short voltage command and opening the valve just a little compared to the full opening sequence.

7.2. Tests protocols

To characterize the mass ejected per pulse, the fluidic system is closed at a well-known initial pressure. Then, several cold-gas pulses are performed by the valve to lower the inner pressure which leads to an approximation of the mass ejected per pulse. This test must be carried as many times as there are valve's opening configurations to test.

Another test consists of using the "µ-thrust" balance which has already been qualified for PJP [6]. Here, the fast-valve ejects cold-gas pulses in front of a flat plate mounted on this balance. By recording the position of the lever arm, the momentum transferred to the balance is known and so by assuming a sonic velocity at valve's exit throat, the mass ejected too.

7.3. Fluidic system benchmark

An entire fluidic system benchmark has been developed to provide an accurate pressure from 0 to 20 bar of Argon, from a standard bottle of 200 bar.

First, the flow is reduced directly from 200 to 20 bar with a pressure regulator and pass through a T-junction with a rupture disk that has been chosen to protect the fast valve (Fig.7). This valve is controlled to fill a closed volume colored in orange (Fig.7) at a certain pressure. This volume is made by a plenum which could vary depending on experimentation needs, and by the dead space between the two manifolds (made by flexible pipes and a rigid feedthrough on the vacuum chamber). An accurate pressure sensor has been chosen to ensure a relative accuracy after N-pulses of gas performed by the fast valve n°1 (Fig.7).

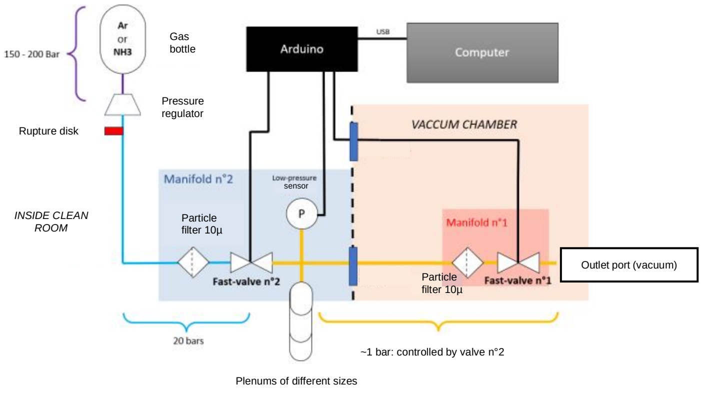

Figure 7. Fluidic system of the test bench

This test bench will be the first step into developing an entire system for MPDT characterization, by combining fluidic and electric inputs.

8. CONCLUSION

In conclusion, the modular propulsion module architecture presented in this paper represents an advancement in the field of space propulsion, paving the way for a range of new possibilities for satellite missions and services in orbit. The ability to provide pulsed thrust offers precise control over the transfer of momentum to satellites, thus facilitating orbit missions such as satellite formations. Furthermore, the flexibility offered by using the same power processing unit for different technologies with complementary performances, whether it's high thrust or mastered impulse, opens the door to the design of missions that were previously unimaginable. By combining these features, this architecture promises to change how we conceive space missions, thus opening new frontiers for space exploration and utilization.

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