EP-DT
Detector Technologies

Strategies for optimizing the usage of greenhouse gas in particle detection systems

R. Guida, B. Mandelli, G. Rigoletti
CERN EP-DT Gas Systems Team

Outline

- Greenhouse gases (GHGs) for particle detection
- F-gas regulations
- Strategies for optimizing GHGs usage: results, new projects and plans
  - Recirculation systems
  - Recuperation systems
  - Ecofriendly gases
  - GHGs disposal
- Conclusions/Lessons to remember

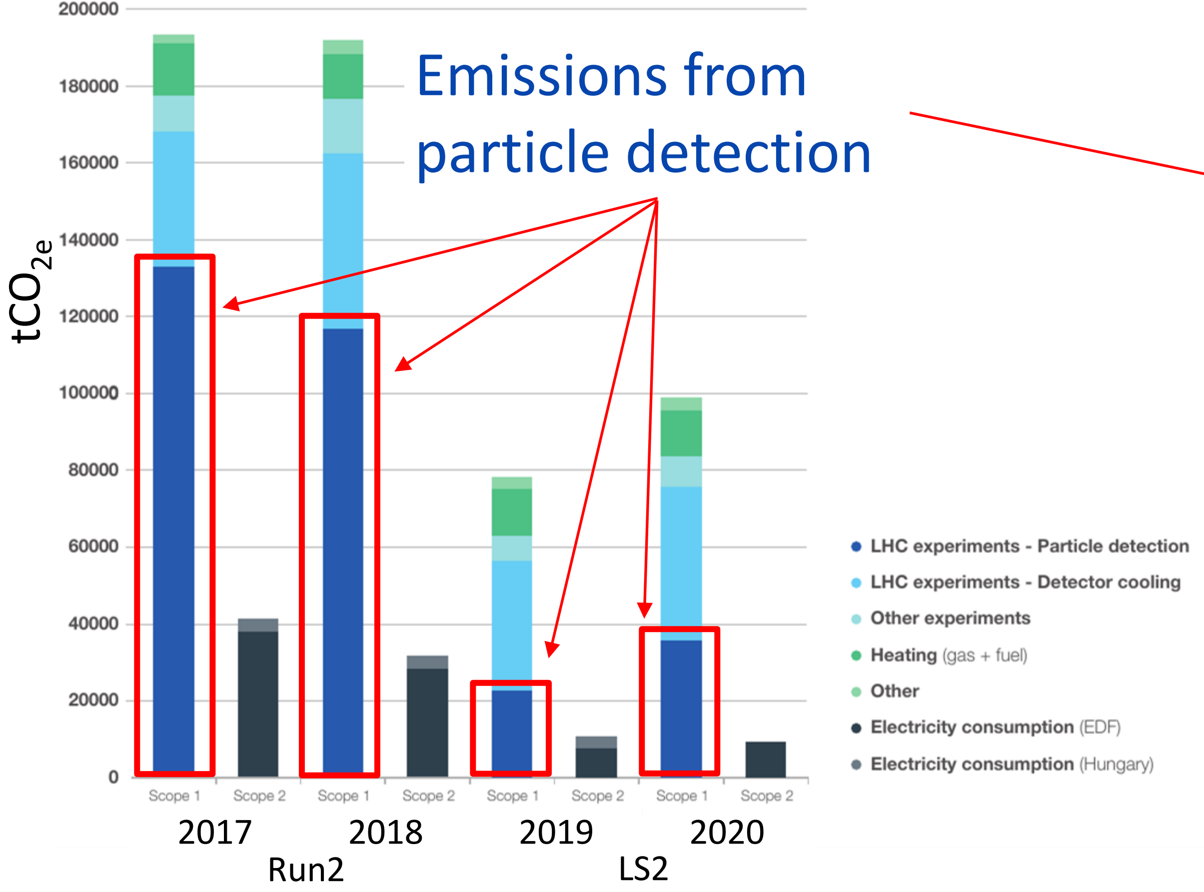
Greenhouse gas usage

- [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]

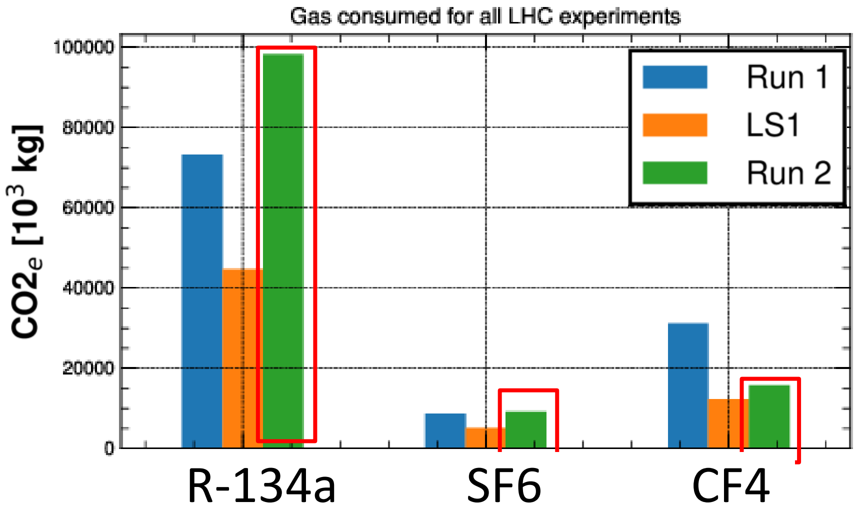
Total CERN emissions during 1 year of Run 2 ~ **200 000 tCO2e**

~ 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



Emissions from particle detection



-40% GHG emissions from Run1 to Run2 excluding ATLAS and CMS-RPCs

-25% GHG emissions from Run2 to Run3 excluding ATLAS and CMS-RPCs

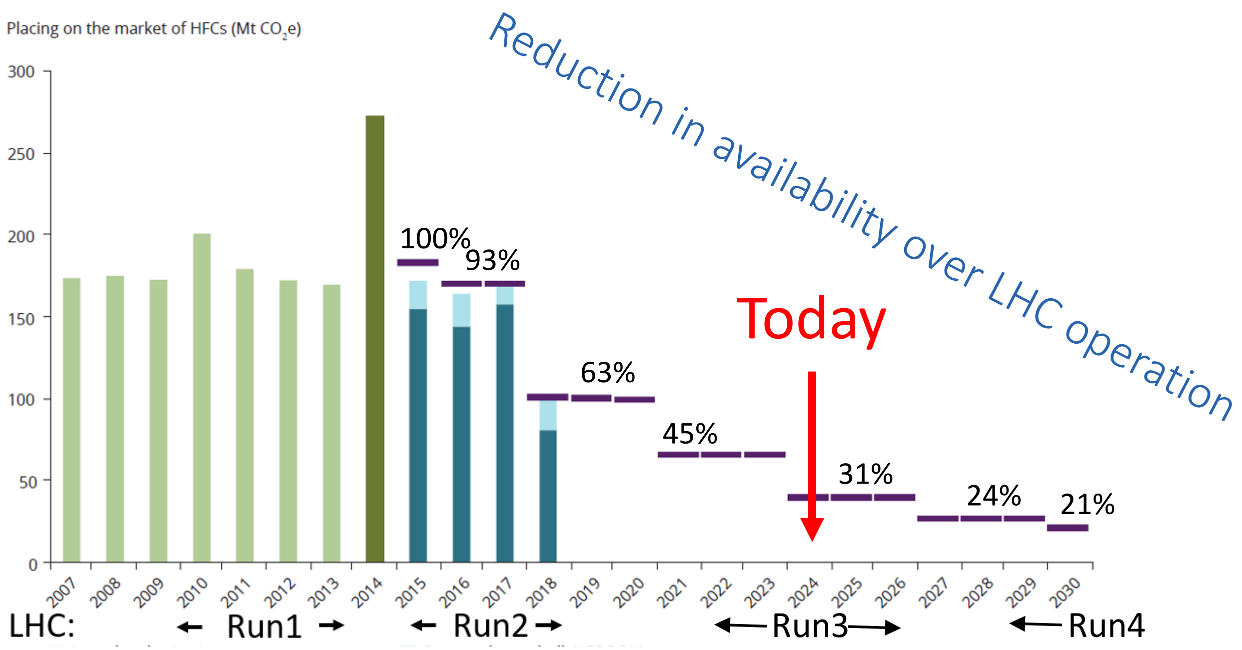
New objective: -28% by 2024 wrt 2018 (Run2)

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.

Figure ES.1 Progress of the EU HFC phase-down

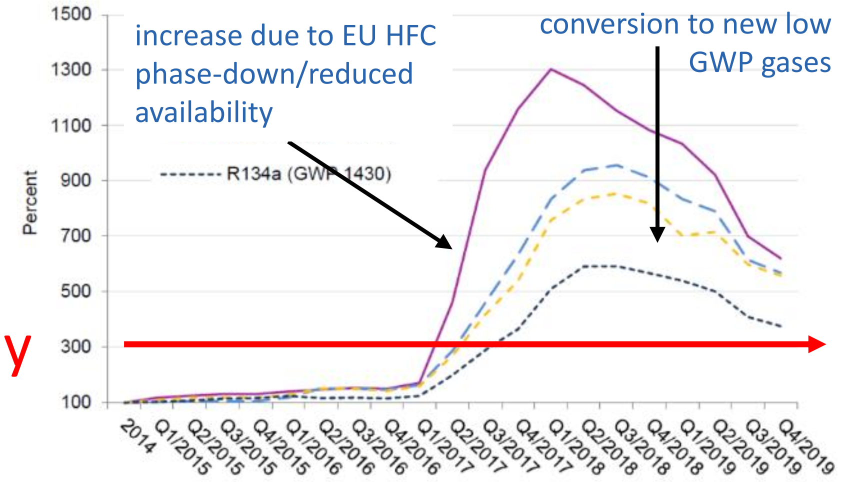


Reduction in availability over LHC operation

Today

HFC phase down: effects on HFC availability and prices

Price fluctuations:



increase due to EU HFC phase-down/reduced availability

decrease due to industrial conversion to new low GWP gases

Today

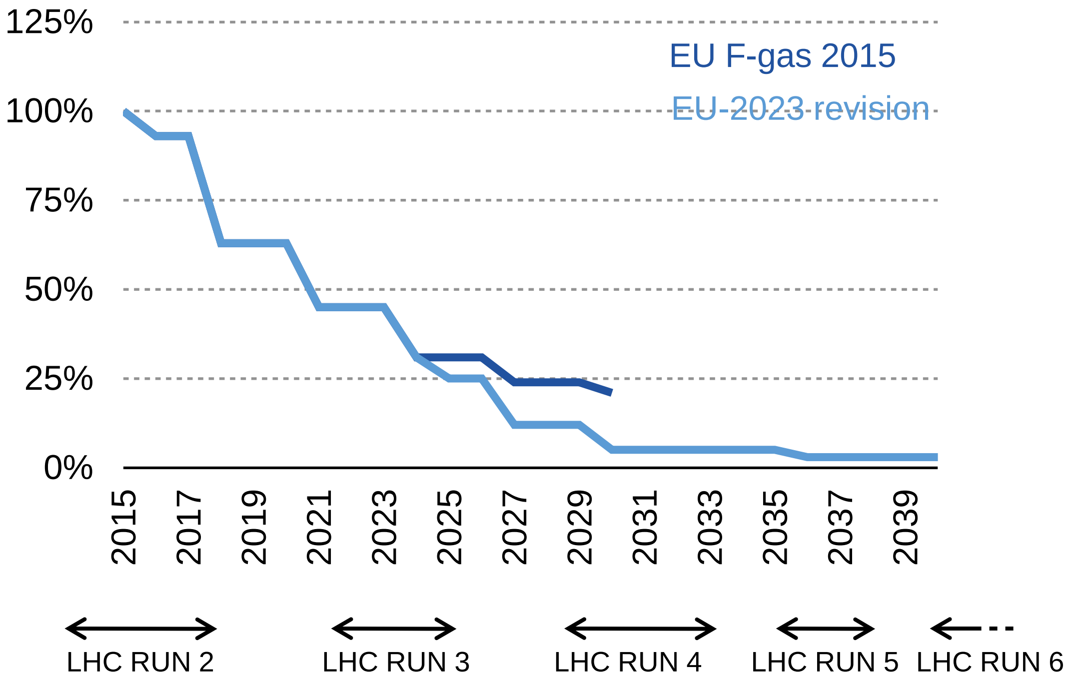
Sources: European Environment Agency, Fluorinated greenhouse gases 2019 report
Öko Recherche report, March 2020 J. Kleinschmidt et al.

