EP-DT
Detector Technologies

16th Pisa Meeting on
Advanced Detectors

Towards more eco-friendly gaseous detectors

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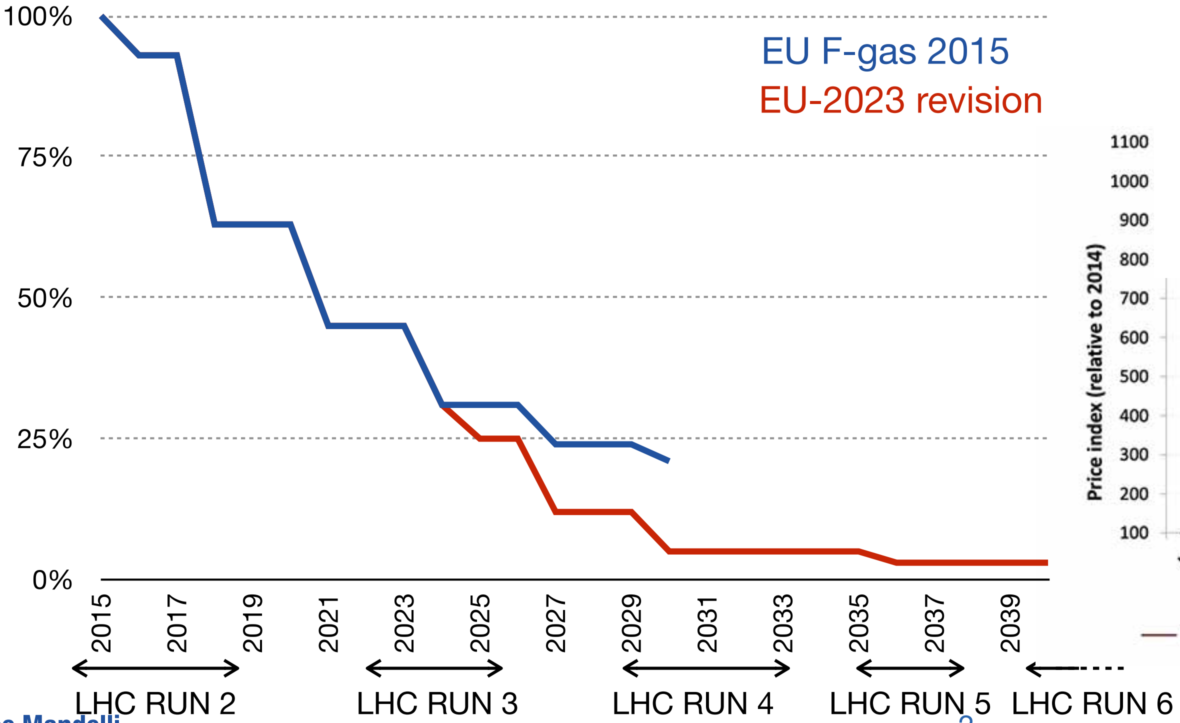
CERN

16th Pisa Meeting on Advanced Detectors
31st May 2024

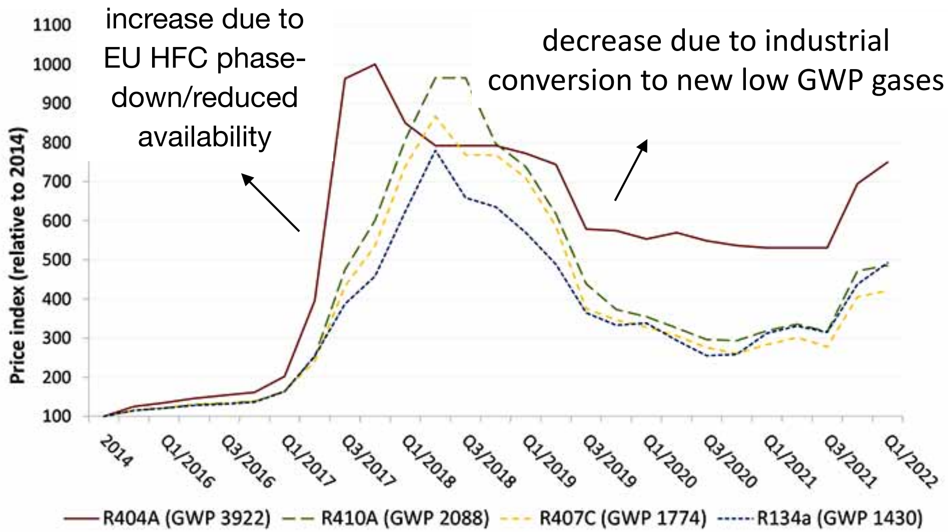
New F-gas regulation: from phase down to out

The new Regulation establishes the total elimination of hydrofluorocarbons 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
- Keywords: to **limit**, to **prevent**, to **ban** the use of F-gases
- In 2023, the European Chemicals Agency (ECHA) released a proposal regarding **PFAS restrictions**
  - PFAS: per- and polyfluoroalkyl substances
  - it envisages covers over 10,000 different PFAS, which are considered environmental pollutants with links to harmful health effects

