EP-DT
Detector Technologies

Gas Systems for

Large Particle Detector systems

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Outline

- Introduction
- Large Gas Systems: the example of the LHC experiments
- Gas systems description:
  - Construction
  - Building blocks
  - Controls software
  - Modules
- Gas systems performances:
  - Operation, maintenance, consolidations, upgrade, …
- Conclusions

Large Gas Systems: the LHC approach

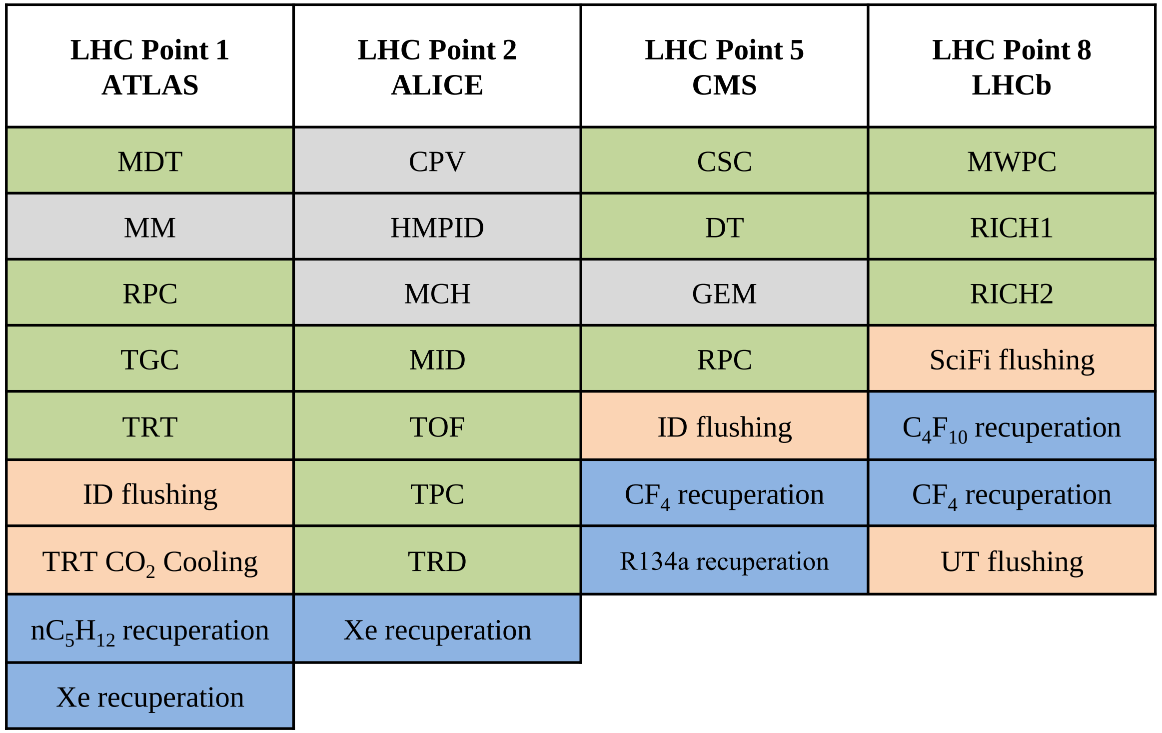
- The basic function of the gas system is to mix the different gas components in the appropriate proportion and to distribute the mixture to the individual chambers.

- 31 gas systems (about 300 racks) delivering the required mixture to the particle detectors of all LHC experiments.

- Gas mixture is the sensitive medium where the charge multiplication is producing the signal.

- Correct and stable mixture composition are basic requirements for good and stable long-term operation of all detectors.

5: single pass gas systems; 14: closed loop gas system;
5: detector flushing systems; 7: gas recuperation systems.



LHC Point 1 ATLAS	LHC Point 2 ALICE	LHC Point 5 CMS	LHC Point 8 LHCb
MDT	CPV	CSC	MWPC
MM	HMPID	DT	RICH1
RPC	MCH	GEM	RICH2
TGC	MID	RPC	SciFi flushing
TRT	TOF	ID flushing	C_4F_{10} recuperation
ID flushing	TPC	CF_4 recuperation	CF_4 recuperation
TRT CO_2 Cooling	TRD	R134a recuperation	UT flushing
nC_5H_{12} recuperation	Xe recuperation		
Xe recuperation			

Gas systems for LHC experiments

Gas systems extend from the surface building to service balcony on the experiment following a route few hundred meters long.

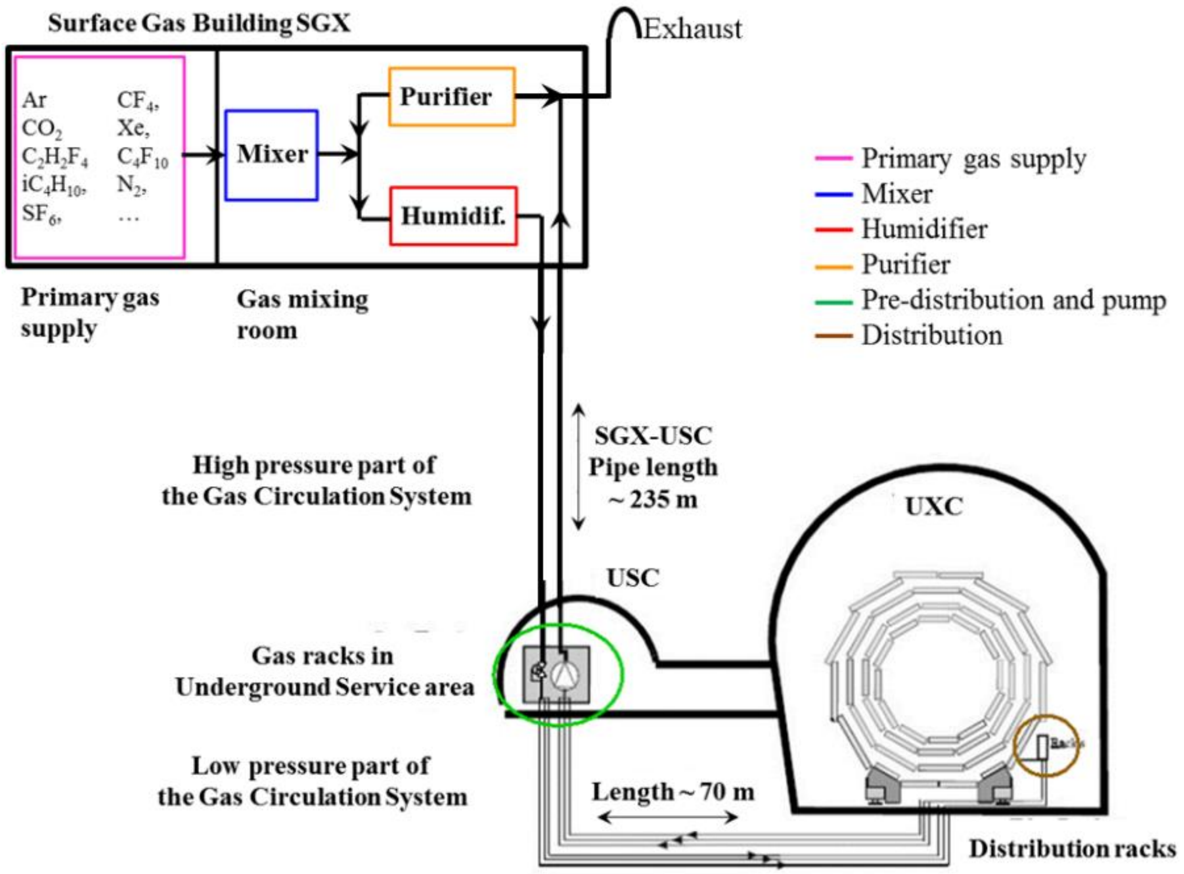
- Primary gas supply point is located in surface building
- Gas system distributed in three levels:
  - Surface (SG)
  - Gas Service room (USC)
  - experimental cavern (UXC)

Large detector volume (from m^3 to several 100 m^3) and use of expensive gas components:

→

The majority is operated in closed loop gas circulation with a recirculation fraction higher than 90-95 %.

- The gas systems were built according to a common standard allowing minimization of manpower and costs for maintenance and operation.



Gas systems for LHC experiments

Few numbers:

- Construction started in 2000
- Operational since 2005-2006
- 30 gas systems detectors at the LHC experiments
- 300 Universal Euroracks → x2 height of Eiffel Tower
- 60 PLCs
- 150 MFCs
- 4000 flow meters in distribution racks
- ~ 70 gas analyzers and 6 gas chromatographers
- Per gas system:
  - ~ 2-3 km pipes
  - > 1000 connectors and 500 welds
  - ~ 40 Pressure sensors
  - ~ 10 Regulation valves
  - < 0.1 l/day leak rate

Team: EP-DT Gas Systems project and BE-ICS

- **Reliability**
  - LHC experiments are operational 24/24 7/7
  - Gas systems must be available all time
- **Automation**
  - Large and complex infrastructure
  - Resources for operation
  - Repeatability of conditions.
- **Stability**
  - Detector performance are strictly related with stable conditions (mixture composition, pressures, flows, …)

Tour Eiffel: 324 m

LHC gas system racks: > 500 m

Requirements and Quality Assurance

Gas systems (as detectors) are subject to severe requirements on material & gas for safe detector operation:

- Mainly (if needed only) stainless steel pipe and components
- Need to validate the gas system components (ageing test setup)
- Documentation for QA and easy operation/maintenance follow up
- Monitoring of gas system operation
- Monitor of supply gases and mixture composition
- Evaluation of operational cost
- Flexible design to accommodate detector requirements/upgrades
- Careful evaluation of
  - resources for operation
  - resources for maintenance activity
  - Stability required
  - Balance requirements vs safety (as much as possible)

Gas system layouts: 1 - open mode

Basic gas system: Open mode operation

Gas mixture prepared and sent to the detector.

→ advantages: very simple to build and operate. No particular need of monitoring impurities.

→ disadvantage: mixture is vented after being used, i.e. potential source of high gas consumption and high emissions


GAS MIXER → DETECTOR → EXHAUST

High gas consumption for a large detector system of several m3 can implies quickly not sustainable costs:

