esa

IN SUPREMÆ DIGNITATIS 1343
UNIVERSITÀ DI PISA

CubeSAT HTP Innovative Propulsion System (CHIPS)

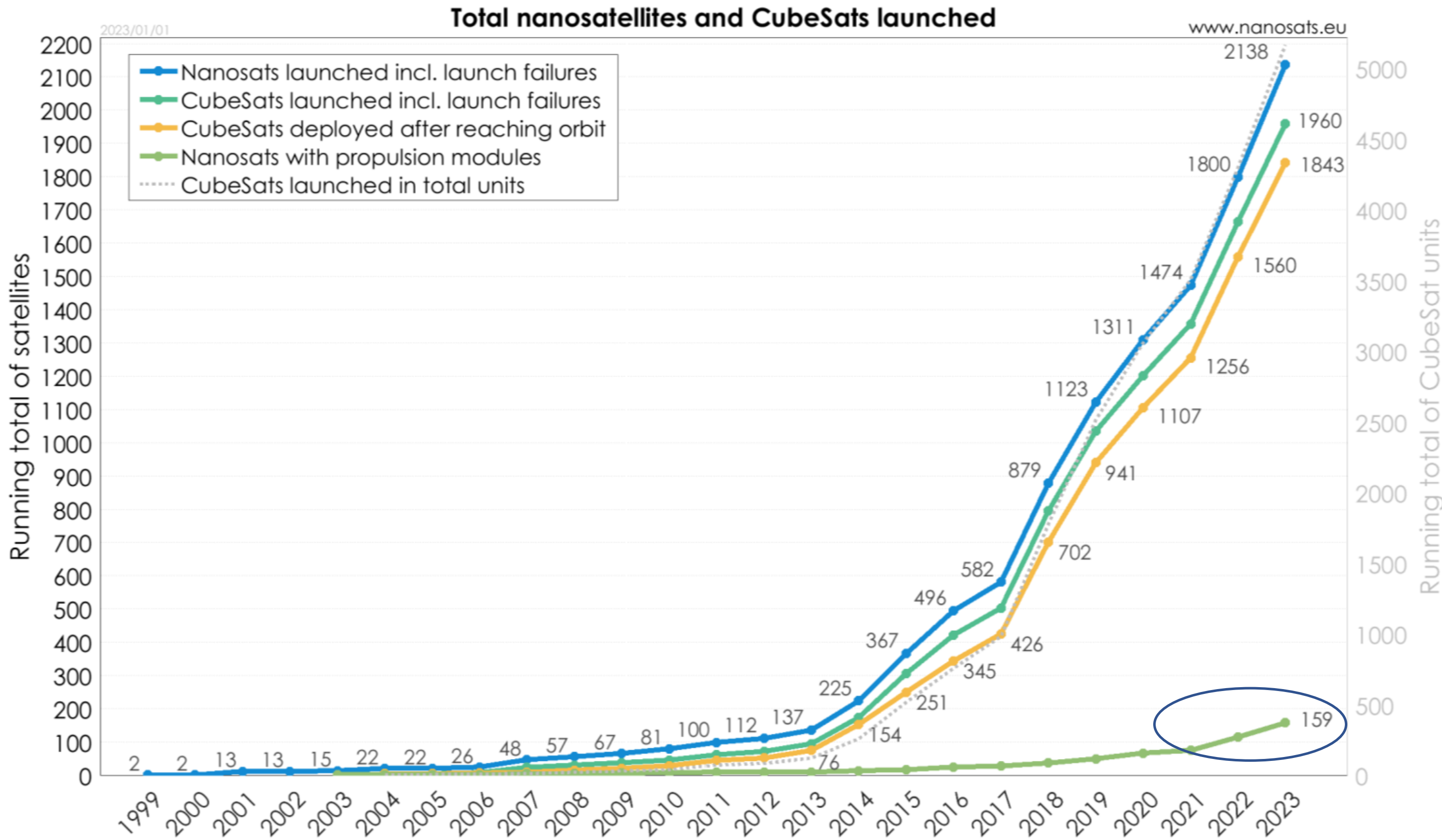
"INNOVATIVE PROPULSION SYSTEMS FOR CUBESATS AND MICROSATS"
ESA Contract No. 4000132061/20/NL/RA

Final Presentation
21 March 2023

Overview of the Project

Key Features:

- Compactness
- Limited Power
- Low cost



Increasing demand of propulsion systems for CubeSats

Overview of the Project

Four main tasks drove the CHIPS project steps:

- **Task 1**: Propulsion System Specification and Design
- **Task 2**: Propulsion Systema MAI
- **Task 3**: Propulsion System Testing
- **Task 4**: Further Development and Road-Mapping

Agenda

- Propulsion System Specification and Design
- Propulsion Systema MAI
- Propulsion System Testing
- Further Development and Road-Mapping

CHIPS Requirements

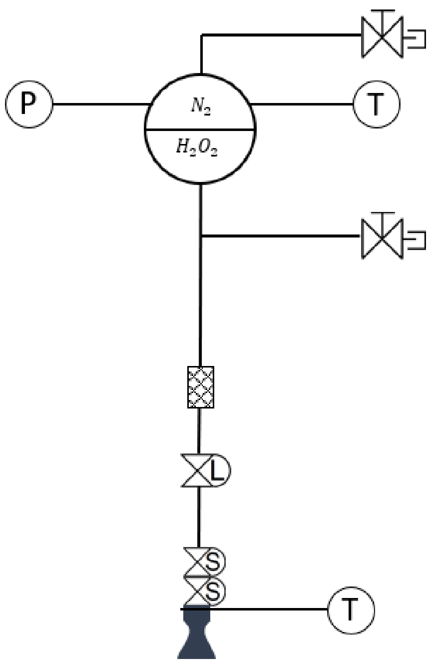
Flight Model Requirements

Parameter	Requirement
Propellant	HTP 98% wt.
Specific Impulse	≥160 s
Power Consumption	≤ 5 W
Thrust	≤ 0.5 N
Minimum Impulse Bit	≤ 25 mN s
Propellant Volume	≥ 0.3 dm^3
MEOP	≥ 24 bar
Dry mass	≤ 1.2 kg
Volume Envelope	≤ 2U
Material HTP compatibility	Grade I and II
Lifetime	≥ 3 yrs
Propellant Management Operation	Blow down
Target Project TRL	≥ 3
Overall Price	≤ 50 k€

Engineering Model Requirements

Parameter	Requirement
Propellant	HTP 98% wt.
Specific Impulse	≥160 s
Power Consumption	≤ 5 W
Thrust	≤ 0.5 N
Minimum Impulse Bit	≤ 25 mN s
Propellant Volume	waived
MEOP	≥ 24 bar
Dry mass	waived
Volume Envelope	waived
Material HTP compatibility	Grade I and II
Lifetime	≥ 3 yrs
Propellant Management Operation	Blow down
Target Project TRL	≥ 3
Overall Price	≤ 50 k€

CHIPS Flight Model Layout:



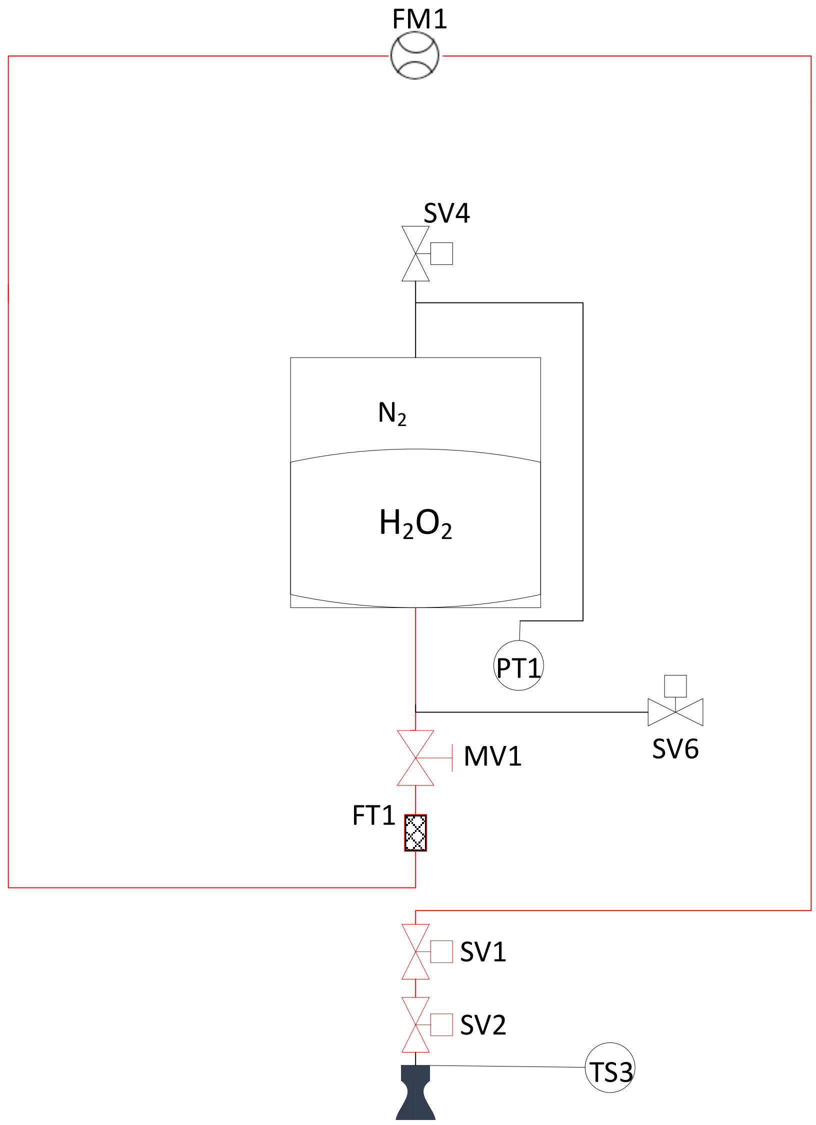
LEGEND	
	Tank
	Fill & Drain / Vent Valve
	Pressure Transducer
	Temperature Sensor
	Filter
	Isolation Valve
	Solenoid Valve
	Catalyst bed and Thruster

Designed by UniPi

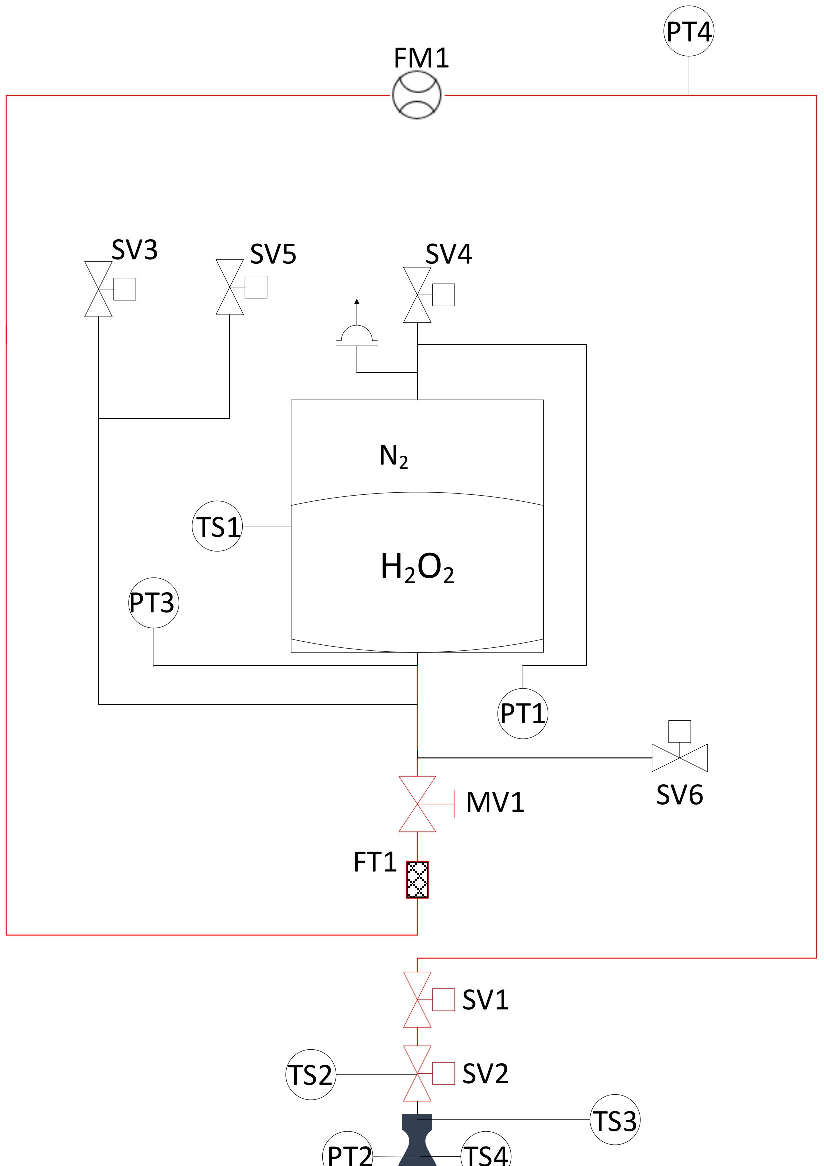
COTS

Designed and developed by UniPi

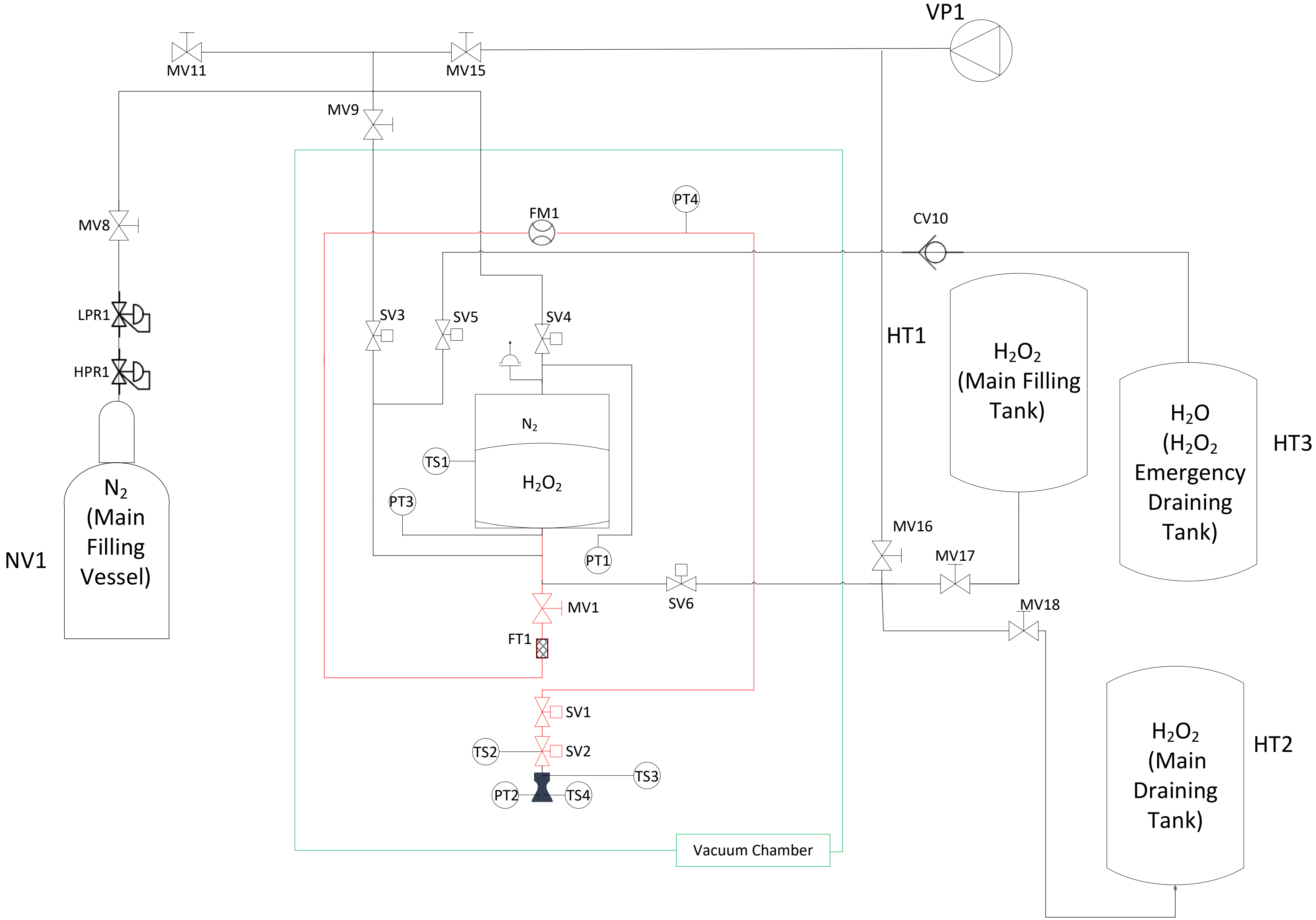
CHIPS Engineering Model Layout:



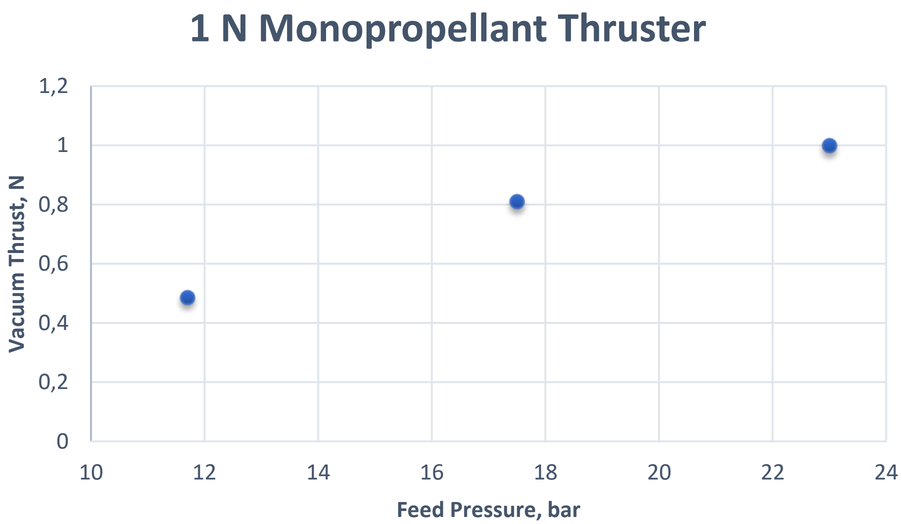
CHIPS Engineering Model Layout:



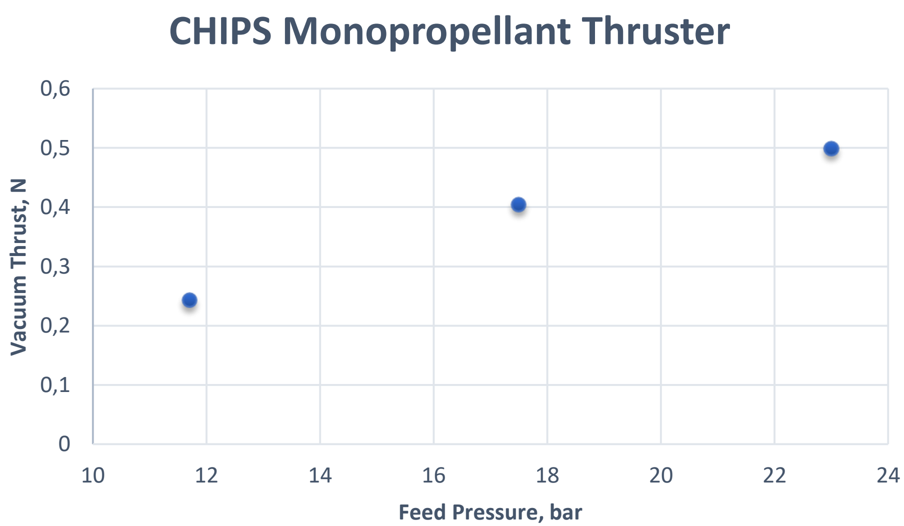
CHIPS Engineering Model Layout:



CHIPS Thruster Design:



Parameter	Value
Maximum Thrust	0.5 N
Nozzle Expansion Ratio	70
Decomposition Chamber Pressure @ BOL	18 bar



CHIPS Innovative Tank Design:

Tank Shell Material					
Material	**Density [g/cm^3]**	**Yielding Stress σ_y [MPa]**	**Ultimate Tensile Strength σ_u [MPa]**	**Young Modulus [GPa]**	**HTP Compatibility Class**
316 SS L	7.9	280	570	200	1/2
Ti6Al4V	4.43	880	950	113.8	4
AlSi10Mg	2.68	200	370	75	1/2
Al5254 H34	2.66	230	290	70.3	1
Al7050	2.8	455	515	70	4

Tank Shape			
Shape	**Sphere**	**Cylinder**	**Cube**
Volume [dm^3]	0.463	0.724	0.922
% of Total Volume	50.2	78.5	100

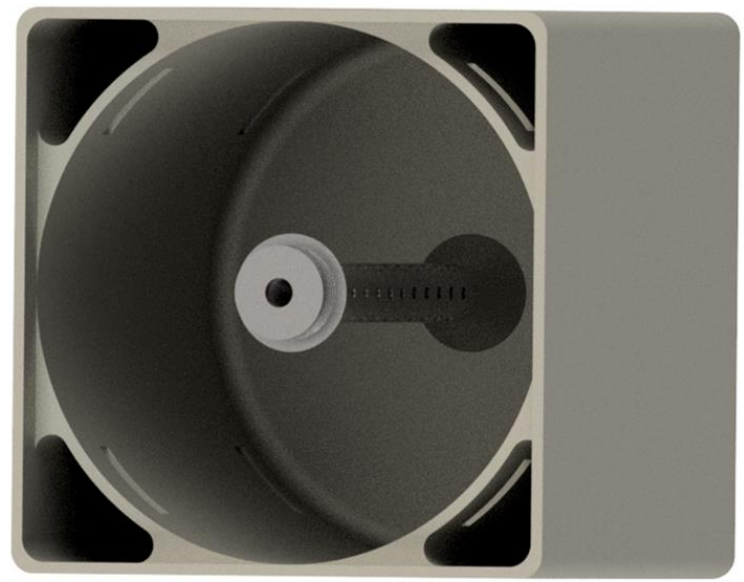
Worst → Best

CHIPS Innovative Tank Design:

