EP-DT
Detector Technologies

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R&D for reducing the use of greenhouse gases in the LHC particle detection systems

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Outline

- Greenhouse gases (GHG) for particle detection
- Gas Systems for the LHC experiments
- Strategies for optimizing GHG usage
- Results, new projects and plans
- Conclusions

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	23900

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

For example, the EU517/2014 is:

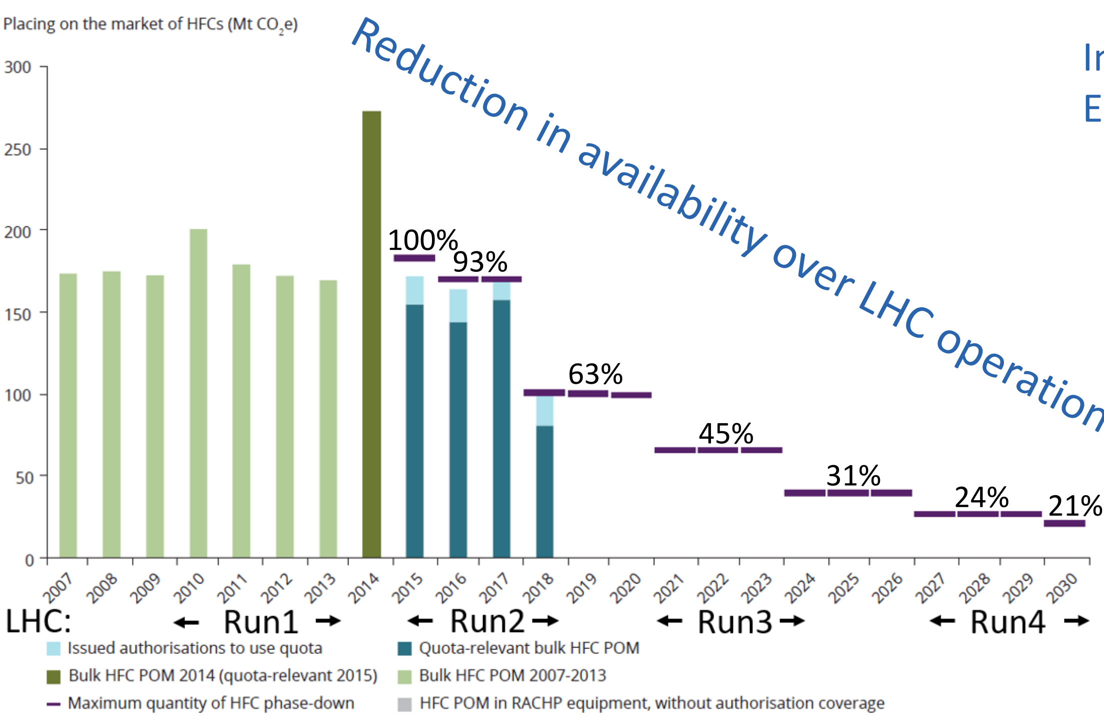
- **Limiting** the total amount of the most important F-gases that can be sold from 2015 onwards. By 2030, it limits the use to one-fifth of 2014 sales.
- **Banning** the use of F-gases in new equipment where less harmful alternatives are available.
- **Preventing** emissions of F-gases from existing 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)

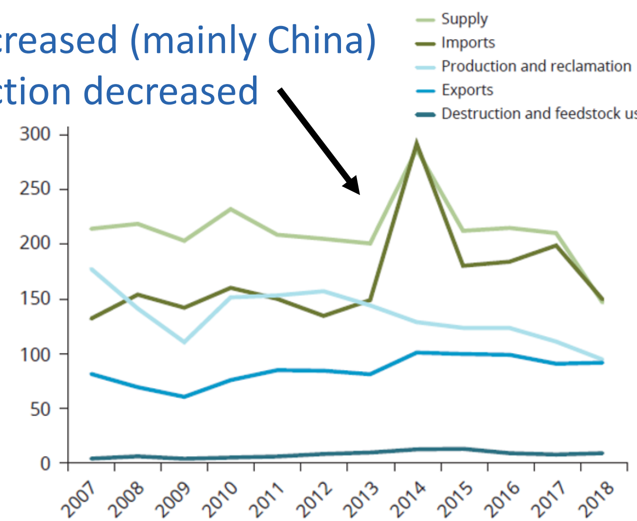
Greenhouse gases: EU HFC phase-down

HFC phase down: effects on HFC availability and prices

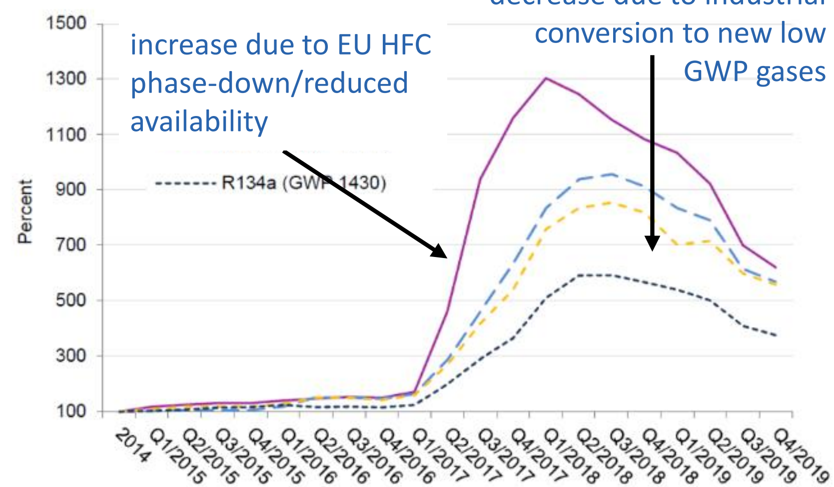
Progress of the EU HFC phase-down



Supply, production, import, export and destruction of F-gases (CO_2e)



Price fluctuations:



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

Gaseous detector systems at LHC

<u>Very Large detector volume</u>
- *From < 1 m^3 up to several 100 m^3*

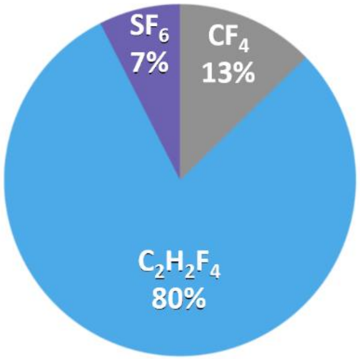
Use of many gas components
- *R134a, SF_6 , CF_4, C_4F_{10}, … (<u>GHG</u>)*
- *many others neutral but some <u>expensive</u> (Xe, …)*

\+ High mixture flow
\+ Operational costs issue
→ ***Optimization of gas usage is need***

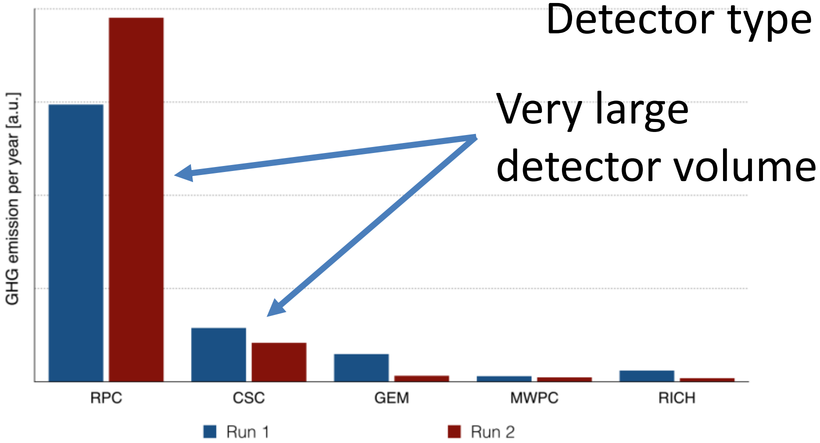
A lot of work already from the design phase
→ otherwise operational costs due to gas consumption would have been huge