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

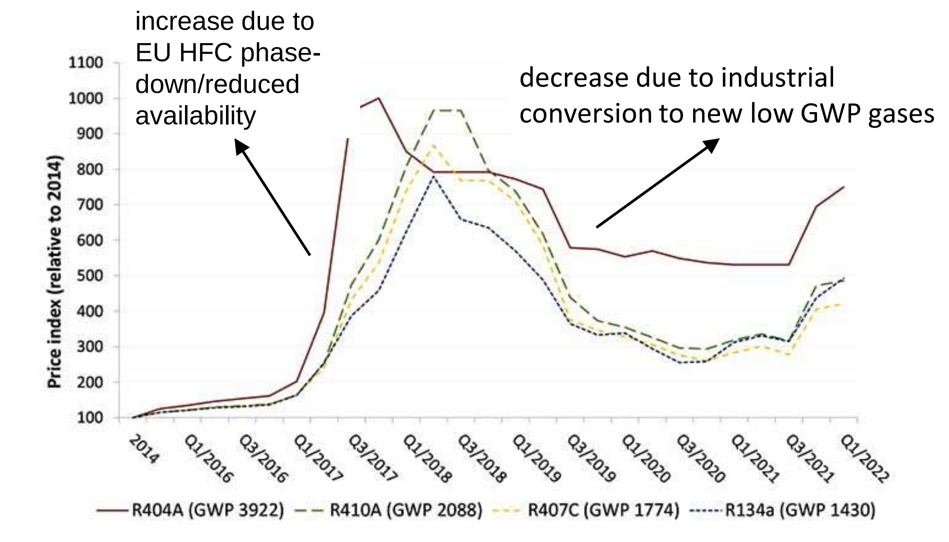
New F-gas regulation: from phase down to phase out

The new Regulation establishes the total elimination of HFCs by 2050

- It is a major step towards climate neutrality
- First goal: reduction of 55% GHG emissions by the end of this decade compared to 1990 levels
- New restrictions also in the use of SF_6 and especially for high GWP gases
- It will result in a reduction in production and reduced quotas for F-Gas refrigerants, leading to an inevitable increase in prices for higher GWP refrigerants
  - It will probably affect not-EU market
- Important also to consider possible new regulation for all PFAS



Average purchase prices of the most commonly used HFC refrigerants



And now: PFAS - *"forever chemicals"*

PFASs: any chemical with at least a –CF3 group or a–CF2– group (without any H/Cl/Br/I atom attached to it)

PFASs play a key economic role. In 2022, 3M announced that it will end PFAS production by 2025

The restriction was proposed by Germany, Netherlands, Sweden, Denmark and Norway for EU
It aims to be the biggest chemical ban out of health considerations
Imports will be also considered in the restriction

1 **13 January 2023** Restriction proposal submitted to ECHA

2 **7 February 2023** Proposal made available on ECHA's website

3 **22 March 2023** Start of a six-month open consultation

4 **5 April 2023** Online information session

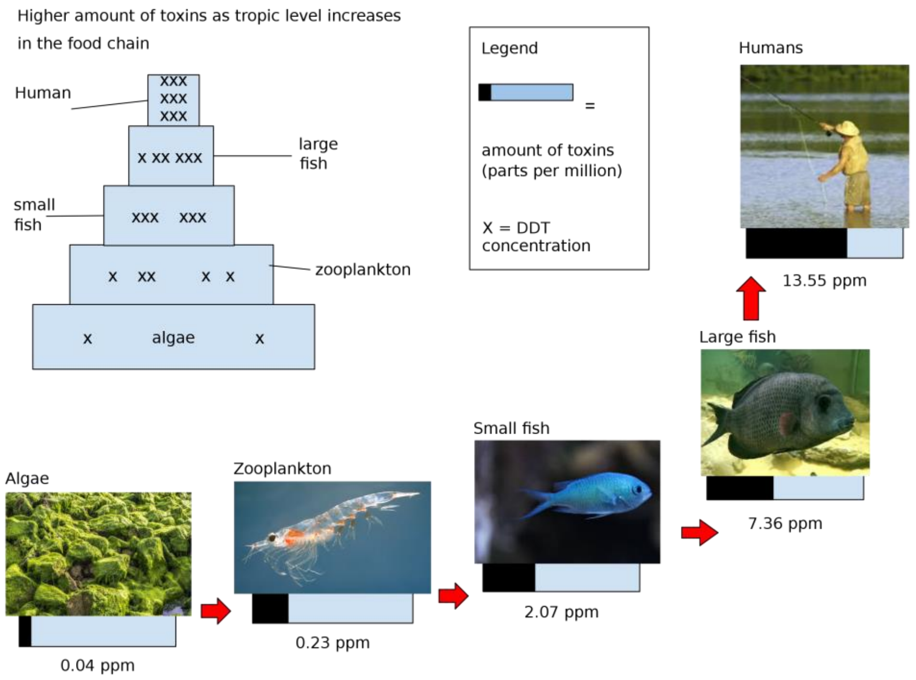
5 ECHA committees' evaluation

September 2023 Consultation

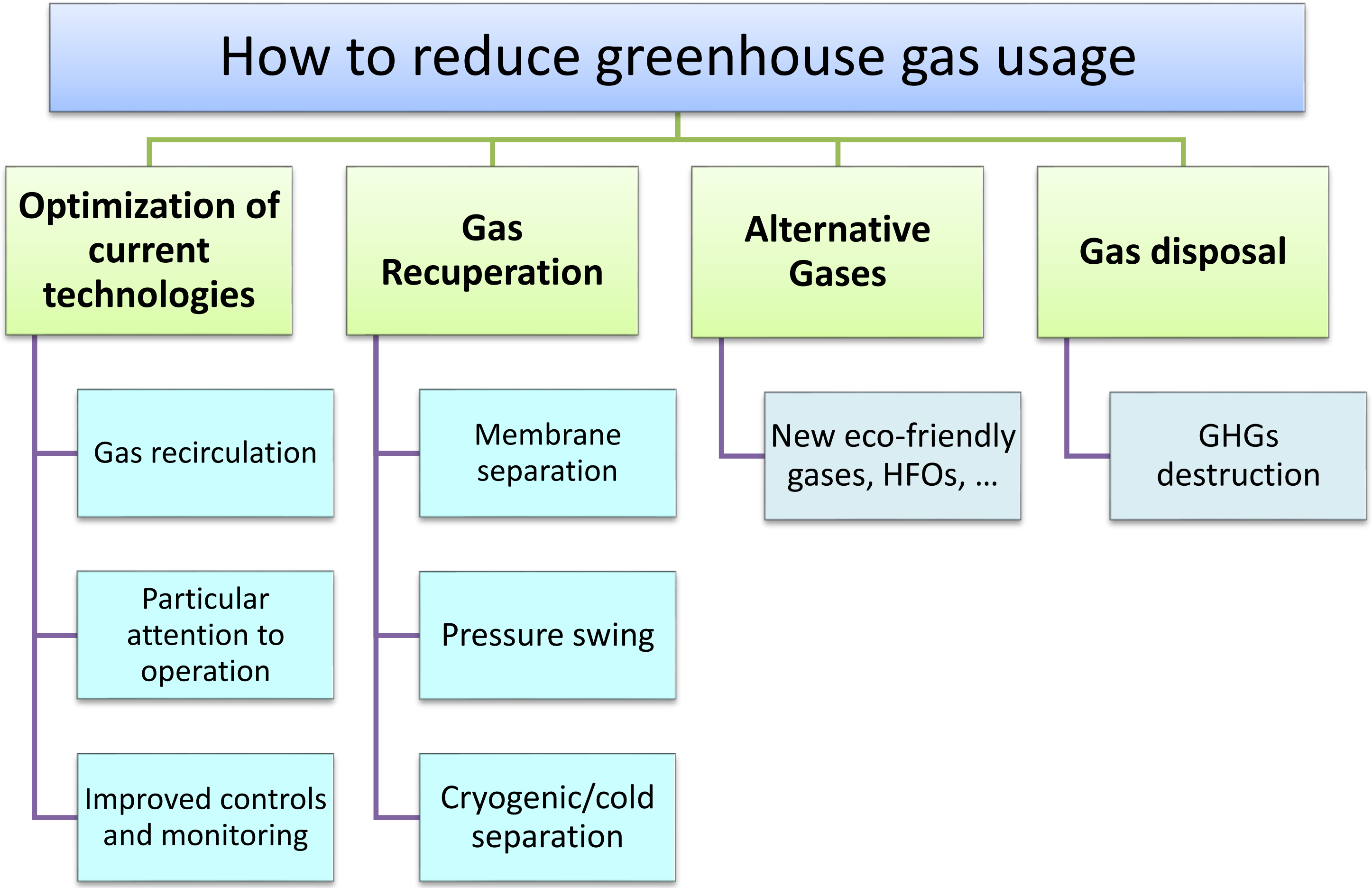
6 ECHA's committees adopt their opinions

