LHCb VELO CO_2 cooling system safety

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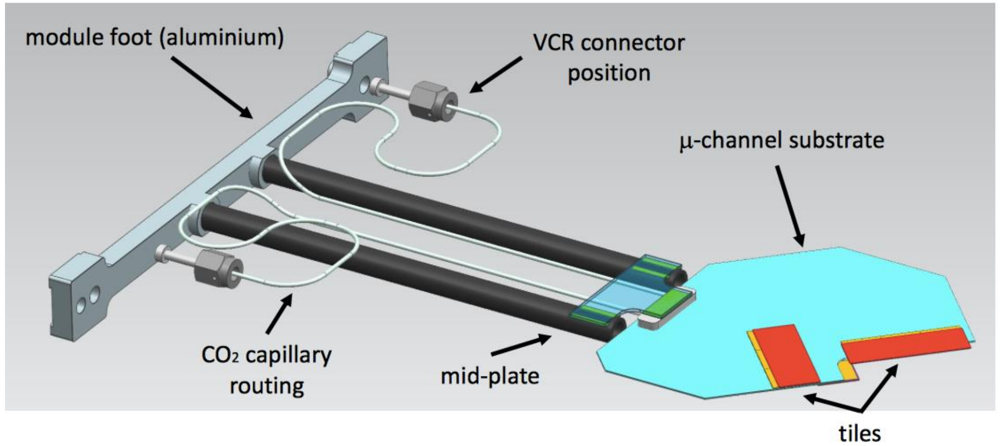
198th Machine Protection Panel Meeting (LHC), 20.11.2020.

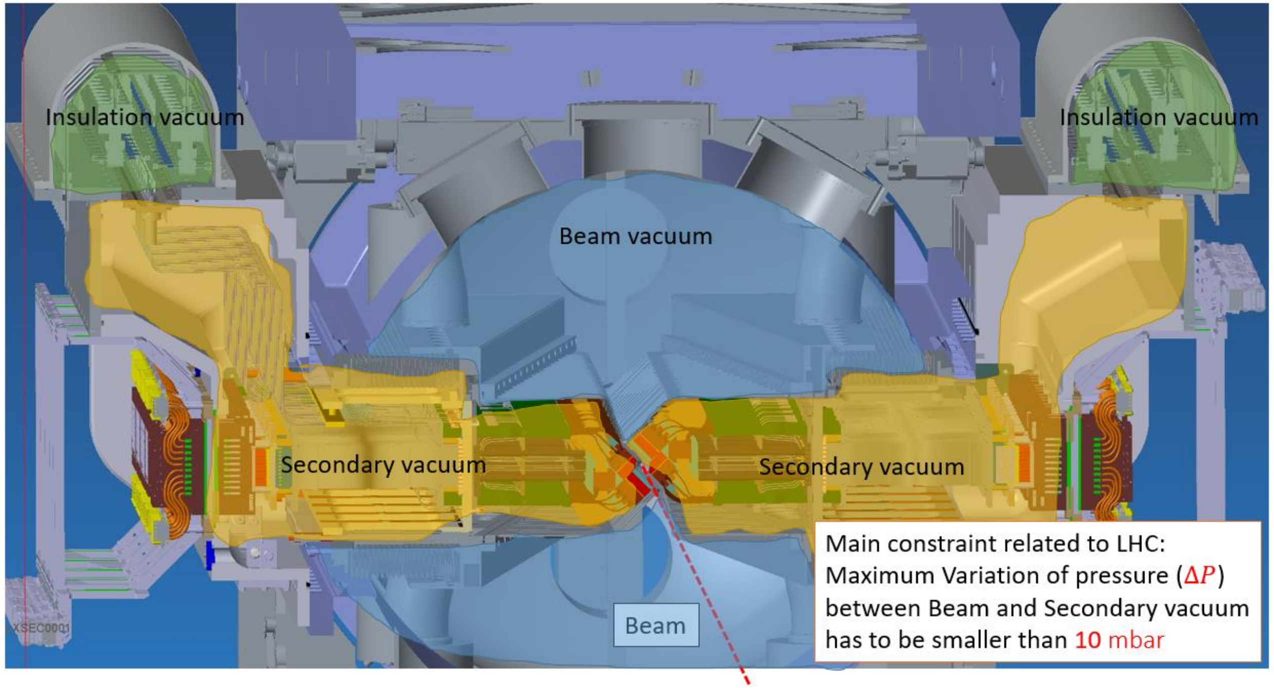
Open Actions on VELO CO2 Safety System

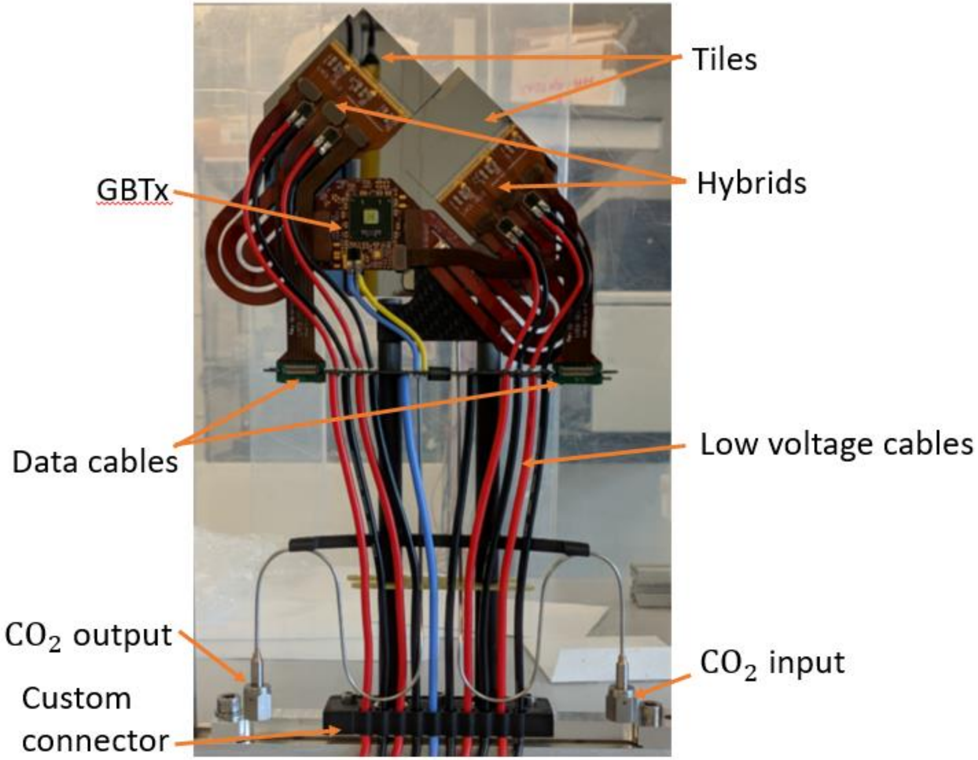
- 174^{th} MPP meeting (25.01.2019) open actions:
  - Functional specifications for the new CO2 cooling safety system have to be written down, including the expected pressure increase and reaction time as well as the expected consequences and required switches and interlocks.
  - Failure cases? Interlocking strategy? Recovery after failures?
- The new version of the "Secondary vacuum pressure estimation in case of CO_2 leaks" EDMS #2138558 (v.15) document is uploaded:
  - https://edms.cern.ch/document/2318558/1
- The latest version includes updated information on:
  - Information on the new pressure sensor as baseline
  - Settings for the new membrane switch dedicated for CO_2 safety
  - VSS based on FPGA readout as baseline (cRIO FPGA 9025, with cycle time ~1 ms)
  - Modified cooling safety system trigger
- Other useful documents links:
  - ECR on modified VELO equipment: https://edms.cern.ch/document/2331410/1.0
  - User manual for the VELO Vacuum Control System: https://edms.cern.ch/document/2370741/1
  - VELO Vacuum Control Signal Box: https://edms.cern.ch/document/2113498/2/

Introduction (reminder)

- Due to increased power dissipation and the minimization of material, CO_2 evaporative cooling in silicon etched micro-channels was chosen.
- A safety system is being developed to quickly react in case of CO_2 leaks and minimize pressure rise up.







LHCb experimental vacuum system Q1-Q1 including Vertex locator (VELO) vacuum system

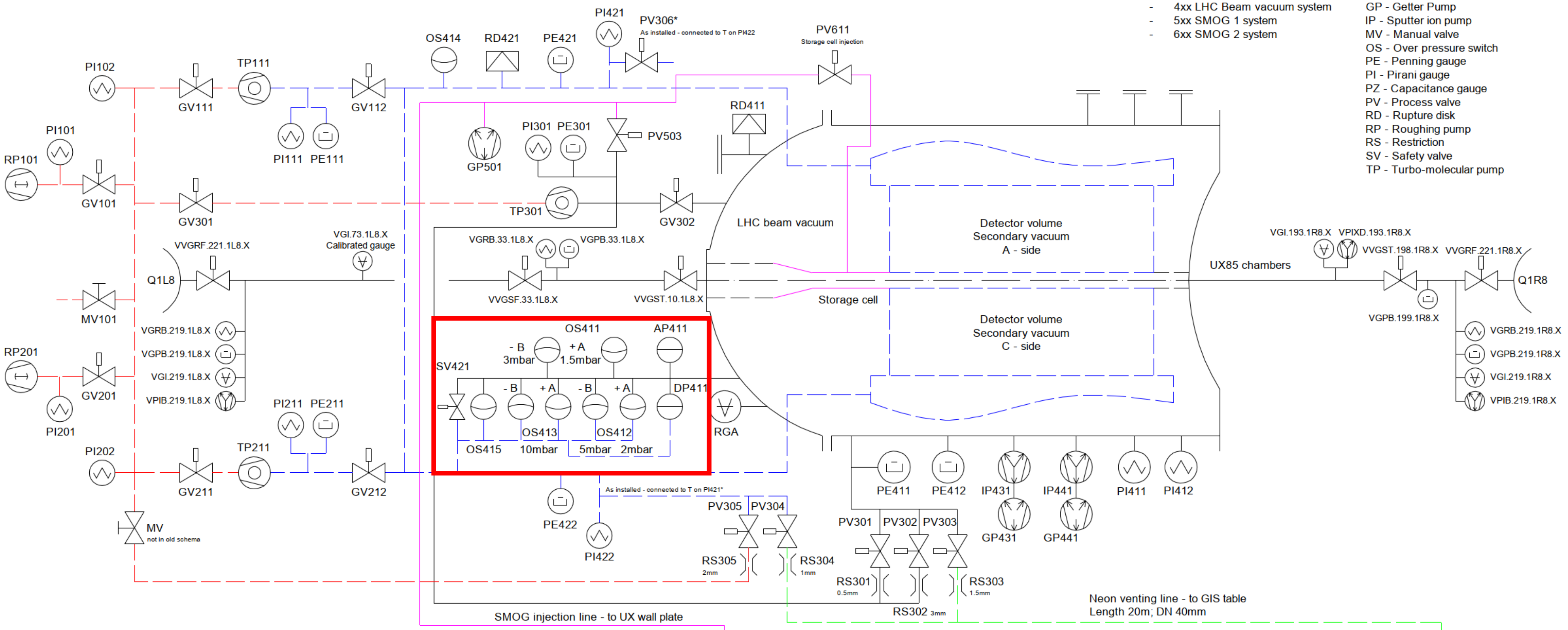
Configuration after end of Long Shutdown 2 - with Storage cell connected via SMOG1

Naming convention for VELO - digits
(1st number defines the sub-system)

- 1xx Primary vacuum A side
- 2xx Primary vacuum C side
- 3xx Injection & Pump-down system
- 4xx LHC Beam vacuum system
- 5xx SMOG 1 system
- 6xx SMOG 2 system

Naming convention for VELO - letters

- AP - Absolute pressure gauge
- DP - Differential pressure gauge
- DV - Dosing valve
- GV - Gate valve
- GP - Getter Pump
- IP - Sputter ion pump
- MV - Manual valve
- OS - Over pressure switch
- PE - Penning gauge
- PI - Pirani gauge
- PZ - Capacitance gauge
- PV - Process valve
- RD - Rupture disk
- RP - Roughing pump
- RS - Restriction
- SV - Safety valve
- TP - Turbo-molecular pump



Vacuum valves:
GV101 - mini UHV gate valve - VAT 01032-KE41
GV201 - mini UHV gate valve - VAT 01032-KE41
GV111 - HV angle valve - VAT 26428-KE41
GV112 - UHV gate valve - VAT 10844-CE44
GV211 - HV angle valve - VAT 26428-KE41
GV212 - UHV gate valve - VAT 10844-CE44
GV301 - HV angle valve - VAT 26428-KE41
GV302 - All-metal gate valve - VAT 48146-CE74
SV421 - mini UHV gate valve - VAT 01032-CE41
PV301 - All-metal angle valve - VAT 57120-XE41-AAN-1
PV302 - All-metal angle valve - VAT 57120-XE41-AAN-1
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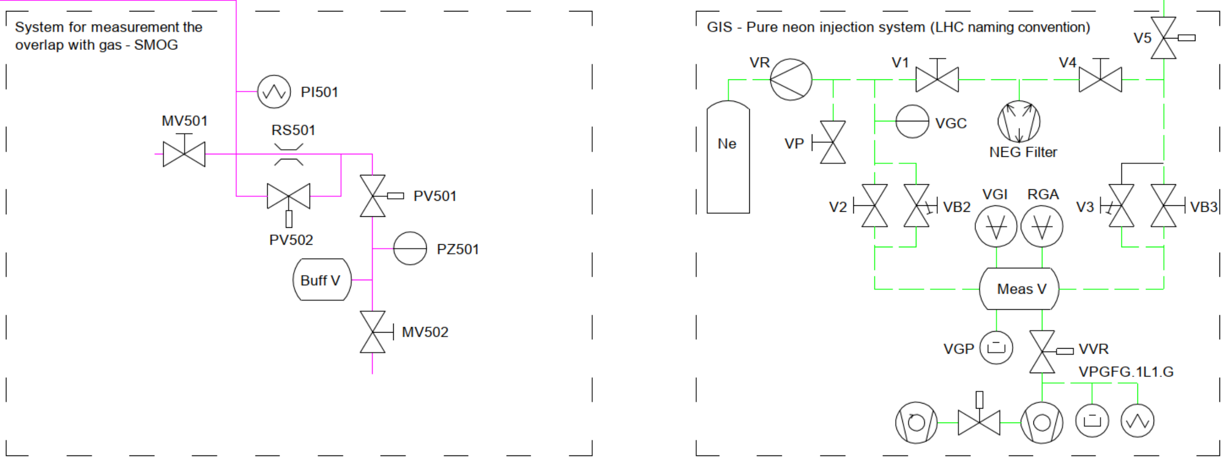
PV306 - UHV angle valve - VAT 28424-GE41

PV501 - All-metal angle valve - VAT 57124-GE44
PV502 - All-metal angle valve - VAT 57124-GE44
PV503 - All-metal angle valve - VAT 57124-GE44
PV611 - All-metal angle valve - VAT 57120-XE41-AAN2

Vacuum gauges:
PI - Pirani gauge - all Pfeiffer TPR-018
PE - Penning gauge - all Pfeiffer IKR-070
DP - MKS Baratron 616A - differential (not connected during OP)
AP - MKS Baratron 615A - absolute (not connected during OP)

Vacuum pumps:
RP - Primary pump - all Alcatel ACP28 S
TP 111 - Pfeiffer TMU 521 P
TP 211 - Pfeiffer TMU 521 P
TP 301 - Pfeiffer HiPace 700
IP - all Agilent Vaclon plus 500 (starcell)
GP - all Saes CapaciTorr D400-2

Other vacuum equipment:
OS - Pressure switch - all Leybold PS115
RGA - Residual gas analyser - Hiden HAL201
RD - Rupture disc



EDMS 2261154 v.3 Josef Sestak TE-VSC-BVO

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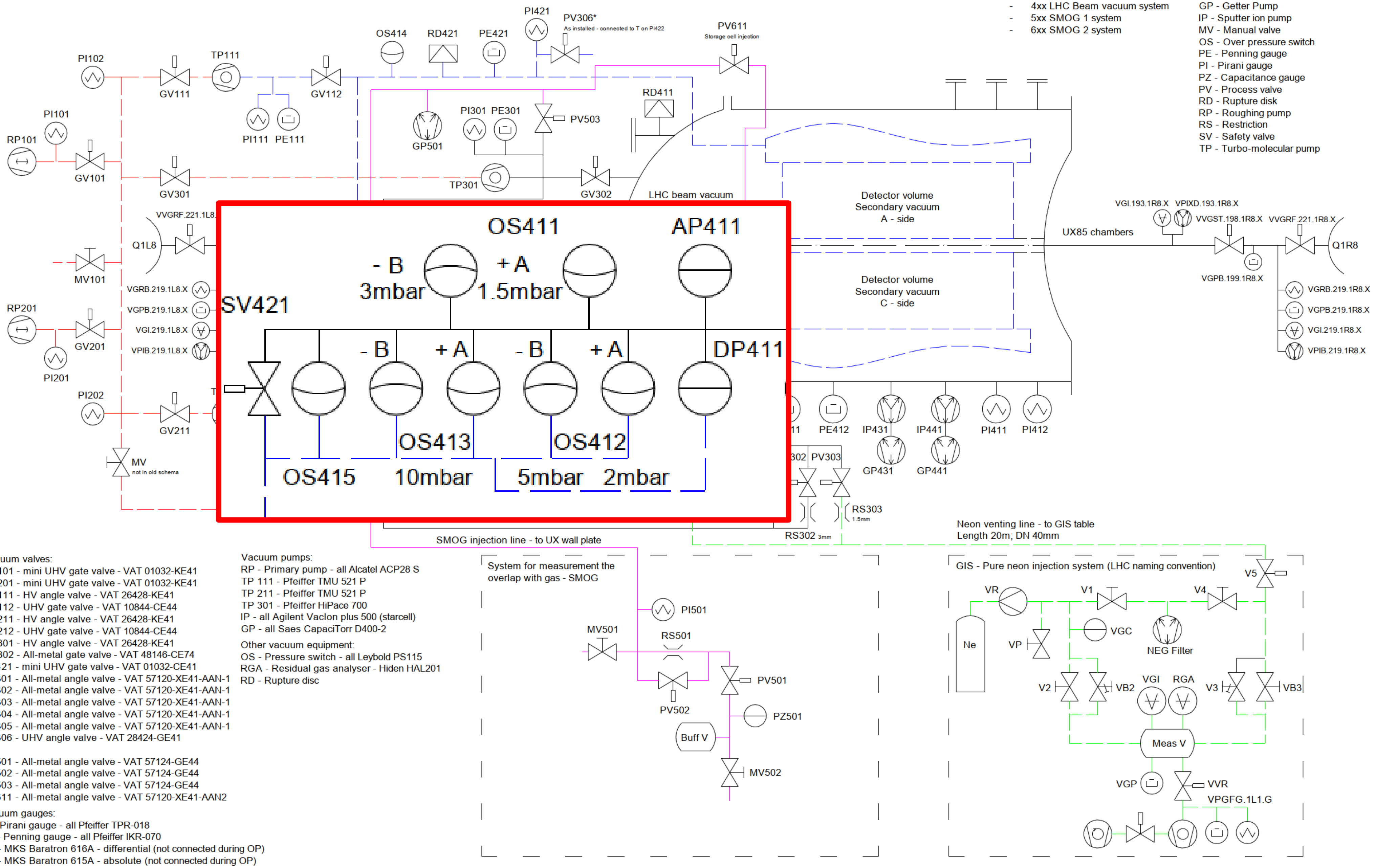

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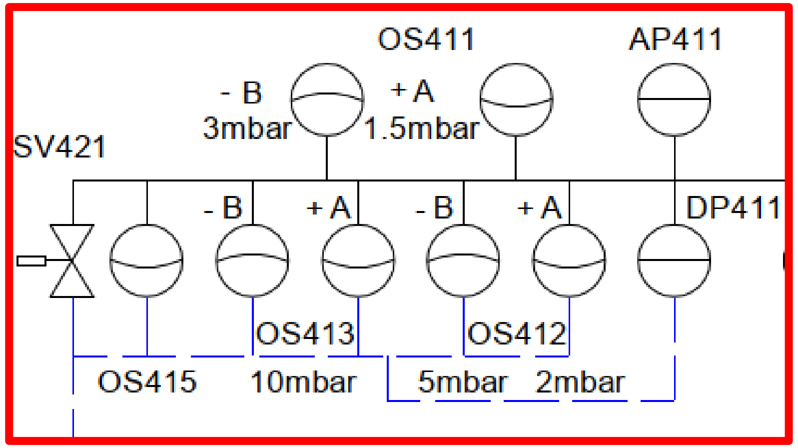
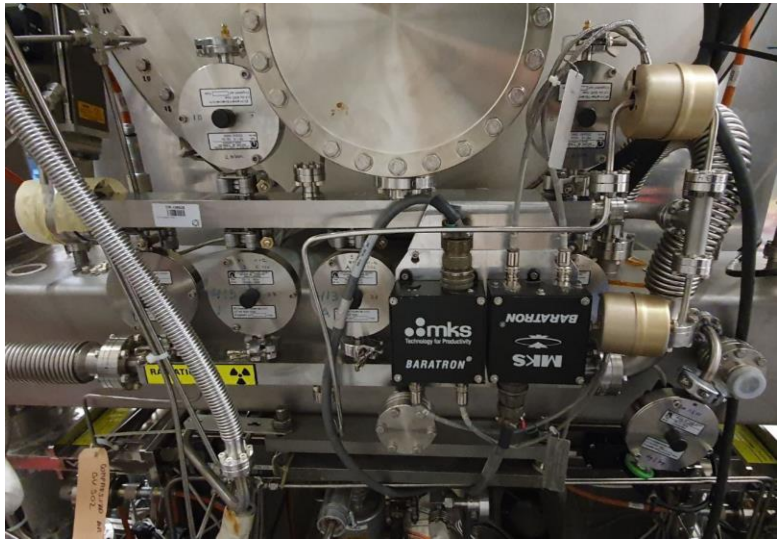
ECR Safety system update (redundancy)





	ΔP Threshold	OK State	Behaviour
OS412A	+2 mbar	Closed	NOK (Opens) on Beam overpressure (> 2 mbar)
OS412B	-5 mbar	Open	NOK (Closes) on Detector overpressure (> 5 mbar)
OS413A	+10 mbar	Closed	NOK (Opens) on Beam overpressure (> 10 mbar)
OS413B	-10 mbar	Open	NOK (Closes) on Detector overpressure (> 10 mbar)
OS415	-6 mbar	Open	NOK (Closes) on Detector overpressure (> 6 mbar)

Table 1. Differential Pressure Switch Characteristics

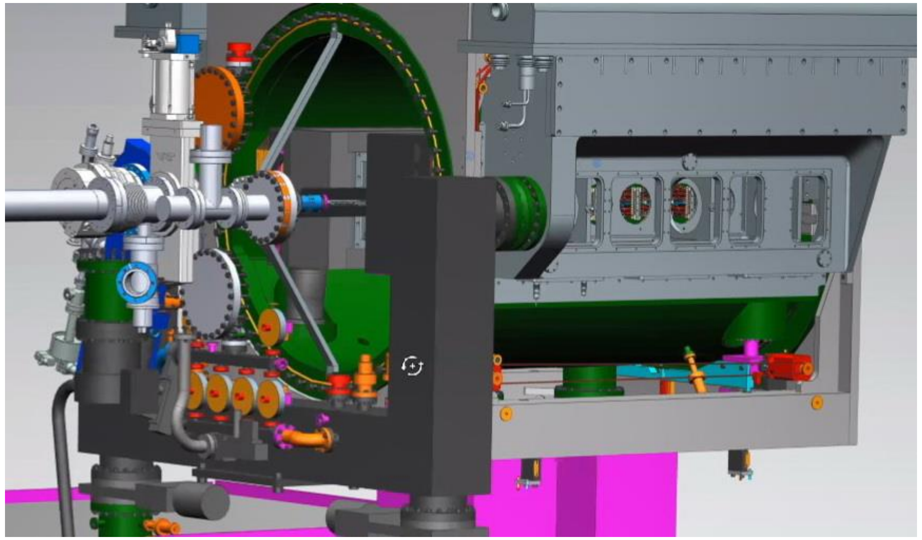
- **OS412**, **OS413** & **OS415** depend on the pressure differential between Beam and Detector Volumes ($\Delta P = P_{beam} - P_{detector}$) – used for evacuation, venting and overpressure safety.
- **AP411** & **DP411** - very precise Baratron gauges, measuring absolute pressure in the Beam volume and differential pressure between Beam and Detector volumes.
- **ΔP_{max} = 10 mbar** (to protect the RF foil). If reached, **SV421** Safety valve opens, connecting the Beam and Detector volume.
- In order to detect a leak in one of the CO_2 lines and shut-off the flow, an **additional pressure switch** (**OS415**) is installed to further reduce the risk of activating SV421.
- The switch is set at **-6 mbar**, as close as possible to OS412B (-5 mbar), and safely far away from OS413B (-10 mbar).

Potential issues in neon mode (=>redundancy)

- Originally, the baseline idea was to use the installed pressure sensors to minimize the reaction time:

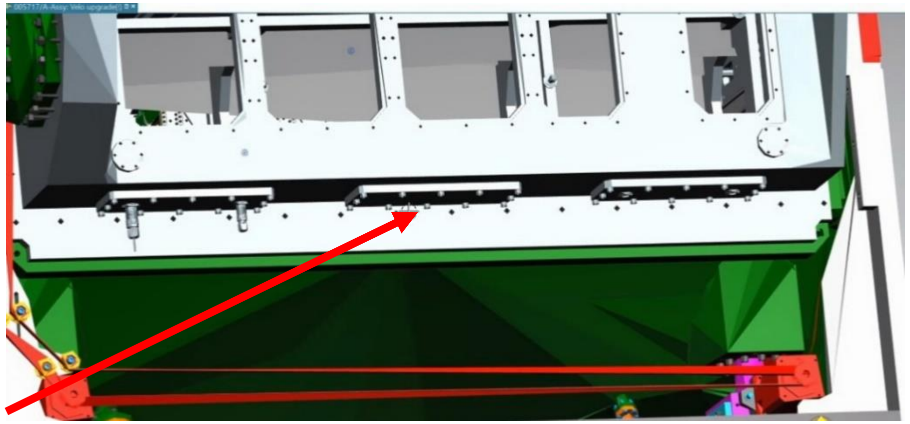
Device name	Sensors reaction time or time constant (*)	Readout response time (ms)
Pirani or Penning	< 50 ms	16, 160 or 1600
Baratron (615A or 616A)	< 25 ms*	1, 40 or 400

- However, reducing the time constants potentially introduces higher background to the measurement data, which was strongly discouraged by TE-VSC (the controller allows down to 1ms).
- Response time of the Baratrons is currently set to 400 ms.
- Vacuum PLC used as readout with cycle time ~50 ms.
- These pressure sensors are connected to the beam volume.
- Quite far away from the (potentially leaking) modules.
- Therefore, our baseline changed to **installing a dedicated pressure sensor on the detector side to minimize the reaction time** (also w/FPGA readout) and not affecting the current vacuum system, making it even more safe.



The new pressure sensor

- The new pressure sensor (SST64X-RT*) would be installed on the middle flange of the hood on both sides; will be much closer and therefore more sensitive.
  - https://www.sigmanetics.com/pdfs/data-sheets/transducers/SN_Datasheets_Transducers_SST643-RT.pdf



STATIC ACCURACY
Linearity: ±0.20% FSO
Hysteresis: ±0.20% FSO
Repeatability: ±0.10% FSO

RESOLUTION
Analog: Infinite

1000 mbar * 0.2% = **2 mbar**

Radiation Tolerance
10 Mrad TID

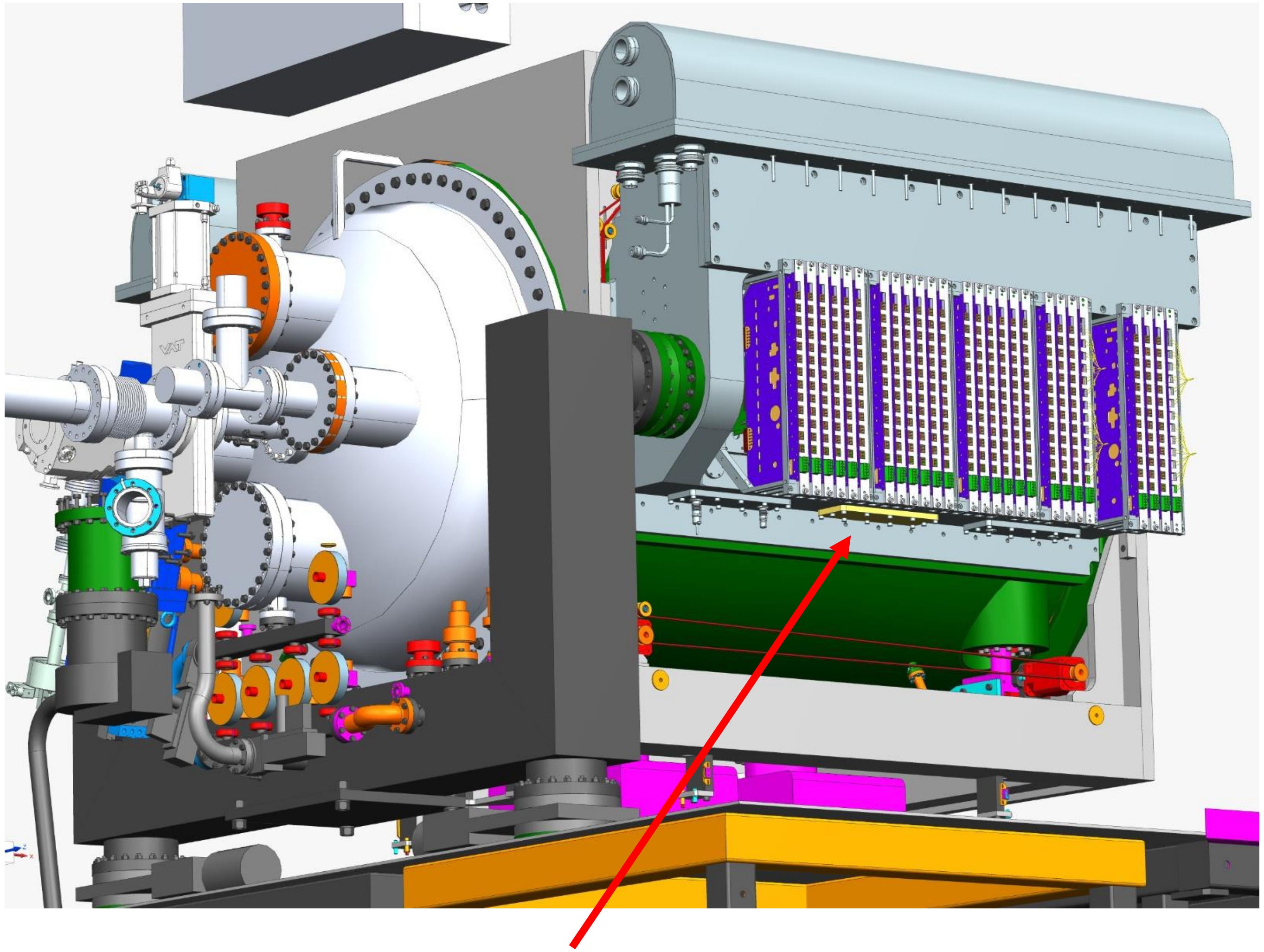
Part Number	Description
Q200903SG02-001	SST64X-RT Pressure Transducer - 1000mBar

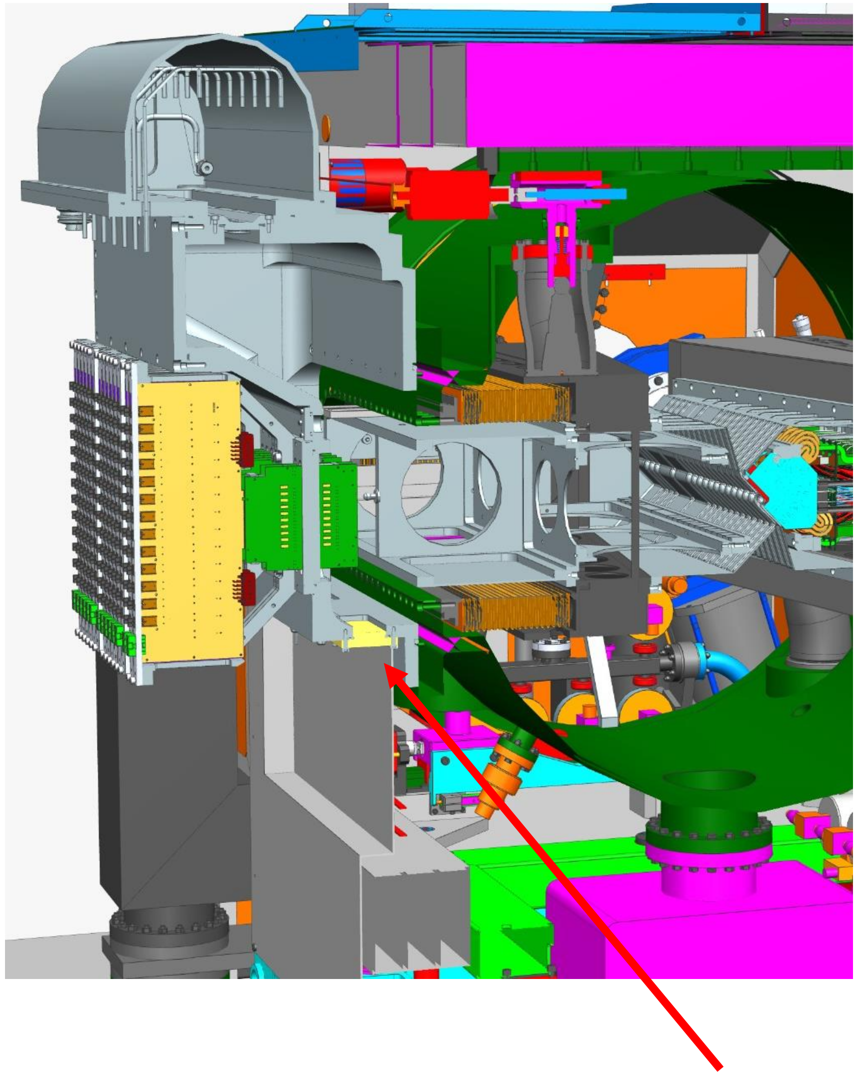
Notes
Pressure Range: 0-1000 mBar
Pressure Reference: Absolute
Pressure Port: AS4395E04 (7/16-20 UNF Male)
Output: 3mV/V analog output
Supply: 10 Vdc
Electrical Termination: PTIH-10-6P
Wetted Material: 15-5 PH SS or 316L SS
CTR: -54C to +121C
Radiation: Up to 10Mrad TID

Lead Time: Test Unit by Nov 20, 2020. Product units 10 Weeks ARO
Shipping not included: Approximate Shipping Weight 1lb

- The unit is currently under production and should arrive in 2 weeks.
- It will be tested in a dedicated setup, making sure the resolution and response time is adequate.
- FPGA readout (cRIO FPGA 9025; cycle time ~1 ms)
- Boolean input would be fed to VSS.