Relative contribution of GHGs used at LHC experiments

Gas type



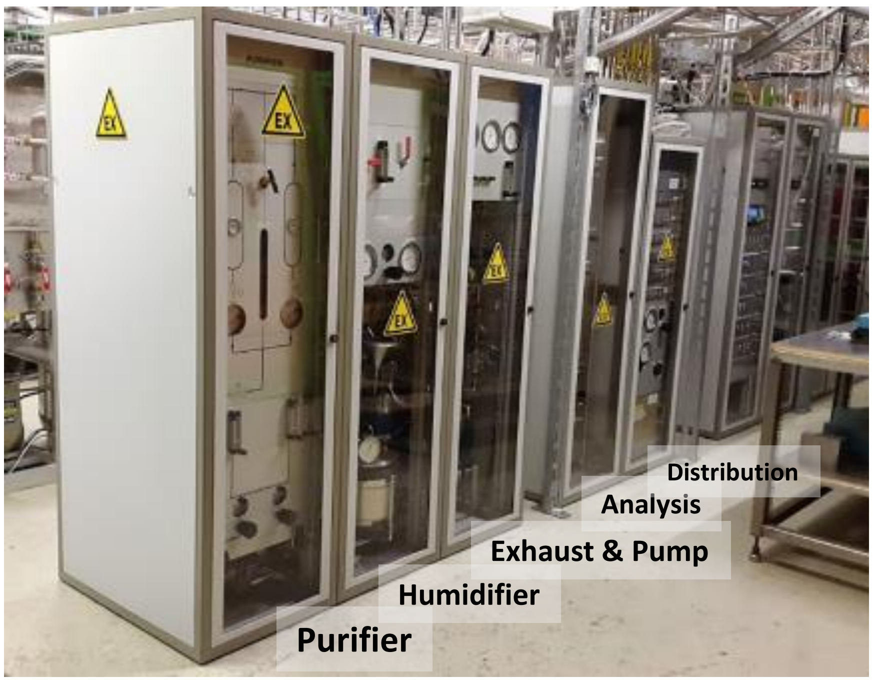
Detector type



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

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:

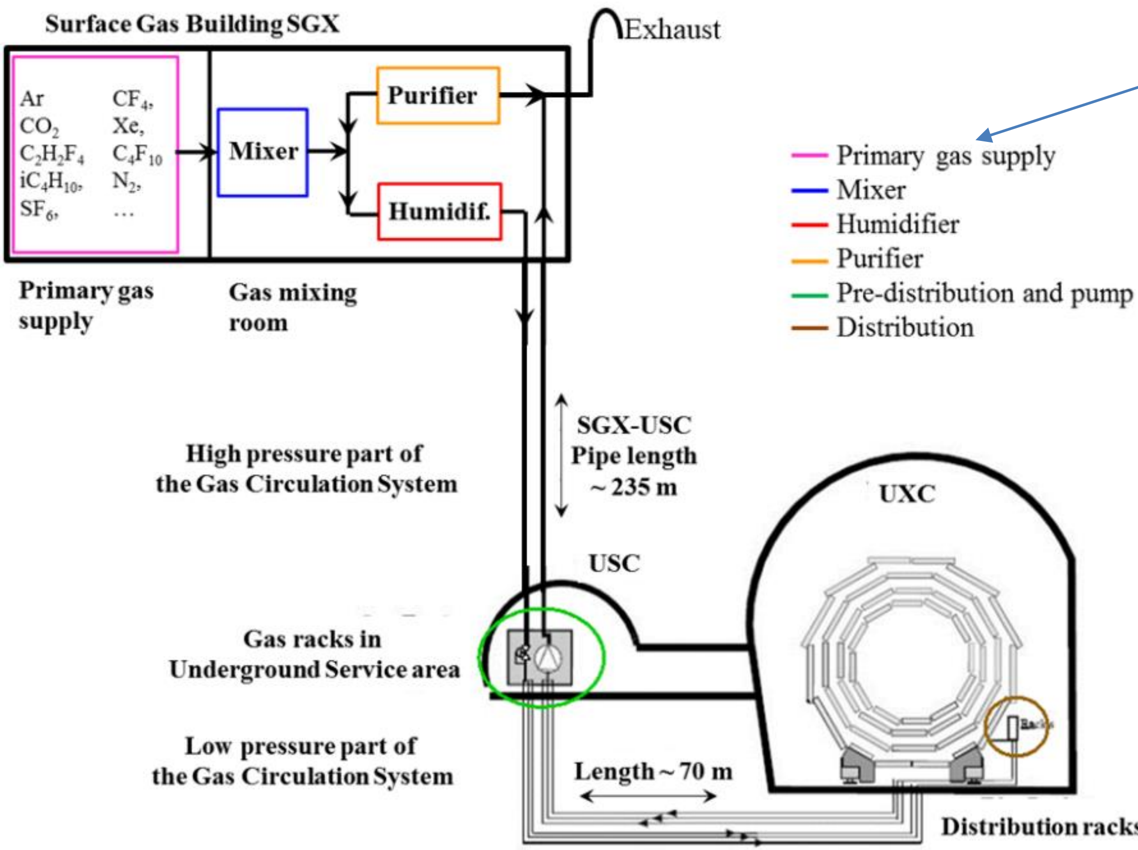
- **Reliability**
  - LHC experiments are operational 24/24 7/7
  - Gas systems must be available all time
- **Automation**
  - Large and complex infrastructure
  - Resources for operation
  - Repeatability of conditions.
- **Stability**
  - Detector performance are strictly related with stable conditions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

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

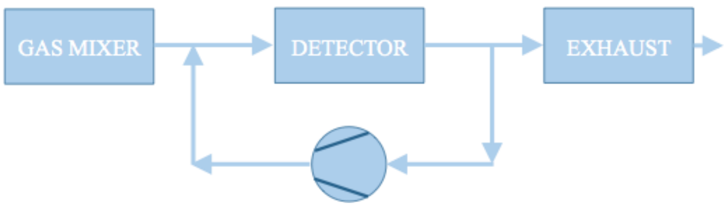
GHG Optimization Strategies

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

- First step done at the early design phase:
  - Most of the systems were 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)
- Sophisticated 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 and LHCb-GEM

ALICE-RPC upgrade

ALICE-Muon Trigger RPCs:

Mixture: **$C_2H_2F_4$ 89.7%, SF_6 0.3%**, iC_4H_{10} 10%

Detector volume: 300 liters (much smaller wrt ATLAS and CMS-RPC systems)

Therefore originally designed in open mode → upgraded to gas recirculation in 2015

From Run1 to Run2: 75% GHG reduction

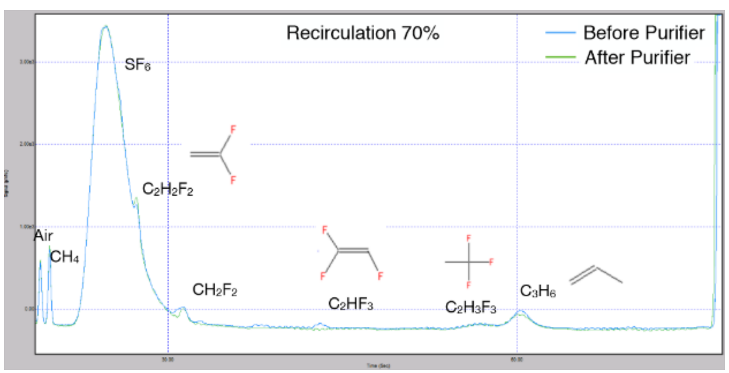
Original investment already largely paid back by gas cost saving during operation

RPC operated in slightly different conditions (higher pulse charge):

→ Impurities due to fragmentation of main gas components are visible

→ Closely monitored

→ Detector performance are not affected by gas recirculation



More details in
[Gas mixture monitoring for the RPC at LHC (RPC2018)]

LHCb-GEM upgrade

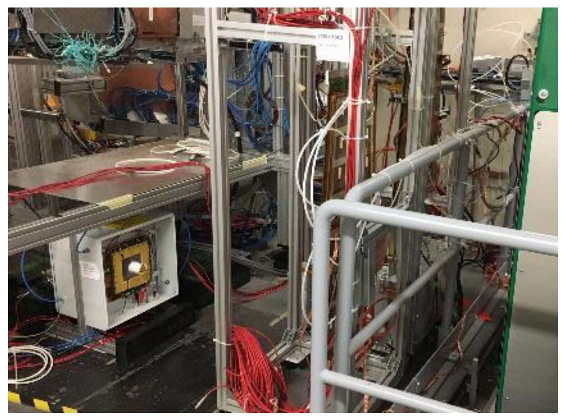
LHCb-GEM
mixture: **CF_4 40%**, Ar 45%, CO_2 15%
Detector volume: ~ 50 liters (but very high flow needed by the detector)
→ R&D for operation of large GEM detector systems with gas recirculation