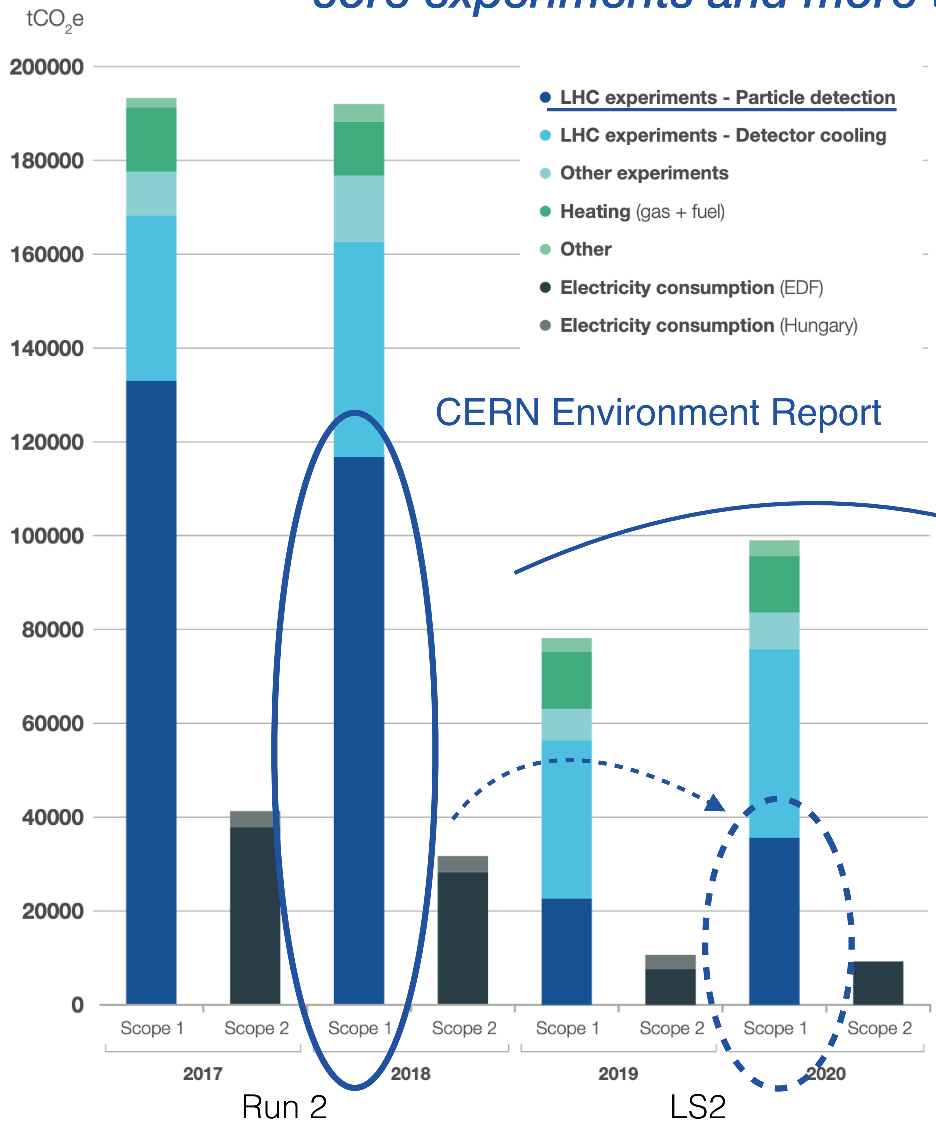


Average purchase prices of the most commonly used HFC refrigerants

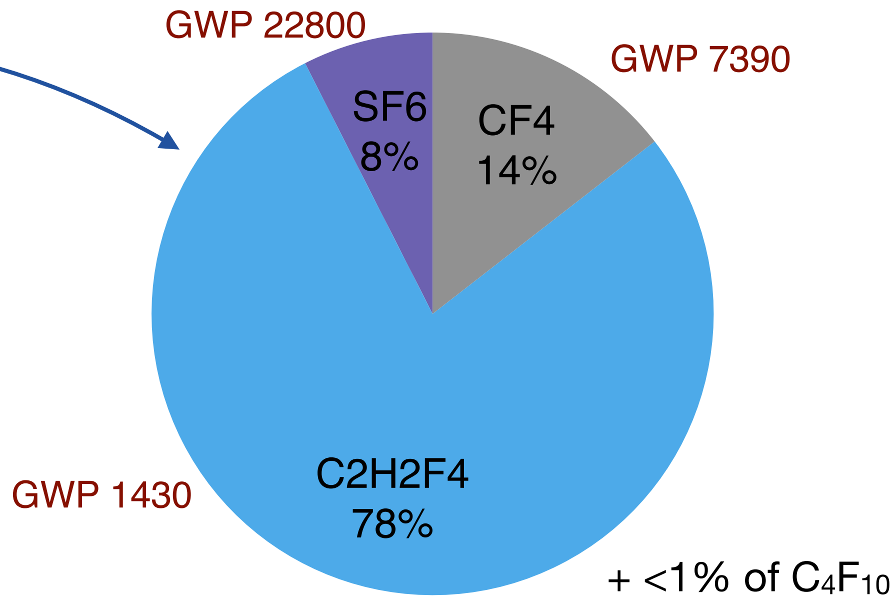


GHG emissions at CERN

Greenhouse gas emissions at CERN arise from the operation of the Laboratory's research facilities. The majority of emissions come from CERN's core experiments and more than 78% are fluorinated gases

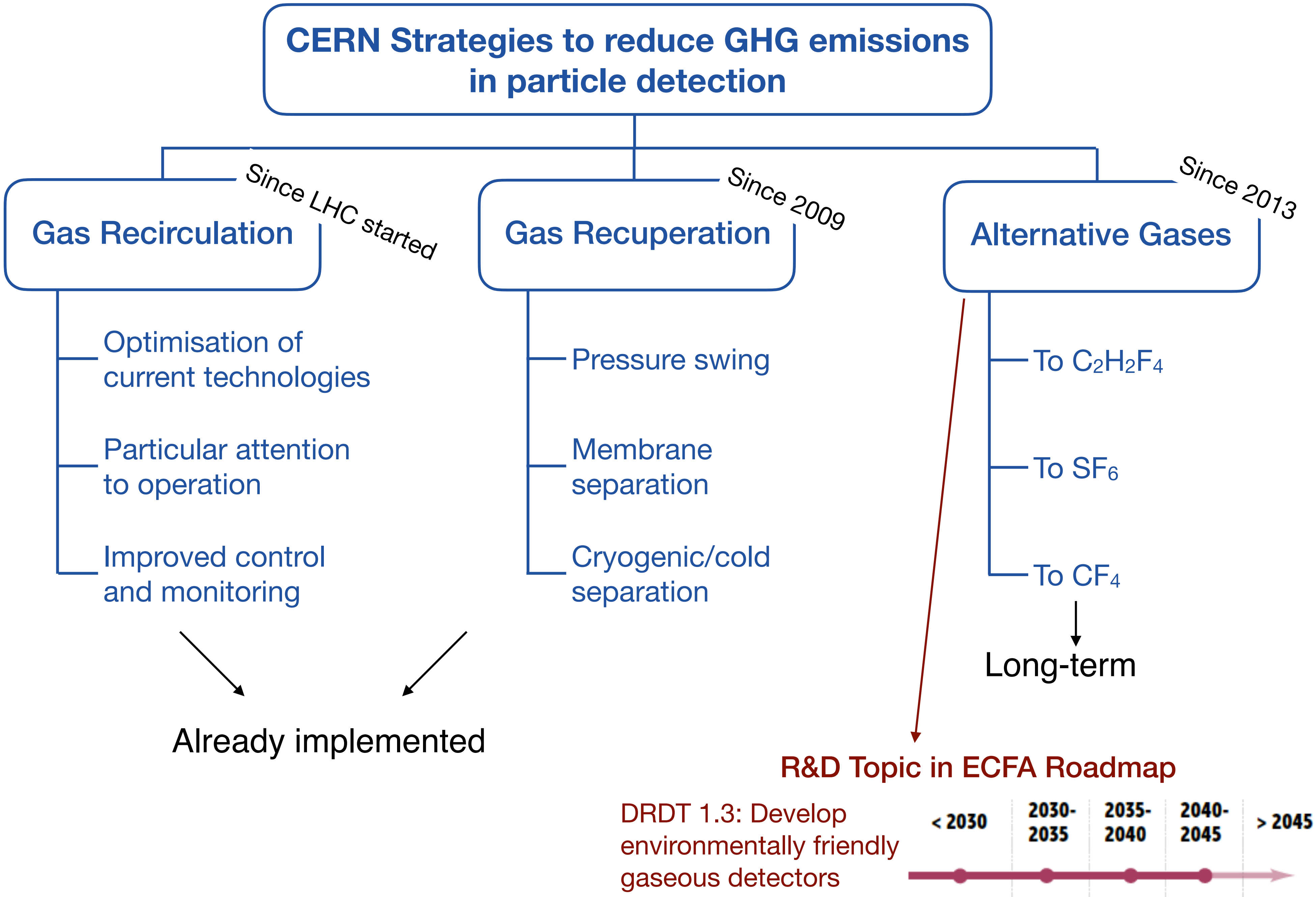


- ~90% of emissions related to large LHC experiments
- Most emissions from particle detection
- Drastic reduction of GHG emissions from particle detection during LS2



The CERN's objective is to reduce its scope emissions by 28% by the end of 2024

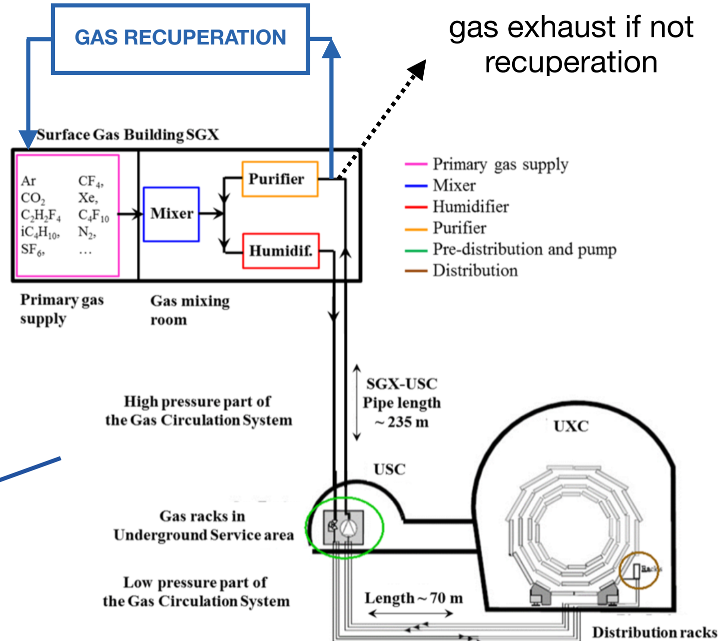
CERN strategies for GHG reduction

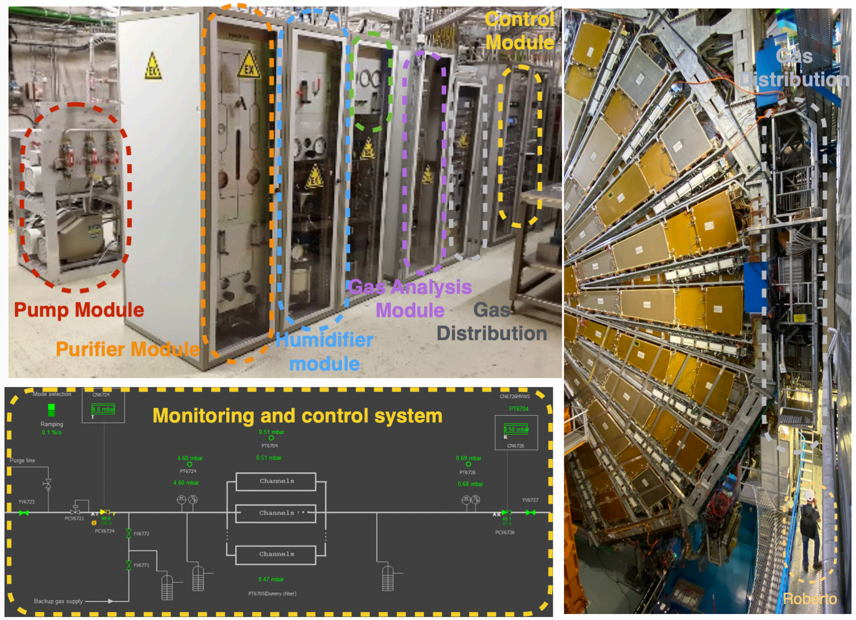


Gas recirculation: primary solution

Gas recirculation (and recuperation) systems are the first way to reduce GHG emissions for now and for future detectors