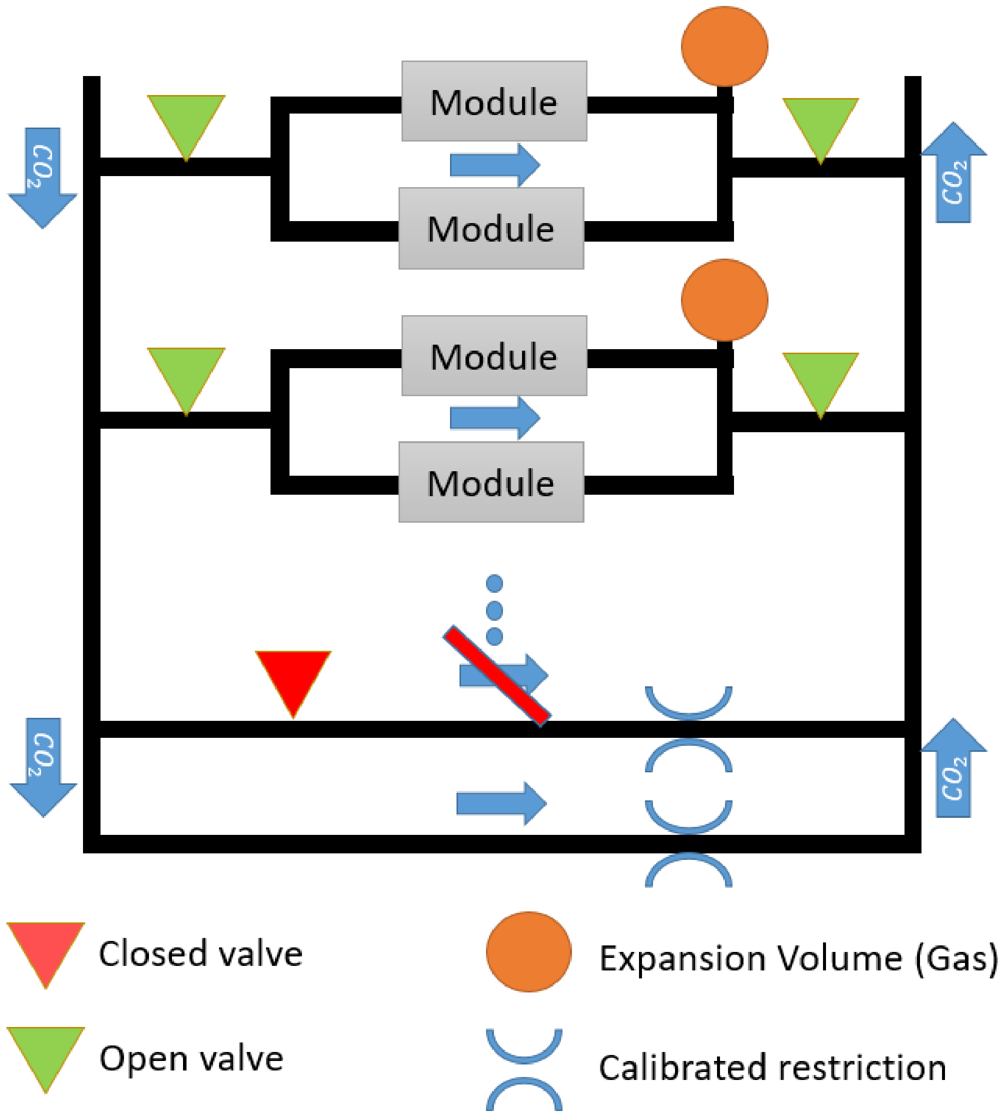
The new pressure sensor location





Leak detection, reaction and potential consequences

- For every 2 modules, 2 NO shut-off valves can close the input and output to CO_2.
- In case of a leak/trigger from the safety system, they are closed with the CO_2 still inside the modules, but not flowing while bypass loop opens (NC shut-off).
- Based on the volume trapped in one cooling branch (two modules), the estimated pressure rise in the Detector volume is ~7.4 mbar.
  - Assuming no delay between leak detection and valves closure
  - During normal operation/vacuum mode, does not take into account the removal of small rates of CO_2 by the vacuum pump.
  - CO_2 in liquid state at I/O lines and gas in the expansion volume (not true during vacuum mode => output = liquid + gas)
  - In case of leak, all coolant between the shut-off valves will be released into the Beam volume.
  - CO_2 solidification might slow down the leak rate.



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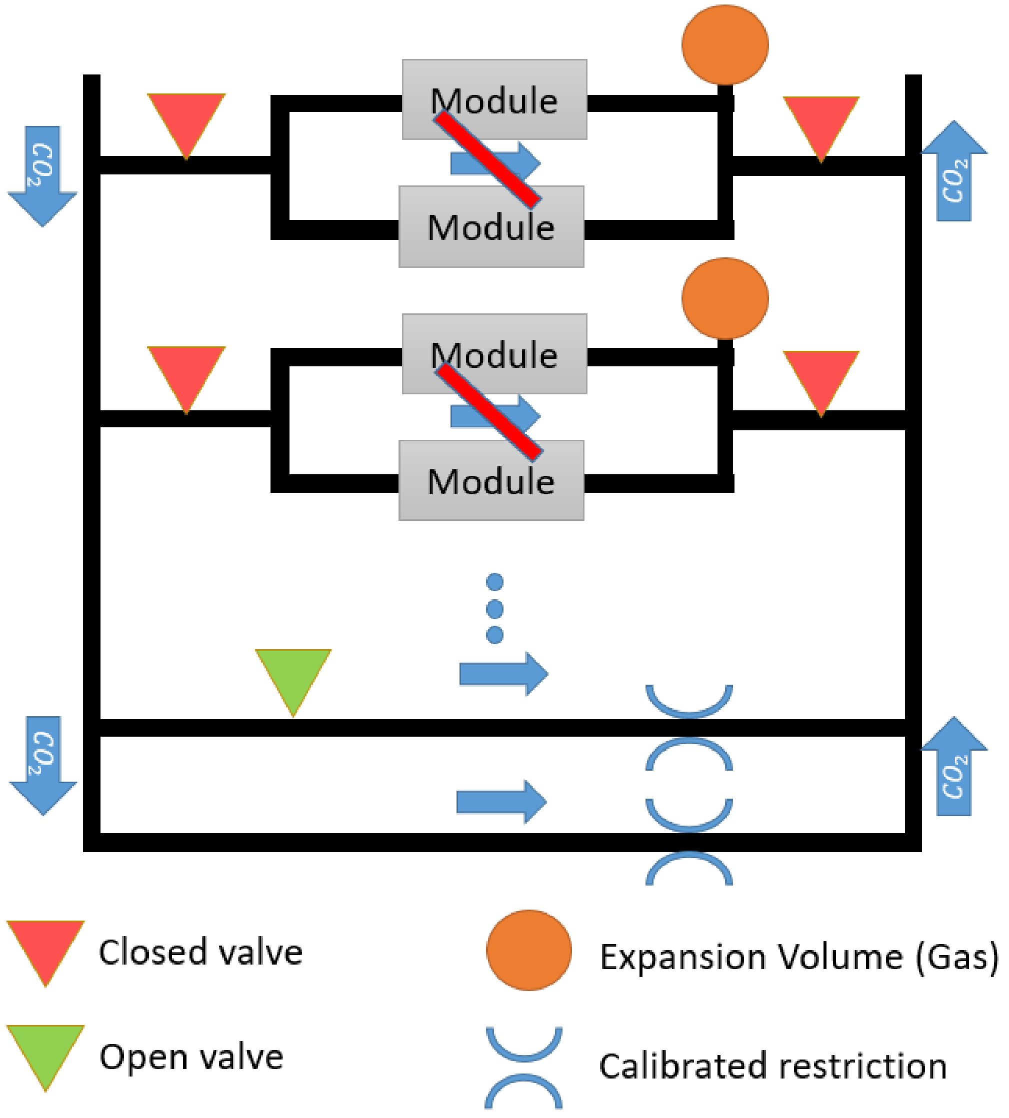
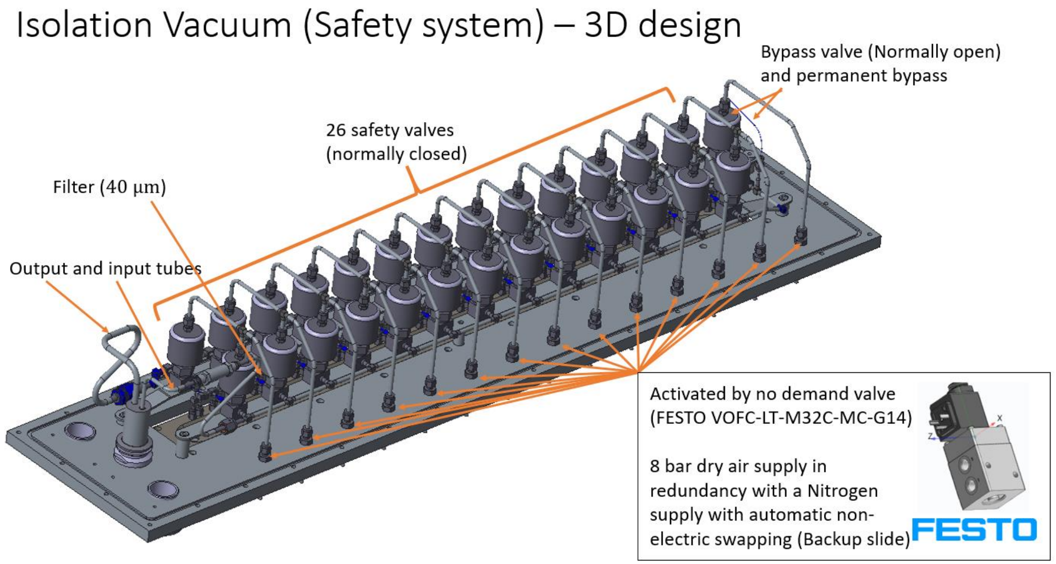
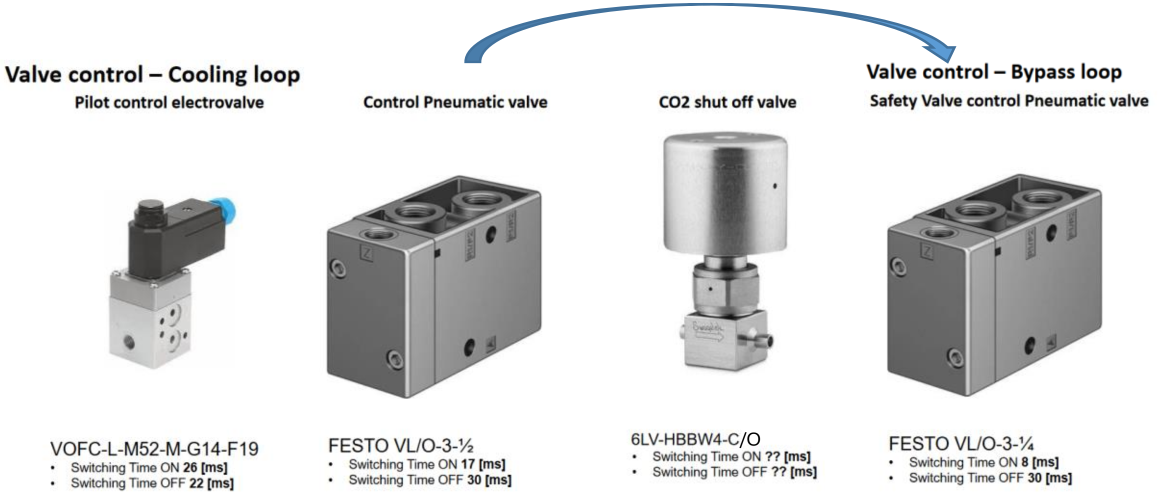


Leak detection, reaction and potential consequences

- The information from switches and pressure sensors will be processed by VSS which will send a signal to a chain of safety valves.
- The safety trigger chain:
  - Sensor + FPGA readout (>1 ms (?) reaction + cycle time)
  - Electro-valve (22-26 ms reaction time)
  - Pneumatic valve (17-30 ms reaction time)
  - The 5 m tube represents the distance from the electro valve (located in the chicane) to the shut-off valve in the insulation volume of the detector.
  - Swagelok shut-off valve (reaction time not known yet)
- For the time being, we have the expected reaction times of most of valves and sensors, apart from the Swagelok. Therefore, we can only theoretically estimate the reaction time based on these numbers.
- These will be known as soon as the new pressure sensor arrives and the full chain tested in the setup.
- Lab tests in a different setup/mock-up trigger chain showed 1.4mbar/s => For ~430 ms => ~-0.6 mbar.





Cooling safety system trigger – Failure cases

- Any mode ($\Delta P < -10$ mbar or $P > 1150$ mbar):
  - All cooling loops will be isolated to minimize the damage to the foil/avoid pressure build-up in Detector volume
  - Absolute pressure information from the new pressure sensor and the Baratrons.
- Pump down (based on response of +2 and -5 mbar switches):
  - The -5 mbar switch stops the pump down in the Beam volume temporarily, while the Detector volume is still being pumped down to reduce the ΔP.
  - In case of a larger leak, an abrupt pressure increase will be observed in the pressure sensor(s) and the cooling safety system will be triggered. In addition, the new pressure switch (-6 mbar) can also trigger the safety system.
- Venting (based on response of +2 and -5 mbar switches):
  - Neon is injected at a controlled rate in both volumes. If the -5 mbar pressure switch is activated, the VCS will try to compensate the pressure increase in the Detector volume by stopping the neon injection for a certain time.
  - In case of a larger leak, an abrupt pressure increase will be observed in the pressure sensor(s) and the cooling safety system will be triggered. In addition, the new pressure switch (-6 mbar) can also trigger the safety system.
- Balancing (whenever the venting procedure is stopped or vented state reached):
  - The entire regulation happens in the Beam volume. Neon is injected in the Beam volume to compensate for an increase of pressure in the Detector volume.
  - In case of moderate to larger leaks, the -5 mbar switch may be activated more often and/or the absolute pressure of the Detector volume will constantly increase, eventually triggering the safety. OS415 may also cause this trigger.

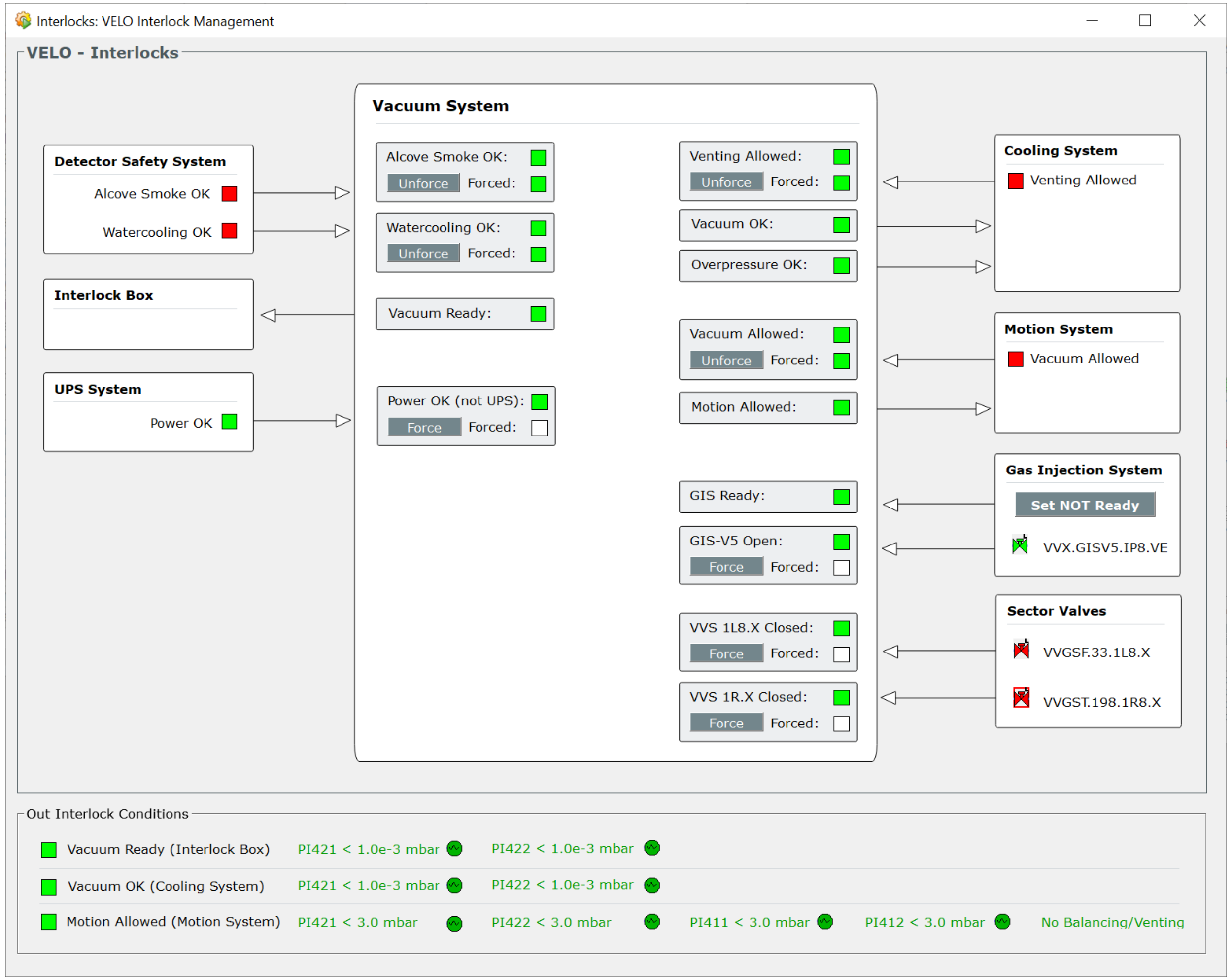
Cooling safety system trigger – Failure cases

- Nominal operation mode (both volumes under vacuum):
  - Small leaks: small quantities of CO_2 would be removed by the pumping system and no significant increase in pressure will be observed (no action).
  - Moderate to large/abrupt leaks: if the pumping system cannot cope with the leak rate and nominal pressure cannot be achieved, the safety system will be triggered from the signal of the pressure sensor(s), isolating the cooling loops.

- Recovery after failure:
  - If a leak is detected in a cooling loop, the VSS will promptly and safely shut-off all the loops automatically and a manual valve would then be used isolate the affected two loops. An access to the VELO alcove would be necessary for this, resulting in those particular affected modules not be operable until the next TS or EYETS.
  - In case of triggering the OS413B membrane switch at -10 mbar, it will activate the SV421 valve connecting the Beam volume with the Detector volume, injecting a certain amount of CO_2 mixture from the Detector volume into the Beam volume, until the pressure drops below the threshold again.
  - Nikhef kindly agreed to do a pressure test on a spare RF foil (A1) at 20 mbar, checking for any permanent deformation or damage. This might potentially allow for changes/increased pressure setting of the OS413 (>10mbar).

Cooling system interlock

- The Vacuum Control System must forcefully work together with several external systems, mutually interlocked.
- The Interlocks Panel enables the monitoring of all Interlocks leaving from and arriving at the VELO Vacuum Control System. The arrows indicate the direction of each interlock signal (Incoming or Outgoing) and the colored squares show their state. Green means that an interlock is in Good condition and Red that it is Bad. For the Forced indication, White means inactive (unforced) and Green active (forced)
- An outgoing "Vacuum OK" interlock tells the detector Cooling system that pressure in the detector vessel is suitably low (under $1.0 \cdot 10^{-3}$ mbar). Another, "Overpressure OK", is directly linked to the OS414 pressure switch and signals that the detector volume is not in gross overpressure (+150 mbar) in relation to atmosphere.
- There is also an incoming "Venting Allowed" interlock from the Cooling System (venting only possible when OK).
- With the new detector cooling system installed during LS2 a lot more data was needed to be provided to the VELO Safety System, for which a dedicated hardware (the VELO Vacuum Signal Box) was implemented. A technical description (EDMS):
  - https://edms.cern.ch/document/2113498/4

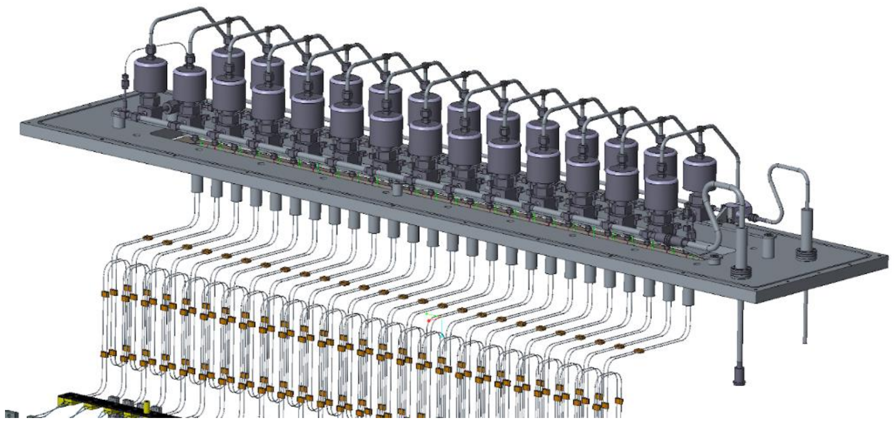


Cooling system interlock – CO_2 leak detected

- Instant CO_2 leak detection system detects leak in secondary vacuum and its State is set to "False" (inputs from VCS). The CO_2 flow should be turned OFF, including closing the safety valves and opening the bypass cooling valve.

  NO_CO2_LEAK set to False:
  - CO2_BYPASS_VALVE_A/C_SIDE_CLOSE_ALLOWED to False followed X ms after by CO2_SAFETY_VALVE_A/C_SIDE_OPEN_ALLOWED
  - VELO_COOLING_PLANT_FLOW_ALLOWED to False (but we should make sure that this is both input and output valves)
  - HV_A/C_SIDE_MOD_X-Y_ALLOWED is False and LV_A/C_SIDE_MOD_X-Y_ALLOWED is False
  - VELO_MOVEMENT_ALLOWED is False

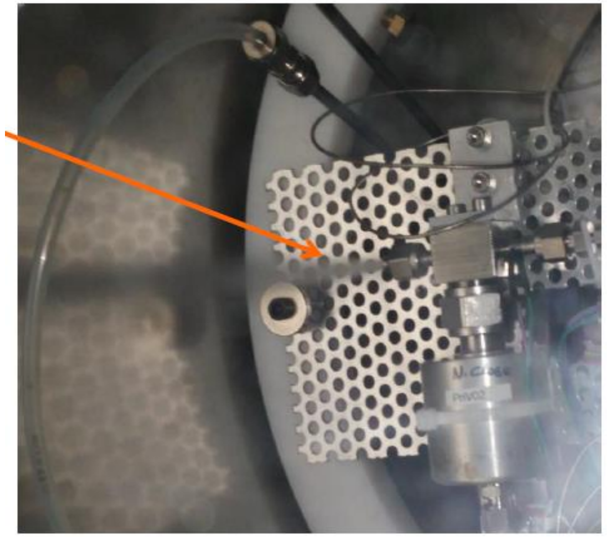
- VSS is giving 1 signal per side to shut down the 26 safety valves and 1 per side to open the by-pass via 2 valve relays per side.
- Possible to permanently close a cooling branch (2 modules) in case of problems using a manual valve.
- Risk that during balancing, overpressure in sec vac <-10mbar -> leads that valve to prim vac is opening -> potential impact on pumping capacity and SEY of NEG coating.
- Fast leak detection system will use several inputs (pressure switches and pressure sensors)



Safety cooling valves and the bypass valve in the tertiary vacuum: The opening of safety valves and the closing of the bypass valve is happening. The Dew-point of pressured air provided by LHCb is -40C or better.

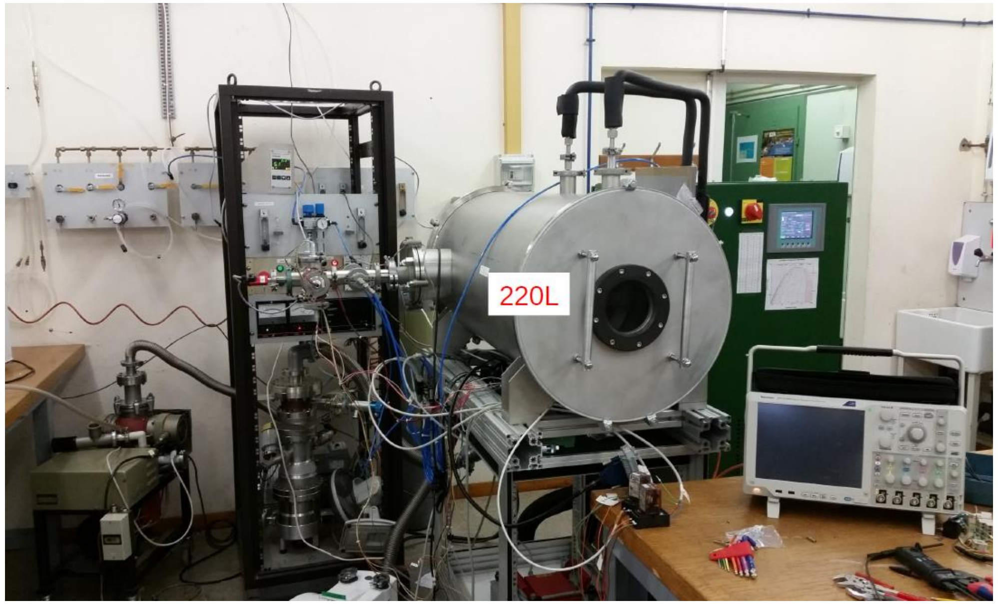
Risks analysis

- An unlikely event of a CO_2 leak may happen during venting/pumping/balancing modes, during which it is not possible to rely on fast detection of leaks, as the ΔP can be anywhere between +2 and -5 mbar.
- If the $\Delta P \approx$ -5 mbar and an abrupt leak occurs injecting -7.4 mbar into the Detector volume, SV421 reacting at -10 mbar might be engaged, injecting a small amount of Neon + CO_2 mixture into the Beam volume until the pressure falls below the threshold again.
- If injected, the CO_2 will stay in the system, with a layer of Neon on the NEG coating of the RF surface.
- When pumping down again, it might happen that the Neon would be released from the surface, but small amount of CO_2 may remain, potentially affecting the Beam Vacuum quality (TBD).
- Extremely difficult to simulate these conditions taking all the variables and constraints into account. Therefore, it is vital to minimize the reaction time of the safety system.



Leaks in neon mode

- During neon mode (~900 mbar) the cooling down effect of the CO_2 (at -56^{o}C) due to the pressure drop might actually create an under-pressure with respect to the beam volume.
- This effect depends on the leak rate, where it happens, how many modules are affected, the solidification rate of the CO_2, heat transfer to Neon (as there are 2 gases) and the heat absorbed by the secondary vacuum/beam volume.
- This is also extremely difficult to simulate.
- The same setup for the new pressure sensor will be used to obtain experience and investigate this effect.
- We will use the slice setup for these tests (realistic tube lengths, valves, layout).



SEY deterioration in case of leaks

- TE-VSC-SCC (Surface Analysis) performed measurements of Secondary Electron Yield (SEY) on NEG coating before and after activation, as well as after exposure to Neon+CO_2 (Holger Neupert, S0261 NEG CO_2-exposure):
  - https://edms.cern.ch/ui/file/2271783/2/1132_SEY_report.pdf
- The conclusion was that the initial SEY value 1.6 decreases during activation to 1.1. However, after exposure for 2h to Neon containing 1000ppm of CO_2, it increases to 1.3.
- It is very difficult to estimate how much of CO_2 would end up in the Beam volume upon opening if the SV421 in case of leak (depending on the CO_2 quantity and time the valve stays open).
- The limits for the SEY are not well defined.