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

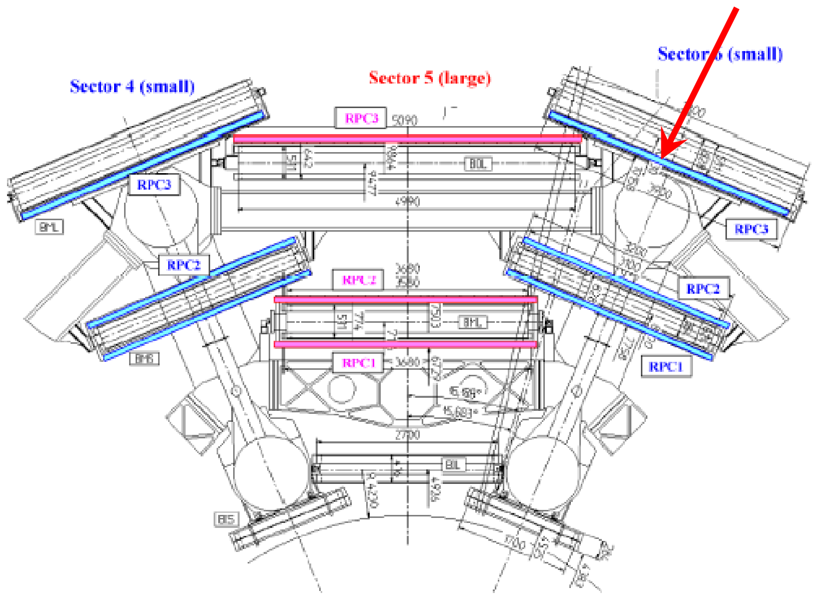
LHCb-GEM detector operation became more stable thanks to less frequent replacement of CF_4 cylinders

ATLAS and CMS RPC systems

GHG usage is dominated by the large RPC systems of ATLAS and CMS

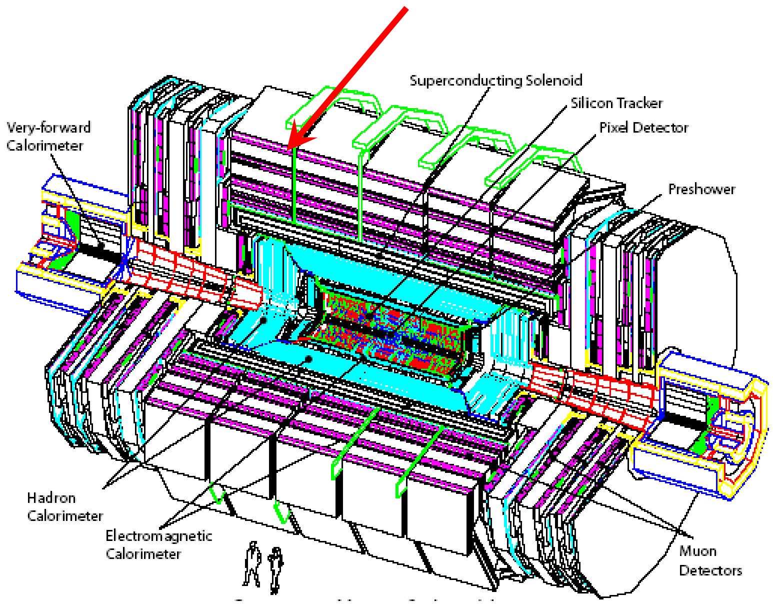
- mixture recirculation already almost at design level (85-90%)

@ ATLAS experiment:



- Active surface 4000 m^2
- **Detector gas volume 16 m^3**
- gas re-circulation systems

@ CMS experiment:



- **$C_2H_2F_4$ 94.7%; SF_6 0.3 %;** iC_4H_{10} 5%
- 40% Relative humidity

ATLAS and CMS RPC systems

Further optimization requires:

- Fixing leaks at detector level
  - Huge ongoing effort of RPC detector communities
  - but critical/fragile gas connectors are extremely difficult to access
  - Good technical progress
- Gas system upgrade to minimize any pressure/flow fluctuation
- Minimize impact of cavern ventilation
- Look for other external causes (vibrations, …)
- Detector R&D to validate higher recirculation fraction
- Gas recuperation plant
- Tools to check gas system tightness

Positive effects already visible:

→ Reduced leak developments at start-up

→ Pressure regulation improved by 70%

All these activities are already ongoing

- Some started as soon as the leaks appeared and now improved
- Others designed recently

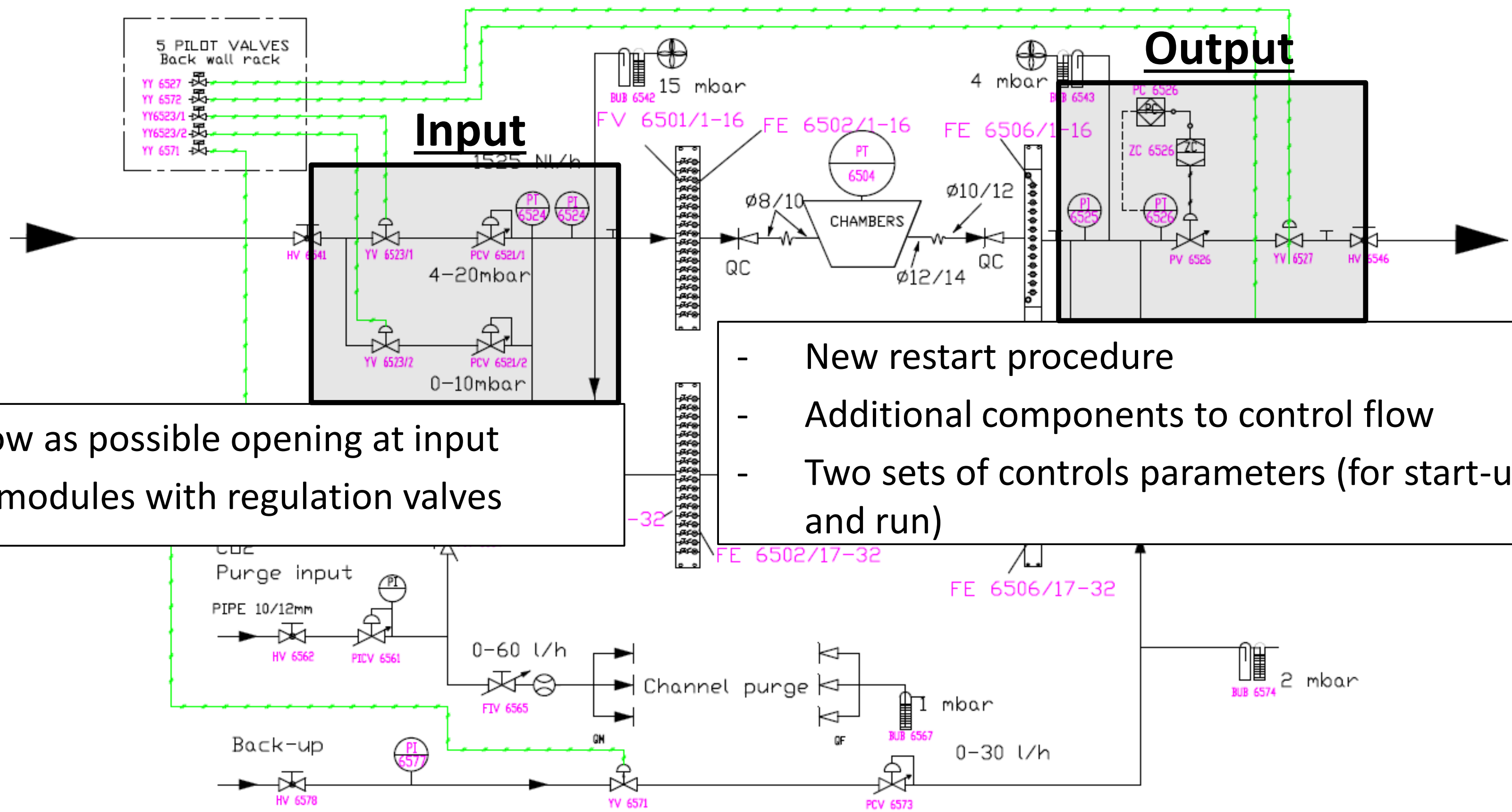
RPC Gas system upgrade

Goal: minimize any chamber pressure/flow fluctuation

from some 0.1 mbar to ~ 0.1 mbar (**not an easy challenge**)

Work on **mixture distribution modules**

some examples



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

- New restart procedure
- Additional components to control flow
- Two sets of controls parameters (for start-up and run)

