EP-DT
Detector Technologies

RPC 2022

R&D strategies for optimizing the greenhouse gas consumption at the CERN LHC experiments

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XVI Workshop on Resistive Plate Chambers and Related Detectors CERN, September 26th-30th, 2022

Outline

- Greenhouse gases (GHGs) for particle detection
- CERN Strategies for optimizing GHGs usage
  - Results, new projects and plans
- Conclusions

Gaseous detector systems at LHC

- Very Large apparatus: detector volume from < 1 m^3 up to several 100 m^3
- High mixture flow
- Operational costs issue

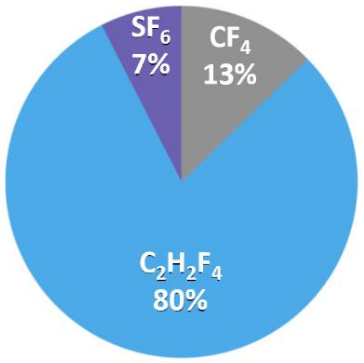
→ ***Optimization of gas usage needed! A lot of work already from the design phase.***

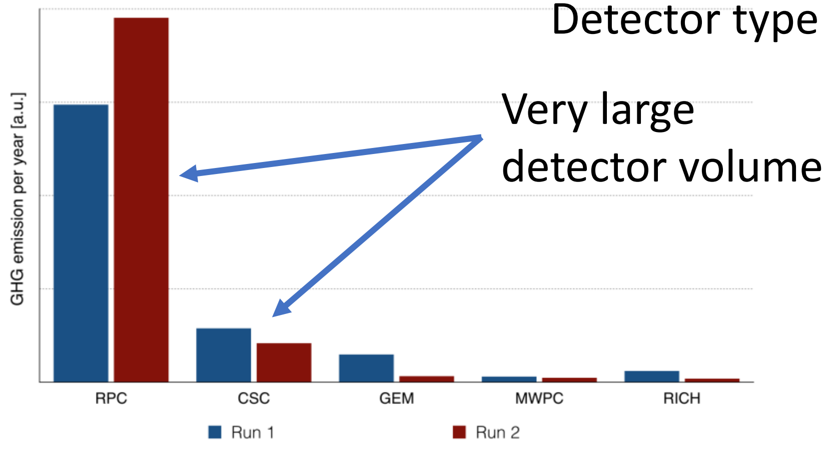
Nowadays increased attention on GHGs emissions: F-gas regulation aims in limiting emissions, GHGs availability, price, …

GHGs used at LHC experiments *and their relative contribution to emissions:*

GHGs like R134a ($C_2H_2F_4$), CF_4, SF_6, C_4F_{10}, … are used by several particle detector systems at the LHC experiments because **needed to achieve specific performance**

Gas	GWP - 100 y
$C_2H_2F_4$	1430
CF_4	6500
SF_6	22800





Of course, GHG usage in particle research is negligible wrt other activities.
However, GHG optimization is mandatory and it can secure operation over the LHC run period and reduce costs.

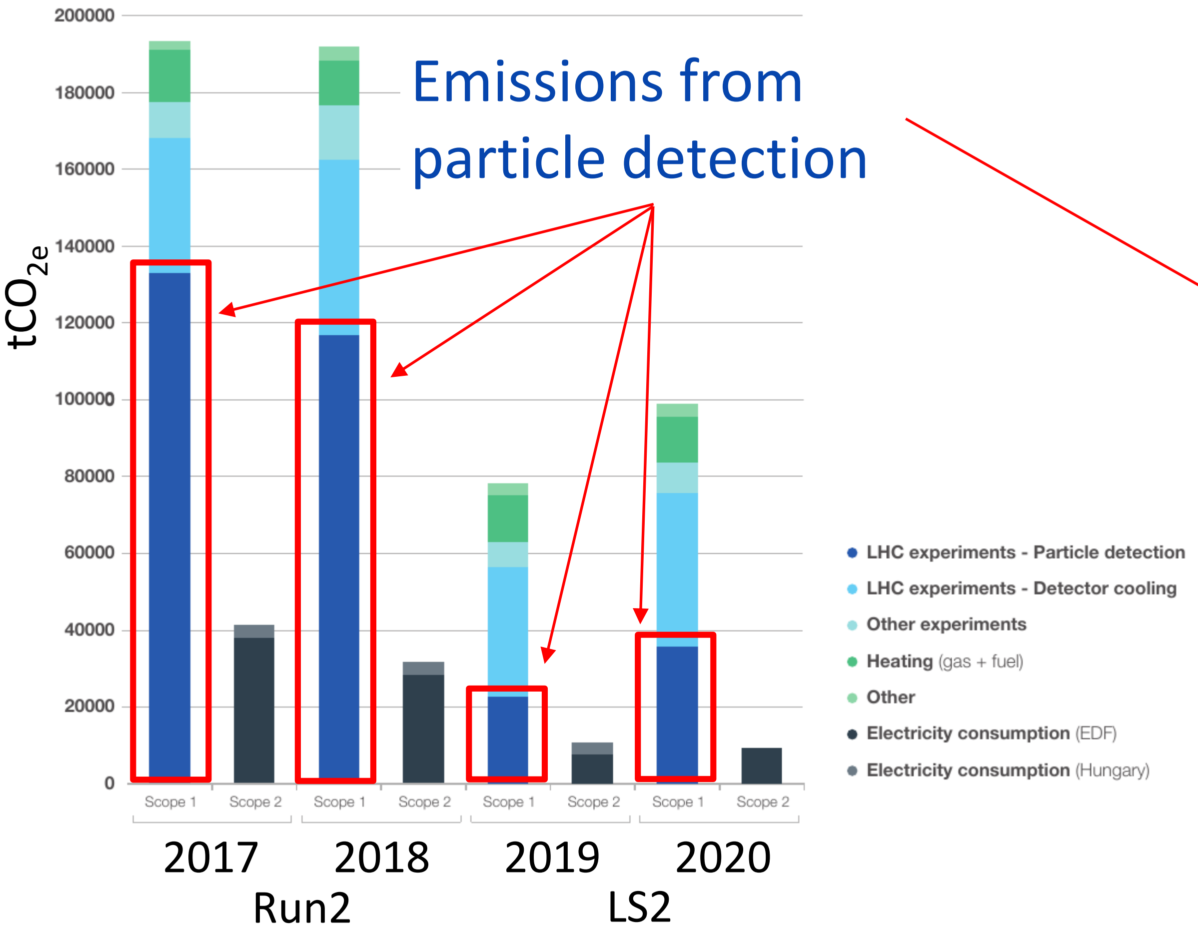
Greenhouse gas usage

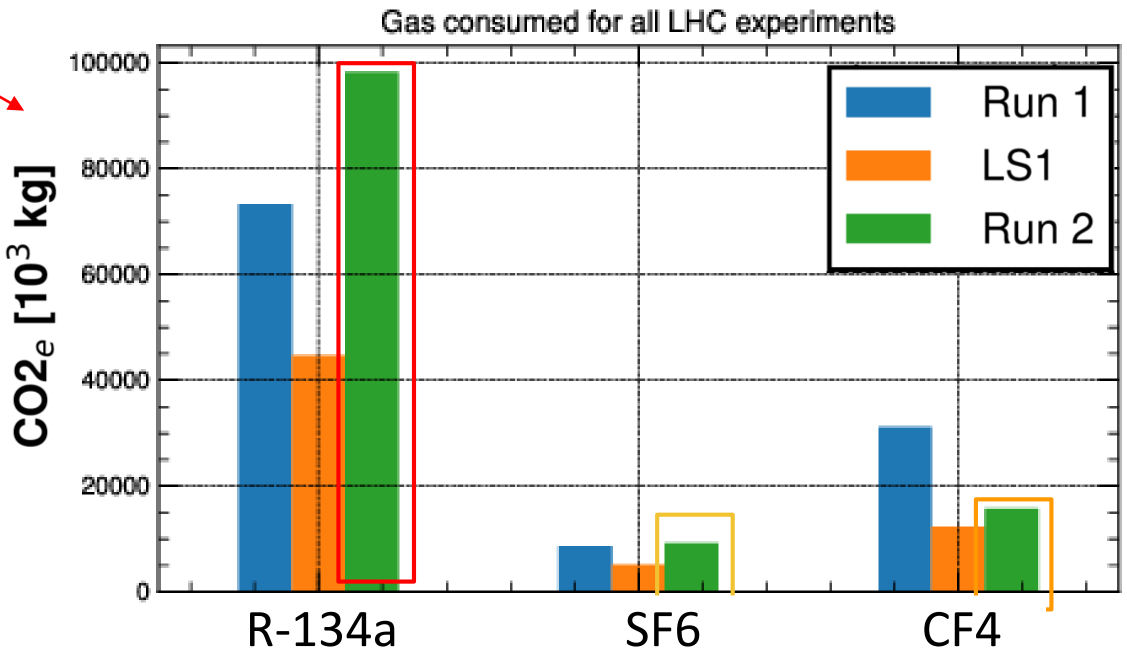
- CERN Environment Report 2019-2020
- 2021: CERN's Year of Environmental Awareness.
- CERN Environment workshop: 12 and 13 October 2022

Total CERN emissions during 1 year of Run 2 ~ **200 000 tCO2e**

~ 50% from particle detectors → mostly due to leaks and operation

- **$C_2H_2F_4$/R-134a** biggest contributor → leaks from RPC detector
- **CF_4** → due to operation of CSC and RICH systems
- **SF_6** → Related to RPCs as R-134a

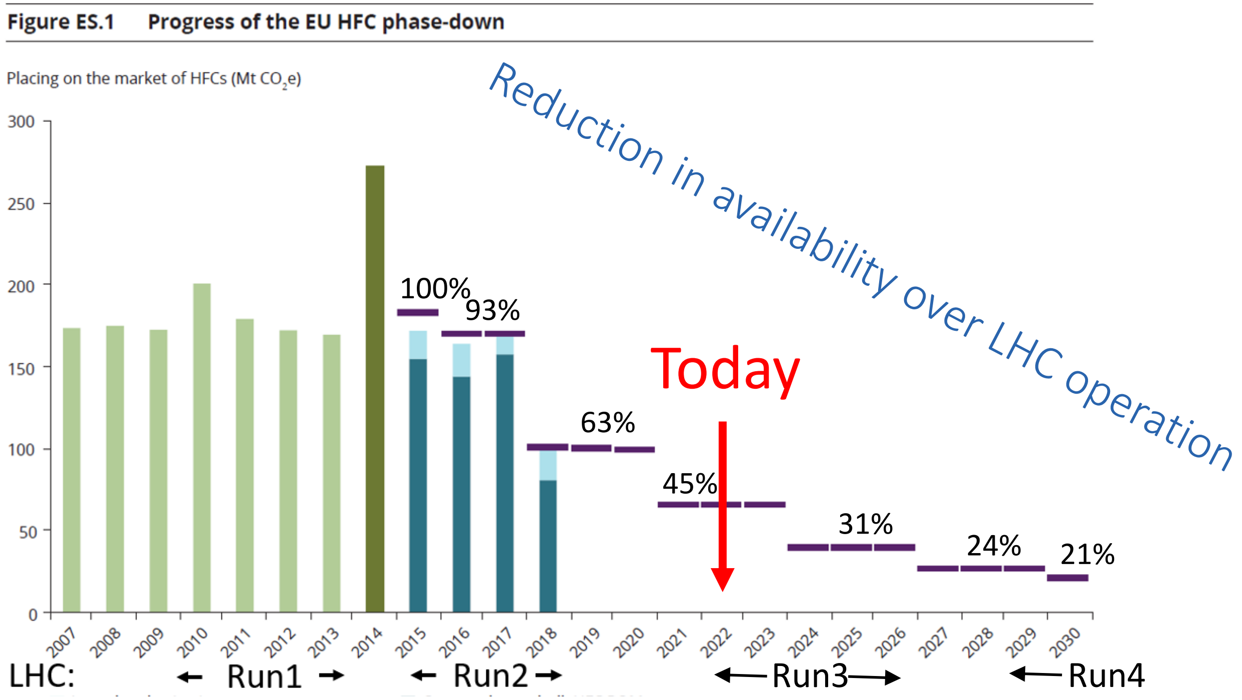




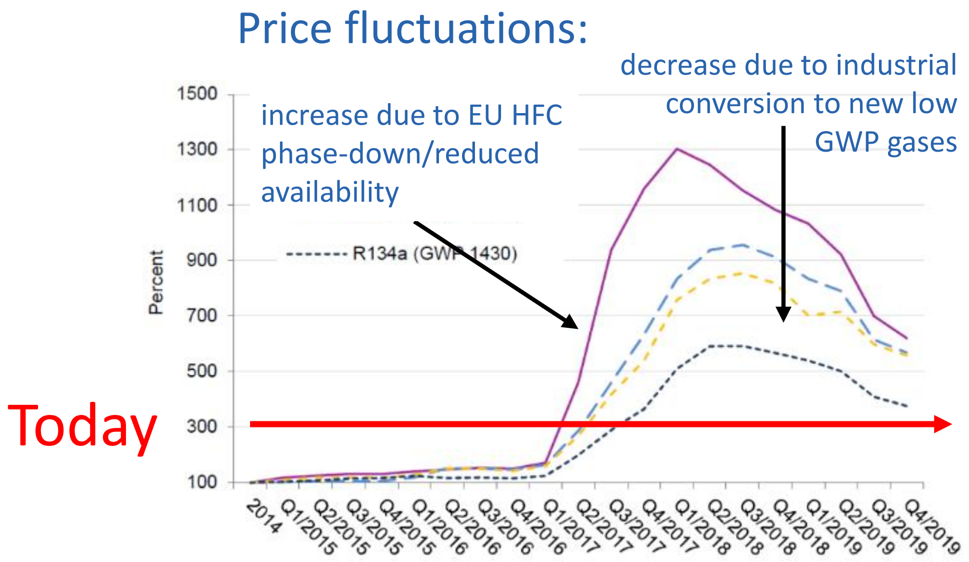
Greenhouse gas regulation

Due to the environmental risk, “**F-gas regulations**” started to appear. For example, the EU517/2014 is:

- **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.