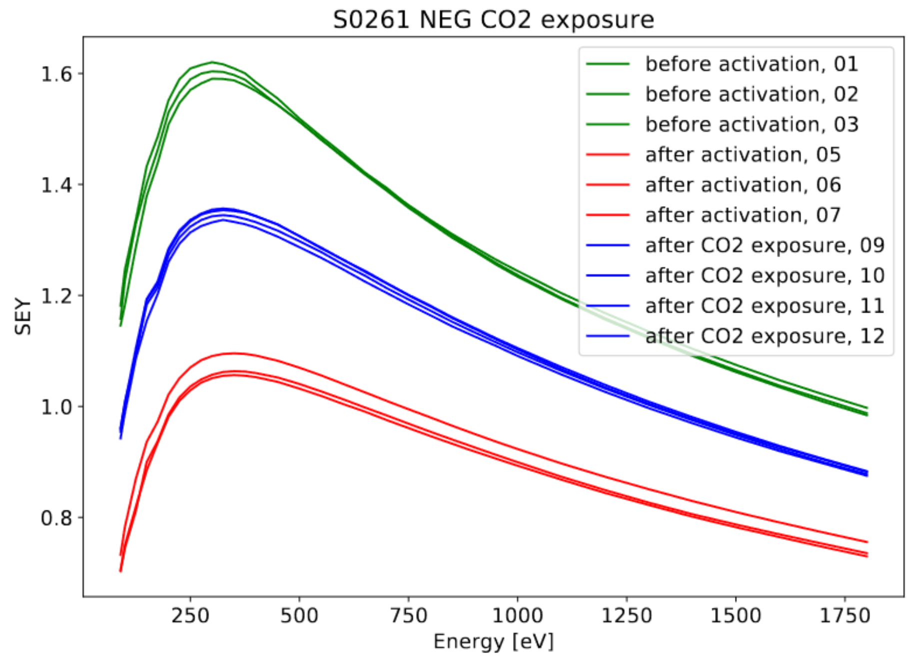


Table 1: maximum SEY values for each step (mean values)

Step	Average maximum SEY
NEG before activation	1.6
NEG after activation	1.1
NEG exposed to CO_2	1.3

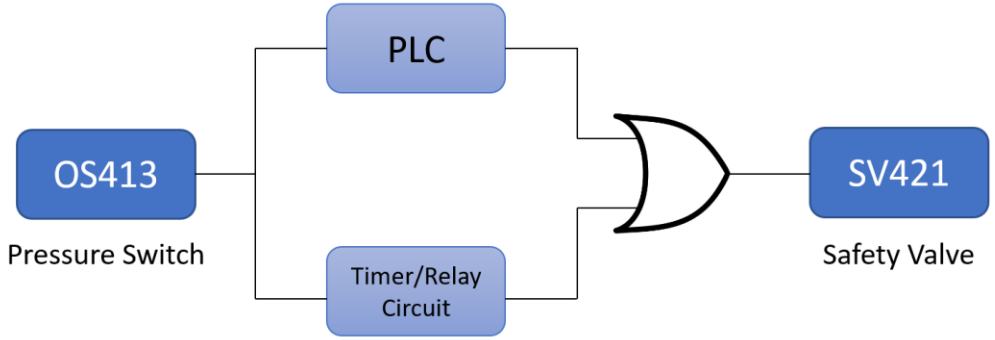
Conclusions

- In addition to the ECR envisaged upgrades to the safety system, a new pressure sensor is envisaged to be placed as close as possible to any potential module leaks in the Detector volume.
- The expected pressure increase is theoretically estimated to ~ 7.4 mbar. A more realistic estimation will be obtained with a new dedicated setup after the new pressure sensor arrives (to be shipped next week)
- It is mandatory to minimize the reaction time in order to ensure prompt response of the safety system not to trigger the opening of SV421, which would cause a small mixture of Neon+CO_2 to be injected into the primary volume, potentially affecting the Beam Vacuum quality.
- All efforts are made to minimize the reaction time, which can only be theoretically estimated at the moment. Further tests still needed in order to determine it more precisely.
- The new tests using the slice setup of total reaction time and other parameters envisaged to start some time in December 2020, upon the new sensor arrival (setup ready).
- In the meantime, a spare RF foil will be tested to withstand pressure up to 20 mbar which could potentially decrease some of the constraints.

Backup slides

Overpressure Safety System

- SV421 connects the Beam and Detector volumes and is normally closed. This valve is only open as a last resort, if the other protection methods were unable to keep the differential pressure below acceptable limits. It is electrically interlocked with OS413, meaning that even if the PLC is stopped the safety system will still be triggered.
- The Overpressure Safety System should act only if, despite all other layers of protection, the differential pressure still rose to a potentially dangerous level. It uses the input from the OS413 pressure switch and, should one of its signals go bad (detecting a pressure differential of at least 10 mbar in either direction) opens the overpressure safety valve SV421. This valve is kept open while the pressure switch is in bad state. It is closed only 10 seconds after the pressure has been equalized and the switch returns to good state.
- To offer some degree of redundancy, two different systems actuate the valve in parallel: the PLC and a dedicated timer/relay-based electrical circuit. Using standard terminology, it is a Safety Instrumented System which is implemented.



- The main advantage of having two logic solvers is that the overpressure safety system should work even if the PLC is OFF of Stopped.

VELO Upgrade:
CO_2 cooling safety system

Oscar Augusto de Aguiar Francisco

CERN

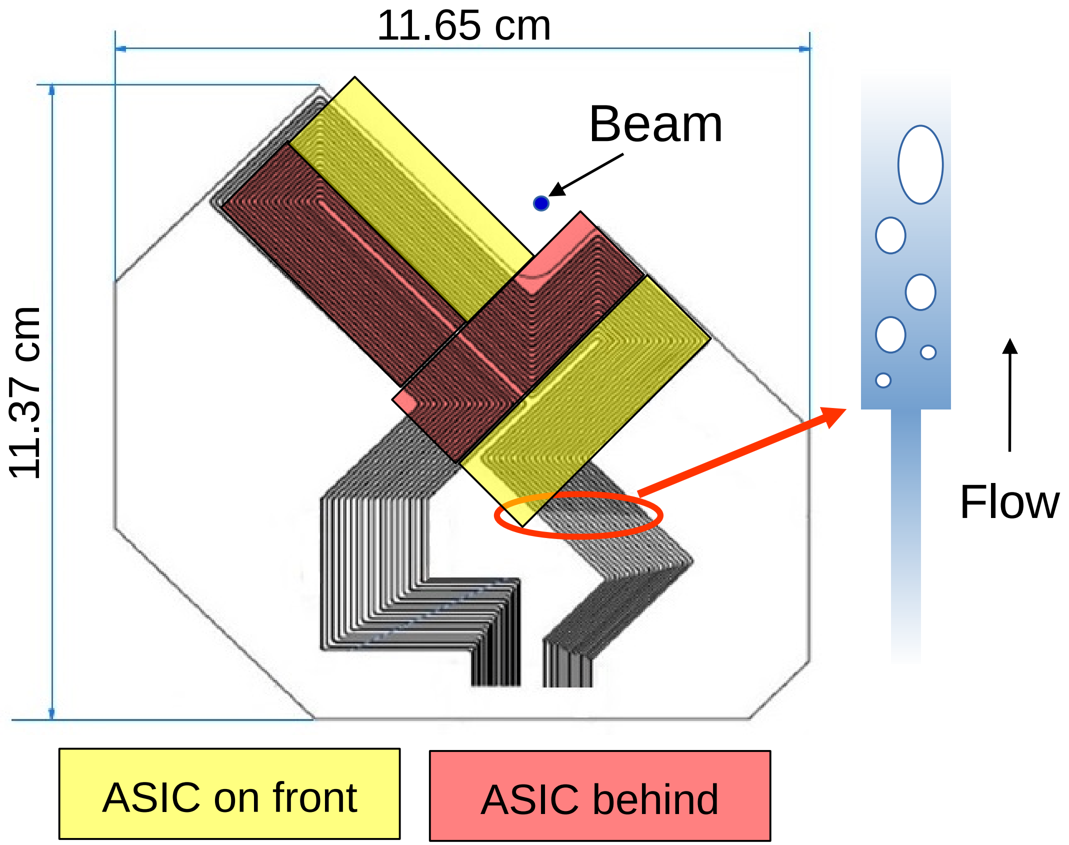
LHC machine protection panel meeting for the VELO upgrade

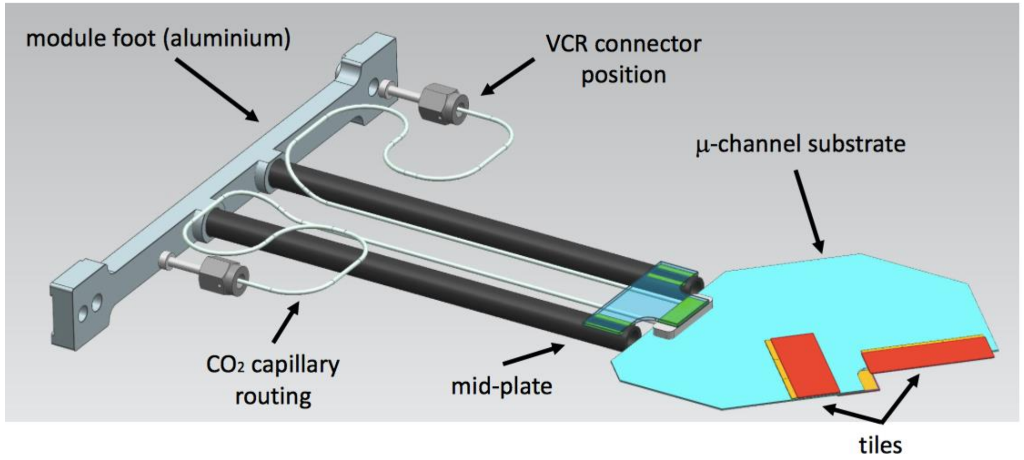
Outline

- Modules
- Cooling safety system
- Leak detection
- Summary

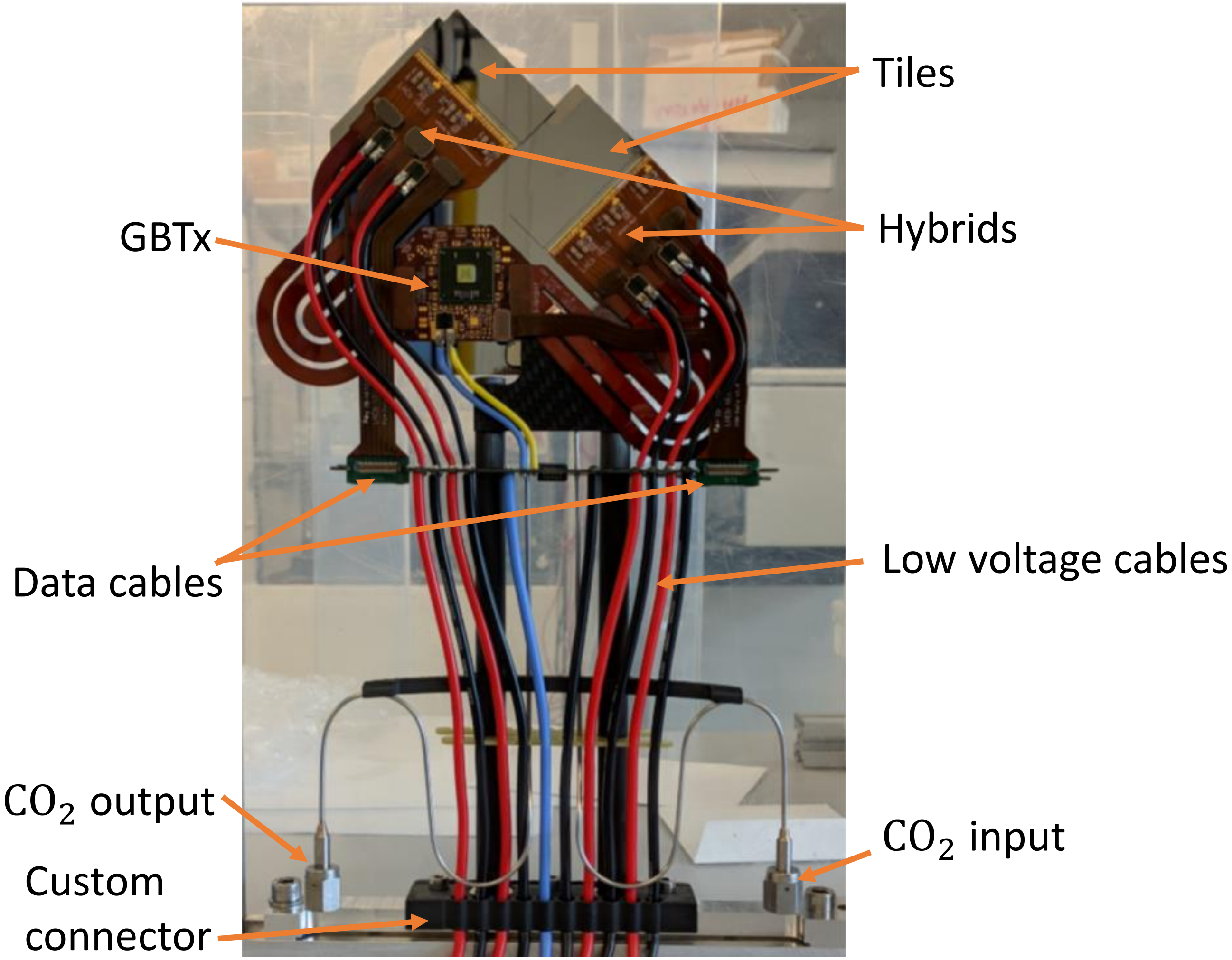
Micro-channels and first modules

- Evaporative cooling: Heat provided by electronics is absorbed by the CO_2 changing the ratio of gas/liquid
- Narrow restrictions at the entrance
  - 60 µm x 60 µm (40 mm long)
  - Prevents instabilities among the channels
- Main channels
  - 120 µm x 200 µm (~260 mm in average)
- Cooling substrate is 500 µm thick

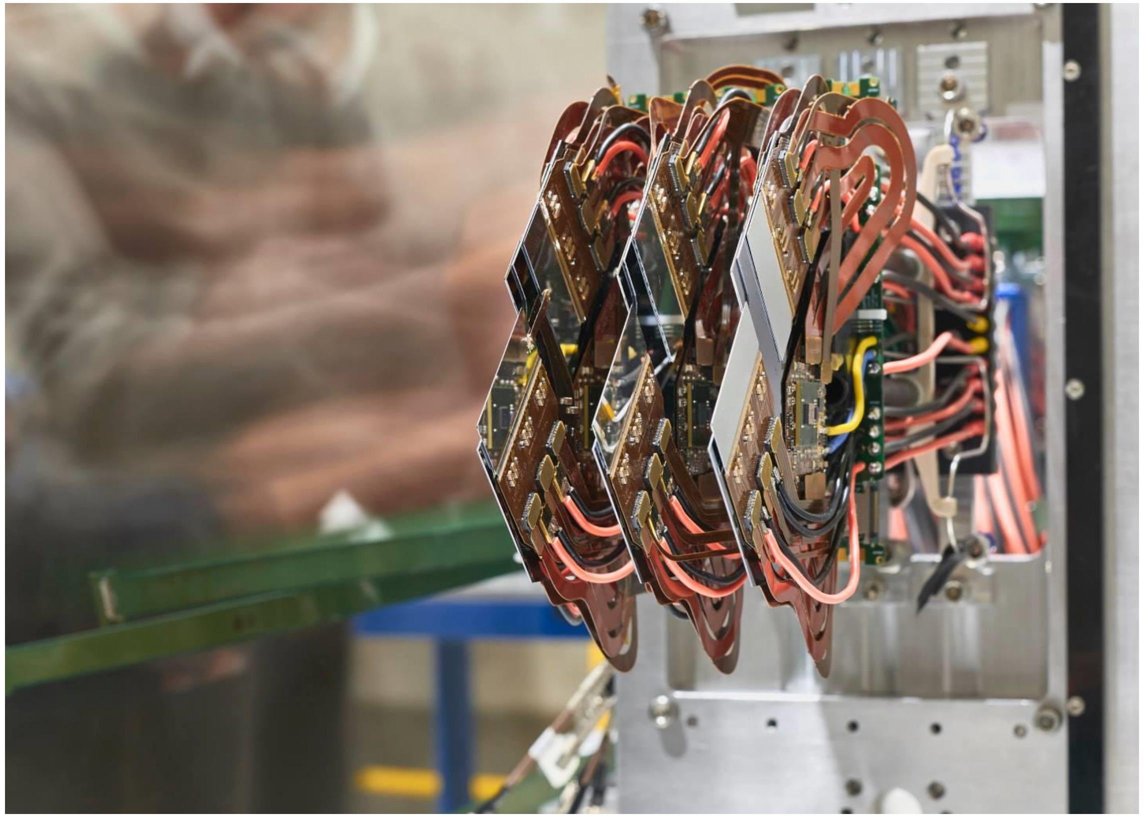




Micro-channels and first modules

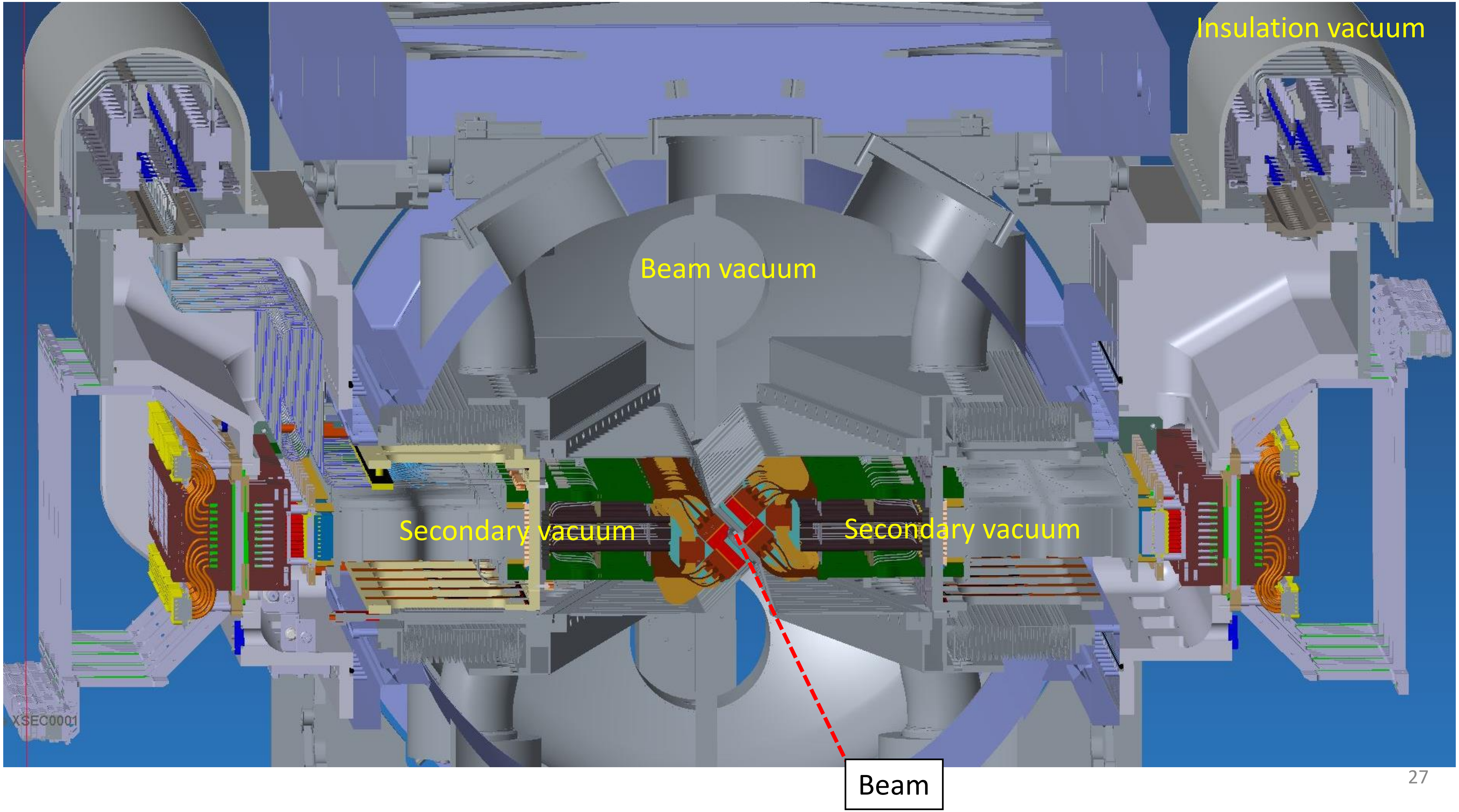


Successful testbeam with three modules

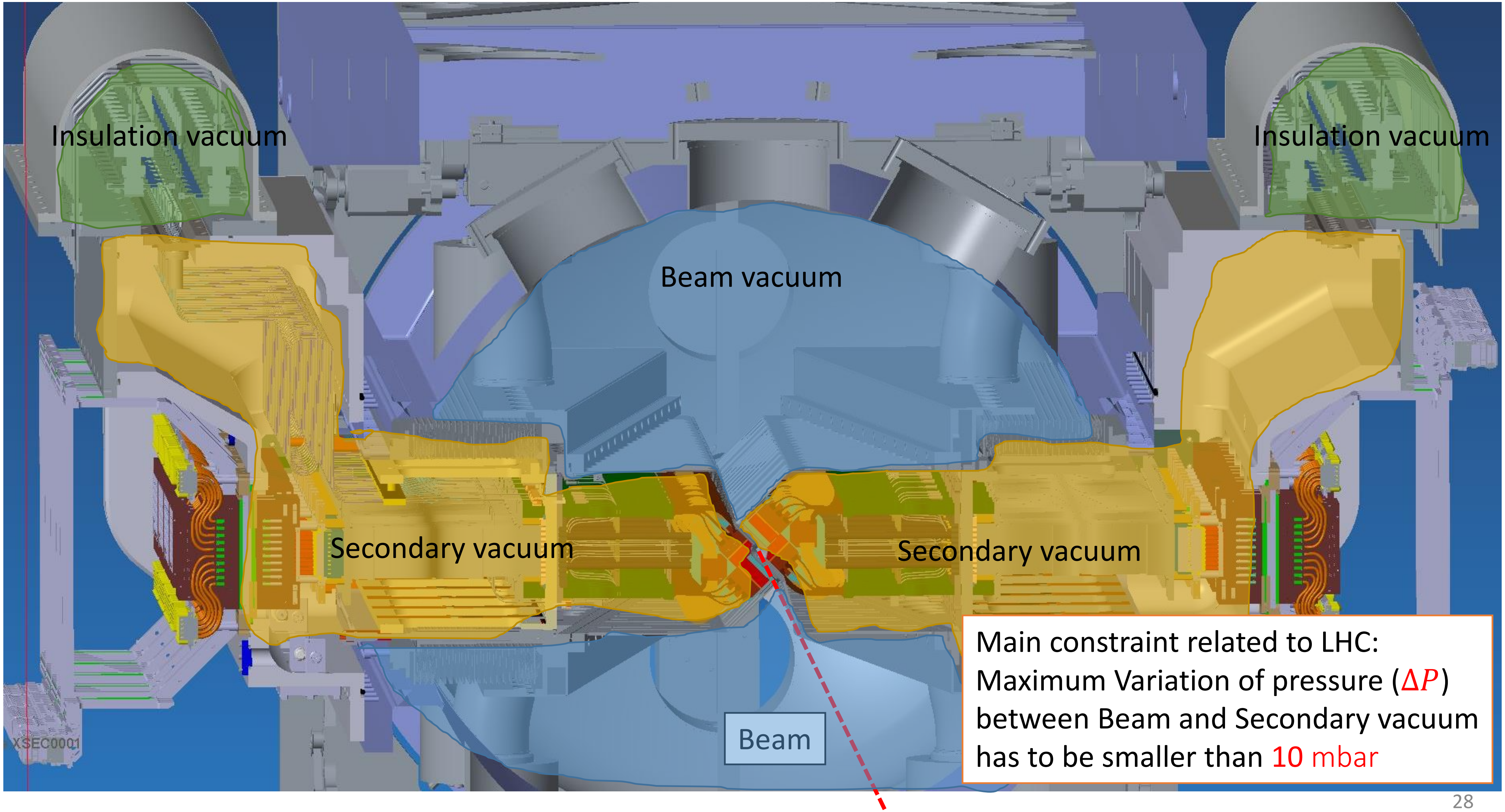


Julien Ordan, 2018

Full 3D design



Full 3D design



Main constraint related to LHC:
Maximum Variation of pressure (ΔP)
between Beam and Secondary vacuum
has to be smaller than 10 mbar

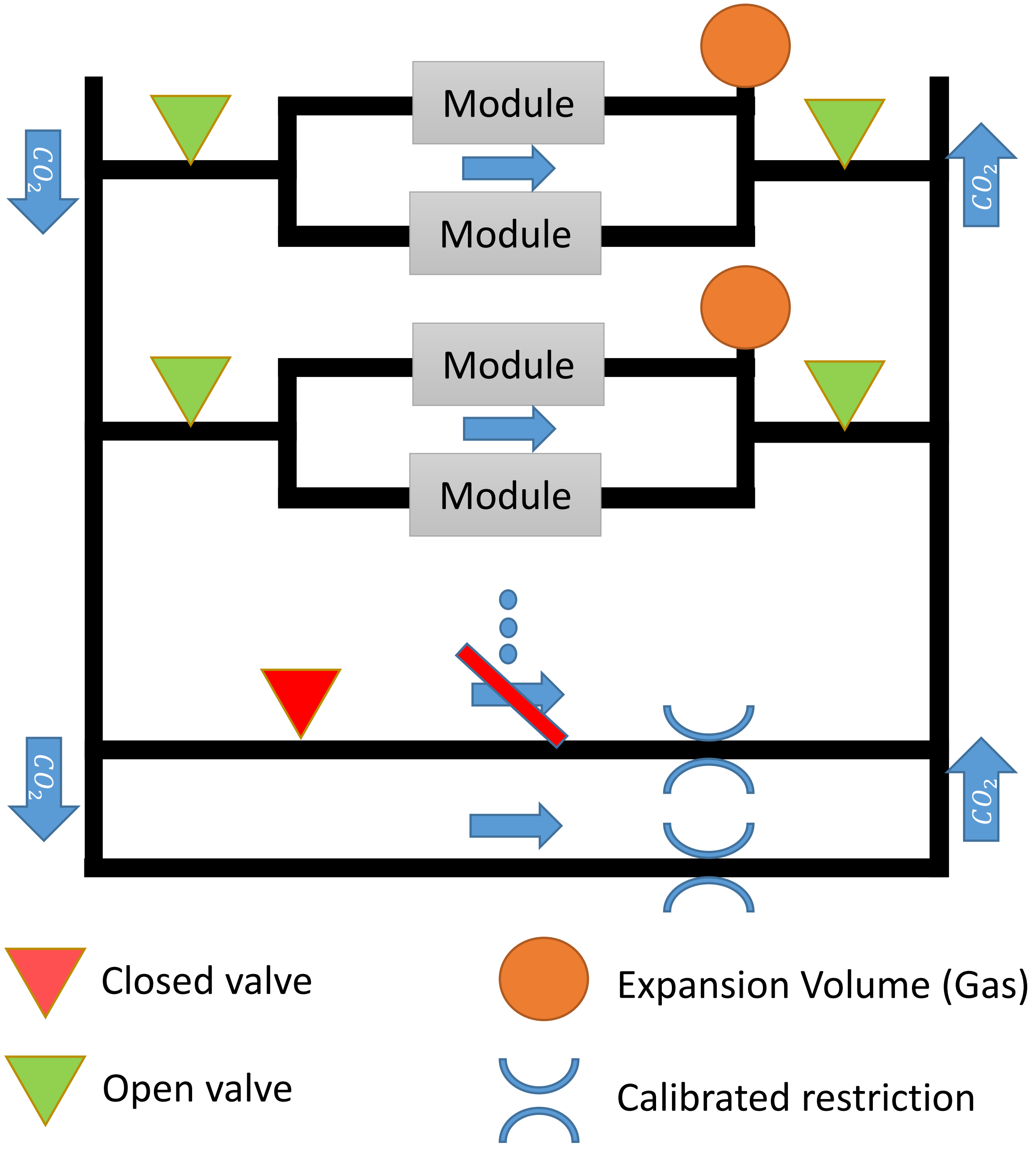
Insulation Vacuum and safety

- Minimize the pressure raise in case of leaks
- An expansion volume is necessary to close the valves and prevent pressure build up while the system warms up

Two bypasses:

1) Always open to ensure minimum flow to keep the distribution lines cold
2) Divert the flow if the safety system is activated in such way that the variation of pressure over the detector is the same

If activated, LV and HV will be inhibited on the modules (no cooling).