RPC Gas system upgrade

Additional LS2 studies/modifications:

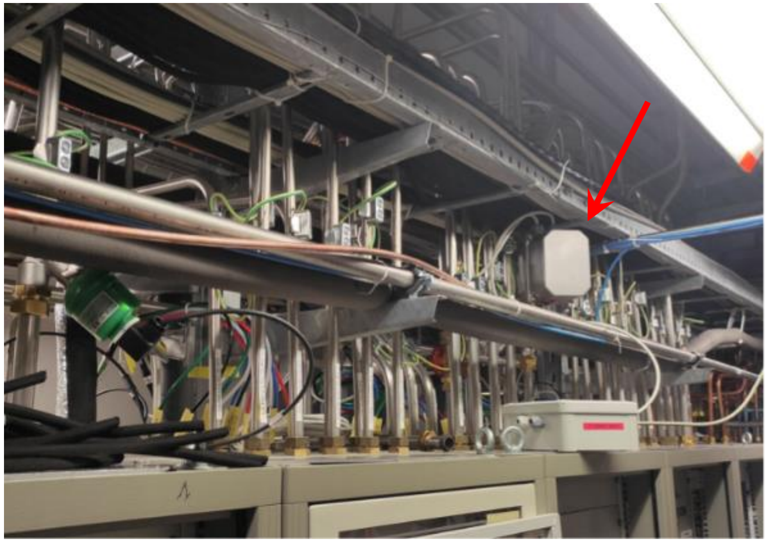
- (ATLAS and CMS): "dummy RPCs" installation, i.e. volumes that simulates detectors at highest point of the distribution sectors allowing a better pressure regulation. Particularly important during transition phases (from RPC mixture to air or N_2) or when hydrostatic column is lost due to leaks during short stop/power-cuts

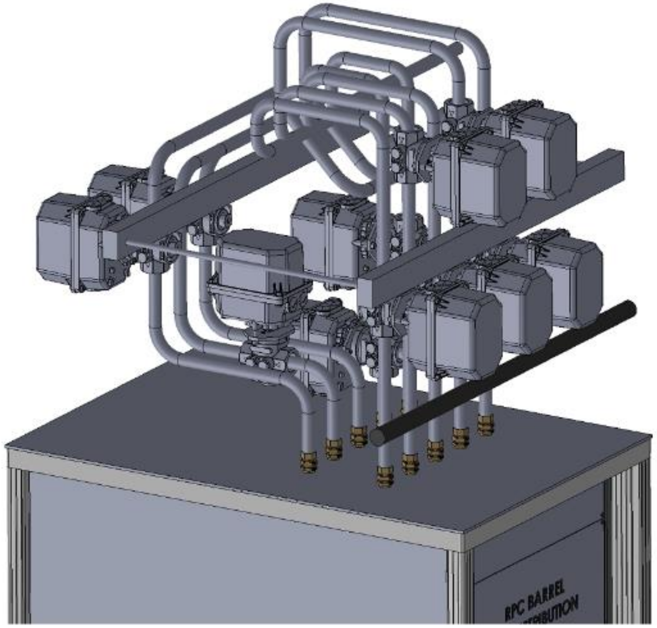
Detector pressure regulation was using sensors at distribution module level and the operator was manually compensating for the hydrostatic column of the gas mixture

RPC Gas system upgrade

Additional LS2 studies/modifications:

(CMS) replace manual valve used to equalize pressure between different detector zones with automatic regulation valves