HFC phase down: effects on HFC availability and prices



Sources: European Environment Agency, Fluorinated greenhouse gases 2019 report
Öko Recherche report, March 2020 J. Kleinschmidt et al.

Goal: reduce F- gases consumption and emissions from particle detectors

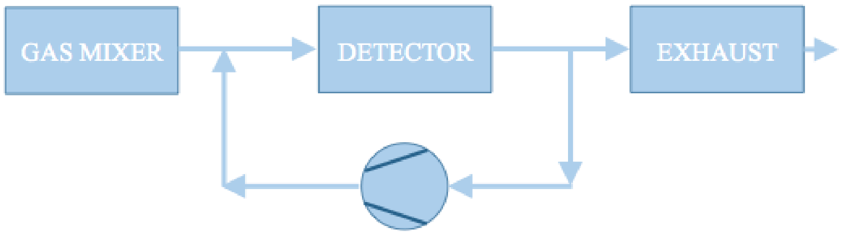
GHG Optimization: CERN Strategies

How to reduce greenhouse gas usage

- **Optimization of current technologies**
  - Gas recirculation
  - Particular attention to operation
  - Improved controls and monitoring
- **Gas Recuperation**
  - Membrane separation
  - Pressure swing
  - Cryogenic/cold separation
- **Alternative Gases**
  - New eco-friendly gases, HFOs, …
- **Gas disposal**
  - GHGs destruction

Optimization of current technologies

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



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:
  - ALICE-MTR: from Run1 to Run2: 75% GHG reduction
  - LHCb-GEM: from Run1 to Run2: 90% GHG reduction

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

- and laboratory setups:
  - 2013: Development of "A portable gas recirculation unit" JINST 12 T10002
  - 2020: Development of Gas recirculation systems for RPC detectors: from LHC experiments to laboratory set-ups - POSTER SESSION

ATLAS and CMS RPC systems

Nowadays GHGs usage for particle detectors @ LHC is dominated by the large ATLAS and CMS RPC systems:

mixture recirculation is already almost at design level (85-90%) and today it is limited by leaks at detector level

Further optimization requires:

- **Fixing leaks at detector level**
  - Huge ongoing effort of RPC detector communities (ATLAS and CMS)
  - but critical/fragile gas connectors are extremely difficult to access
  - Good technical progress
- **Gas system upgrade to minimize any pressure/flow fluctuation**
  - → Goal: new upgrades to cope with observed fragility of some detector components
  - → Positive effects already visible at end of Run2:
    - Reduced leak developments at start-up
    - Pressure regulation improved by 70%
- **Minimize impact of cavern ventilation (tests in collaboration with EN-CV)**
- **Look for other external causes (vibrations, …)**
- **Detector R&D to validate higher recirculation fraction**
- **Tools to check detector and gas system tightness**

Optimization strategies

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Optimization of gas systems → **Helps reducing gas emissions**

Optimization of gas systems → **Affects detector performances**

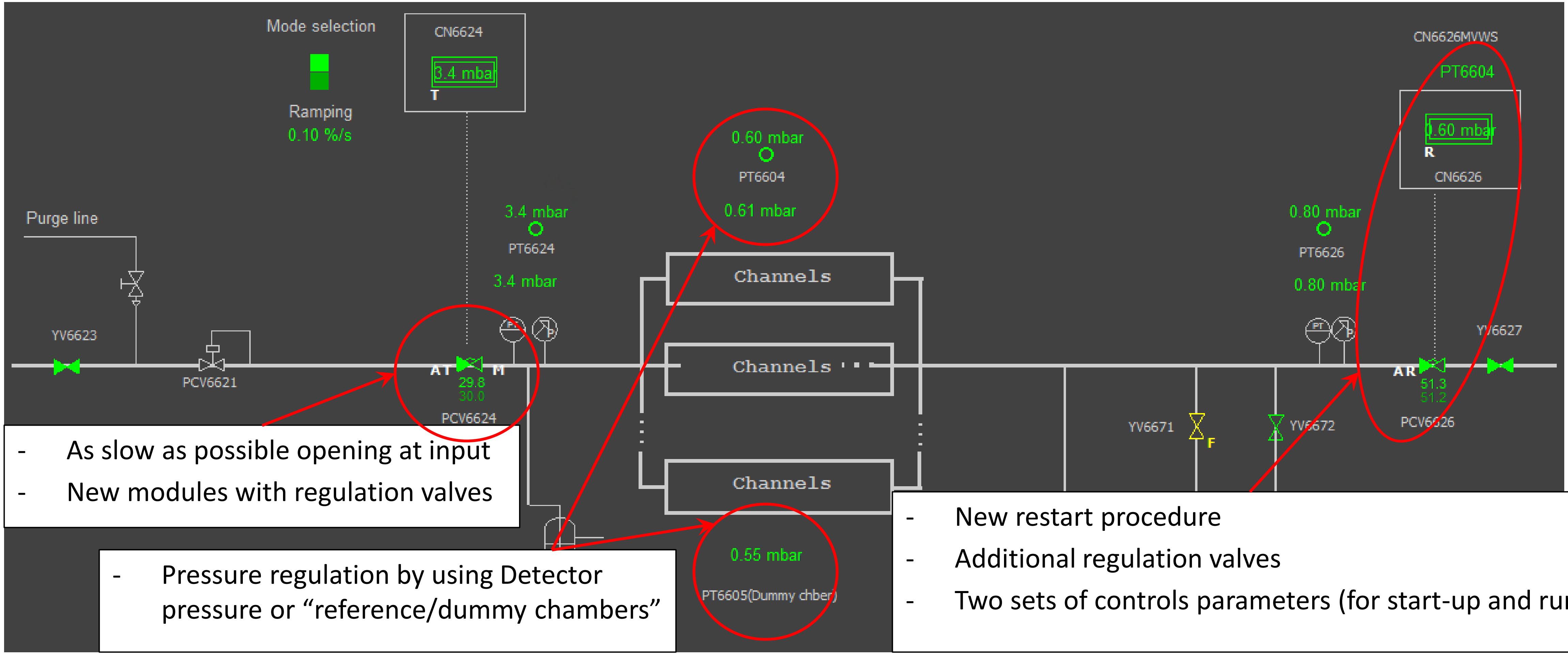
	Optimization strategy	Technical implementation	Goal	Examples
	Gas recirculation	Mixture recirculation systems	Consumption reduction, detector performance	RPC, RICH, CSC, …
Direct effects	**Flow, Pressure regulation**	Automatic regulation, PID controllers	Detector stability, leak reduction	RICH detectors, RPC leaks
	Software upgrades	Additional control features	Operation stability	All LHC gas systems during LS2 upgrades
	Monitoring	HMI, Control panels, dashboards	Anomaly detection	Impurities intake, malfunctioning of gas component
Indirect effects	**Offline analysis**	Data analysis	Deeper understanding of the dynamics	System startups, additional regulation valves when needed

Examples: RPC Gas system upgrade

Goal: minimize any chamber pressure/flow fluctuation to cope with observed fragility of some detector components

from some 0.1 mbar to ~ 0.1 mbar: not an easy challenge

Example of upgrades on **mixture distribution modules:**



- As slow as possible opening at input
- New modules with regulation valves

- Pressure regulation by using Detector pressure or "reference/dummy chambers"

- New restart procedure
- Additional regulation valves
- Two sets of controls parameters (for start-up and run)

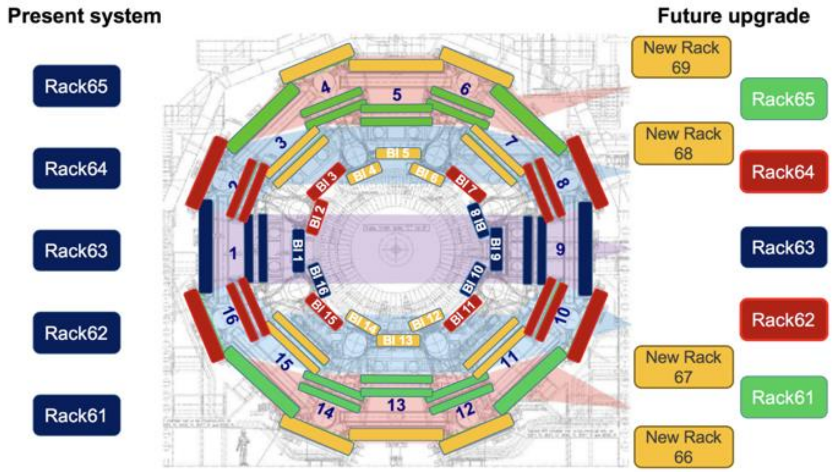
Examples: ATLAS – RPC gas system

4 New distribution racks (i.e., from 5 to 9 modules):

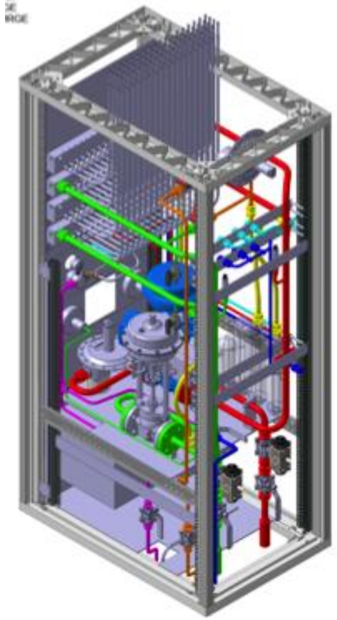
- To minimize hydrostatic pressure effect
- for the addition of new channels needed for upgrade

Upgrade of existing racks:

to minimize any chamber/flow fluctuation from some 0.1 to ~0.1 mbar



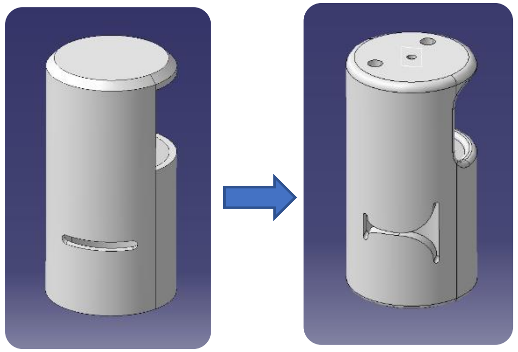
From design to installation:



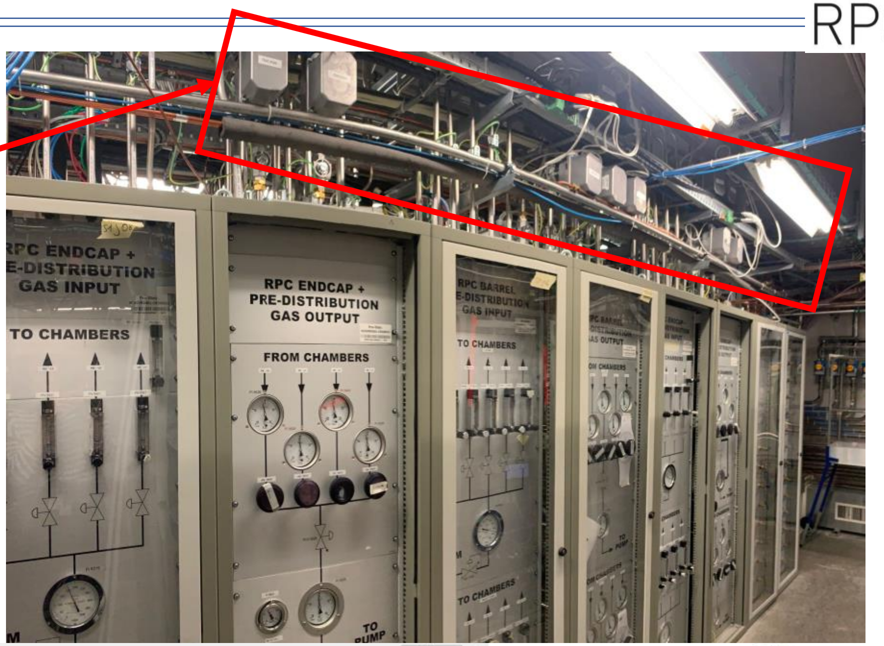
Examples: CMS – RPC gas system

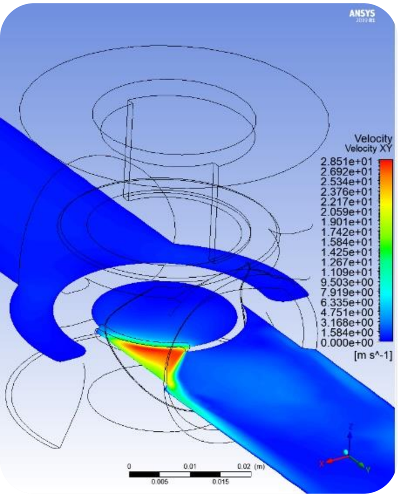
Many tests performed in laboratory and at CMS

- One valve selected: ECONEX
- Valve seats specific for distribution module:
  - Different in BARREL and ENDCAP
  - **R&D to improve/design seat shape**

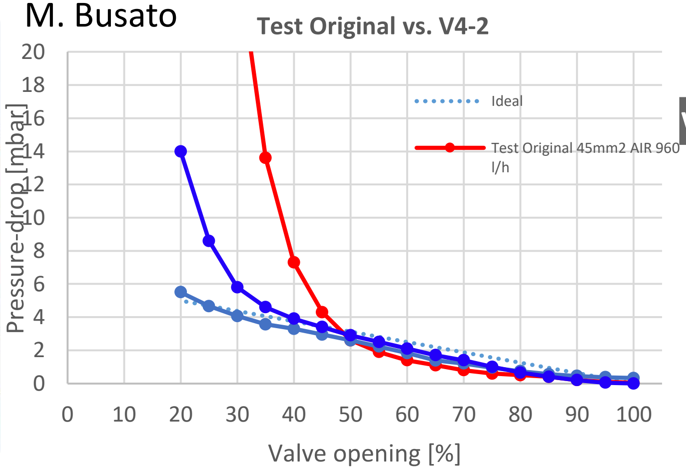


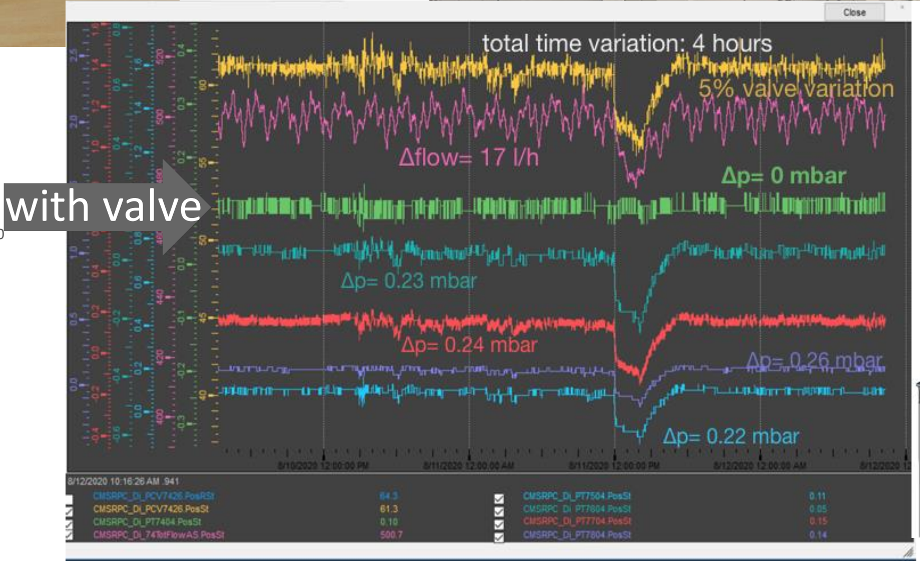
Valves installed

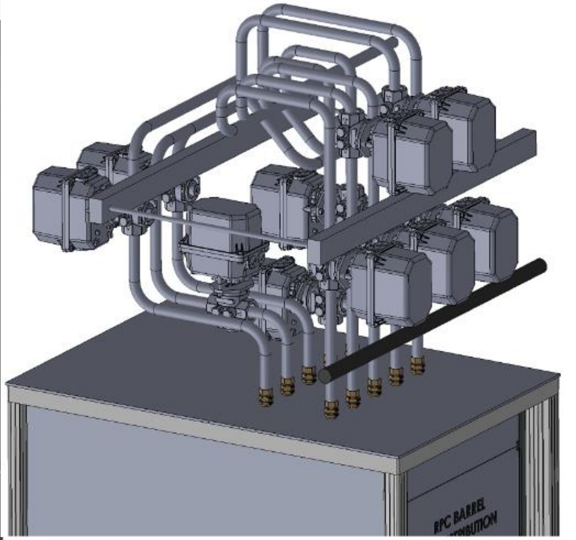




M. Busato







Examples: ATLAS and CMS – RPC gas systems

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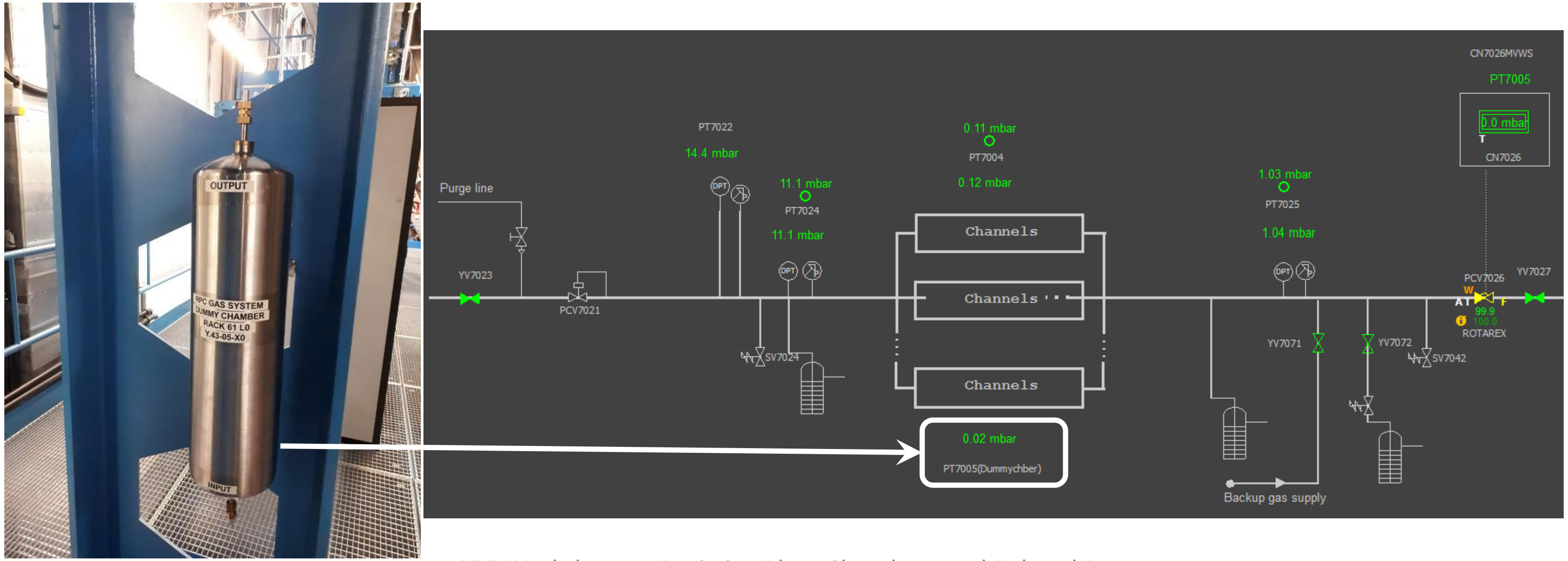
Detector pressure regulation was done using sensors at rack level:

- Weight of hydrostatic column was not taken into account
- Particularly critical during fill and emptying phases
- Pressure sensors already present at detector level cannot be used due to risk of detector leak presence/development

→ Installation of volumes that simulates detectors (reference sensors/“dummy RPC”)

→ Extremely useful during detector filling after shutdown (when mixture hydrostatic pressure is changing significantly)

→ Minimize over-pressure at chamber level

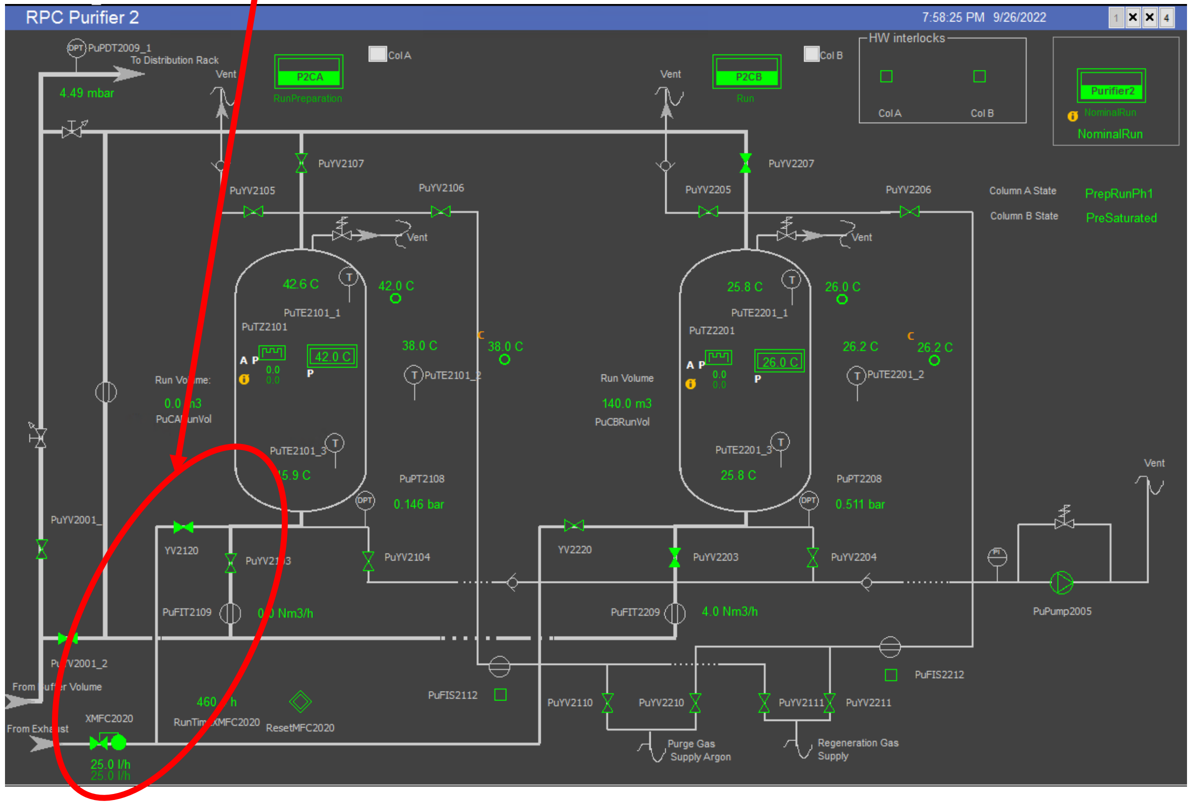


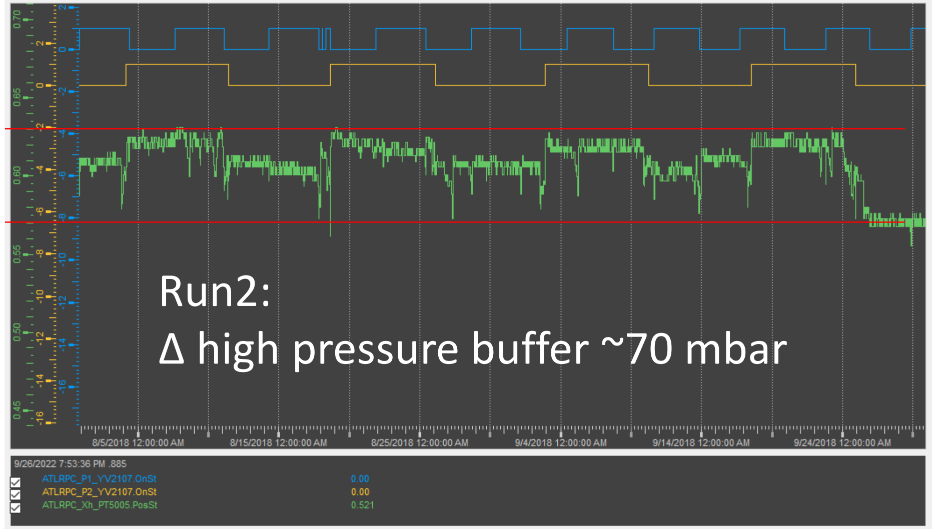
Examples: ATLAS and CMS – RPC gas systems