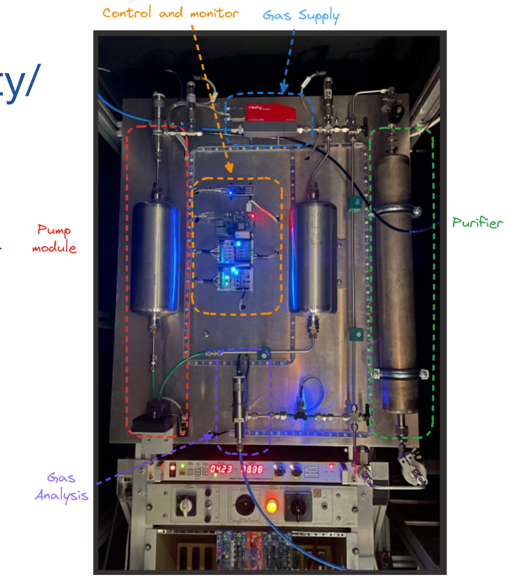
- The gas mixture is taken at the output of the detectors, it is purified and afterwards sent back to the detectors
  - Creation of several impurities
  - Recirculation usually from 90% to 100%
  - Necessary to not have leaks at detector level
- Possible to recirculate 100%: almost zero emissions
- At CERN: ~30 gas recirculation systems
  - Detector volumes up to 100 m³
- When it is not possible to recirculate 100%, a recuperation system can be envisaged





From LHC gas systems to facility/ laboratory small (and cheap) recirculation systems

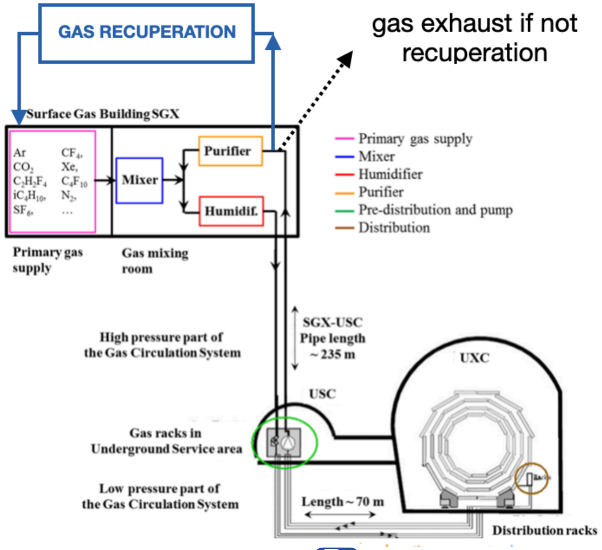
This necessity is growing up due to restrictions and increasing of prices



Gas Recuperation: a second step

Sometimes it is not possible to recirculate 100% of gas mixture due to detector constrains

- Detector air **permeability**, max recirculation **fraction**, presence of impurities, etc.
- A fraction of gas has to be **renewed**
  - Some gas is sent to the atmosphere
- This fraction of gas mixture can be sent to a recuperation plant
  - The GHG is extracted, stored and re-used
- **Challenges:** R&D, custom development, operation and recuperated gas quality
- Gas recuperation can also be used to **empty/fill** the detectors during long shutdown periods

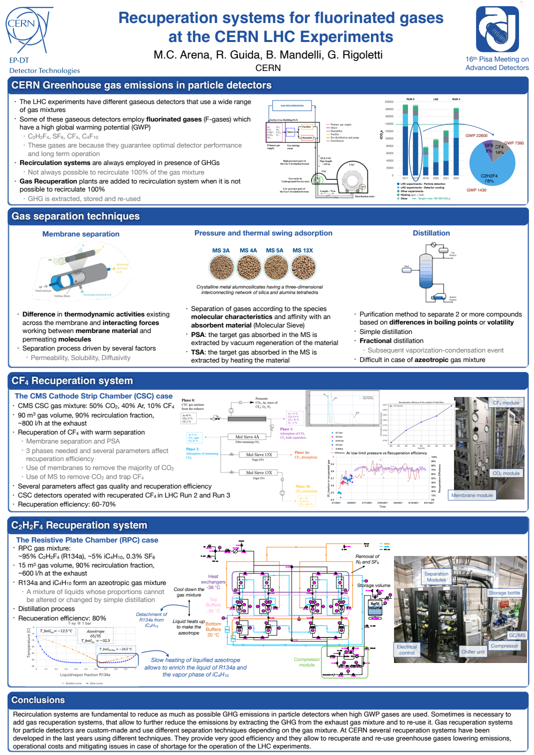


Gas recuperation systems for GHGs at CERN:

CF_4: CMS Cathode Strip Chambers and LHCb RICH2
- Membrane and pressure swing

$C_2H_2F_4$ and **SF_6**: Resistive Plate Chambers (RPC)
- Distillation process for azeotrope

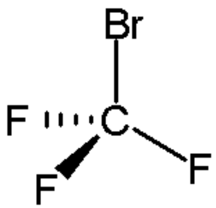
C_4F_{10}: LHCb RICH1
- Distillation process


Recuperation systems for fluorinated gases at the CERN LHC Experiments
M.C. Arena, R. Guida, B. Mandelli, G. Rigoletti
CERN
CERN Greenhouse gas emissions in particle detectors
Gas separation techniques
Membrane separation
Pressure and thermal swing adsorption
Distillation
CF_4 Recuperation system
The CMS Cathode Strip Chamber (CSC) case
$C_2H_2F_4$ Recuperation system
The Resistive Plate Chamber (RPC) case
Conclusions

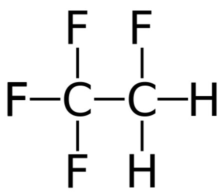
Alternatives gases

New eco-friendly liquids/gases have been developed for industry as refrigerants and HV insulating medium… not straightforward for detector operation

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)
- hydrogen-containing
- fluorine-containing
- C=C double bond

and

3M™ Novec™
GWP <10 - ODP 0

O=C=O

and

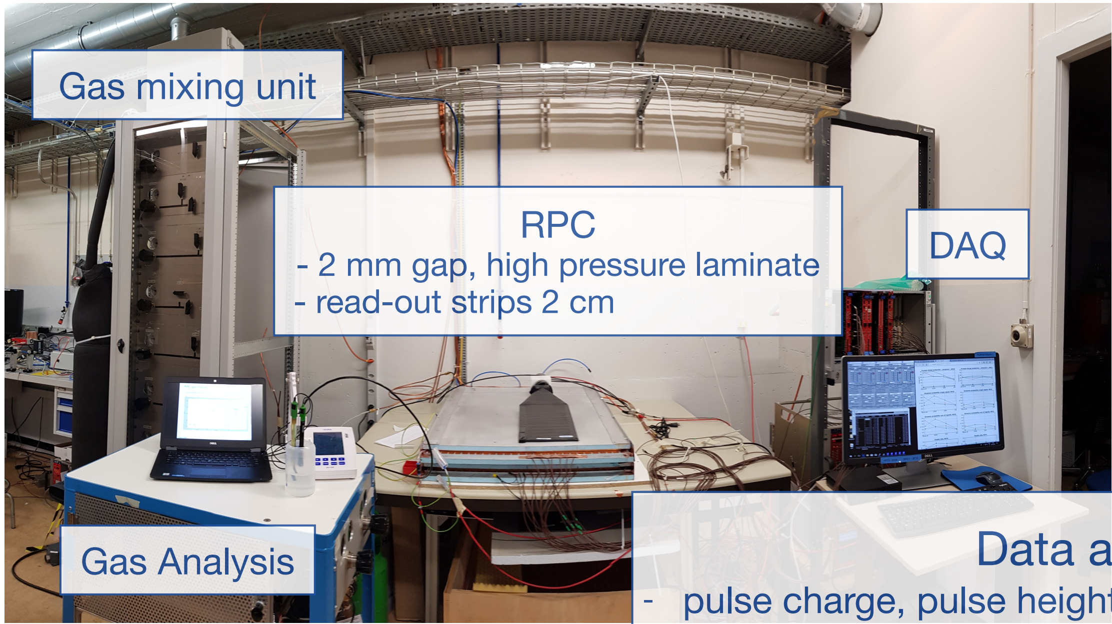
hydrocarbons

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

Set-ups: laboratory and irradiation facility

Set-ups to test different types of gas mixtures and detectors: RPC, wire chambers, MPGD



