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

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Abstract: In this paper, a "plug & Play" 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 (~200W) pulsed 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.

Nomenclature

I, J	=	current, and current density
B	=	magnetic field
F	=	force
r	=	radius of an electrode
l_a	=	chamber length
I_{sp}	=	specific impulse
$\frac{T}{P}$	=	thrust-to-power ratio
η	=	efficiency
m_p, I_{bit}	=	mass ejected and impulse per pulse
$\langle . \rangle$	=	time average
t, x, v	=	variables for time, position and velocity
$\dot{m}$	=	mass flow rate
P_e	=	electric power
E	=	energy
f	=	working frequency
τ_p	=	time per pulse
V	=	voltage
R, L, C	=	resistance, inductance and capacitance
τ	=	characteristic time of RLC circuit
ξ	=	damping factor of RLC circuit
b, k	=	characteristic length for mass distribution and anode divergence

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I.Introduction

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 and the plasma generation part (nozzle) from the power generation/control part (PPSCU).

The two sub-elements are housed in separate boxes that are connected by harnesses. 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.

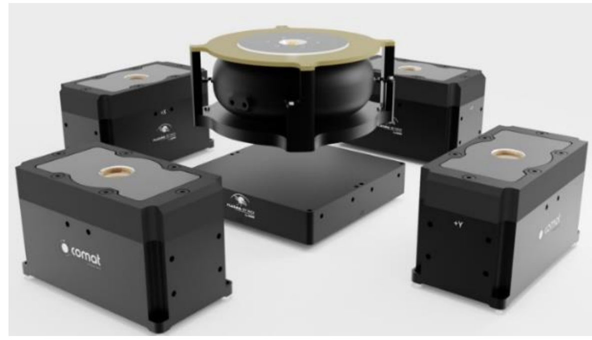

Figure 1. MP²S combining four PJPs and one P-MPDT, controlled by one PPSCU

II.Project presentation

A. 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).

B. Partners presentation

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 CNRS 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

Figure 2. Partners' location.

deposition plasmas. The company also works on propulsion, having already collaborated with Comat on the development of the PJP.

Endurosat is a supplier of cube satellites and space systems. They have a global, satellite-scale vision of thruster development.

III.VAT technology

The PJP is a vacuum arc thruster. The principle of this technology is to generate an arc between two electrodes, eroding one and accelerating the ejected particles to create the thrust. It is impossible to generate an arc in a vacuum due to the absence of matter. It is therefore necessary to add material to the electrode gap to create the electrical continuity between anode and cathode, which will enable the arc to be generated. 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. This erodes just the right amount of material to increase the interelectrode pressure that enables the low-voltage breakdown. The energy is stored in capacitors that discharge in the electric arc. The arc erodes the cathode in a zone called cathode spot, sublimating the matter and then transforming it into plasma. The ejected plasma is then accelerated at high velocity, creating the thrust. 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.

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.

A. PJP history

The PJP has been developed at Comat since 2014. Numerous Breadboard Models have been developed to reach, today, a thruster with a flight heritage on two satellites and a third in 2025. Between 2020 and 2023, PJP was at the heart of a European Project Horizon 2020, in a consortium with CNRS, Universität der Bundeswehr München, OHB Sweden, Thales Alenia Space and PlasmaSolve.

This leads to the latest version of the PJP which separates the control and power unit from the energy and plasma generation. This modular system is composed of one PPSCU (control and power) and up to 4 nozzles (propellant and energy), which allows to increase the total impulse of the thruster by multiplying the number of discharge chambers. This modular version enables a wider range of missions to be covered, including attitude control maneuvers by placing the nozzles on different axes of the satellite.

Figure 3. ISISpace PJP flight model (in-orbit)

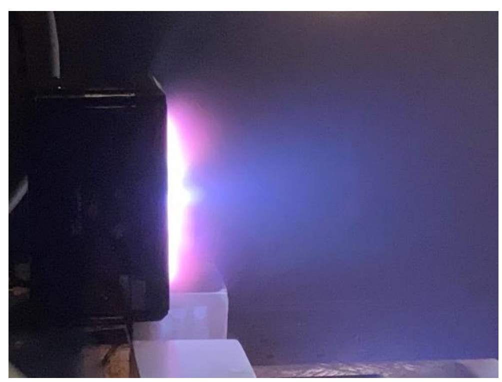

Figure 4. Synchrocube PJP qualification model (soon-in-orbit)

B. PJP performances

On the latest version, the PJP is more compact and generates an impulse per pulse equal to $I_{bit} \sim 20 \mu Ns$ for each nozzle with a global thrust-to-power ratio $\frac{T}{P} \sim 4\ \mu N/W$. The technology and the electric discharge parameters (high current and short duration) allow a high velocity of the exhausted matter, which lead to a specific impulse $I_{sp} \sim 2400s$. Each nozzle contains enough propellant for a total impulse $I_{tot} > 120Ns$.