7 Opinions of ECHA's committees sent to the European Commission

Bioaccumulation and biomagnification



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, …

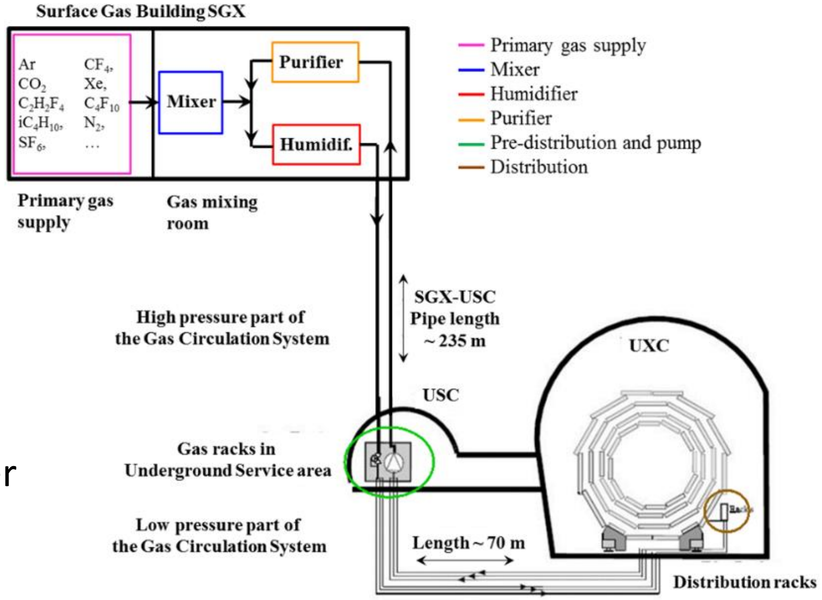
Gas disposal
- GHGs destruction

In collaboration with HSE/CEPS

Gas mixture recirculation system

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

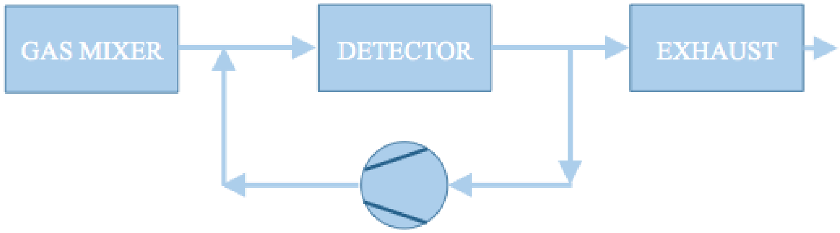
- Primary gas supply point is located in surface building
- Gas system distributed in three levels:
  - Surface (SG)
  - Gas Service room (USC)
  - experimental cavern (UXC)
- The gas systems were built according to a common standard allowing minimization of manpower and costs for maintenance and operation.
- Few numbers:
  - Construction started in 2000; Operational since 2005-2006
  - Need to validate the gas system components (ageing test setup)
  - 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 analysers and 6 gas chromatographers
- The CERN gas service team (EP-DT-FS, 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, …)

Optimization of current technologies: gas 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:
- ALICE-MTR: from Run1 to Run2: 75% GHG reduction
- LHCb-GEM: from Run1 to Run2: 90% GHG reduction

→ *For both detector systems:* ***Original investment was totally 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 - RPC2022

Gas recirculation and “small” detector system: LHCb-GEM example

Mixture: **CF_4 40%**, Ar 45%, CO_2 15%

Detector volume: ~ 50 liters (but very high flow needed) → R&D for operation of GEM detector systems with gas recirculation

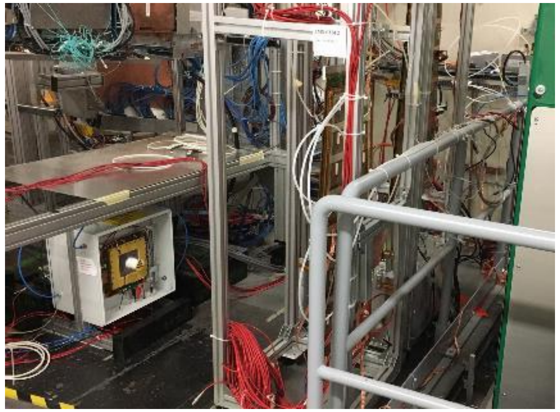
2013:

Development of small gas recirculation systems
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

From Run1 to Run2: 90% GHG reduction

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

Need to consider longer time scale:
as this example shows also for a small system there can be a positive balance on longer time

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 (tested 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**

ATLAS and CMS RPC systems

Since Run 1 the ATLAS and CMS RPC systems experience the development of leaks at the chambers level

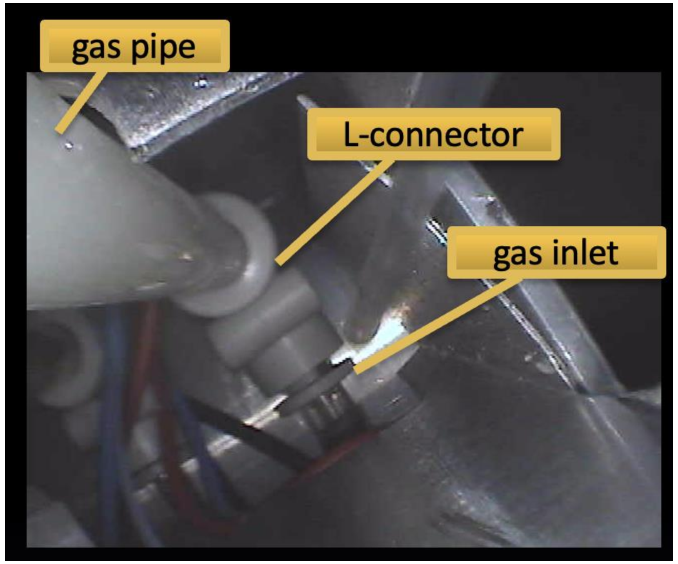
ATLAS RPC case

- Leaks originate at the gas inlets which tend to crack due to inborn fragility
  - Aggravated by mechanical and chemical stress
  - Cracks develop slowly (over months) until reaching a breaking point
- 8000 inlets in total, located in couples in 4000 boxes on chamber corners, often with difficult access
  - Difficult to localize some types of leaks
- Reparation campaign during EYETS and LS
  - But new leaks keep developing

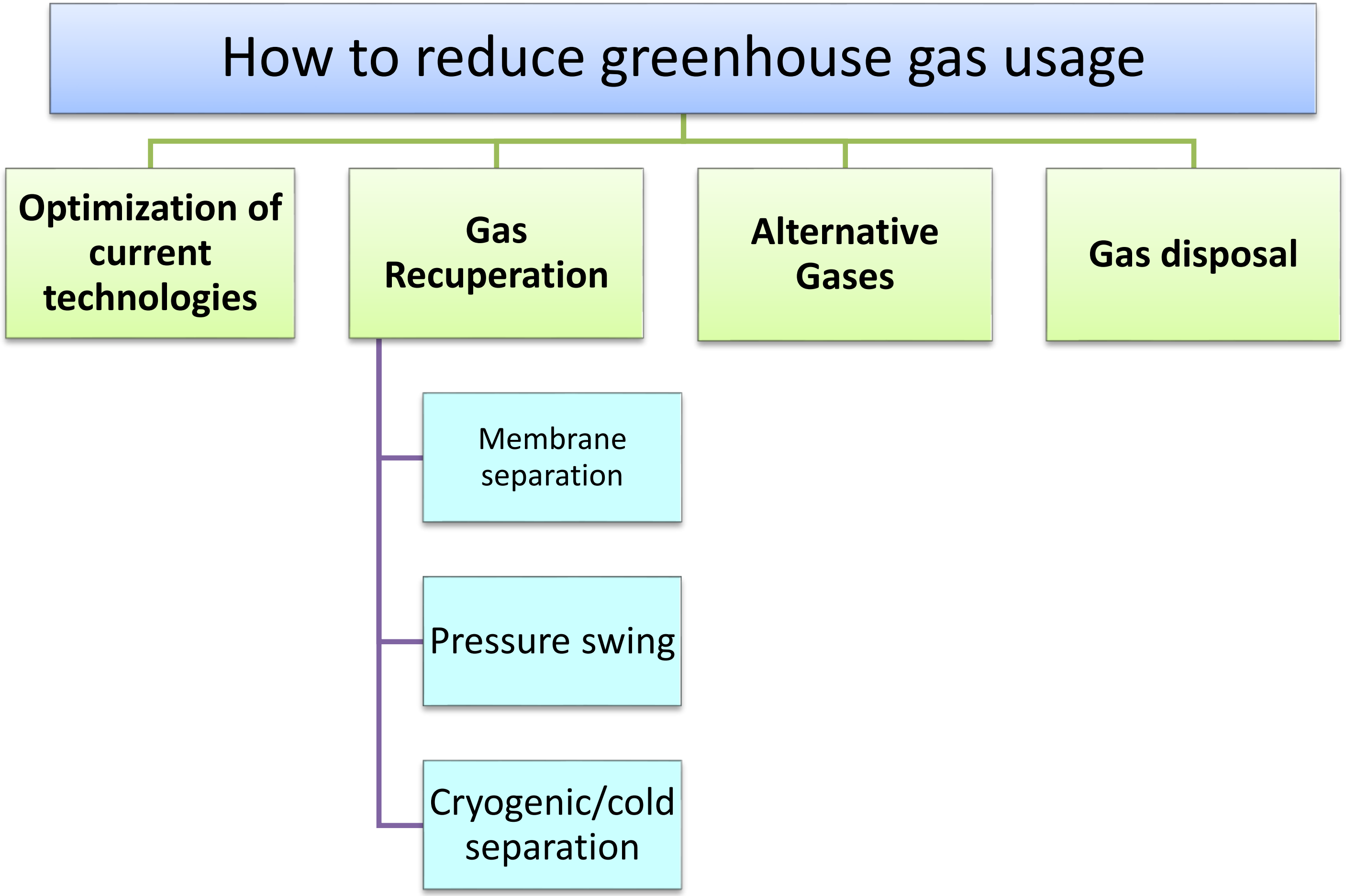
CMS RPC case

- Two sources of gas leaks appeared at different time scale
  - T or L polycarbonate gas connectors break due to original construction fragility in few of them
  - Polyethylene LD pipes become brittle/deteriorated
- Very difficult *(or sometimes impossible)* access to reach these connectors and pipes
- Reparation campaign during LS
- New policy of disconnecting chambers with big leaks (RPC system redundant for CMS trigger)

- **Avoid plastic pipes**
- **More attention to mechanical coupling of pipes and detectors**