Laboratory

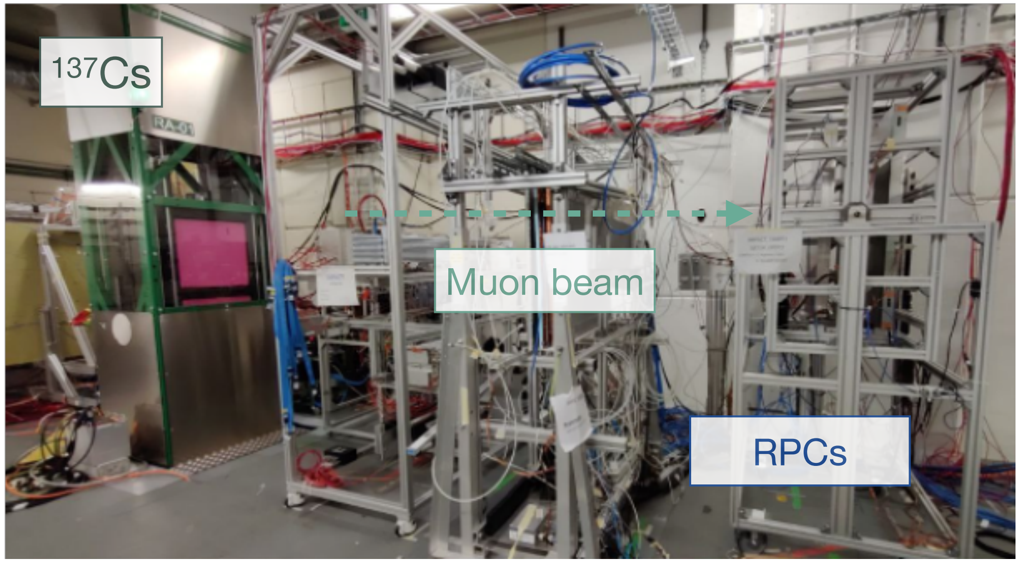
- Gas mixing unit
  - Gas mixture up to 6 components
- DAQ
  - CAEN Digitizer V1730: resolution 0.12 mV, sampling 500 MS/s
- Gas analysis
  - GC, MS and ISE

Data analysis for RPC

- pulse charge, pulse height, time, etc.
- efficiency, avalanche/streamer ratio, cluster size, time resolution

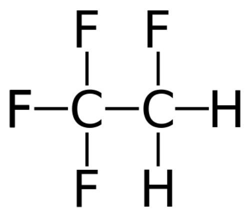
Gamma Irradiation Facility (GIF++)

- Gamma source
  - ^{137}Cs of 12 TBq —> 662 keV gamma
  - Lead filters to allow attenuation factors (ABS) between 1 and 46000
- Muon Beam
  - 100 GeV and 10^4 muons/spill (core beam size 10 x 10 cm^2)
- Detectors tested up to to ~ kHz/cm^2
- Very similar DAQ, gas system and gas analysis of laboratory



Alternatives for RPC gas mixture: R134a and SF_6

~95%

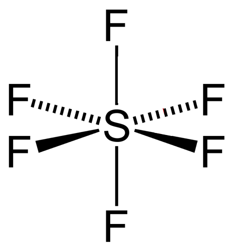


$C_2H_2F_4$

GWP 1430

\+

~0.3%
(up to 7% for glass RPC)



SF_6

GWP 22800

\+

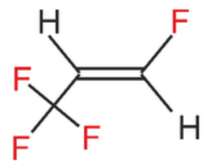
~5% iC_4H_{10}

O=C=O

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

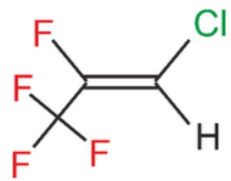
Detector performance slightly affected

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

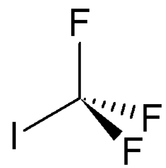


HFO-1234ze(E)

Detector performance affected and long-term effects to investigate



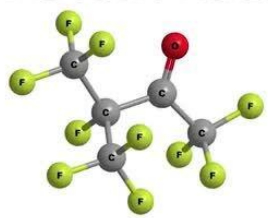
HCFO-1224yd



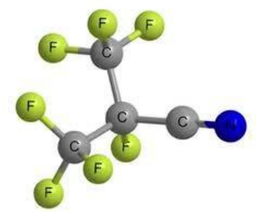
CF_3I

GWP 0.4

“Forever chemicals”
Possible concerns for environment



3M™ Novec™ 5110
(CF3C(O)CF(CF3)2)
GWP <1

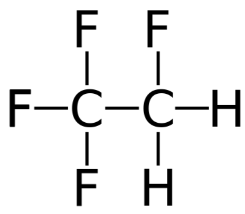


3M™ Novec™ 4710
((CF3)2 CFCN)
GWP 2100

Very good detector performance

Alternatives for RPC gas mixture

~95%



$C_2H_2F_4$

GWP 1430

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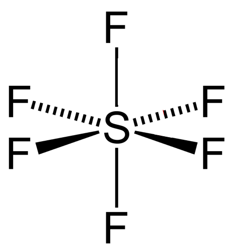
(up to 7% for glass RPC)



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
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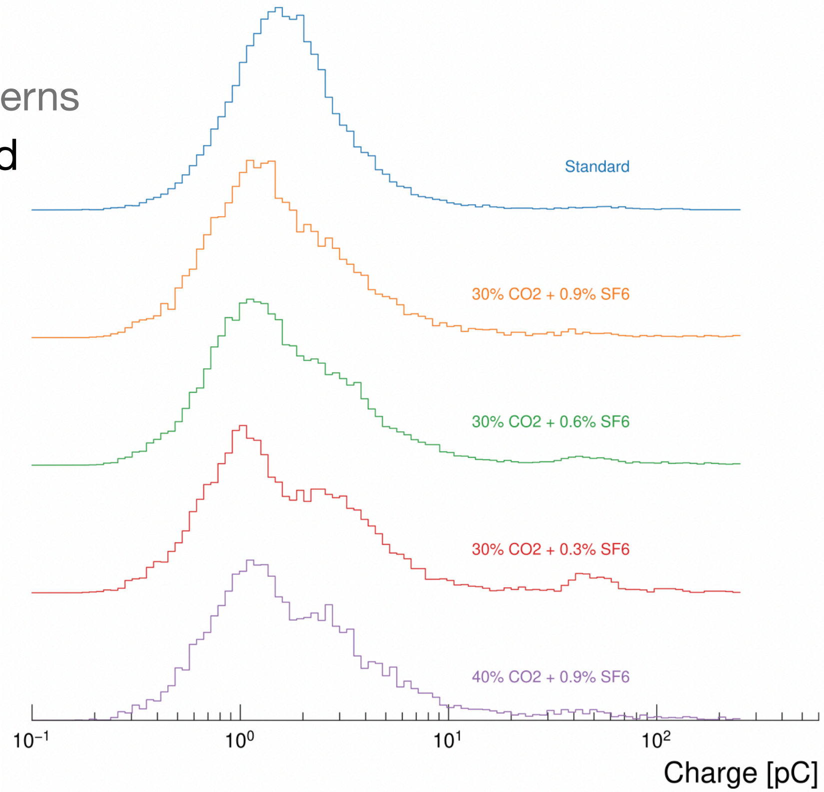
→ Very good detector performance