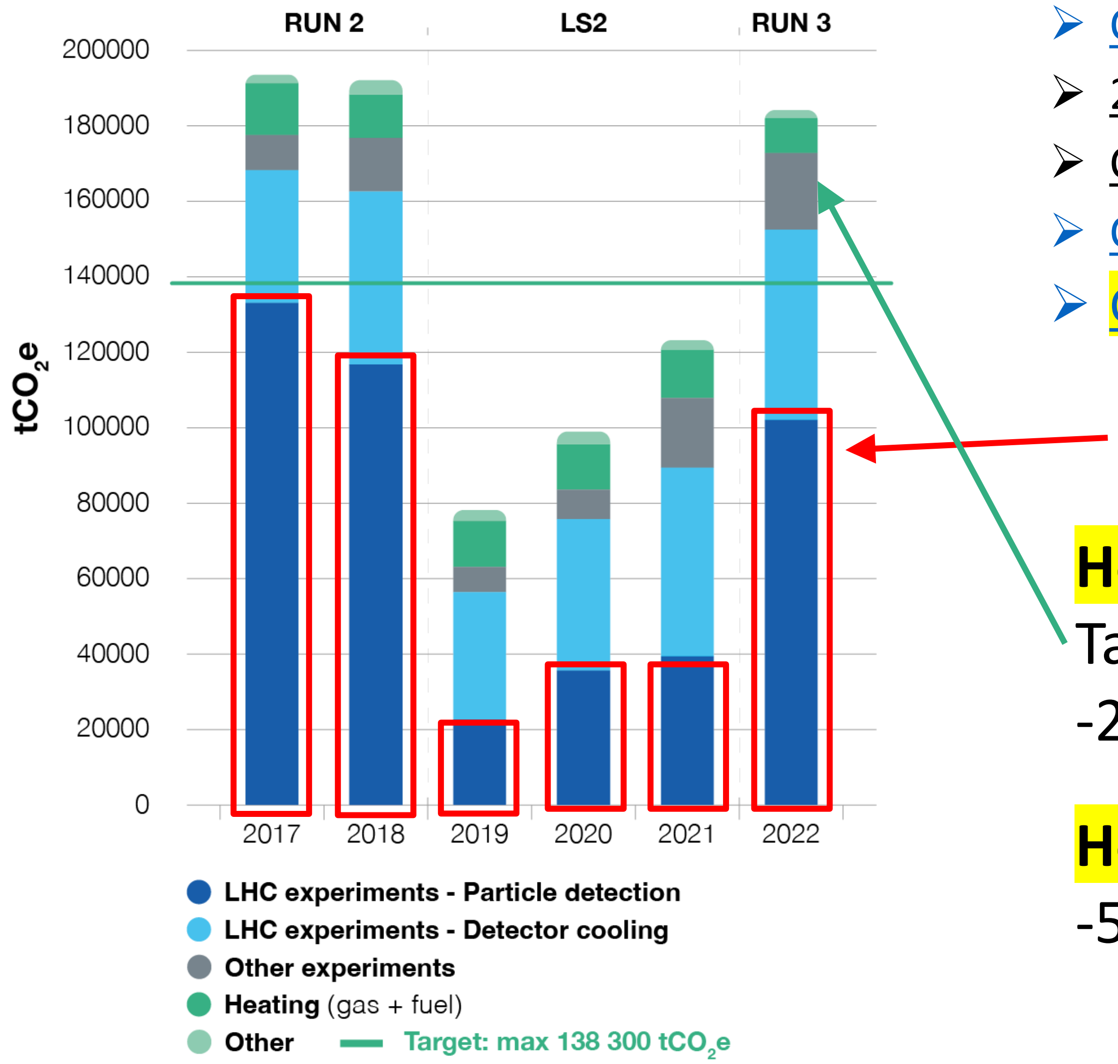
- Mixture cost can range from 1 CHF/m3 (Ar/CO2) to more than 100 CHF/m3 (Ar/CO2/CF4).
- RPC mixture is exactly in the middle (about 50 CHF/m3).
- Typical flow 10 m3/h for about 300 days/year

→ Gas cost can range from 72 kCHF (Ar/CO2) up to 7.2 MCHF for (Ar/CO2/CF4)

→ In addition, sometimes: use of greenhouse gases

→ Open mode cannot be the solution

F-gas emissions



- ➢ [CERN Environment Report 2019-2020]
- ➢ 2021: CERN's Year of Environmental Awareness.
- ➢ CERN Environment workshop: 12 and 13 October 2022
- ➢ [CERN Environment Report 2021-2022]
- ➢ [CERN and the Environment Town Hall (2024, Nov. 8th)]

Emissions from particle detection

Horizon 2025:

Target emission by end of Run3:
-28% wrt 2018 (end Run2)

Horizon 2030:

-50% wrt 2018 (end Run2)

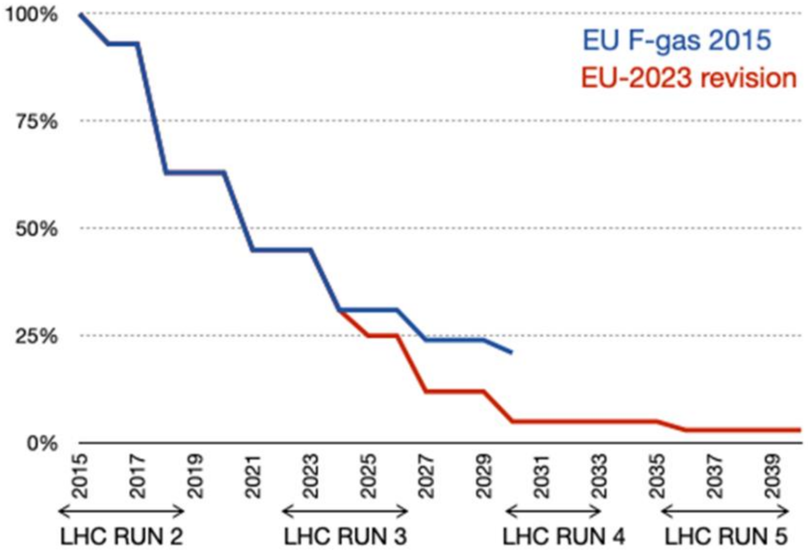
Greenhouse gas regulation

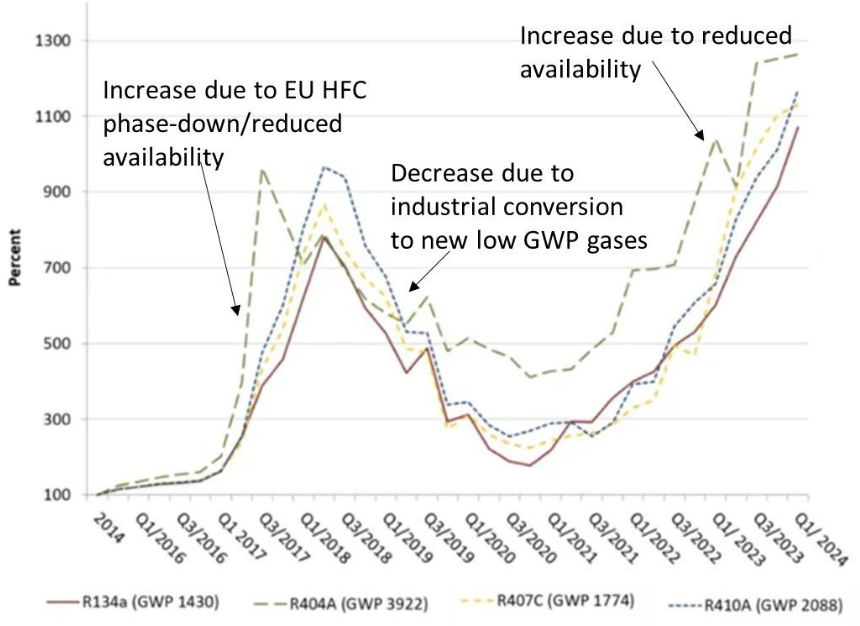
CERN has adopted an F-gas policy which is in line with the content of “F-gas regulations”

For reference, the key principles of EU517/2014 are:

- **Limiting the total amount** of the most important F-gases that can be sold from 2015 onwards. By 2030, it limits the use to 1/5 of 2014 sales
- **Banning the use of F-gases** in new equipment where less harmful alternatives are available
- **Preventing emissions of F-gases** from existing equipment by requiring checks, proper servicing and recovery of gases

The new EU Regulation (2023) calls for the total elimination of HFCs by 2050





Increase due to EU HFC phase-down/reduced availability

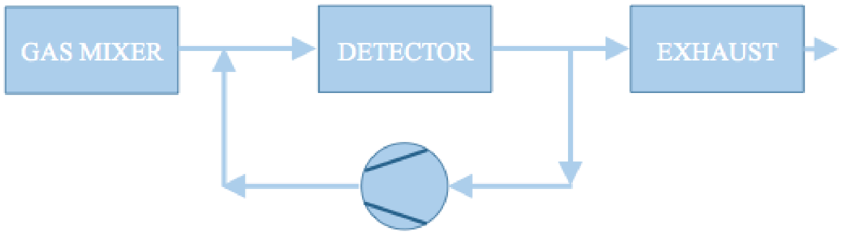
Decrease due to industrial conversion to new low GWP gases

Increase due to reduced availability

Also important to consider new regulations concerning PFAS

Gas system layouts: 2 – gas mixture recirculation

- All gas systems are designed to recirculate the gas mixture: average 90% gas recirculation → 90% reduction of consumption/emissions



Advantages:

- Reduction of gas consumption

Disadvantages:

- Complex systems

- Constant monitoring (hardware and mixture composition)

- Use of gas purifying techniques

- The remaining 10% is what we started to address from LS1. It is needed to compensate for:
  - Leaks at detector: 85 % (mainly ATLAS and CMS RPC systems)
  - 15% N_2 intake (CMS-CSC, LHCb-RICH1, LHCb-RICH2)

- Two remaining open mode systems upgraded to gas re-circulations from Run1 to Run2

  → *For both detector systems:* ***Original investment was totally paid back by gas cost saving during few years of operation***

- and laboratory setups

Gas Mixture Recirculation: LHCb-GEM example

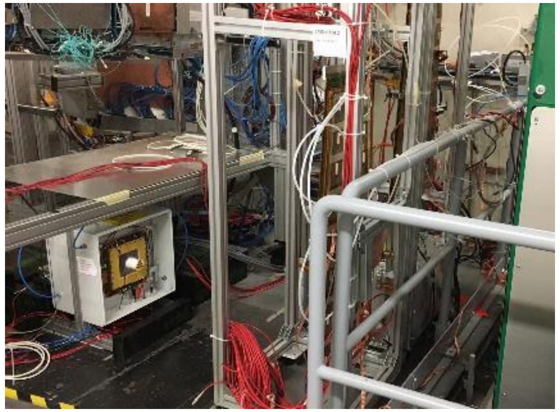
Mixture: **CF_4 40%**, Ar 45%, CO_2 15%
Detector volume: ~ 50 liters (but very high flow needed by the detector)
→ R&D for operation of large GEM detector systems with gas recirculation

From Run1 to Run2: 90% GHG reduction

2013: Development of small gas recirculation systems for R&D
Started test in lab with radioactive source (GEM never operated in recirculation before)

"A portable gas recirculation unit" JINST 12 T10002

2016-…:
Validation continued at CERN Gamma Irradiation Facility



Gas mixture purification studies

2016-…:
LHCb-GEM upgraded to gas recirculation

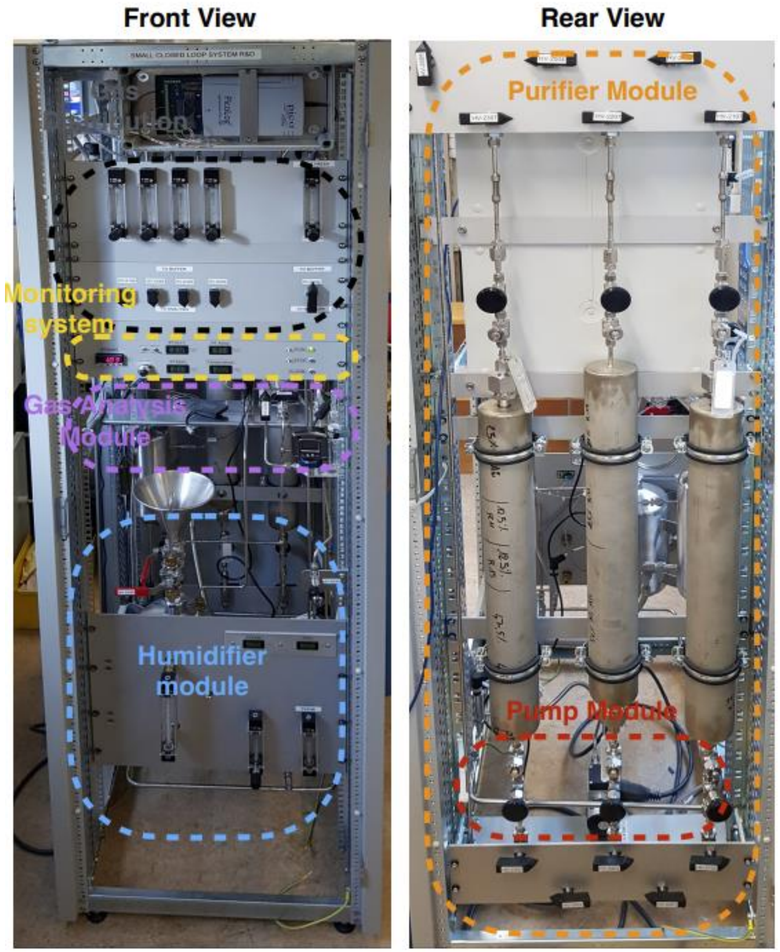
Original investment already largely paid back by gas cost saving during operation