GHG Optimization Strategies



How to reduce greenhouse gas usage

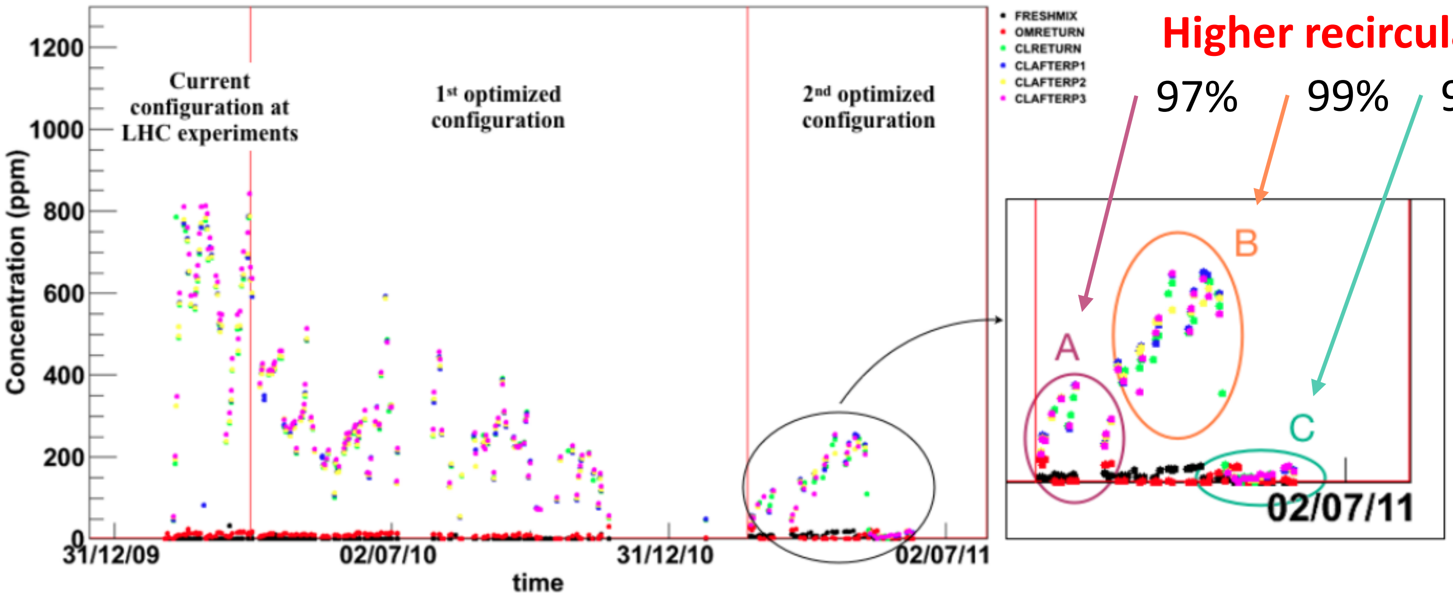
- **Optimization of current technologies**
- **Gas Recuperation**
  - Membrane separation
  - Pressure swing
  - Cryogenic/cold separation
- **Alternative Gases**
- **Gas disposal**

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:

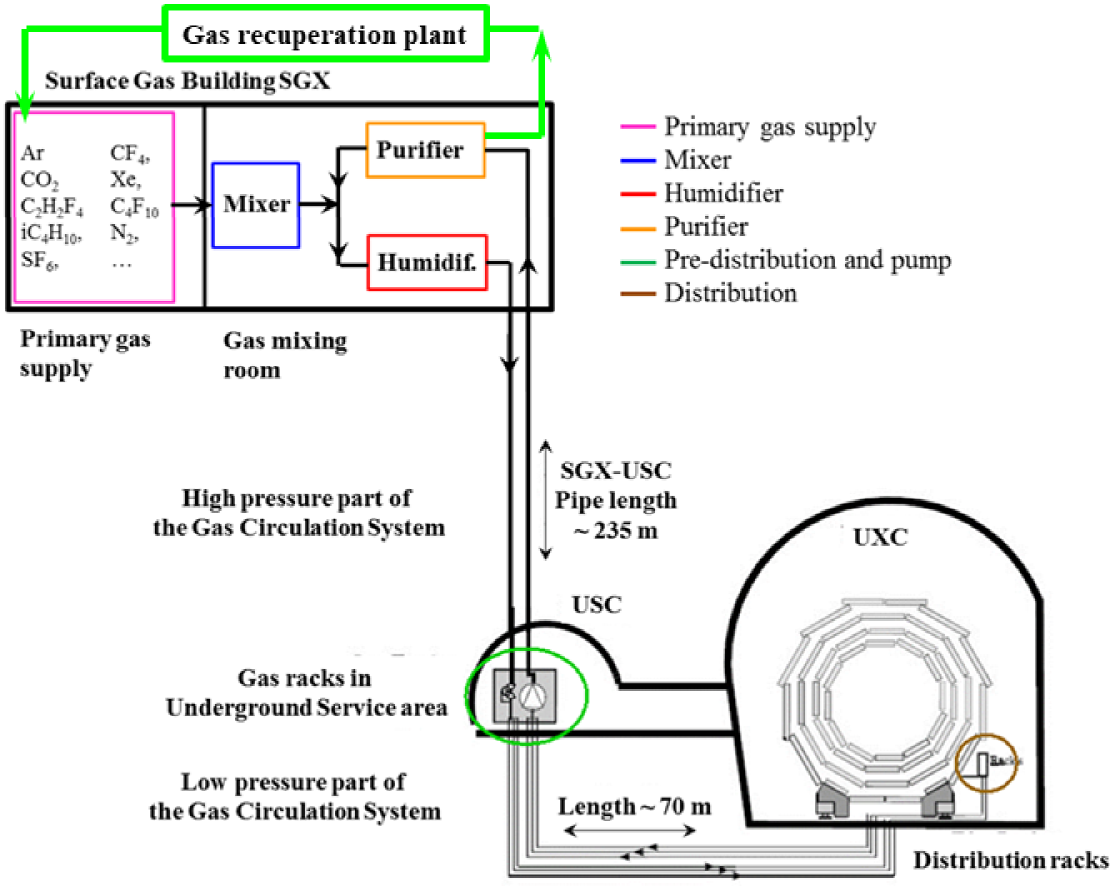
97% 99% 94%

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

- **Need to validate at max recirculation rate the detector operation since the beginning of the R&D phase**
- **Avoid materials permeable to air for the detector construction**

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 is effective only if leaks at detector level will be reduced
- R134a recuperation can drastically decrease GHG consumption
- Costs for R134a recuperation system paid back in two years

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:

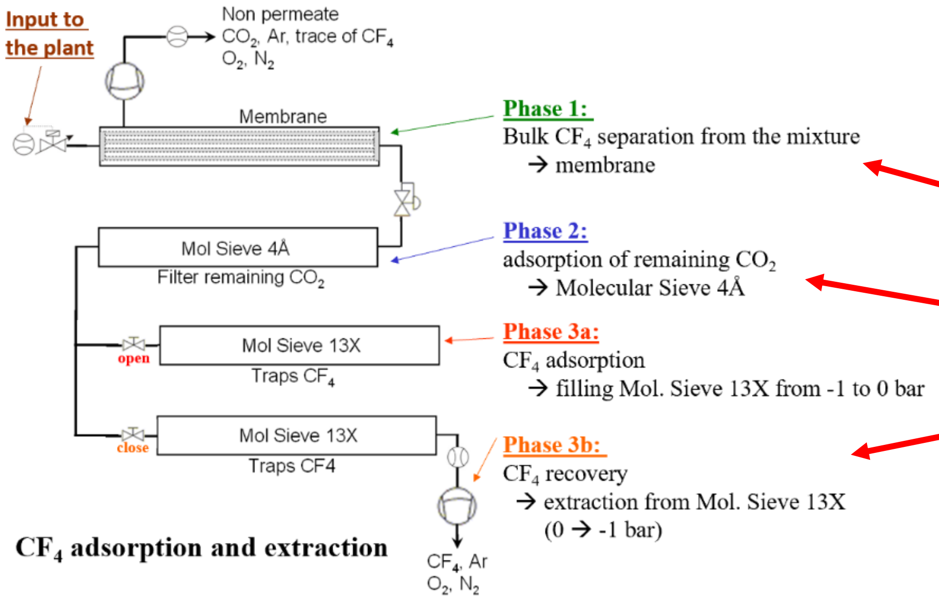
First plant built for CF_4 warm adsorption

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% reached in 2021 (with additional resources)



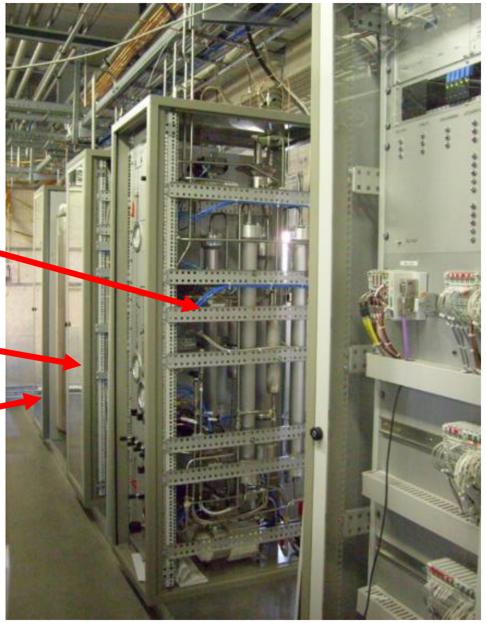
Phase 1:
Bulk CF_4 separation from the mixture
→ membrane

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)

CF_4 adsorption and extraction



If gas recuperation system is needed: fundamental to invest in R&D and resources since the beginning

Gas Recuperation: costs vs benefits

Positive effects – 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)

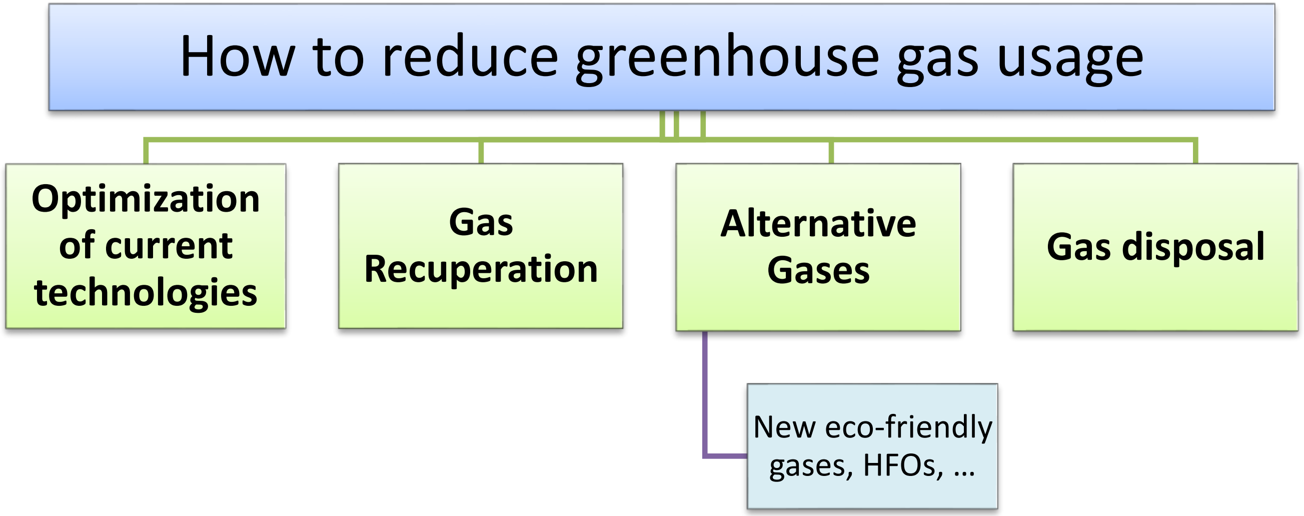
With 80% or recuperation efficiency

→ 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

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.