	Cylindrical Flat Heads Reinforced	Cylindrical Ellipsoidal Heads	Cuboidal Tank Reinforced
	Al 5254 H34	Al 5254 H34	Al 5254 H34
Internal Volume [l]	0.60	0.52	0.68
Propellant Volume [l]	0.45	0.39	0.51
Propellant Mass [g]	629	546	710
Tank Dry Mass [g]	255	119	592
Propulsion System Dry Mass [g]	555	519	892
Tankage Fraction	0.41	0.22	0.83
1U Volume Fraction	0.68	0.59	0.77
Total Impulse [Ns]	740	643	840
Δv for 3U CubeSat [m/s]	250	227	255

Worst → Best

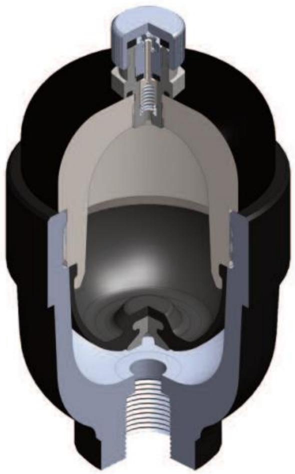
CHIPS Innovative Tank Design:



Parameter (unit)	Tank in Ti6Al4V	Tank in Al 5254 H34
Dry Mass [kg]	0.69	0.59
Propellant Volume [dm^3]	0.58	0.51
Δv for 3U CubeSat [m/s] (I_{sp}=150 s)	278	255
Total Impulse [N*s] (I_{sp}=150 s)	963	840

CHIPS Main Tank and Back-up Tank:

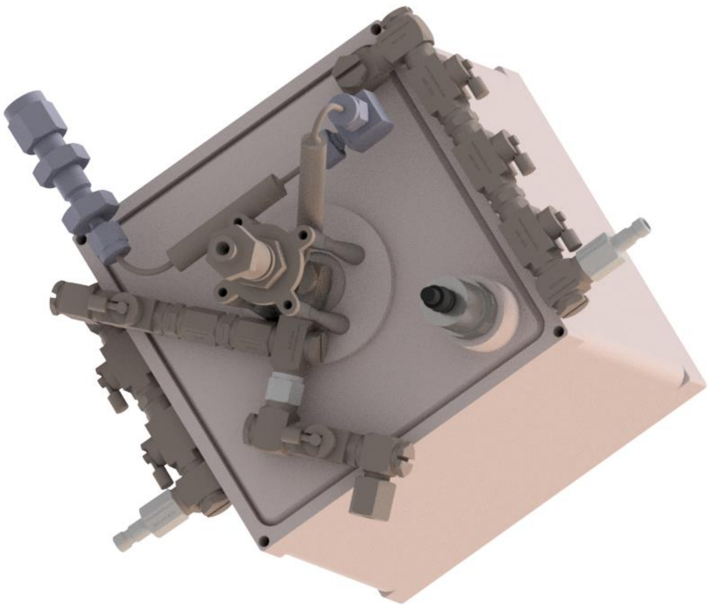
The COTS back-up tank did not satisfy important FM requirements as the dry mass and envelope

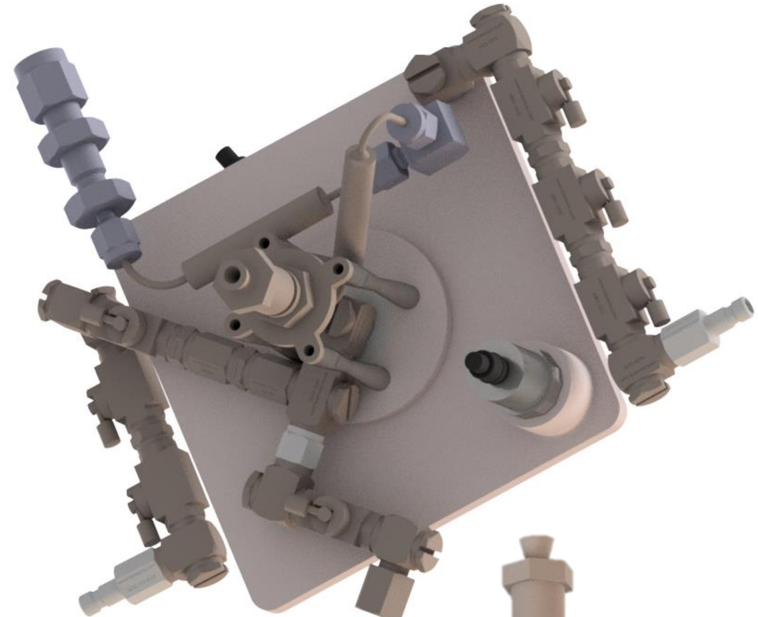


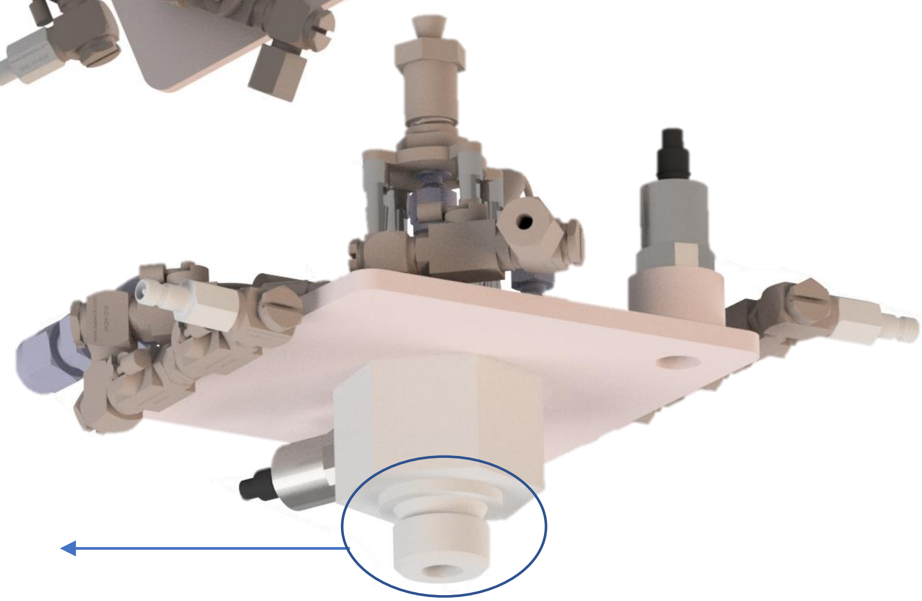
Parameter	Main Tank	Back-up Tank
Maximum Operating Pressure	24 bar	150/210 bar
Internal Nominal Volume	0.7 liter	0.35 liter
Tank Mass	0.6 kg	2.6 kg
Tank Envelope	1U	>1.5U
Operating Temperature	-40/+150 °C	-40/+150 °C
Compression Ratio	Max 1:4	Max 1 : 6
Material of the Body	Al 5254 H34	Stainless Steel AISI 316L
Supports/Valves Material	Al 5254 H34	Stainless Steel AISI 316L
Membrane Material	FKM	FPM

Switch Main Tank and Back-up Tank

The idea is to maintain the same plate and propulsion system assembly among the two configurations







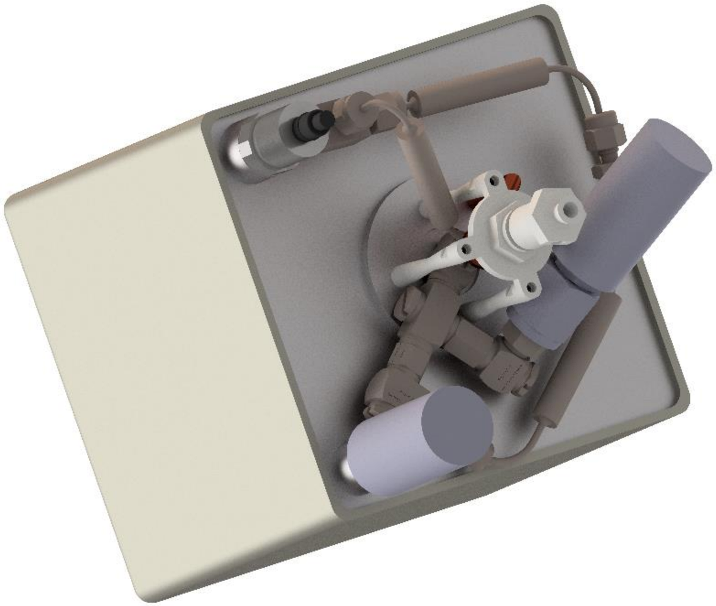
M18 threaded connection to EPE accumulator

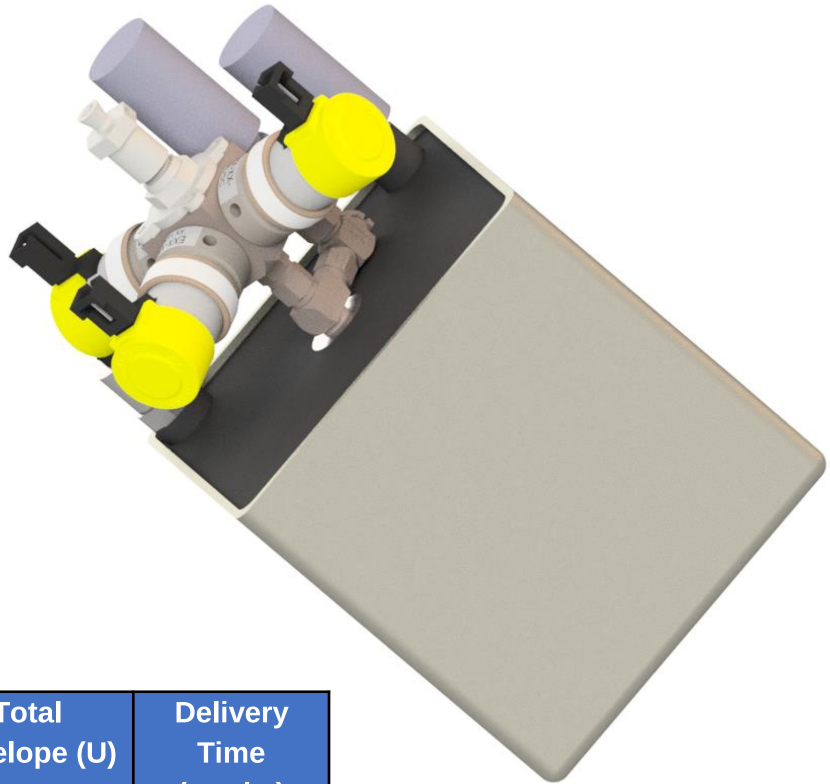
CHIPS COTS Tank and Plate Integration:

The upper plate connected to the tank allowed to obtain a configuration closer to the one of the FM

Reduction of the differences between the propulsion system EM and FM configurations

CHIPS Configuration:





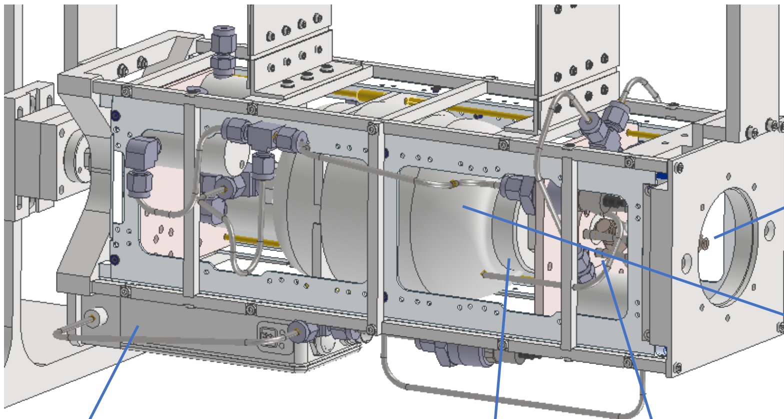
	Line Total Length (mm)	Valves Total Pressure Drop (bar)	Total Dry Mass (kg)	Total Envelope (U)	Delivery Time (weeks)
Manifold Configuration	120	0.006	1.05	1.75	< 12
Stand-Off Configuration	206	0.18	0.8	1.5	< 6

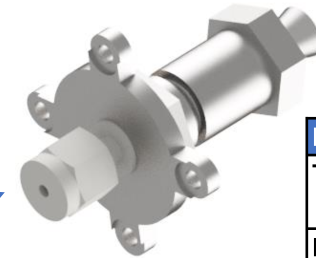
CHIPS FM Specification and Performance:

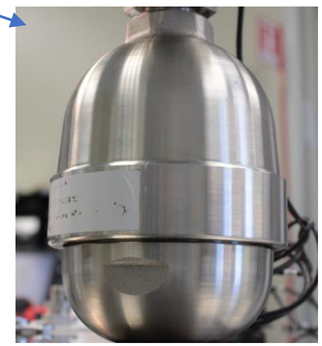
Maneuver	Value	CHIPS case
Orbit change		
Altitude change	0.5-0.6 m/s per km in LEO	About 510-610 km of altitude change using all the available propellant
Plane change	135 m/s per degree	About 2.27° of plane change using all the available propellant
Orbit control		
Drag compensation @ 300 km altitude	0.1-0.4 km/s/yr	Guarantees 3-1 years of drag compensation
Drag compensation @ 500 km altitude	4.4-25.8 m/s/yr	Guarantees at least 3 years of drag compensation

Parameter	Specification
Propellant	98% wt. H2O2
Catalyst	Pt/α-Al2O3 pellets
Operational mode	Blowdown mode
Tank MEOP @BOL	22 bar
Combustion Chamber MEOP @BOL	18 bar
Blowdown ratio	4:1
Specific impulse	160 s
Characteristic Velocity	909 m/s
Characteristic velocity efficiency	> 0.9
Thrust Coefficient efficiency	> 0.9
Nozzle expansion ratio	70
Adiabatic HTP decomposition temperature	1200 K
Propellant density	1.4 kg/m^3
Nozzle type	Conical
Thrust	0.5 N (@BOL) - 0.125 N (@EOL)
Propellant mass flow rate	0.32 g/s (@BOL) -0.08 g/s (@EOL)
Propulsion system total dry mass	0.9 kg
Propulsion system total envelope	1.5 U
Propulsion system total power consumption	5 W
Propellant mass	0.710 kg
Expulsion Efficiency	> 0.9
Tank Internal Volume	0.68 dm^3
Tank Propellant Volume	0.51 dm^3

CHIPS EM Configuration:

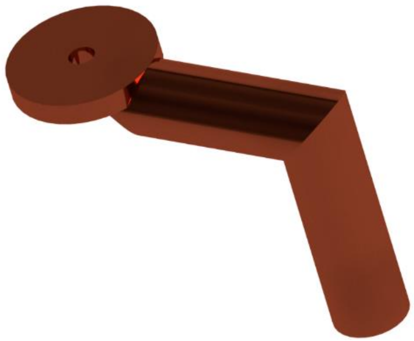


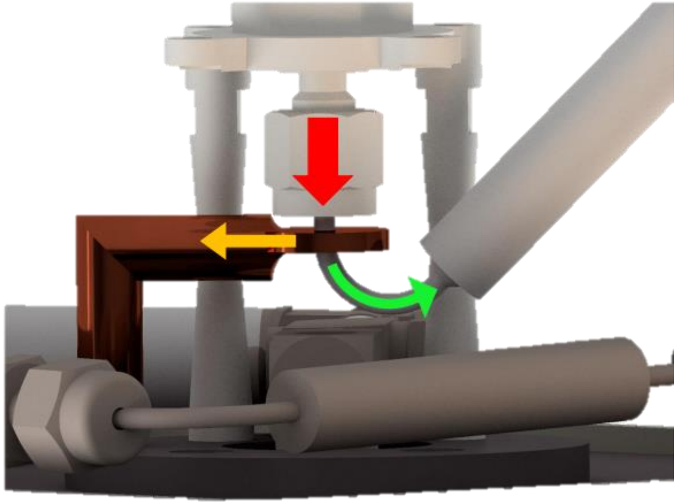




Part	Engineering Model
Tank	AM0,35V150XM18/1,5VX-0 EPE Italiana
Propellant Fill and Drain Valve	AG Series Gems Sensor
Gas Fill and Drain Valve	AG Series Gems Sensor
Pressure Transducers	
Tank Gas Side	Kulite ETL/T-500-375M
Tank Prop. Side	Kulite ETM-500-375M
Feeding Line	Kulite ETM-500-375M
Thrust Chamber	Kulite XTEL 190 M
Temperature Sensors	
Tank Gas Side	ETL/T-500-375M
Tank Surface	TCF-A-J-3000 Tersid
Feeding Line	Bronkhorst M13
Firing Valve Surface	MTS-40053-K-150-3000 Tersid
Thruster Surface	MTS-40053-K-150-3000 Tersid
Thrust Chamber	MTS-40103-K-150-3000 Tersid
Purging Valve	AG Series Gems Sensor
Draining Valve	AG Series Gems Sensor
Isolation Valve	MBV-1010 Beswick
In-line Valve	Lee EP Solenoid Valve
Firing Valve	Lee EP Solenoid Valve
Thruster	CHIPS Thruster

CHIPS By-Pass:





All the CHIPS components downstream the thruster have an operating temperature that shall not exceed 60°C

The firing valve is the component more subject to temperature increments due to the heating from the thruster

A copper by-pass is introduced to reduce the thermal load on the firing valve and maintain its temperture below the limit

Agenda

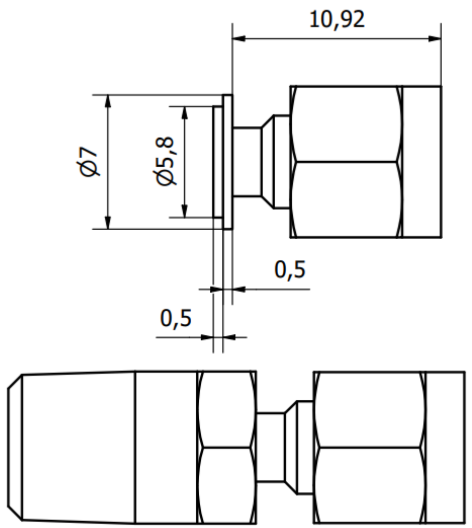
- Propulsion System Specification and Design
- Propulsion Systema MAI
- Propulsion System Testing
- Further Development and Road-Mapping

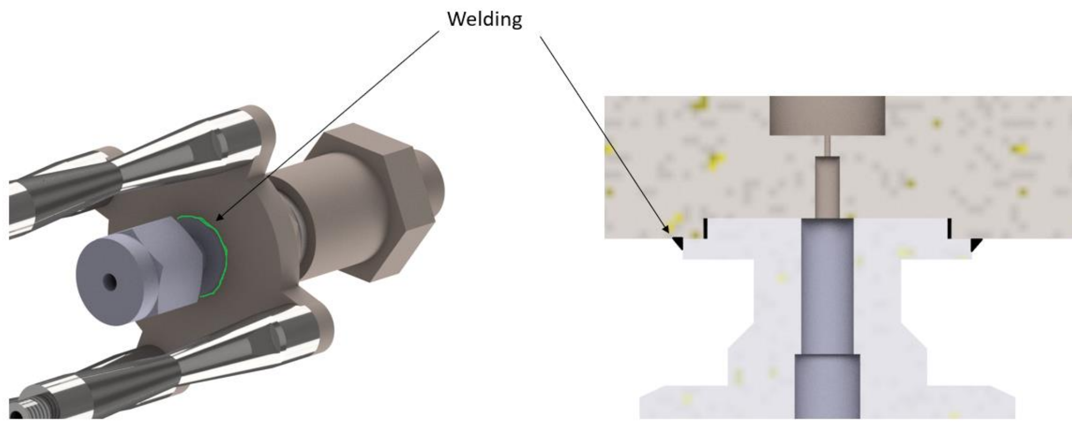
Task 2: Processes/Manufacturing

Part	Manufacturer	Machining
Thruster assembly	OMS-Precision Machining	• Milling • Turning • Drilling
Back-up tank assembly and support fittings	Brusa s.r.l	• Milling • Turning • Drilling • Laser cutting
Thrust Balance Interface Components	Brusa s.r.l	• Milling • Turning • Drilling • Laser cutting • Welding
SW-1, T8-20, T8-21	Swagelok	• COTS
Back-up tank	EPE Italiana	• COTS

Processes used for the manufacturing of all the CHIPS EM components

Task 2: Processes/Manufacturing

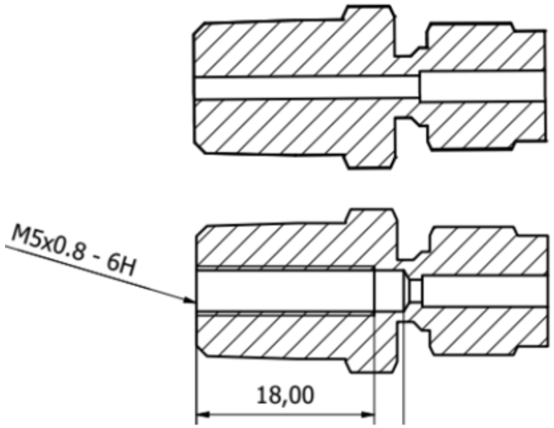




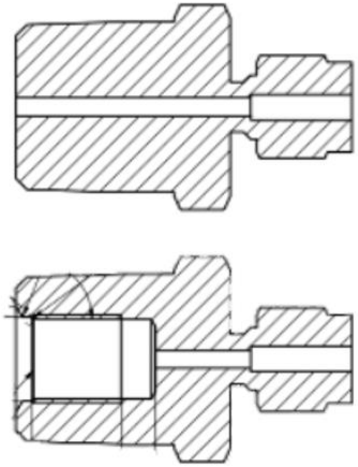
Cutting of the threaded side made by Brusa s.r.l