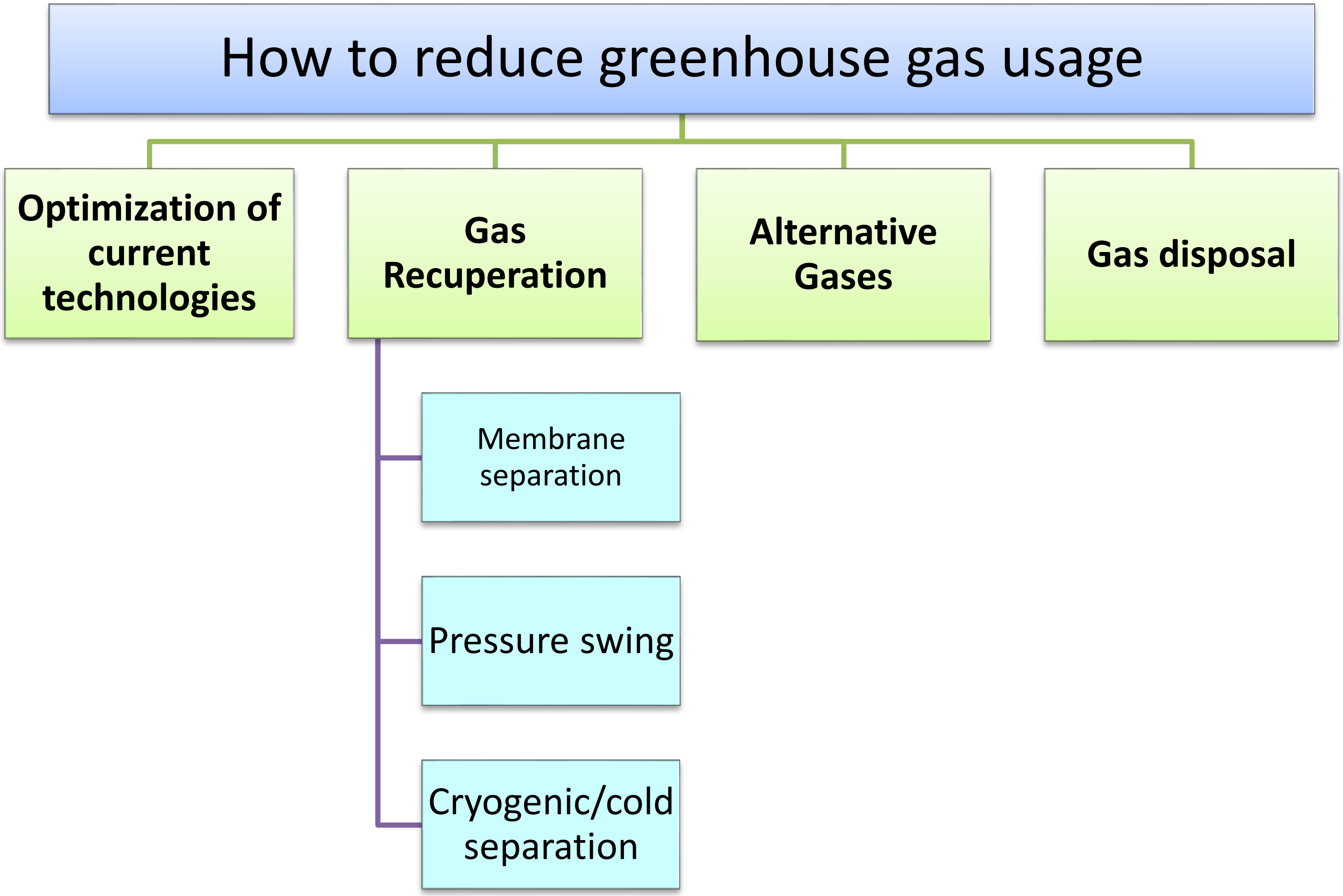




Requirements

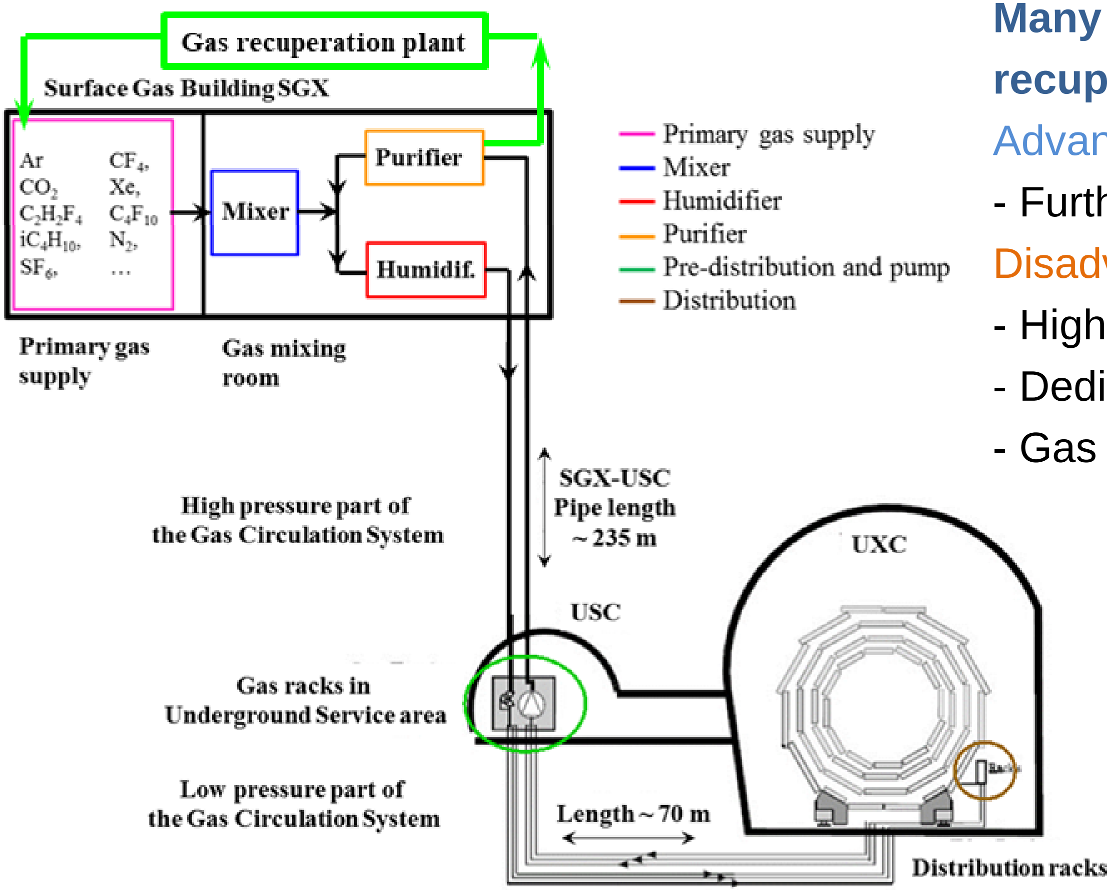
- Regulation in the range of few tens of mbar
- Compact (no space available in existing racks)
- Silicon free
- Operation in magnetic field (up to 100 mT)
- Cheap (<1000 CHF) since many needed
- Search on the market for new regulation valves
- ~ 20 regulation valves were tested

GHG Optimization Strategies



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

Gas Recuperation systems

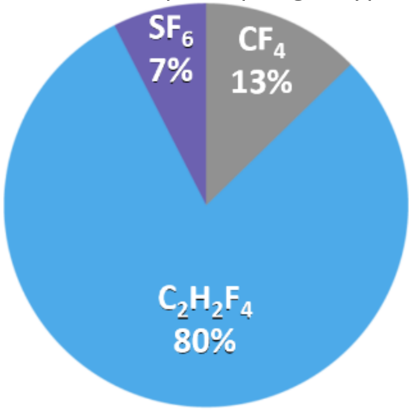
The mixture recirculation ratio is sometime limited by accumulation of impurities, i.e. balance of detector intake and filtering capacity (as it is the case in presence of N_2).

Gas recuperation can be seen also as a way of “cleaning”. It is already used for many detectors

- ALICE-TRD (Xe), ATLAS-TGC (nC_5H_{12}), ATLAS-TRT (Xe), CMS-CSC (CF_4), LHCb-RICH1 (C_4F_{10}), LHCb-RICH2 (CF_4)

- *The 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

Relative consumption per gas type



- Recuperation systems 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 already at 50% efficiency

Gas recuperation: the CF_4 case

From Run1 to Run2 up to 44% GHG reduction

CMS-CSC CF_4 recuperation plant

Problem:

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

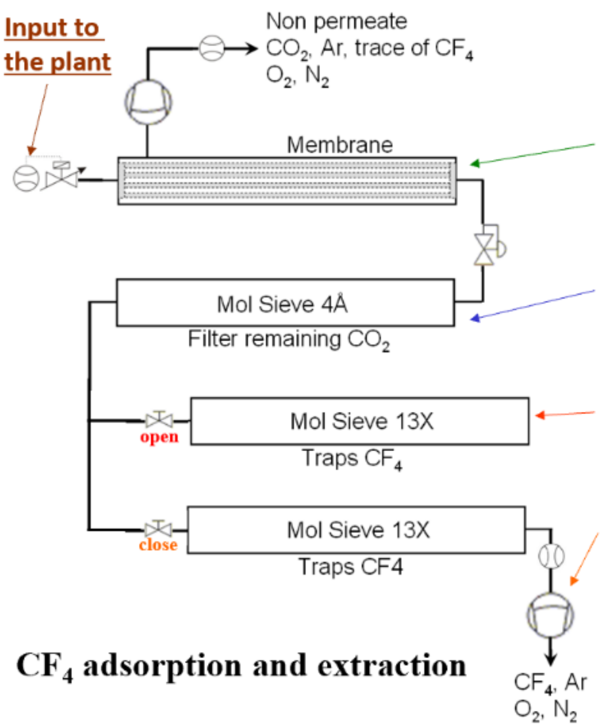
Technical challenge:

First plant built for CF_4 warm adsorption

A completely non-standard system

Operation started in 2012. Several technical and resource problems → Average efficiency ~50%

R&D will either solve current limitations or convert the last module for cryogenic separation



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

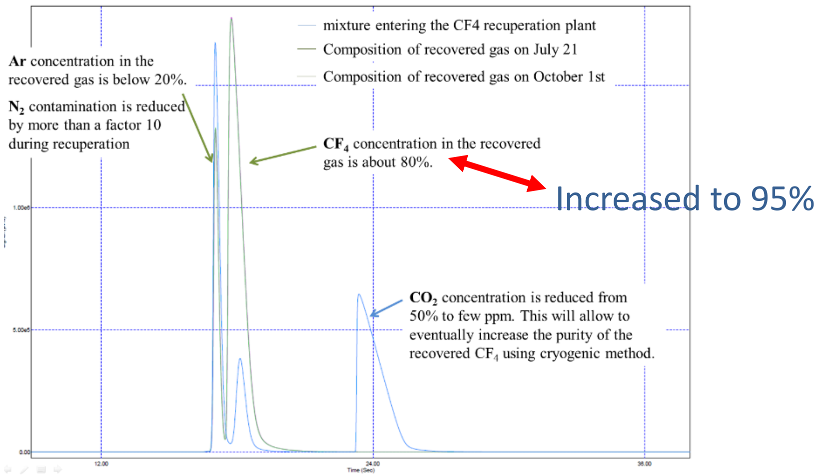
Phase 3a:
CF_4 adsorption
→ filling Mol. Sieve 13X from -1 to 0 bar