GHG Optimization: CERN Strategies



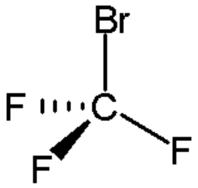
How to reduce greenhouse gas usage

- Optimization of current technologies
- Gas Recuperation
- Alternative Gases
  - New eco-friendly gases, HFOs, …
- Gas disposal

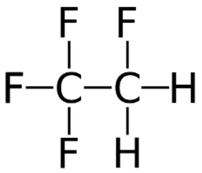
Gases for particle detectors

It is not the first time we are looking for “new” ecofriendly gases…and, probably, not the last

ODP
Ozone Depletion Potential → GHG
Greenhouse gases → “ECO” gases → Natural gases



R13B1
(CBrF3)
GWP 6900 - ODP 10



R134a
($C_2H_2F_4$)
GWP 1430 - ODP 0

Hydro-Fluoro-Olefin (HFO)
- C=C double bond
- fluorine-containing
- hydrogen-containing

and

3M™ Novec™

GWP <10 - ODP 0

$O=C=O$

and

hydrocarbons

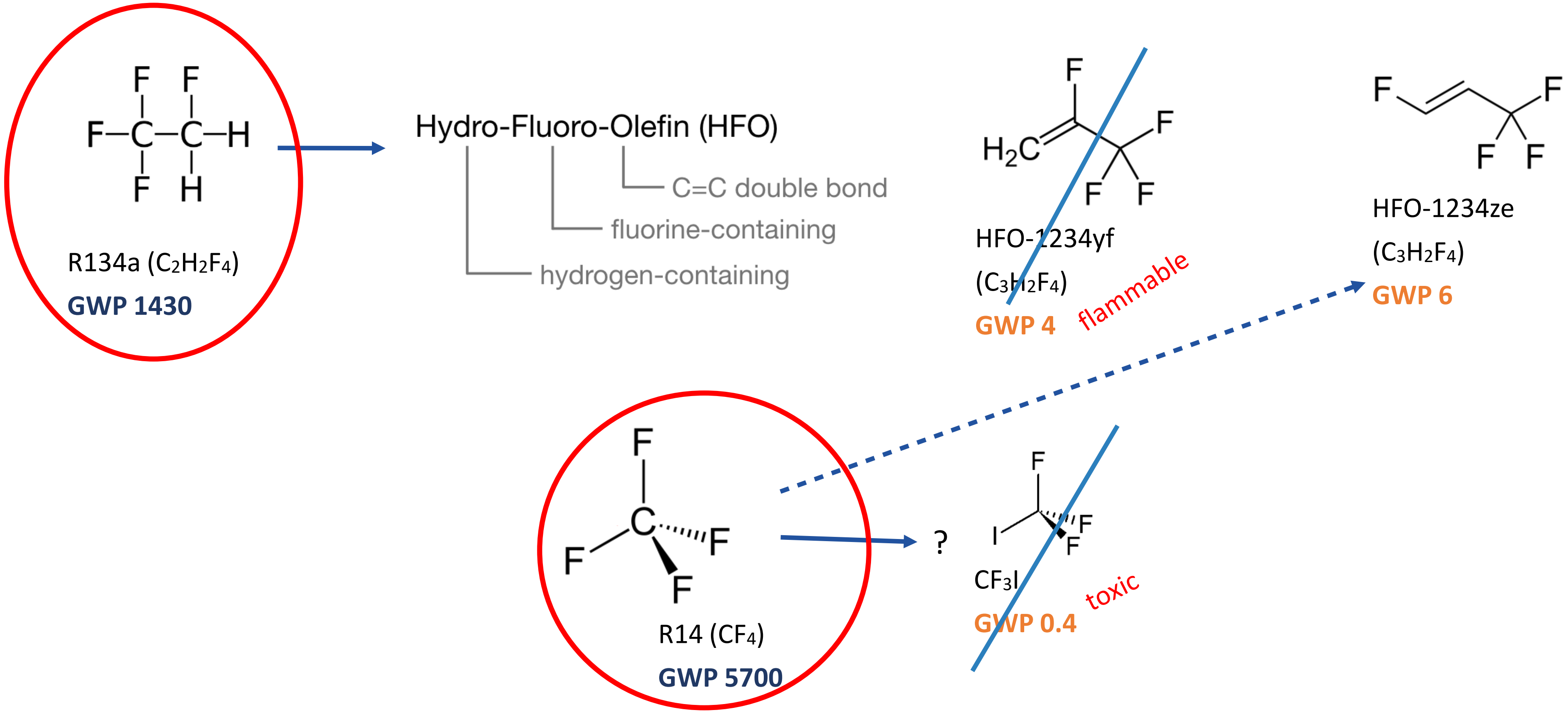
GWP 1 - ODP 0

- ~20-30 years ago, it was the time to get rid of ODP gases
- There was not the awareness on the use of GHGs
  - Many gaseous detectors were conceived with use of GHGs
- Now it is time to address the usage of GHG worldwide, including particle detectors
- New concerns are already raising for the use of new “eco-friendly” gases, most of which are PFAS

Possible alternatives to GHG gases

New eco-friendly liquids/gases have been developed for industrial applications as refrigerants and HV insulating medium…

→ many gases tested, but not straightforward for detector operation. Best options:



R134a ($C_2H_2F_4$)

GWP 1430

Hydro-Fluoro-Olefin (HFO)

C=C double bond

fluorine-containing

hydrogen-containing

~~HFO-1234yf~~

~~($C_3H_2F_4$)~~

GWP 4 flammable

HFO-1234ze

($C_3H_2F_4$)

GWP 6

R14 (CF_4)

GWP 5700

?

~~CF_3I~~

~~**GWP 0.4**~~ toxic

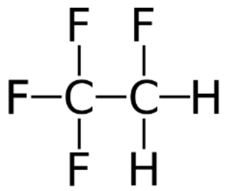
Very difficult challenge for already installed detectors where it is not possible to change of FEB electronics, HV system, etc

However, in any case to be considered

- Long-term operation (to evaluate possible aging issues)
- No flammability or toxicity of the gas mixture

Alternatives for RPC gas mixture: R134a and SF6

~95%

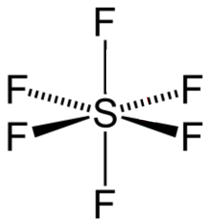


$C_2H_2F_4$

GWP 1430

+

From 0.3% up to 7%



SF_6

GWP 22800

+

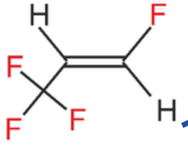
~5% iC_4H_{10}

O=C=O

Replacement of R134a with ~30-50% CO_2 to lower GHG emissions

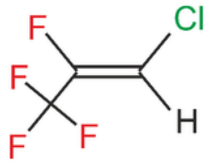
Detector performance slightly affected

Hydro-Fluoro-Olefin (HFO)
- C=C double bond
- fluorine-containing
- hydrogen-containing

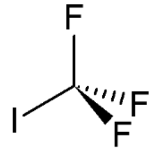


HFO-1234ze(E)

Detector performance affected and long-term effects to investigate



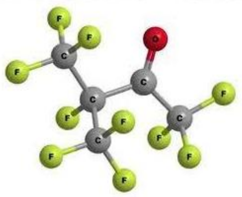
HCFO-1224yd

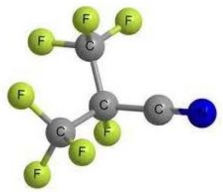


CF_3I

GWP 0.4

“Forever chemicals”
Possible concerns for environment





3M™ Novec™ 5110
($CF_3C(O)CF(CF_3)_2$)
GWP <1

3M™ Novec™ 4710
($(CF_3)_2CFCN$)
GWP 2100

Very good detector performance, but “reactive” in detector environment

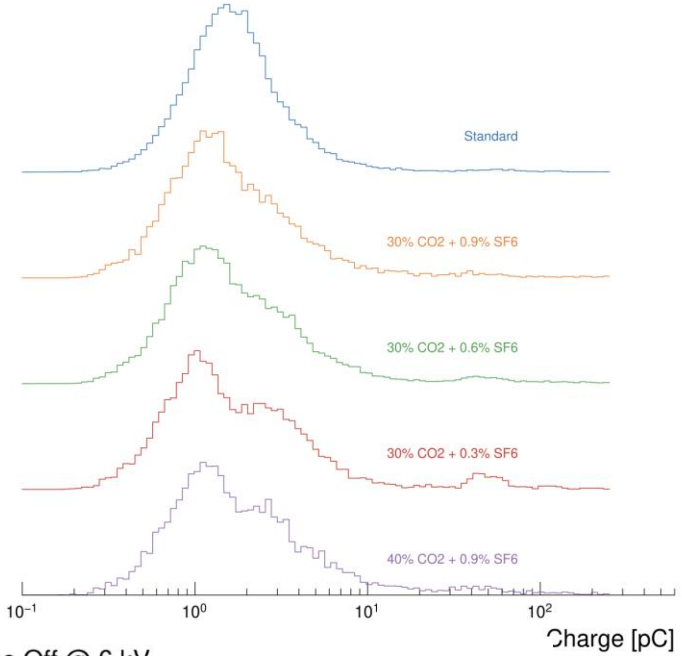
Mid-term solution: addition of CO2 to std gas mix

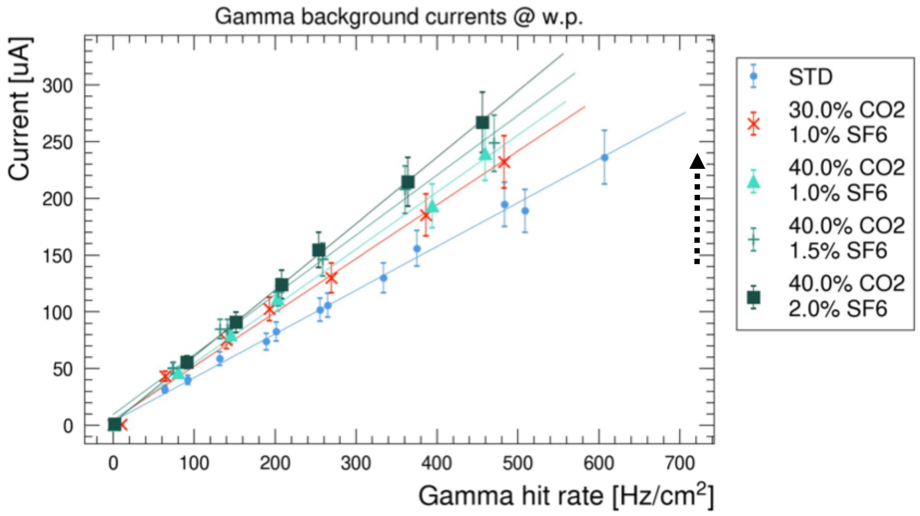
CO_2 as mid-term solution for RPC to mitigate GHG emissions of LHC RPC systems