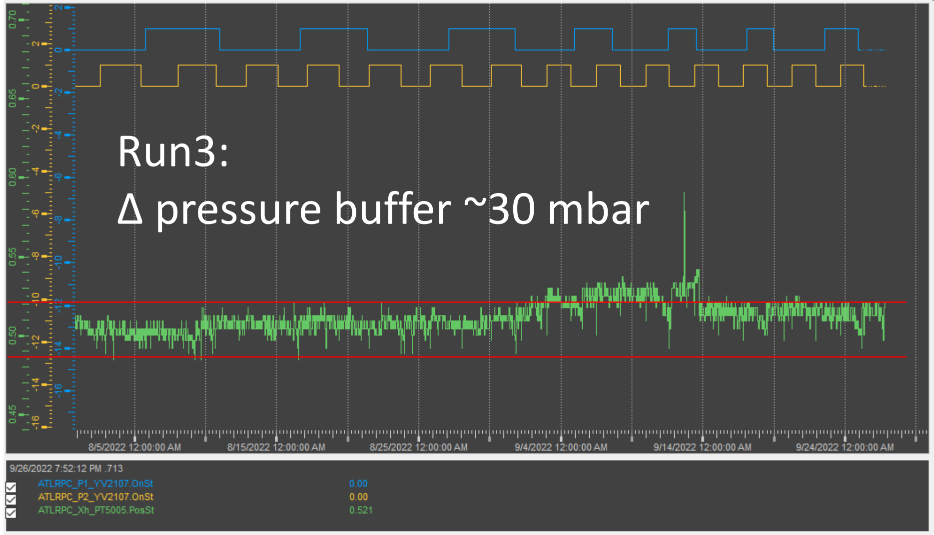
Upgrade of purifier modules

→ Smoother change to run conditions:

modification of preparation for run phases



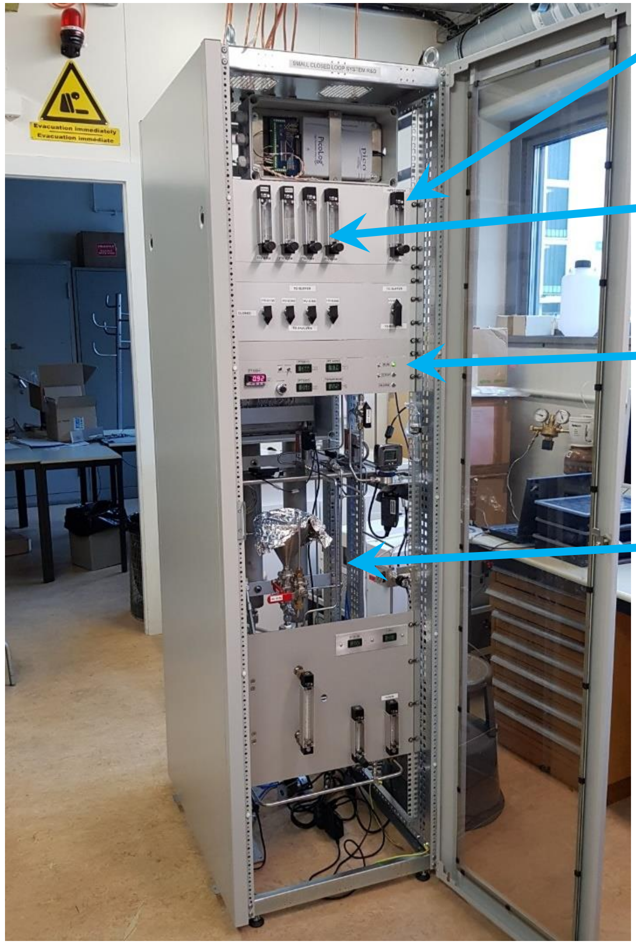




"Lab size" gas systems

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



Fresh input from mixer

Distribution to detectors

Monitoring of pressure, O_2/H_2O, temperature, atmospheric pressure

Humidifier

- 2013: Development of "A portable gas recirculation unit" JINST 12 T10002
- 2019: Development of Gas recirculation systems for RPC detectors: from LHC experiments to laboratory set-ups - POSTER SESSION

Other group working on similar topics:

- E. Pastori, B. Liberti Low-cost Gas recirculation system for the RPCs chamber - POSTER SESSION

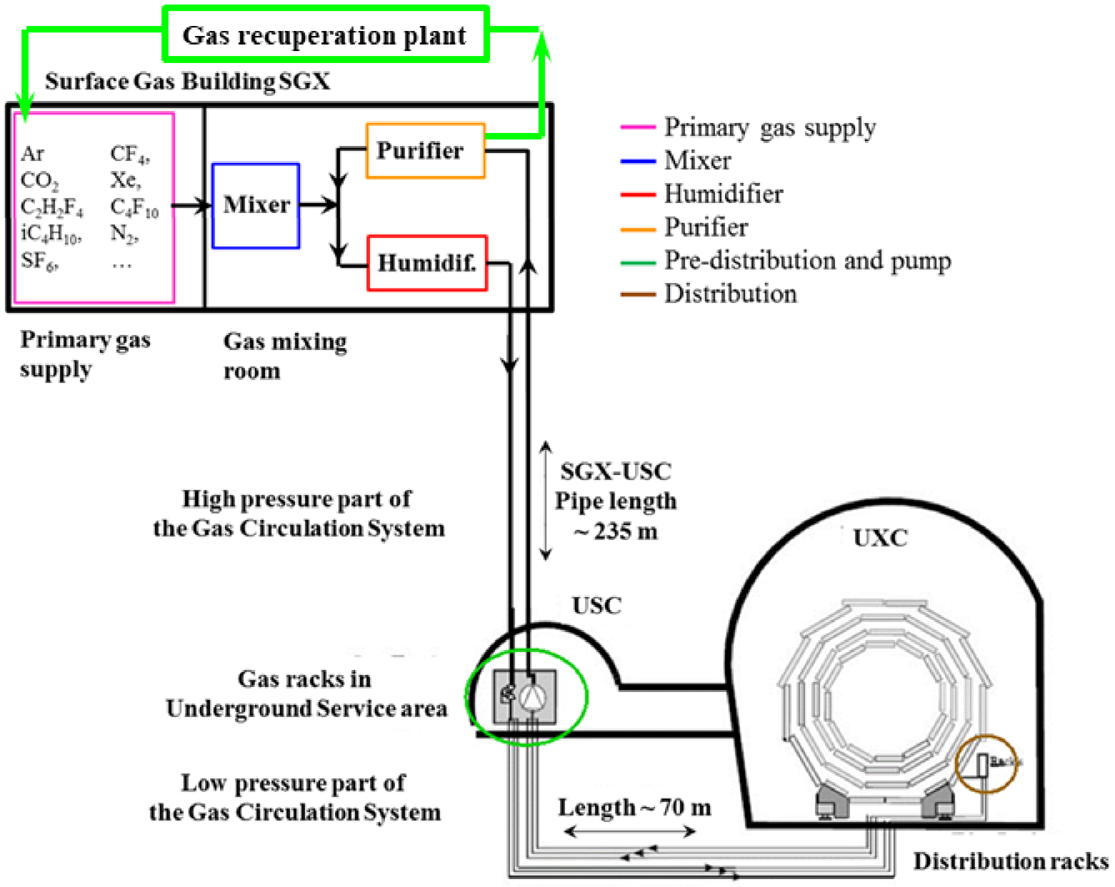
GHG Optimization Strategies

How to reduce greenhouse gas usage

- **Optimization of current technologies**
- **Gas Recuperation**
  - Membrane separation
  - Pressure swing
  - Cryogenic/cold separation
- **Alternative Gases**
- **Gas disposal**

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*:**
  - **R134a for ALICE-RPC, ATLAS-RPC, CMS-RPC, ALICE-TOF**
- ***and substantial improvements of existing systems:***
  - **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 Recuperation: the R134a case

2018: Prototype0 tested in ATLAS-RPC (100 nl/h)

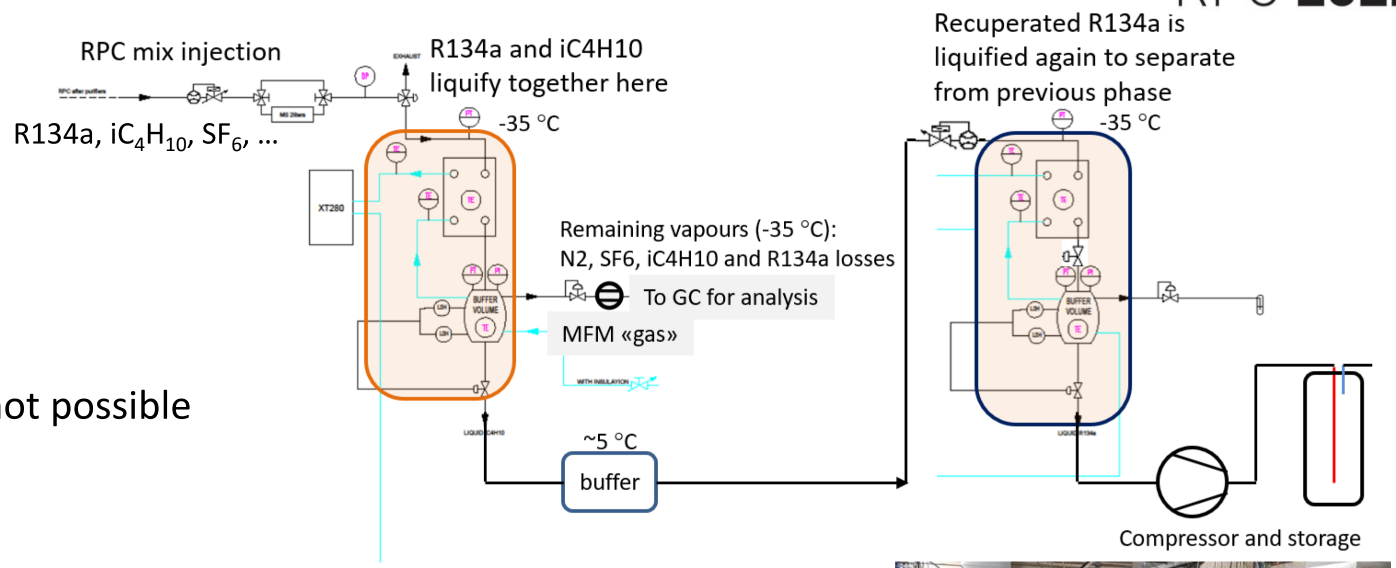
- encouraging results, air/N2 and iC4H10/SF6 removed

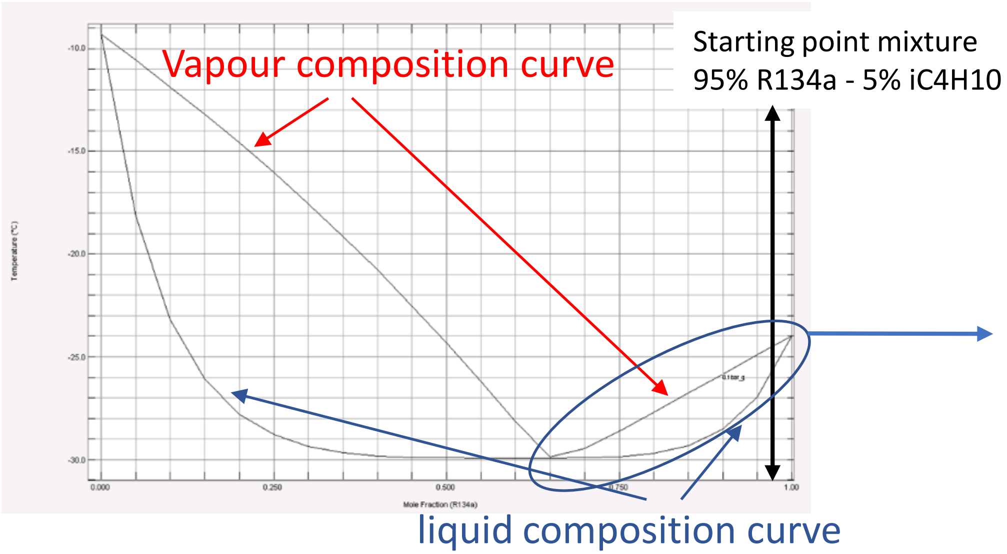
2019: Prototype0 moved to CMS

2020: test restarted at CMS with CMS-RPC

- R134a/iC4H10 form an **azeotrope**

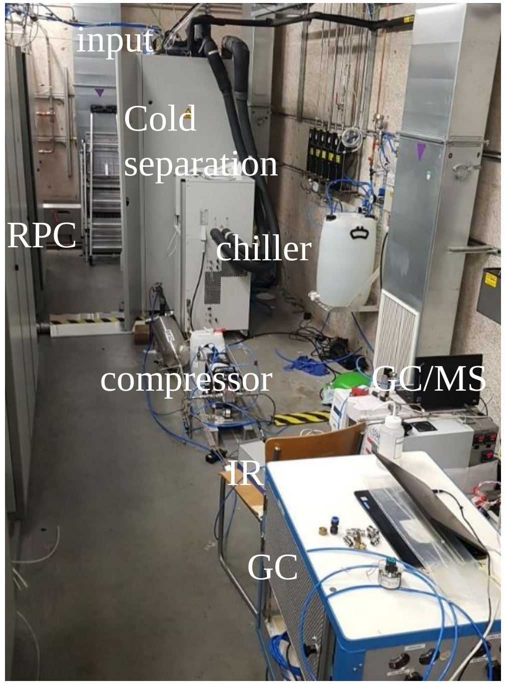
→ simple separation thanks to difference in boiling points is not possible