Welding to the catalytic bed made by Mira Laser s.r.l

Task 2: Processes/Manufacturing

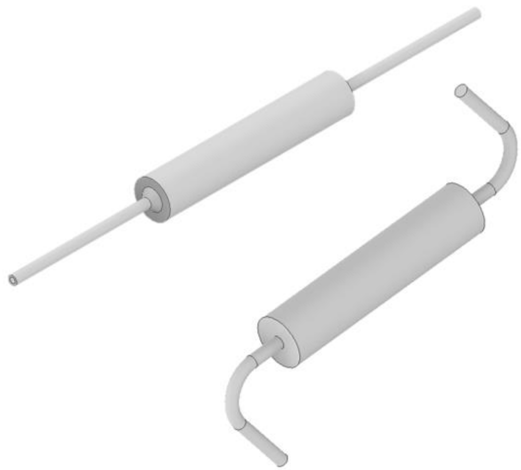


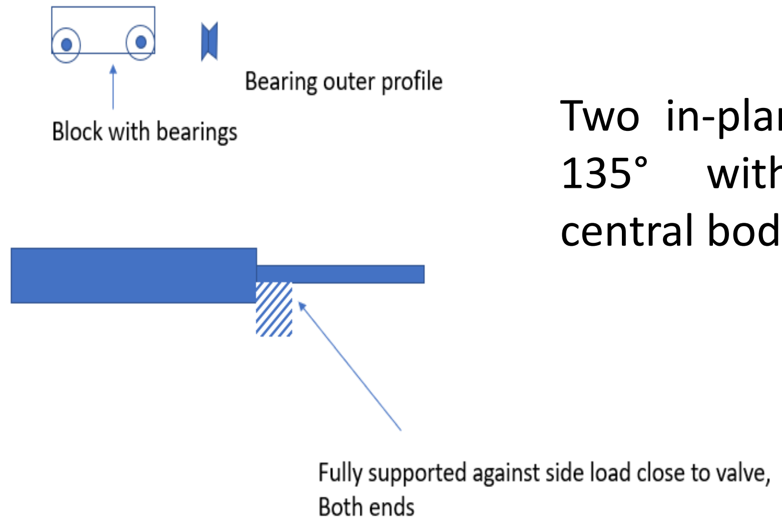
Threaded M5 hole to be made on the NPT threaded side of the component to allocate a pressure transducer made by Brusa s.r.l



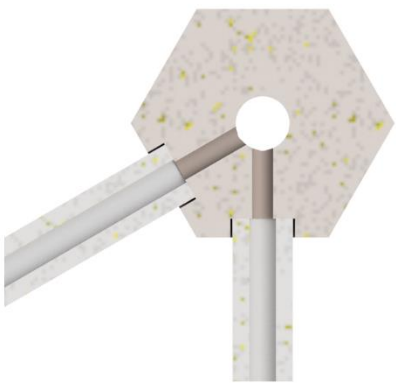
Threaded M10 hole compliant with ISO 7320 to be made on the NPT threaded side of the component to allocate a pressure transducer made by Brusa s.r.l

Task 2: Processes/Manufacturing





Two in-plane bendings of 135° with respect to central body axis



Welding of two 1/8“ tubes to the thruster to allocate a thermocouple and a pressure transducer

Task 2: Processes/Cleaning Procedure

The main contaminants that can be present during the CHIPS MAI are:

- **Human sources**
- **Processes**
- **Other sources**

Mechanical cleaning:

- **Dry wiping**
- Wet wiping
- Grinding, brushing and blasting

Solvent cleaning:

- **Solvent cleaning**: washing, dipping, spraying, vapor cleaning and ultrasonic cleaning.
- Detergent cleaning or soap cleaning
- Chemical or electrochemical cleaning: acids, alkalines and salts

Film strapping

Gas jet cleaning

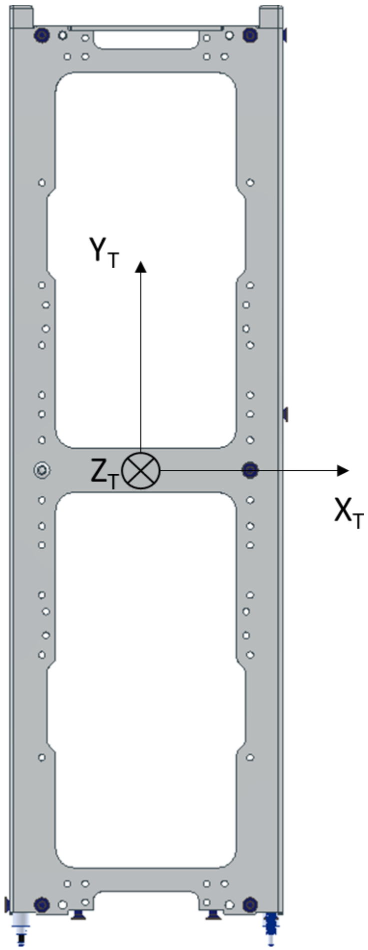
Task 2: Processes/Passivation

Steps followed for the passivation

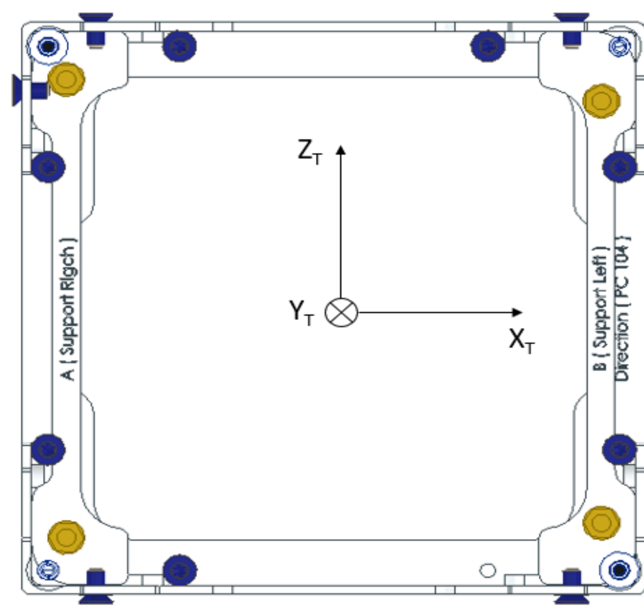
1. Degreasing of the metallic components to remove oil and grease films (10% solution of orthophosphoric acid is recommended to be used for at least 2 hours)
2. Cleaning of the surfaces with deionized water
3. Passivating with nitric acid (5% solution) to form an oxide film (1 hour)
4. Cleaning of the surfaces with deionized water
5. Passivating with hydrogen peroxide (30% wt., 1 hour)
6. Cleaning of the surfaces with deionized water
7. Testing with dilute hydrogen peroxide to ensure successful treatment (e.g. 30% wt.)
8. Bathing with deionized water and keeping it clean (storing in a clean environment)

Four Macro Steps

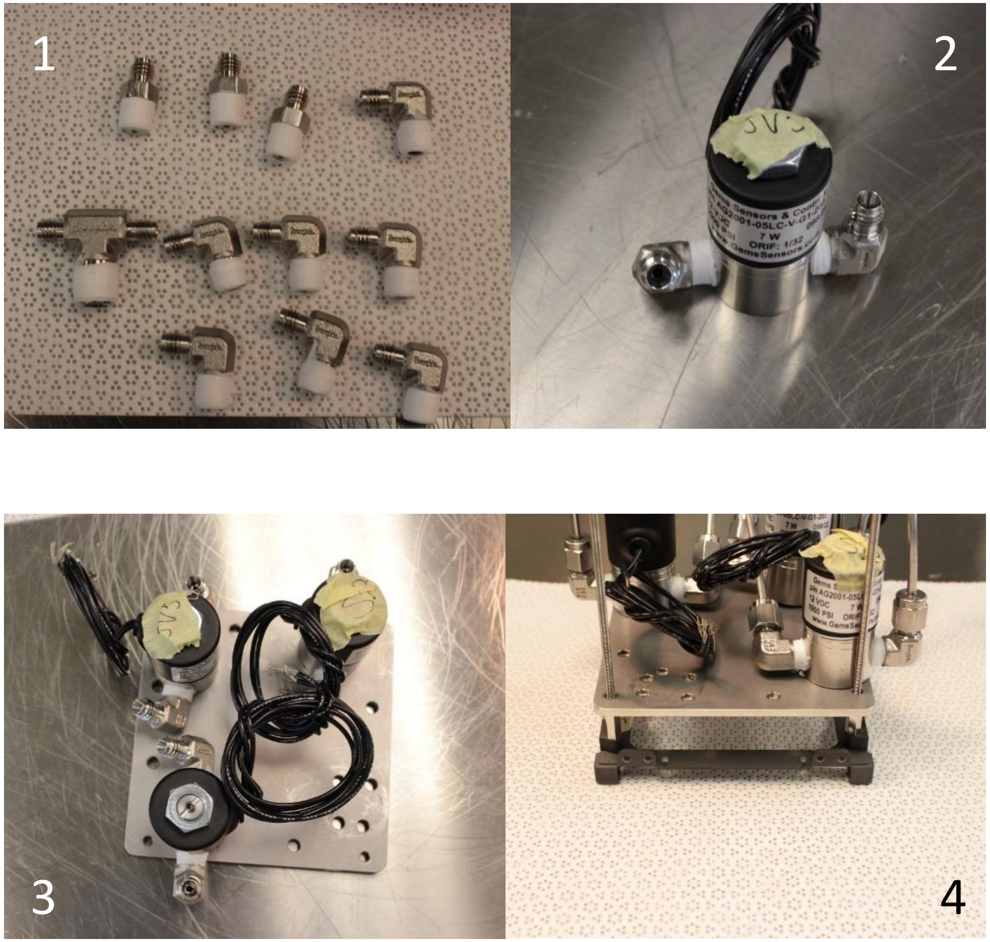
Inspection; Cleaning; | Fit-check; Final Assembly



Reference system



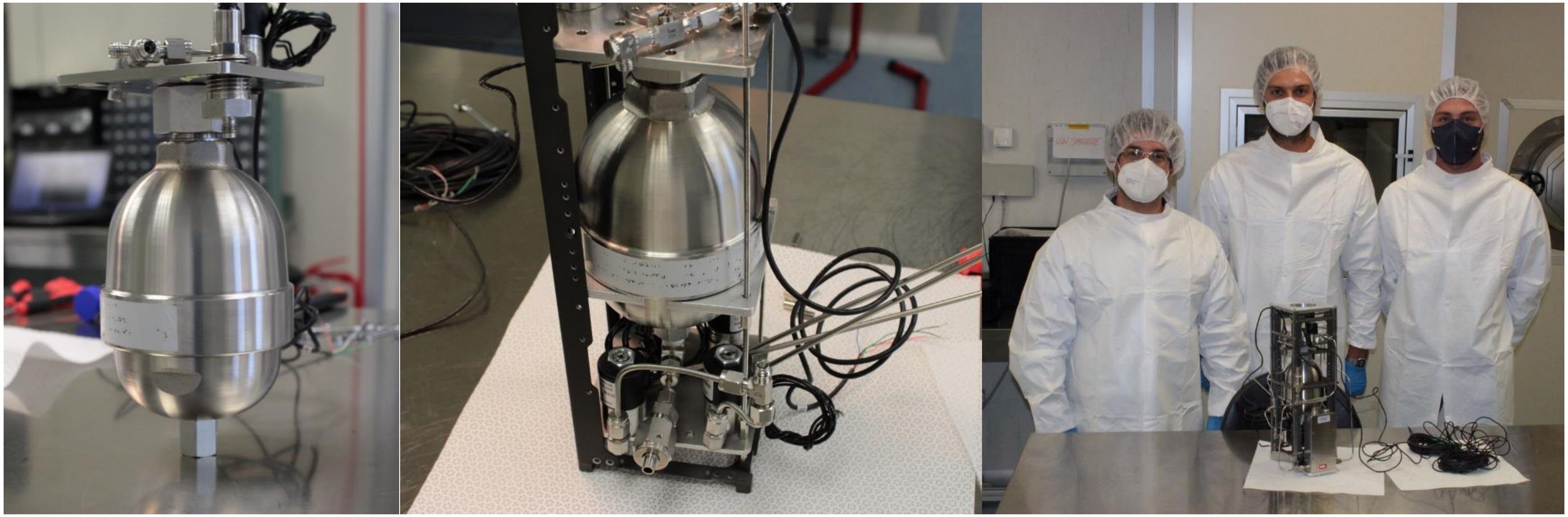
Task 2: Assembly



Sub-assembly of the components in the clean room:

1. Taping of the connectors with Teflon
2. Sub-assembly of the solenoid valve
3. Sub-assembly of the plate
4. First assembly inside the 3U structure

Task 2: Assembly

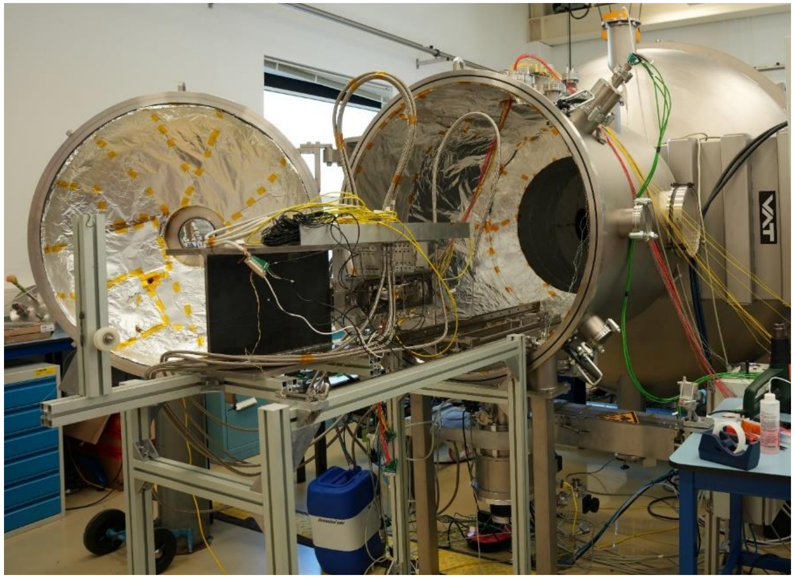


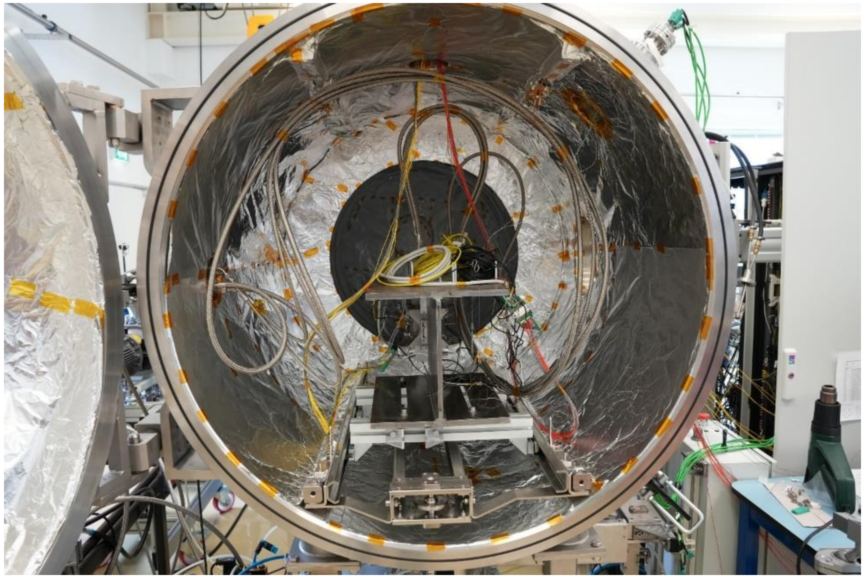
Final sub-assembly with the tank

Final assembly (with team picture)

Task 2: Integration

- Thrust Balance and all the sensor fully integrated in the vacuum chamber
- Reduction of spurious forces





- Vacuum chamber adapted for chemical propulsion
- New vacuum pump

Agenda

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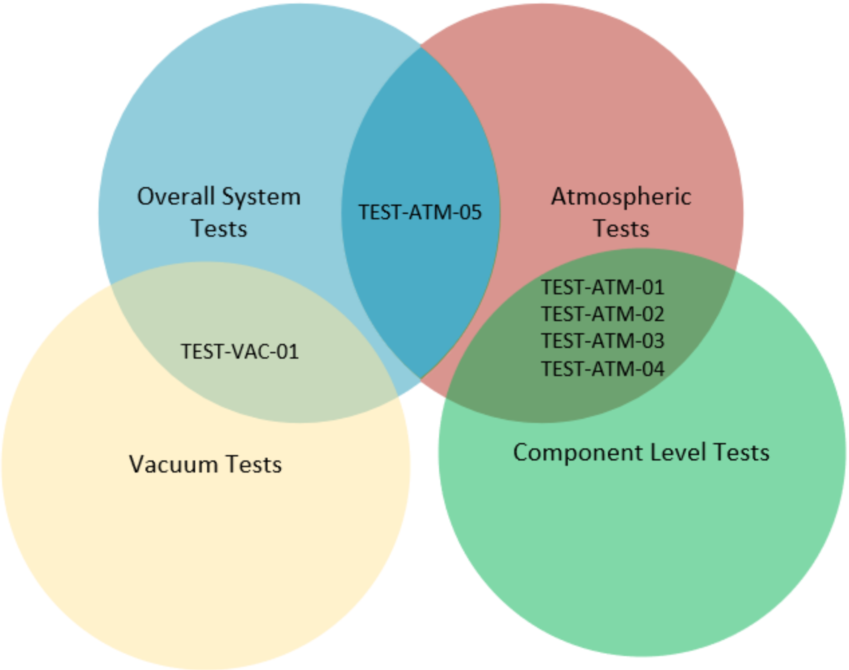
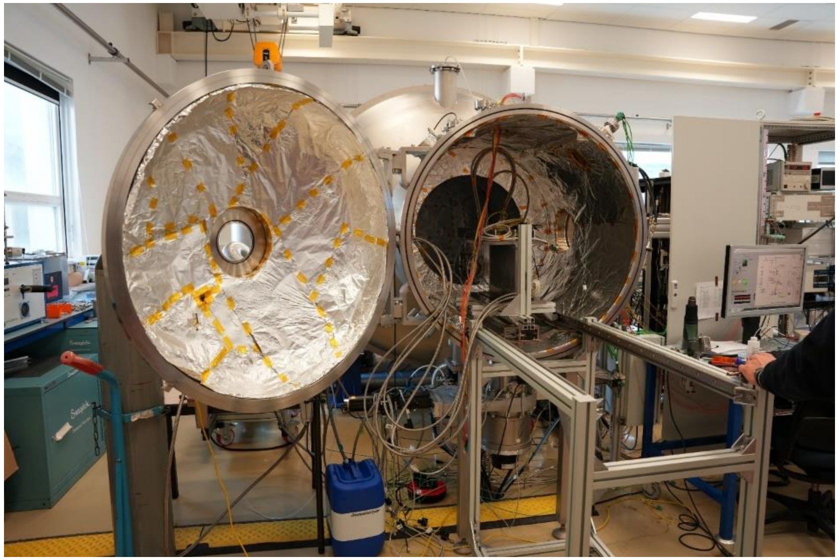
- Further Development and Road-Mapping

Test Plan





- ATM tests were performed at University of Pisa facilities
- VAC tests were performed at ESTEC SPF Facility

CHIPS Test Campaign:

	Test ID	CHIPS Test
Group I	TEST-ATM-01	Tank Leakage Test
	TEST-ATM-02	Tank Proof Pressure Test
	TEST-ATM-03	Tank Pressure Cycling Test
	TEST-ATM-04	Tank Burst Pressure Test
Group II	TEST-ATM-05-01	Propulsion System Assembly Flow Test
	TEST-ATM-05-02	30% H_2O_2 Filling and Draining (passivation)
	TEST-ATM-05-03	98% H_2O_2 Filling and Draining (dry run)
Group III	TEST-ATM-05-04	Propulsion System Hot Firing Tests in Atmosphere
	TEST-VAC-01	Propulsion System Hot Firing Test in Vacuum

Test Sequence

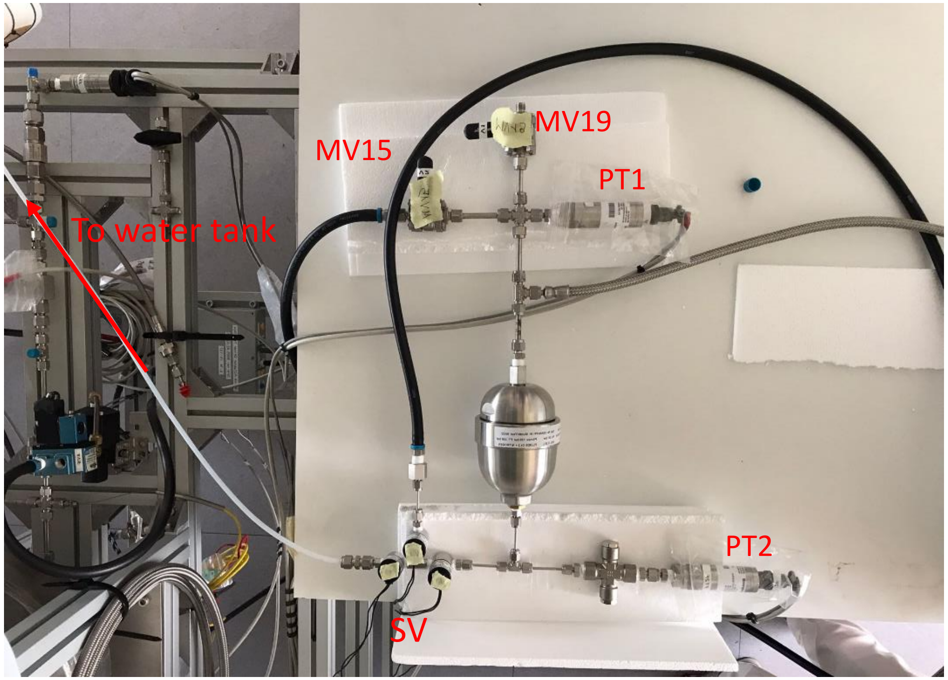
Group I → Group II → Group III

Test Objective-Group I

Test Id:	**TEST-ATM-01**
Title:	Tank Leakage Test
Requirement ID verification	TANK-INT-02
Description:	BOL pressure of 22 bar. Then the pressure is tracked in time by the pressure sensors. The leak rate will be measured based on the variation of the pressure. During the test, the interfaces with gas are wetted by a soap solution to see if there is any formation of bubbles to see if there is any evident gas leakage.
Environment:	Atmosphere
Facility:	University of Pisa
Successful criteria:	The pressure level after 24 hours shall be at a level compatible with leakage rate of 10^{-6} sccs for each tank interface
Test Id:	**TEST-ATM-02**
Title:	Tank Proof Pressure
Requirement ID verification	TANK-FUN-04
Description:	The objective of the test is to evaluate the proof pressure of the designed pressure vessel. The pressure is set at 24*1.25 bar (36 bar in the case of EPE-1 tank). The pressure inside the tank will be maintained at this level for at least 5 minutes.
Environment:	Atmosphere
Facility:	University of Pisa
Successful criteria:	The tank shall not present any visible deformation neither structural ruptures.