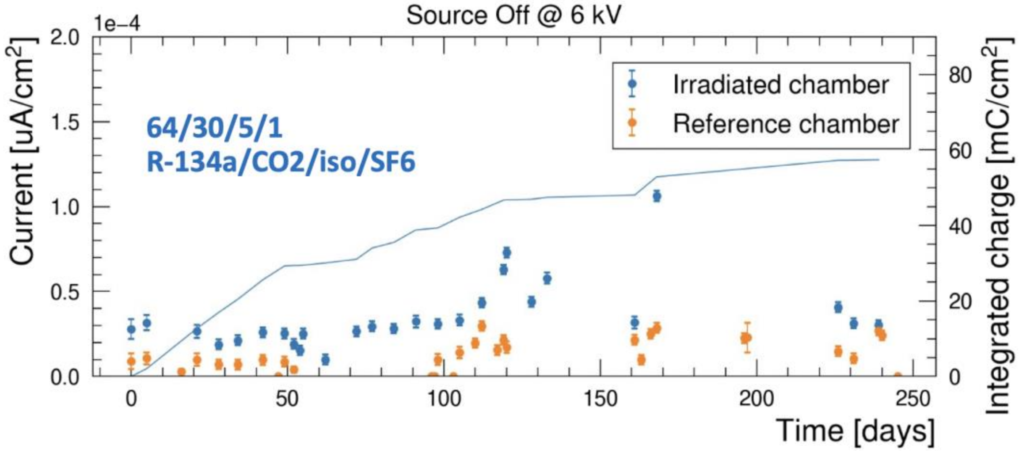
doi 10.1016/j.nima.2023.168088

- CO_2 selected as best compromise
  - He also good candidate but cannot use in experimental caverns
- The addition of CO_2 increases the streamer probability and broad the charge distribution
  - Necessary to increase the SF_6 concentration up to 1%
  - Increase of currents of >15% under irradiation
- Very good time resolution
  - The CO_2 reduce the mean free path
- Long-term performance studies under gamma irradiation
  - Up to now, no sign of performance degradation

Already in use in ATLAS RPC system since summer 2023







Mid-term solution: addition of CO2 to std gas mix

Positive effects:

Replacement of 30% R134a with CO2 brings a reduction of 14% of the tCO2eq emitted per year

mixture	GWP	tCO2e/year
R134a+iC4H10+SF6	1482	52373
CO2+R134a+iC4H10+SF6	1529	44784
		-14%

In addition, the operational cost is lower

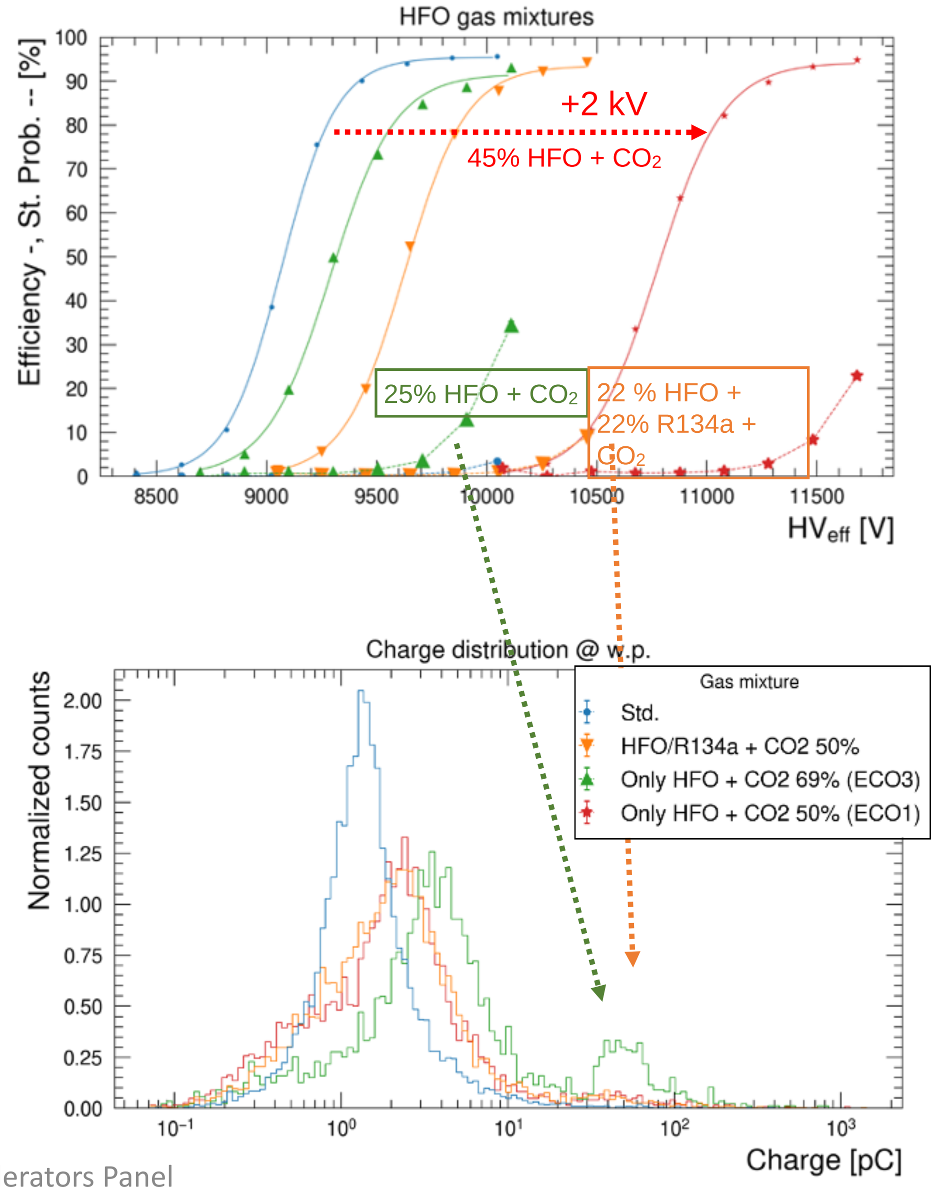
mixture	R134a used (kg/m3 gas mix)	SF6 used (kg/m3 gas mix)	
R134a+iC4H10+SF6	4.3	0.02	
CO2+R134a+iC4H10+SF6	2.91	0.065	
	-11 t/year	**+356 kg/year**	
	-115 kCHF	**+13 kCHF**	**-102 kCHF/year** **-29%** **1 year with std+CO2 mix ~ 250 kCHF**

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

Use of HFO in RPC detectors

HFO1234ze identified as possible replacement of R134a

- Cannot replace 1:1 the R134a
  - Too high w.p.: add He or CO_2 to lower it
  - The HFO and CO_2 move the charge distribution towards higher values
  - Currents increase seems to be dominated by the CO_2
- HFO brings a higher prompt charge content than R134a
- The addition R-134a helps lowering the background currents and prevent w.p. to be too high



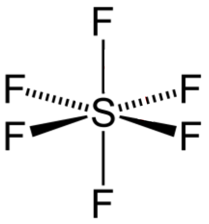
R-1234ze performance with CO2 (+ R-134a) with cosmic muons

- 45% HFO + CO2 (ECO1)
  - Too high w.p. and high charge
- 25% HFO + CO_2 (ECO3)
  - Low GWP
  - High charge content and presence of streamers. Higher currents
- 22% HFO + 22% R134a+ CO_2
  - Higher GWP
  - Lower charge content than HFO only
  - **Possible compromise** between performance and environment

Alternatives to SF_6

Scrivi good/bad

6 F



SF_6

GWP 23900

- Chemical inertness: extremely stable
- Exceptionally long lived in the atmosphere
- Excellent dielectric property
  - SF_6 x 2.5 than Air
- Non-flammable and toxic
- Gaseous form
- No major reactions
  - Ok with H_2O, Cl and acids

10 F

3M™ Novec™ 5110

($CF_3C(O)CF(CF_3)_2$)

GWP <1 - Atm. lifetime 15 days

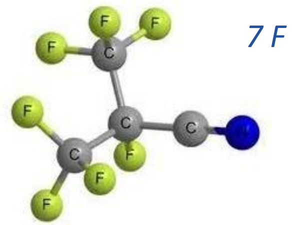
High boiling point: 27 C

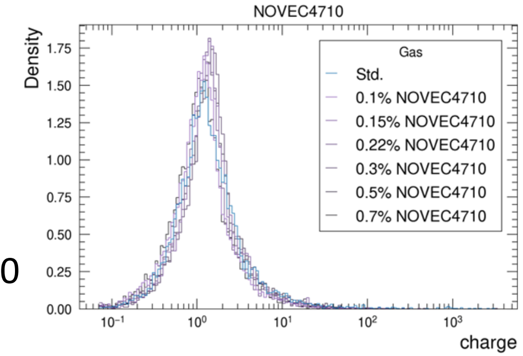
Sensitive to UV radiation

Higher HV working point

Not very good performance

7 F





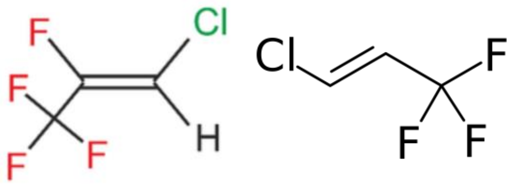
3M™ Novec™ 4710

($(CF_3)_2CFCN$)

GWP 2100 - Atm. lifetime 30 years

Good performance, but it may react with H2O

3-4 F



AMOLEA™ HFO-1224yd

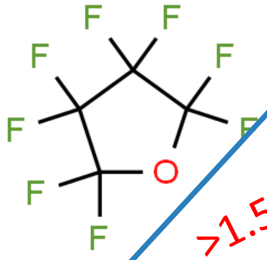
(CF_3-CF=CHCl)

GWP <1 - Atm. lifetime 20 days

Good performance.

Presence of Cl (aging test mandatory)

8 F



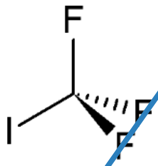
C_4F_8O

GWP 8700

Atm. lifetime >3000 years

>1.5% needed
No gain in GWP

3 F



CF_3I

GWP 0.4

Atm. lifetime 6 days

toxic

Not only detector performances….