LHCb-GEM detector operation became more stable thanks to less frequent replacement of CF_4 cylinders

Gas Mixture Recirculation: “Lab size” gas systems

Sometimes lab test are using relatively high gas quantity if compared with large LHC systems:
example from GIF++ tests (RPC, CSC, GEM), test beam activities (CALICE RPC-SDHCAL), EEE telescope, …

Development of Recirculation system for laboratory applications



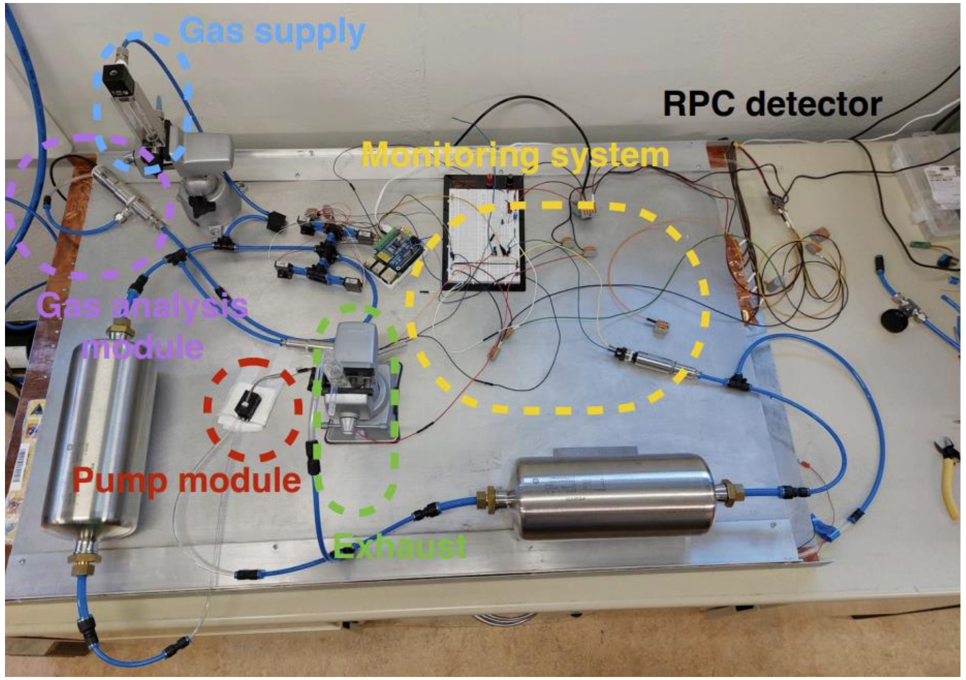
- 2013: Development of "A portable gas recirculation unit" JINST 12 T10002

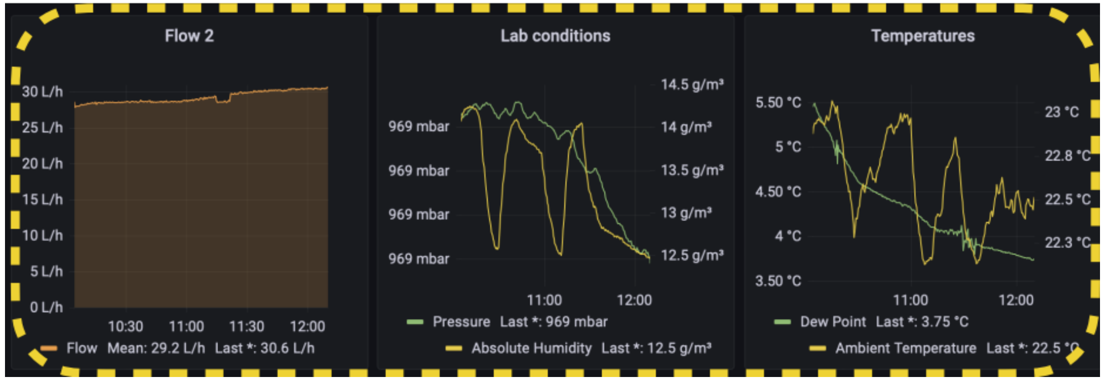
- ~10 detectors
- ~100-200 l/h
- One single rack can contain the full system
- Control system based on simple PLC
- Monitoring system based on Grafana
- Possible to have some parameters controlled remotely
- Few sensors
- Five gas systems already produced and in use

- 20-30 kCHF

Gas Mixture Recirculation: “Lab size” gas systems

Development of Recirculation system for ~1-2 detectors – 20-30 l/h





- 2019: Development of [Gas recirculation systems for RPC detectors: from LHC experiments to laboratory set-ups - RPC2022]

  - It should fit in a small box
  - Monitoring system based on RaspBerry PI and Grafana
  - Manual (optional remote) control
  - Limited number of electronic sensors
  - Very cheap components

  - few kCHF

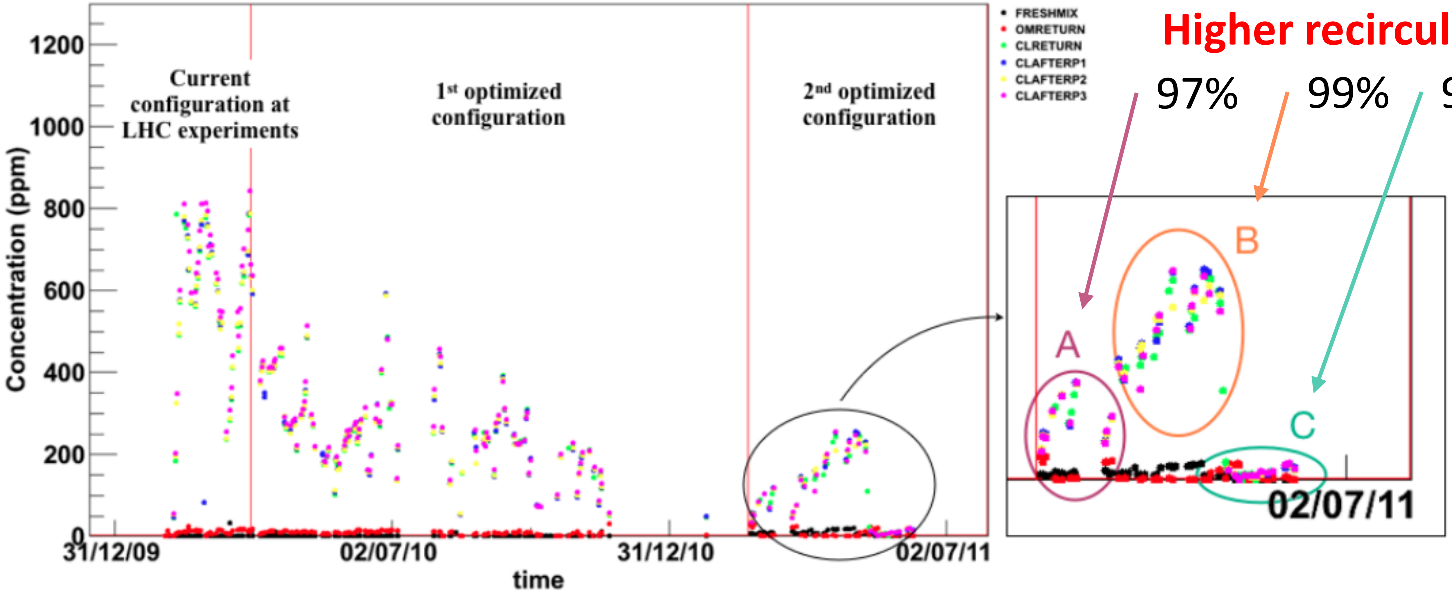
Beyond gas recirculation: why?

Not always the recirculation fraction can be increased easily: two examples

1) Detector operation validated for ageing up to 90%
    - What about recirculating more? (example RPC: only short test performed in the past (2011) up to 97-99%)

2) N2 intake by diffusion (example: CMS-CSC detector)

RPC: Gas recirculation and impurities in past test



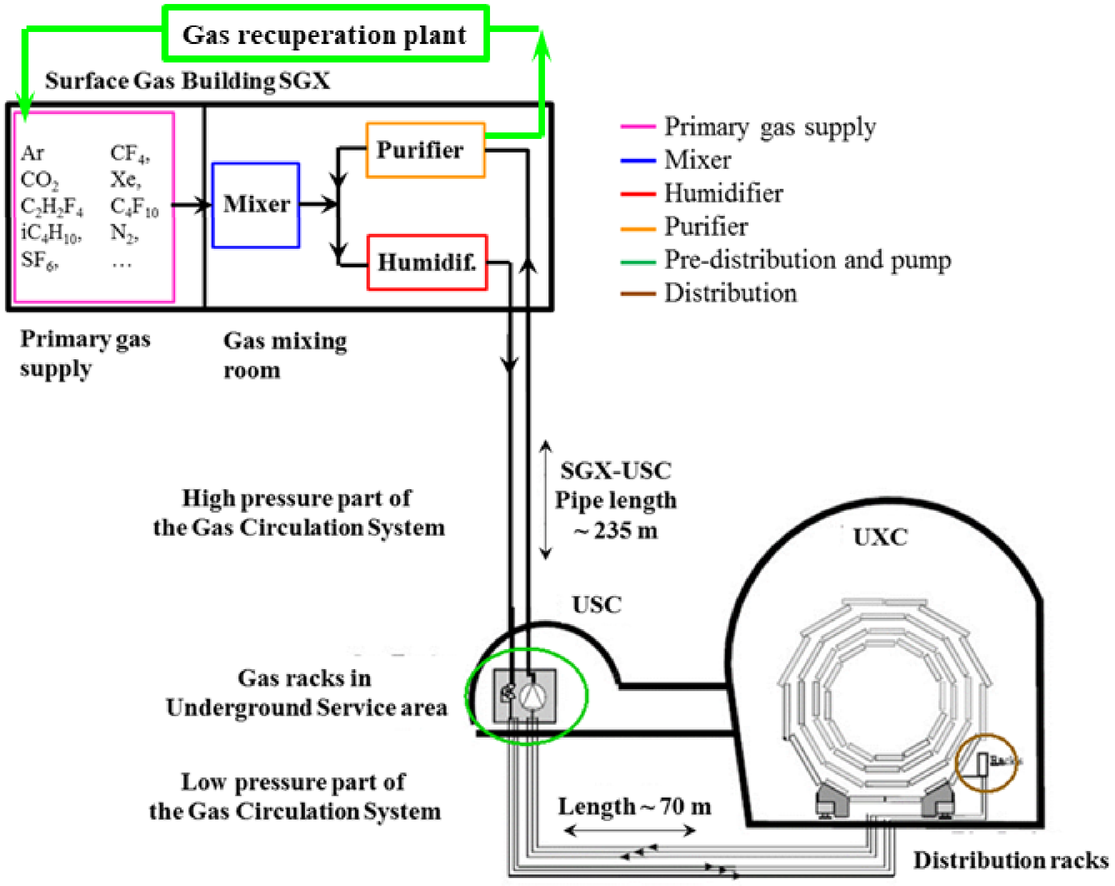
Higher recirculation fraction:

97% 99% 94%

https://pos.sissa.it/159/029/pdf

Gas systems and recuperation

Possibility to recuperate a single gas component from exhausted mixture



Many LHC gas systems already with gas recuperation

Advantages:

- Further reduction of gas consumption

Disadvantages:

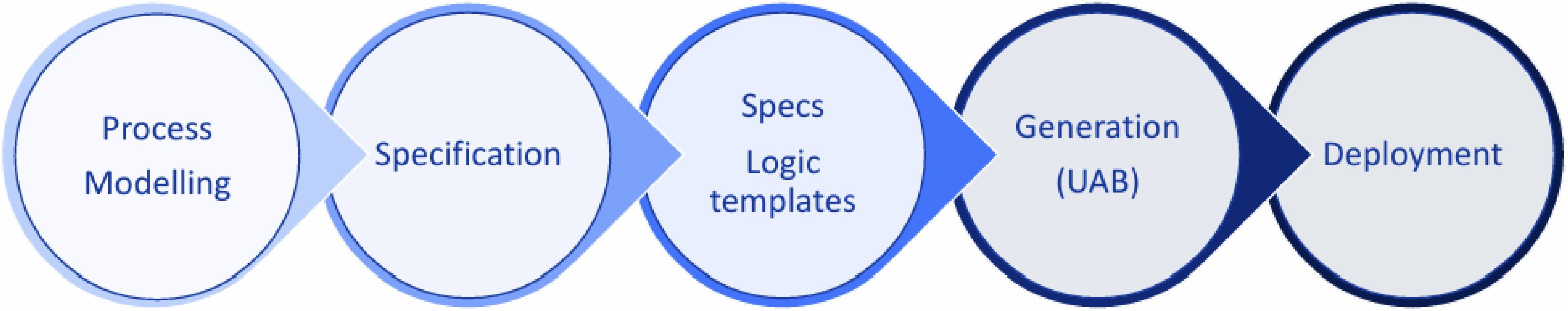
- Higher level of complexity

- Dedicated R&D

- Gas mixture monitoring fundamental

- ***Ongoing R&D aims in testing the feasibility for new recuperation systems***:
  - **SF_6 for ALICE-RPC, ATLAS-RPC, CMS-RPC, ALICE-TOF**
- ***and substantial improvements of existing systems:***
  - **R134a for ALICE-RPC, ATLAS-RPC, CMS-RPC, ALICE-TOF**
  - **CF_4 for CMS-CSC, LHCb-RICH2**
  - **C_4F_{10} for LHCb-RICH1**
- Recuperation will be effective only if leaks at detector level will be reduced
- R134a recuperation can drastically decrease GHG consumption
- R&D costs for first R134a recuperation system can be potentially paid back with one year of operation

Gas Systems: from design to operation



P&ID
Process decomposition
Functional Units

Functional Analysis:
System requirements
Instrumentation
Electrical diagrams

UNICOS-CPC specs
Logic Templates
Expert templates (grafcets)

UAB CPC wizard

PLC Instances
PLC logic
HMI tags
WinCC OA object instances
Comm resources

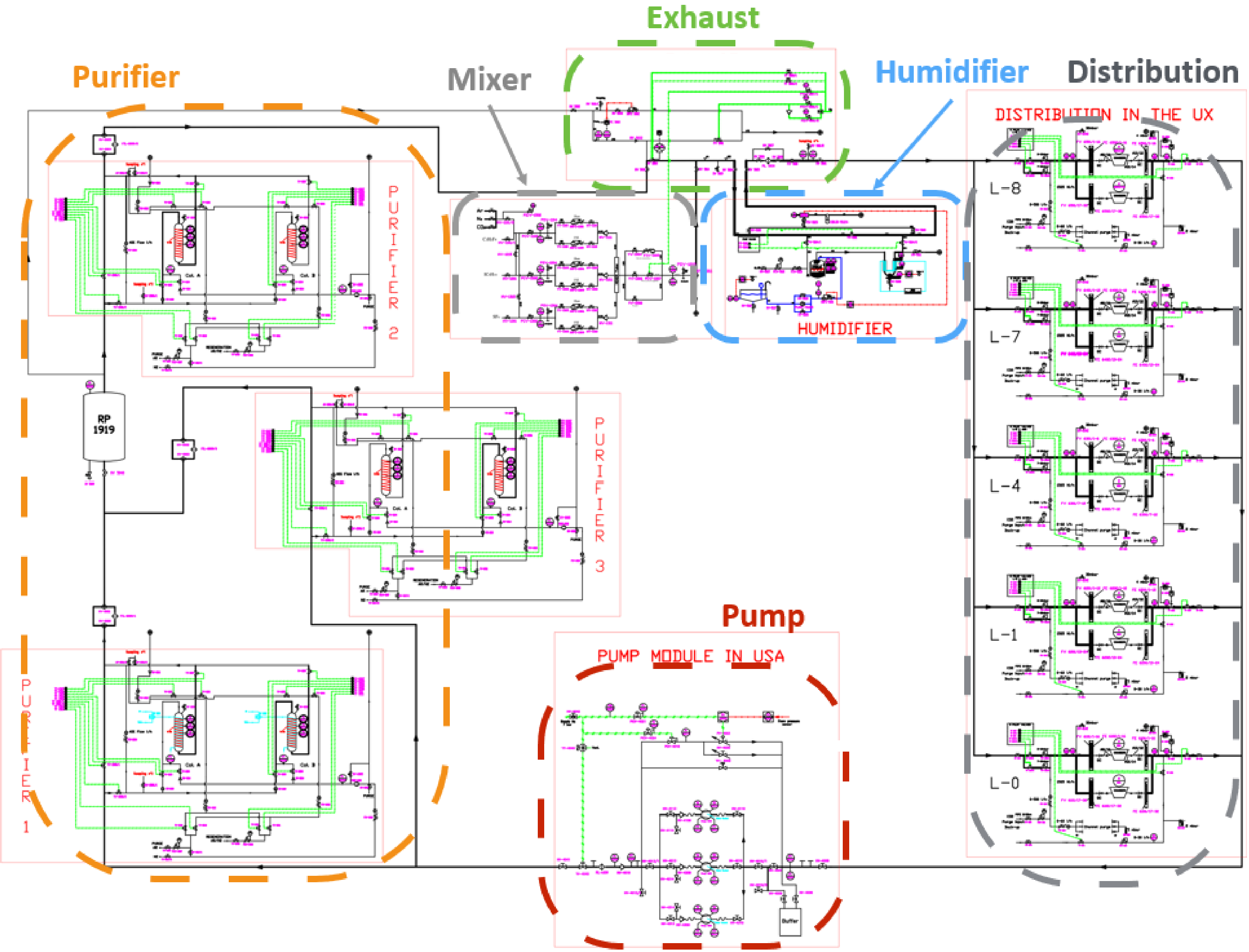
SCADA set-up (synoptics)

From CERN, Beams Department, UNICOS Team

Gas Systems: design phase - identifying functional units

Piping and Instrumentation Diagram (P&ID or PID):
it is a detailed diagram in the process industry which shows process equipment together with the instrumentation and control devices.

P&ID and modules:
identifying functional units. Example:



Gas Systems: design phase - functional units

- <u>Gas systems are made of several modules </u>(***building blocks***): mixer, pre-distribution, distribution, circulation pump, purifier, humidifier, membrane, liquefier, gas analysis, etc.
- Functional modules are equal between different gas systems, but <u>they **can be configured** to satisfy the specific needs</u> of all particle detector.
- Implementation: control rack and crates (**flexible during installation phase and max modularity for large systems**)

Control rack

Control crate
(PLCs)

Modules crates
Profibus connection
to control crate

Gas Systems: from P&ID to controls

Functional analysis:
a document describing the automatic behaviour of the process

Logic Templates
Expert Templates (grafcets)

NALDocumentation for Software
IT-CO group, Gas Working Group, JCOP project.

LHC GCS
A common approach for the control of the LHC experiments gas systems.

URD
User Requirement Document

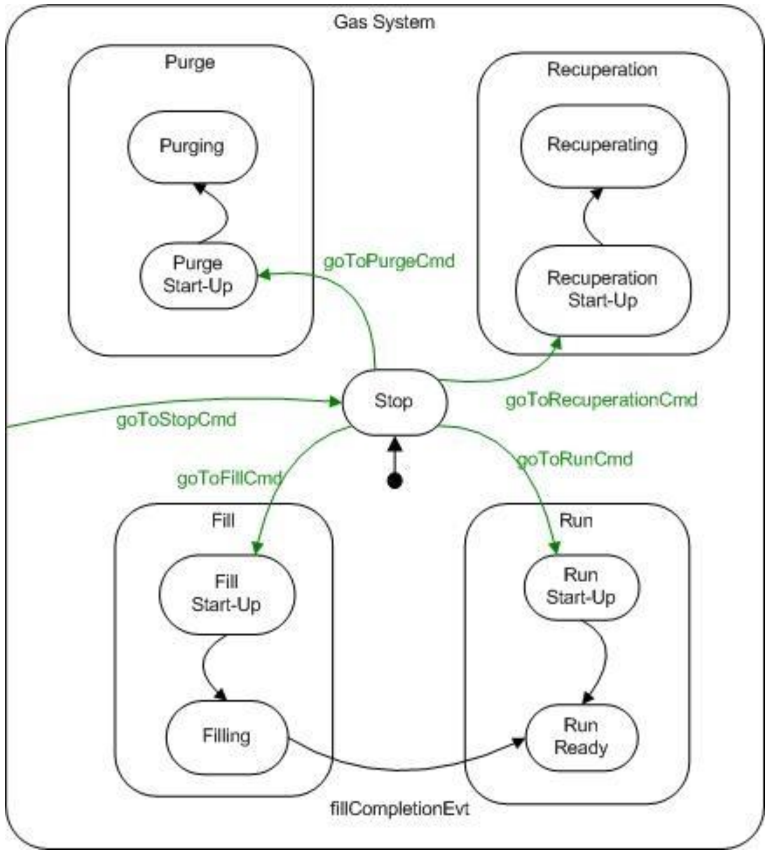
Document Version: 2.67
Document Issue: 1
Document ID: CERN-JCOP-2002-14
Document Date: 23 June 2011

LHC Experiments
Gas Control

European Laboratory for Nuclear Physics
Laboratoire Européen pour la Physique des Particules
CH-1211 Genève 23 - Suisse

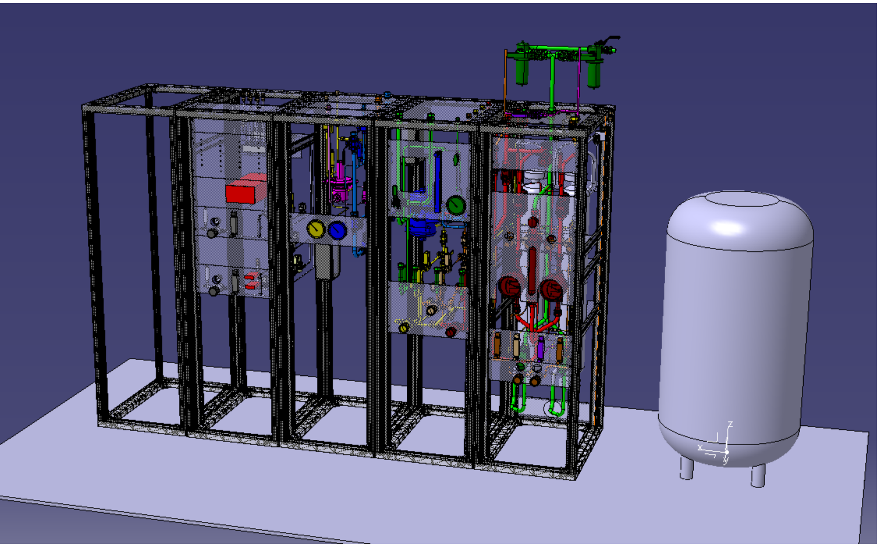
https://cernbox.cern.ch/s/DZmA2Uymugv0Ud4