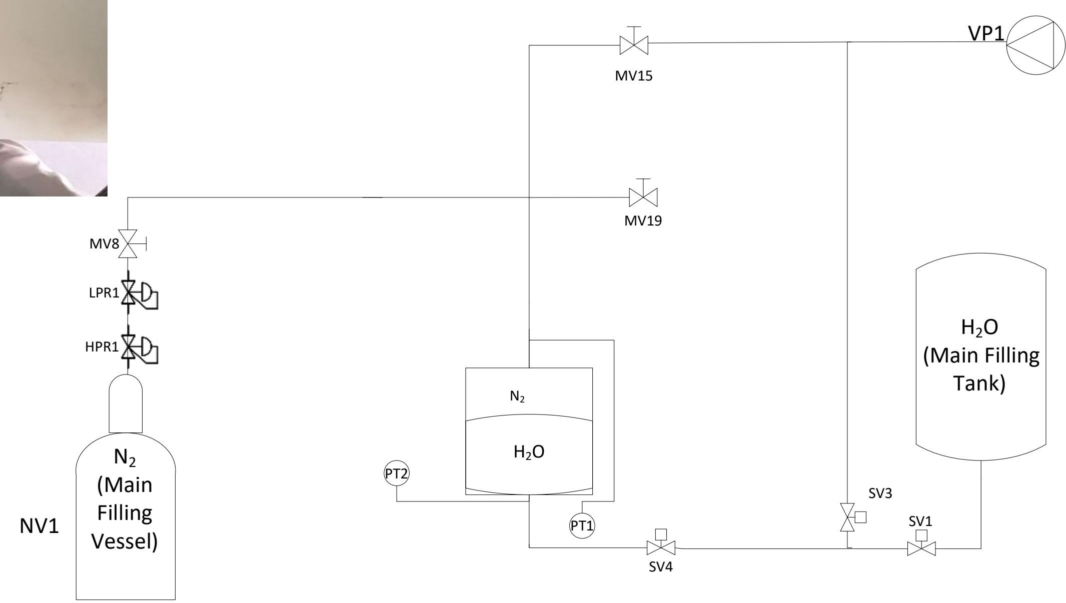
Test Objective-Group I

Test Id:	**TEST-ATM-03**
Title:	Tank Pressure Cycling
Requirement ID verification	TANK-FUN-04, TANK-OPE-01, TANK-OPE-02
Description:	The objective of the test is to evaluate the resistance of the designed pressure vessel to pressure cycles. 50 cycles of pressurization and depressurization between the two limiting values of pressure of 22 bar (BOL) and 8 bar. The integrity of the tank will be assessed by visual inspection.
Environment:	Atmosphere
Facility:	University of Pisa
Successful criteria:	The tank shall not present any plastic deformation neither structural ruptures.
Test Id:	**TEST-ATM-04**
Title:	Tank Burst Pressure
Requirement ID verification	TANK-FUN-04
Description:	The objective of the test is to evaluate the structural behavior of the designed tank at the burst pressure). The burst pressure level is set at 24*1.5 bar. The burst pressure level inside the tank will be maintained for at least 30 seconds. The integrity of the tank will be assessed by visual inspection and tomographic analysis
Environment:	Atmosphere
Facility:	University of Pisa
Successful criteria:	The tank shall not present any structural ruptures.



The COTS tank used was already tested by the supplier and it did not need to pass through the qualification process foreseen for the CHIPS tank.

However, the tank tests were performed to check the status of the COTS tank and the applicability of the proposed procedures



Test Performed:
TEST-ATM-01 (leakage)
TEST-ATM-02/04 (proof at 36 bar)
TEST-ATM-03 (cycling)

Test Objective-Group II

Test Id:	**TEST-ATM-05-01**
Title:	Propulsion System Assembly Flow Test
Description:	The objectives of this activity are: • Verify the test bench assembly, cleanliness and calibration. • Verify the valves and fittings flow characteristics • Verify the capability of propulsion system components to withstand a cycle of pressurization, depressurization and draining with water
Test Id:	**TEST-ATM-05-02**
Title:	30% H_2O_2 Filling and Draining (passivation).
Description:	The objectives are: • Passivation of all the components made in 316 SS (the passivation for all the components will be carried out at this step at overall system level). • Performance of a complete filling, pressurizing, de-pressurizing and draining sequence with 30% H2O2 for the overall system. • Verification that the pressure build-up is acceptable (< 2bar).
Test Id:	**TEST-ATM-05-03**
Title:	98% H_2O_2 Filling and Draining (dry run).
Description:	The objectives are: • Performance of a complete filling, pressurizing, de-pressurizing and draining sequence with 98% H2O2 for the overall system. • Verification that the pressure build-up is acceptable (< 2 bar).

Test Objective-Group II

Test Id:	TEST-ATM-05-04
Title:	Atmospheric Hot Firing Test.
Description:	The objectives are: • Verification of the CHIPS propulsive capabilities. • Verification of the functional requirements of the CHIPS thruster. The test consists to measure in time: • The propellant and pressurant temperature (T_{tank}). • The propellant and pressurant pressure (p_{tank}). • The mass flow rate ($\dot{m}$). • The decomposition chamber pressure (p_c) • The decomposition chamber temperature (T_c) • The thrust (F)
Succesfull criteria	The successful criteria are: • The requirements on the CHIPS propulsive performance are satisfied. • The requirements on the CHIPS thruster function are satisfied.

- The system will be tested in both pulse mode and steady state mode

Test Objective-Group III

Test Id:	TEST-VAC-01
Title:	Vacuum Hot Firing Test.
Description:	The objectives are: • Verification of the CHIPS propulsive capabilities. • Verification of the functional requirements of the CHIPS thruster. The test consists to measure in time: • The propellant and pressurant temperature (T_{tank}). • The propellant and pressurant pressure (p_{tank}). • The mass flow rate ($\dot{m}$). • The decomposition chamber pressure (p_c) • The decomposition chamber temperature (T_c) • The thrust (F)
Succesfull criteria	The successful criteria are: •The requirements on the CHIPS propulsive performance are satisfied. •The requirements on the CHIPS thruster function, design and interface are satisfied

- The system will be tested in both pulse mode and steady state mode

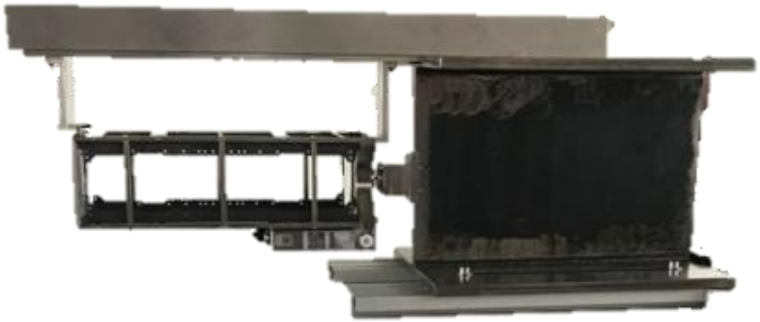
Test Matrix

Repeat the following process for four times (all the pulses will have a period of the cycle of 1 s and a t_{on} as specified in the list below, the t_{off} will be adjusted as consequence):

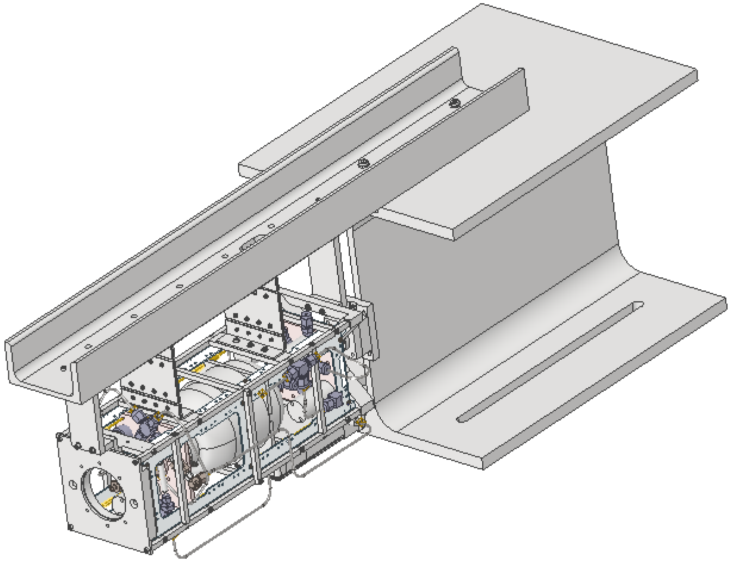
- First cold start and firing for 80 s
- Hot start and firing in pulse mode with t_{on}=25 ms for 80 times
- Hot start and firing in pulse mode with t_{on}=50 ms for 80 times
- Hot start and firing in pulse mode with t_{on}=100 ms for 80 times
- Hot start and firing in pulse mode with t_{on}=200 ms for 80 times
- Hot start and firing in pulse mode with t_{on}=300 ms for 80 times
- Hot start and firing in pulse mode with t_{on}=400 ms for 20 times
- Hot start and firing in pulse mode with t_{on}=500 ms for 20 times
- Hot start and firing in pulse mode with t_{on}=600 ms for 20 times
- Hot start and firing in pulse mode with t_{on}=700 ms for 20 times
- Hot start and firing in pulse mode with t_{on}=800 ms for 20 times
- Hot start and firing in pulse mode with t_{on}=900 ms for 20 times

- Wait until catalytic bed temperature decreases to the value required by cold start
- Repeat cold starts and firing for 1 s until 100 cold restarts are reached
- Final continuative firing will be performed until emptying of the tank (for at least 2000 s)

CHIPS Thrust Balance:



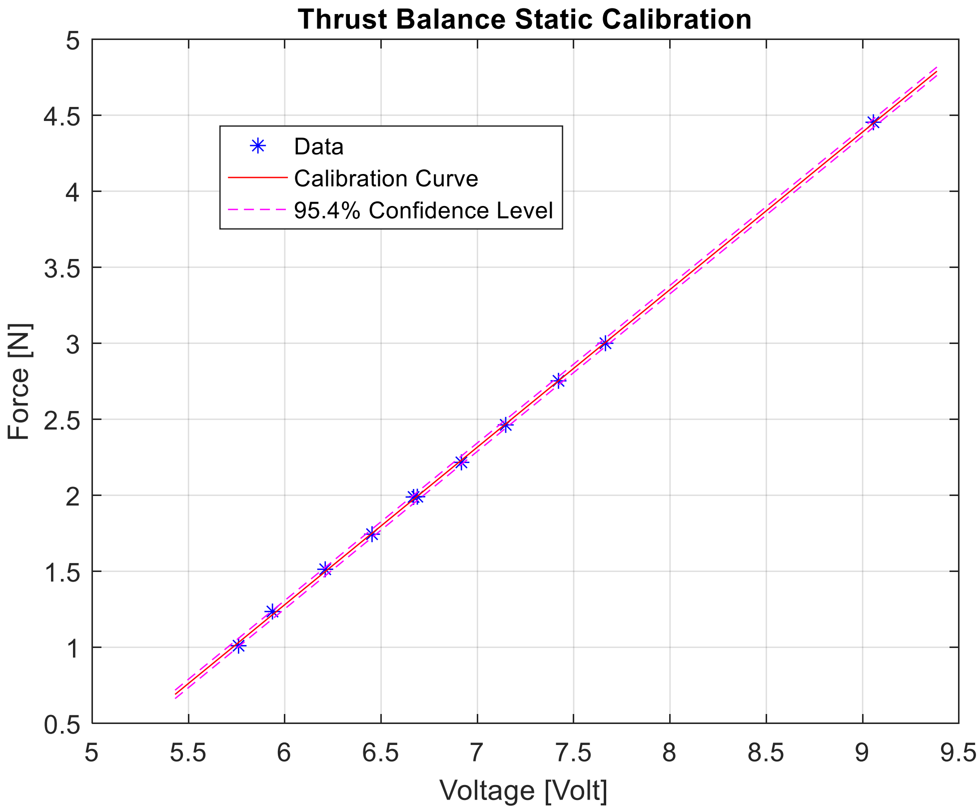
The CHIPS designed thrust balance is capable to house an whole 3U CubeSats on which are mounted the propulsion system and all the other required components



The thrust balance allows to measure the thrust of the propulsion system with a precision of some mN and is designed to rigidly transmit external excitations to the load cell inserted between the 3U structure and the beam

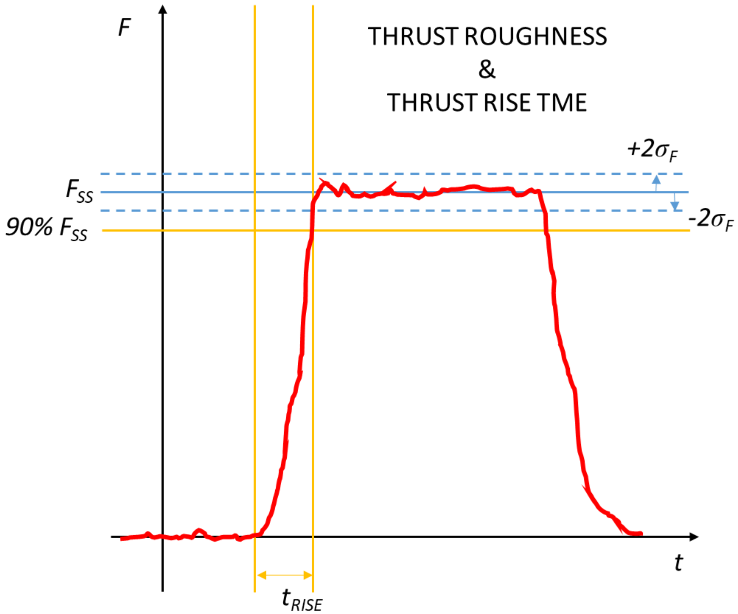
Thrust Balance Static Calibration

Voltage [V]	Weight [N]	Mass [kg]
5,47	0,762032	0,0776
5,76	1,010478	0,1029
5,936	1,235356	0,1258
6,21	1,513262	0,1541
6,453	1,744032	0,1776
6,6687	1,98855	0,2025
6,688	1,990514	0,2027
6,917	2,216374	0,2257
7,147	2,462856	0,2508
7,421	2,752546	0,2803
7,6648	3,00001	0,3055
9,056	4,45337	0,4535

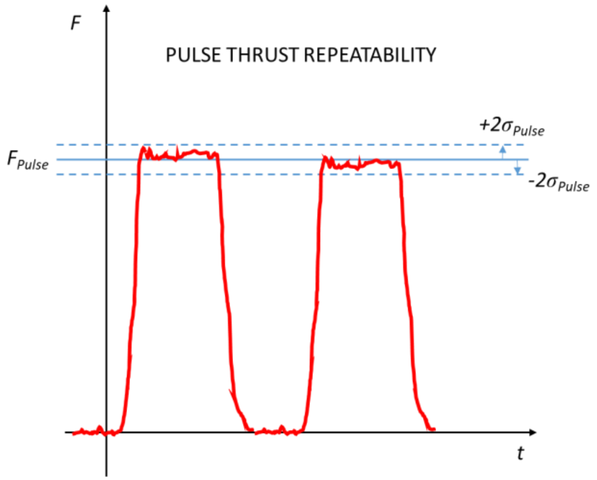


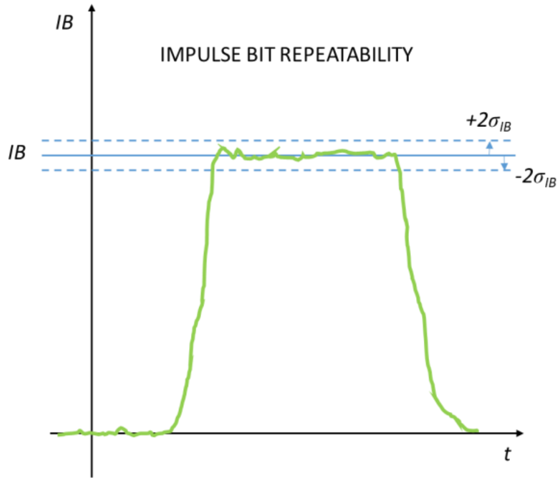
Thrust Balance Features	Value
Calibrated Full-Scale (FS)	4,453 N
Standard Deviation (σ_F)	0,014 N
Accuracy (95.4% Confidence Level)	0.6% FS

Propulsive Performance Characterization



Measured Physical Quantities	Measured Propulsive Parameters
$F(t)$ $\dot{m}(t)$ $p_c(t)$	F $MIB = \int_0^{T_{pulse}} F(t)\,dt$ $I_{sp} = \frac{F}{\dot{m}g} \Rightarrow \eta_{I_{sp}} = \frac{I_{sp}}{I_{sp}^{(theo)}}$ $C_F = \frac{F}{p_c A_{th}} \Rightarrow \eta_{C_F} = \frac{C_F}{C_F^{(theo)}}$ $c^* = \frac{p_c A_{th}}{\dot{m}} \Rightarrow \eta_{c^*} = \frac{c^*}{c^{*(theo)}}$





Group II: TEST-ATM-05-04 Setup

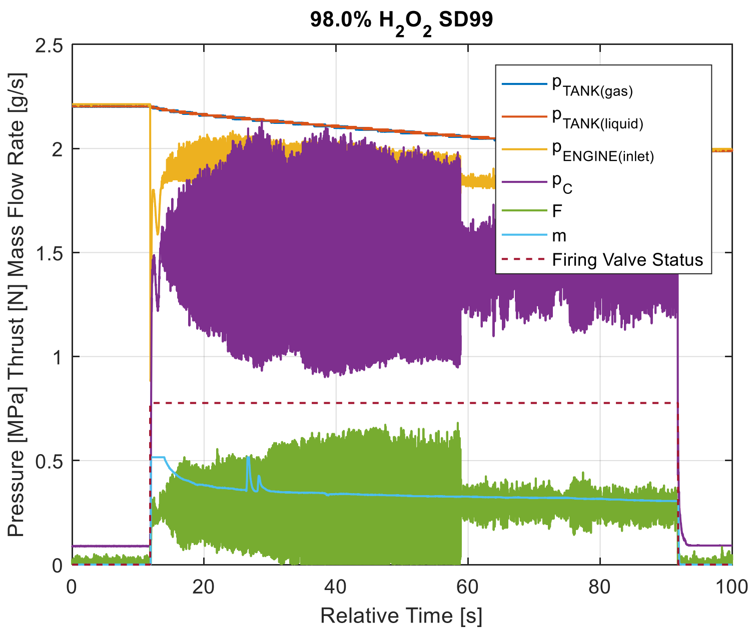
Component	Description
Catalyst	SD99- Pt/α Al_3O_2 0.4 mm
Catalytic Bed	2.8 mm diameter
Nozzle	Area ratio 70
Propellant	H_2O_2 98.0% wt.
Tank	EPE-0.35 liters (total volume)

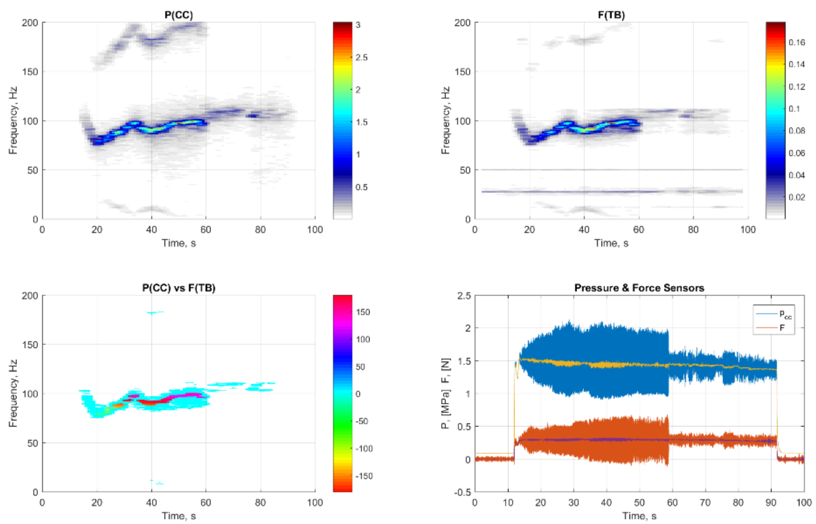
The total throughput was about 0.1 kg

Mode	t_{on} (ms)	t_{cycle} (ms)	repetition	start
Continuous	80000	N/A	2	Cold
Continuous	10000	N/A	1	Hot
Pulse	25	1000	2x80	Hot
Pulse	50	1000	1x80	Hot
Pulse	100	1000	1x80	Hot
Pulse	200	1000	1x80	Hot
Pulse	300	1000	1x80	Hot
Pulse	400	1000	1x20	Hot
Pulse	500	1000	1x20	Hot
Pulse	600	1000	1x20	Hot
Pulse	700	1000	1x20	Hot
Pulse	800	1000	2x20	Hot
Pulse	900	1000	2x20	Hot

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.3 (s.l.)	PROP-FUN-02/THRU-FUN-03	$\leq$ 0.5
Isp (s)	90 (s.l.)	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
Thrust Roughness	<50%	PROP-FUN-14	$\pm$5% at 2σ
η_{c*} (c*-efficiency)	0.9	PROP-FUN-11	0.9

- During the first 80 s continuous firing an instability has been detected only in the first half of the firing by the pressure sensors and the load cell.
- Its frequency ranges roughly from 80 Hz to 100 Hz.
- This instability disappeared in all the other tests performed in this atmospheric campaign.