IV.MPD technology

The acceleration mechanism of MPD technologies lies on Lorentz's force $\vec{J} \times \vec{B}$. This force accelerates the plasma to a high speed, inducing a high I_{sp}. 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" (Fig. 5, a).

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" (Fig. 5, b).

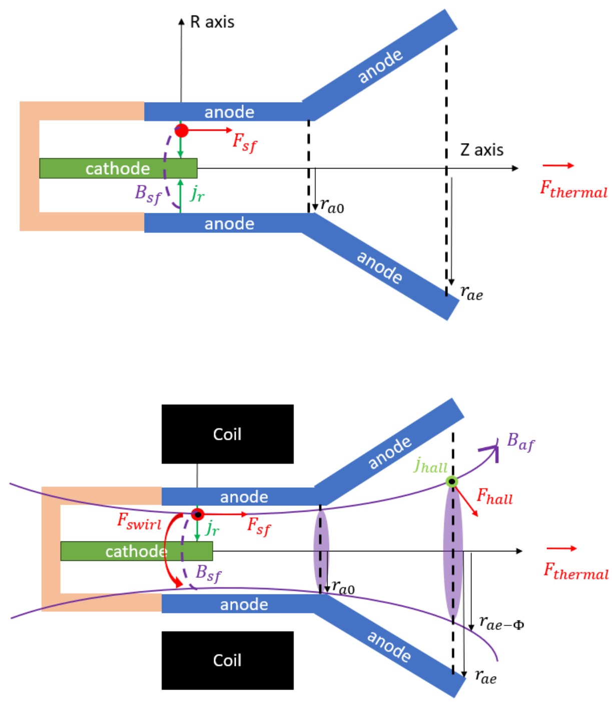

Figure 5. a) SF-MPDT thrust components (top) AF-b) MPDT thrust components (bottom).

V.Performances

C. Pulsed thruster performances definition

First, let us recall some usual quantities which are used to describe the performances of a pulsed thruster such as the specific impulse I_{sp} and the thrust-to-power ratio $\frac{T}{P}$ on Eq. (1) and Eq. (2). 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 $I_{sp} \sim 2000\ s$ and a $\frac{T}{P} \sim 20\ \mu N/W$ (Fig. 6). The total impulse target is $> 20\ kNs$ to cover a wide range of missions, even at low power and in a small volume. Considering a full charge of the capacitors during $1/f$ (so the energy accumulated is $E = \frac{P_e}{f}$), the efficiency is deduced according to the I_{sp} and the $\frac{T}{P}$ (Eq. (3)). Computing with the performances above: $\eta =$

$$I_{sp} = \frac{I_{bit}}{m_p g_0} = \frac{v_e}{g_0} \qquad (1)$$

$$\frac{T}{P} = \frac{\langle \dot{m} v_e \rangle}{P_e} = f \frac{m_p v_e}{P_e} \qquad (2)$$

$$\eta = \frac{g_0}{2} I_{sp} \left(\frac{T}{P}\right) \qquad (3)$$

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 $m_p = 20\ \mu g$. Therefore, a whole fluidic system must be qualified to control as accurately as possible the mass ejected.

D. Propellant selection

Regarding a wide range of existing MPDT prototypes [3] (Fig. 6), lots of propellants can be used for the discharge which represents an advantage compared to other technologies. Argon is a very common gas, non-reactive, has good performances, and is easy to supply. For safety, it has been decided to avoid hydrogen and ammonia despite their good performances because of the toxicity and explosion risks. Taking also the cost factor into account makes argon the most relevant choice for the moment.