About 500 pages where are defined:
- Objects (units, actuator, controller)
- Operational states
- Interlocks (Full stop, Temporary stop, start interlock)
- Alarm
- User command
- Computed variables



Gas Systems: from P&ID to construction

3D view of gas systems modules
in the surface gas building



Assembly

Gas systems modules
In the workshop for QC

Gas Systems: installation and commissioning

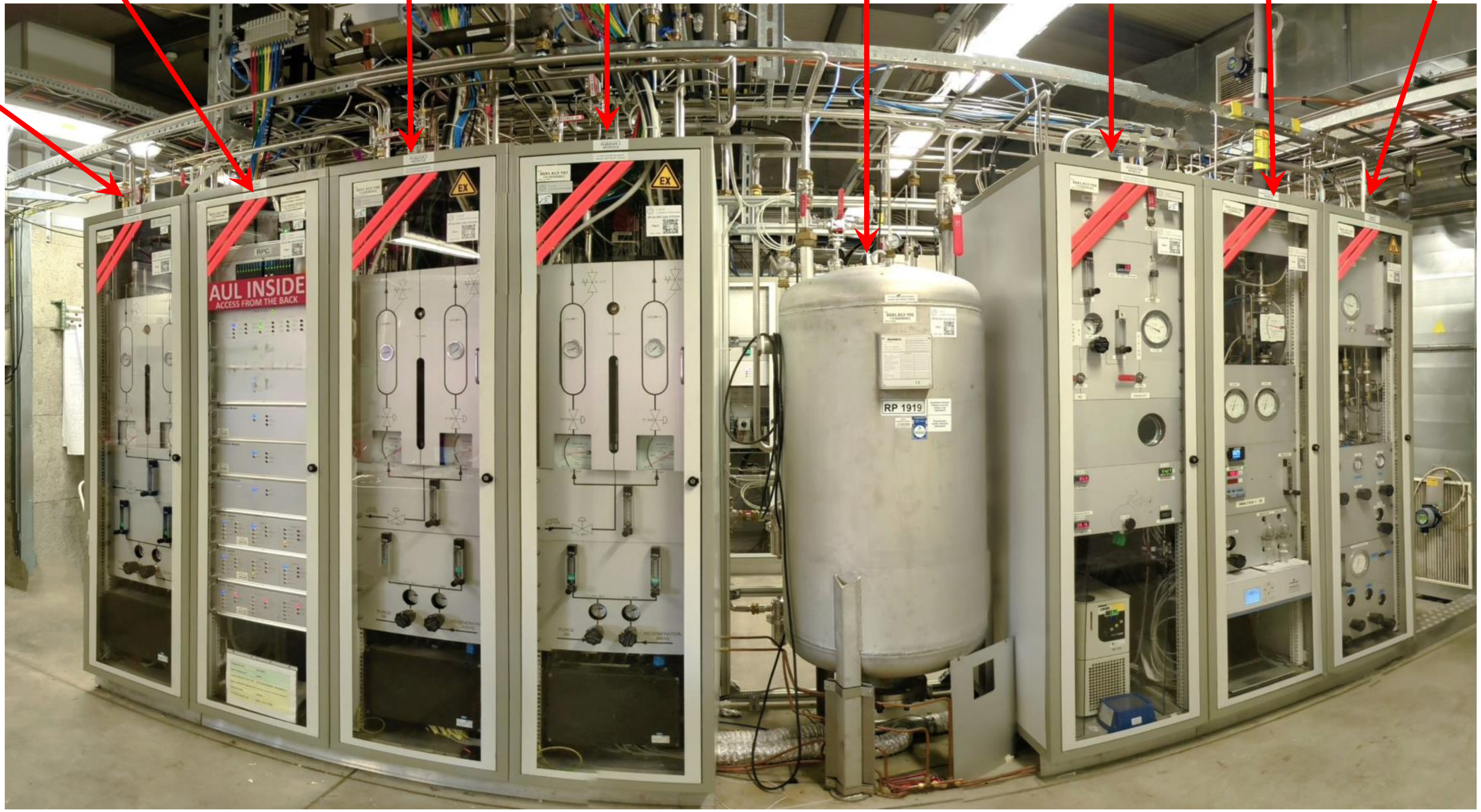
Arrival

Unboxing

Installed

Gas system construction: modularity

Gas systems modules in surface building. In the following each module will be briefly discussed



Purifier 1

Controls module

Purifier 2

Purifier 3

High pressure buffer

Humidifier

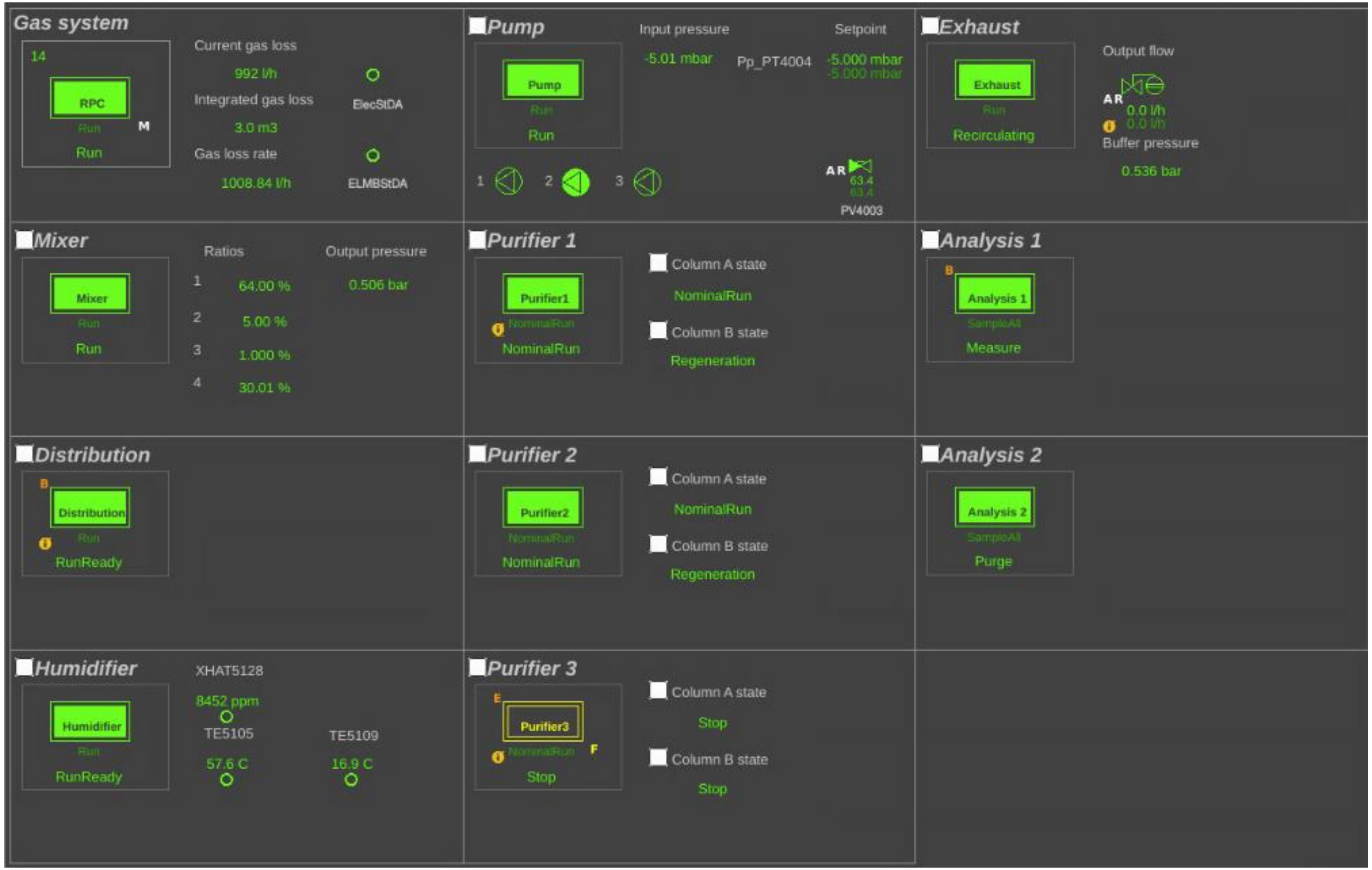
Analysis

Mixer

Gas system construction: modularity

View from software controls

Each rectangle is a Functional module



Gas system
14
RPC
Run
M
Run
Current gas loss
992 l/h
Integrated gas loss
3.0 m3
Gas loss rate
1008.84 l/h
ElecStDA
ELMBStDA

☐ **Pump**
Pump
Run
Run
Input pressure
-5.01 mbar
Pp_PT4004
Setpoint
-5.000 mbar
-5.000 mbar
1 2 3
AR
63.4
63.4
PV4003

☐ **Exhaust**
Exhaust
Run
Recirculating
Output flow
AR
0.0 l/h
0.0 l/h
Buffer pressure
0.536 bar

☐ **Mixer**
Mixer
Run
Run
Ratios
1 64.00 %
2 5.00 %
3 1.000 %
4 30.01 %
Output pressure
0.506 bar

☐ **Purifier 1**
Purifier1
NominalRun
NominalRun
☐ Column A state
NominalRun
☐ Column B state
Regeneration

☐ **Analysis 1**
B
Analysis 1
SampleAll
Measure

☐ **Distribution**
B
Distribution
Run
RunReady

☐ **Purifier 2**
Purifier2
NominalRun
NominalRun
☐ Column A state
NominalRun
☐ Column B state
Regeneration

☐ **Analysis 2**
Analysis 2
SampleAll
Purge

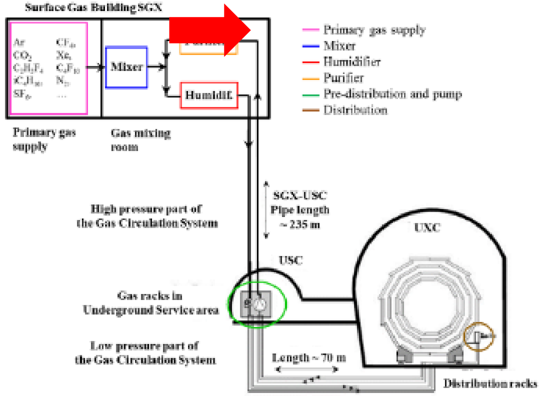
☐ **Humidifier**
Humidifier
Run
RunReady
XHAT5128
8452 ppm
TE5105
57.6 C
TE5109
16.9 C