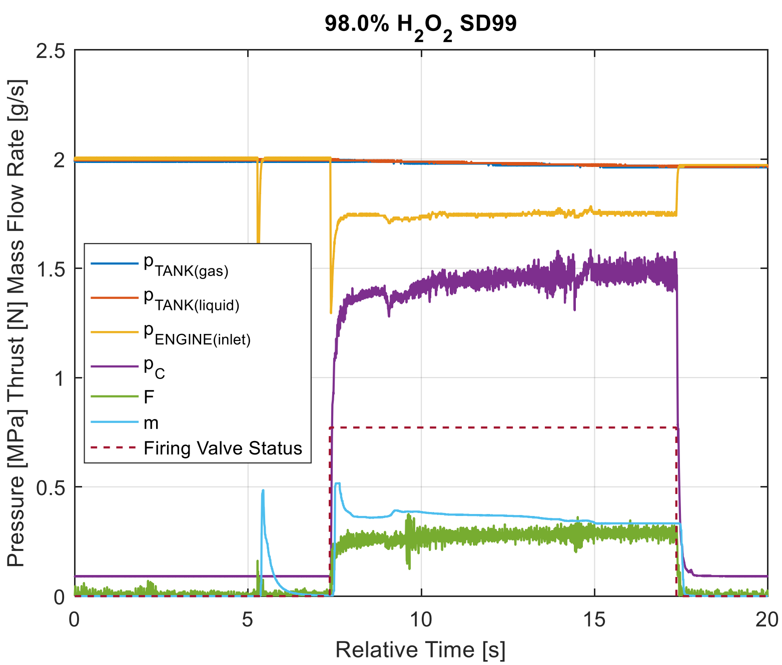


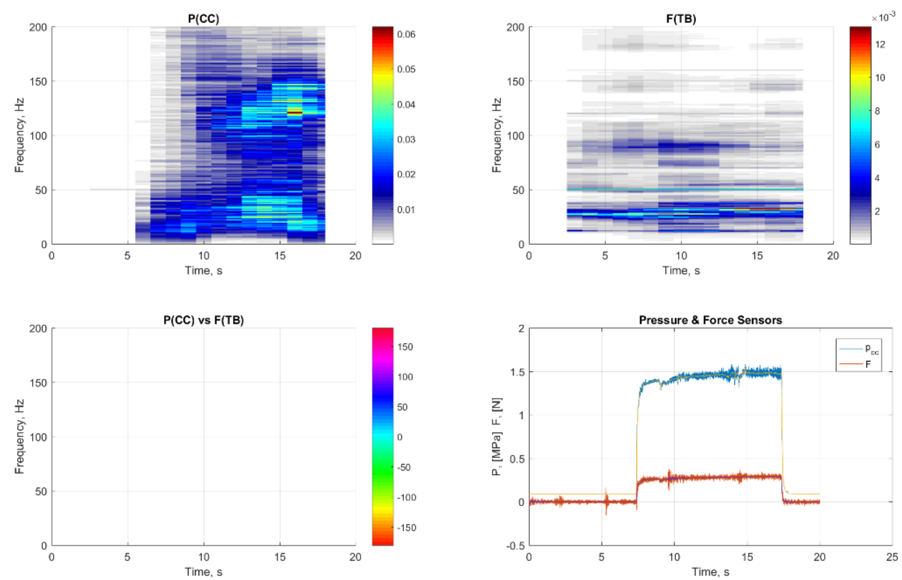


Group II: TEST-ATM-05-04 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.3 (s.l.)	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	80 (s.l.)	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
Thrust Roughness	<3.5%	PROP-FUN-14	±5% at 2σ
η_{c*} (c*-efficiency)	0.9	PROP-FUN-11	0.9

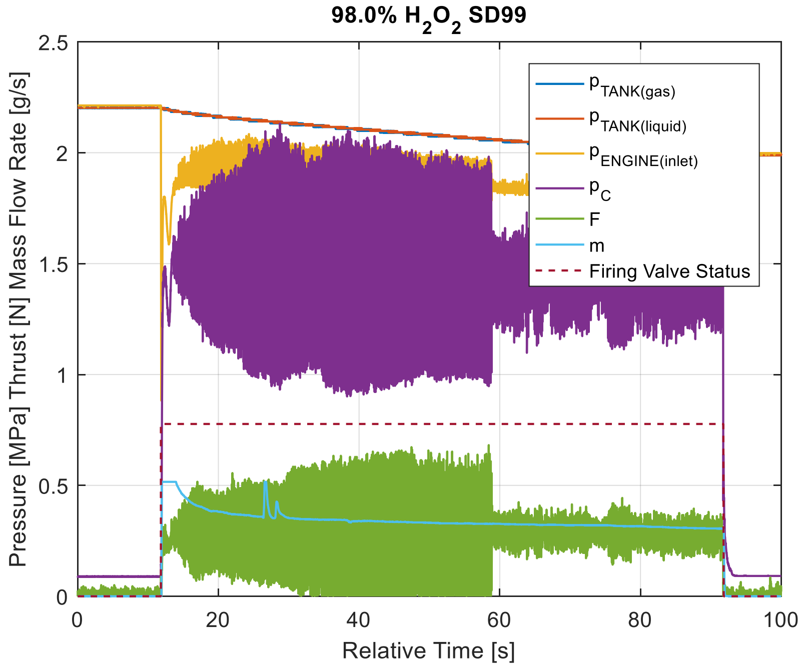
All the requirements were satisfied except for the Specific Impulse, due to the atmospheric exit conditions (10 s firing). The instability was not present.

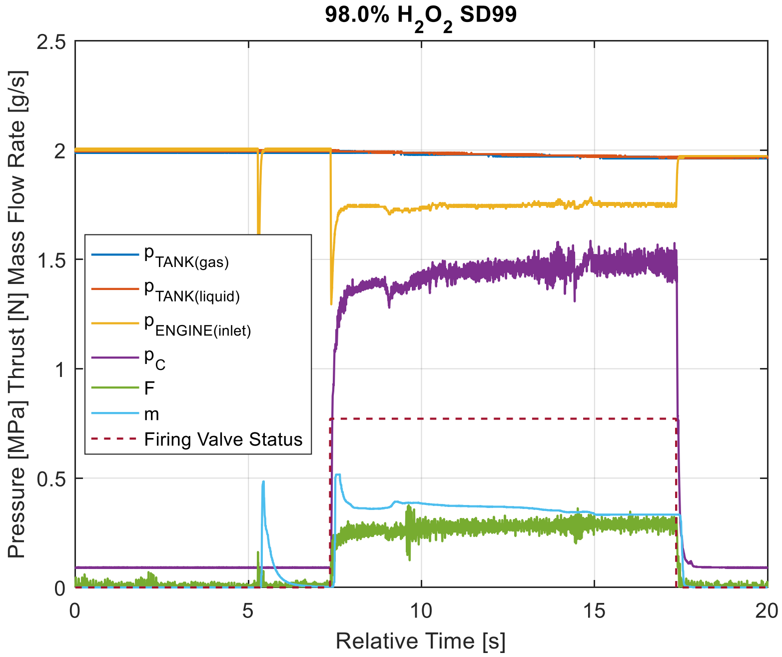




Group II: TEST-ATM-05-04 Main Achievements

First continuative firing of 80 s and second continuative firing of 10 s comparison (unfiltered graphs):

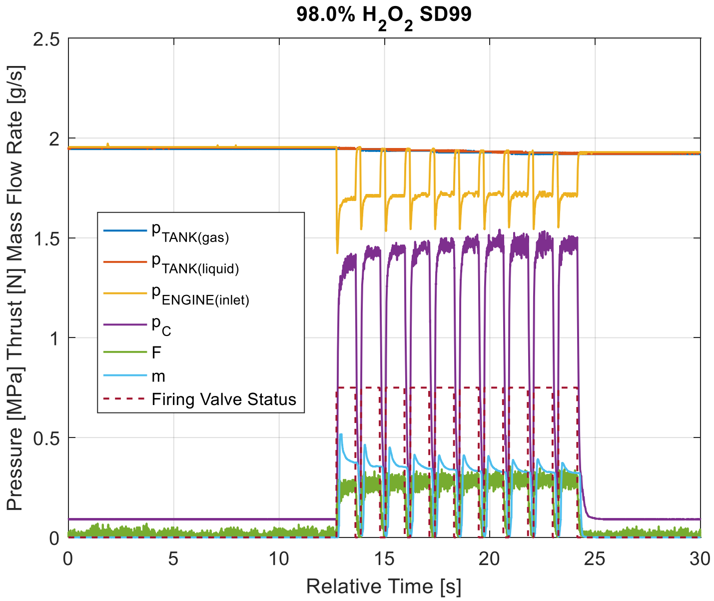


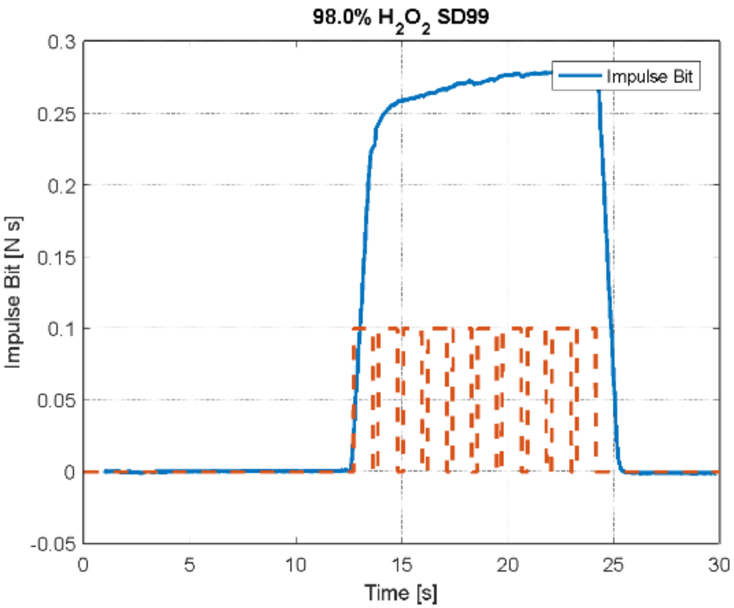


Group II: TEST-ATM-05-04 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.3 (s.l.)	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	80 (s.l.)	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
IB Repeatability	<6%	PROP-FUN-12	±12% at 2σ
Thrust Repeatability	<3%	PROP-FUN-12	±12% at 2σ
Impulse Bit (Ns)	0.26	PROP-FUN-08	≤ 0.025 (MIB)

All the requirements were satisfied except for the Specific Impulse, due to the atmospheric exit conditions, and MIB (t_{on} 900 ms, high duty cycle)



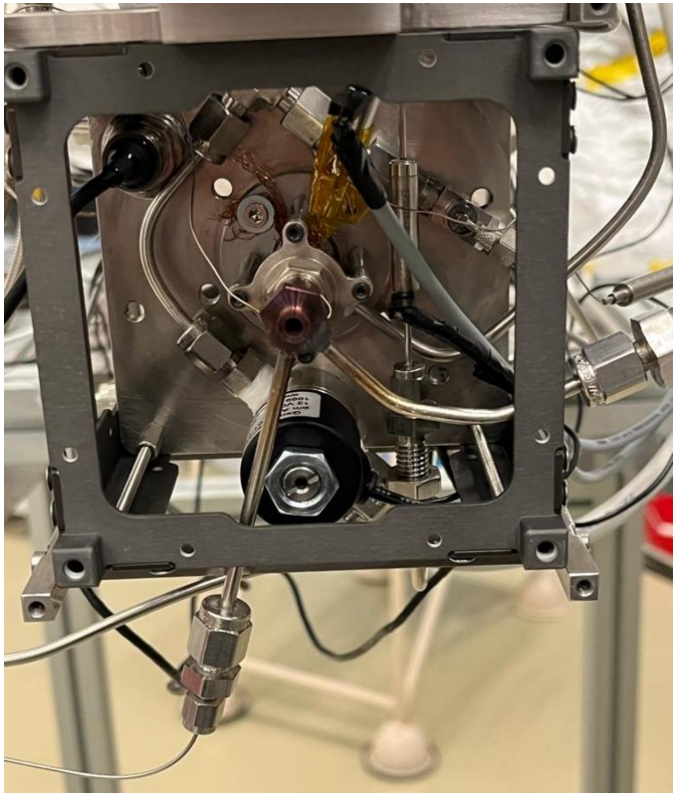


Group II: TEST-ATM-05-04 Main Achievements

Ton (ms)	N° Pulses	P_{in} (bar)	F (N)	Isp (s)	Impulse Bit (Ns)
900 (first series)	20	20	0.3 (s.l.)	80 (s.l.)	0.26
900 (second series)	20	16	0.19 (s.l.)	64 (s.l.)	0.22
800 (first series)	20	19	0.3 (s.l.)	80 (s.l.)	0.23
800 (second series)	20	Not completed due to catalyst degradation			
700 (first series)	20	19	0.27 (s.l.)	78 (s.l.)	0.19
600 (first series)	20	18	0.27 (s.l.)	70 (s.l.)	0.15
500 (first series)	20	18	0.25 (s.l.)	65 (s.l.)	0.12
400 (first series)	20	18	0.25 (s.l.)	62 (s.l.)	0.11
300 (first series)	80	17	0.23 (s.l.)	55 (s.l.)	0.077
200 (first series)	80	17	0.23 (s.l.)	45 (s.l.)	0.05
100 (first series)	80	17	0.22 (s.l.)	25 (s.l.)	0.025
50 (first series)	80	16	0.2 (s.l.)	15 (s.l.)	0.016
25 (first series)	80	16	0.15 (s.l.)	10 (s.l.)	0.010
25 (second series)	80	16	0.13 (s.l.)	15 (s.l.)	0.015

Group III: TEST-VAC-01 First Test Setup

Component	Description
Catalyst	SD99 Pt/α Al_3O_2 0.4 mm
Catalytic Bed	4 mm diameter
Nozzle	Area ratio 70
Propellant	H_2O_2 98.0% wt.
Tank	EPE-0.35 liters (total volume)

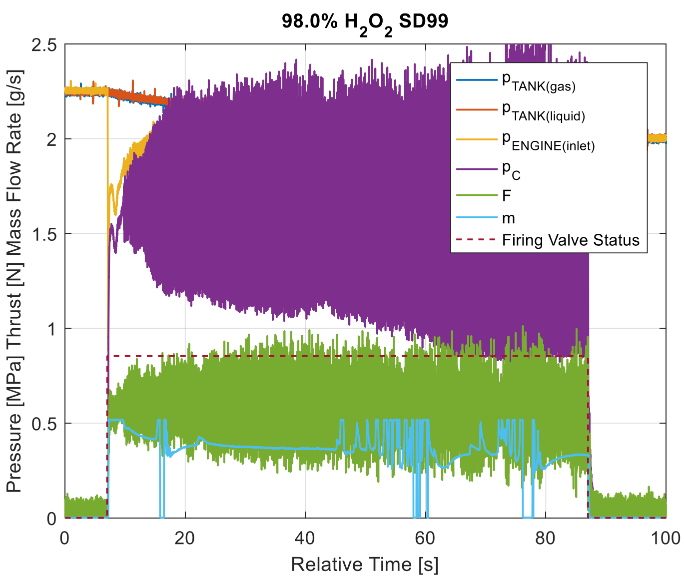


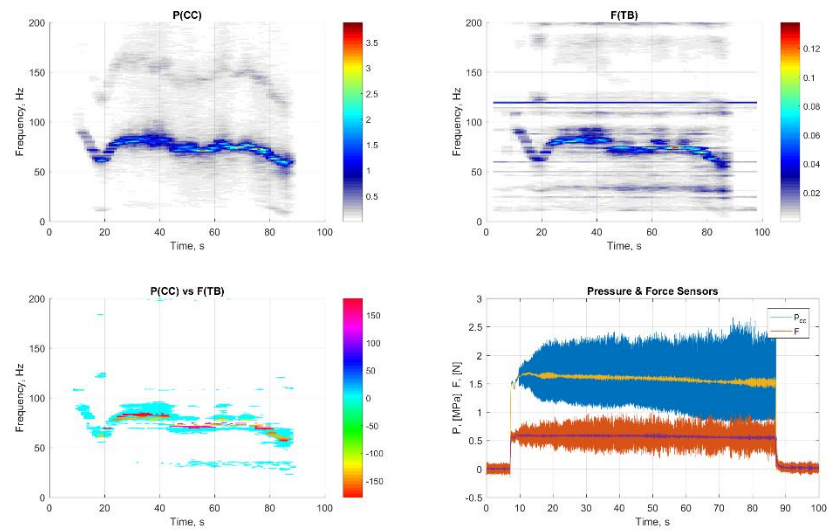
Mode	t_{on} (ms)	t_{cycle} (ms)	repetition	start
Continuous	80000	N/A	2	cold
Continuous	30000	N/A	1	Hot
Pulse	25	1000	2x80	Hot
Pulse	50	1000	2x80	Hot
Pulse	100	1000	2x80	Hot
Pulse	200	1000	2x80	Hot
Pulse	300	1000	2x80	Hot
Pulse	400	1000	2x20	Hot
Pulse	500	1000	2x20	Hot
Pulse	600	1000	2x20	Hot
Pulse	700	1000	2x20	Hot
Pulse	800	1000	2x20	Hot
Pulse	900	1000	2x20	Hot

The total throughput was about 0.160 kg

Group III: TEST-VAC-01 Main Achievements

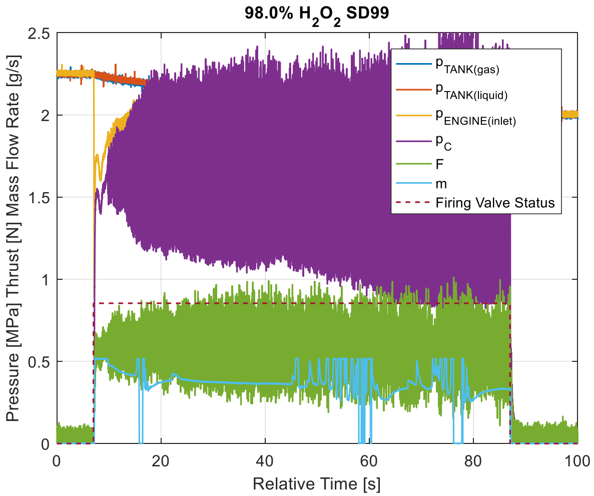
Intense chamber pressure instability originated inside the thrust chamber. Both sensors at the inlet and in the decomposition chamber detected this instability, as shown in the spectral analysis





Group III: TEST-VAC-01 Main Achievements

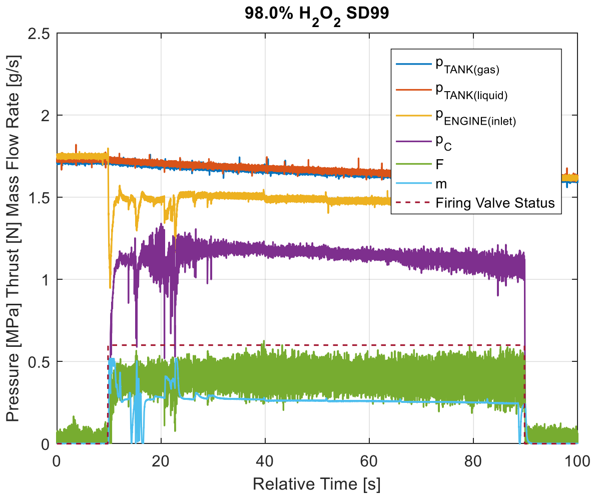
First serie
80 s firing



Parameter	Value	Threshold Value
F (N)	0.55	≤ 0.5
Isp (s)	160	160
Rise-time (ms)	<100	150
Thrust Roughness	20%	$\pm 5\%$ at 2σ
η_{c^*} (c*-efficiency)	0.9	0.9

All the requirements are respected except the thrust roughness, due to the instability

Second serie
80 s firing



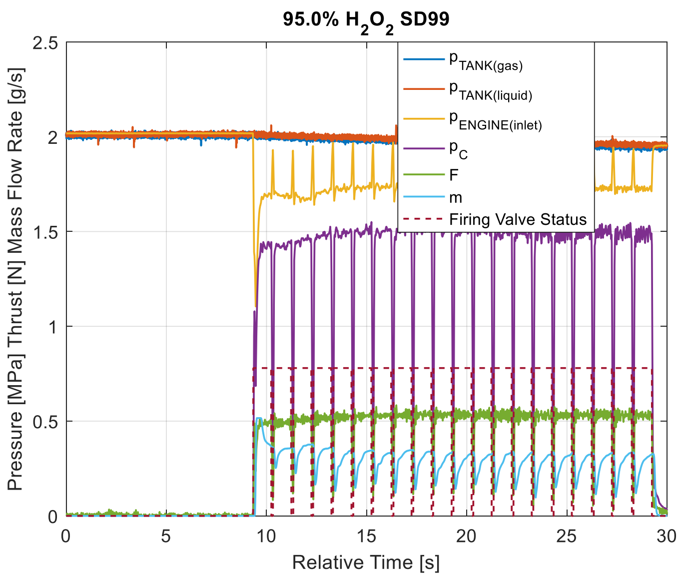
Parameter	Value	Threshold Value
F (N)	0.4	≤ 0.5
Isp (s)	160	160
Rise-time (ms)	<100	150
Thrust Roughness	<3%	$\pm 5\%$ at 2σ
η_{c^*} (c*-efficiency)	0.9	0.9

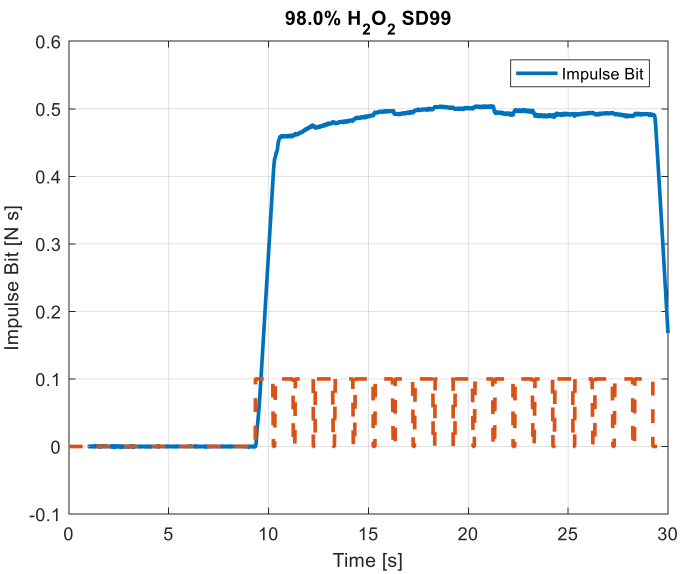
No instability has been detected and all the requirements are satisfied