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

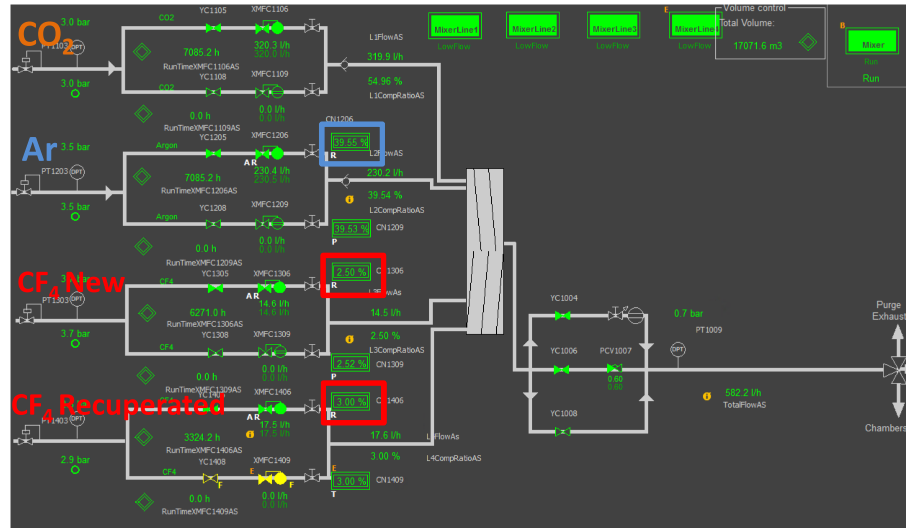
Gas recuperation: the CF_4 case

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

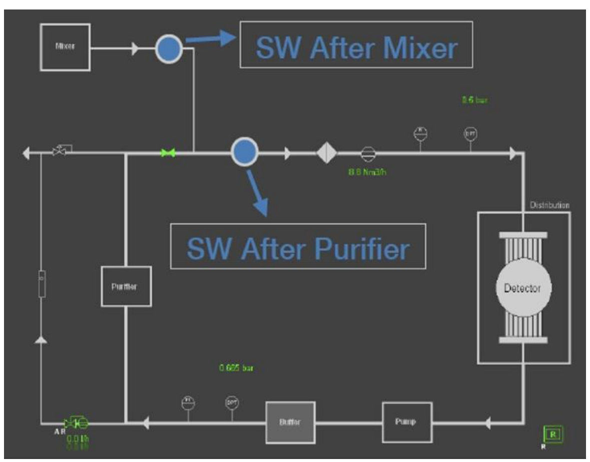
Quality of recuperated CF_4

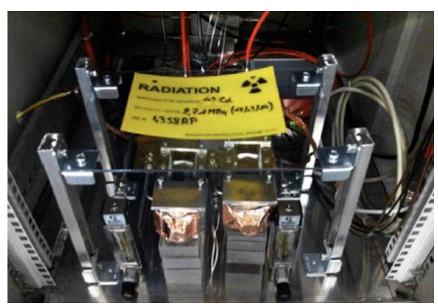


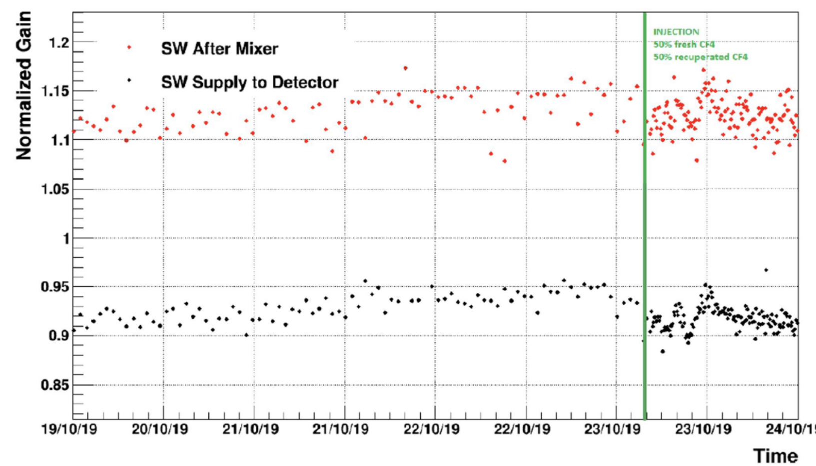
Mixed injection of CF_4 50% recuperated and 50% new



Gas mixture monitoring: Single Wire Chambers





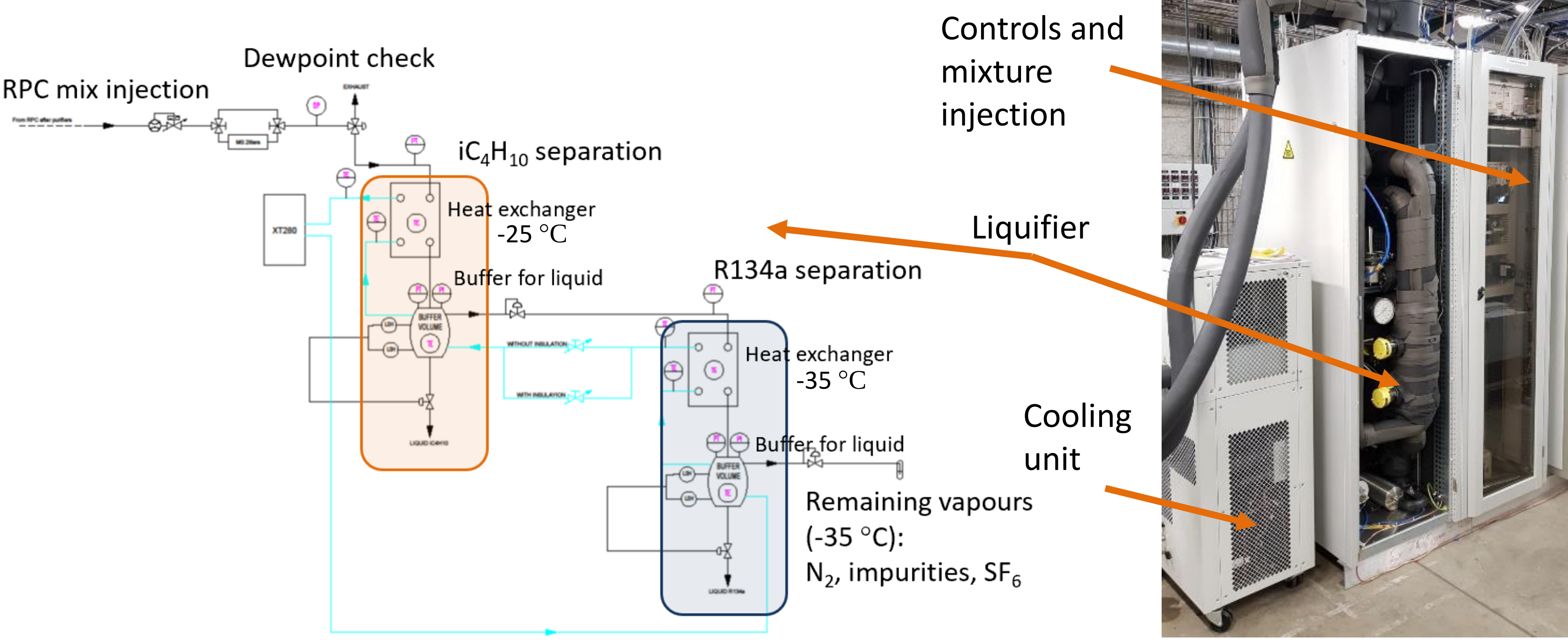


Gas recuperation: R134a prototype0

Prototype0 was tested connected to ATLAS-RPC (end-2018)

Objectives:

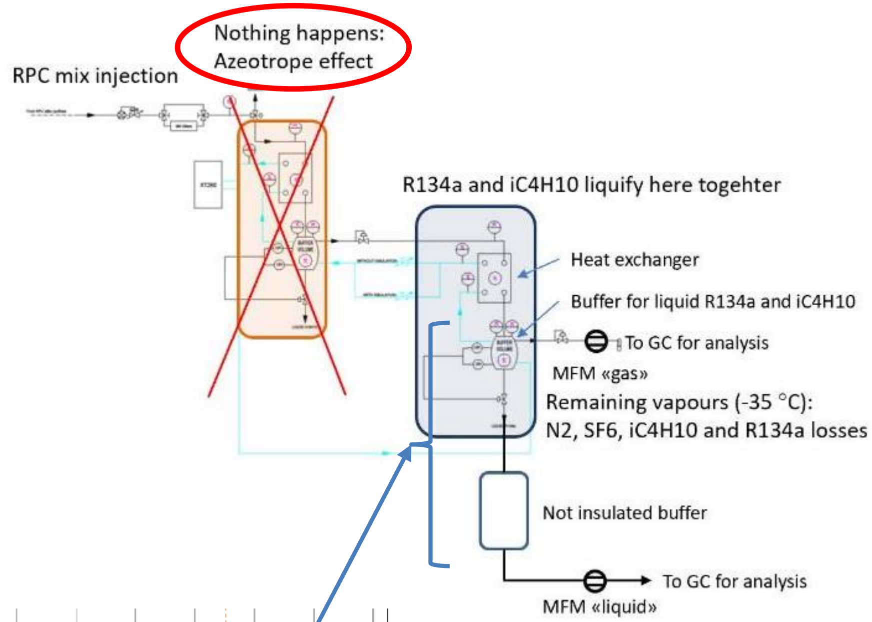
- Prove principle of operation/gas separation
- measurement of recuperation efficiency
- effectiveness of air/N_2 removal
- separation of iC_4H_{10} and SF_6 from recuperated R134a