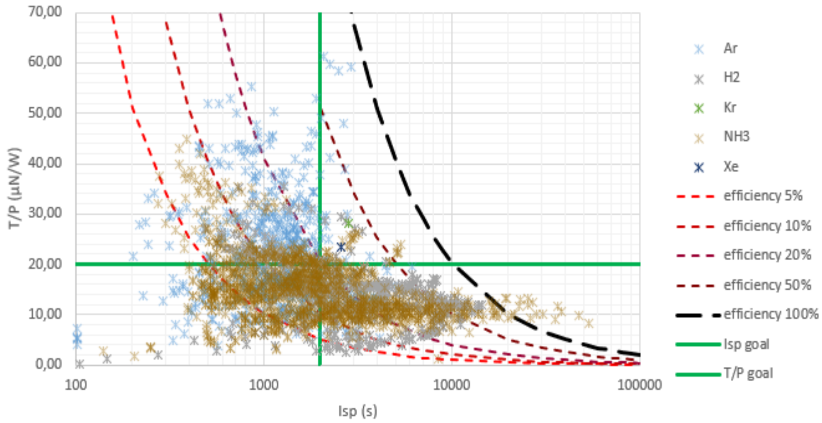

Figure 6. Isp vs. Thrust-to-power ratio with iso-efficiency lines for MPDTs, MP²S's performances are represented by the 2 green lines – Princeton university database [4].

VI. Electric dimensioning

First, it is important to have an idea of what are the orders of magnitude present in such electric thrusters. In this section, some models have been made for a Self-field MPDT configuration.

A. First model: RLC circuit

The duration of the electric discharge must be the same as the duration of the gas pulse to maximize the ionization rate and to increase the performances. So 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], with a time variating inductance and resistance representing the plasma (see Fig. 7). The capacitance is defined according to the input voltage and the energy of the discharge from the performances defined above (see Eq. (4)).

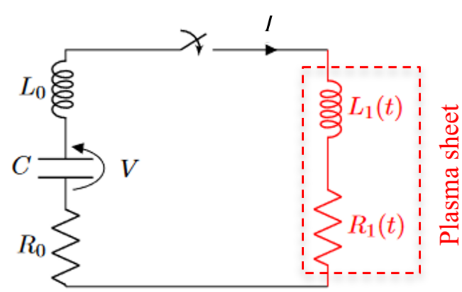

Figure 7. Equivalent Circuit of an MPDT discharge.

$$E = \frac{1}{2} C V^2 \tag{4}$$

Therefore, as the initial voltage takes values from 250 to 500 V and the input energy is 20 J, the capacitor bank range is from 160 to 640 µF. 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:

$$\xi = \frac{R_0}{2} \sqrt{\frac{C}{L_0}} = 1 \tag{5}$$

As the circuit's inductance is in the order of 20 nH, the resistance needed for a critically damped system varies from 11 to 22 mΩ, depending on the input capacitance. With those parameters, the discharge time, which can be estimated as 5 times the characteristic time of the RLC circuit: $\tau = \frac{2L_0}{R_0}$, varying from ~ 10 to 20 µs. This is a very short time compared to the minimal opening time found for the fastest off-the-shelf gas valves (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.

B. Second model: the 1-D snowplow model

To go further into the electric dimensioning and to introduce some geometric parameters, it is useful to model the plasma in a pulsed thruster as a current sheet propagating along the electrodes. This one-dimensional model is called a snowplow model because the plasma sheet has an initial mass which increases as it moves forward into the chamber, depending on the initial gas distribution stated as an input for the model [6], [7]. To simplify the calculation, the gas distribution here is assumed to be constant in time, and the first simulated geometry is a simple coaxial chamber with constant anode and cathode radii. As seen previously, the equivalent circuit is thus a RLC with space dependent anode and cathode resistances, $R_a(x)$ and $R_c(x)$ respectively, and space dependent plasma inductance $L_p(x)$ (Fig. 8). The plasma resistance in this case is supposed to be constant with $R_p \approx 1\ m\Omega$. The 2 equations of this system (Eq. (8) and Eq. (9)) are deduced from Kirchhoff's circuit law and Newton's first law of dynamic system (Eq. (6) and Eq. (7)), by considering that the space dependent variables induce some time dependencies involving the velocity and the acceleration of the current sheet.

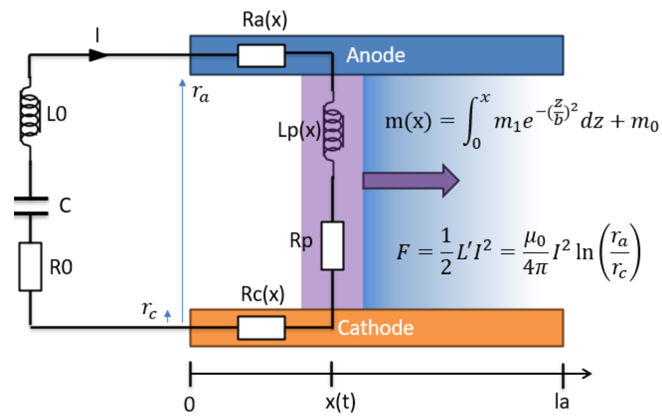

Figure 8. Snowplow model : mass distribution and force definition.