R134a/iC4H10 remaining mixture is totally liquefied and it is sent to buffer at 5 °C:

- azeotropic mixture is slowly heats up
- liquid is enriched of pure R134a
- vapour of azeotrope which escapes from exhaust

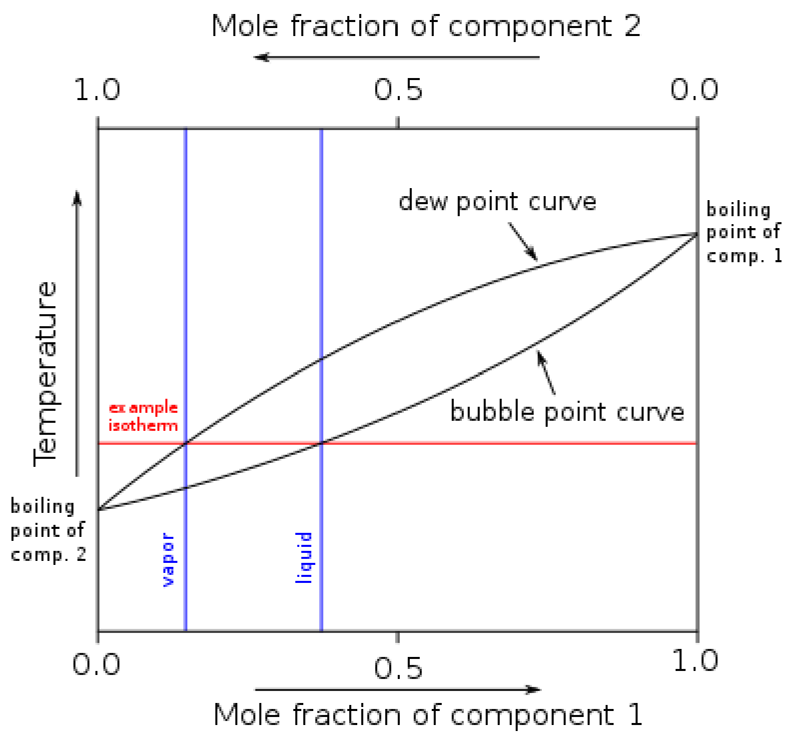


Gas Recuperation: the R134a case

Ideal mixture:

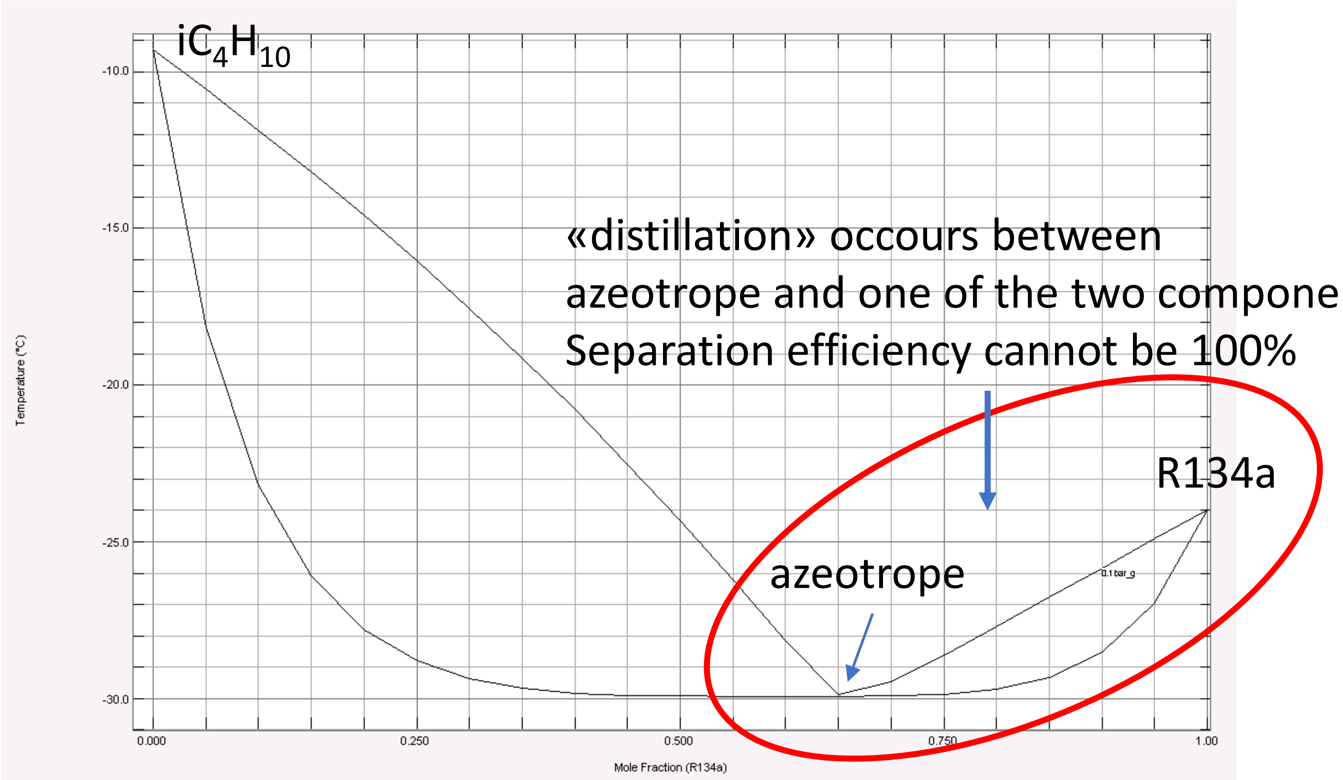
Two boiling termeratures (component1 and component2)

No other min/max for vapour and liquid curves



Azeotropic mixture:

In the boiling temperature vs composition plot is present a min or a max



«distillation» occours between azeotrope and one of the two components

Separation efficiency cannot be 100%

Gas Recuperation: the R134a case

Status (Master Thesis F. Cambiè, D. Burragato, M. Di Toma)

collaboration with:

- **Chemistry department University of Pavia, Italy**
- **Politecnico of Torino, Italy**

- **Input flow tested up to 600 l/h**
- **Good R134a quality with good recuperation efficiency (~80% limit due to azeotrope)**
  - **Contaminants: air and SF6 (<50 ppm) and iC_4H_{10} (close to detection limit)**
- Integration of compressor unit and storage of recuperated R134a completed

Tests still needed

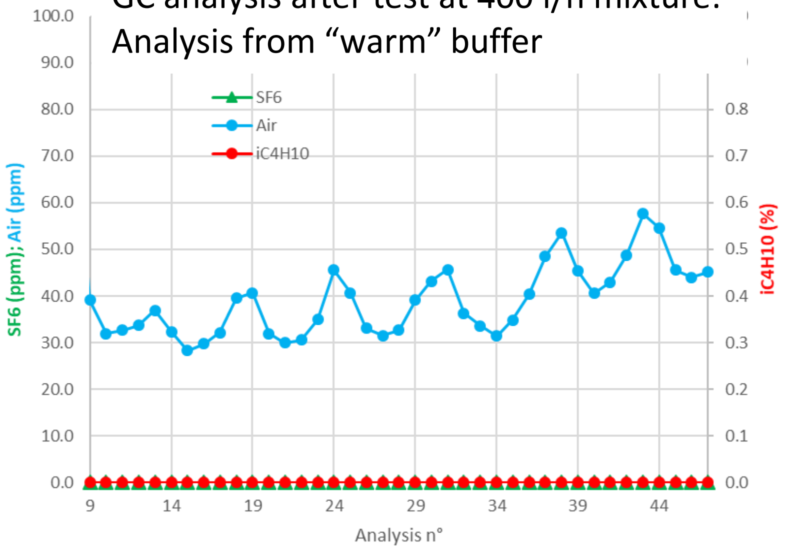
- **Input flow up to 1000 l/h**

  Azeotrope can be a problem for high flow
- **Re-use of recuperated R134a in mixer: end-2022**
- **Separation studies of possible RPC impurities: 2023**
- **R&D for possible recuperation of SF_6 (timescale to be defined)**

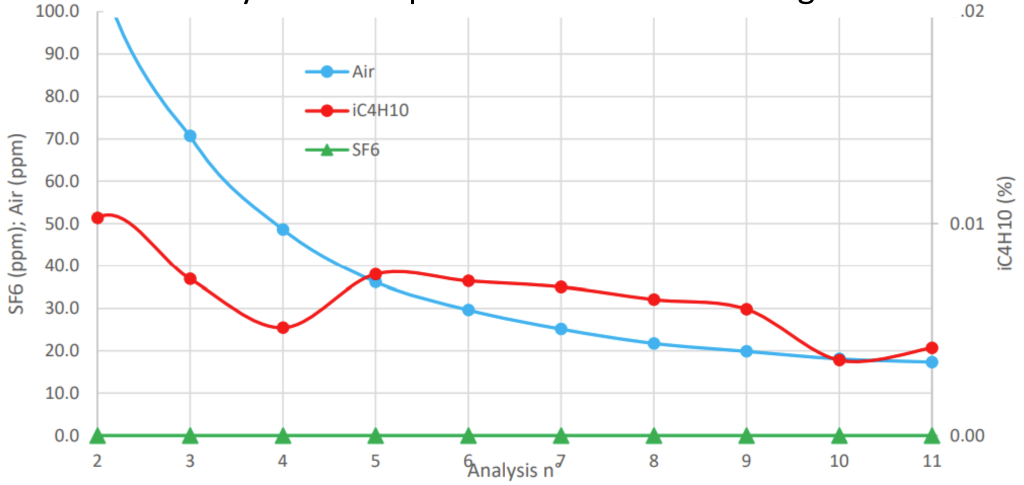
Final system

- Construction of a second prototype: end-2022
  - It should be very similar to final system
- Final recuperation system: construction end of 2022
  - …if satisfactory results from second prototype

GC analysis after test at 400 l/h mixture:
Analysis from "warm" buffer



GC analysis of recuperated R134a from storage bottle



Conclusions

Program described aims in developing systems for optimization of GHG usage

- For many gases used today there is no equivalent replacement available for our application
- Availability and price of used GHGs can be affected (one more good reason for optimizing consumption)

Four strategies identified:

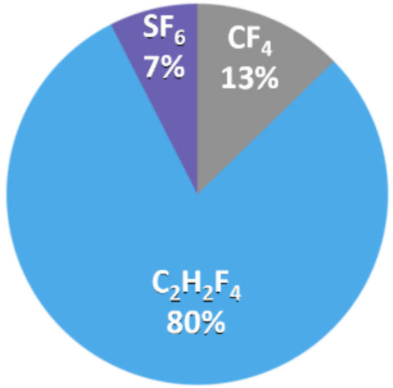
1) Optimization of current technologies

- Particular attention to gas system and detector operation
- Gas systems upgrade beyond original design
- Improved/higher gas recirculation

2) Gas recuperation plant

- Gas recuperation will be effective only if leaks at detector level will be reduced
- R&D costs for R134a recuperation system is well justified by running costs
- R134a recuperation prototype0 is more complicated than expected but showed good performance:
  - ~ 80% recuperation efficiency and good gas quality
- Consolidation of existing plants (CF_4, C_4F_{10}) ongoing:
  - CMS-CSC-CF4 recuperation efficiency increased to 70%
  - LHCb-RICH2-CF4 installed
  - LHCb-RICH1-C4F10 design ongoing

Recuperation of R134a can drastically decrease GHG consumption



Conclusions

3) New eco-gases

- HFO1234ze and others promising but difficult for already installed detectors (many constrains) at LHC experiments
- Mid-term possibility to be further investigated: RPC mixture dilution with inert gas
- First test of gas recirculation with HFO started (in lab and with high radiation background)
- However, it is not for the near future

4) GHGs abatement/disposal

- Commercial systems exist. Adopted when gases cannot be reused.
- Heavy infrastructures required (CH_4+O_2 supply, Waste water treatment)
- Since availability/price can become a real problem in the future it is better to optimize consumption
- Destruction in external companies: more expensive than Gas abatement system.