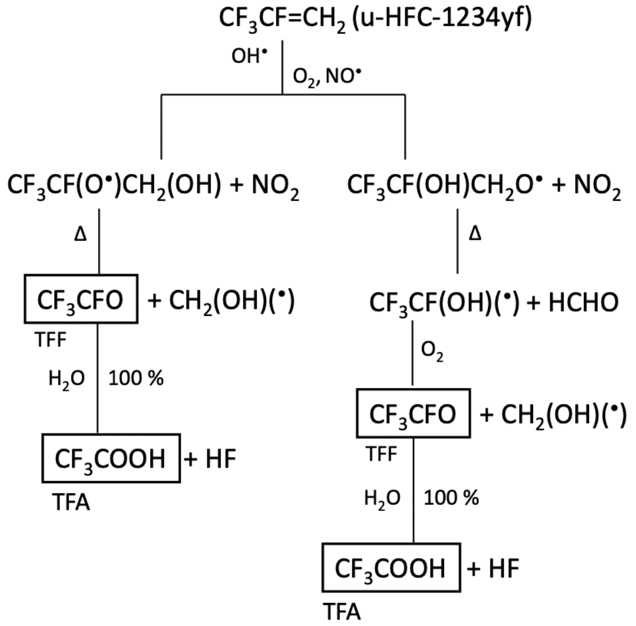
Two factors identify the greenhouse gases and their effects on climate: the radiative efficiency and lifetime in the atmosphere

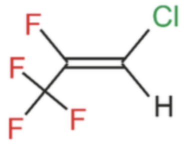
The lower are the GWP and the lifetime, the easier is the creation of sub-products

Do these sub-products have an impact on detector lifetime?

Three factors determine the atmospheric lifetime

Rain out → Water solubility
Oxidation → Reactivity with OH
Photolysis → UV absorbance

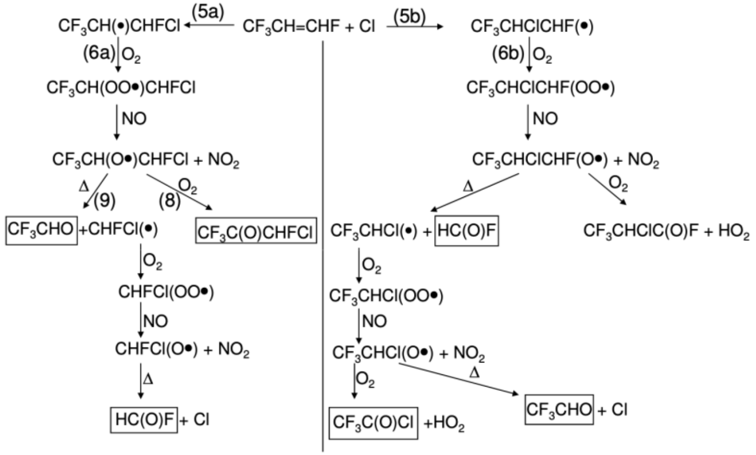




HFO-1224yd

Degradation products:

TFA, CO2, HF, HCl



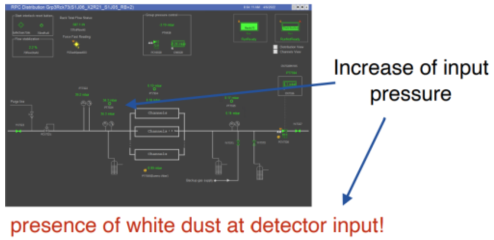
Hydrofluoric Acid (HF)

HFO produces much more HF than R134a in RPC detectors

Trifluoroacetic acid (TFA)

- HFO1234ze is estimated to break down into TFA at less than 10%, whereas R-1234yf will break down into TFA at 100% (R134a at 21%)
- TFA highly soluble: no formation of insoluble salts
- Phytotoxic

Observation with ppm of HCFC (importance of long-term validation tests):



ATLAS and CMS - RPC upgrade programs: new detectors & FEB

New detectors for upgrades (ATLAS-BIS/BI)

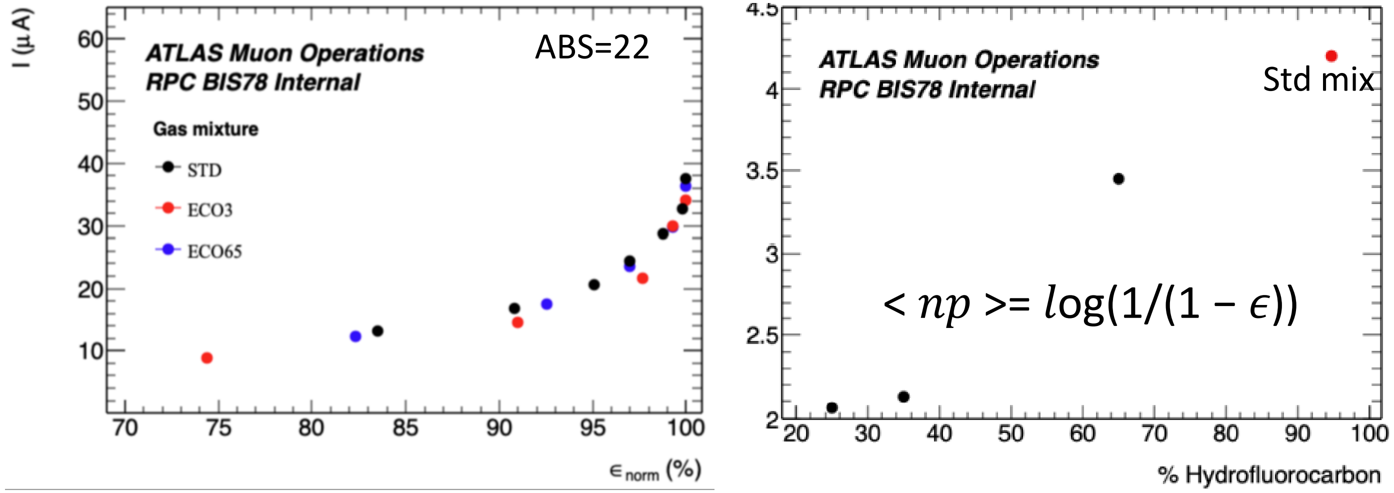
- Triplet (3 single gaps; 1 mm gas gap)
- Very effective Faraday cage allowing to operate with low noise and trigger on 2/3 coincidence
- New FEB with new chip:
  - Low noise
  - Allowing threshold as low as 1 fC
    - → from 30 to 3 pC per photon count
      - → Increased rate capability (x10)
      - → Low ageing (÷10)
- 3 independent singlets providing 3D+time
- Combined σ_t 160 ps

New detectors for upgrades (CMS-iRPC)

- double gap (1.4 mm gas gap)
- new FEB:
  - PETIROC2C re-designed
  - Threshold < 50 fC
  - TDC σt 20 ps
  - TDC and detector σt ~ 160 ps
    - → position resolution of ~1.6 cm

Mixtures from ECOGAS@GIF collaboration:

ECO3 = 25%HFO/70%CO2/4%ISO/1%SF6
ECO2 = 35%HFO/60%CO2/4%ISO/1%SF6
ECO65 = 65%HFO/30%CO2/4%ISO/1%SF6



From:

CERN EP Seminar: Summary of RPC workshop

RPC 2022 workshop: Overview:

Exploring the performance limits of the new generation of ATLAS RPCs

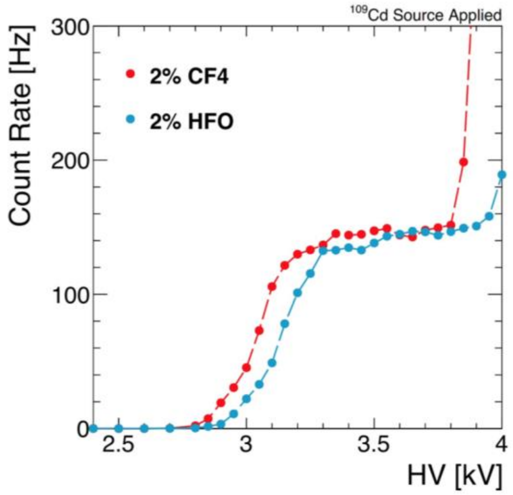
XVI Workshop on Resistive PlaCMS iRPC FEB development and validation

Not only RPC: Possible CF_4 and C_4F_{10} replacements

CF_4 is used in different types of particle detectors to prevent aging, to enhance time resolution or because of its scintillation photon emission

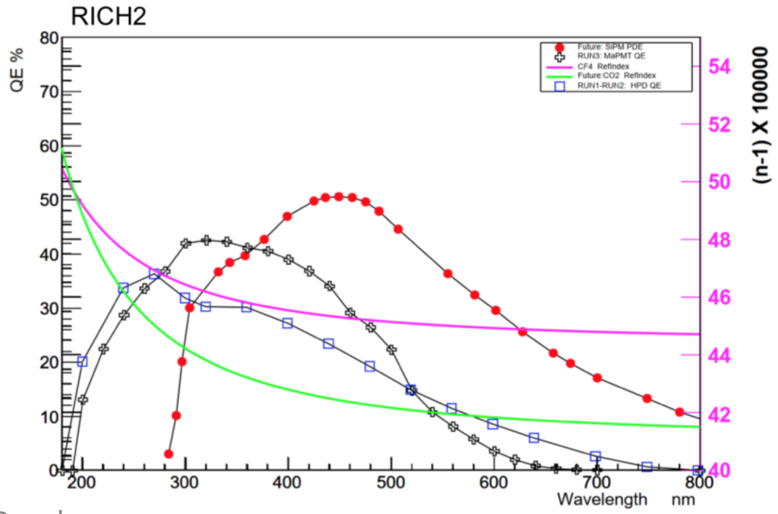
CMS CSC studies (K. Kuznetsova)

- CF_4 is a source of fluorine radicals to protect against anode ageing
  - Now 10% CF_4 in CSC gas mixture
- Two possibile approaches to reduce GHG consumption (beyond the recirculation and recuperation systems)
  - **Decrease the CF_4 concentration**: preliminary results show that 5% could be safe for operation
  - **CF_3I and HFO1234ze not best candidates**
  - Look for other alternatives to CF_4 on-going

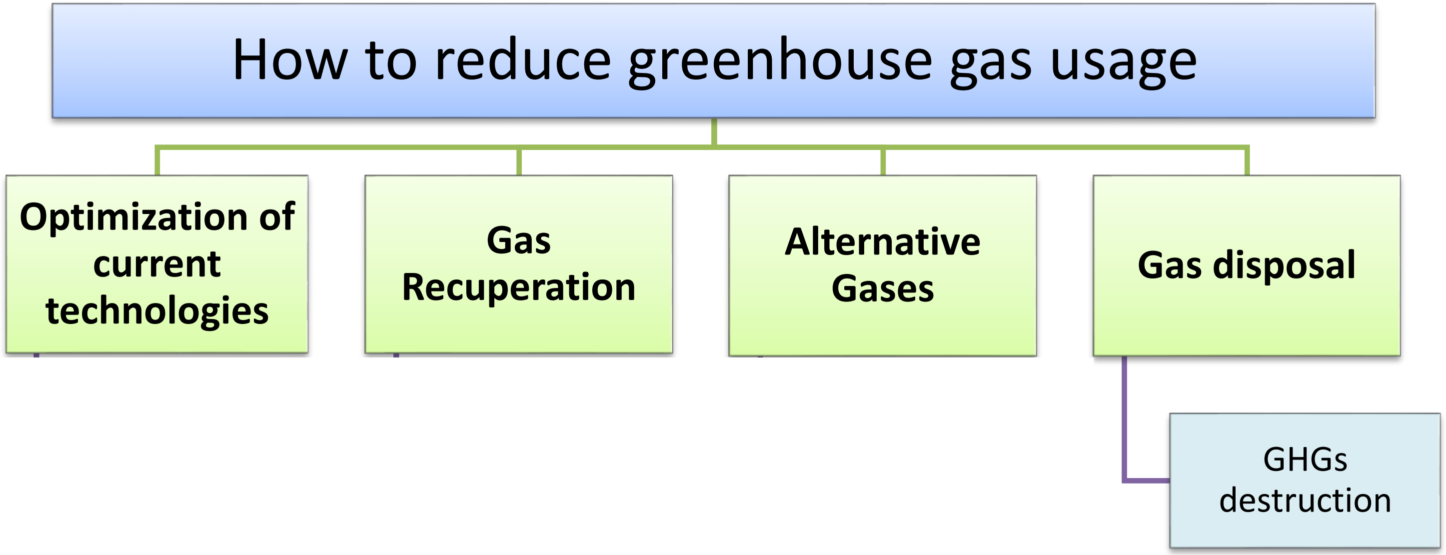


LHCb RICH studies (S. Easo and O. Ullaland)