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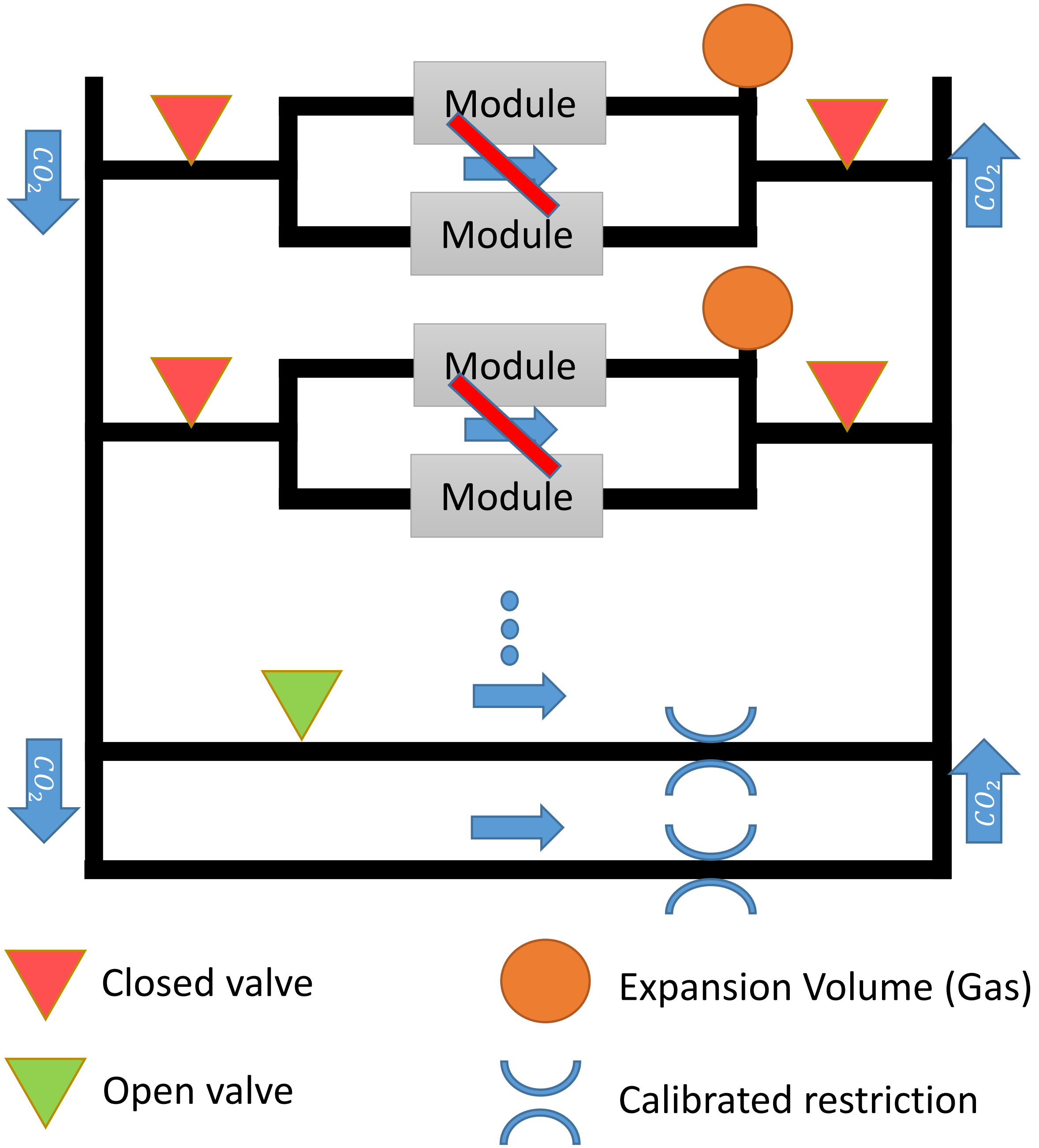
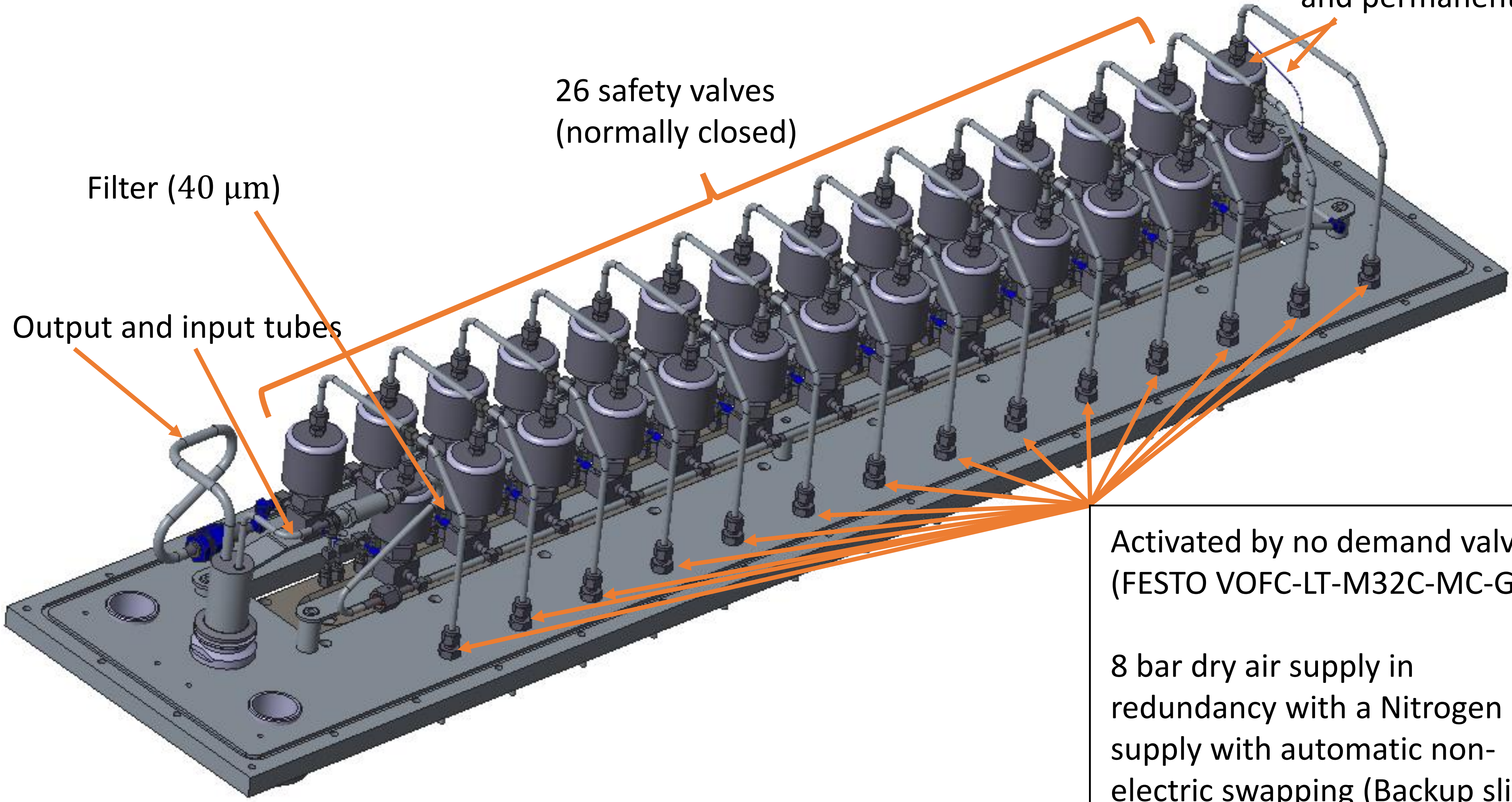
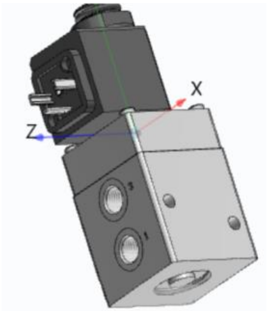


Isolation Vacuum (Safety system) – 3D design



Activated by no demand valve
(FESTO VOFC-LT-M32C-MC-G14)



8 bar dry air supply in redundancy with a Nitrogen supply with automatic non-electric swapping (Backup slide)

Pressure in the secondary volume in case of leaks

- Scenario with the failure of one cooling loop containing two modules

- Considerations:
  - The CO_2 inside the tubes/module is on the liquid state
  - During operation, the CO_2 will be boiling (gas/liquid)
  - The CO_2 in the expansion reservoir is on the gas state

- The reaction time was not considered on this exercise!
  - In discussion with the LHCb vacuum group
- The CO_2 solidification slows down the leak rate (neglected)
- The suction of the vacuum pump was neglected

- Total CO_2 in the loop:

$$m_l = \rho_{lCO2_{-35C}} \times V = 1096.5 \frac{\mathrm{kg}}{\mathrm{m}^3} \times 5.5\, ml = 6.03\, g$$

$$m_g = \rho_{gCO2_{+20C}} \times V = \frac{194.2\mathrm{kg}}{\mathrm{m}^3} \times 5.5\, ml = 1.07\, g$$

Pressure in the secondary volume in case of leaks

- Total pressure using ideal gases equation:

$$P_{leak} = m_T \times \frac{RT}{44V} = 7.1\ g \times \frac{8.31 \times 10^{-2} L.bar.K^{-1}\ mol^{-1} \times 300K}{600\ L \times 44\ g\ mol^{-1}}$$

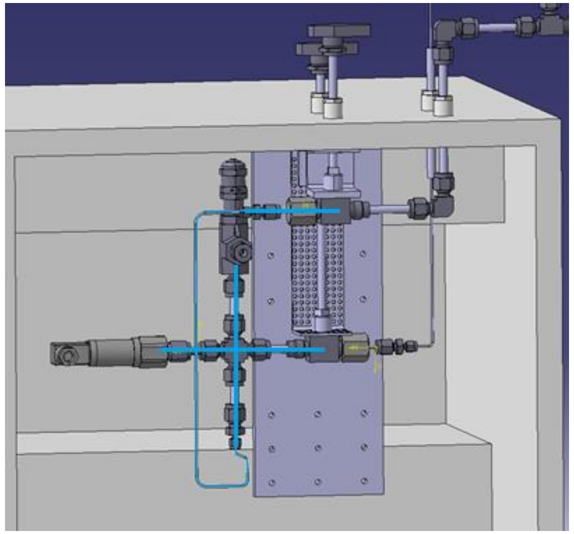
$$P_{leak} = 6.70\ mbar$$

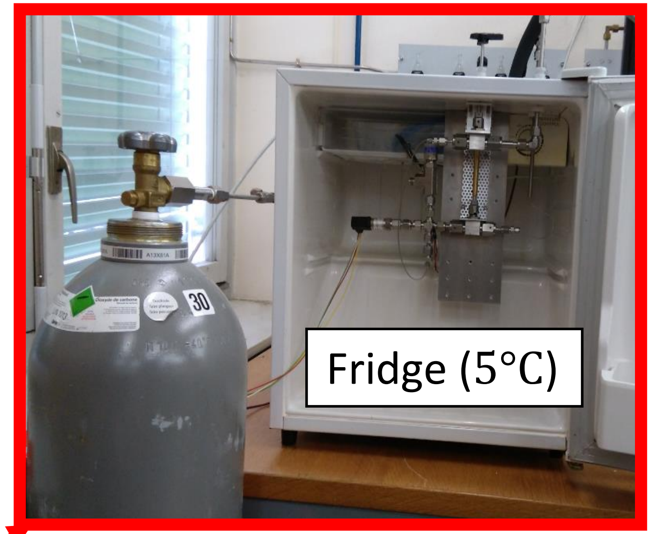
Baseline is to use a container made using a standard 10 cm long tube with of ½” outer diameter pipe (ID 1.0922 mm):

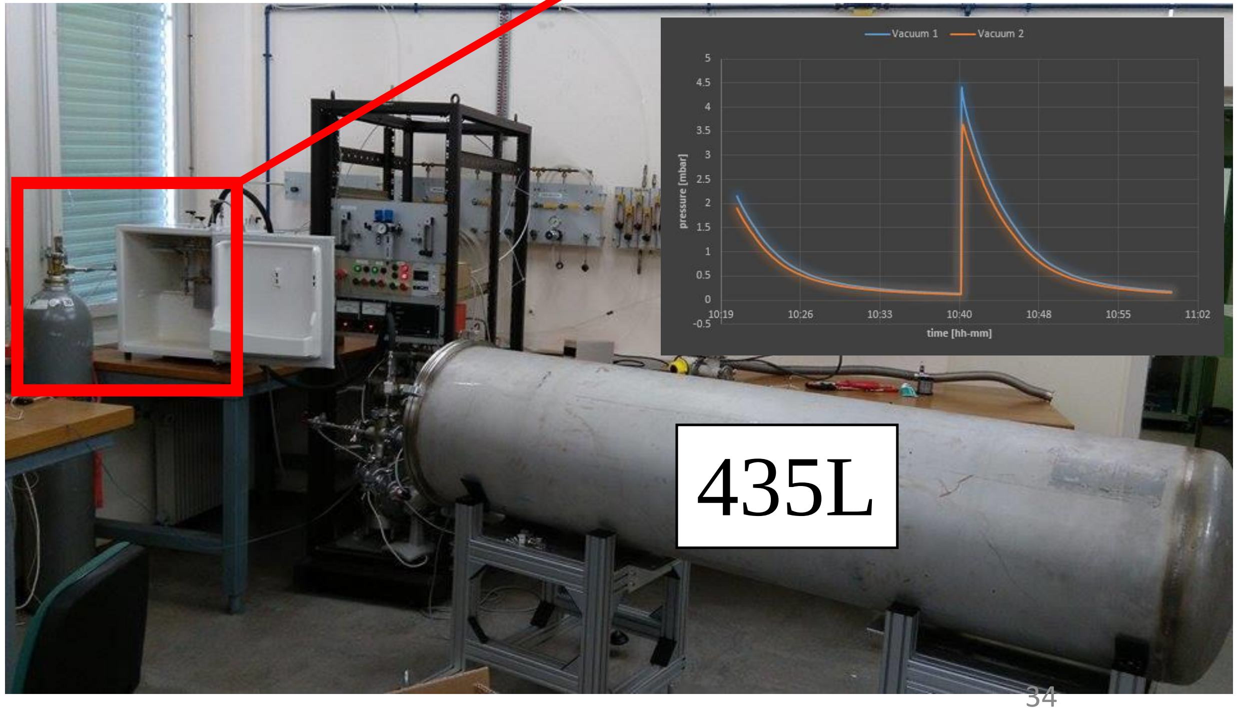
- Expansion volume would be ~8.2 ml for the expansion volume (1.6g CO2)
- Total mass of 7.63 g
- $P_{leak} = 7.2\ mbar$ (Safety margin of 38% with respect to 10 mbar)

Experimental test #1

Capillary length [cm]	Pipes volume	CO2 mass [g]	Total volume (L)	CO2 Liquid density [kg/m3]	Max. Pressure [mbar]
100 (Fully liquid)	4.35161	4	435	895.9	4.5
VELO Upgrade Liquid(Scaled)	5.5	6.03075	600	1096.5	5.05
VELO Upgrade Gas (Scaled)	8.2	1.59244	600	194.2	1.33
VELO Upgrade total (Scaled)	13.7	7.62319	600	-	6.38







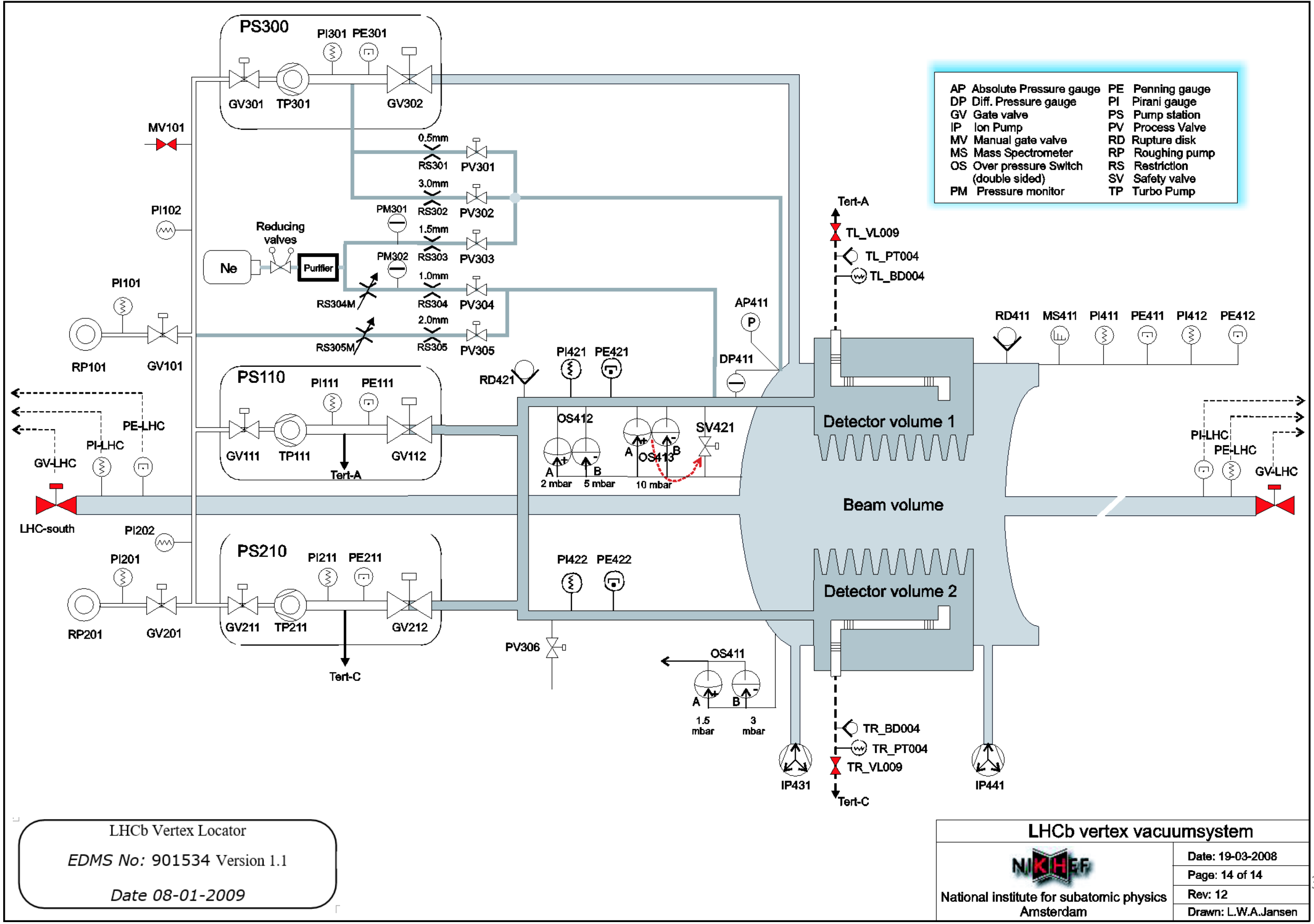
The reaction time was neglected!

Takes into account the pump speed (Adixen?)

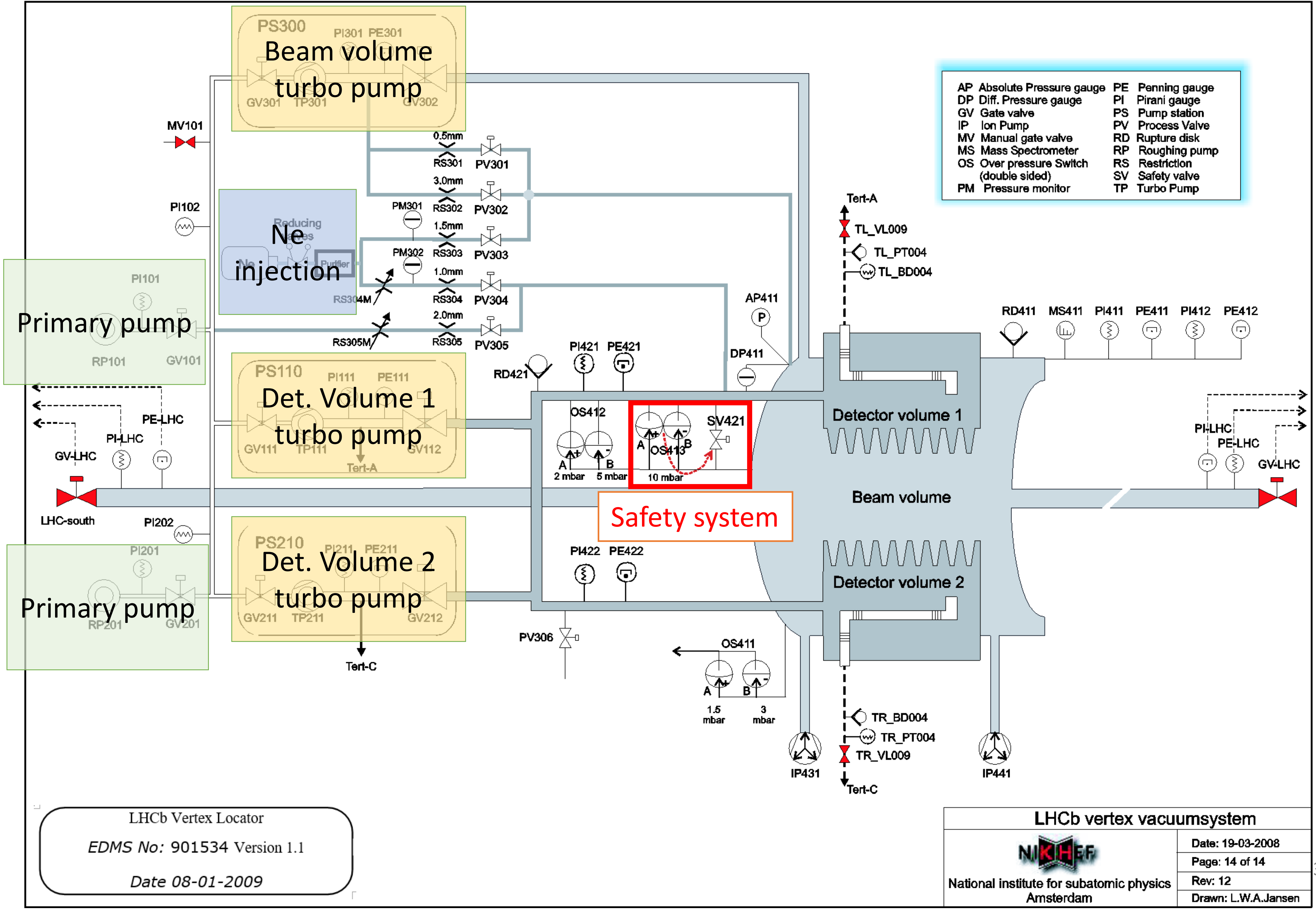
VELO leak detection

- Dedicated pressure sensors:
  - Penning: 10^{-11} mbar < p < 10^{-4} mbar
  - Pirani: 10^{-4} mbar < p < 1 bar
  - Absolute Baratron: 1 mbar < p < 1 bar
- Possibility to analyze the variation of pressure over time but it is challenging
- Additional pressure sensors on the vacuum system side could also inform us about leaks (redundancy)
- Membrane switches (+10 mbar) which give almost instantaneous response (no processing time)

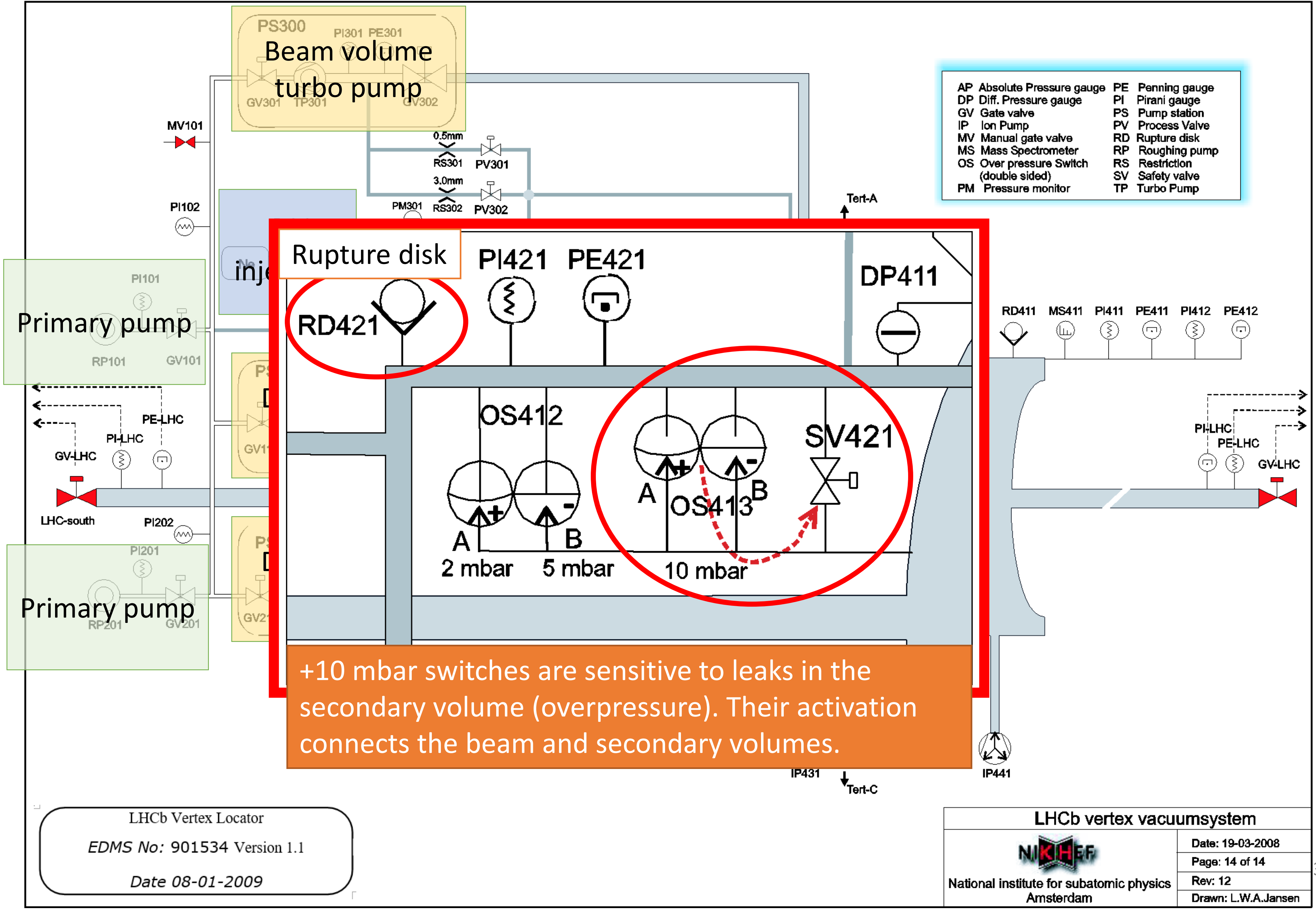
VELO Vacuum system



VELO Vacuum system



VELO Vacuum system



+10 mbar switches are sensitive to leaks in the secondary volume (overpressure). Their activation connects the beam and secondary volumes.

Summary

The first protection against unlikely leaks are the two shutoff valves that can isolate every two modules from the cooling plant and mitigate pressure increase in the secondary vacuum.

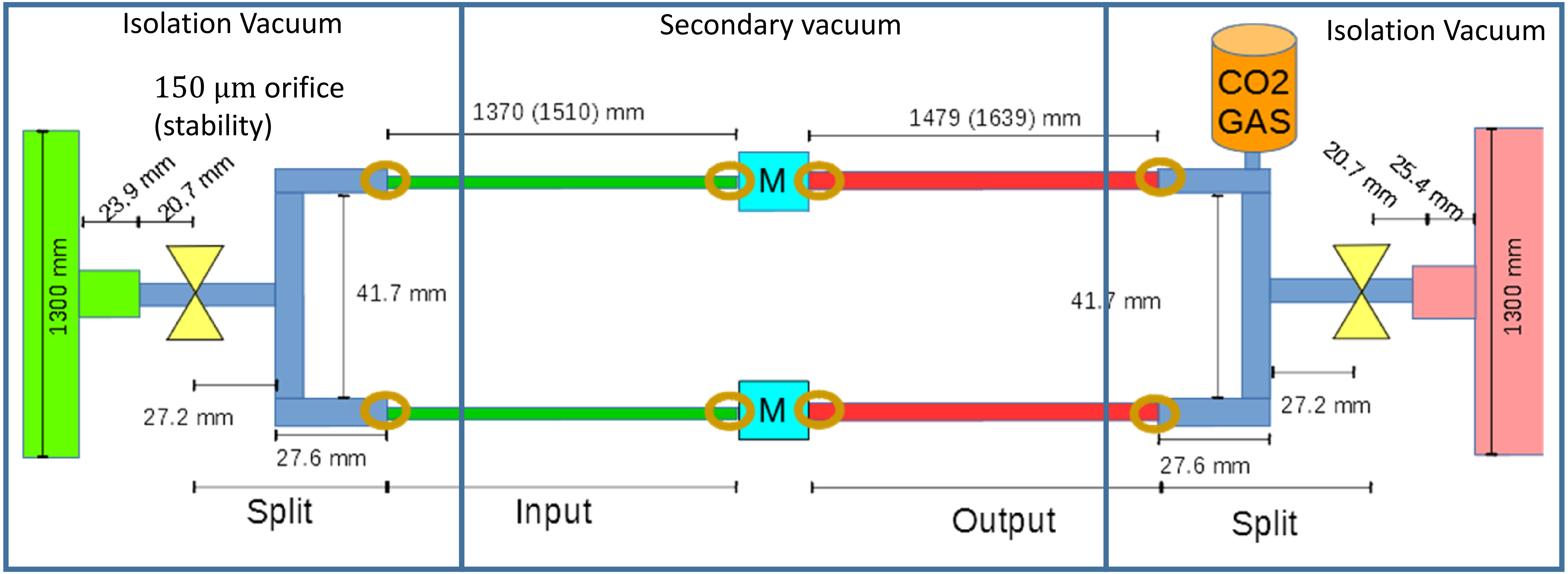
The second protection is the connection of beam and secondary volumes to prevent the RF plastic deformation/rupture if $|\Delta P| > 10\ mbar$

The CO_2 present in the cooling loops (ignoring the reaction time) would increase the pressure in the secondary volume by 6.38 (6.70) mbar

The redundancy of the leak detection mechanism can be achieved by signals provided by the vacuum system and additional pressure sensors

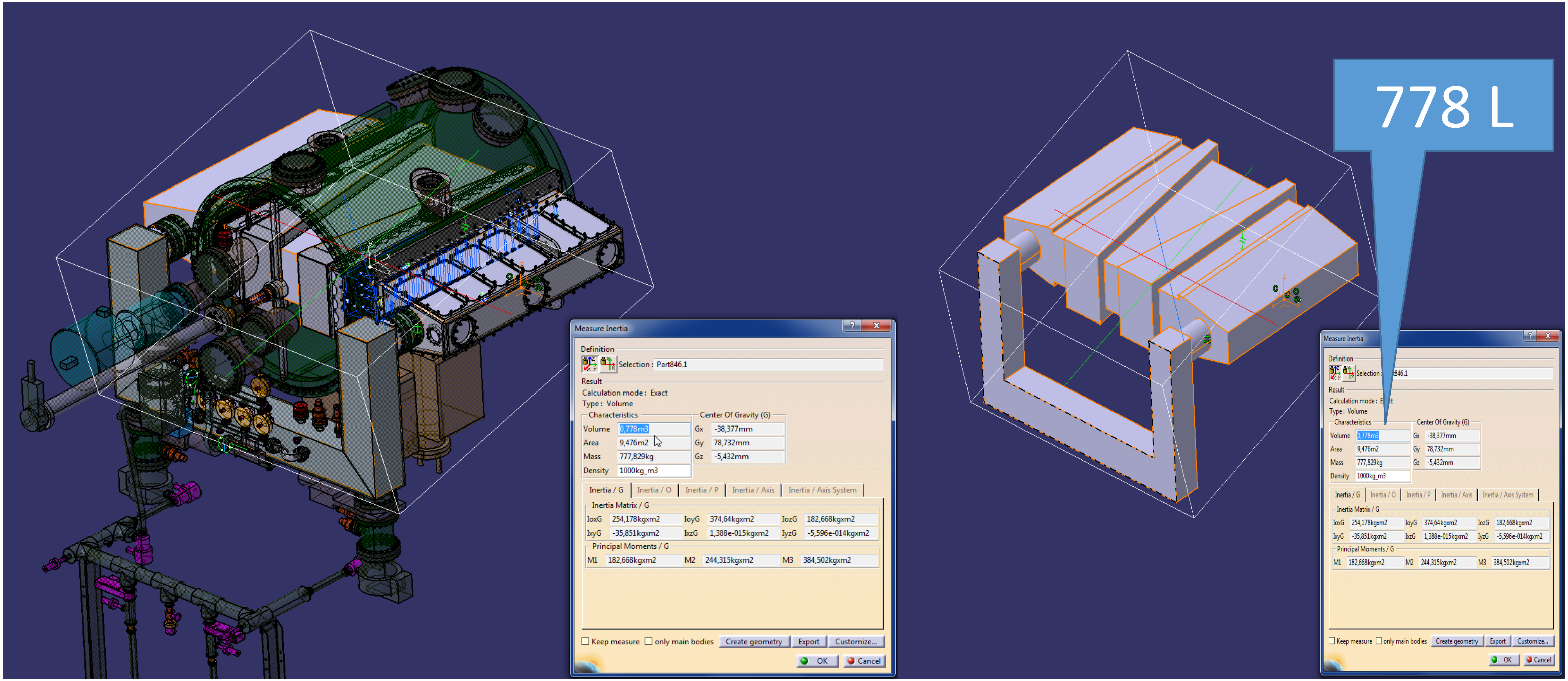
Thank you!!!