Thank you!

Optimization of gas consumption

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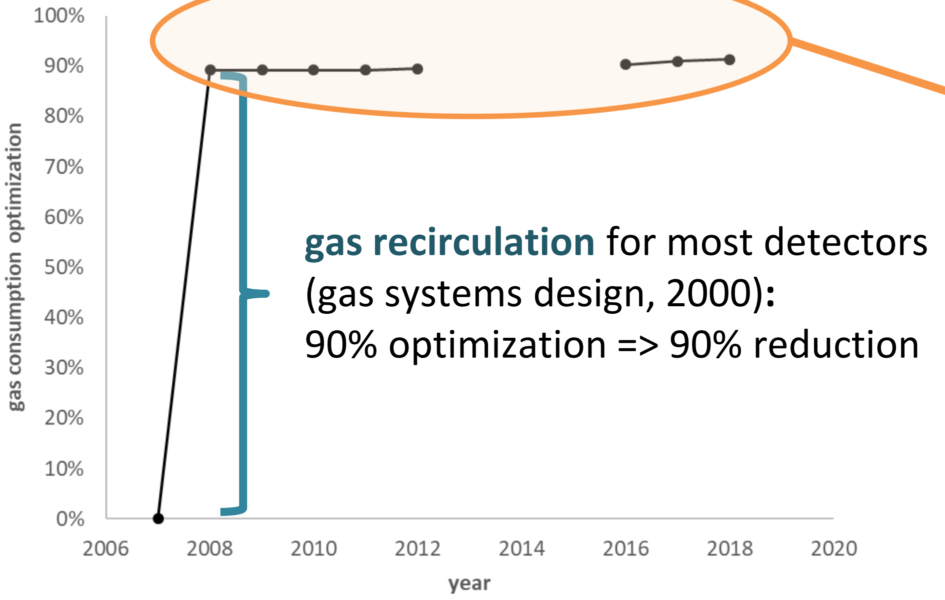
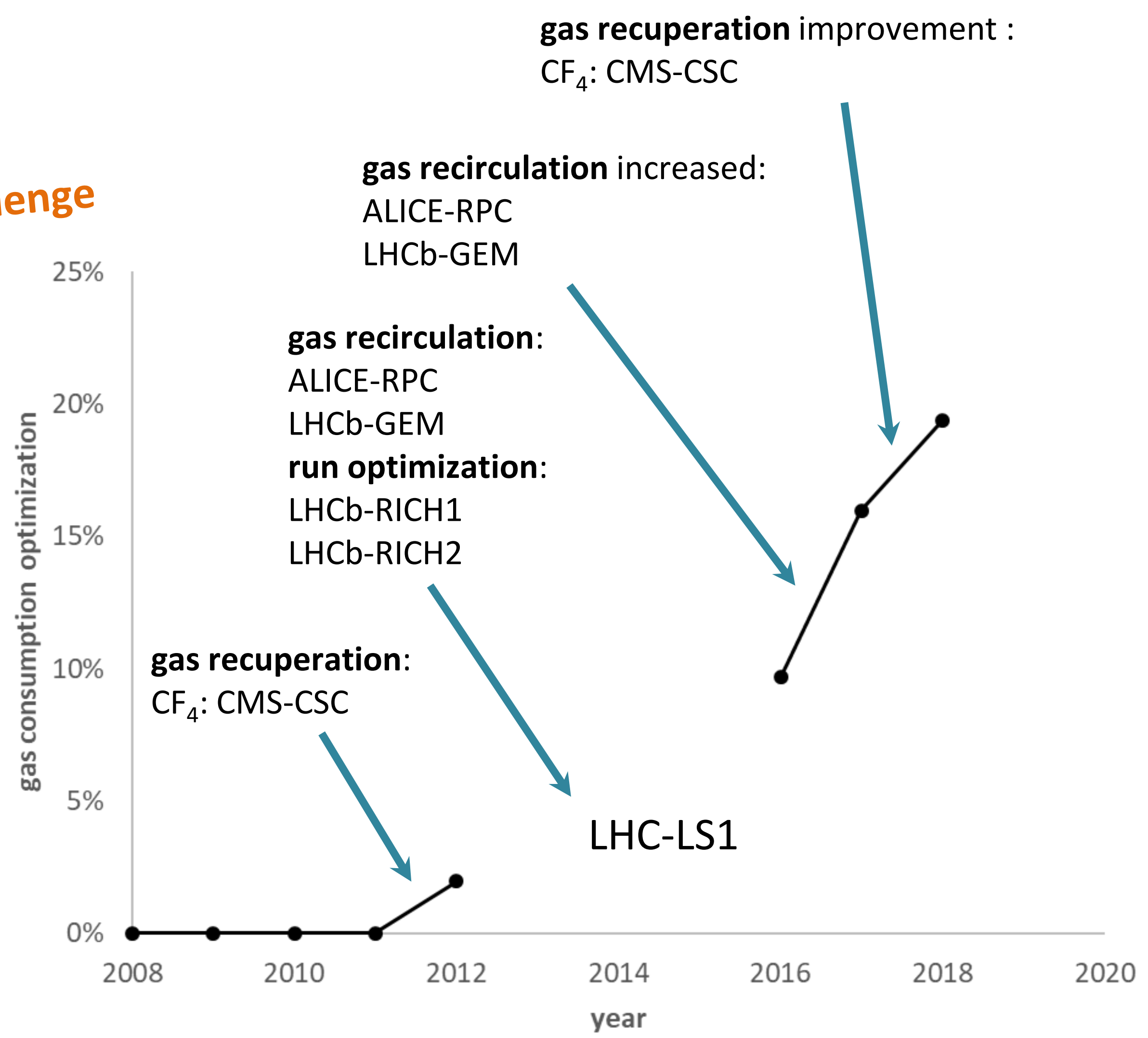
Today optimization challenge





Spare Slides

GHG equivalent emissions

Run 2 emissions from F-gases ~ 130 000 tCO2e

Geneva emissions 2019 ~ 2 650 000 tCO2

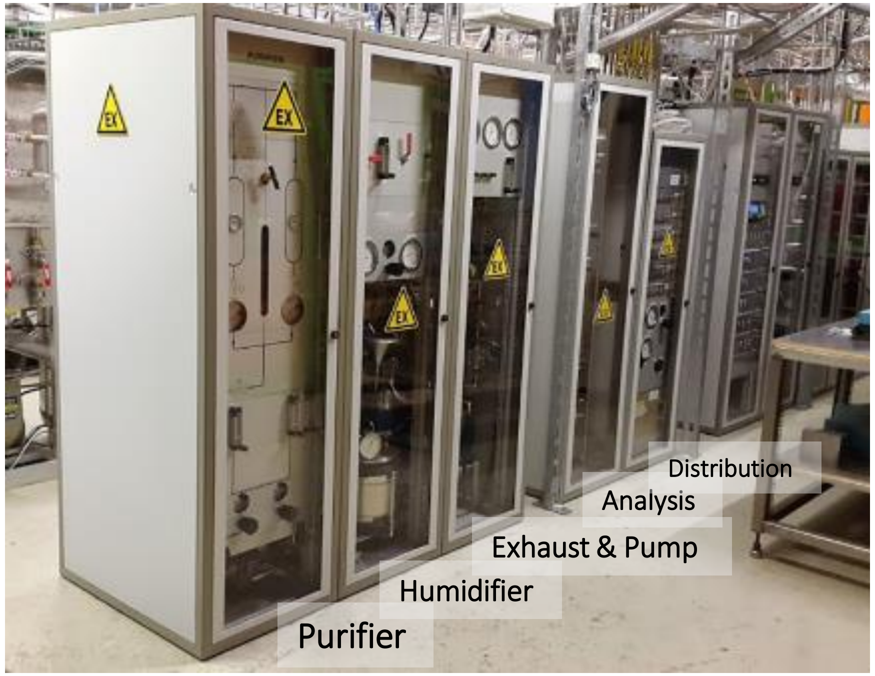
Switzerland emissions 2018 ~ 39 637 007 tCO2e

CERN contribution ~ 5% of Geneva, 0.3 % of Switzerland GHG emissions

https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator

Gas systems for LHC experiments

- <u>Gas system for detector at LHC experiments:</u>
  - Very large apparatus
  - Mixing the different gas components in the appropriate proportion
  - Distributing the mixture to the individual chambers
- <u>Gas systems are made of several configurable functional modules</u> (*building blocks*):
  - Simplifies maintenance, operation, training of personnel, …



Three keywords for such a large infrastructure:

- 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, …)

Greenhouse gases used for particle detection

A **greenhouse gas** (GHG) is any gaseous compound that is capable of absorbing infrared radiation, thereby trapping and holding heat in the atmosphere

The **Global Warming Potential** (GWP) is a relative measure of how much heat a greenhouse gas traps in the atmosphere with respect to CO_2

GHGs like R134a ($C_2H_2F_4$), CF_4, SF_6, C_4F_{10}, … are used by several particle detector systems at the LHC experiments

Gas	GWP - 100 years
$C_2H_2F_4$	1430
CF_4	6500
SF_6	22800

Due to the environmental risk, "**F-gas regulations**" started to appear in many countries.

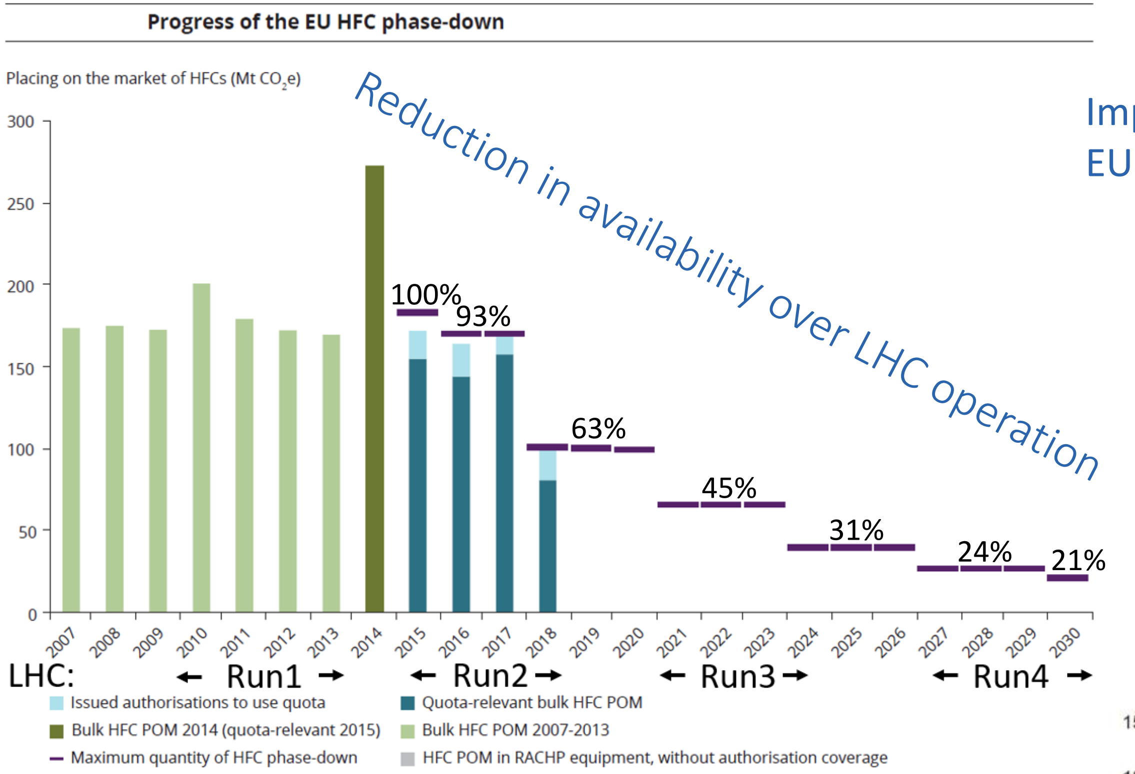
For example, the EU517/2014 is:

- **Limiting** the total amount of the most important F-gases that can be sold from 2015 onwards. By 2030, it limits the use to one-fifth 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.