Group III: TEST-VAC-01 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.5	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	160	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
IB Repeatability	<5%	PROP-FUN-12	±12% at 2σ
Thrust Repeatability	<6%	PROP-FUN-12	±12% at 2σ
Impulse Bit (Ns)	0.48	PROP-FUN-08	≤ 0.025 (MIB)

During this pulsed firing with t_{on}=900 ms (high duty cycle) all the requirements are satisfied, except the MIB (filtered graphs)

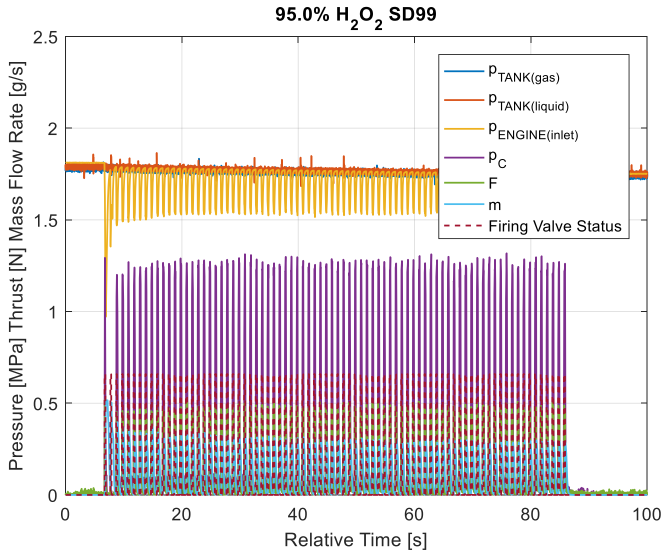


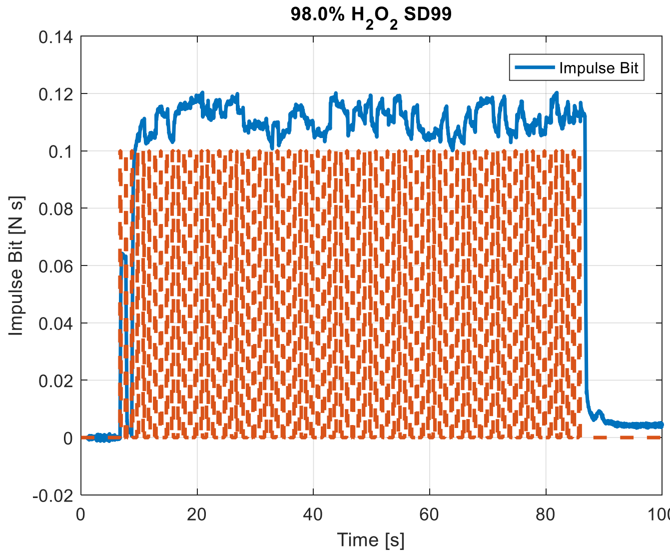


Group III: TEST-VAC-01 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.4	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	90	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
IB Repeatability	<6%	PROP-FUN-12	±12% at 2σ
Thrust Repeatability	<8%	PROP-FUN-12	±12% at 2σ
Impulse Bit (Ns)	0.11	PROP-FUN-08	≤ 0.025 (MIB)

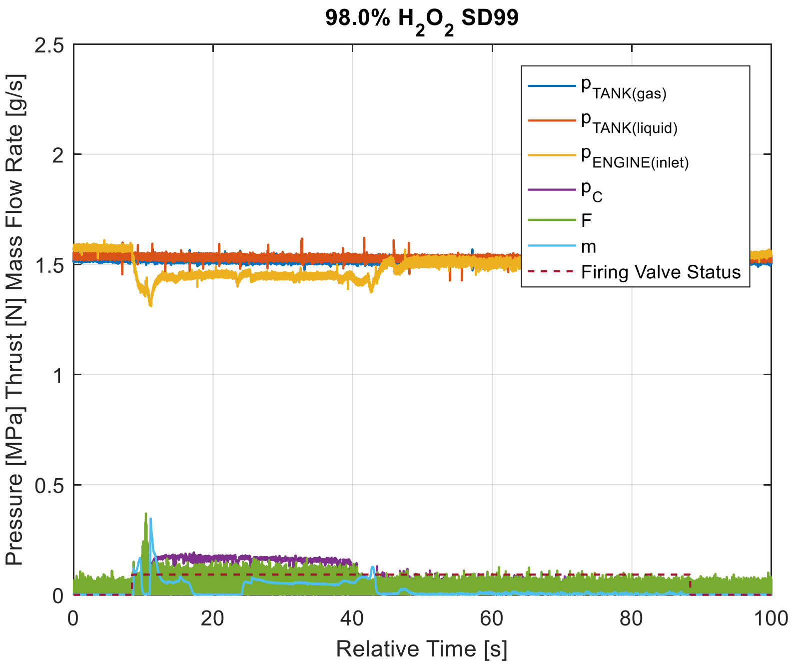
For lower t_{on} (50 and 25 ms) the rise-time is labeled as “Not applicable” since the propulsion system did not reach a steady value of the thrust during the t_{on} (100 ms t_{on}, low duty cycle)





Group III: TEST-VAC-01 Main Achievements

- Third series continuos firing for 80 s: the performance given by the propulsion system were lower than expected
- No more propellant was available inside the tank
- This cause the end of the test

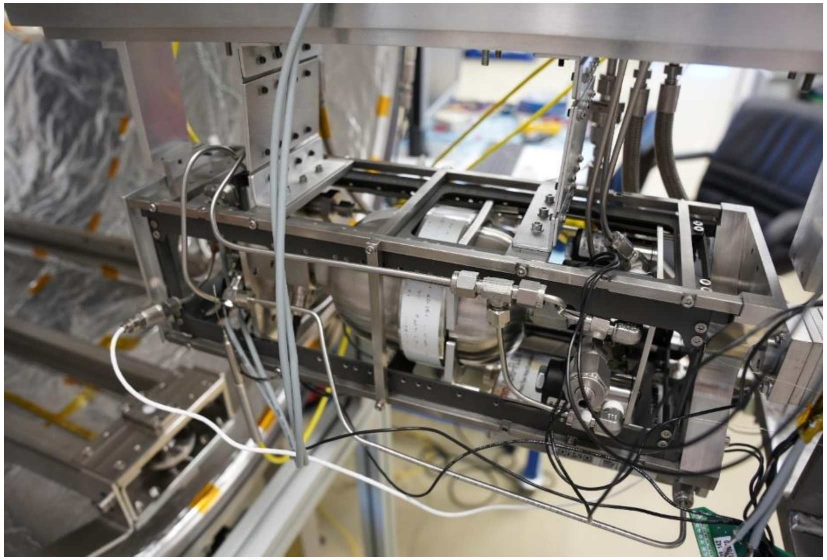


Group II: TEST-VAC-01 Main Achievements

Ton (ms)	N° Pulses	P_{in} (bar)	F(N)	Isp(s)	Impulse Bit (Ns)
900 (first series)	20	17	0.5	160	0.48
900 (second series)	20	14	0.4	145	0.36
800 (first series)	20	17	0.5	150	0.43
800 (second series)	20	14	0.35	140	0.3
700 (first series)	20	17	0.5	150	0.37
700 (second series)	20	13.5	0.35	150	0.27
600 (first series)	20	16.5	0.5	140	0.32
600 (second series)	20	Not performed			
500 (first series)	20	16.5	0.45	135	0.26
500 (second series)	20	14.5	0.25	100	0.1
400 (first series)	20	16	0.45	125	0.21
400 (second series)	20	14	0.25	100	0.13
300 (first series)	80	16	0.4	110	0.16
300 (second series)	80	14	0.3	100	0.13
200 (first series)	80	15.5	0.4	90	0.11
200 (second series)	80	14.5	0.05	15	0.005
100 (first series)	80	15.5	0.4	60	0.065
100 (second series)	80	14	0.05	5	0.005
50 (first series)	80	16	0.2	30	0.02
50 (second series)	80	14	0.07	5	0.005
25 (first series)	80	16	0.2	30	0.02
25 (second series)	80	14	0.05	20	0.01

Group III: TEST-VAC-01 Second Test Setup

Component	Description
Catalyst	SD99 Pt/α Al_3O_2 0.4 mm
Catalytic Bed	2.8 mm diameter
Nozzle	Area ratio 70
Propellant	H_2O_2 98.0% wt.
Tank	EPE-0.35 liters (total volume)

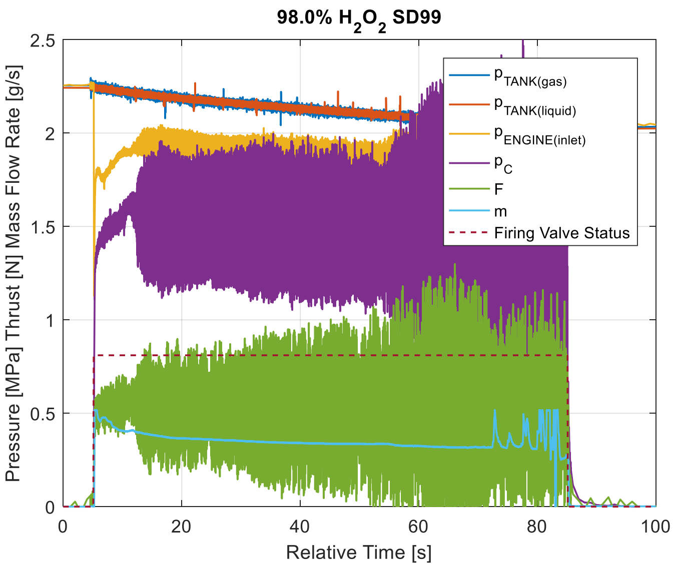


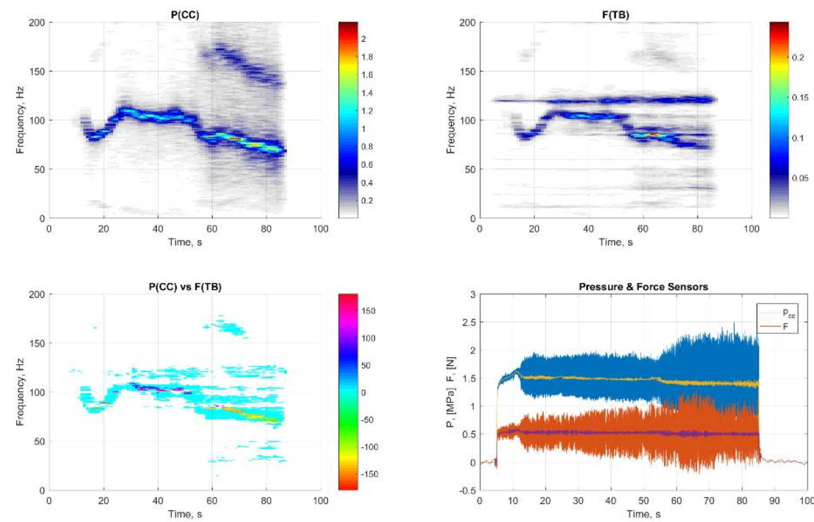
The total throughput was about 0.120 kg

Mode	t_{on} (ms)	t_{cycle} (ms)	repetition	start
Continuous	80000	N/A	2	Cold
Continuous	10000	N/A	1	Hot
Pulse	25	1000	2x80	Hot
Pulse	50	1000	2x80	Hot
Pulse	100	1000	2x80	Hot
Pulse	200	1000	2x80	Hot
Pulse	300	1000	2x80	Hot
Pulse	400	1000	2x20	Hot
Pulse	500	1000	2x20	Hot
Pulse	600	1000	2x20	Hot
Pulse	700	1000	2x20	Hot
Pulse	800	1000	2x20	Hot
Pulse	900	1000	2x20	Hot

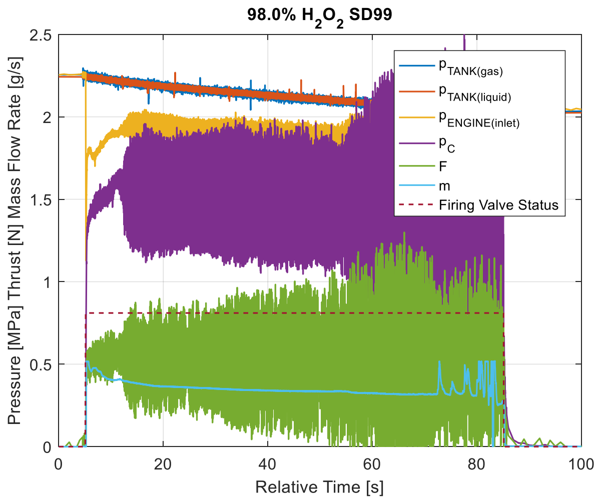
Group III: TEST-VAC-01 Main Achievements

Changing the catalityc bed didn't help solving the instability issue. We can see a significant chamber pressure instability that seems to increase its amplitude in the last 30 s





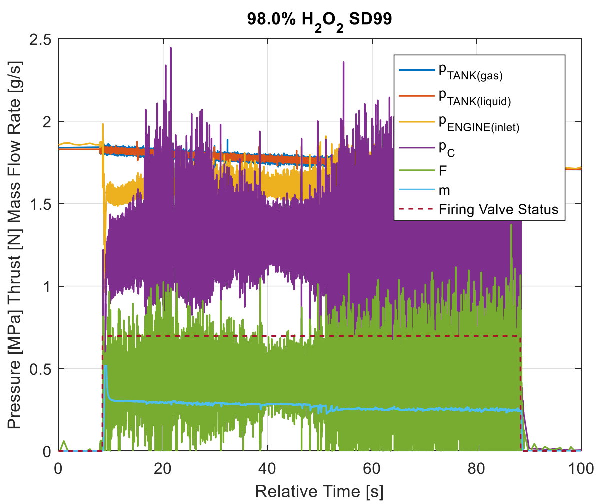
First serie
80 s firing



Parameter	Value	Threshold Value
F (N)	0.5	$\leq$ 0.5
Isp (s)	160	160
Rise-time (ms)	<100	150
Thrust Roughness	<50%	$\pm$5% at 2σ
η_{c*} (c*-efficiency)	0.85	0.9

c* efficiency and thrust roughness are not satisfied due to the instability

Second serie
80 s firing



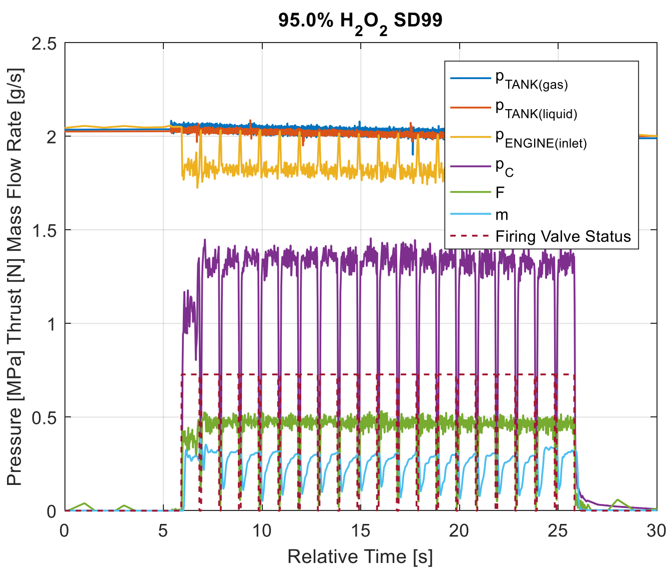
Parameter	Value	Threshold Value
F (N)	0.4	$\leq$ 0.5
Isp (s)	160	160
Rise-time (ms)	<100	150
Thrust Roughness	<35%	$\pm$12% at 2σ
η_{c*} (c*-efficiency)	0.9	0.9

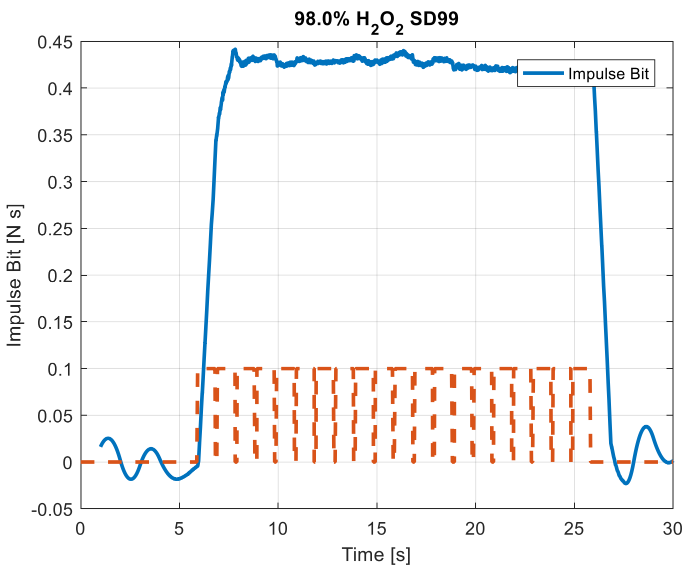
Thrust roughness is not satisfied due to the instabilty

Group III: TEST-VAC-01 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.48	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	165	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
IB Repeatability	<5%	PROP-FUN-12	±12% at 2σ
Thrust Repeatability	<5%	PROP-FUN-12	±12% at 2σ
Impulse Bit (Ns)	0.43	PROP-FUN-08	≤ 0.025 (MIB)

During this pulsed firing with t_{on}=900 ms (high duty cycle) all the requirements are satisfied, except the MIB

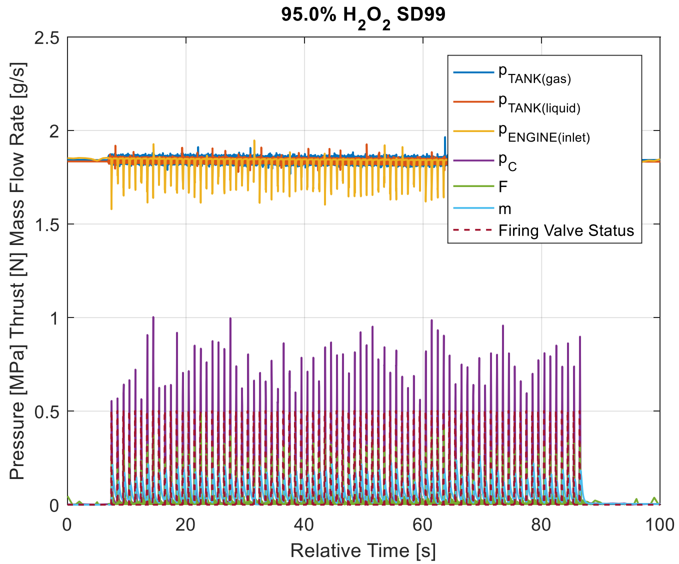


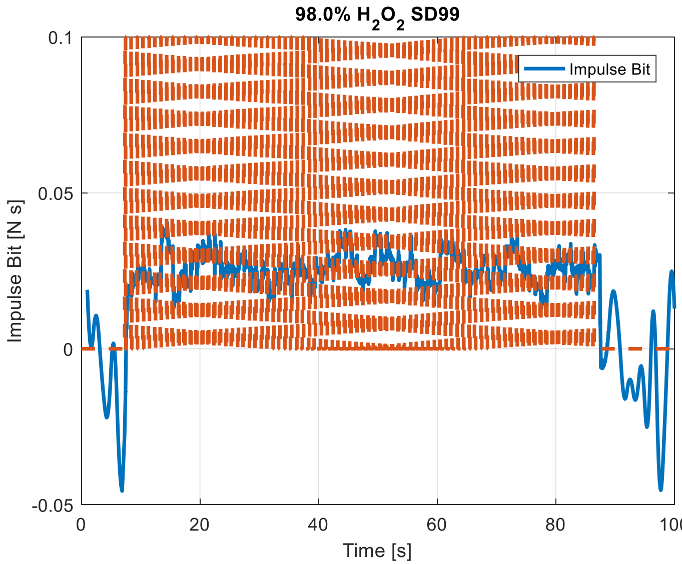


Group III: TEST-VAC-01 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.2	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	40	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
IB Repeatability	<40%	PROP-FUN-12	±12% at 2σ
Thrust Repeatability	<50%	PROP-FUN-12	±12% at 2σ
Impulse Bit (Ns)	0.025	PROP-FUN-08	≤ 0.025 (MIB)

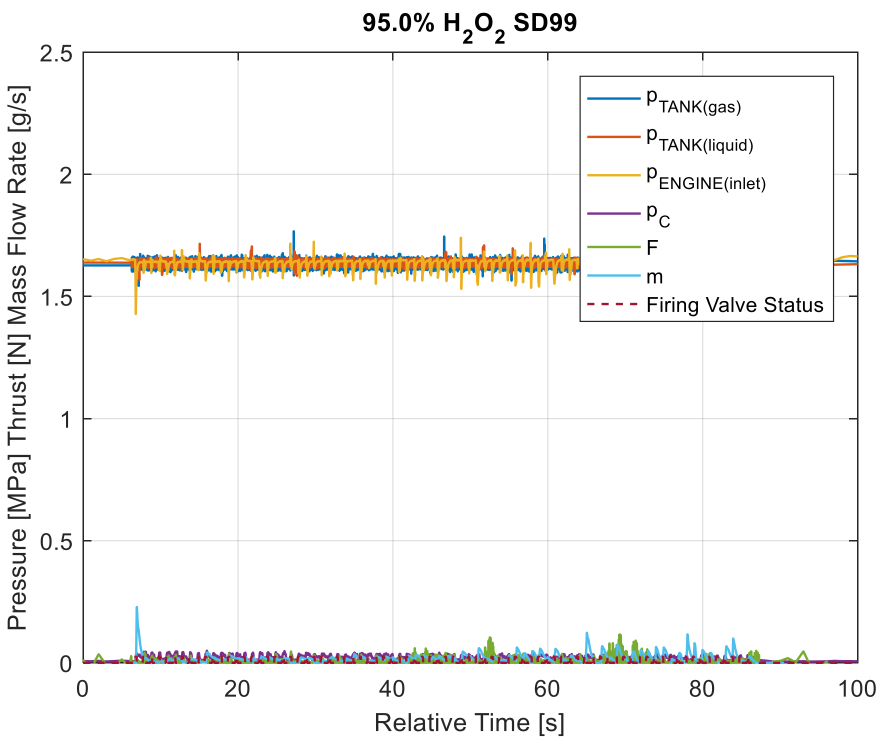
For lower t_{on} (50-25 ms) the rise-time is labeled as "Not applicable" since the propulsion system did not reach a steady value of the thrust during the t_{on} (100 ms t_{on}, low duty cycle)