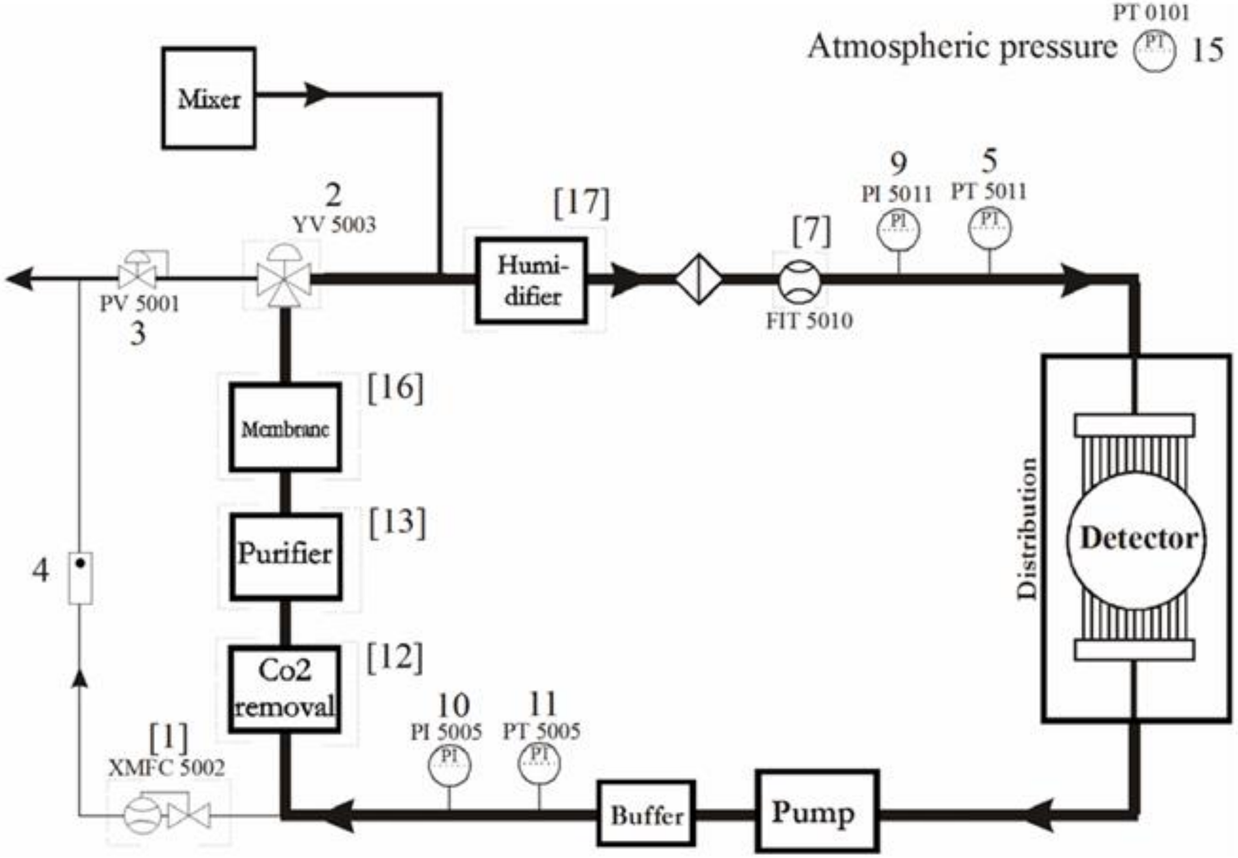
☐ **Purifier 3**
E
Purifier3
NominalRun
F
Stop
☐ Column A state
Stop
☐ Column B state
Stop

Exhaust module

The exhaust module is:

- Ensuring the balance between mixture injected by the mixer module and mixture flow exhausted
- Measuring the circulation flow
- Controlling the pressure of the high-pressure buffer to compensate for atmospheric pressure changes





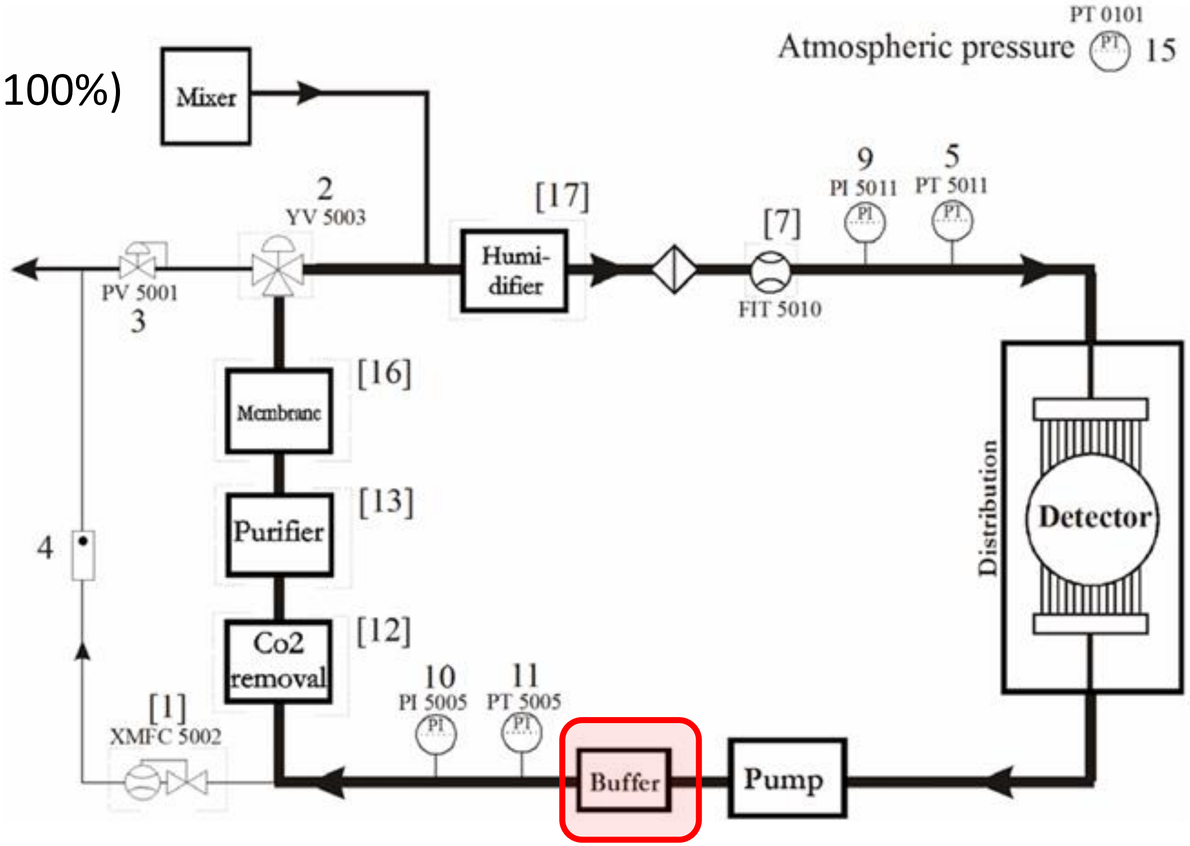
Exhaust module

The control of the high-pressure buffer pressure aims in minimizing the gas usage by compensating for atmospheric pressure changes using the gas stored in the high-pressure buffer.
It is particularly important when:

- A very expensive gas is used
- The mixer injection is negligible (recirculation fraction close to 100%)

During the year, the atmospheric pressure is changing in a relatively large range:

During a storm, the atmospheric pressure can change by several mbar
For a detector of 100 m3, 1 mbar represents 100 litres
1) The MFCs in the mixer may not have a large enough flow capacity to cope with the exceptionally high demand



High-pressure buffer

Exhaust module

During the year, the atmospheric pressure is changing in a relatively large range:
from 935 mbar up to 990 mbar (if we take CERN)

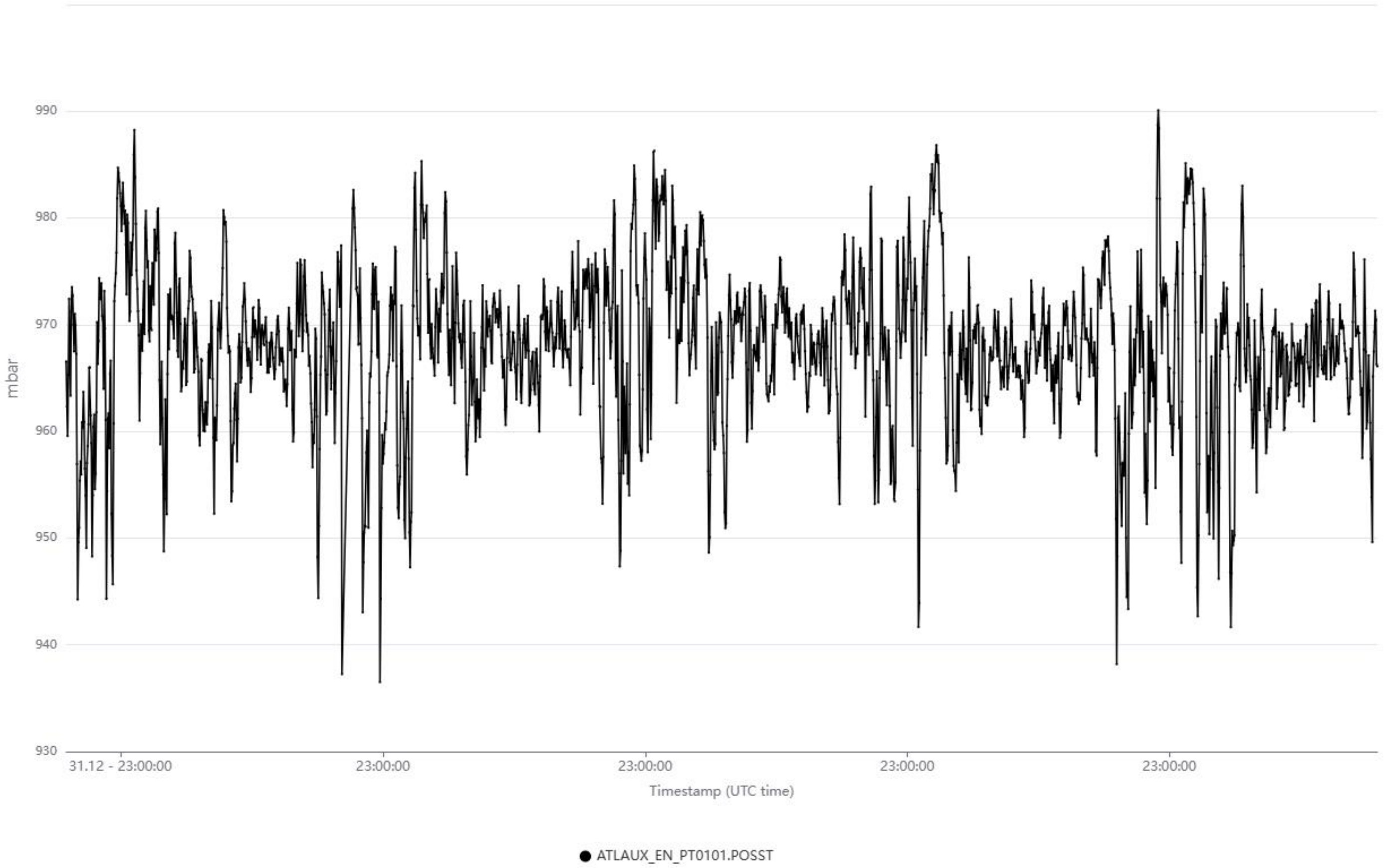
For a detector of 100 m3, working at constant relative pressure this implies:

When Patm decreases → the detector release 100 l of mixture per each 1 mbar of decrease

If the detector is using Xenon → 100 l = 2100 CHF

A decrease from 990 mbar to 935 mbar would release 5.5 m3 and it would cost 120 kCHF

→ The high-pressure buffer is the place where this volume is stored, avoiding gas loss and reducing operational cost
→ The exhaust module is controlling the high-pressure buffer setpoint



Exhaust module

During/after a storm, the atmospheric pressure can increase by several mbar

If we consider a change of + 1 mbar/h

For a detector of 100 m3, a flow of 100l/h is needed to maintain constant the relative pressure

→ The MFCs in the mixer may not have a large enough flow capacity to cope with the exceptionally high demand since they are tuned for order of l/h injection (in a system which recirculate basically 100% of the mixture)