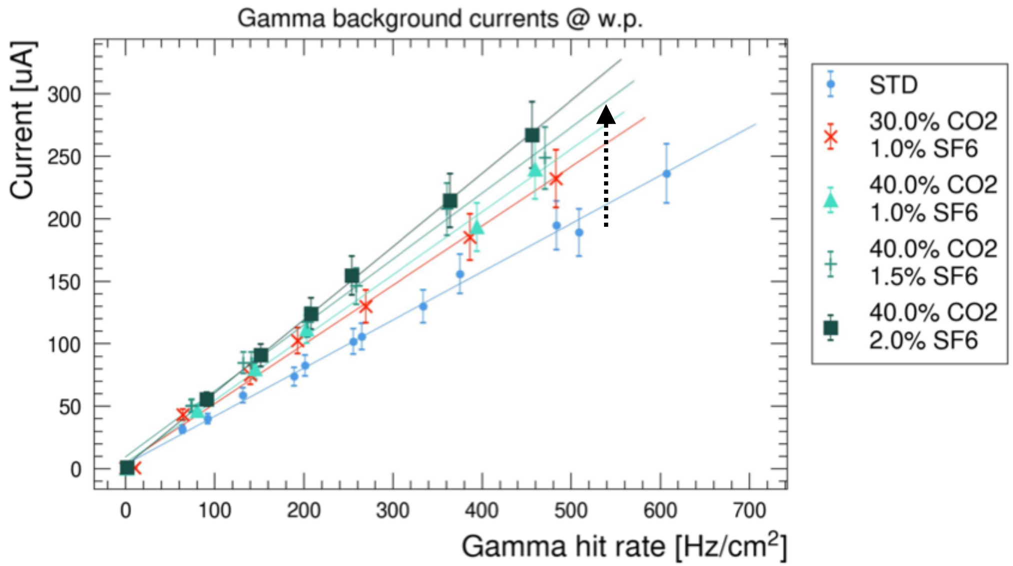
Mid-term solution: addition of CO_2 to std gas mix

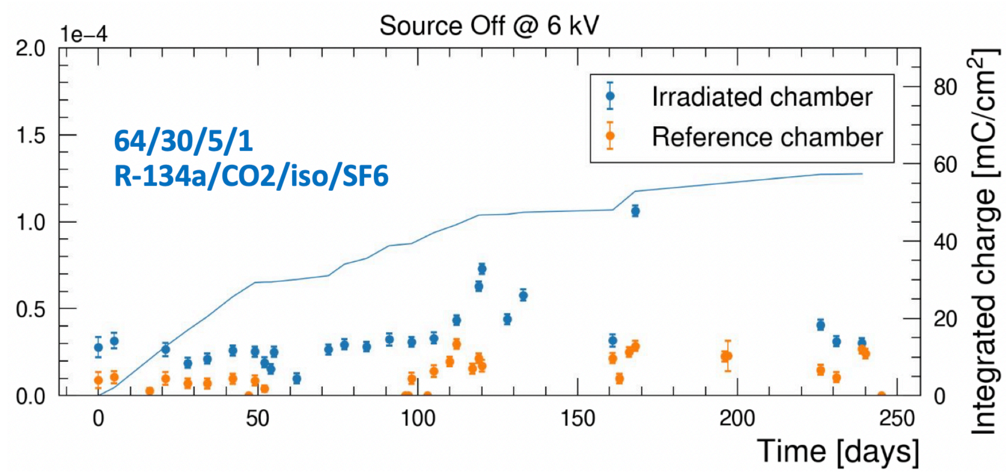
CO_2 as mid-term solution for RPC to mitigate GHG emissions of LHC RPC systems

- 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







Alternatives for RPC gas mixture

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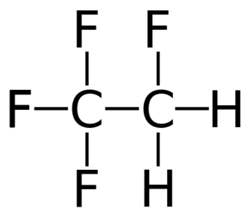
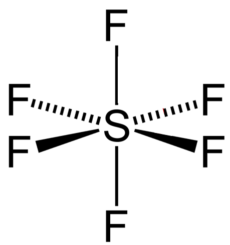


$C_2H_2F_4$

GWP 1430

+

~0.3%
(up to 7% for glass RPC)



SF_6

GWP 22800

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O=C=O

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

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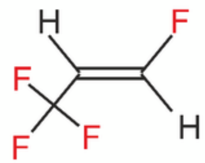


HFO-1234ze(E)

Detector performance affected and long-term effects to investigate

“Forever chemicals” Possible concerns for environment

HCFO-1224yd

CF_3I

GWP 0.4

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

GWP <1

3M™ Novec™ 4710
($(CF_3)_2$ CFCN)

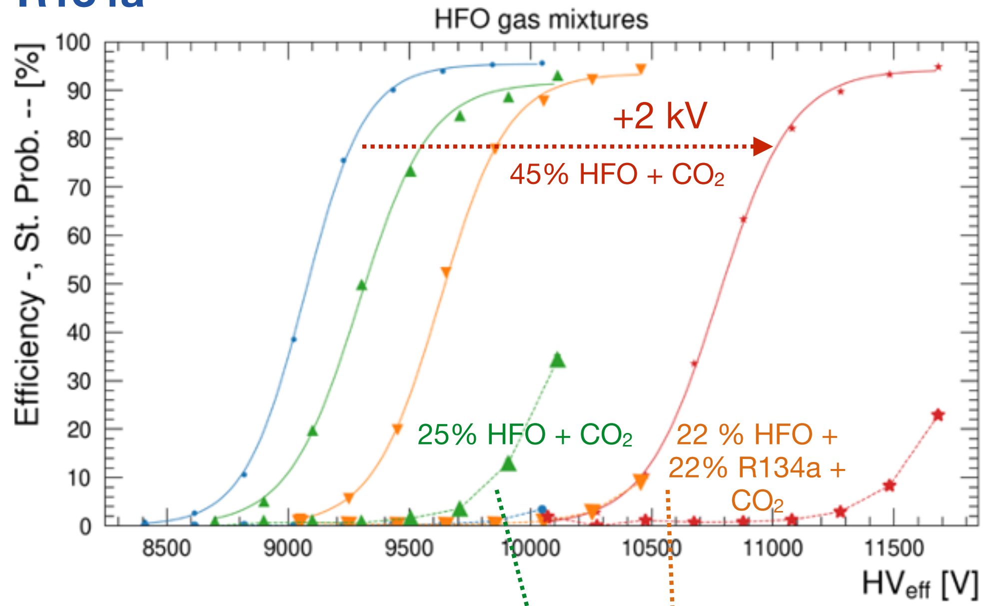
GWP 2100

Very good detector performance

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 increase the charge concentration
  - Currents are 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



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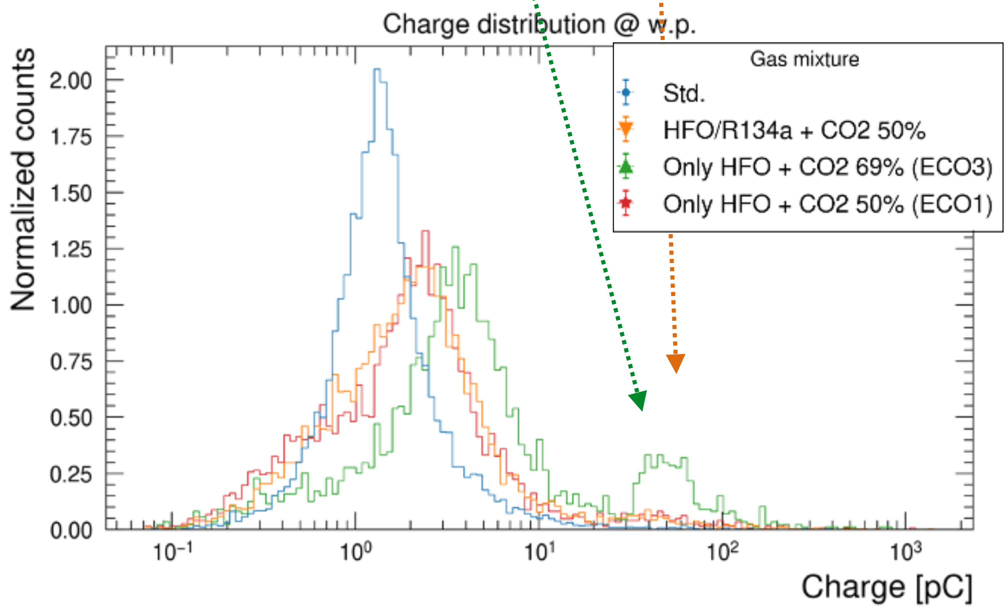
R-1234ze performance with CO2 (+ R-134a) with cosmic muons