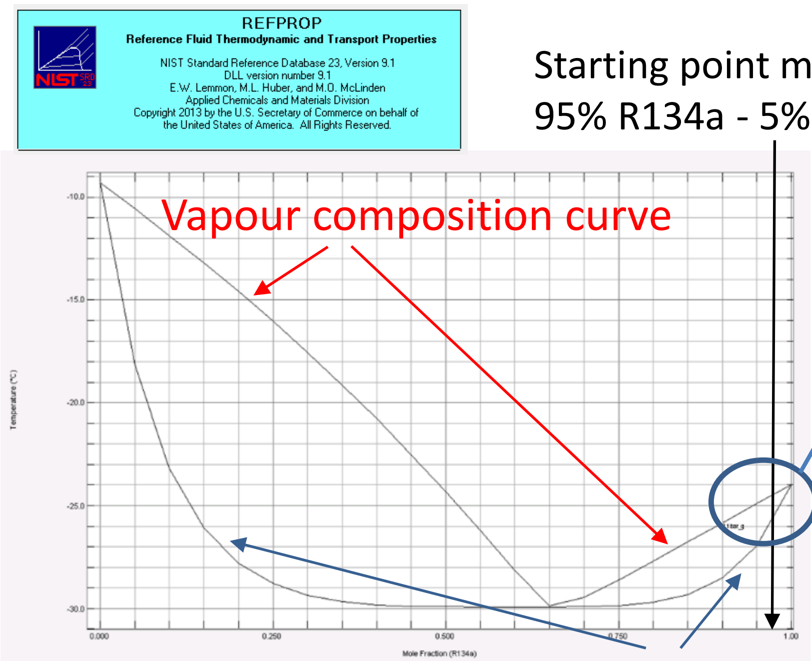
Gas recuperation: R134a prototype 0

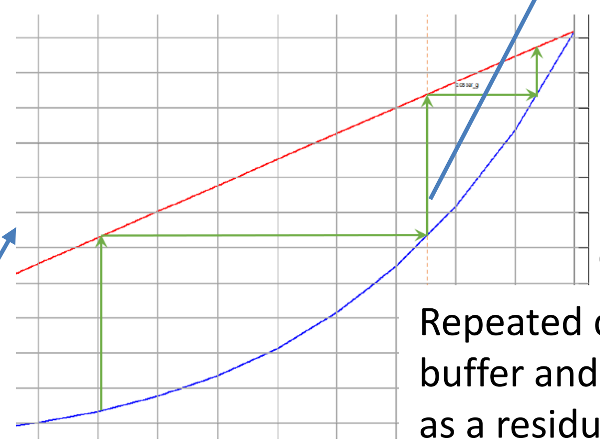
R134a and iC_4H_{10} form an azeotrope:
a mixture of liquids whose proportions cannot be altered or changed by simple distillation

Simple separation due to difference in boiling points is not possible



Starting point mixture
95% R134a - 5% iC4H10





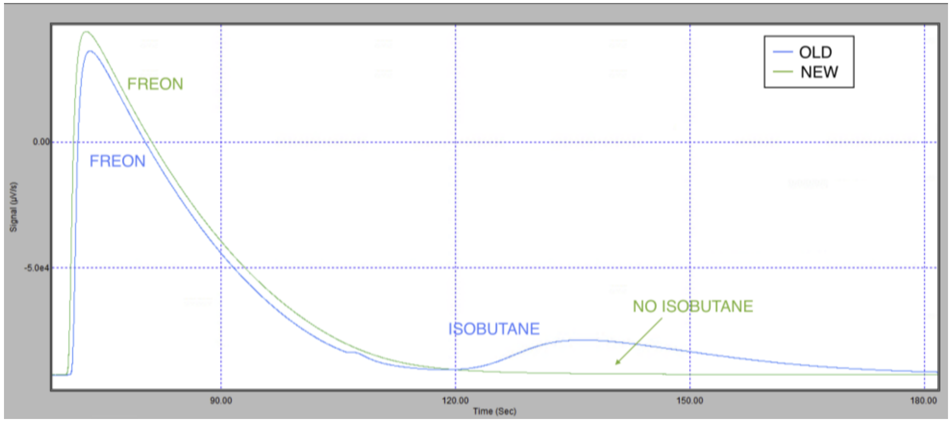
Repeated distillations between cold buffer and “warm volume” produce as a residual pure R134a but some R134a is lost in the distillate

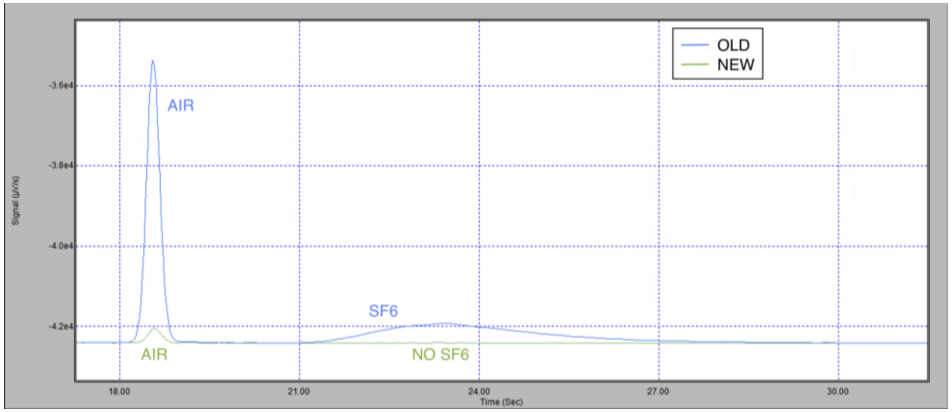
liquid composition curve

Gas recuperation: R134a prototype 0

Present status:

- Input flow: 100 – 400 l/h
- Good separation achieved
- Tests performed in a temperature range between -32.5 C and -36.5 C
- Good efficiency (~85%): tests still ongoing

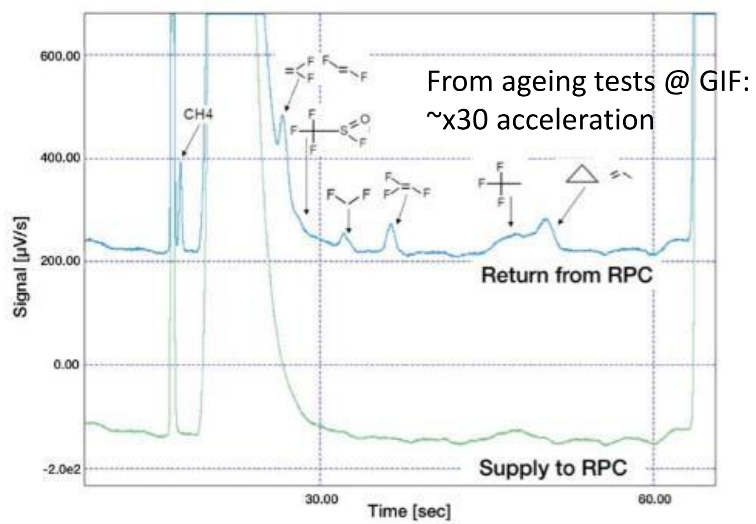




Gas recuperation: R134a prototype 0

From Run2 to Run3
Potential 90% GHG reduction

- Next steps:
  - Compress recuperated R134a for storage/reuse (ongoing tests, more difficult due to azeotrope effect)
  - Separation study of specific RPC impurities: to be evaluated before Run 3