One branch of the cooling system



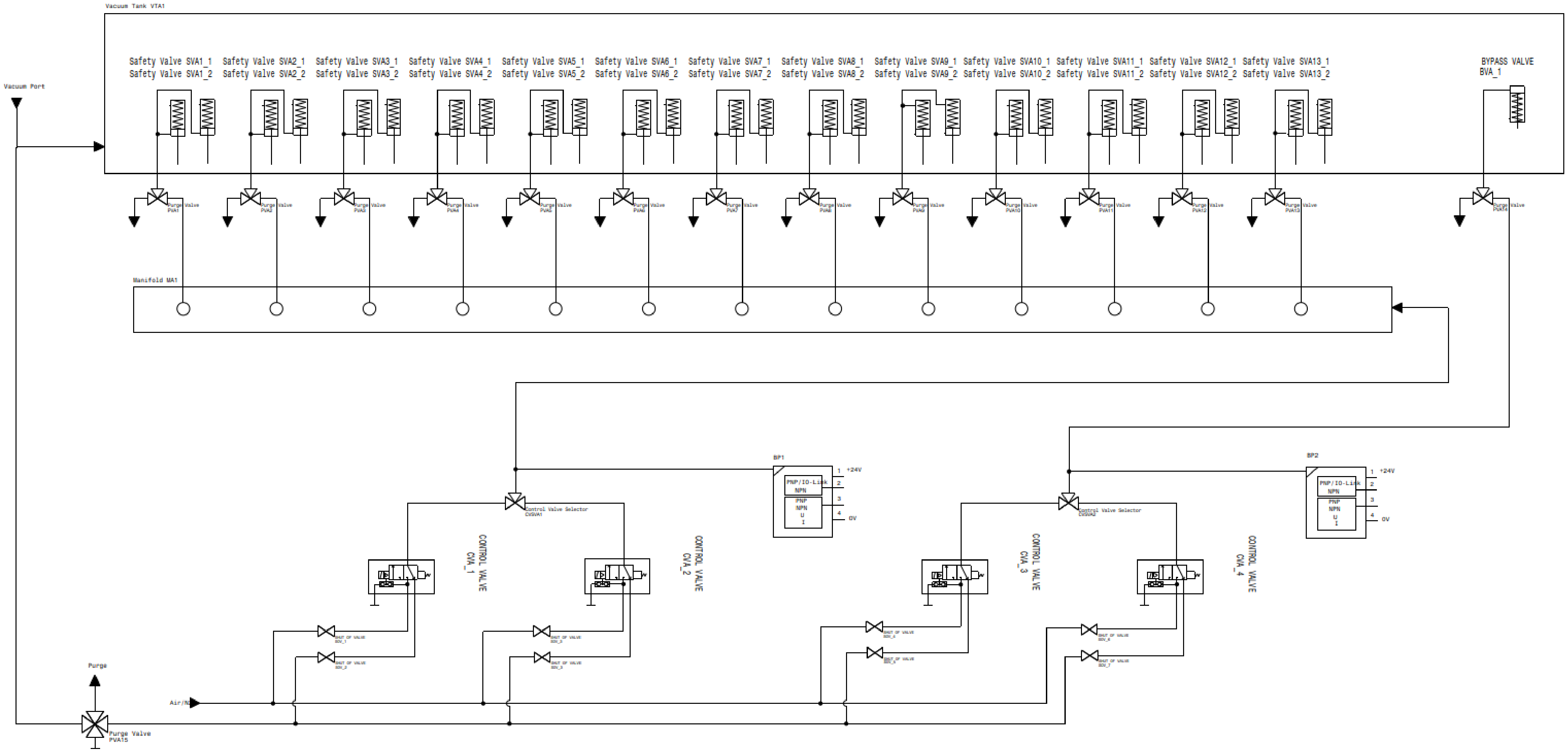
- 1/8" (ID 1.397 mm)
- 1/16" (ID 0.5715 mm)
- 1/16" (ID 1.2 mm)
- 1/4" (ID 6.223 mm)
- VCR connector 1/8" (~5mm)
- 3/8" (ID 9.398 mm)
- Same volume between the valves
- M: 2x320 mm 1/16 " to the connector in the module (Microchannels – Input + output)

Total secondary volume

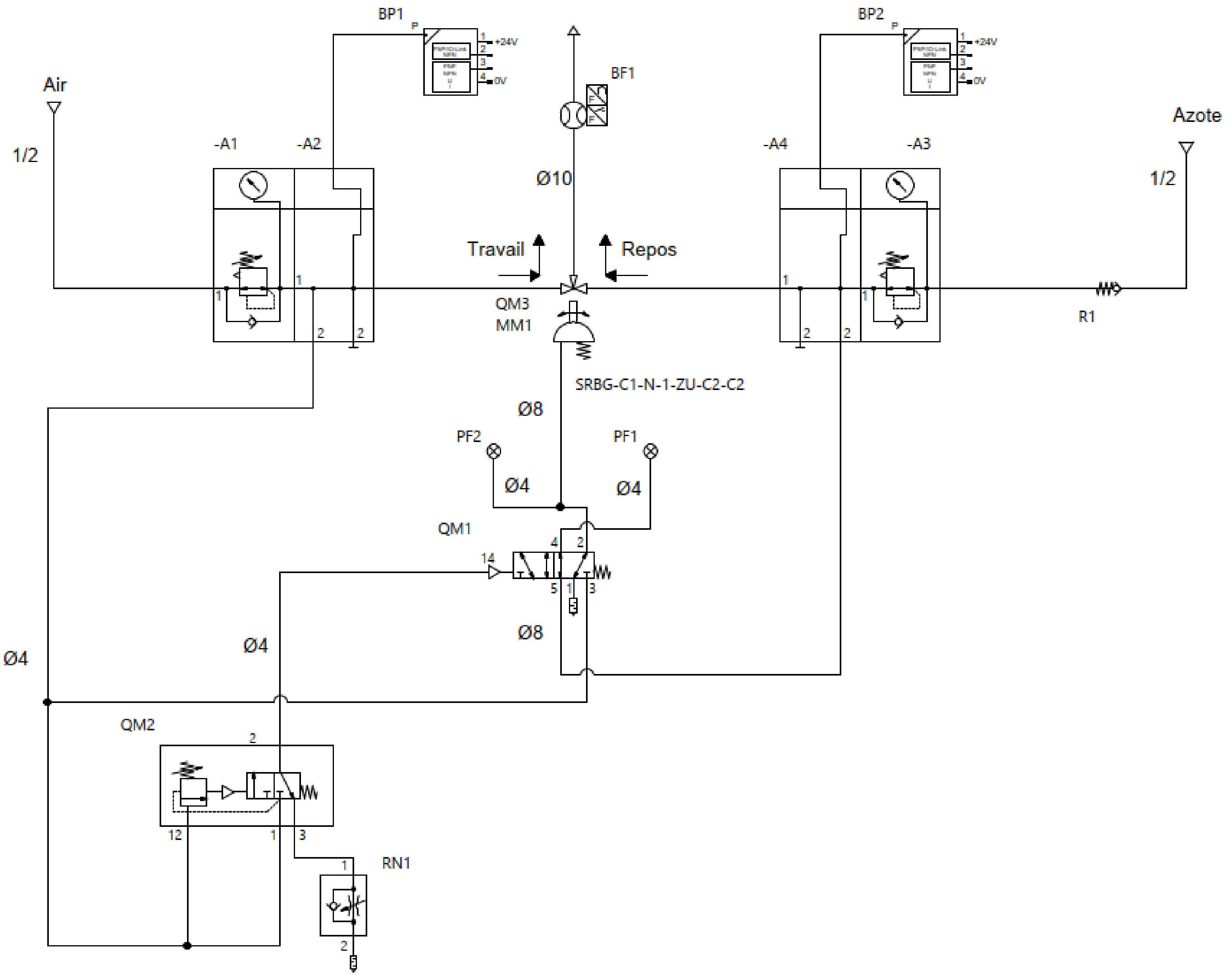


Due to the cables, modules and mechanics, we are assuming that the effective volume is 600 L.

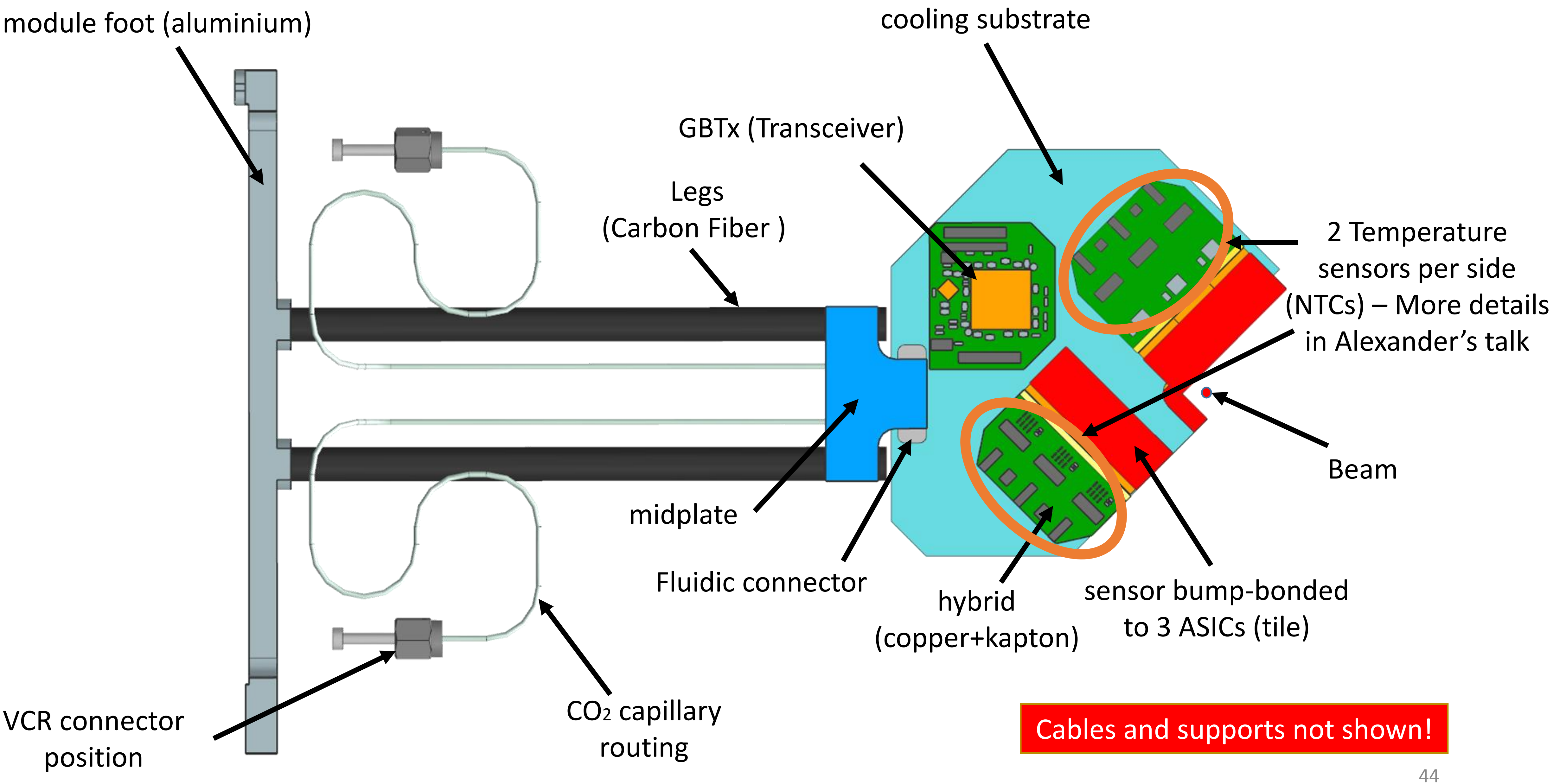
Shutoff valves trigger system



High pressure gas redundancy system

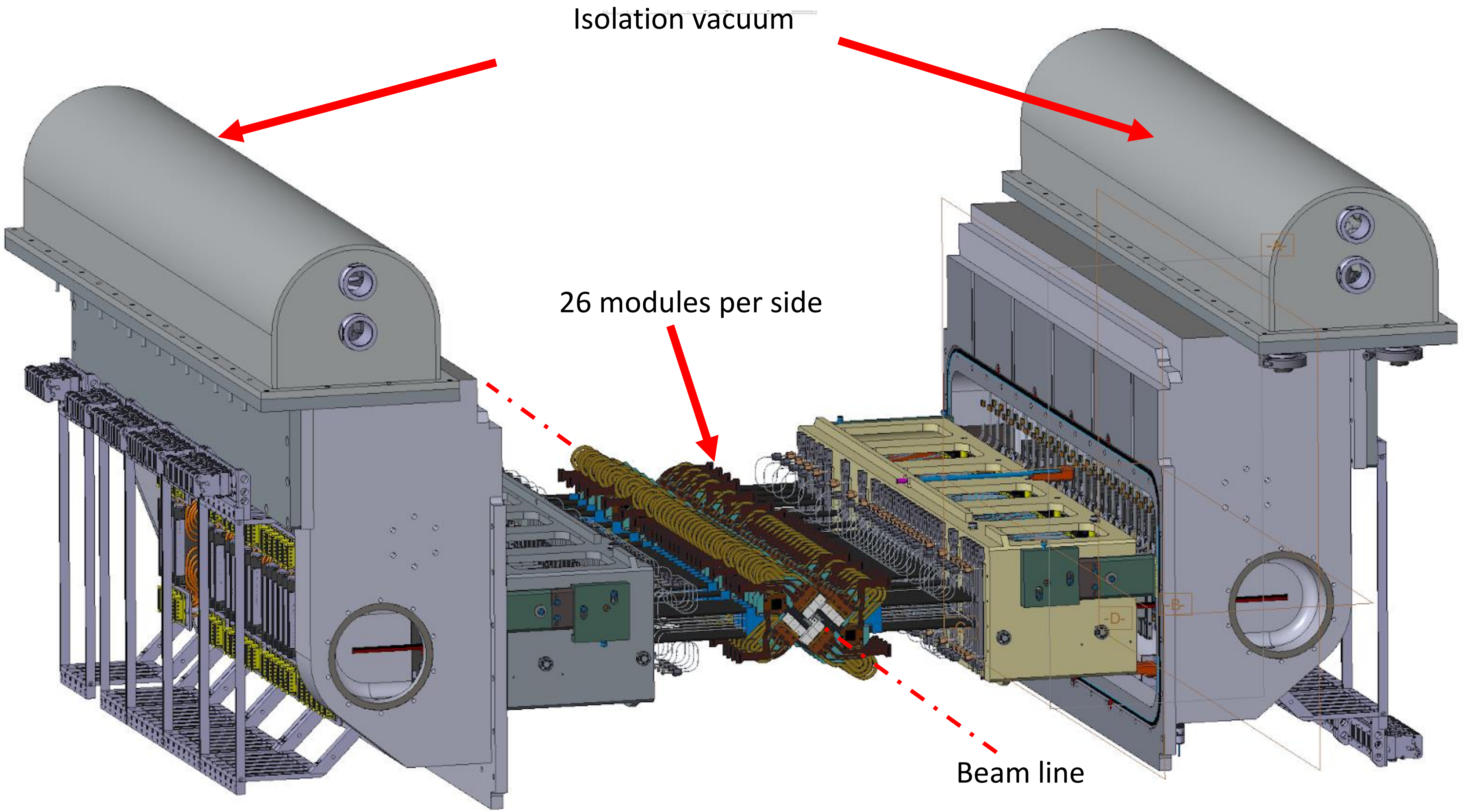


Module design



Cables and supports not shown!

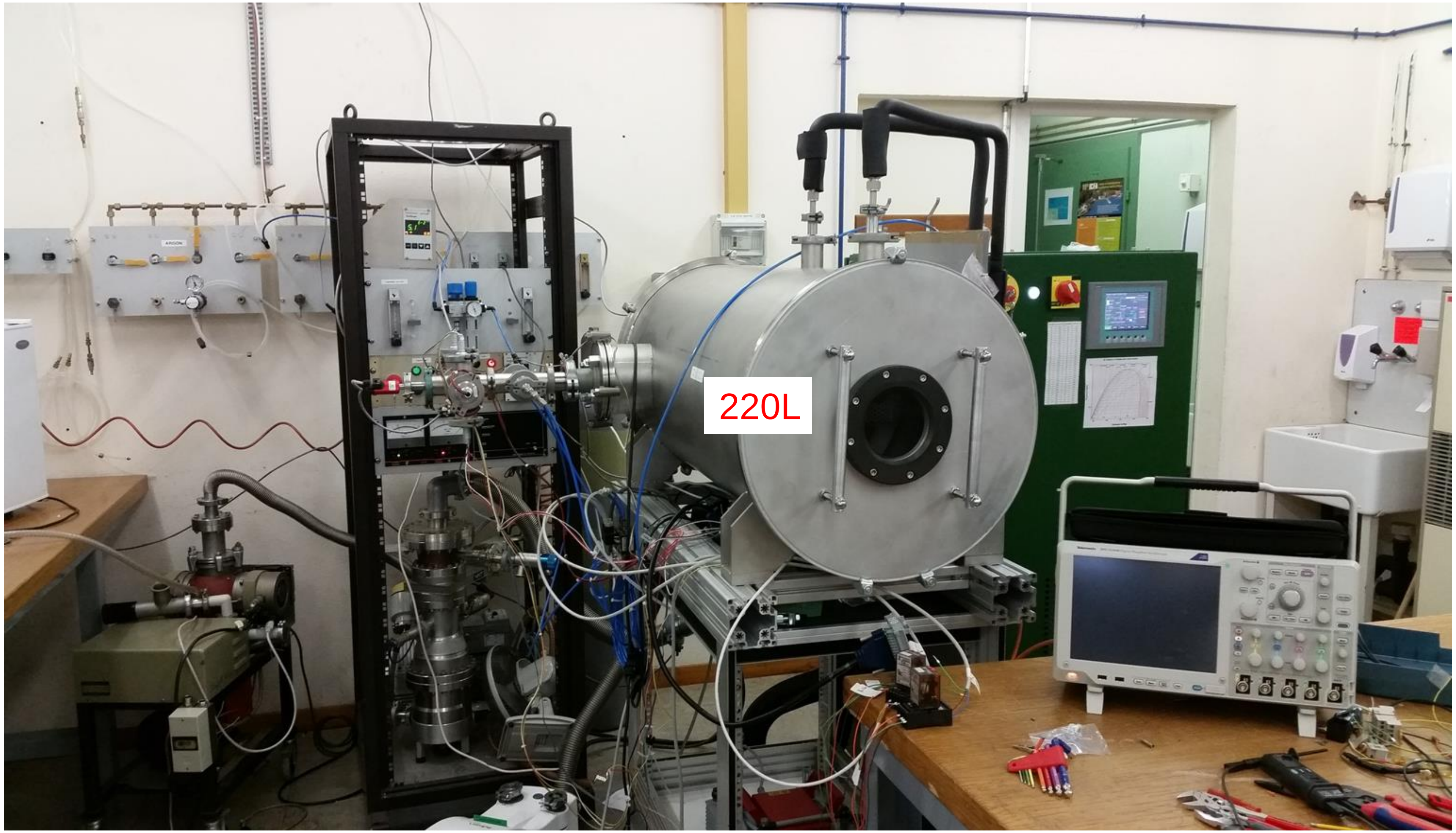
Modules, mechanical supports and Isolation vacuum



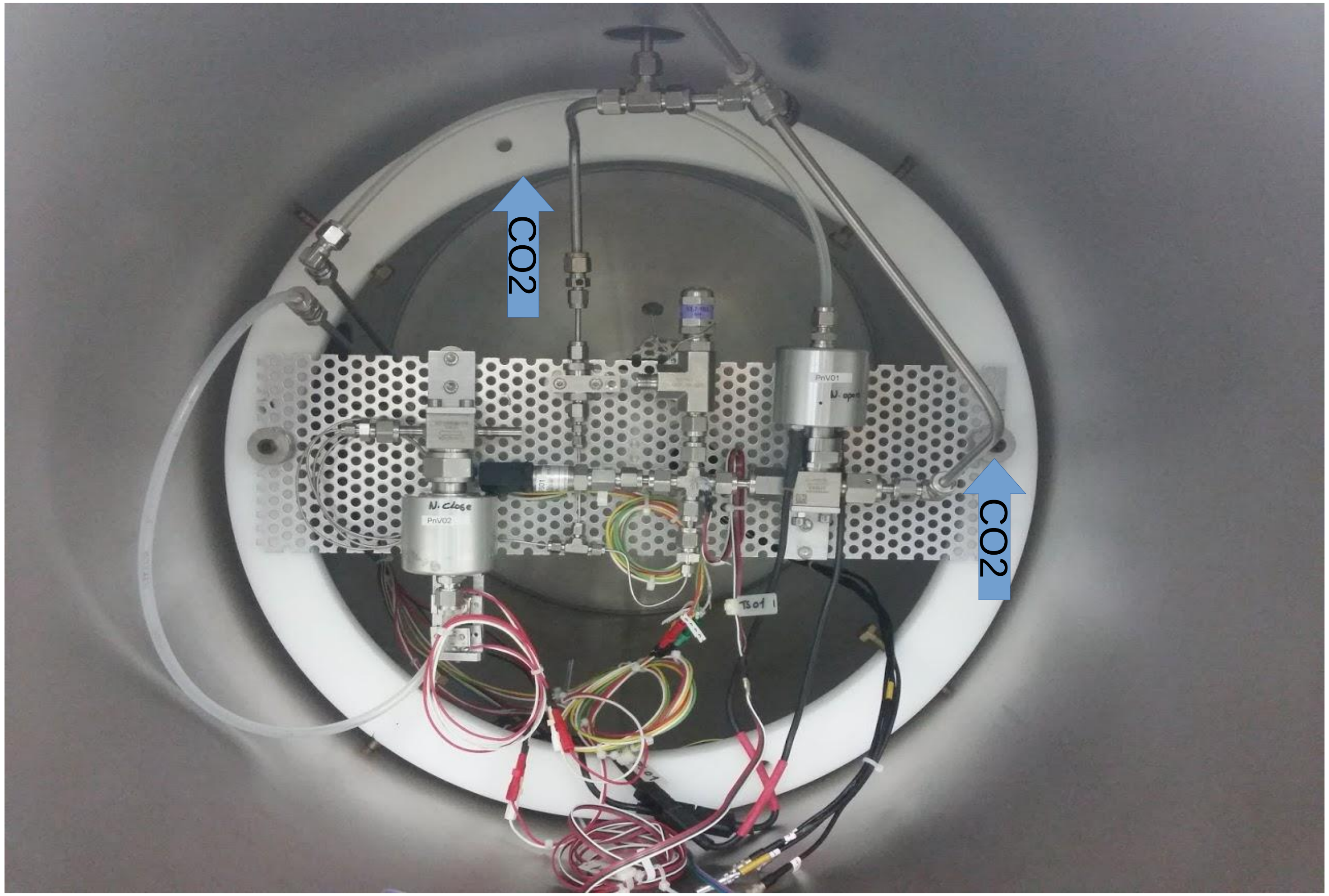
Experimental tests

- Summary of results:
  - Up to 6 m x 1 mm ID capillary with pure liquid CO_2 (up to 7.6 g) release in a vacuum chamber with volume 435l -> maximum pressure 4 mbar with the pump running
  - Up to 50 cm x 1 mm ID plus additional components (4.55 ml volume) released in a vacuum chamber of 220 l -> maximum pressure of 5.8 mbar with reaction time of ~ 433 ms and vacuum pump running
  - Failure of the safety system test in a volume of 220 l -> Pressure stabilized at 15 mbar with the vacuum pump running (CO_2 solidification)