F-gas regulations have already affected **gas price** (especially for R134a in EU)
Future **availability** can also be affected (especially where replacements are available)

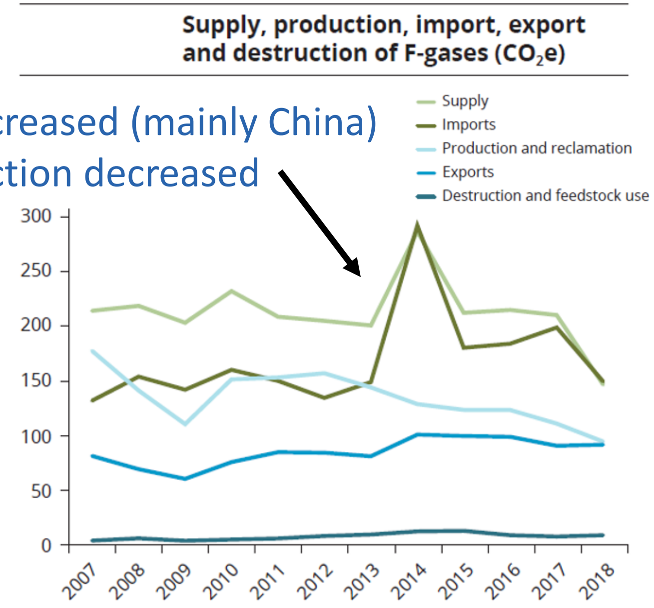
Greenhouse gases: EU HFC phase-down

HFC phase down: effects on HFC availability and prices



Import increased (mainly China)

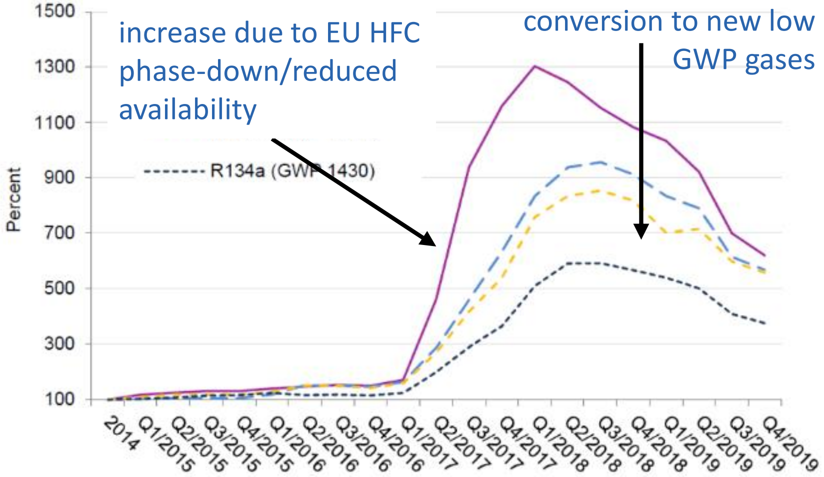
EU Production decreased



Price fluctuations:

increase due to EU HFC phase-down/reduced availability

decrease due to industrial conversion to new low GWP gases

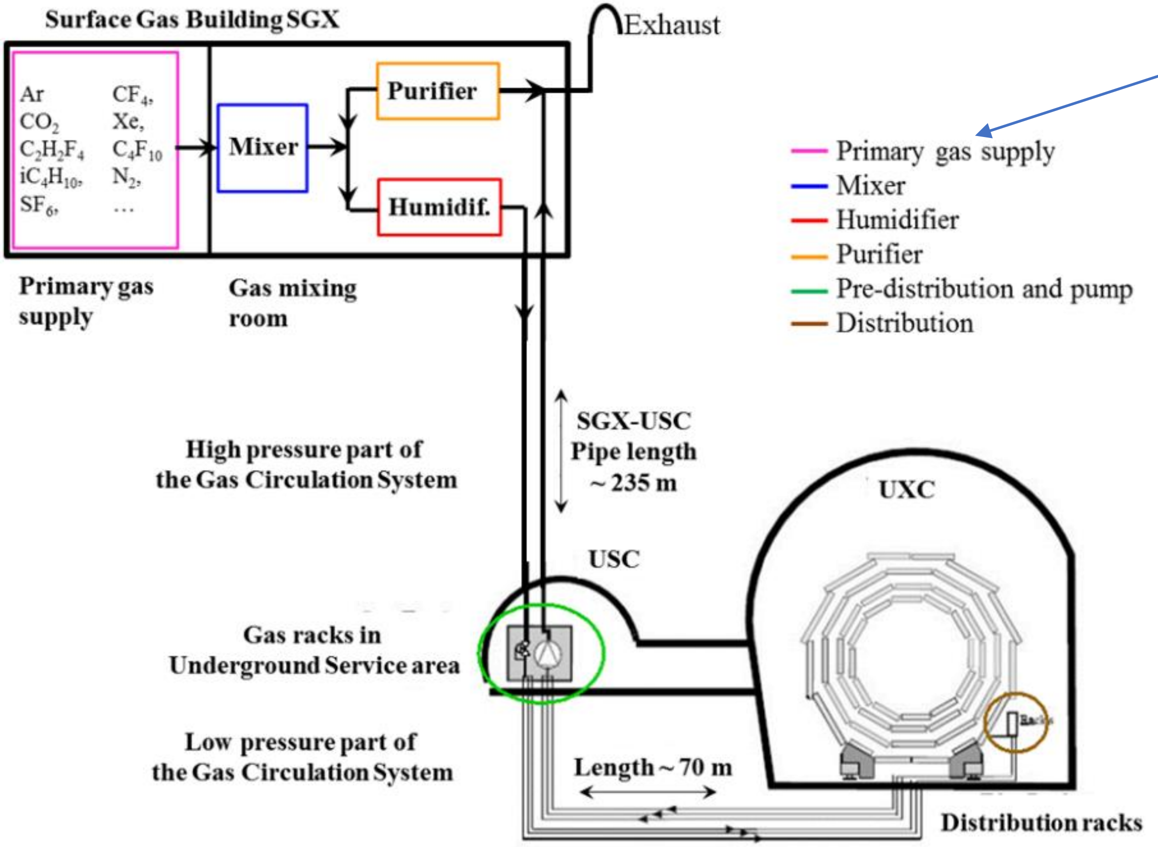


Sources:
European Environment Agency, Fluorinated greenhouse gases 2019 report
Öko Recherche report, March 2020 J. Kleinschmidt et al.

Gas systems for LHC experiments

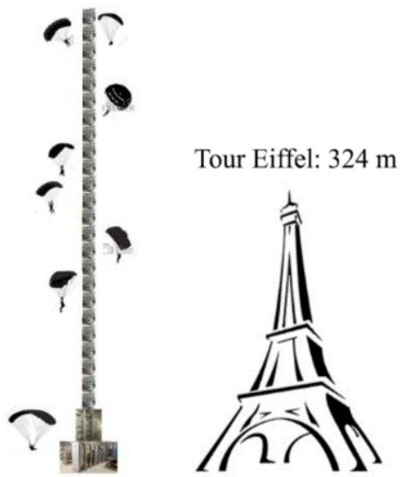
Gas systems extend from the surface building to the service balcony on the experiment following: a route few hundred meters long.

1 gas system = ~ 10 active modules



LHC gas systems = 30 systems =
= 300 modules

LHC gas systems modules > 500 m



Concerning *Optimization of current technologies* for reduction of GHG usage

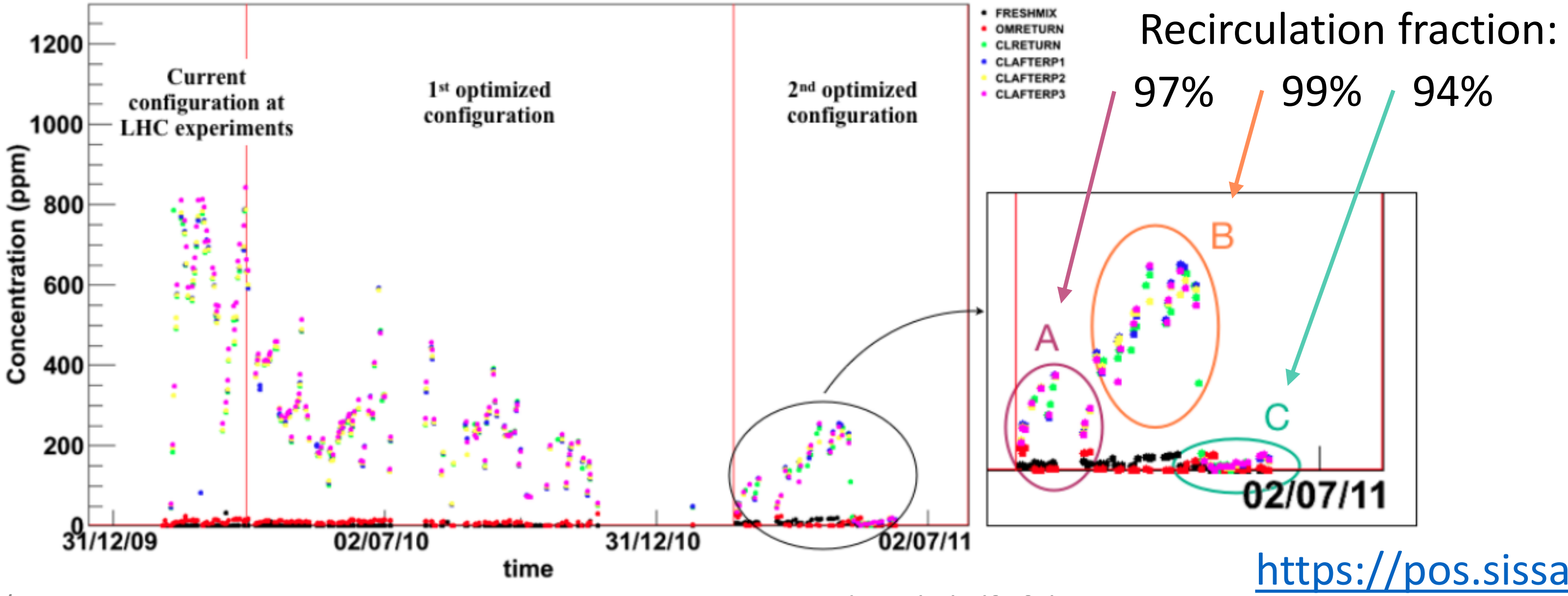
→ RPC operation at higher recirculation fraction

Today mixture recirculation is limited at about 85%

Detector validated up to 90%

What about recirculating more? Only short test performed in the past (2011) up to 97-99%

Gas recirculation and impurities in past test

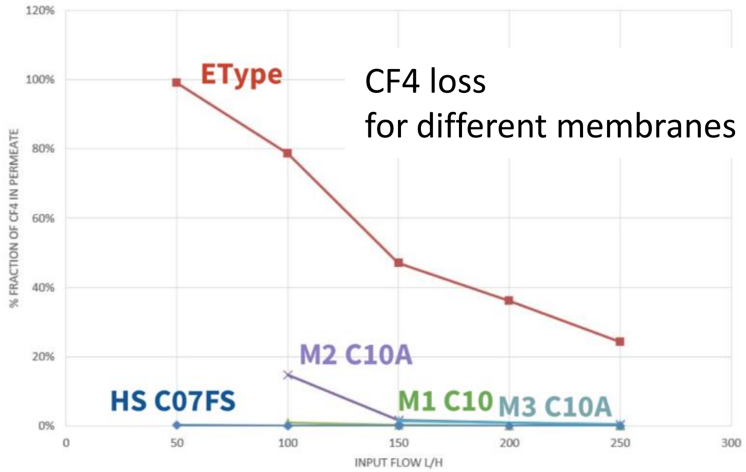


https://pos.sissa.it/159/029/pdf

CSC CF4 Recuperation Plant: recent R&D studies

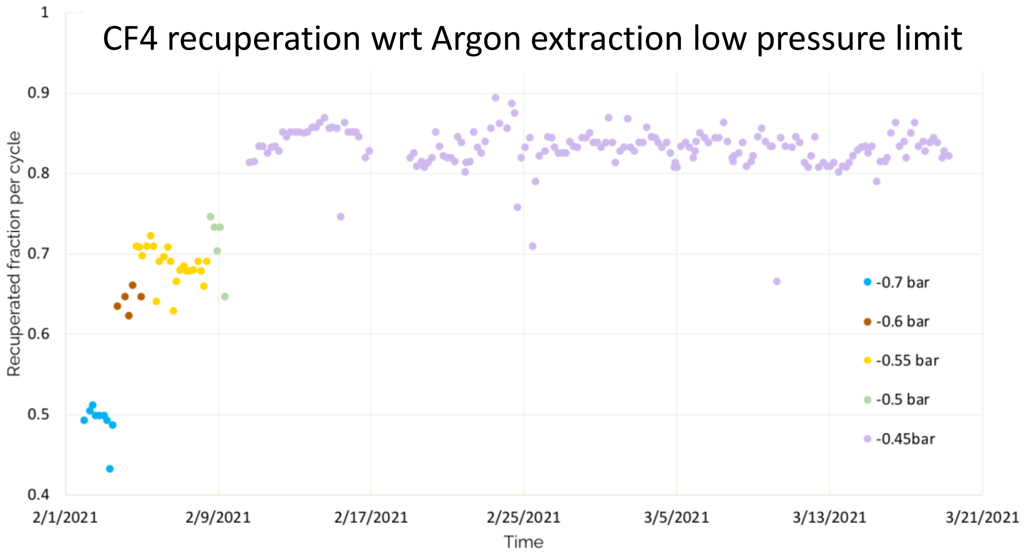
Membrane module

- **Search and characterization of new membranes**
  - Membranes used in industry to recuperate CO_2
  - For different flow and with different sensitivity
- **Characterization of existing membranes to improve CF_4 loss**
  - Impact of different permeate side pressures for Ar, CO_2, O_2, N_2 extraction
  - Impact of input flow fluctuations on the membrane efficiency
  - Monitoring and fine tuning of membrane parameters