- 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

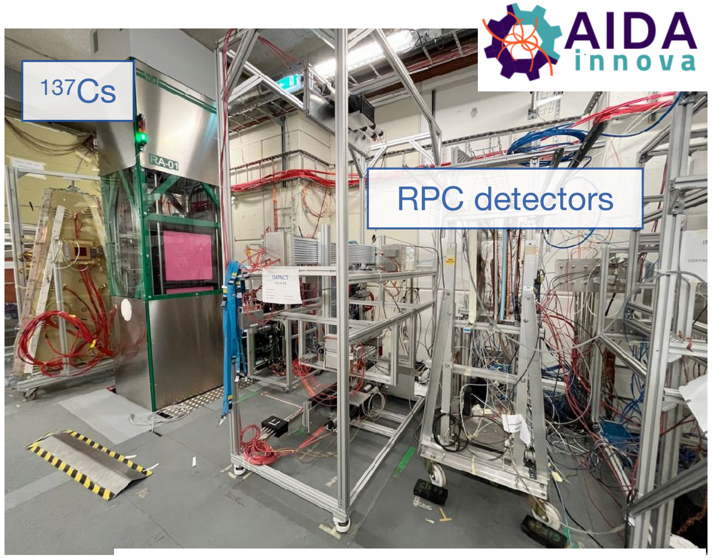


RPC long-term studies with HFO gas mixtures

ECOGAS@GIF++ collaboration

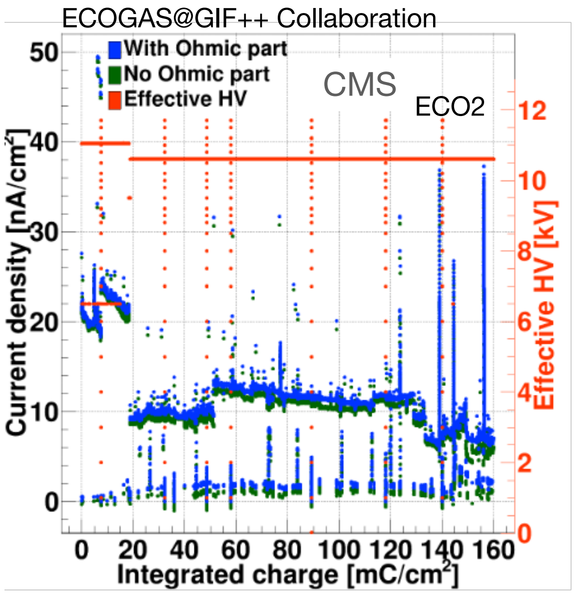
RPC long-term operation with eco-friendly gas mixtures under high background radiation and possible ageing effects must be investigated

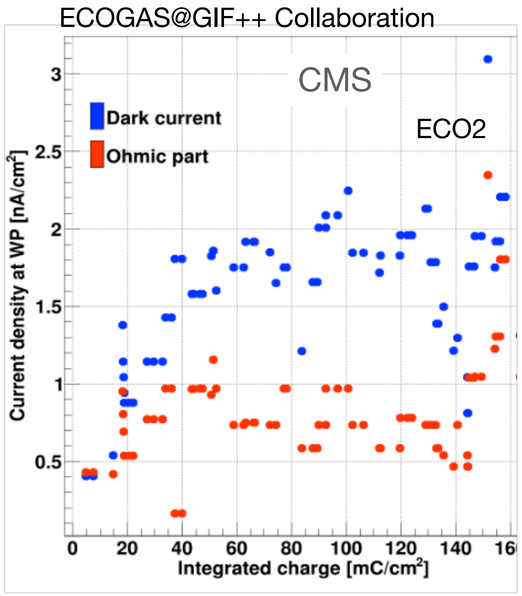
- Set-up at CERN Gamma Irradiation Facility (**GIF++**)
  - 12 TBq ^{137}Cs and H4 SPS beam line
- Several RPCs under test from different experiments
- Detector **performance studies**
  - At different background radiations
  - Three gas mixtures tested (ECO1,ECO2, ECO3): CO_2 50-70% + HFO 45-25% with~5% iC_4H_{10} and 1% SF_6
- **Long-term** performance studies under gamma irradiation
  - Monitor of dark and ohmic currents
  - Goal: to accumulate an **equivalent charge of the HL-LHC Phase**



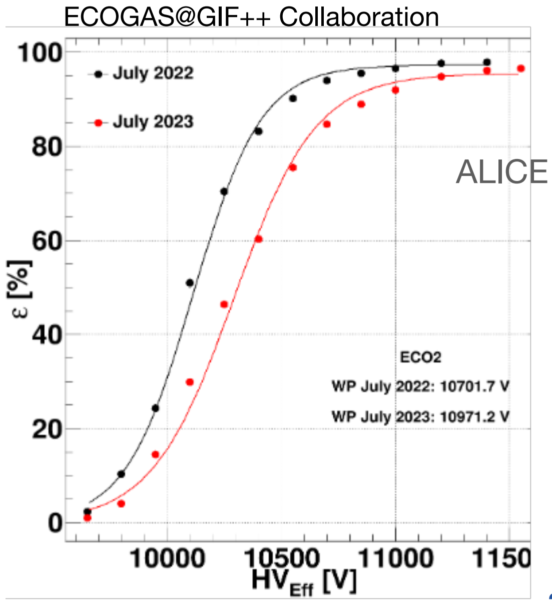
ECO2: 35% HFO, 60% CO_2 4% iC_4H_{10}, 1% SF_6

Long-term irradiation





Test-beam performance



Alternatives for RPC gas mixture

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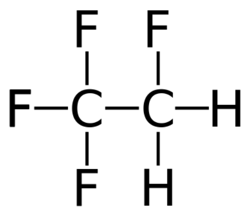

$C_2H_2F_4$

GWP 1430

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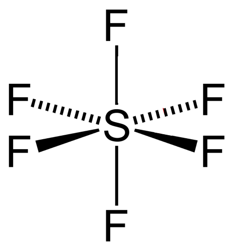

SF_6

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Detector performance slightly affected

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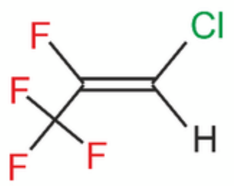
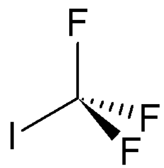
HFO-1234ze(E)

Detector performance affected and long-term effects to investigate



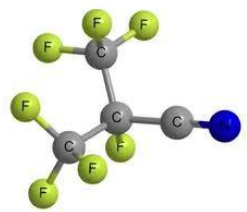
HCFO-1224yd



CF_3I

GWP 0.4

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



3M™ Novec™ 4710
($(CF_3)_2$ CFCN)
GWP 2100

“Forever chemicals”
Possible concerns for environment

Very good detector performance

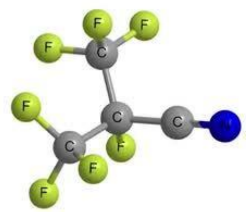
SF_6 alternatives

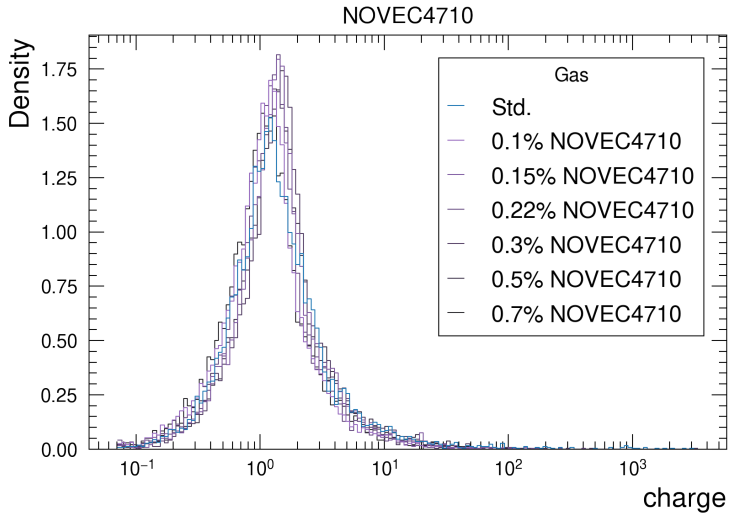
SF_6 has a very high GWP and it contributes for ~5% in the GWP of RPC gas mixture

All SF_6 alternatives tested in several concentrations as replacement of SF_6 in standard gas mixture