- RICH detectors use either CF_4 or C_4F_{10}
  - Necessary for good refractive index
- Replacement of C_4F_{10} with $\mathbf{C_4H_{10}}$
  - Refractive index matches very well
  - But C_4H_{10} flammable
- Replacement of CF_4 with $\mathbf{CO_2}$
  - Under investigation
- Use of SiPM to reduce the chromatic error and increase the yield



GHG Optimization: CERN Strategies



How to reduce greenhouse gas usage

- **Optimization of current technologies**
- **Gas Recuperation**
- **Alternative Gases**
- **Gas disposal**
  - GHGs destruction

GHG abatement system

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.

Very high costs if compared with recirculation and recuperation plants.

Found also companies available to take PFC/HFC based mixture for disposal, but extremely expensive.

In addition, the **GHGs disposal is not helping in the current market situation where availability decreases and price increase**.

On the contrary, the advantages of gas recuperation plants are going beyond the reduction of GHG emissions and the economical aspects:
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.

Conclusions

GHGs usage in particle detectors

F-gas regulation

- Due to the environmental risk, “F-gas regulations” started to limit the GHGs usage and requiring recovery, proper servicing to prevent emission (EU case)
- availability and price are today critical for old F-gases

Detector design

- It is fundamental to look not only at detector performance but also at the infrastructure
- New generation detectors should limit the risk of developing leaks
- If detectors are tight, gas consumption can be limited thanks to gas recirculation and recuperation plants (useful not only for GHGs but also for any expensive gases)

Strategies for GHG usage optimization

Optimization of current technologies

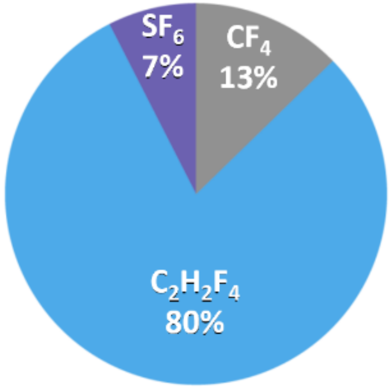
- Particular attention to gas system and detector operation
- Gas systems upgrade beyond original design
- Improved/higher gas recirculation

Conclusions

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 (CF4, C4F10) 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



New eco-gases

- New low-GWP gases can easily break
  - **Sensitive to UV, humidity and oxidation**
  - HF, TFA sub-products are produced and their effects on long-term operation need to be evaluated
- **Missing cross-section to perform simulation studies**
  - Dedicated measurements needed
- R-1234ze, NOVEC, … are currently the main fluorinated alternative but:
  - For 2 mm gas gap RPC, the addition of a 4th mixture components (CO2, ?) is needed to maintain reasonable HV working point
  - availability and price are still a matter of concern
  - long term operation in high radiation environment to be studied
- **New generation detectors and electronics seems to be more compatible with new eco-friendly gases** than old-generation 2 mm gas gap RPC
  - Upgrades for LHC experiments (ATLAS and CMS RPC Phase2 upgrades)

Conclusions

GHGs abatement/disposal

- Commercial systems exist. Adopted when gases cannot be reused.
- Heavy infrastructures required (CH_4+O_2 supply, Wastewater 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.

Additional challenge: finding right profile for resources for R&D and new recuperation plants operation:

- Chemist, industrial chemistry engineer, engineer, physicist
- **Right level of resources** should be allocated to GHGs related activities since the beginning (detector and infrastructures design phase)

GHG abatement system

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.

However, PFCs are stable and difficult to abate

Carbon-fluorine bond is the fourth strongest single bond

- Multiple C-F bonds on the same carbon enhance stability
- C-C or C-H bonds are weaker and decrease stability
- S-F bond is strong too

Stability is reflected in atmospheric lifetimes

Stability is closely related to ease of abatement

Fluorinated gas lifetime in atmosphere (years)	
CF_4	**50000**
C_2F_6	10000
SF_6	**3200**
C_3F_8	2600
c-C_4F_8	3200
NF_3	740
CHF_3	270
$C_2H_2F_4$	**14**
CH_2F_2	5

GHG abatement system

Reaction of CF_4 to CO_2 and HF is very exothermic, but also requires a big push to break the very strong C-F bonds

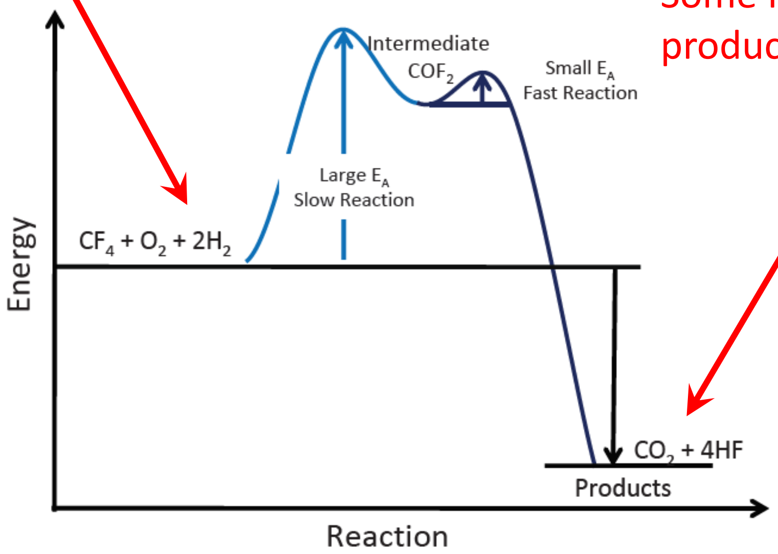
-This is why CF_4 abatement is so difficult

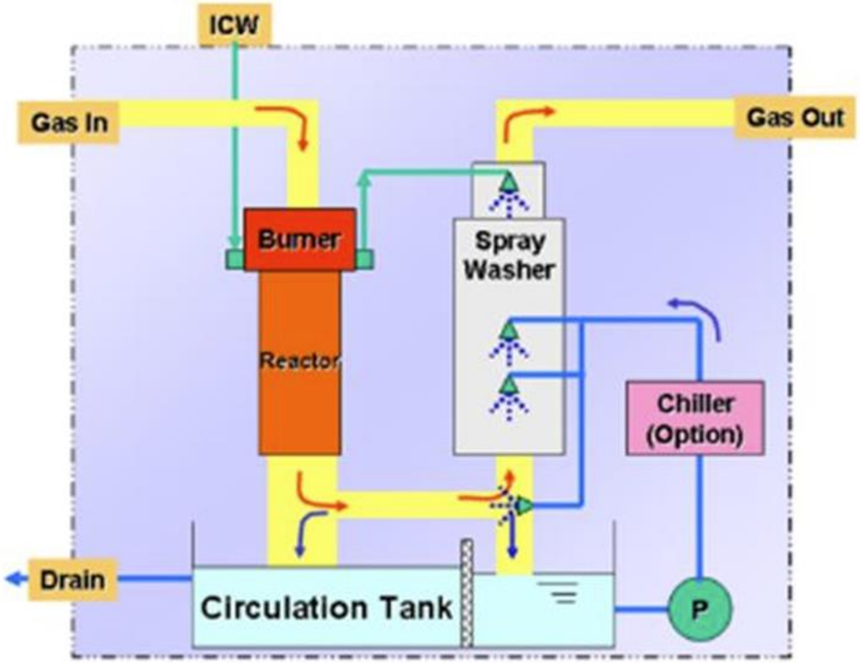
-Actual reaction is much more complicated than shown

Burn-wet is the primary POU (point of use) abatement technology

Huge quantities of
O_2 and CH_4
needed to overcome E_A
Some 100 m^3/day needed

Final product is HF!
One liter of CF_4 generates
4 liters of HF
Water treatment plant
required!
Some m^3/day wastewater
produced





Small commercial systems for burn-wet exist
but require heavy infrastructures:

- CH_4+O_2 supply
- **Waste water treatment**

GHG abatement system

Industrial system able to destroy GHGs: two options considered

Ebara G5 system

Edwards ATLAS Etch system

Utilities & services	Consumption
Fuel (city gas)	40-130 m^3/day
Soft water	15 m^3/day
Chilled water	10-90 m^3/day
O_2 (combustion)	80 m^3/day
N_2 (purge)	200-350 m^3/day
Dry Air (purge)	200 m^3/day
Ventilation	1-3 m^3/min
Operation cost	9-16 kCHF/month

Approximative cost of burner system: 130 kCHF

abatement phase	Chemical reaction
Burning phase	$CF_4 + O_2 \rightarrow CO_2 + 2\ F_2$
	$SF_6 + O_2 \rightarrow SO_2 + 3\ F_2$
	$2\ C_2H_2F_4 + 5\ O_2 \rightarrow 4\ CO_2 + 2\ H_2O + 4\ F_2$

GHG abatement system

Waste water treatment plant

abatement phase	Chemical reaction
Washer phase	$2\ F_2 + 2\ H_2O \rightarrow 4\ HF + O_2$
	$SO_2 + H_2O \rightarrow H_2SO_3$
	$SO_3 + H_2O \rightarrow H_2SO_4$

Sewage resulting from operation are compressed for disposal

The EnviroChemie “STEP” wastewater treatment plant
One already in operation at CERN and similar to what we would need

Approximative cost of wastewater treatment system:

500 kCHF

Economic analysis: recovery vs abatement

	Recovery systems			**Abatement systems**		
gas potentially recovered (2012 -2025)	R134a (kg)	SF6 (kg)	CF4 (kg)	R134a (kg)	SF6 (kg)	CF4 (kg)
Beginning of operation	2023	~2025	2012			
	17200	96	6505	0	0	0
Money saved from gas recovered (kCHF) (2012 -2025)	~500			0		
Money spent for construction – CAPEX (kCHF)	525			617		
M&O (kCHF/year)	15			16		
Manpower (kCHF/year)	60			84		
Emissions (tCO2eq/year)	39114			2600		