→ The high-pressure buffer is the place from where this gas volume is taken

→ The exhaust module is controlling the high-pressure buffer setpoint

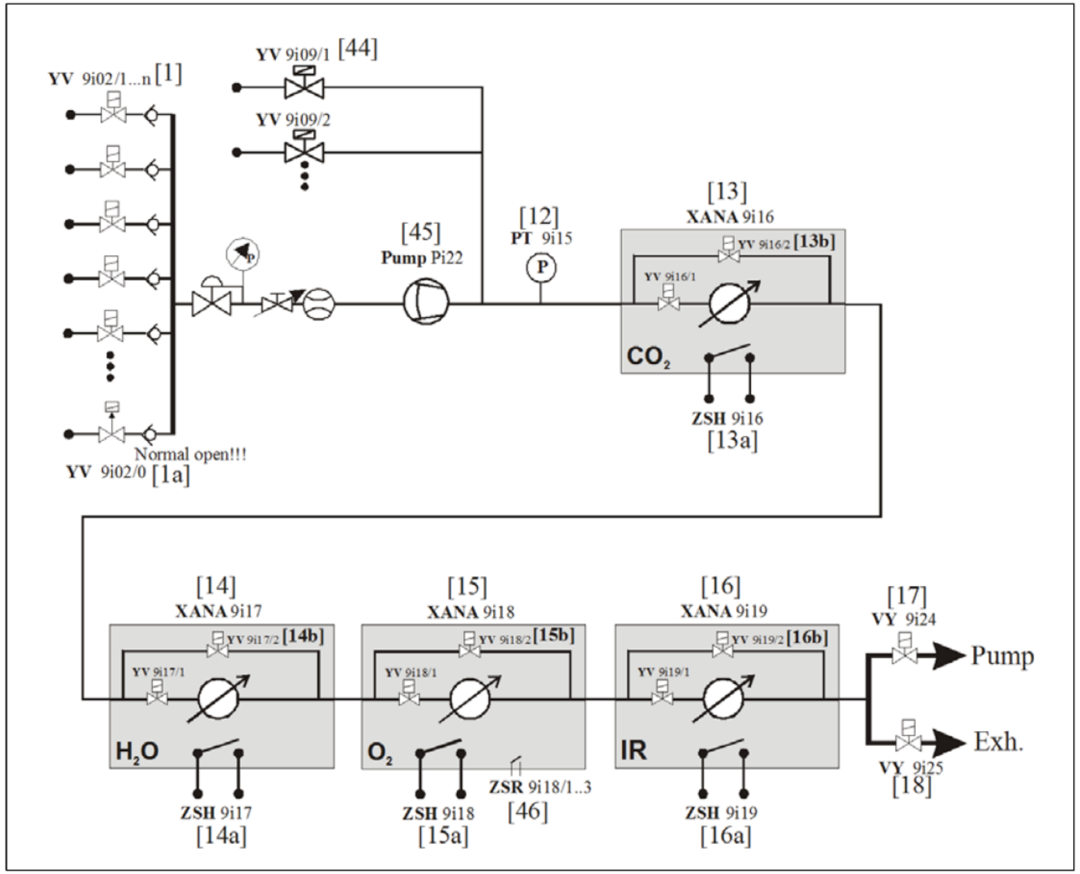
+10 mbar/10 h
→ + 1 mbar/h

Gas analysis module

basically everywhere

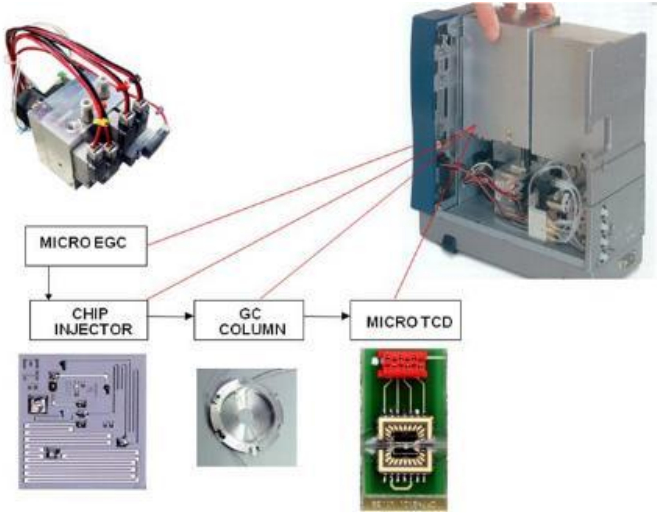
- Used to analyze the gas mixture
- Two types: gas source selected by means of standard valves or n-way valves
  - Several sample chains may be organized in several physical location.
  - Each sample chain completely independent

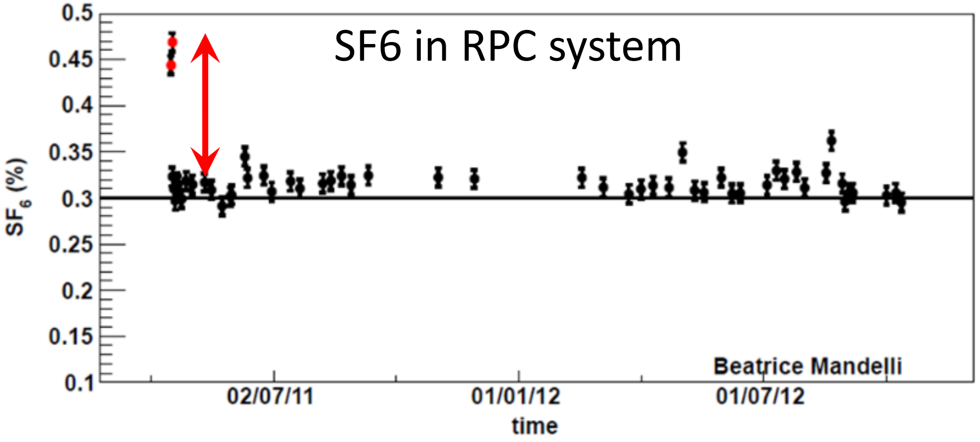
- The module operated in automatic mode:
  - sample the gas streams or the reference gases selected by experts.
  - experts can trigger sampling of selected sources.
  - length of the sampling lines taken in considerations to define flushing delays.
- Alarm and data exchange with detector DCS
- Used for safety (flammability level)
- Gas chromatographs connected for more specific analysis

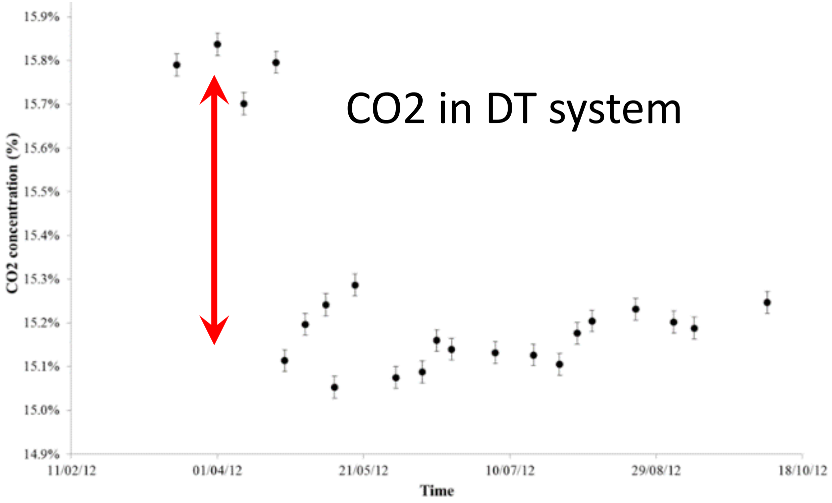


Gas analysis module

- Gas chromatographs are used to monitor:
  - Stability of mixture composition
  - Presence of more complex impurities
- CMS and LHCb equipped with GC connected to the selection manifold of the standard analysis rack.
- Others GC are directly operated by users





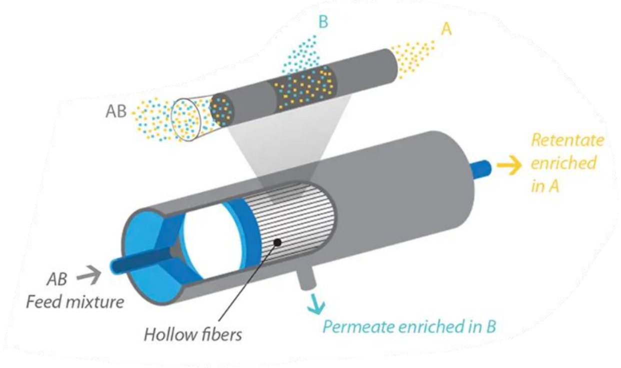


- Other monitoring system based on detector are under development

Gas recuperation systems: separation techniques

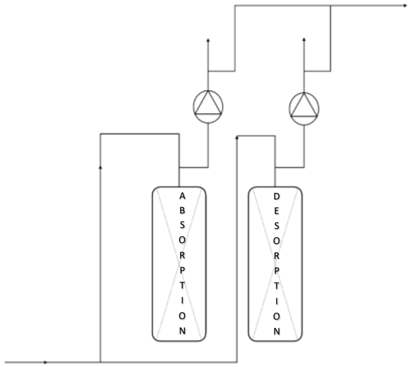
Gas recuperation systems: developments for specific mixtures

MEMBRANE SEPARATION



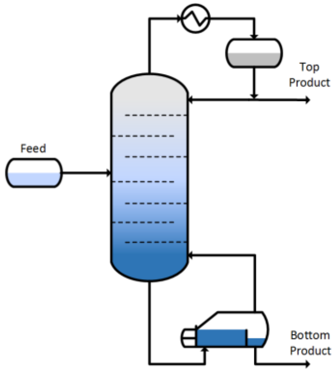
- CMS CSC CF_4
- LHCb RICH2 CF_4

PRESSURE & THERMAL SWING ADSORPTION (PSA & TSA)



- CMS CSC CF_4
- LHCb RICH2 CF_4
- Old LHCb RICH1 C_4F_{10}

DISTILLATION



- CMS RPC R134a
- CMS RPC SF_6
- Old LHCb RICH1 C_4F_{10}
- New LHCb RICH1 C_4F_{10}

Gas Recuperation: the CF4 case

CMS-CSC CF_4 recuperation plant

Problem:

Too high N_2 concentration for gas recirculation due to diffusion leak from detector components

Technical challenge:

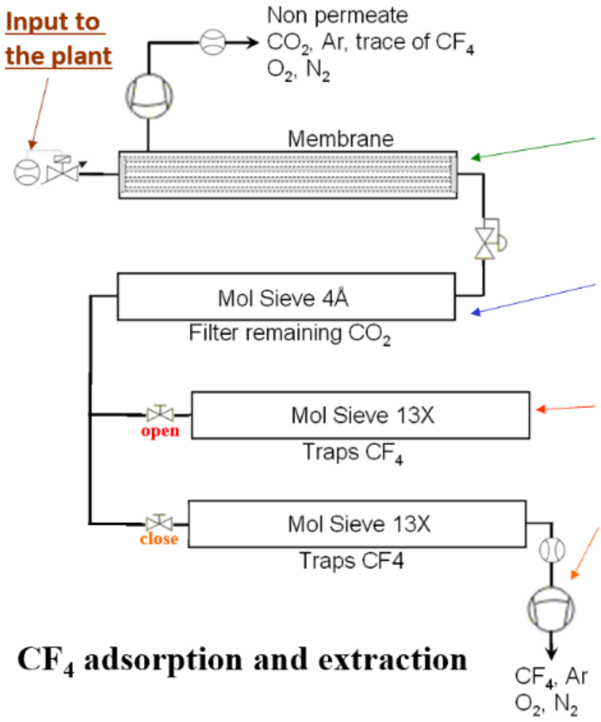
First plant built for CF_4 warm adsorption

A completely non-standard system

From Run1 to Run2 up to 44% GHG reduction

R&D started in 2009, Operation from 2012. Several technical and resource problems → Average efficiency 60-70%

More selective sieves or cryogenic separation considered in case of further upgrades



CF_4 adsorption and extraction

Phase 1:
Bulk CF_4 separation from the mixture
→ membrane

Phase 2:
adsorption of remaining CO_2
→ Molecular Sieve 4Å

Phase 3a:
CF_4 adsorption
→ filling Mol. Sieve 13X from -1 to 0 bar

Phase 3b:
CF_4 recovery
→ extraction from Mol. Sieve 13X
(0 → -1 bar)

Gas Recuperation: costs vs benefits

Costs/benefits – CF4 and R134a examples:

CF4 recuperation for CMS-CSC

10% CF4 in gas mixture ~ 70 l/h ~ 2200 kg/year ~ 100 kCHF/year (at current price)

With 65% or recuperation efficiency

→ 1400 kg/year CF4 saved ~ **-60 kCHF/year** ~ **-10500 tCO2e/year**

R134a recuperation for CMS-RPC

95.2% R134a in gas mixture ~ 700 l/h ~ 12t/year ~ 130 kCHF/year (at current price)

With 80% or recuperation efficiency

→ 12 t/year R134a saved ~ **-130 kCHF/year** ~ **-18000 tCO2e/year**

allowing to maintain constant operational cost and GHG emissions despite the increase in fresh flow required to cope with the increase of luminosity

In detector operation is less subject to market crisis affecting price and availability.