3M™ Novec™ Dielectric fluids

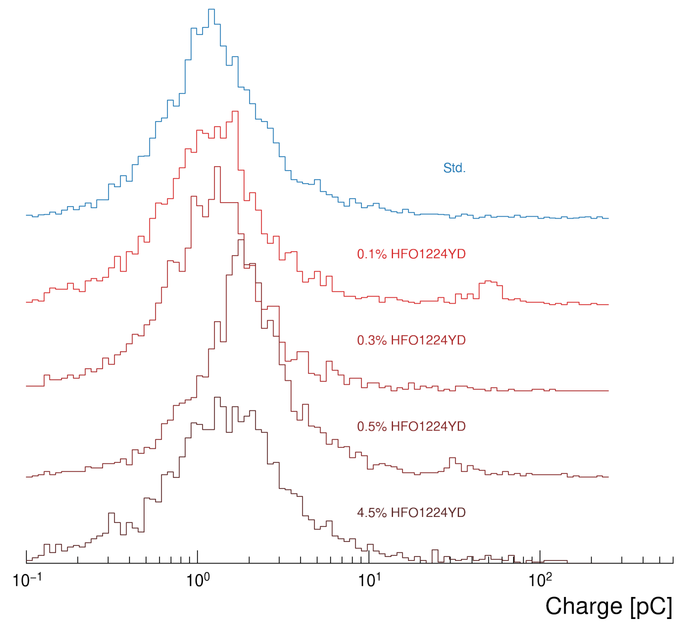
- Alternatives to SF_6 for arc quenching and insulation applications
  - Dielectric breakdown strength ~1.4-2 times that of SF_6
- Novec 4710 (GWP 2100)
  - Very good performance but…
  - It reacts with water: need further studies
- Novec 5110 (GWP <1)
  - Very low GWP but..
  - Sensitive to UV radiation and higher wp
- They are considered PFAS and 3M stopped to produce them
  - Production is moving to China



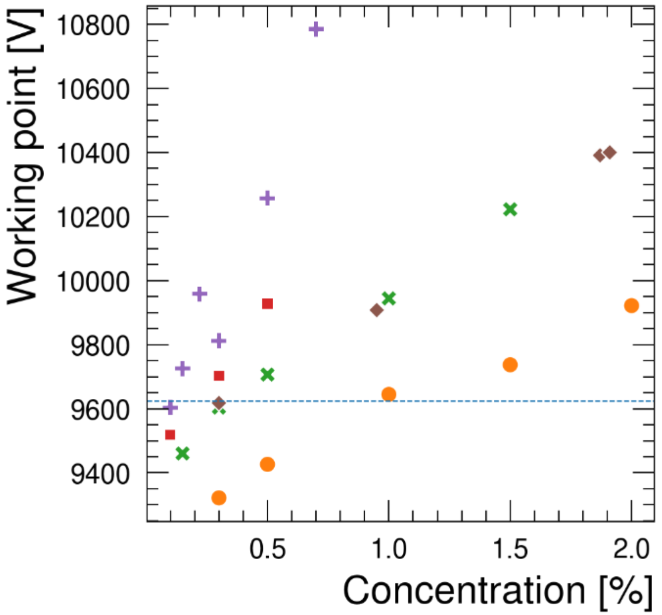


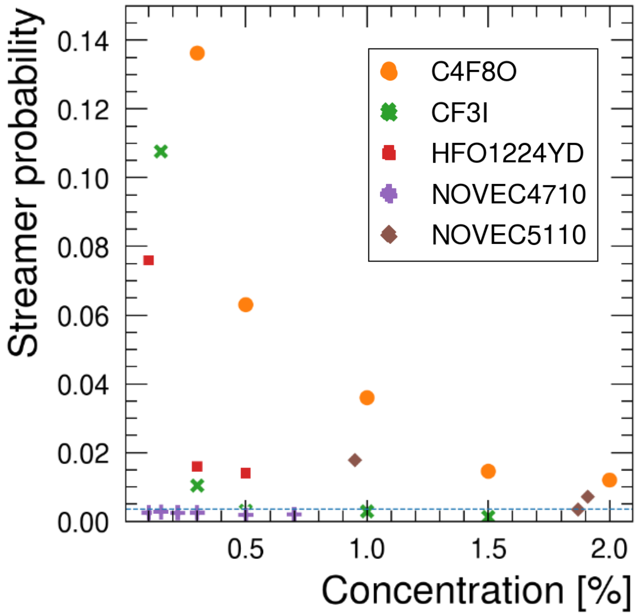
Other alternatives

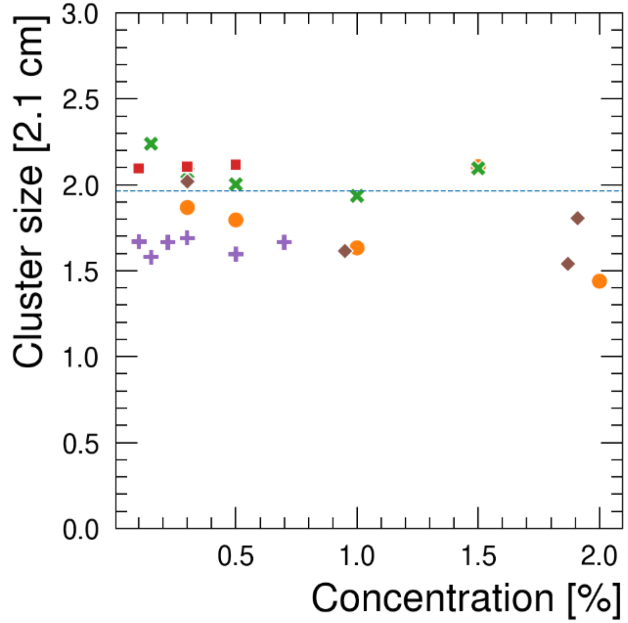
- Looks for other gases not used only for HV plants
  - Other electronegative gases could work
- AMOLEA HFO1224yd (GWP <1)
  - Good performance
- CF_3I (GWP 0.4)
  - Good performance but toxic and mutagenic
- C_4F_8O (GWP ~8000)
  - Good performance at 1.5%
  - 1.5% C_4F_8O GWP equivalent to 0.5% SF_6



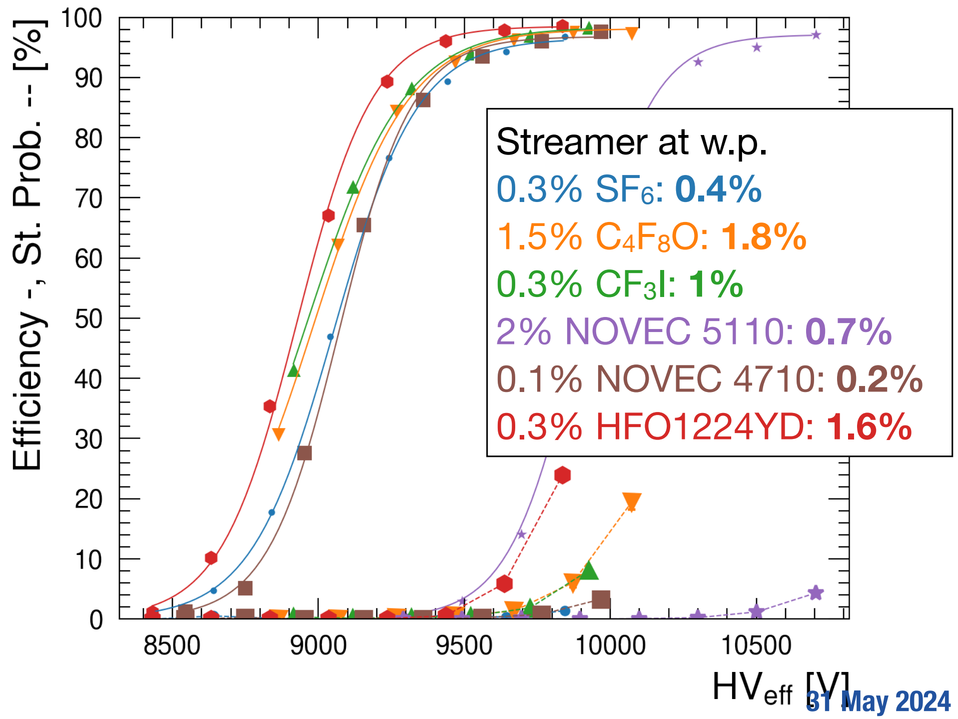
SF_6 alternatives







- Streamer probability
  - Decreasing with increase of concentration except for NOVE4710 where it is stable
- Avalanche charge similar for all gases tested
- Cluster size
  - Lower for NOVECs and C_4F_8O
- Very small concentration of NOVEC 4710, Amolea and CF_3I are enough to obtain satisfactory performance
  - But CF_3I now discarded
- Best streamer probabilities obtained with NOVEC gases
  - Excellent dielectric strength