CF_4 adsorption module

- Pressure-swing method
- **Timing/optimization of run parameters**
  - Example: Ar extraction low pressurelimit
- Characterization of recuperated gas during full cycle
  - GC analyses for recuperated and exhaust gas



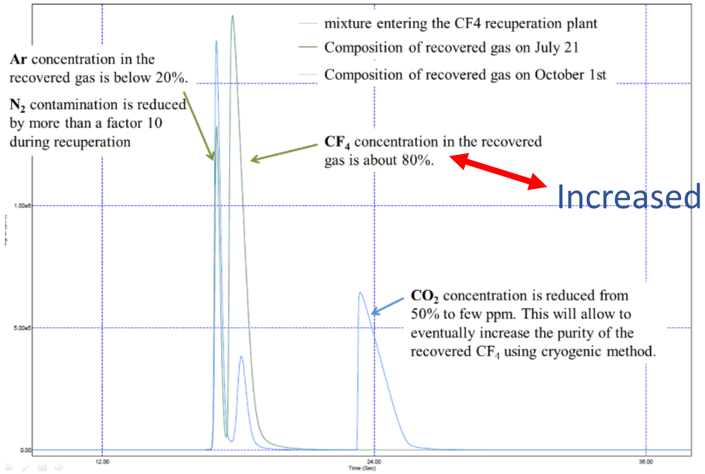
→ ***CF4 recuperation efficiency increased to about 70%***

- and more studies still ongoing
- improvements possible thanks to additional resources
- Need of dedicated qualified personnel

Gas recuperation: monitoring quality of recuperated gas

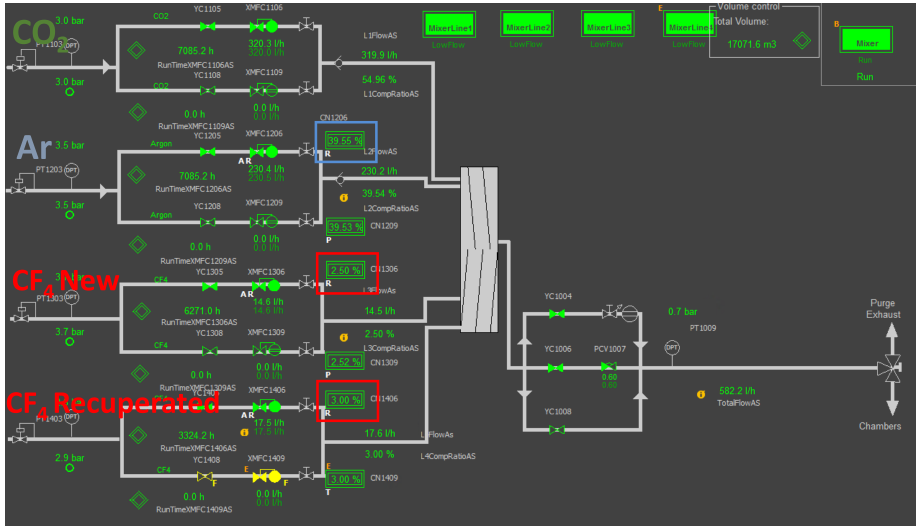
Complexity of using a recuperated gas: mixture quality monitoring ensuring good composition and avoiding ageing

Quality of recuperated CF_4 is monitored: with **GC analysis**

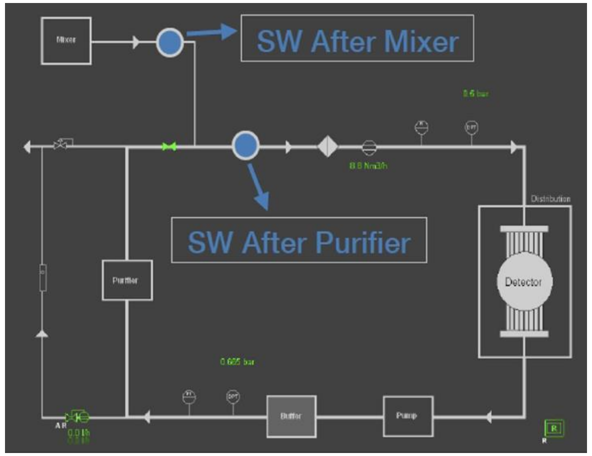


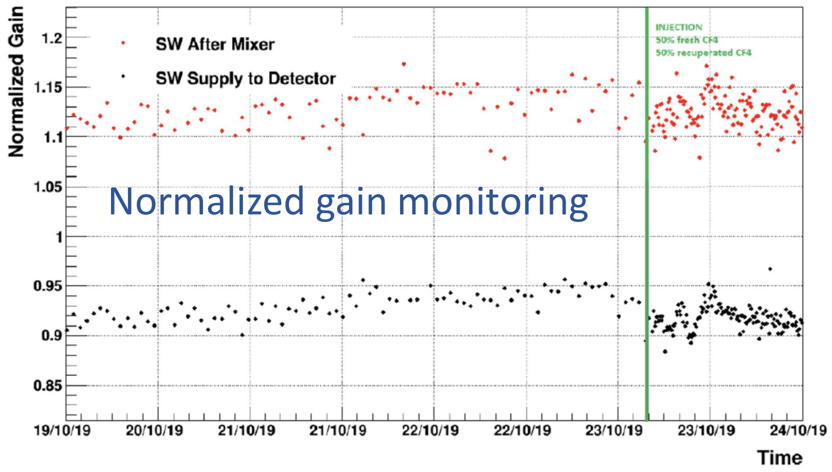
Increased to about 95%

Mixed injection of CF_4 50% recuperated and 50% new



and with gas mixture monitoring: **Single Wire Chambers**

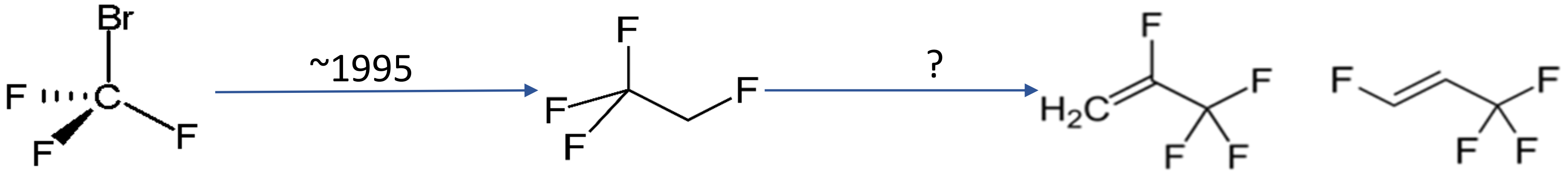




Alternative Gases

New low GWP gases alternative to R134a are already available on the market and used by industry

It is not the first time this happens in particle detection:



R13B1		R134a		HFO1234yf	HFO1234ze
($CBrF_3$)		($C_2H_2F_4$)		($C_3H_2F_4$)	($C_3H_2F_4$)
ODP* 10	→	ODP 0		ODP 0	ODP 0
GWP 6900	→	GWP 1430	→	GWP 4	GWP 6

HFOs refrigerant properties are well known while studies of ionisation processes just started…

R&D studies are ongoing. *Main constrain is coming from need of maintaining current infrastructures (HV cables, Front End electronics) very difficult to access for replacement.*

More details on Thursday, Detectors for Future Facilities session:
"Performance studies of RPC detectors operated with new environmentally friendly gas mixtures in presence of LHC-like radiation background"

*The Ozone Depletion Potential (ODP)

GHG abatement system

In case all studies on recuperation will not bring to efficient recuperation plants, industrial system able to destroy GHGs avoiding their emission into the atmosphere have been considered

Abatement plants are employed when GHG are polluted and therefore not reusable.

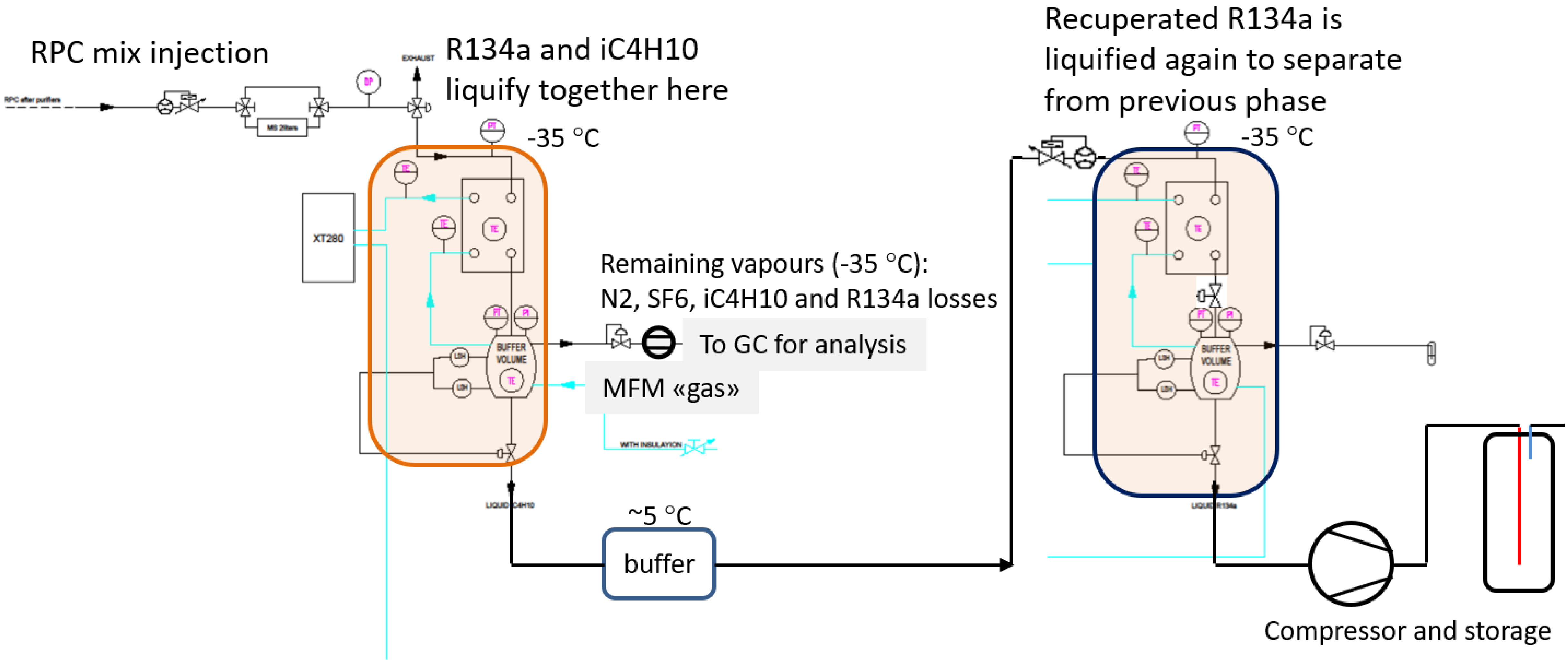
Quite heavy infrastructure required:

- CH_4/city gas + O_2 supply + N_2 supply
- Waste water treatment
  - PFC/HFC are converted in CO_2 + HF acid dissolved in water
  - disposal of remaining waste/mud

Joint CMS and EP-DT gas team is studying the feasibility

Found also companies available to take PFC/HFC based mixture for disposal:

but extremely expensive


RPC mix injection
R134a and iC4H10
liquify together here
-35 °C
Recuperated R134a is
liquified again to separate
from previous phase
-35 °C
Remaining vapours (-35 °C):
N2, SF6, iC4H10 and R134a losses
To GC for analysis
MFM «gas»
~5 °C
buffer
Compressor and storage
XT280
BUFFER VOLUME
EXHAUST