Group III: TEST-VAC-01 Main Achievements

- Second series pulsed firing t_{on} 200-25 ms: the performance given by the propulsion system were lower than expected
- No more propellant was available inside the tank
- This cause the end of the test

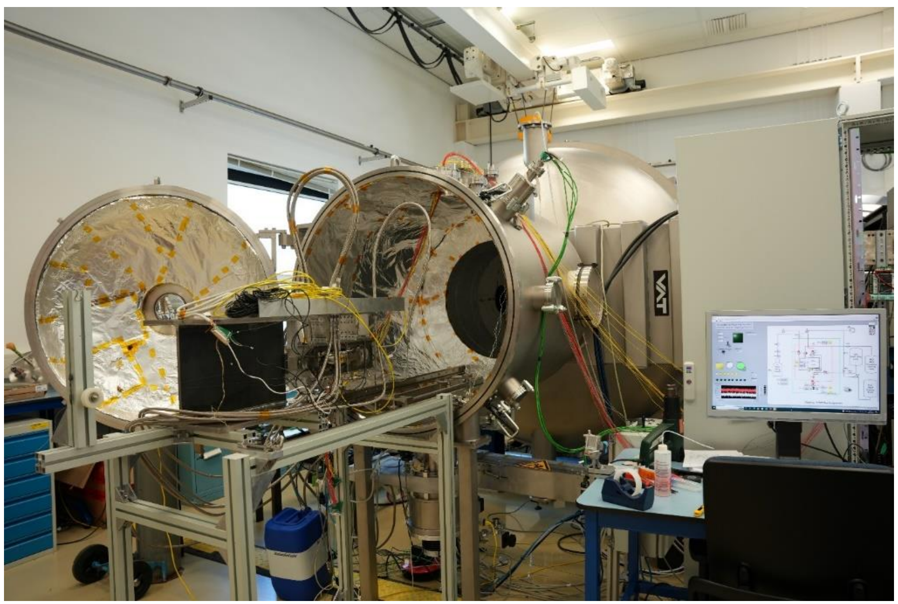


Group III: TEST-VAC-01 Main Achievements

Ton (ms)	N° Pulses	P_{in}(bar)	F(N)	Isp(s)	Impulse Bit (Ns)
900 (first series)	20	18.5	0.48	165	0.43
900 (second series)	20	16	0.4	150	0.28
800 (first series)	20	18	0.45	150	0.37
800 (second series)	20	16	0.26	160	0.23
700 (first series)	20	18	0.5	150	0.28
700 (second series)	20	16	0.23	155	0.16
600 (first series)	20	18	0.35	150	0.22
600 (second series)	20	15.5	0.22	140	0.14
500 (first series)	20	17.5	0.35	150	0.18
500 (second series)	20	15.5	0.25	140	0.12
400 (first series)	20	17.5	0.35	150	0.16
400 (second series)	20	15.5	0.2	105	0.09
300 (first series)	80	17	0.35	135	0.12
300 (second series)	80	15	0.25	110	0.075
200 (first series)	80	17	0.3	130	0.09
200 (second series)	80	No more propellant inside the tank			
100 (first series)	80	16.5	0.2	40	0.025
100 (second series)	80	No more propellant inside the tank			
50 (first series)	80	17	0.15	40	0.02
50 (second series)	80	No more propellant inside the tank			
25 (first series)	80	16.5	0.1	40	0.02
25 (second series)	80	No more propellant inside the tank			

Group III: TEST-VAC-01 Third Test Setup

Component	Description
Catalyst	• SD99 Pt/α Al_3O_2 0.4 mm (41% of length) • LBbi-220 Pt/α Al_3O_2 0.09 mm (59% of length)
Catalytic Bed	2.8 mm diameter
Nozzle	Area ratio 70
Propellant	H_2O_2 98.0% wt.
Tank	EPE-0.35 liters (total volume)



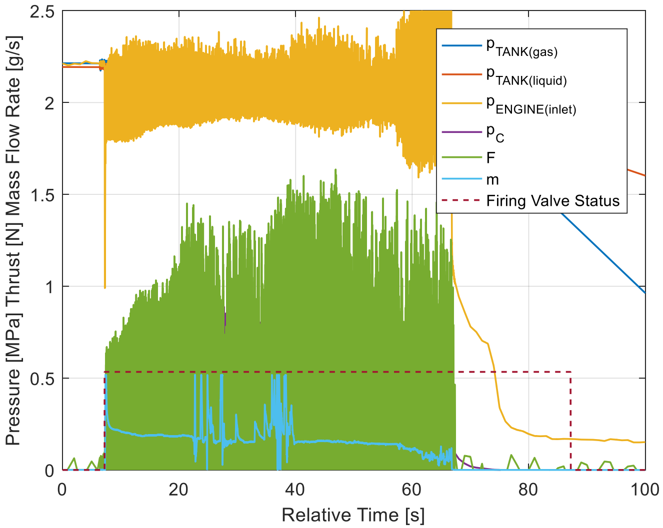
Mode	t_{on} (ms)	t_{cycle} (ms)	repetition	start
Continuous	80000	N/A	1	Cold

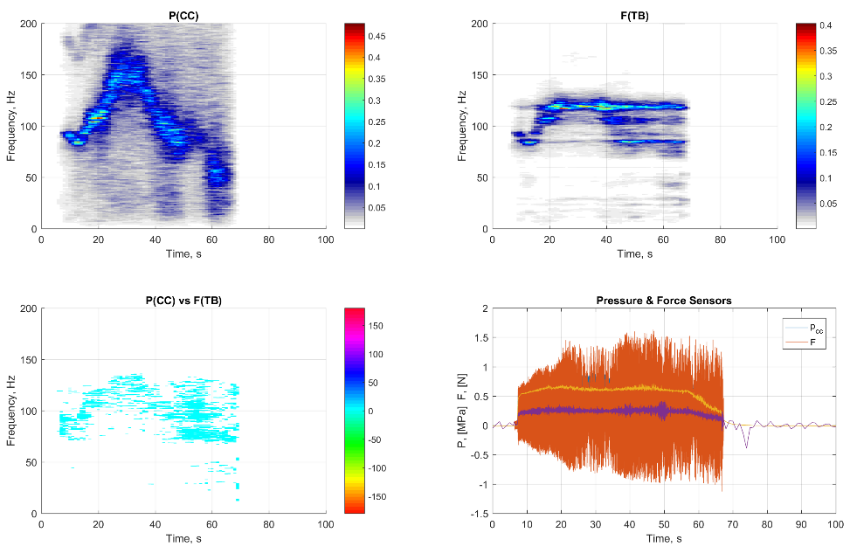
The total throughput was about 0.01 kg

Group III: TEST-VAC-01 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.25	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	140	PROP-FUN-04	160
Rise-time (ms)	<100	PROP-FUN-09	150
Thrust Roughness	<150%	PROP-FUN-14	±5% at 2σ
η_{c*} (c*-efficiency)	0.85	PROP-FUN-11	0.9

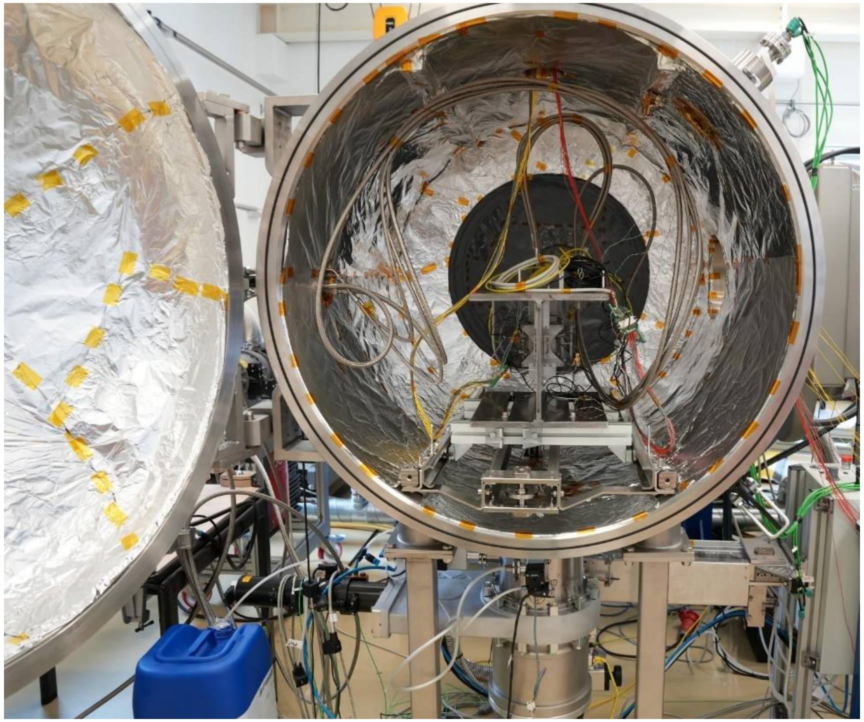
- The instability developed inside the propulsion system rose the pressure inside the tank above the MEOP.
- The “red button” procedure was activated.
- This cause the end of the test





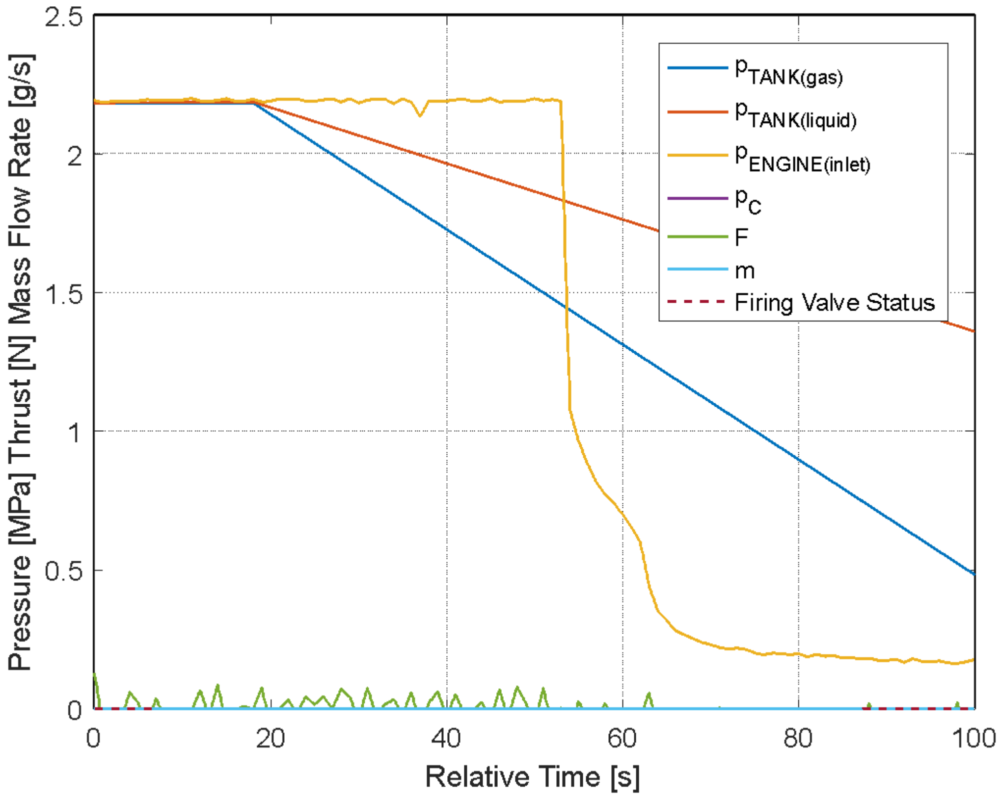
Group III: TEST-VAC-01 Fourth Test Setup

Component	Description
Catalyst	• SD99 Pt/α Al_3O_2 0.4 mm (88% of length) • LBbi-220 Pt/α Al_3O_2 0.09 mm (12% of length)
Catalytic Bed	2.8 mm diameter
Nozzle	Area ratio 70
Propellant	H_2O_2 98.0% wt.
Tank	EPE-0.35 liters (total volume)



Group III: TEST-VAC-01 Main Achievements

Before the continuous first firing lasting 80 s, an electrical spike generated inside the acquisition system triggered the activation of the “red button” procedure, and the tank of the propulsion system was automatically emptied.



Group III: TEST-VAC-01 Fifth Test Setup

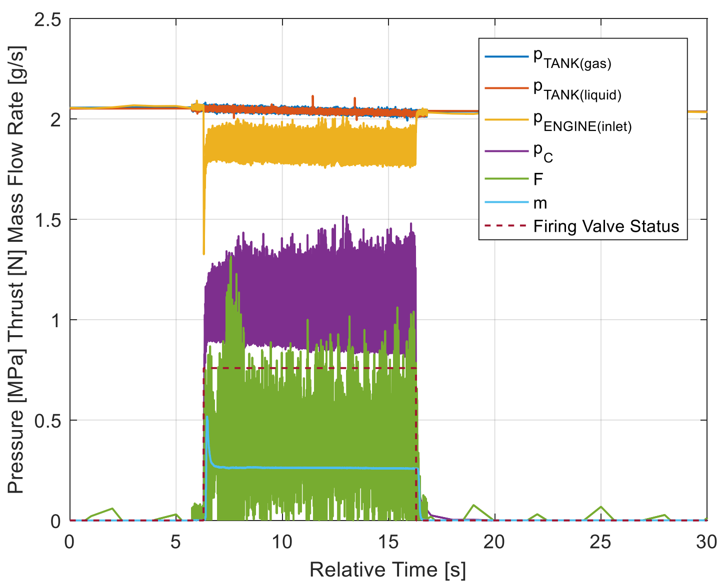
Component	Description
Catalyst	• SD99 Pt/α Al_3O_2 0.4 mm (88% of length) • LBbi-220 Pt/α Al_3O_2 0.09 mm (12% of length)
Catalytic Bed	2.8 mm diameter
Nozzle	Area ratio 70
Propellant	H_2O_2 98.0% wt.
Tank	EPE-0.35 liters (total volume)

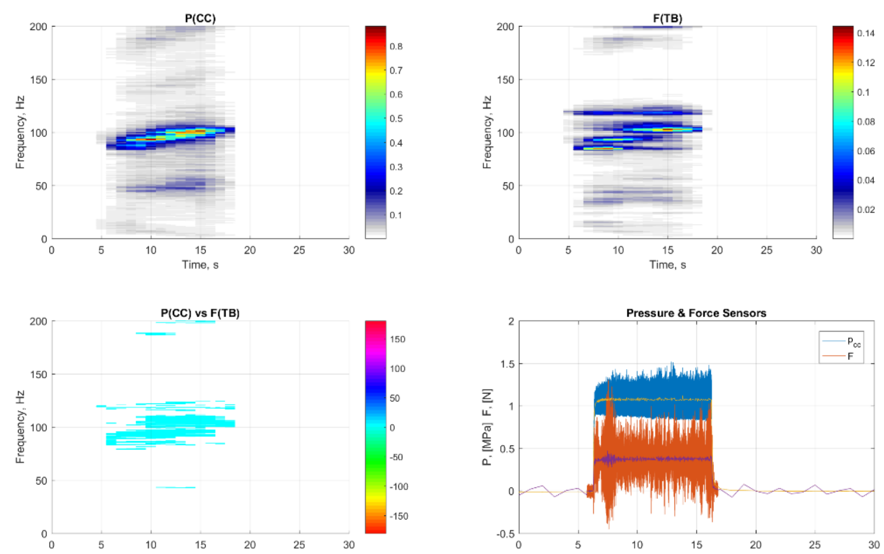
Mode	t_{on} (ms)	t_{cycle} (ms)	repetition	start
Pulse	1000	1000	1x10	Cold
Continuous	20000	N/A	1	Hot
Continuous	80000	N/A	1	Hot
Pulse	700	1000	1x20	Hot
Pulse	800	1000	1x20	Hot
Pulse	900	1000	1x20	Hot

The total throughput was about 0.07 kg (fifth and sixth tests)

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.4	PROP-FUN-02/THRU-FUN-03	$\leq$ 0.5
Isp (s)	145	PROP-FUN-04	160
Rise-time (ms)	<120	PROP-FUN-09	150
Thrust Roughness	<30%	PROP-FUN-14	±5% at 2σ
η_{c^*} (c*-efficiency)	0.8	PROP-FUN-11	0.9

The instability occured also during this test (firing for 20 s).
The temperature of the thruster did not reach high values.

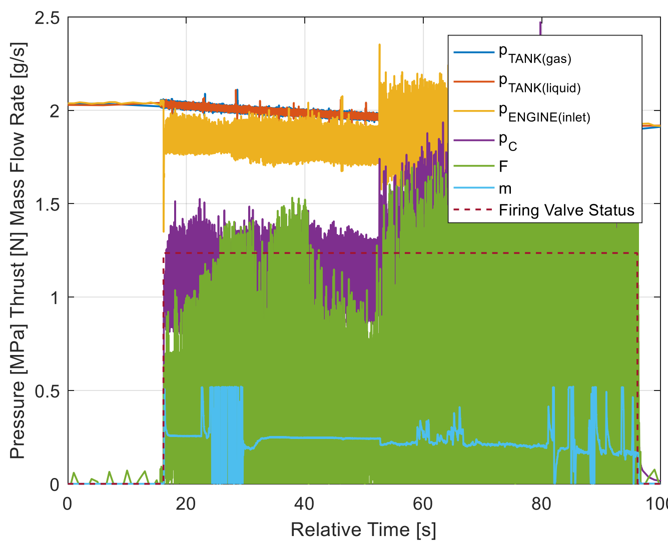


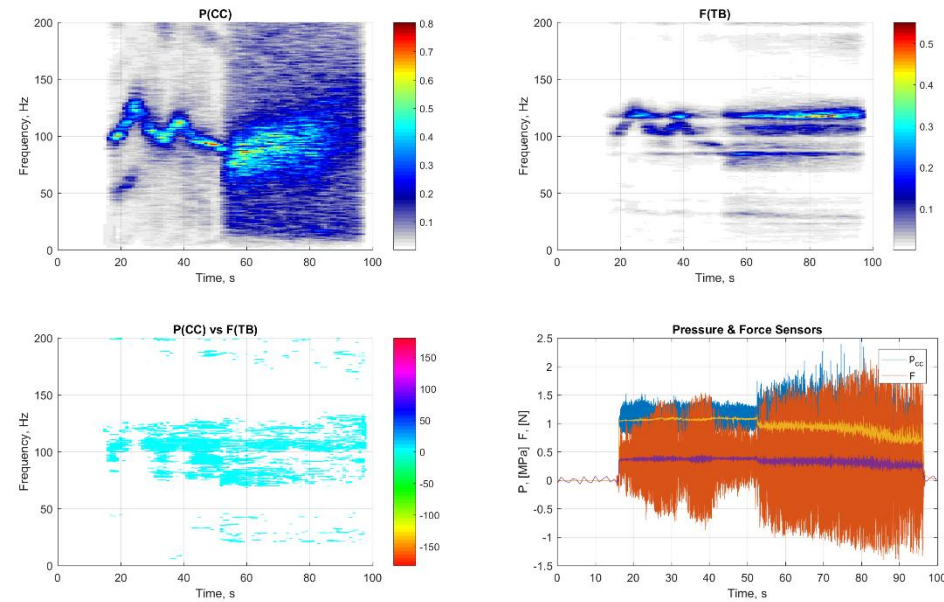


Group III: TEST-VAC-01 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.3	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	160	PROP-FUN-04	160
Rise-time (ms)	<150	PROP-FUN-09	150
Thrust Roughness	<150%	PROP-FUN-14	±5% at 2σ
η_{c*} (c*-efficiency)	0.9	PROP-FUN-11	0.9

The instability occured also during this test. However, looking at the average of the obtained quantities, all the imposed requirements were satisified, except for the thrust roughness (80 s firing)

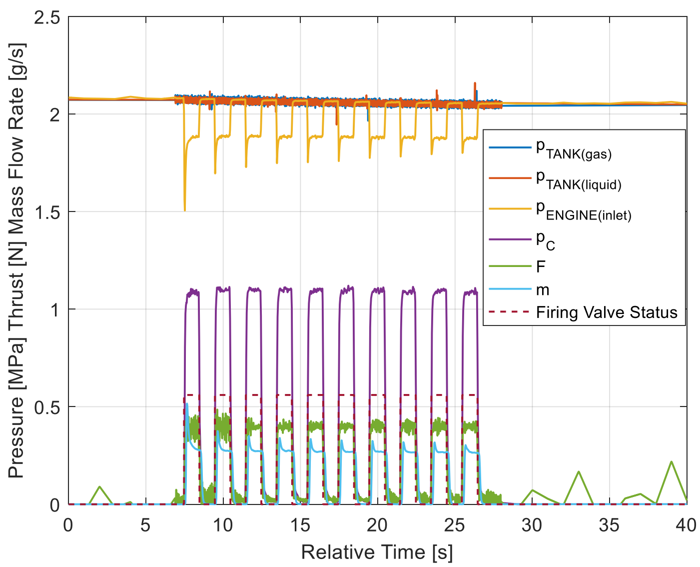


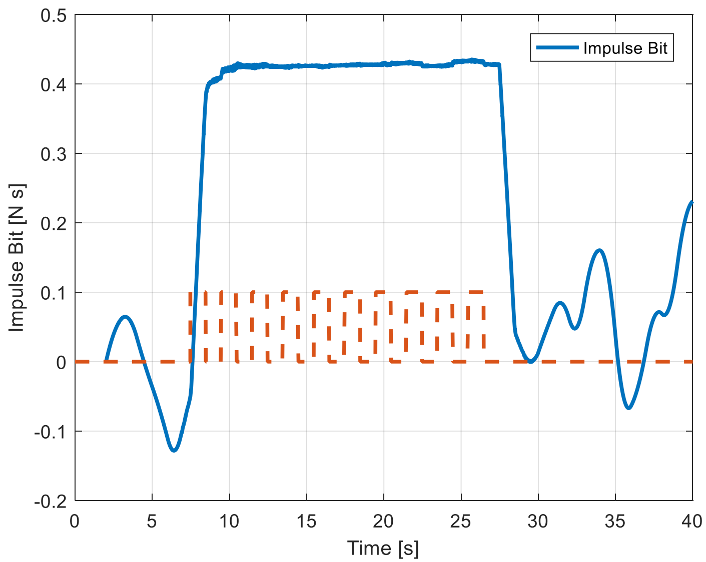


Group III: TEST-VAC-01 Main Achievements

Parameter	Value	Verified Req.	Threshold Value
F (N)	0.45	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	160	PROP-FUN-04	160
Rise-time (ms)	<150	PROP-FUN-09	150
IB Repeatability	<4%	PROP-FUN-12	±12% at 2σ
Thrust Repeatability	<5%	PROP-FUN-12	±12% at 2σ
Impulse Bit (Ns)	0.43	PROP-FUN-08	≤ 0.025 (MIB)