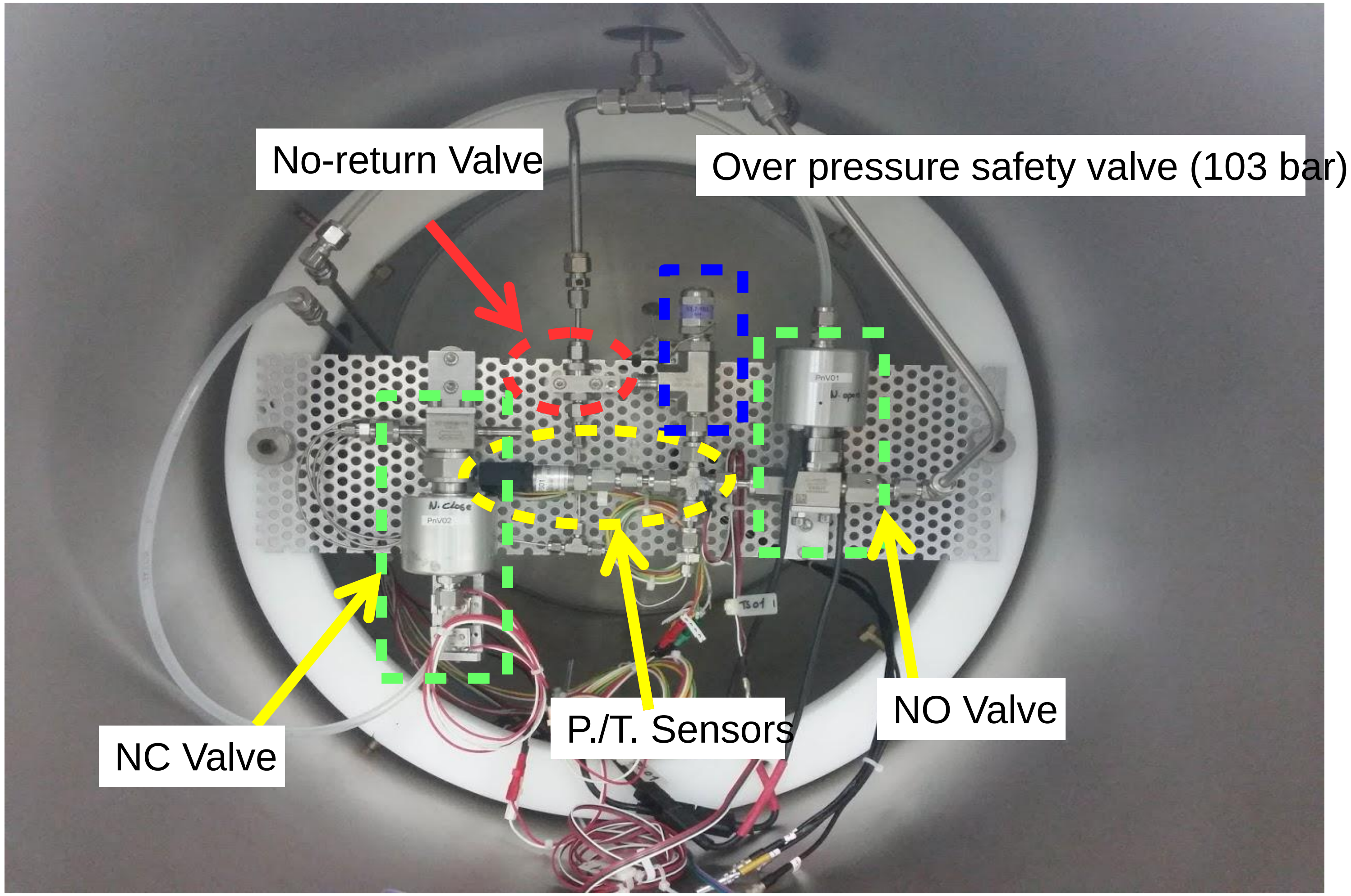
Safety system setup



Safety system setup

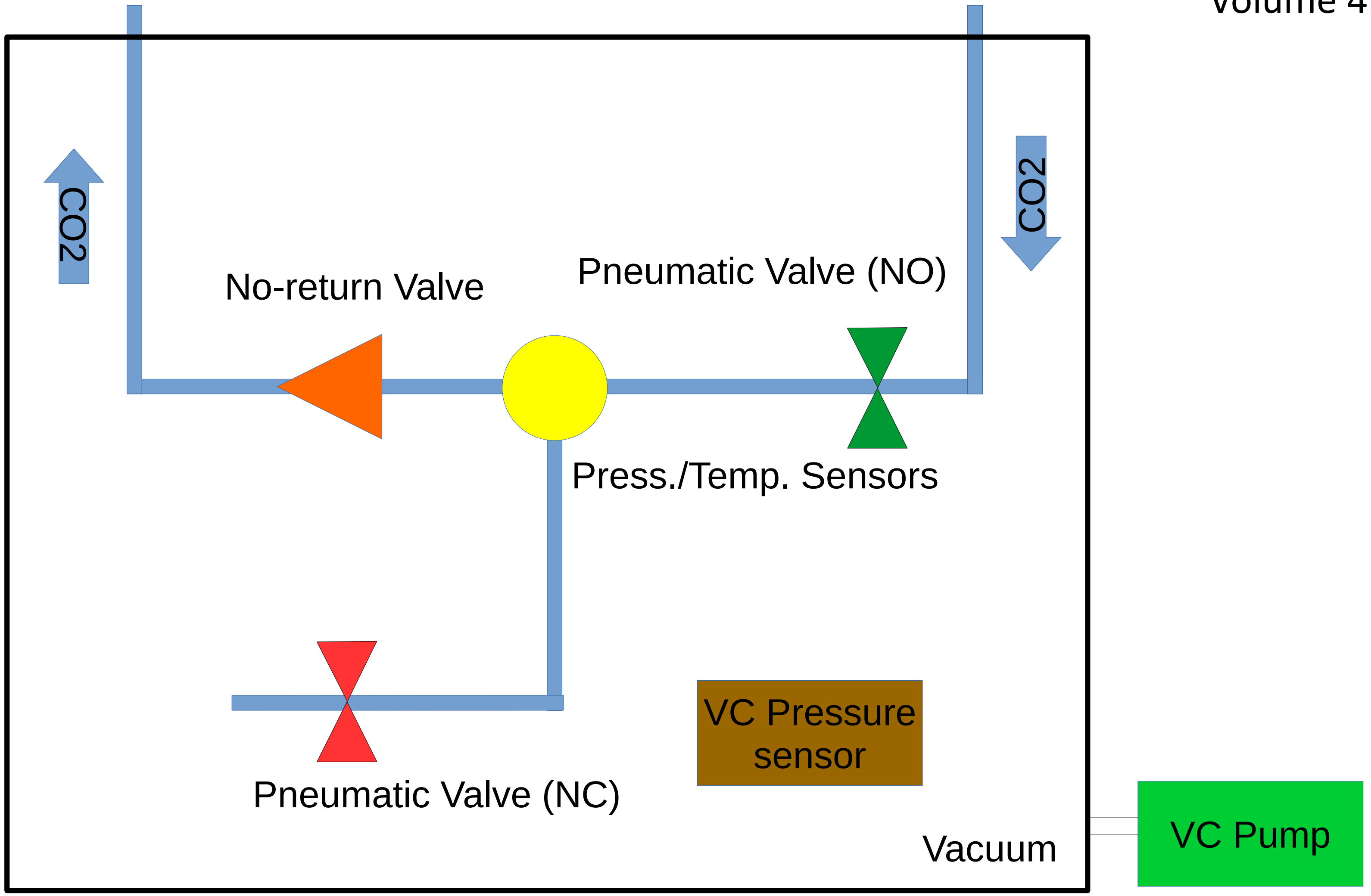


Safety system setup

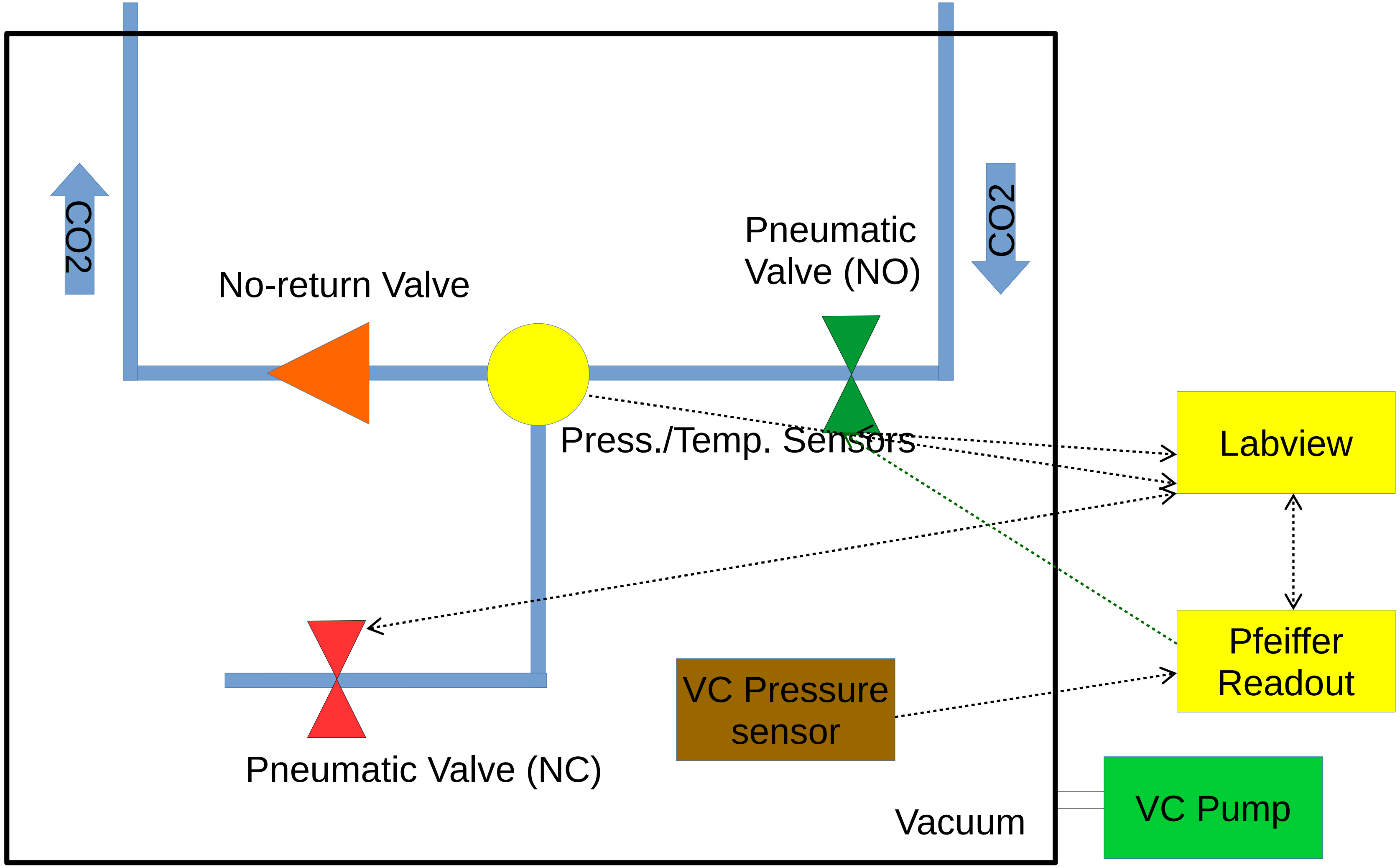


Safety system test

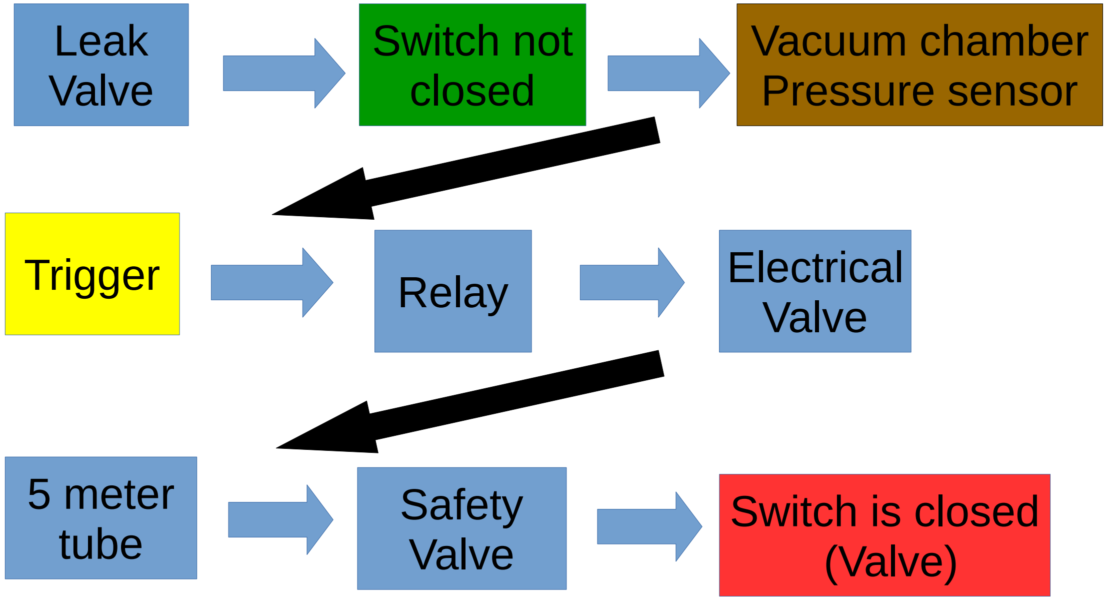
Volume 4.55 ml

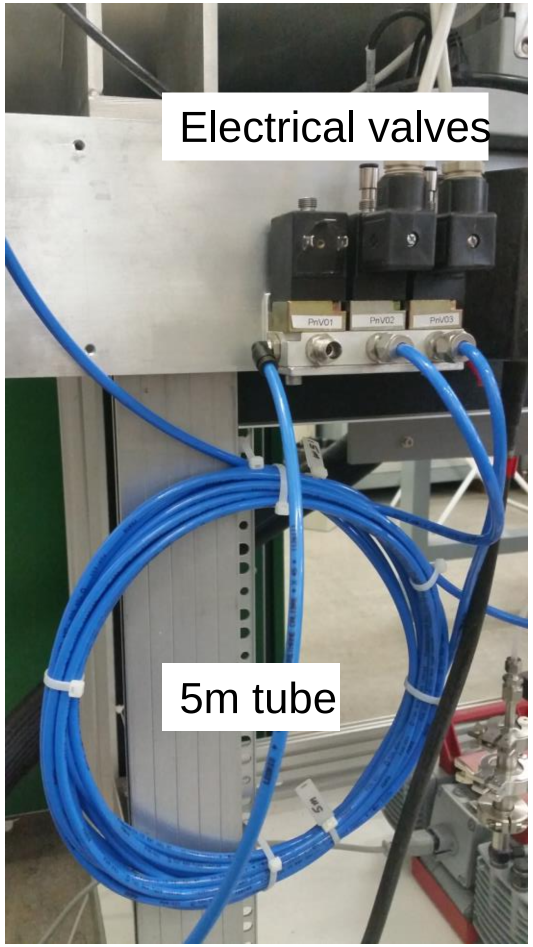


Safety system test

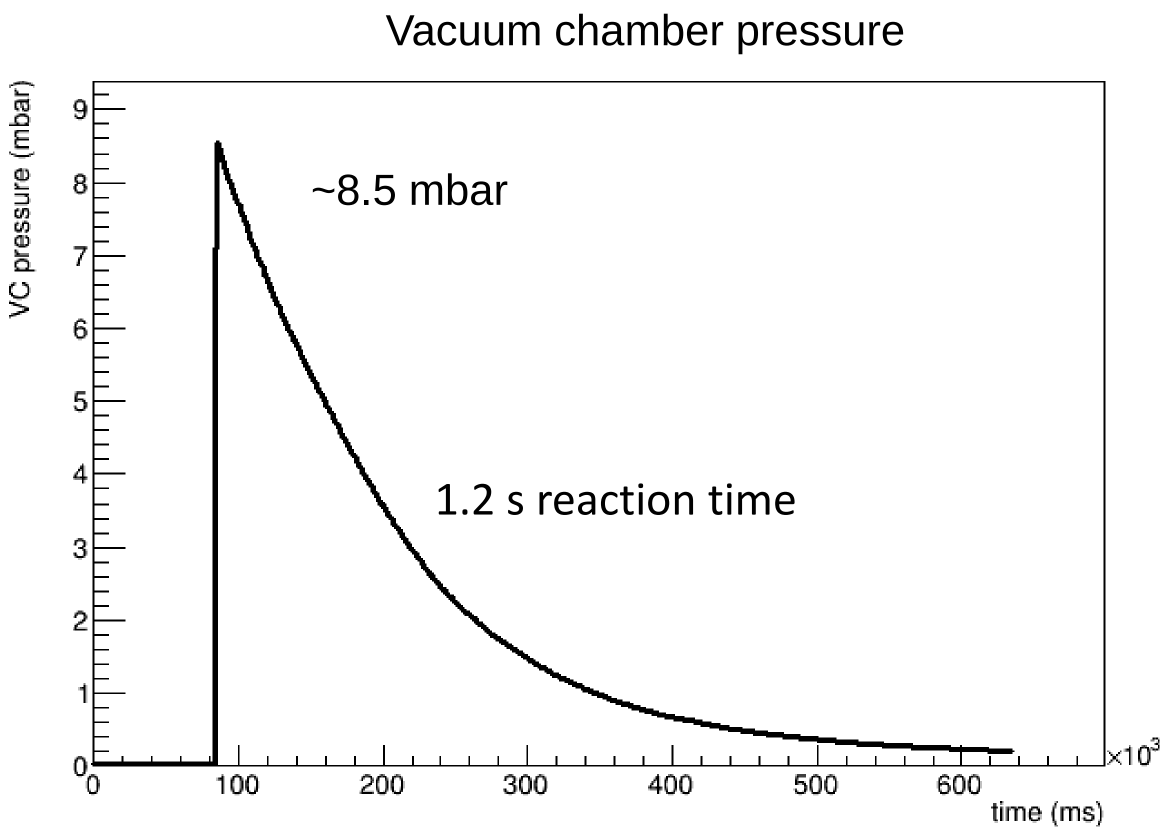


Activation chain



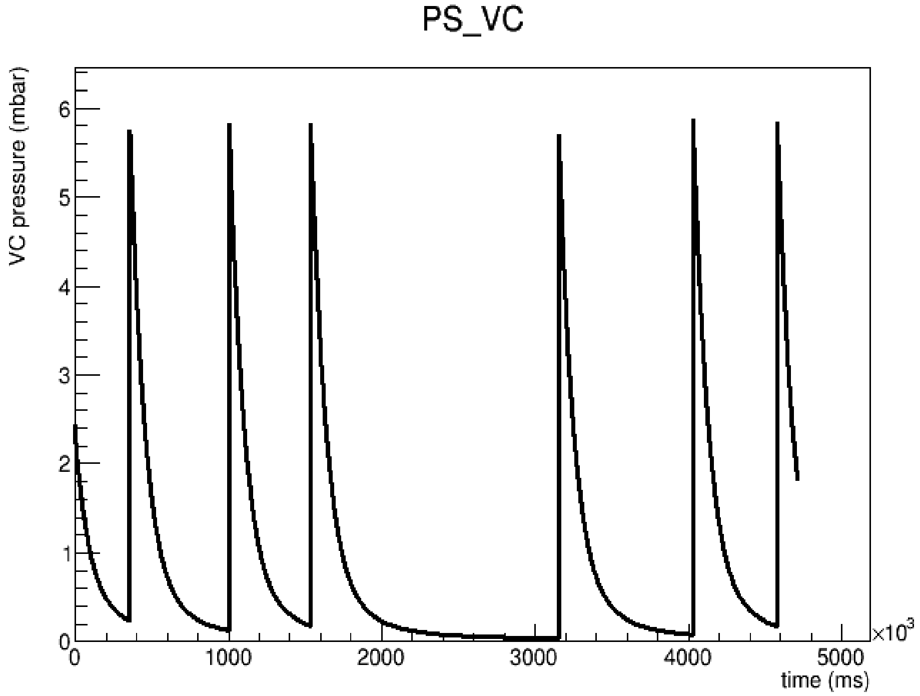


Safety system test (Labview)

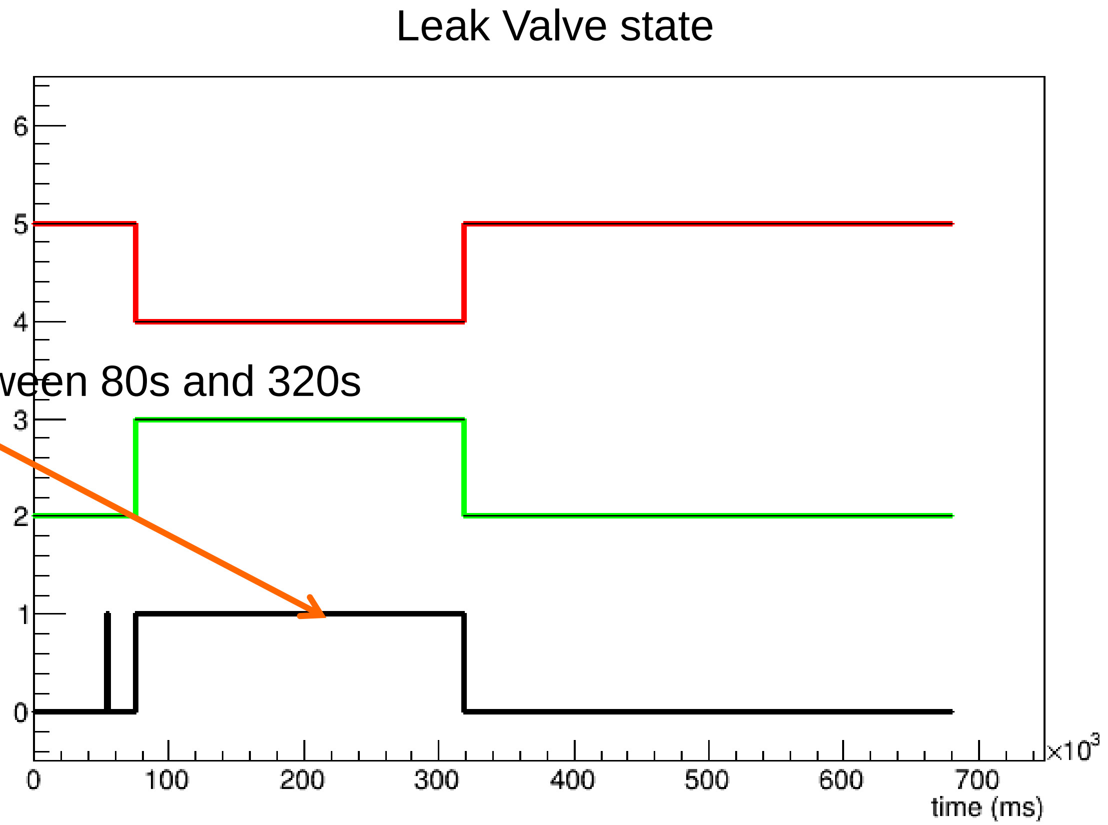


Safety system test (Pfeiffer)

- The Pfeiffer readout can be used to trigger the pneumatic valve (faster)
- Trigger set to 1 mbar threshold
- TRACI: -15C
- Maximum pressure: ~5.8mbar
- Faster reaction time (433ms)