$$\begin{cases} V_0 = \frac{1}{C}\int_0^t I(\tau)d\tau + \frac{d}{dt}(LI) + RI & (6) \\ \frac{d}{dt}(mv) = F & (7) \end{cases}$$

$$\begin{cases} \frac{d^2I}{dt^2} = -\frac{1}{L}\left[\frac{dI}{dt}\left(R + v\frac{dL}{dx}\right) + I\left(\frac{1}{C} + v\frac{dR}{dx} + \frac{dv}{dt}\frac{dL}{dx}\right)\right] & (8) \\ \frac{d^2x}{dt^2} = \frac{dv}{dt} = \frac{1}{m}\left[F - v^2\frac{dm}{dx}\right] & (9) \end{cases}$$

With $R = R_0 + R_p + R_a(x) + R_c(x)$ and $L = L_0 + L_p(x)$. As the chamber is coaxial, the plasma inductance is $L_p(x) = xL' = \frac{\mu_0}{2\pi} x \ln\left(\frac{r_a}{r_c}\right)$. The mass distribution and the force are described on Fig. 8. Some assumptions are made about anode and cathode resistivities (copper for example with $\rho \approx 17.10^{-9}\ \Omega m$), about anode thickness ($\delta \approx 5\ mm$), about the initial mass ($m_0 \approx m_p/10$), and about the mass distribution factor ($b \approx 10$), which is then almost constant along the chamber. Indeed, those approximations about the mass distribution are made knowing that the valve is slow compared to the cold gas expansion in the chamber, inducing a quasi-steady flow and therefore some mass losses at the exit plane, which are neglected here.

The only remaining input parameters are the geometric parameters r_a, r_c and l_a which are used to optimize the model by the mean of a genetic algorithm. The equation system is solved on Python using a 4th order Runge-Kutta method, and the best result for a coaxial geometry (with the best I_{sp}, $\frac{T}{P}$ and η) is shown on Fig. 9 and Table. 1.

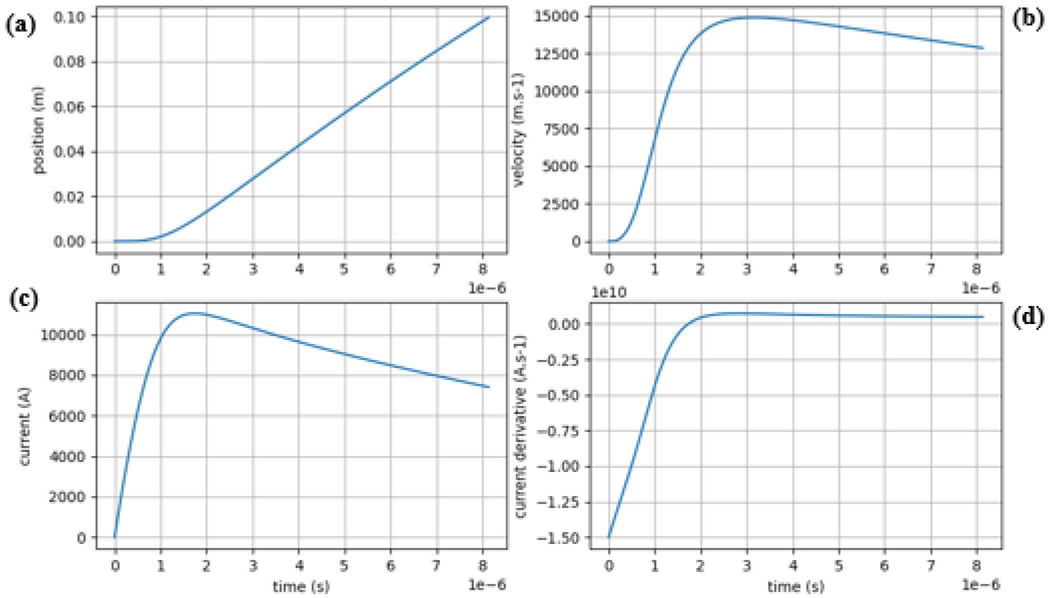

Figure 9. Position (a), velocity (b), current (c) and current derivative (d) curves of an optimized solution for the coaxial geometry (current inversed)

Parameters	r_a (mm)	r_c (mm)	l_a (mm)	I_{sp} (s)	$\frac{T}{P}$ (µN/W)	η (%)
Values	50	1	100	1311	13	8.3

Table 1. Performances of an optimized solution for the coaxial geometry

As expected, the optimized solution takes the biggest r_a/r_c ratio possible regarding the input bounds for those values, increasing the force. In the same way, the chamber length is taken as the biggest possible. It is important to notice that for this simple model, all the mass is supposed ionized, and no heat effects and erosion problems are considered. Also, the radius of the anode has an impact on the gas discharge and thus the mass distribution, but it is not considered here. Those are some improvements that will be added to the model, the same way that it requires also a better model for the evolution of the ionization fraction and the plasma resistance, which have a considerable impact on the final performances.