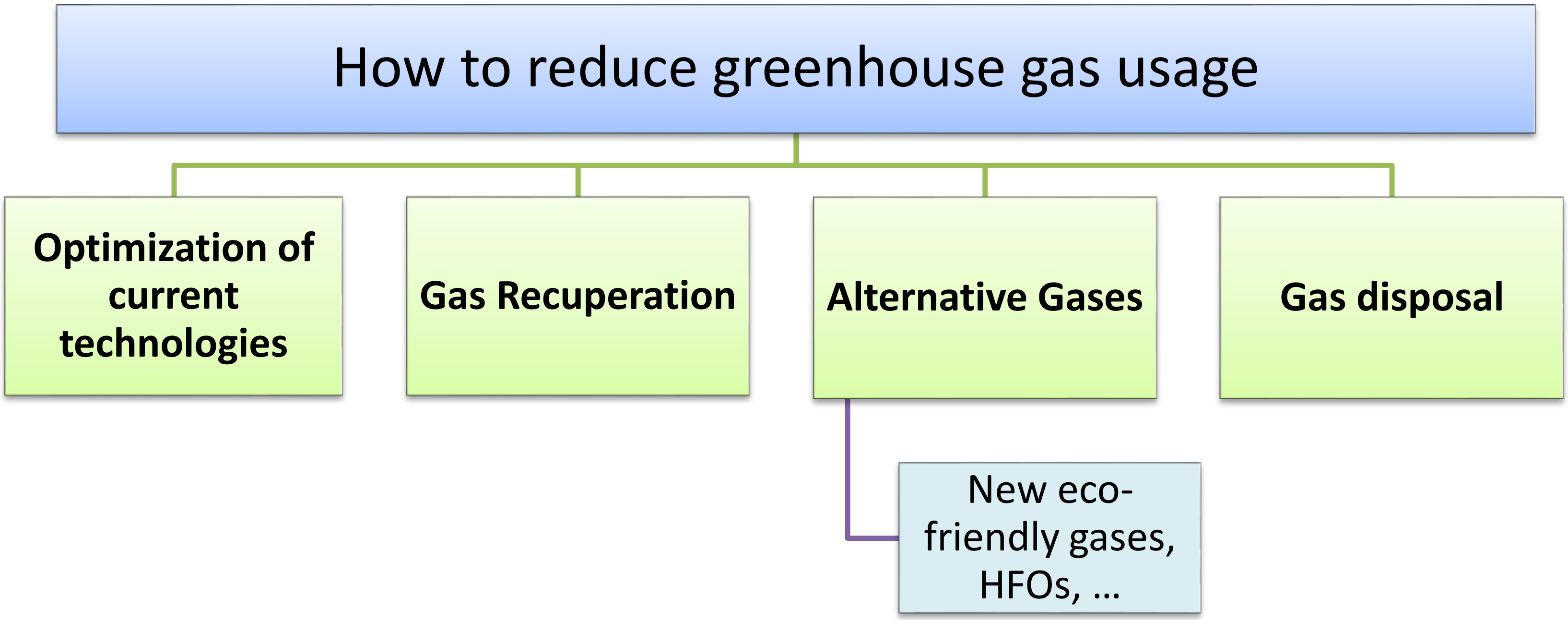
Molecule	Boiling point (°C)	Molecule	Boiling point (°C)
C2H2F4	-26	C2H2F2(e)	-42
iC4H10	-12	CH2F2	-51
SF6	-64	CHF3	-84
		C2HF3	-51
CH4	-161	C2H3F3	-47
C2H4F2	-117	C3H6 (propene)	-33
CF4SO	110	C3H6 (cyclopropane)	-47
C2H2F2(z)	-20		

  - Test possibility of SF_6 recuperation

Gas recuperation: complete overview

Project	2019	2020	2021	2022	2023	2024	2025	2026	Experiment
Prototype system for R134a recuperation	■	■	■						ATLAS, CMS, ALICE
First pilot system for R134a				■					ATLAS, CMS, ALICE
CF4 recuperation system (LHCb-RICH2)	■	■							LHCb
C4F10 recuperation system (LHCb-RICH1)		■	■						LHCb
Optimization of present CF4-CMS-CSC recuperation system	■	■	■						CMS
Upgrade of CF4-CMS-CSC system with cryogenic separation				■	■				CMS
Studies for upgrade of gas systems to cope with new detector requirements (ATLAS and CMS RPC)	■	■	■	■					
Detector performance with new environmentally friendly gases and new gas system (collaboration and support to experiments)	■	■	■	■	■	■	■	■	

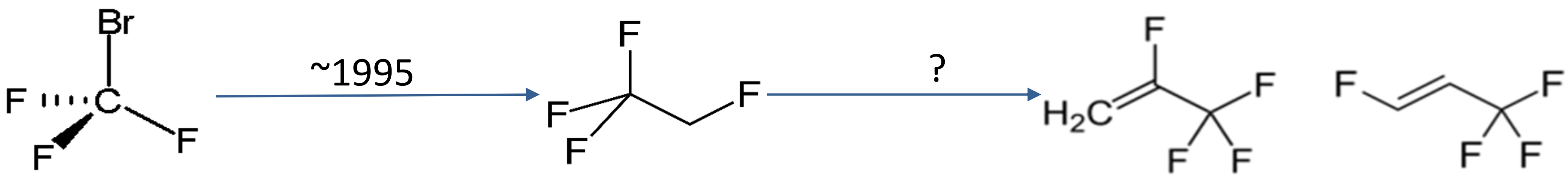
GHG Optimization Strategies



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

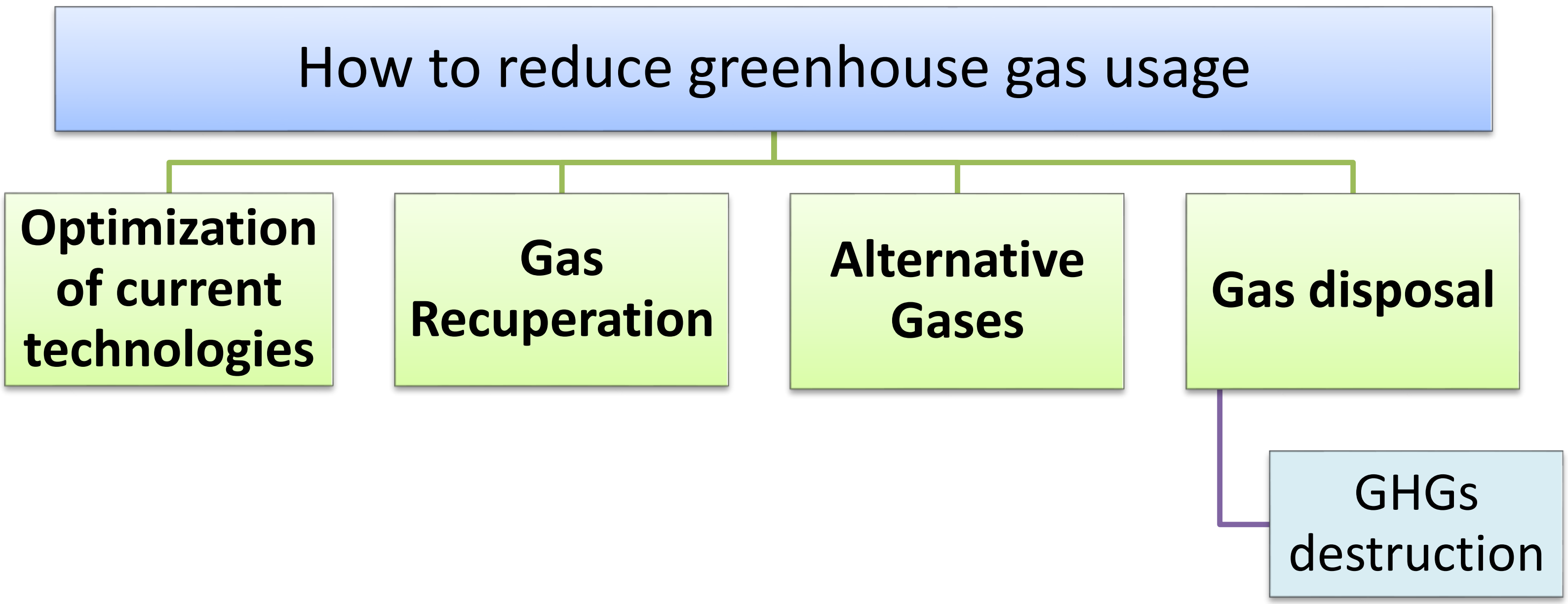
HFOs refrigerant properties are well known while studies of ionisation processes just started…

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 Optimization Strategies



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

Conclusions

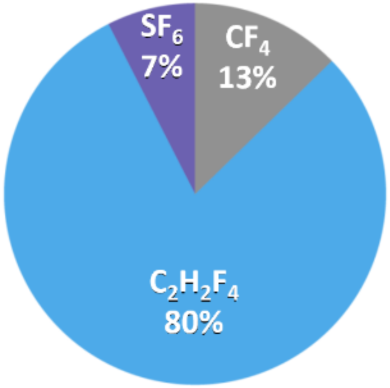
Program described aims in developing systems allowing for optimization of GHG usage

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

Four strategies identified:

- **Optimization of current technologies**
  - Particular attention to gas system and detector operation
  - Gas systems upgrade beyond original design
  - Improved/higher gas recirculation
- **Gas recuperation plant**
  - Recuperation system for R134a, SF_6 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 showed very good performance
  - Consolidation of existing plants (CF_4, C_4F_{10}) needed

Recuperation of R134a can drastically decrease GHG consumption



Conclusions

- **New eco-gases**
  - HFO1234ze promising but difficult for already installed detectors (many constrains)
  - First test of gas recirculation with HFO started (in lab and with high radiation background)
  - However, it is not for tomorrow
  - More details on Thursday https://indico.cern.ch/event/868940/contributions/3813912/

- **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.

Optimized gas systems, new recirculation plants, … are

- Nevertheless increasing complexity for operation
- Requiring qualified personnel
- Development and application of strict maintenance and operation procedures

Optimization of gas consumption

gas recirculation introduced for most detectors (gas systems design, 2000): 90% optimization => 90% reduction