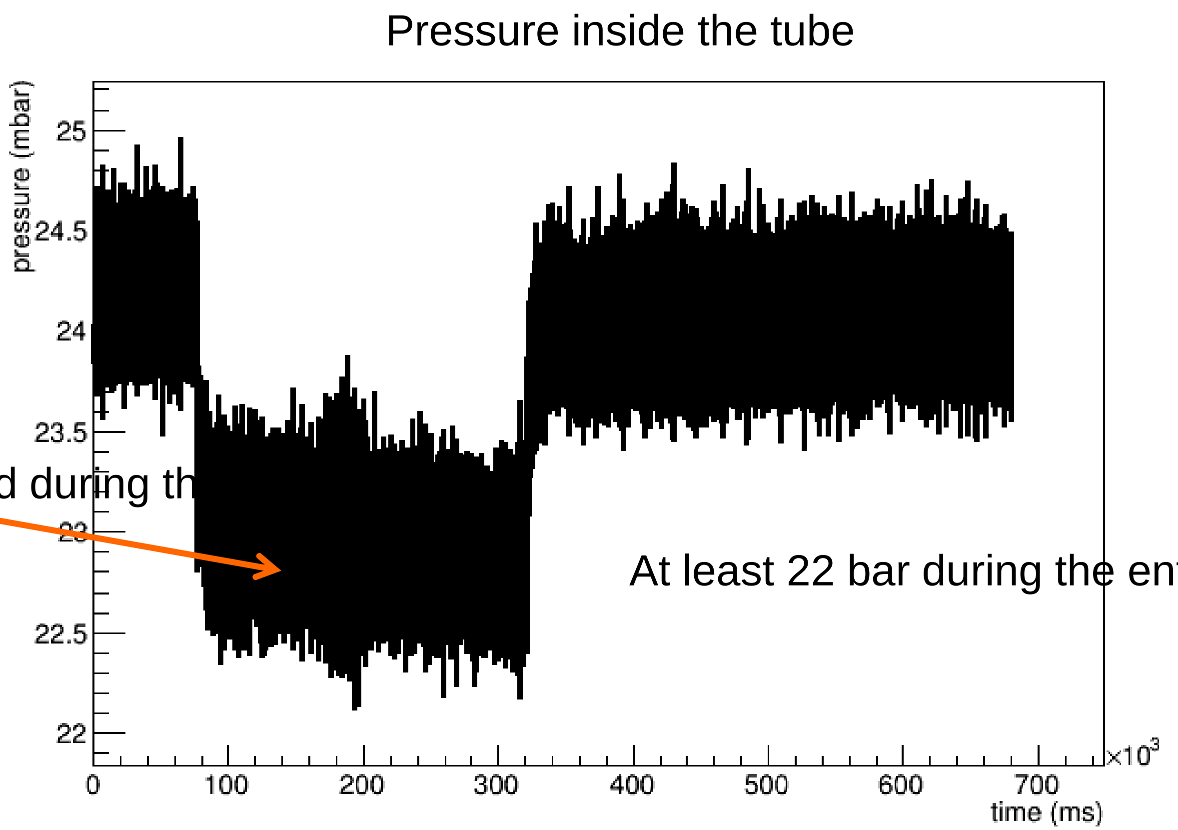


Safety system failure test



Leak valve open between 80s and 320s

Safety system failure test

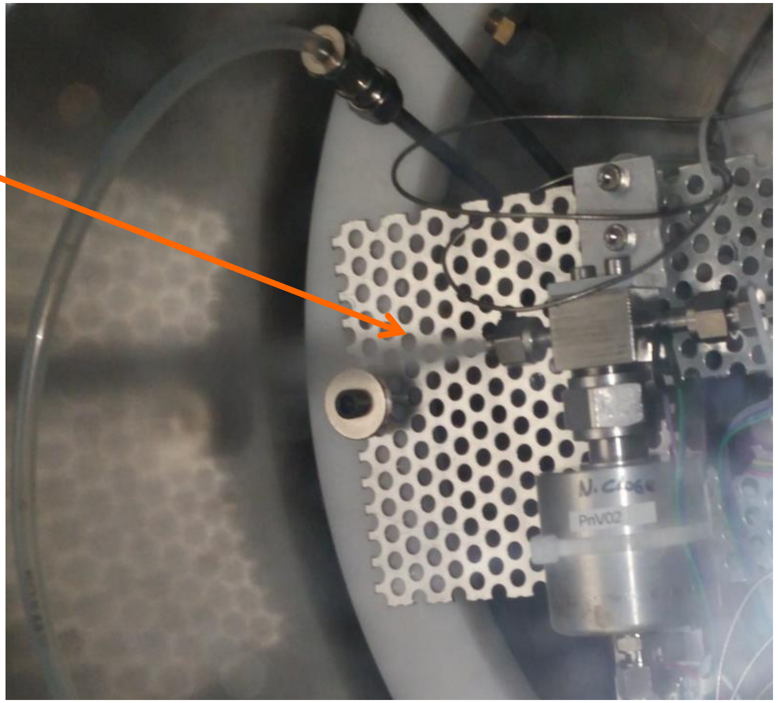


Pressure dropped during th

At least 22 bar during the entire test

Safety system failure test

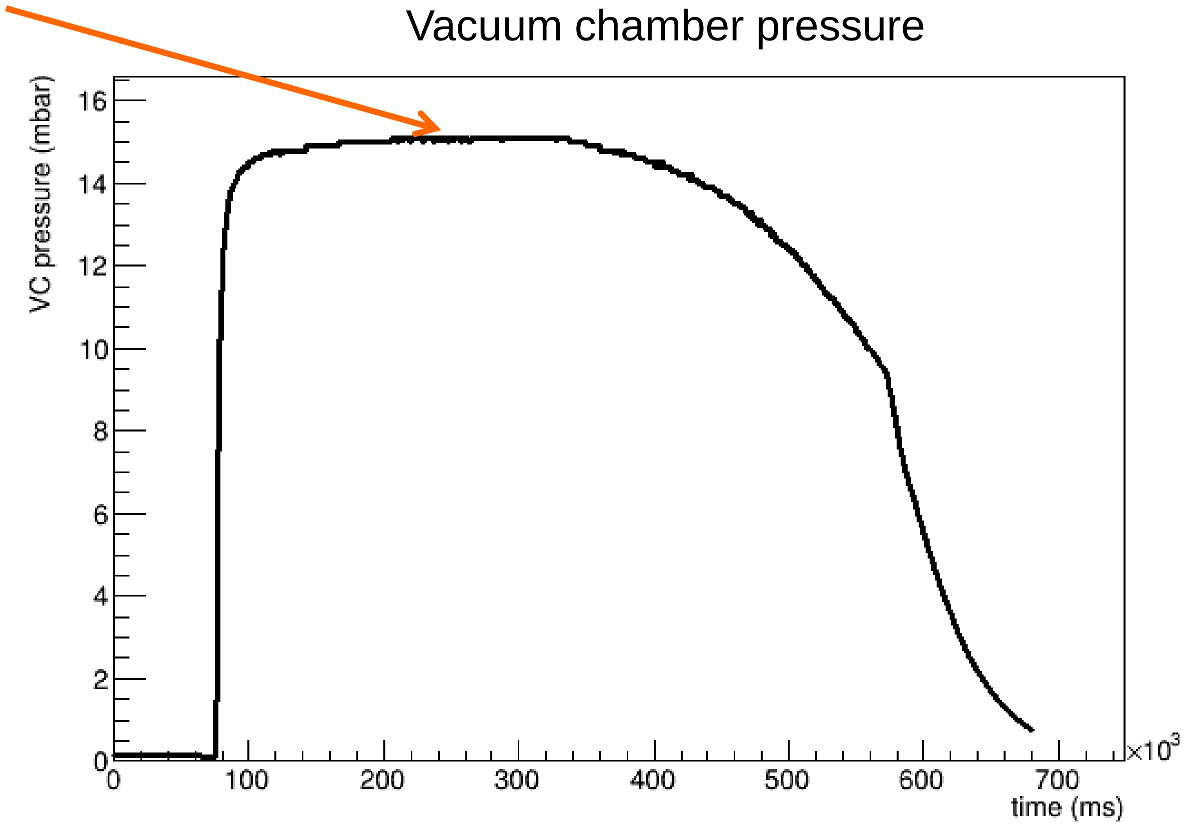
CO2 Leak



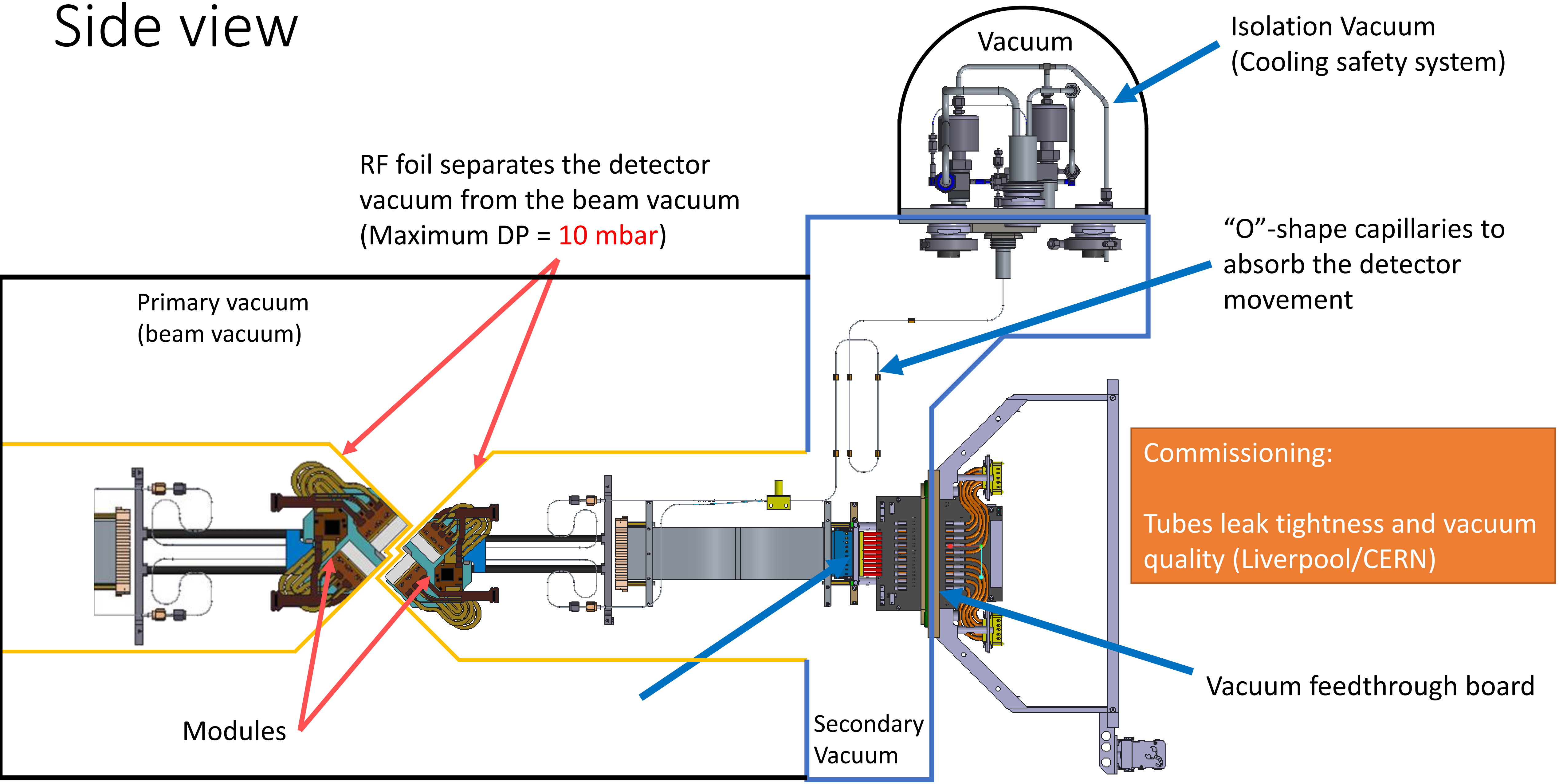
The leak was not continuous

Safety system failure test

Dry ice formation inside
the tubes greatly reduce the leak



Side view

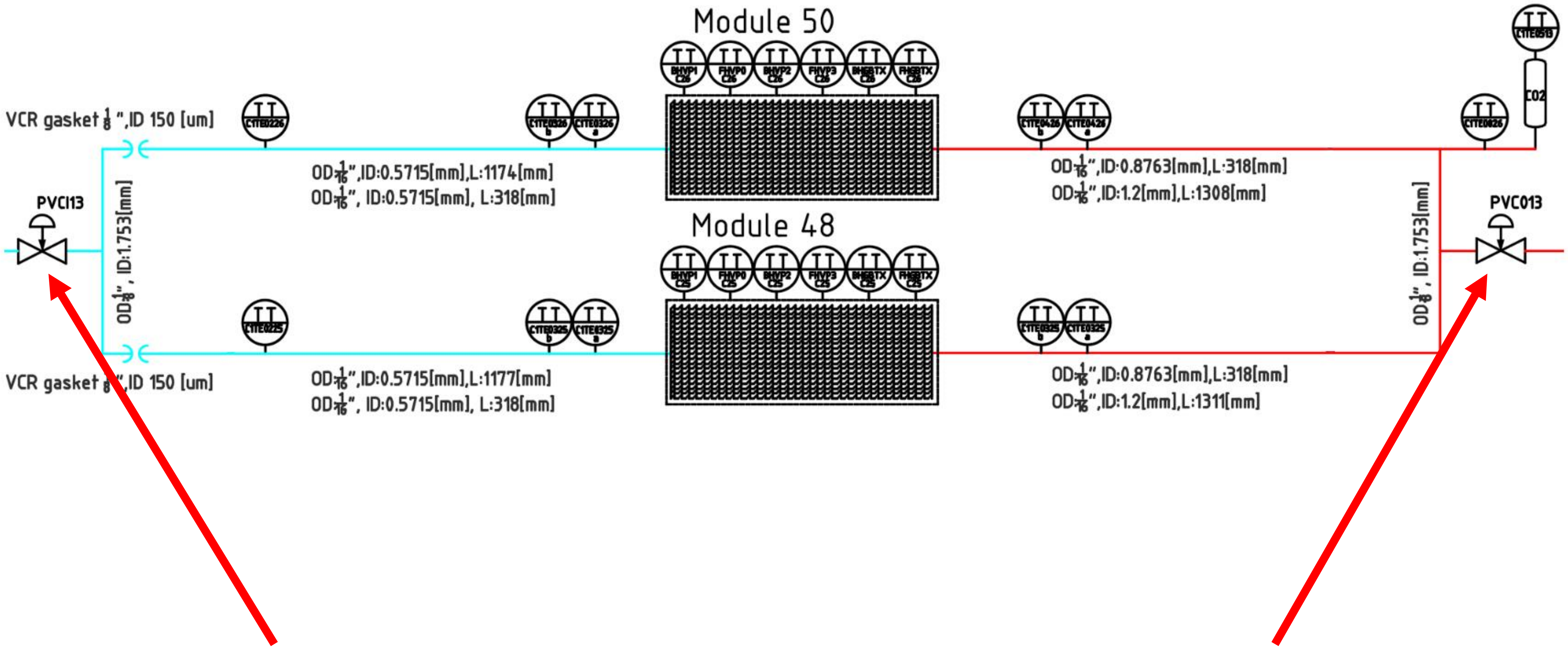


*Most of the cables are not in the drawing

VELO Upgrade Safety System Pneumatic Control

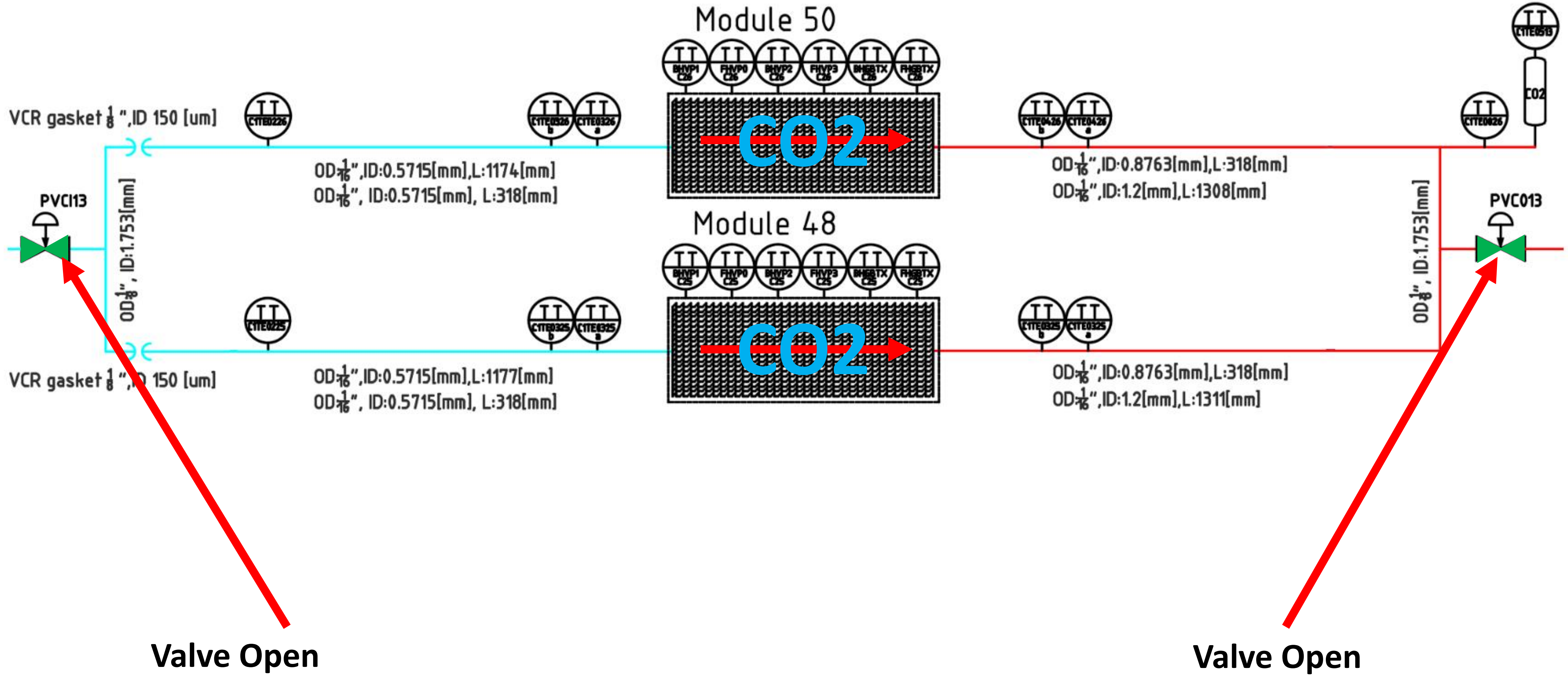
Wiktor Byczynski

Cooling Loop

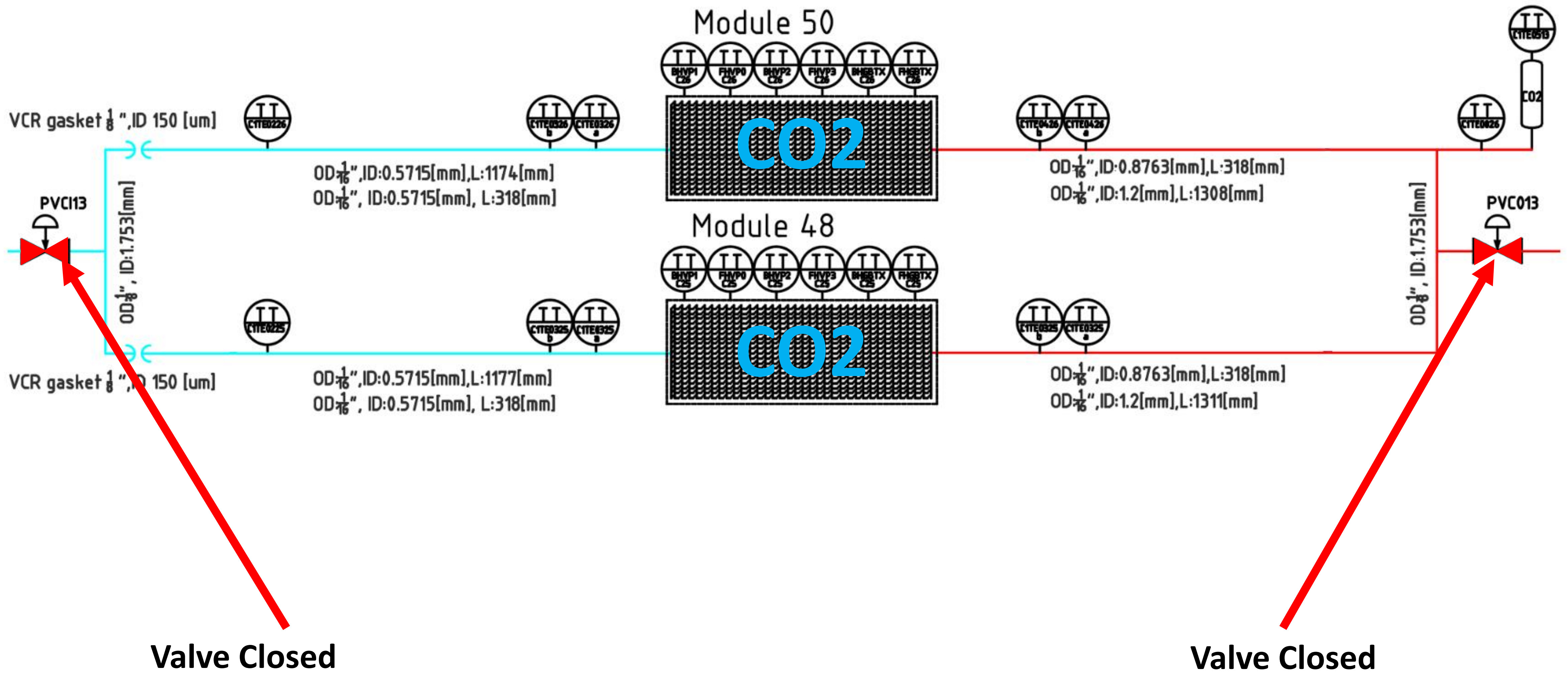


Safety system is controlling CO2 Flow through the modules using two Pneumatic Valves

Cooling Loop – Cooling ON, CO2 flowing



Cooling Loop – Cooling OFF, CO2 not flowing



Valve control – Cooling loop

Pilot control electrovalve	Control Pneumatic valve	CO2 shut off valve
		

VOFC-L-M52-M-G14-F19

- Switching Time ON **26 [ms]**
- Switching Time OFF **22 [ms]**

FESTO VL/O-3-½

- Switching Time ON **17 [ms]**
- Switching Time OFF **30 [ms]**

6LV-HBBW4-C

- Switching Time ON **?? [ms]**
- Switching Time OFF **?? [ms]**

Valve control – Bypass loop

Pilot control electrovalve

VOFC-L-M52-M-G14-F19

- Switching Time ON **26 [ms]**
- Switching Time OFF **22 [ms]**

Safety Valve control Pneumatic valve

FESTO VL/O-3-¼

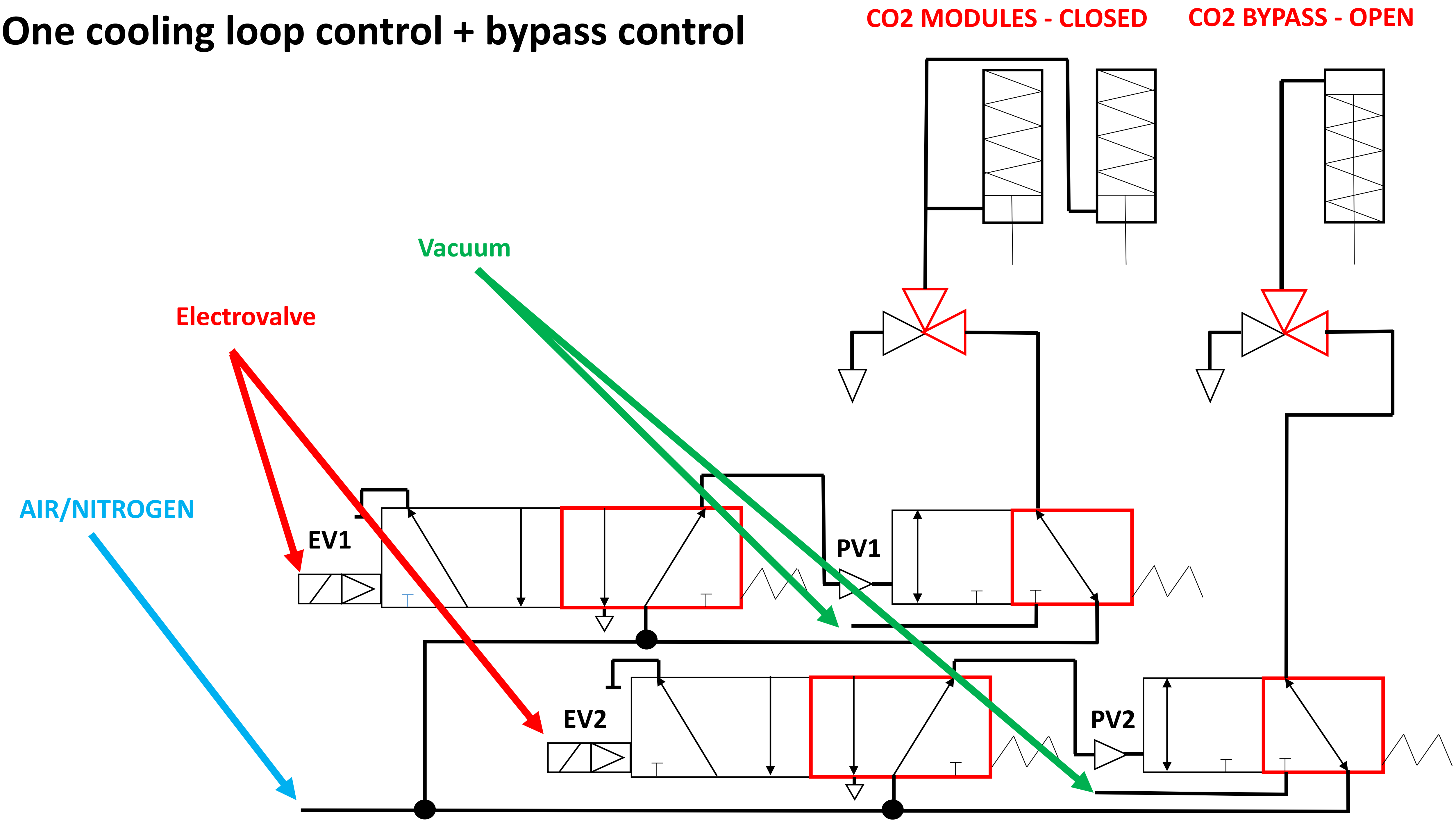
- Switching Time ON **8 [ms]**
- Switching Time OFF **30 [ms]**

CO2 shut off valve

6LV-HBBW4-0

- Switching Time ON **?? [ms]**
- Switching Time OFF **?? [ms]**

One cooling loop control + bypass control



State Table

Electrovalve	Air/Nitrogen	Vacuum	Modules Valve	Bypass Valve
0	0	0	0	1
0	0	1	0	1
0	1	0	0	1
0	1	1	0	1
1	0	0	0	1
1	0	1	0	1
1	1	0	1	0
1	1	1	1	0

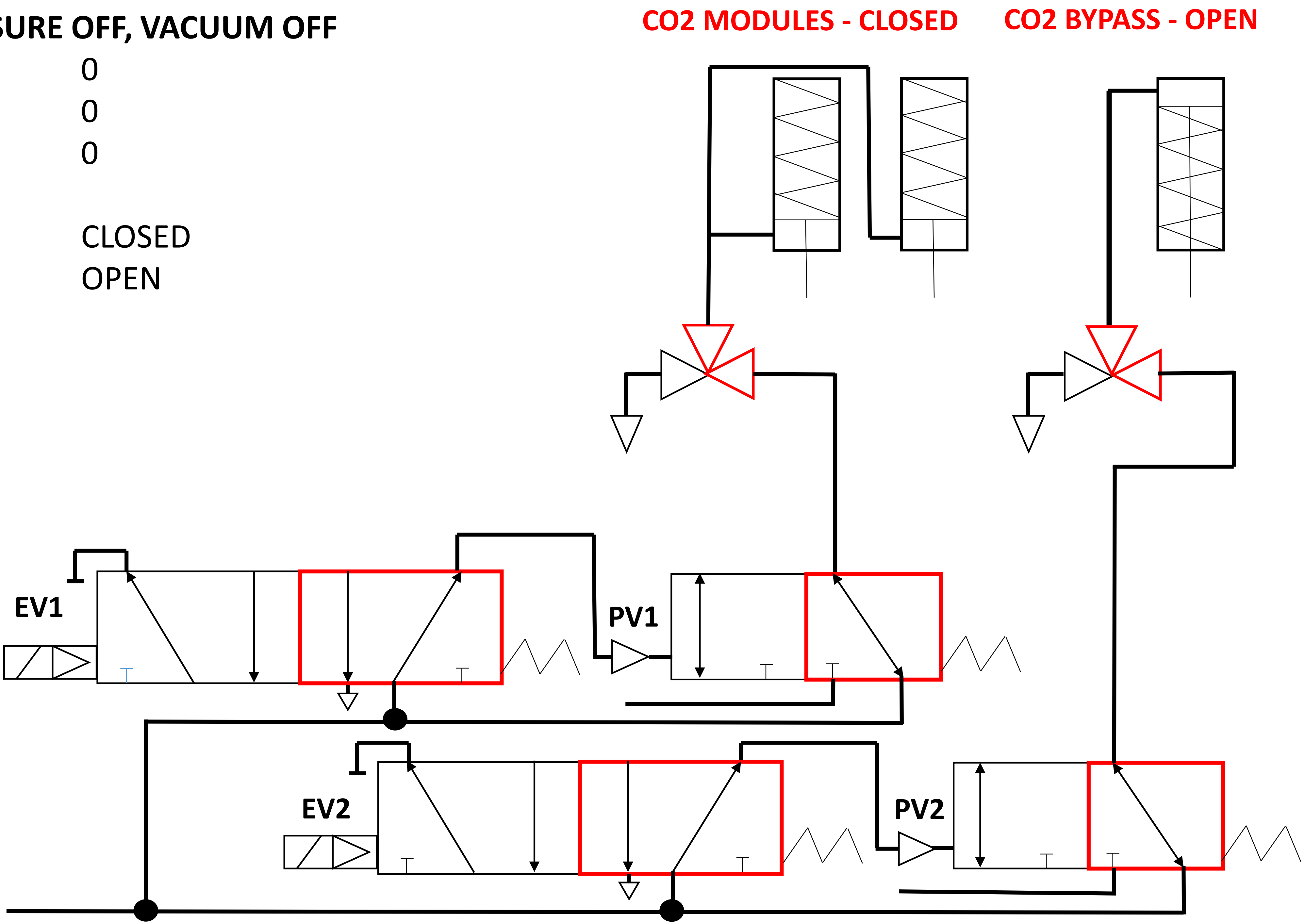
Input variables

Output variables

COOLING OFF, PRESSURE OFF, VACUUM OFF

- ELECTROVALVE: 0
- AIR/NITROGENE: 0
- VACUUM: 0

- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN



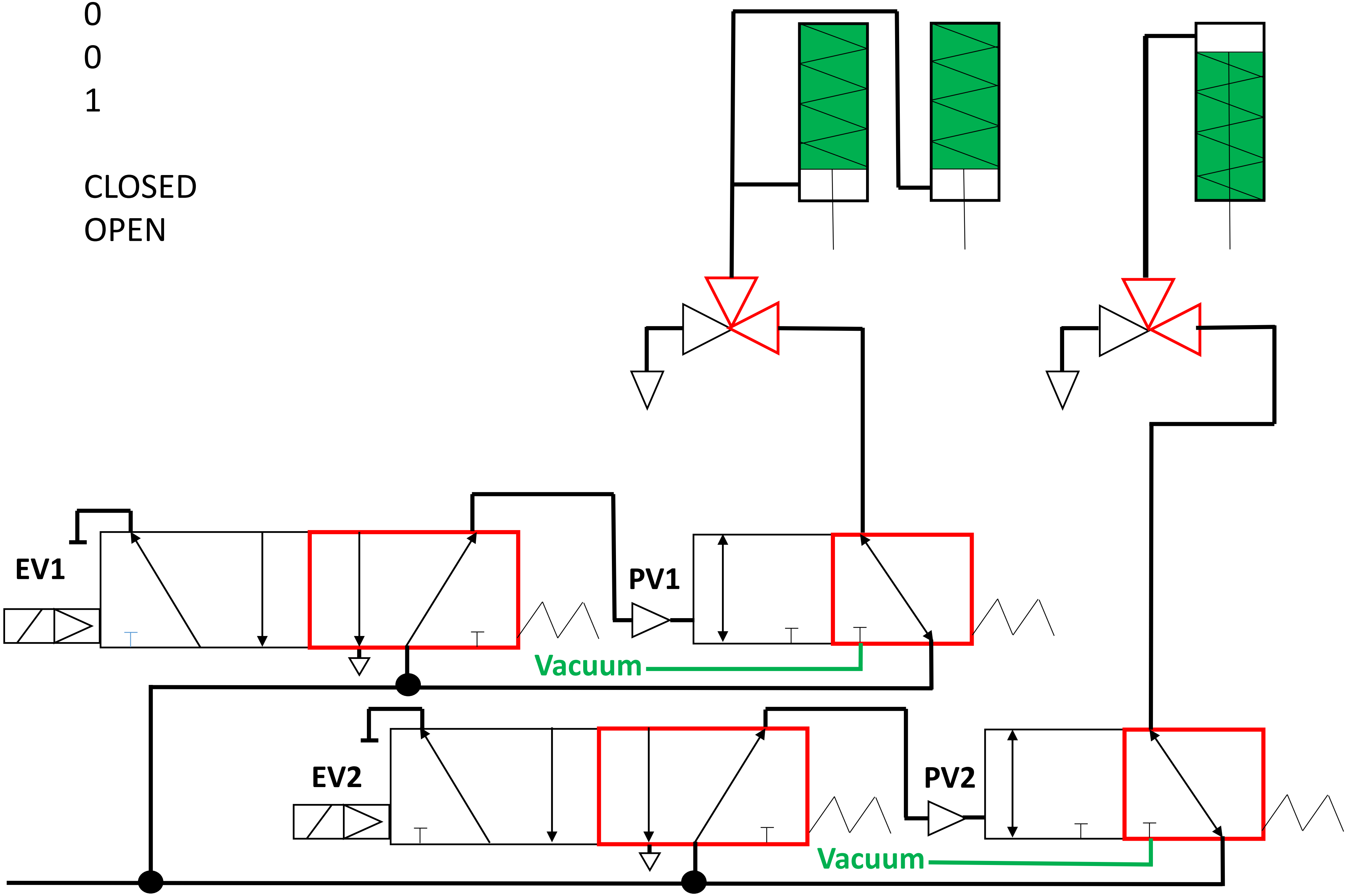
COOLING OFF, PRESSURE OFF, VACUUM ON

- ELECTROVALVE: 0
- AIR/NITROGENE: 0
- VACUUM: 1

- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN

CO2 MODULES - CLOSED

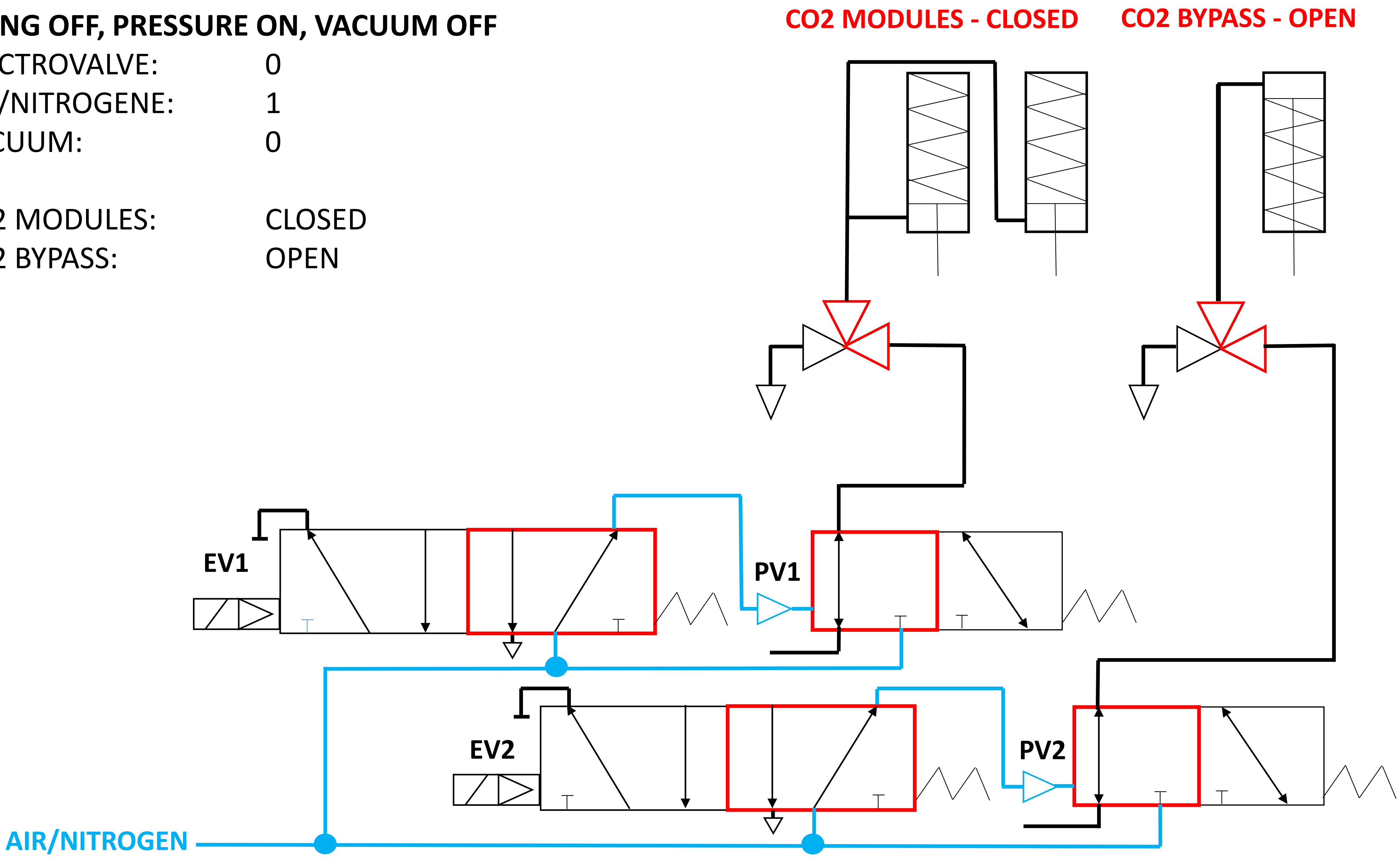
CO2 BYPASS - OPEN



COOLING OFF, PRESSURE ON, VACUUM OFF

- ELECTROVALVE: 0
- AIR/NITROGENE: 1
- VACUUM: 0

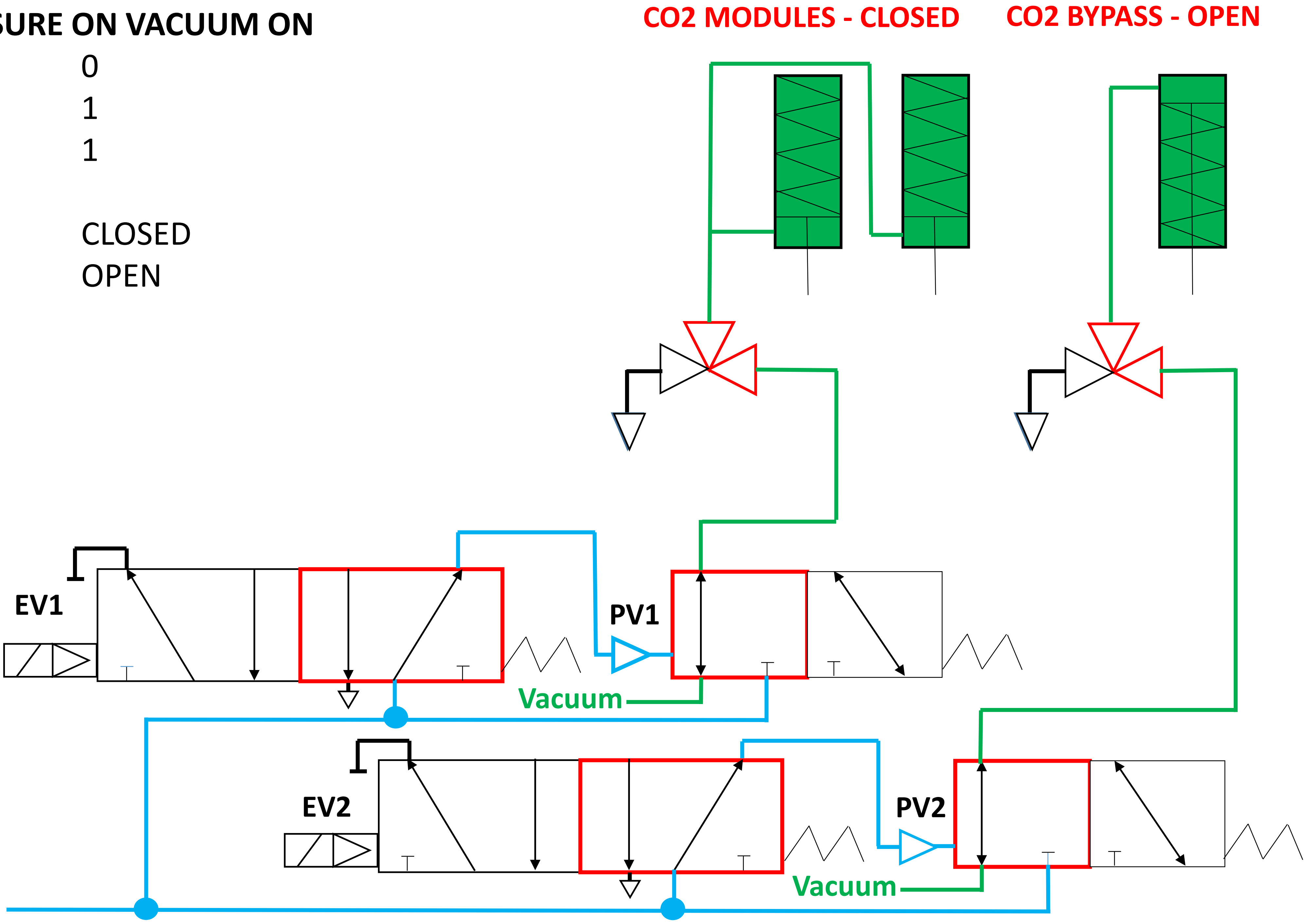
- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN



COOLING OFF, PRESSURE ON VACUUM ON

- ELECTROVALVE: 0
- AIR/NITROGENE: 1
- VACUUM: 1

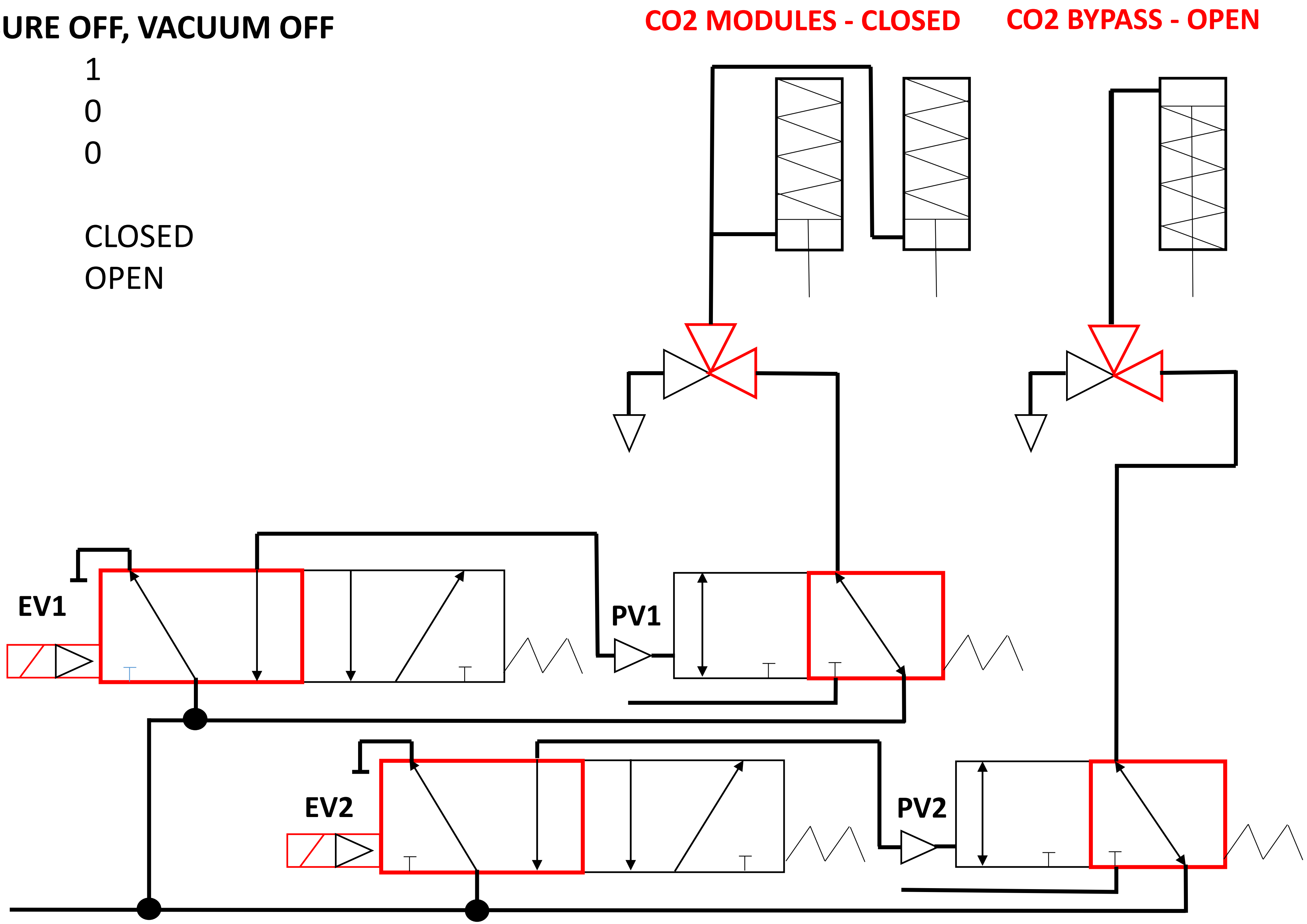
- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN



COOLING ON, PRESSURE OFF, VACUUM OFF

- ELECTROVALVE: 1
- AIR/NITROGENE: 0
- VACUUM: 0

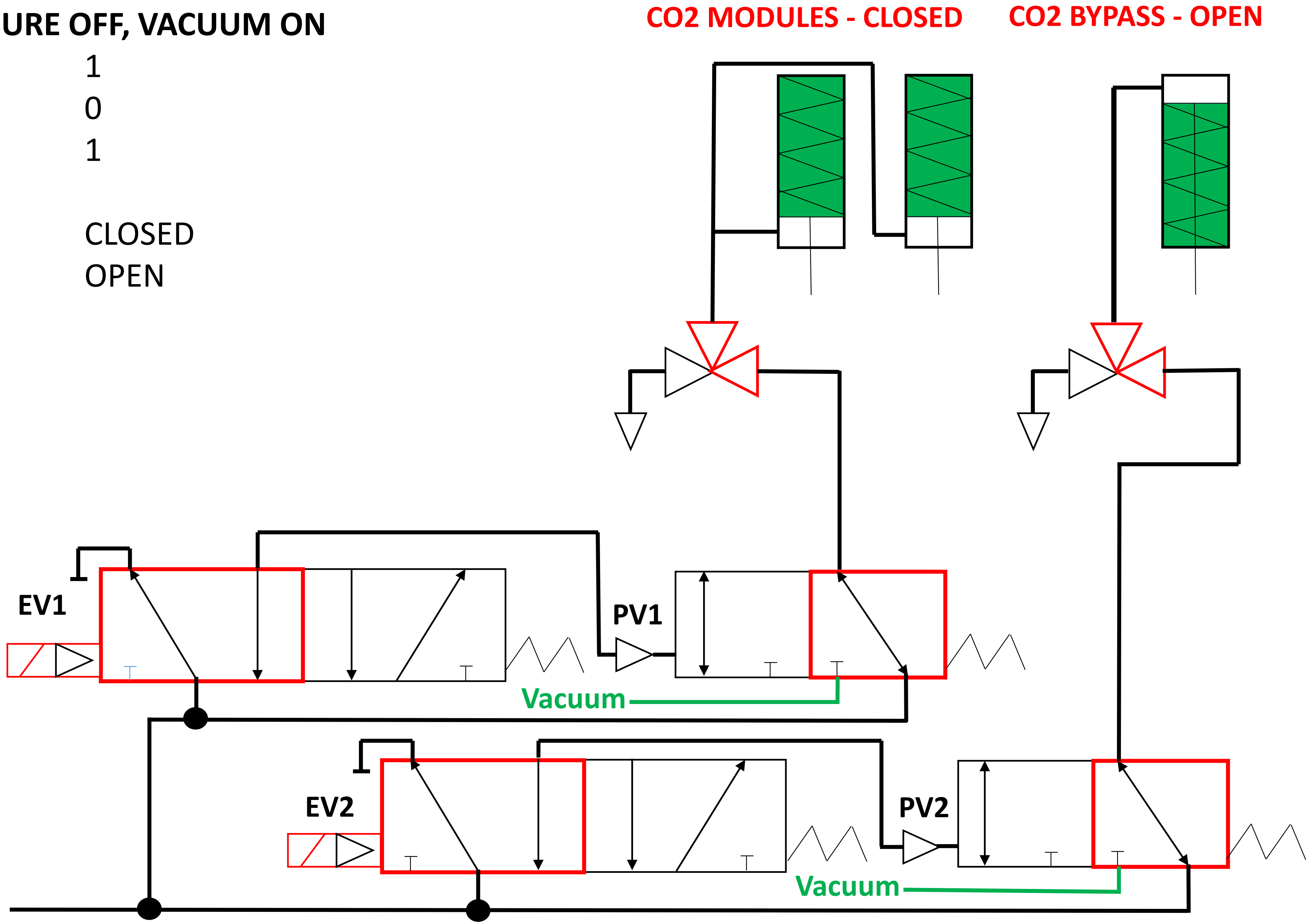
- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN



COOLING ON, PRESSURE OFF, VACUUM ON

- ELECTROVALVE: 1
- AIR/NITROGENE: 0
- VACUUM: 1

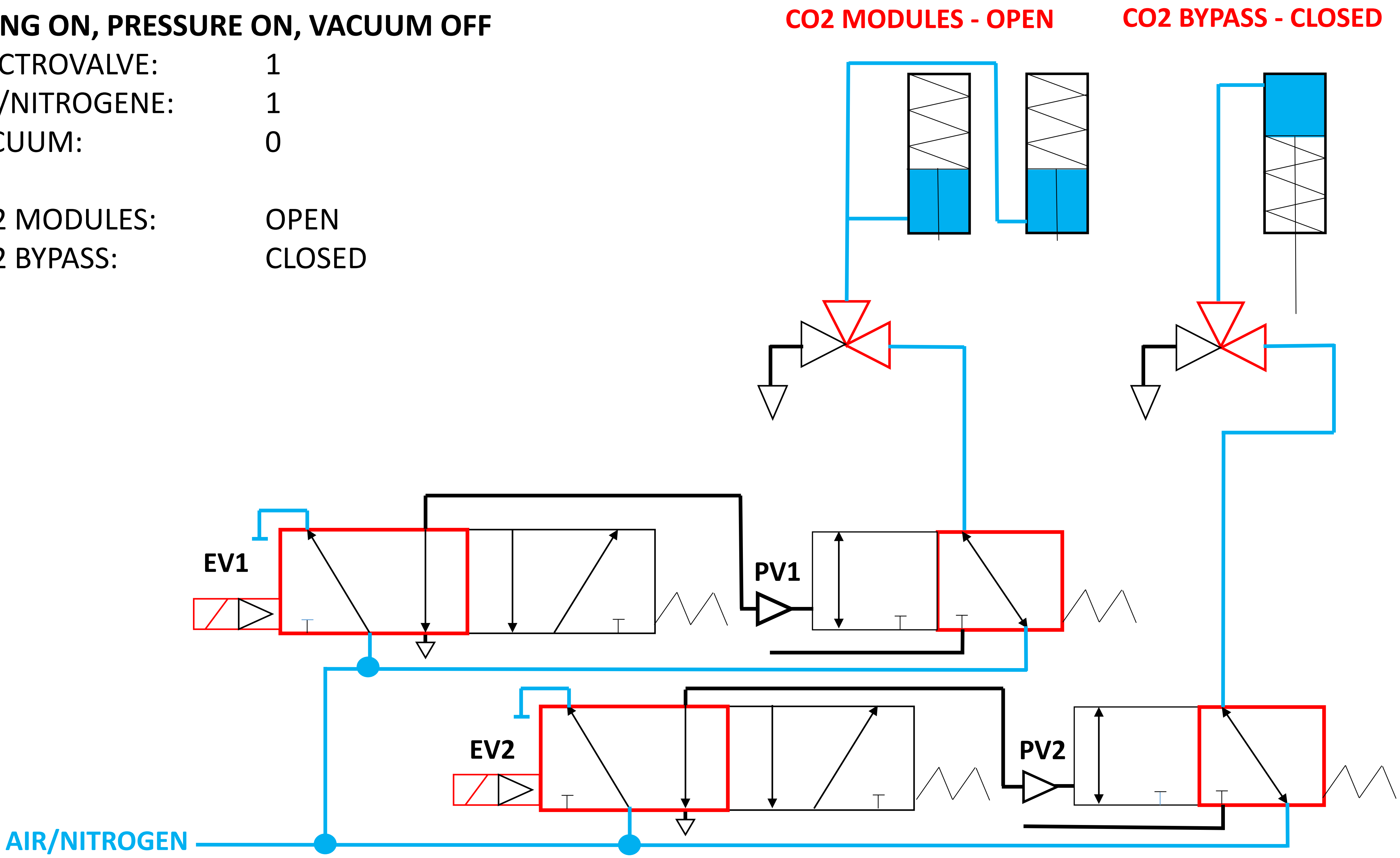
- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN



COOLING ON, PRESSURE ON, VACUUM OFF

- ELECTROVALVE: 1
- AIR/NITROGENE: 1
- VACUUM: 0

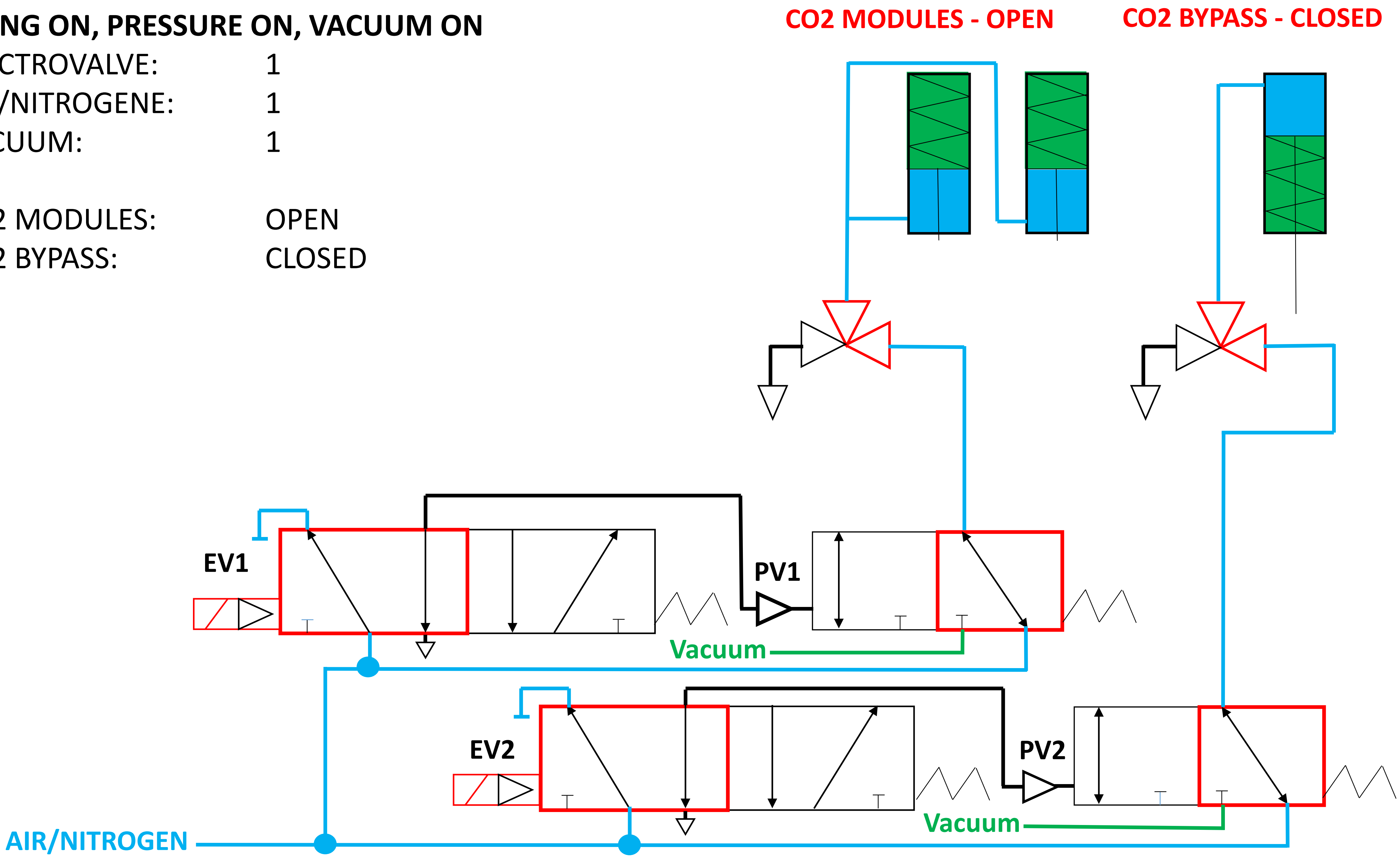
- CO2 MODULES: OPEN
- CO2 BYPASS: CLOSED



COOLING ON, PRESSURE ON, VACUUM ON

- ELECTROVALVE: 1
- AIR/NITROGENE: 1
- VACUUM: 1

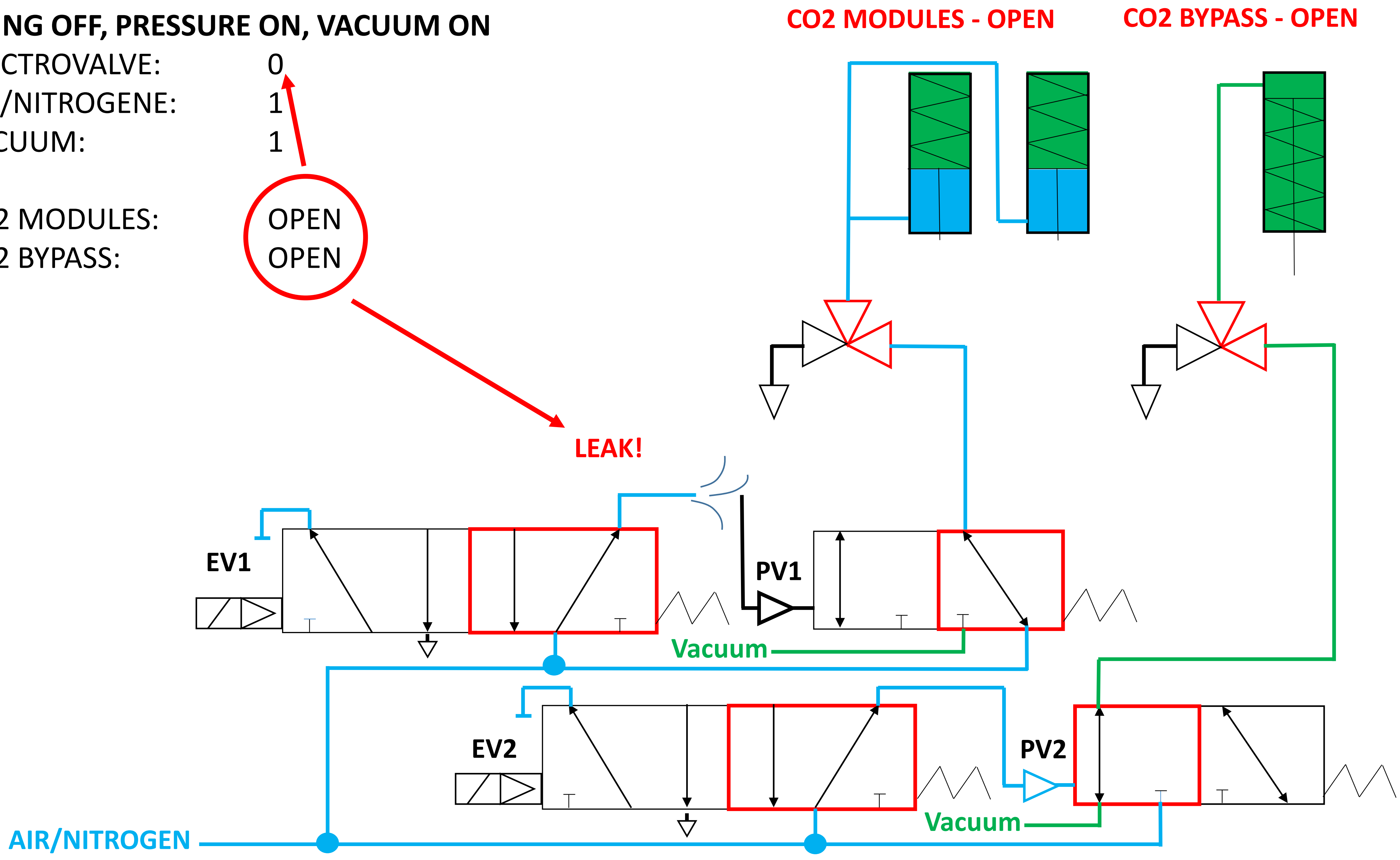
- CO2 MODULES: OPEN
- CO2 BYPASS: CLOSED



COOLING OFF, PRESSURE ON, VACUUM ON

- ELECTROVALVE: 0
- AIR/NITROGENE: 1
- VACUUM: 1

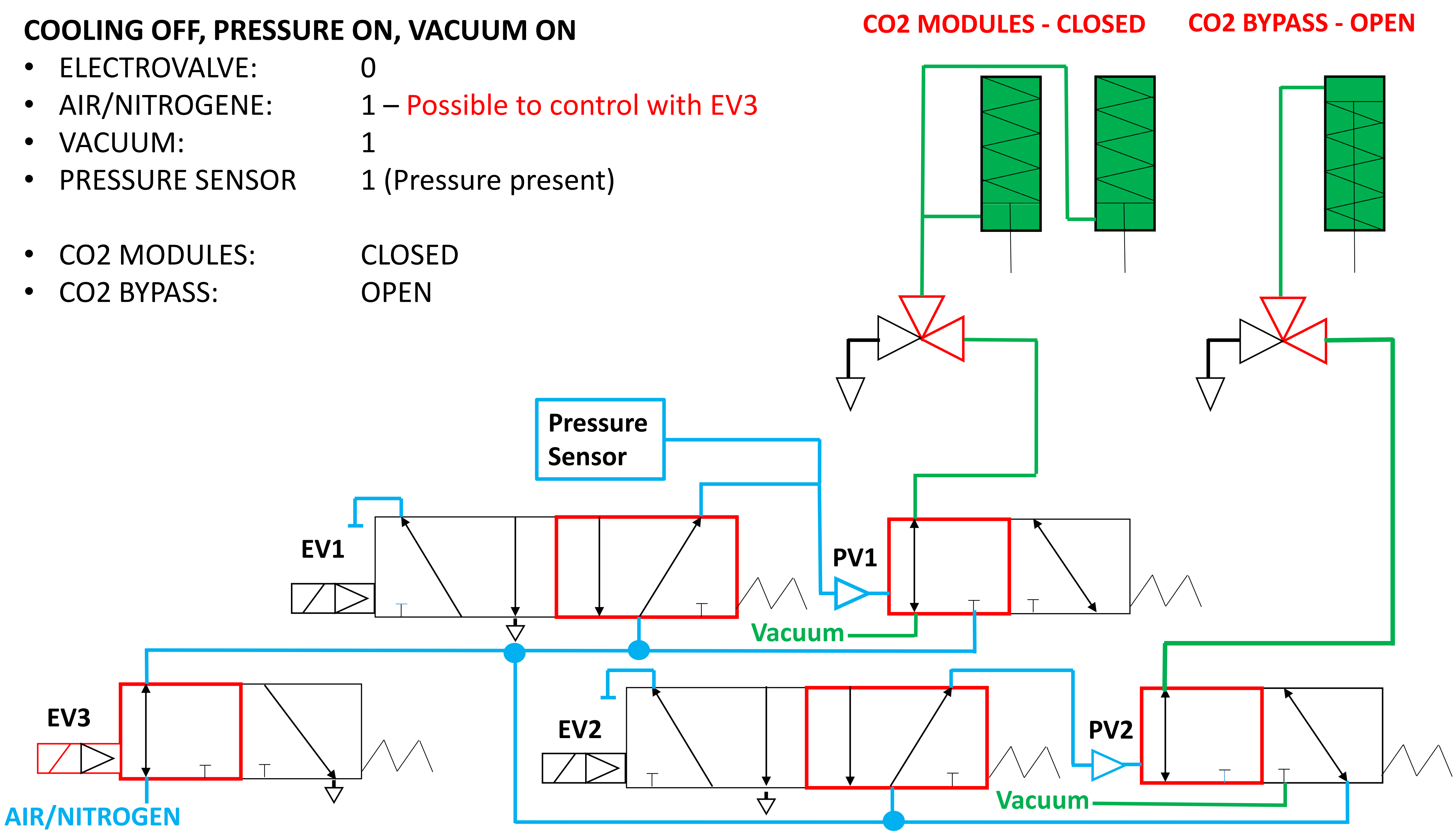
- CO2 MODULES: OPEN
- CO2 BYPASS: OPEN



COOLING OFF, PRESSURE ON, VACUUM ON

- ELECTROVALVE: 0
- AIR/NITROGENE: 1 – Possible to control with EV3
- VACUUM: 1
- PRESSURE SENSOR 1 (Pressure present)

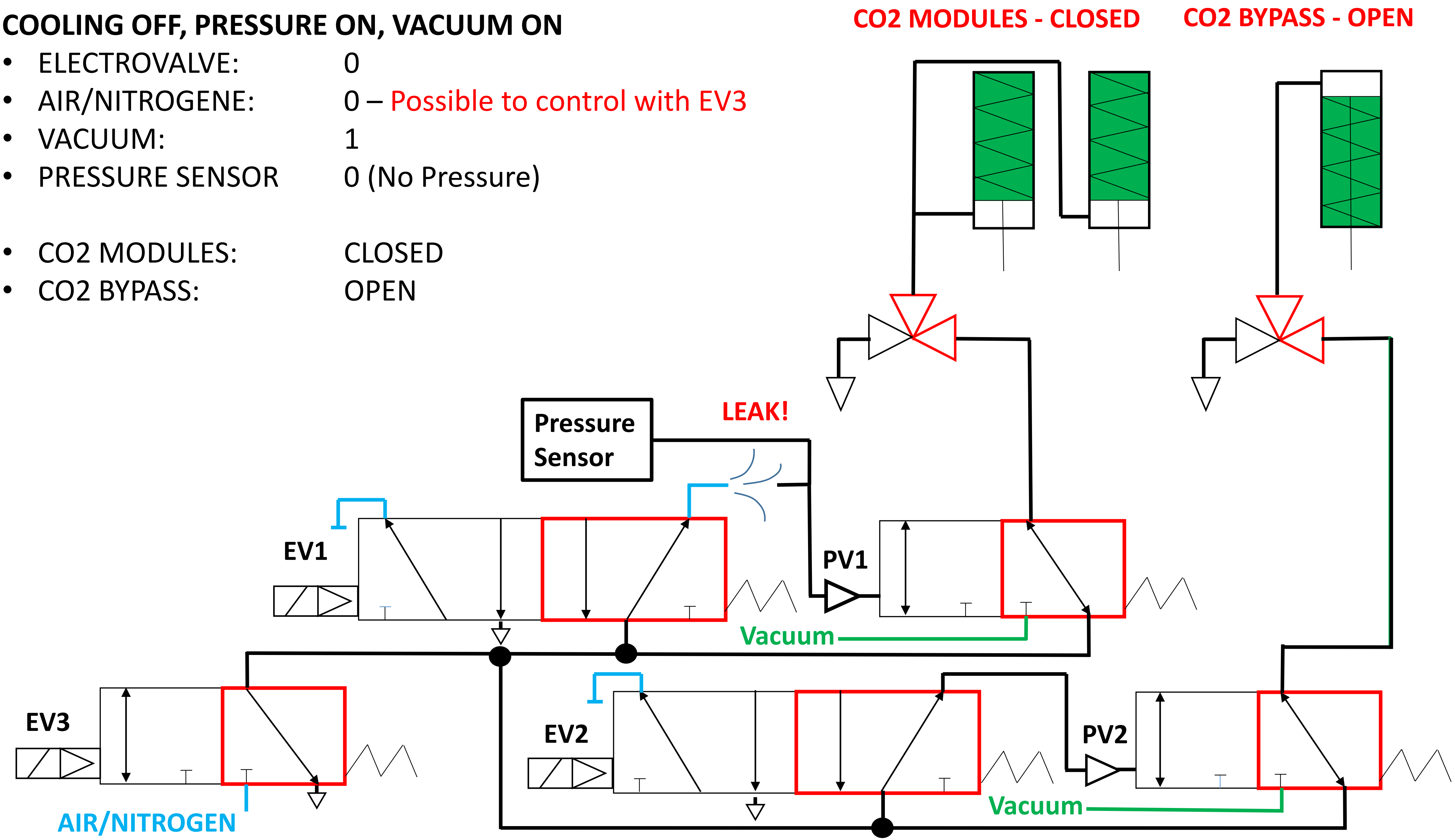
- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN



COOLING OFF, PRESSURE ON, VACUUM ON

- ELECTROVALVE: 0
- AIR/NITROGENE: 0 – Possible to control with EV3
- VACUUM: 1
- PRESSURE SENSOR 0 (No Pressure)

- CO2 MODULES: CLOSED
- CO2 BYPASS: OPEN



State Table – Normal Operation

Electrovalve	Air/Nitrogen	Vacuum	PV1 pilot pressure expected status	Modules Valve	Bypass Valve
0	0	0	0	0	1
0	0	1	0	0	1
0	1	0	1	0	1
0	1	1	1	0	1
1	0	0	0	0	1
1	0	1	0	0	1
1	1	0	0	1	0
1	1	1	0	1	0

Input variables

Output variables

State Table – PV1 pilot pressure LEAK

Electrovalve	Air/Nitrogen	Vacuum	PV1 pilot pressure expected status	PV1 pilot pressure status	Modules Valve	Bypass Valve
0	0	0	0	1	0	1
0	0	1	0	1	0	1
0	1	0	**1**	**0**	**1**	**0**
0	1	1	**1**	**0**	**1**	**0**
1	0	0	0	1	0	1
1	0	1	0	1	0	1
1	1	0	0	1	1	0
1	1	1	0	1	1	0

Input variables (green)

Output variables (blue)

COOLING OFF, BUT CO_2 is flowing!

State Table – PV1 pilot pressure LEAK

Electrovalve	Air /Nitrogen	Vacuum	PV1 pilot pressure expected status “a”	PV1 pilot pressure Status ‘b’	EV3 XNOR a,b	Modules Valve	Bypass Valve
0	0	0	0	1	0	0	1
0	0	1	0	1	0	0	1
0	1	0	1	0	0	0	1
0	1	1	1	0	0	0	1
1	0	0	0	1	0	0	1
1	0	1	0	1	0	0	1
1	1	0	0	1	0	0	1
1	1	1	0	1	0	0	1

Input variables (green)

Output variables (blue)

CO_2 is not flowing!

Summary

- Pilot control line protection (extra hardware?)
- EV3 – to check if it will not restrict the system.
- When system is empty and pressurized for the first time - check if Swagelok valves will not open (for short period of time) before Valve PV1,PV2 changes state to OPEN.

  If yes – necessary to change position of the manual valve. Pipe will be initially filled with AIR/NITROGEN and when valves PV1,PV2 changes to OPEN volume will be pumped by vacuum pump.
- Finale reaction time have to be tested

Update on the settings for the new pressure switch

- Optimal settings for the pressure switches that were requested:

	ΔP Threshold	OK State	Behaviour
OS412A	+2 mbar	Closed	NOK (Opens) on Beam overpressure (> 2 mbar)
OS412B	**-3 mbar**	Open	NOK (Closes) on Detector overpressure (**> 3 mbar**)
OS413A	+10 mbar	Closed	NOK (Opens) on Beam overpressure (> 10 mbar)
OS413B	-10 mbar	Open	NOK (Closes) on Detector overpressure (> 10 mbar)
OS415	**-5 mbar**	**Open**	**NOK (Closes) on Detector overpressure (> 5 mbar)**

Table 1. Differential Pressure Switch Characteristics

- However, refused because the vacuum system itself is not originally intended for UHV use and therefore had to be modified and also because the membrane switches are also not rated as radiation hard.
- Development and of new equipment envisaged throughout Run3 and envisaged to be installed and commissioned during LS3.

Update on pressure sensors (backup)

- <u>Tests with baratron</u>:
  - strongly discouraged by the vacuum group because they have only one spare per type (absolute and differential) dedicated for VELO. The same type is no longer available on the market due to obsolescence and therefore cannot be purchased. No solution before LS2 end.
  - Baratrons not used during the run, so idea how would the beam effect the gauge reading, despite decoupled pre-amp electronics making it radhard. These tests were never done.
  - MKS nevertheless does not recommend using gauges in radiation harsh areas and because the new Baratrons have active solid-state electronics onboard, an intensive test campaign should be performed before putting it in a safety system.
- <u>Increasing baratron sensitivity</u>:
  - hardware-wise, 615A has a time constant <25ms, while 617A <1ms. The controller (670B) allows setting the response up to 1ms. Default setting is 400ms to avoid noise. The controller allows making averaging for displayed/communicated values. The controller can be set to 400ms, 40ms or 1ms; 40ms still allows 4-9 averagings.
  - Josef agreed to test this setting during commissioning (end of September or in November), as long as we can confirm that the location of their baratrons is optimal at all for this use.

SIG-440-2020-09-24 14:53:00

SIGMA-NETICS

Quote Number:	**Q2009030SG02B**
Sales Person:	**Sean Gregory**
Valid until:	**12/31/2020**

2 North Corporate Drive, Riverdale, NJ 07457
Phone (973) 616-6900 | Fax (973) 616-6910
www.sigmanetics.com | sales@sigmanetics.com

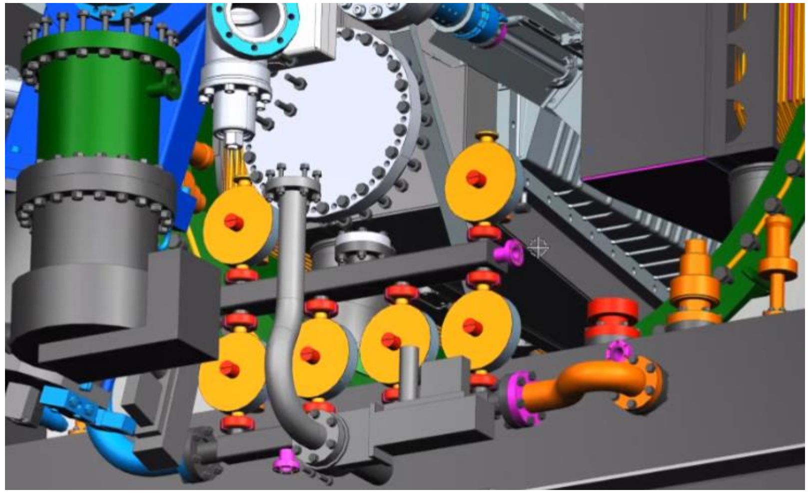
Quote Details

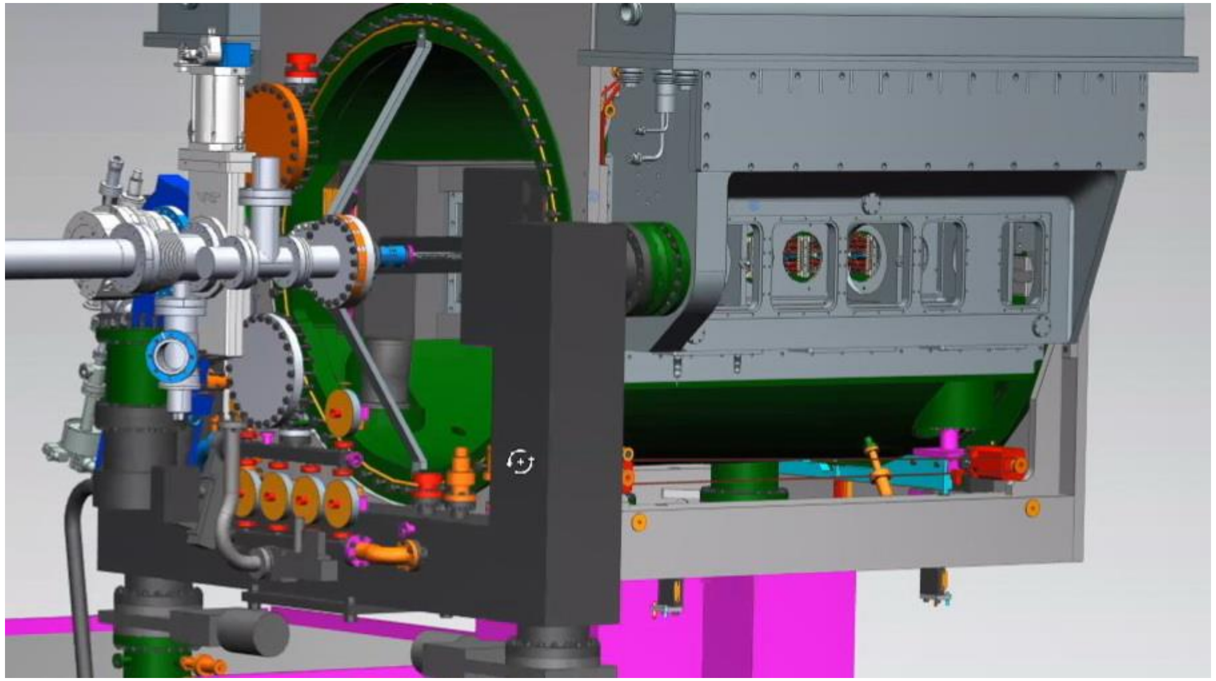
Line	Part Number	Description	Quantity	Unit Price	Set up Fee
1	Q200903SG02-001	SST64X-RT Pressure Transducer - 1000mBar	1-9	$1500.00	
			10-19	$1385.00	
			20-49	$1225.00	
			50-99	$1180.00	
			100+	$1150.00	

Notes
Pressure Range: 0-1000 mBar
Pressure Reference: Absolute
Pressure Port: AS4395E04 (7/16-20 UNF Male)
Output: 3mV/V analog output
Supply: 10 Vdc
Electrical Termination: PTIH-10-6P
Wetted Material: 15-5 PH SS or 316L SS
CTR: -54C to +121C
Radiation: Up to 10Mrad TID

Lead Time: Test Unit by Nov 20, 2020. Product units 10 Weeks ARO
Shipping not included: Approximate Shipping Weight 1lb

CFD analysis (backup)





- Josef recommended contacting the CFD group about performing the atmospheric CFD calculation of the propagation time between the modules/micro-channels and the installed baratrons.
- Michele Battistin responded saying that their CFD tool is not adapted to evaluate this (would not trust the results) and suggest searching in literature some correlation that gives a propagation speed of a pressure wave in 900 mbar. Suggested to contact Jordan Minier (jordan.minier@cern.ch) in case some further help is needed with the calculation.