Indeed, the availability of recuperated gases can mitigate difficult situations when there is a shortage of fresh gas.

In 2022 when there was a major disruption of CF4 availability in Europe: the CMS-CSC detectors could be operated and therefore participate to the CMS data taking only thanks to the usage of recuperated CF4.

Failure Mode, Effects and Criticality Analysis - FMECA

- **System decomposition**: the systems are divided into the functional modules; for each of them, the components listed in the P&iD are considered for the analysis as Lowest Replaceable Units (LRU)

- **Operational phase**: *normal run*

- **Failure mode and cause identification**: the input information were retrieved from eLOGs analysis

- **Failure effects classification**: evaluation of *local effects*, *effects on the module* and *on the system*

- **Criticality analysis**: assignment of *risk indexes*
  - **Frequency** of occurrence (from eLOGs)
  - **Severity** of effects

- Building of **risk matrixes**

FREQUENCY INDEX	DESCRIPTION
1	The event is not expected in system lifetime
2	The event could happen one time in system lifetime
3	The event is expected few time in system lifetime (less than 1/5y)
4	The event is expected more than 1/5y but less than 1/y
5	The event is expected to occur more than 1/y

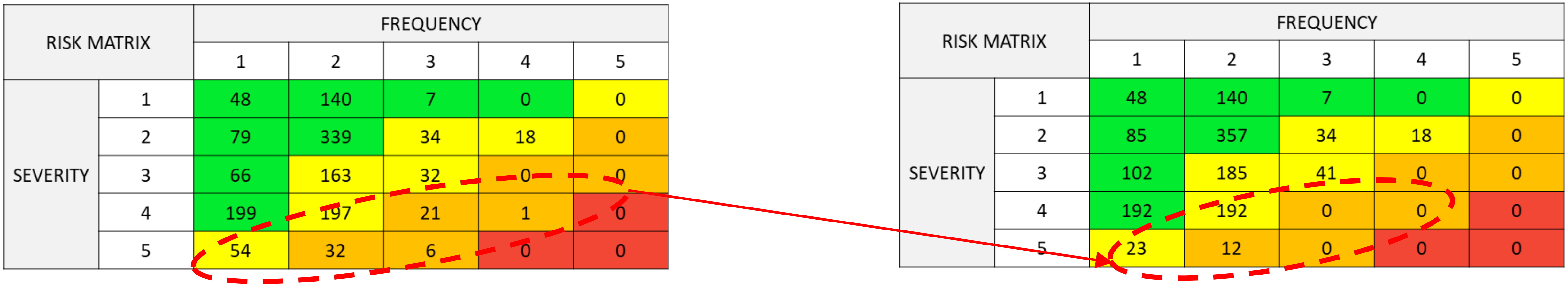
SEVERITY INDEX	DESCRIPTION
1	Negligible effect
2	Module is slightly affected, no stop required
3	Module is stopped for less than 1 hour or performances reduced, or system is slightly affected
4	Module is stopped for more than 1 hour or system is affected
5	Gas system is stopped or detector is damaged

Failure Mode, Effects and Criticality Analysis - FMECA

639 components analysed and 1436 failure modes found

🟥	High critical events, measures for prevention and/or mitigation are requested (NON ACCEPTABLE)
🟧	Critical events, dedicated interventions are required (ALARP)
🟨	Less critical events, few actions are needed (ALARP)
🟩	Non critical events (ACCEPTABLE)

The resulting risk matrix for a Gas System is the following:



RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	48	140	7	0	0
	2	79	339	34	18	0
	3	66	163	32	0	0
	4	199	197	21	1	0
	5	54	32	6	0	0

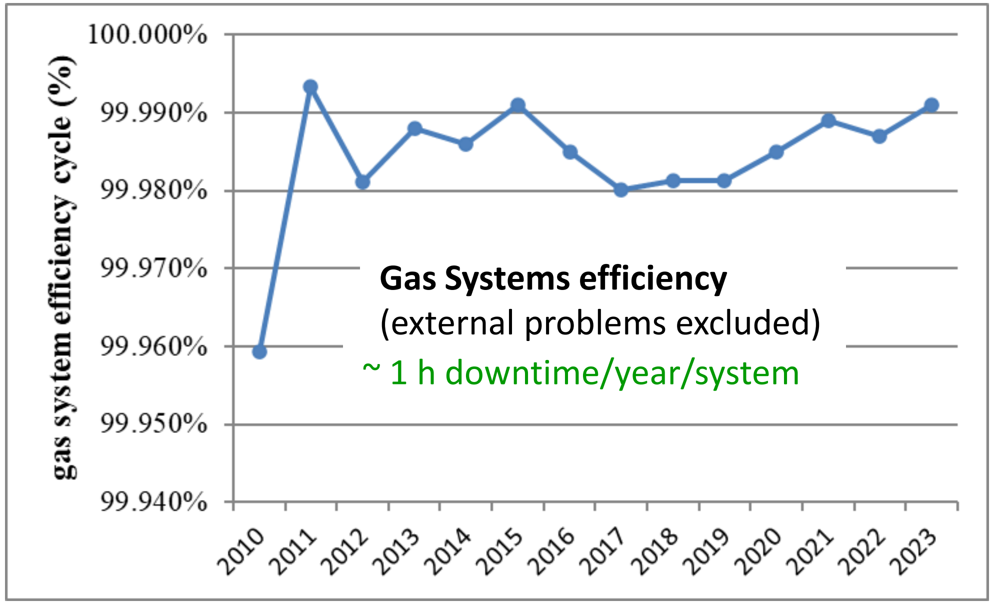
RISK MATRIX		FREQUENCY				
		1	2	3	4	5
SEVERITY	1	48	140	7	0	0
	2	85	357	34	18	0
	3	102	185	41	0	0
	4	192	192	0	0	0
	5	23	12	0	0	0

SEVERAL IMPROVEMENT ACTIONS IDENTIFIED

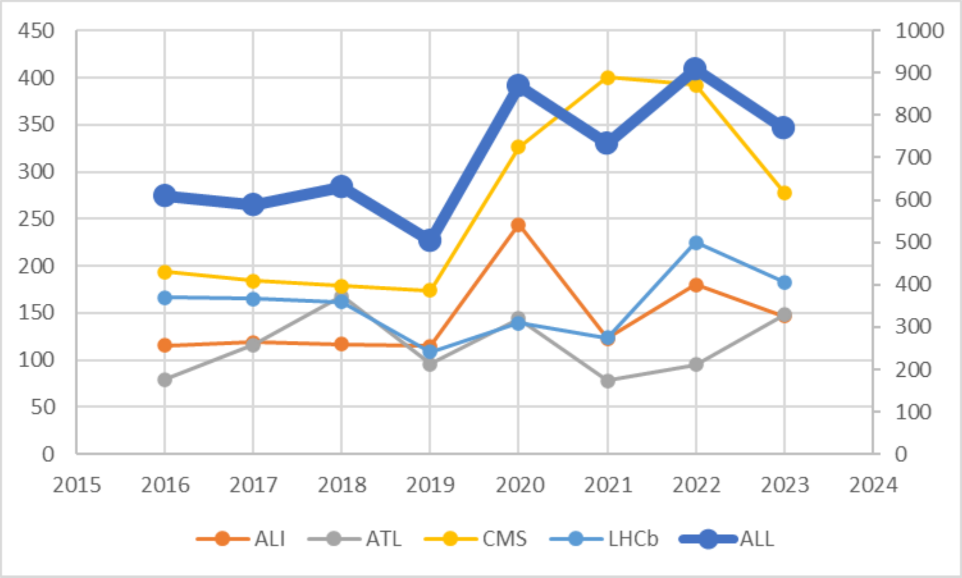
Gas Systems for LHC experiments: few numbers

M&O in few numbers:

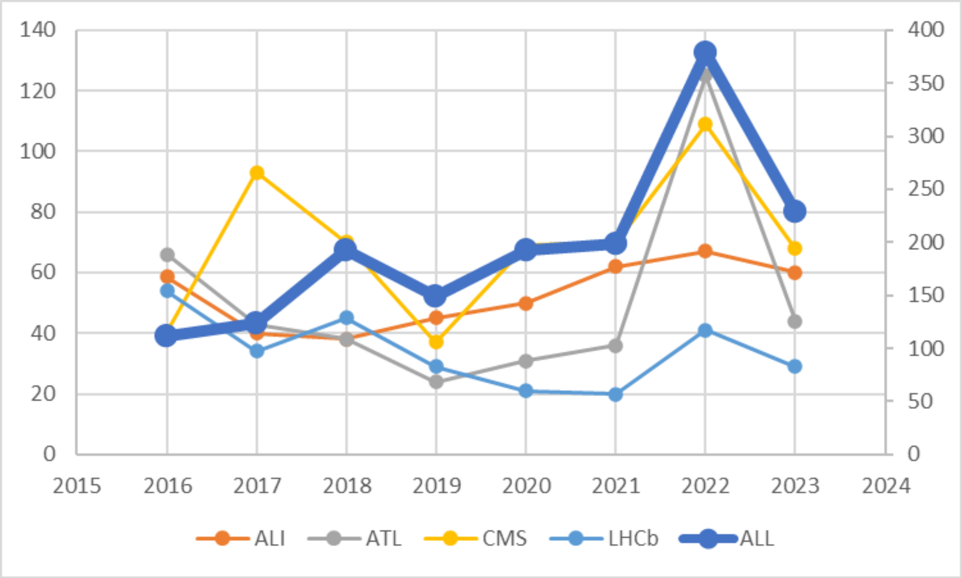
- ~100 intervention during oncall service
- 800 checks/interventions recorded (M&O, oncall, projects, …)
- Consolidation/upgrades



Gas Systems efficiency
(external problems excluded)
~ 1 h downtime/year/system



M&O elogs



On-call elogs

Summary

Gas systems at CERN

- 30 gas systems (about 300 racks) delivering the required mixture to the particle detectors of all LHC experiments (and one delivering H_2 to LINAC4 and many others for non-LHC experiments).
- Designed and built according to functional modules:
  - Simplified maintenance and operation activities for the team
  - Fully **automated** systems with remote control/monitoring
  - few examples briefly presented
- Gas systems have demonstrated an impressive **reliability** level:
  - On average about 1 h downtime/year (excluded external causes, i.e. power-cuts, …)
- Maintenance and consolidation are fundamental to ensure **stability** and reliability at long term

F-gas policy

- CERN F-gas policy is in line with “F-gas regulations” which aim to **limit the GHG usage**
- Decreasing the consumption makes detector operation less subject to crisis affecting price and availability
- Horizon 2025: -28% and Horizon 2030: -50%

Detector design

- It is fundamental to look not only at detector performance but also at the infrastructure