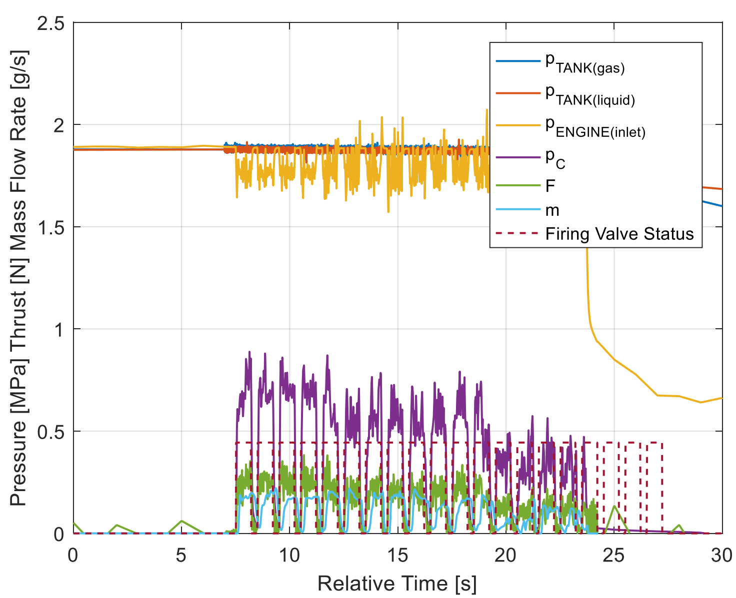
The instability occured also during this test. However, looking at the average of the obtained quantities, all the imposed requirements were satisified (ton 1000 ms, high duty cycle)

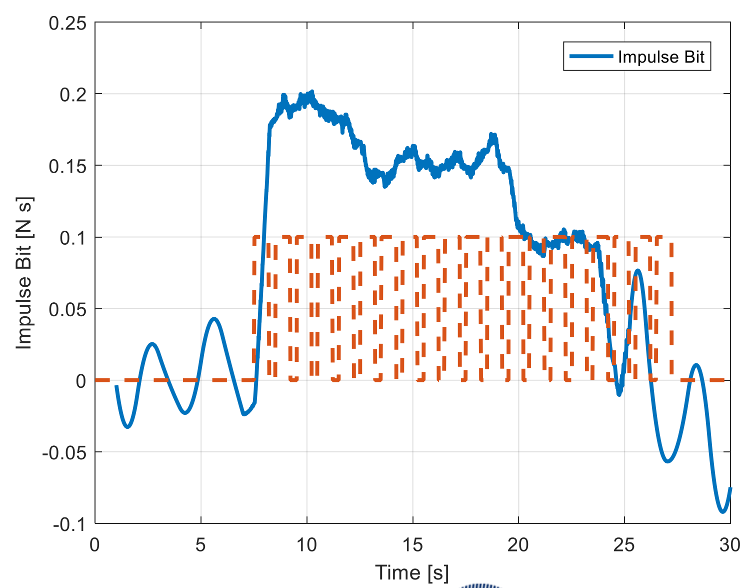




Parameter	Value	Verified Req.	Threshold Value
F (N)	0.2	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	130	PROP-FUN-04	160
Rise-time (ms)	<150	PROP-FUN-09	150
IB Repeatability	<35%	PROP-FUN-12	±12% at 2σ
Thrust Repeatability	<60%	PROP-FUN-12	±12% at 2σ
Impulse Bit (Ns)	0.15	PROP-FUN-08	≤ 0.025 (MIB)

- During the fifth run (pulsed 700 ms t_{on}, high duty cycle), a pressure oscillation upstream the thruster triggered the activation of the “red button” procedure
- The tank of the propulsion system was automatically emptied
- The test was concluded



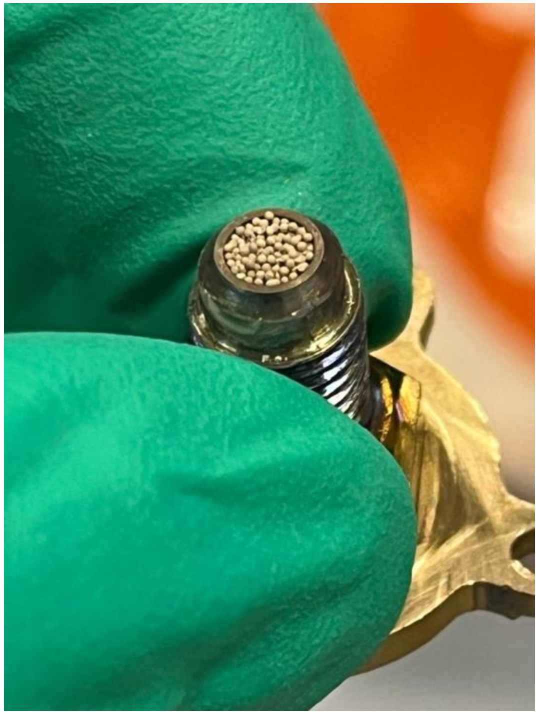


Group III: TEST-VAC-01 Main Achievements

Ton (ms)	N° Pulses	P_{in} (bar)	F (N)	Isp (s)	Impulse Bit (Ns)
1000 (first series)	10	22	0.45	160	0.43
900 (second series)	20	19	0.28	140	0.225
800 (first series)	20	19	0.25	140	0.21
700 (first series)	20	18	0.2	130	0.15

Group III: TEST-VAC-01 Sixth Test Setup

Component	Description
Catalyst	• SD99 Pt/α Al_3O_2 0.4 mm (88% of length) • LBbi-220 Pt/α Al_3O_2 0.09 mm (12% of length)
Catalytic Bed	2.8 mm diameter
Nozzle	Area ratio 70
Propellant	H_2O_2 98.0% wt.
Tank	EPE-0.35 liters (total volume)



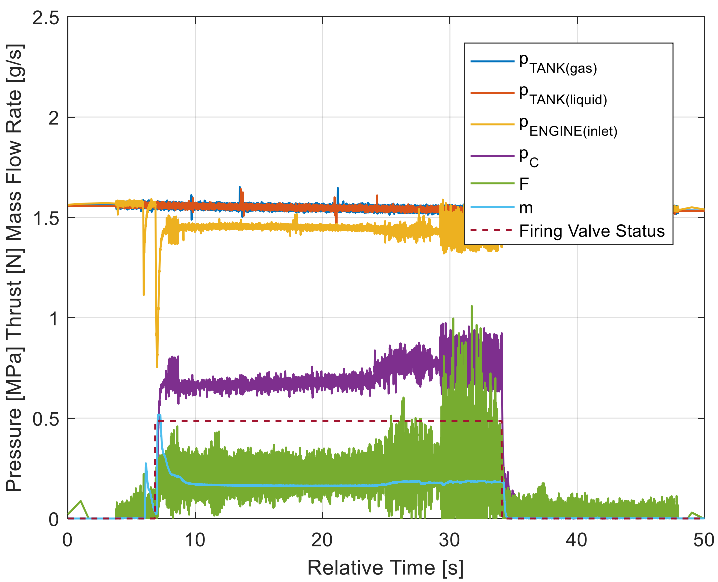
Mode	t_{on} (ms)	t_{cycle} (ms)	repetition	start
Continuous	30000	N/A	1	Cold
Continuous	30000	N/A	1	Hot
Continuous	60000	N/A	1	Hot
Continuous	10000	N/A	1	Hot

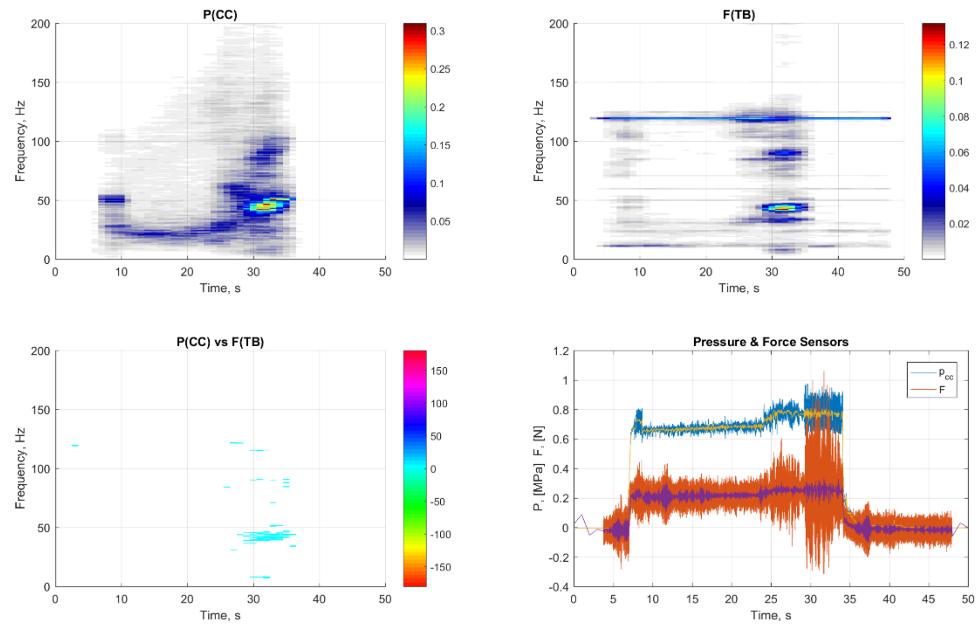
The total throughput was about 0.07 kg (fifth and sixth tests)

Group III: TEST-VAC-01 Main Achievements

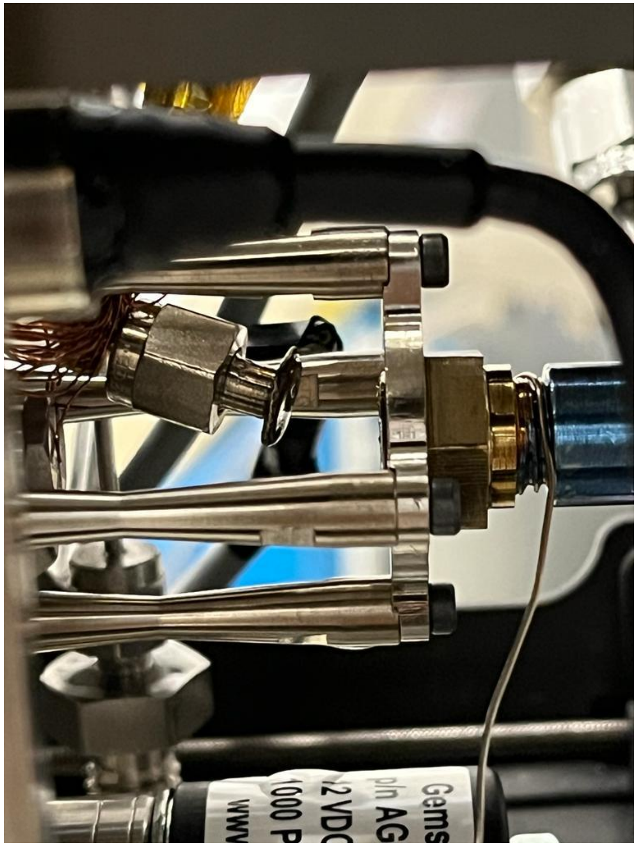
Parameter	Value	Verified Req.	Threshold Value
F (N)	0.25	PROP-FUN-02/THRU-FUN-03	≤ 0.5
Isp (s)	150	PROP-FUN-04	160
Rise-time (ms)	<150	PROP-FUN-09	150
Thrust Roughness	<45%	PROP-FUN-14	$\pm 5\%$ at 2σ
η_{c^*} (c*-efficiency)	0.85	PROP-FUN-11	0.9

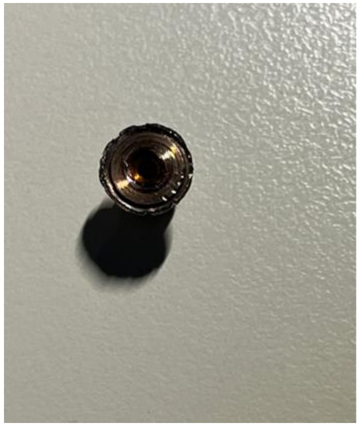
The instability occured also during this test. However, looking at the average of the obtained quantities, all the imposed requirements were satisified, except for the thrust roughness (first firing for 30 s)

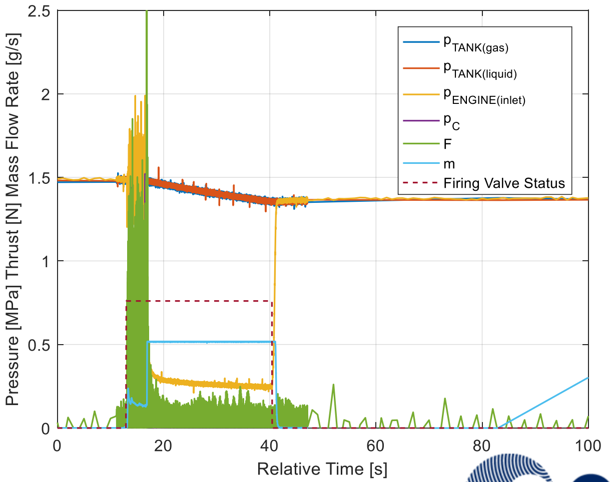




During this test only continuous firings were performed. A failure of the propulsion system caused the abort of the fifth continuous firing. This was the last test of the test campaign.







Agenda

- Propulsion System Specification and Design
- Propulsion Systema MAI
- Propulsion System Testing
- Further Development and Road-Mapping

CHIPS Conclusions

For what concern the **propulsion system**, the main achievements can be summarized as follows:

- The **system** was able to verify most of the **requirement specifications**:
  - the **MEOP** was set to be equal to **24 bar**
  - the system is capable of **firing more than one time, and in pulse-mode**.
  - system was able to reach **90% of the steady state thrust** in nominal conditions in **less than 150 ms**, respecting also the limit of **0.5 N** for the **thrust** and **160 s** for the **SI,** and the **MIB** ≤ **0.25 mNs.**
  - The **c* efficiency** obtained was equal to or **greater than 90%.**
- The system was tested in a vacuum chamber (real operational environment):
  - Some **components** (e.g**. firing Lee Valves**) present in both the **flight and engineering model** were tested in their **operational environment** with success.
- All the requirements on the temperature of the components have been fulfilled.
  - The **by-pass** allowed the **firing valve** to maintain its **temperature below the imposed threshold**
  - The **stand-off configuration** prevented the whole system from exceeding the **60 ºC limit**.
- The whole propulsion system is confirmed to occupy no more than **1.5 U**.
- The thruster has been designed to be easily substituted during the tests.

CHIPS Conclusions

Concerning the **test facility** and the **test diagnostics**, the following remarks can be highlighted:

- **The propulsion system** together with **the thrust balance** and all the sensors have been **successfully integrated inside the hatch of the vacuum chamber.**
- The use of **solenoidal valve** and the procedure for **remotely loading and unloading the propellant** it allowed a **safe operation** throughout all the tests.
- During the tests it was possible to have a **direct measurement** of:
  - ➢ The **thrust** of the system (load cell aligned with the thrust vector)
  - ➢ The **mass flow** (Coriolis mass flow meter positioned on the bottom face of the 3U structure)
  - ➢ The **pressure** inside the combustion chamber (pressure transducer directly assembled to the chamber)
- The **thrust balance** developed during the project, showed really good results in terms of **sensibility to external excitations** and permits the test a generic **3U CubeSat with its own propulsion system**
- The tests underlined that the pressure level (10^{-3}-10^{-2} mbar) reached inside the vacuum chamber was enough to allow a correct **simulation of the real operational conditions of the propulsion system**.
  - ➢ Testing a chemical propulsion system inside a vacuum chamber is feasible and that it doesn't need vacuum levels as low as the ones for the electric propulsion

Future Developments

The future activities of CHIPS can be summarized in three main points:

- **Conversion of EM towards the FM:** The next objective is the realization of the Flight Model, and to accomplish this the next steps are the developing of the cuboidal tank and the reduction of the number of sensors needed for the actual test campaign. In the qualification process, the developed thrust balance can be used also for testing the FM.

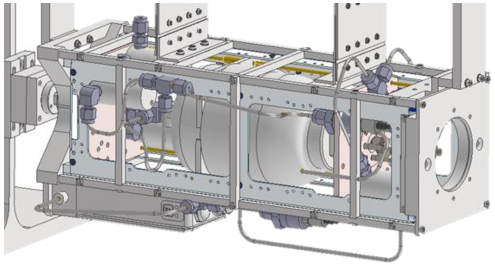
- **Instability Investigation:** During the experiments both in atmosphere and in vacuum, the system presented a propulsive instability. Further studies are needed to have a better understanding of all the causes generating the instability.

- **Innovative Tank Development:** The principles adopted during the preliminary design, that will be further developed in detail, of the innovative tank were the maximization of the storable propellant volume, minimization of the dry mass, low cost and simplicity. All of the materials composing the tank shall be of Grade I or II, following the CHIPS imposed requirements. The tank will be subjected to the verification process that will follow the requirements set by the applicable ECSS.

Future Developments Schedule

Task / Expected Duration	t_o+6 months	t_o+12 months	t_o+18 months
Innovative Tank Development: • Design conclusion • Manufacturing			
Material Compatibility Analysis and **Passivation Procedure Improvement**			
Instability Analysis: • Deeper analysis of the results • Further atmospheric test			
Conversion of EM towards FM: • Procurement of new components • Modifications of test setup • Test campaign for TRL=5/6			

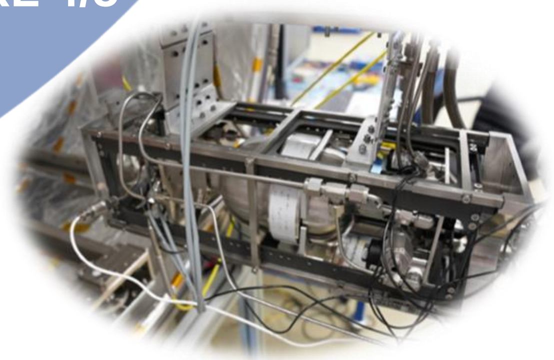
CHIPS Next Steps

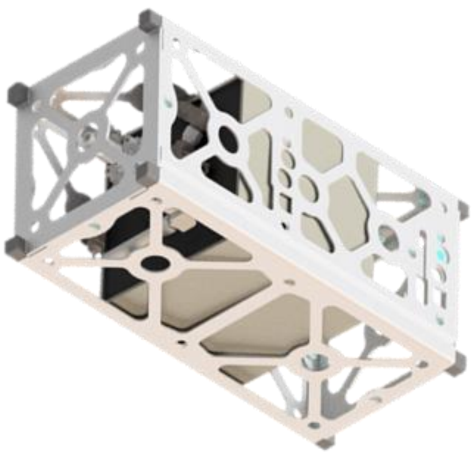


TRL 2/3

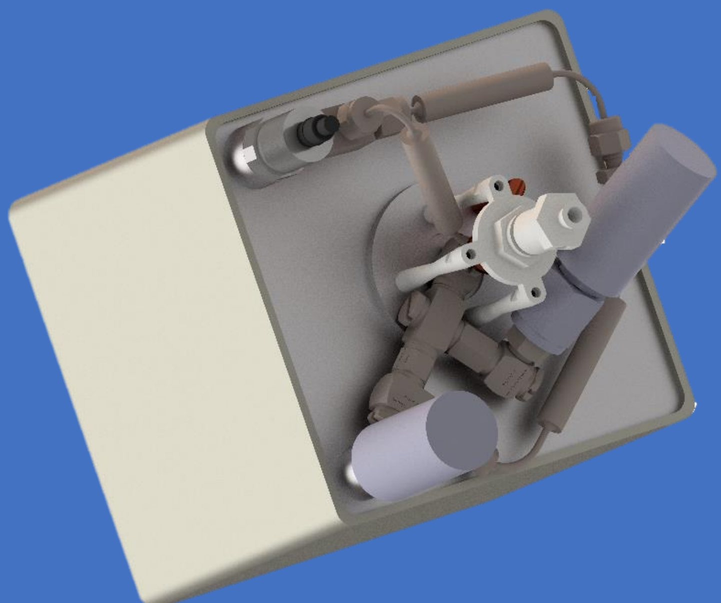
CHIPS reached the target TRL (>3) fixed at the beginning of the activity.

TRL 4/5





CubeSAT HTP Innovative Propulsion System



Propellant	HTP
Inlet Pressure, Range	8 to 22 bar
Thrust, Range	0.1 to 0.5 N
Mass Flow, Range	0.22-0.38 g/s
Isp, Nominal	170 sec
Total Impulse	> 840 Ns (TBD)
Cycle Life	> 2000 cycles (TBD)
Minimum Impulse Bit	0.025 Ns
Proof Pressure	30 bar (TBD)
Burst Pressure	36 bar (TBD)
Operating Temperature	0°C to +60°C
Power Consumption	5 W
Envelope	1.5 U (TBD)
Dry Mass	0.9 kg (TBD)
Wet Mass	1.6 kg (TBD)