Not only detector performance

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

↓

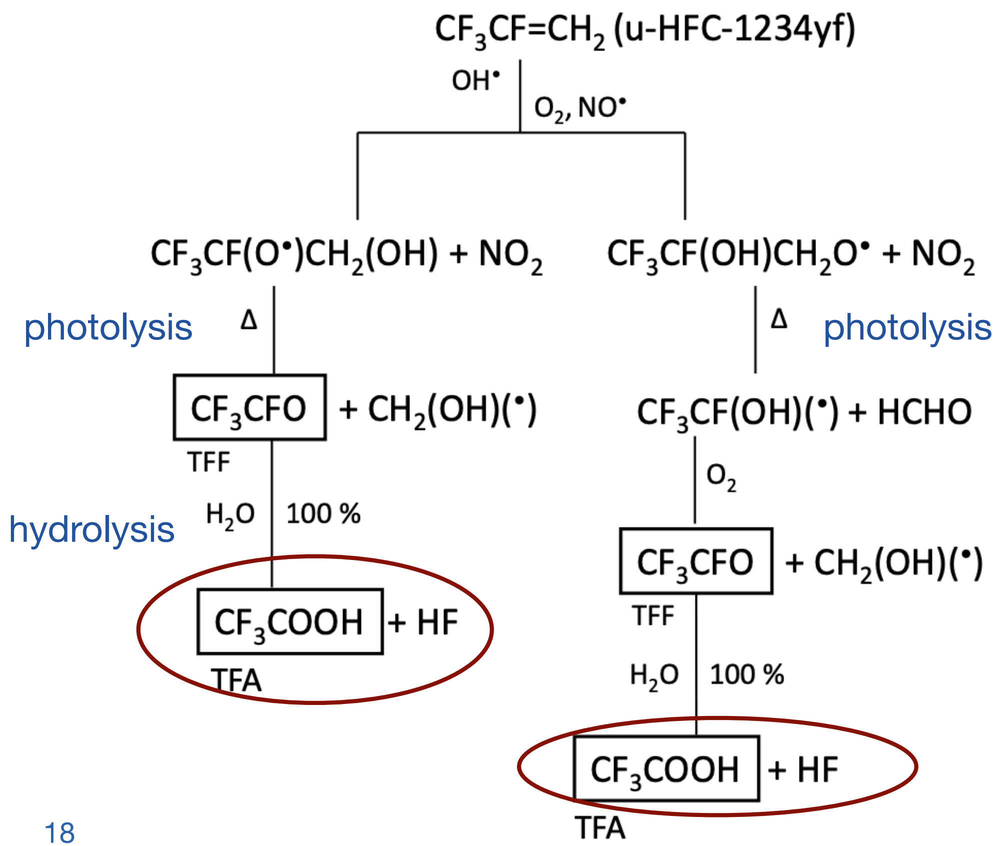
The lower are the GWP and the lifetime, the easier is the creation of sub-products

↓

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



Studies on F-gases properties: examples

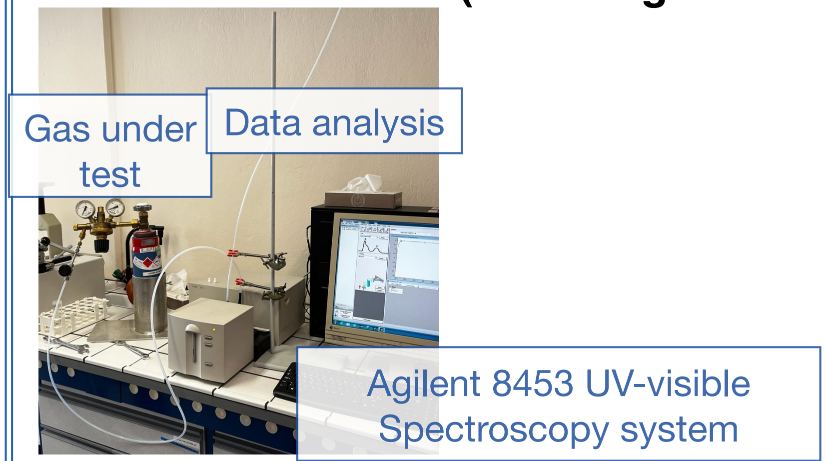
NOVEC 5110

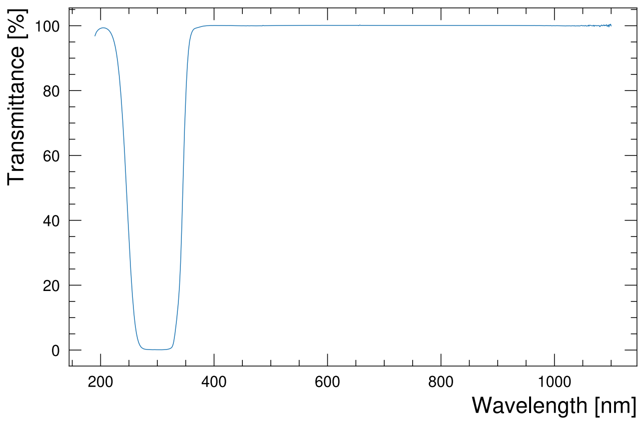
$(CF_3)_2CFC(=O)CF_3$

Rain out → water solubility (1ppmw)

Oxidation → unreactive with OH

Photolysis → strong absorbance in near UV (wavelength > 300 nm)





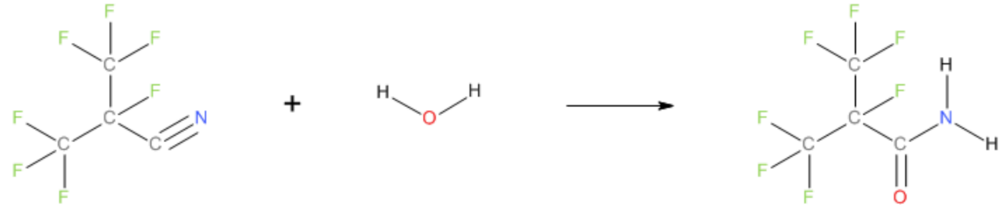
NOVEC 4710

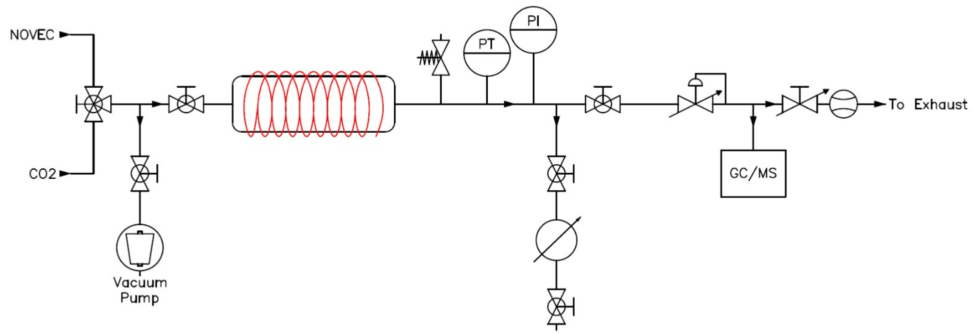
$(CF_3)_2CFC \equiv N$

Rain out → Water solubility (272 ppbw)

Oxidation → reactivity with OH radicals

Photolysis → transparent in near UV





- Bakelite RPCs use 40% relative humidity
- Production of an amide from NOVEC 4710 + H_2O
  - Sub-products in the order of ppb
  - Solid at room T with a melting point of 49°C
  - The amide has appreciable vapour pressure at 60°C, it remains in gas phase at low concentrations
- Tests on-going in laboratory
  - Try to reproduce 3M tests
  - Analysis at the output of an RPC

Conclusions

With climate change a growing concern and implementation of F-gas regulations, it is fundamental for existing and future particle detector applications to reduce GHG emissions and search for eco-friendly gas mixtures

Gas Recirculation

- It is the first way to reduce GHG emissions: up to 100% reduction
- Fundamental to not have leaks at detector level
- Development of small (and cheap) recirculation systems for small experiments/labs

Gas Recuperation

- Second way to reduce GHG emissions when it is not possible to recycle 100% of the gas mixture due to detector constrains
- Very complex and custom-made systems (not feasible for small experiments)

Alternative gas mixtures

- The way for the future to get rid of GHG
- Very difficult to find eco-friendly gas mixtures for current LHC gaseous detectors
- Need to understand detector lifetime with new eco-friendly gases
- Some concerns also in the use of these “eco-friendly” gases for the future