Then, another step would be to add the AF-MPDT configuration effects, such as the swirl acceleration and the extra force from the Hall current interaction with the external magnetic field (Fig. 5, b). This configuration is very promising and might increase the performances to what is expected for this MPDT, but it induces new problems and levels up the complexity of the system. More heat is coming from the additional coil thus requiring a cooling system, which decreases the power available for the thruster and become a real problem for low-power applications [8]. Moreover, the electric part controlling the current in the coil will have to be synchronized with both the gas and the main electric discharge.

VII.Valve characterization

A. 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 an optimized mass utilization and a maximum of efficiency. For this purpose, a fast valve has been chosen. Its opening time is about 2 ms, and the goal is now 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 reduced as much as possible, which could be achieved by pulsing short voltage command and partially opening the valve.

B. Tests protocols

To characterize the mass ejected per pulse, the low-pressure part of the fluidic system is closed at a well-known initial pressure (Fig.10, orange part). 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. Another test consists in using the "µ-thrust" balance which has already been qualified for PJP [8]. Here, the fast-valve ejects cold-gas pulses in front of a flat plate mounted on the 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.

C. 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 then passes through a T- junction with a rupture disk that has been chosen to protect the fast valve (Fig. 10). This valve is controlled to fill a closed volume colored in orange (Fig. 10) 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. 10). This test bench will be the first step into developing an entire system for MPDT characterization, by combining fluidic and electric inputs.

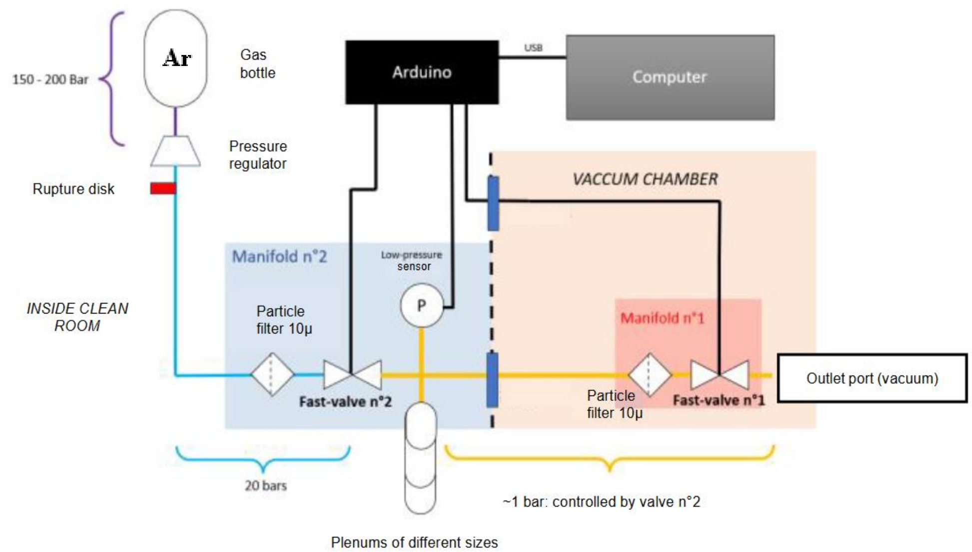

Figure 10. Fluidic system used for the valve characterization.

VIII. Conclusion

In conclusion, the modular approach for COMAT's thrust system is taking a leap forward by the development of a low-power pulsed MPDT that will complete the modular architecture introduced after the qualification of the PPSCU and the Vacuum Arc Thruster nozzles called PJP. During this first phase of development, the performances and the propellant type have been chosen, and simple models such as the snowplow model have been investigated. Then, an entire fluidic system has been designed to characterize a fast valve which is crucial in determining its opening behavior as the mass of gas to inject in one pulse is very small (20 μg). The next steps will be to design a modular discharge chamber to test several geometries coming from the convergence of a more complete numerical model and from partners' experience.

The separation of the thrust nozzles from the power supply and the choice of operating at a pulsed regime are the two key points of COMAT's vision for its modular thrust system. Indeed, new combinations of in-orbit missions will be possible for smaller satellites such as attitude control, air drag compensation and orbit rising/transfer with one and unique thrust system.

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