EP-DT
Detector Technologies

Towards more eco-friendly gaseous detectors

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CERN

CEA Seminar
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Outline

GHGs for particle detectors

- GHG emissions from particle detection at LHC experiments
- EU F-gas regulation
- GHG studies in ECFA Roadmap and DRD collaboration

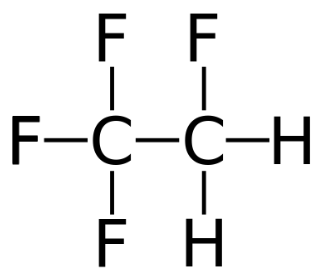
Strategies for reduction of GHG emissions

- Gas recirculation
- Gas recuperation
- Eco-friendly gas mixtures

Conclusions

GHGs for particle detection (at LHC experiments)

GHGs are used in several gaseous detectors mainly due to their properties necessary for optimal detector performance and long term operation

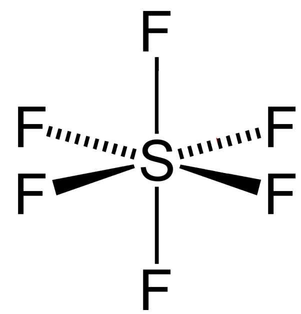


$C_2H_2F_4$

GWP 1430

- **Containment of charge**
- **Rate capability**

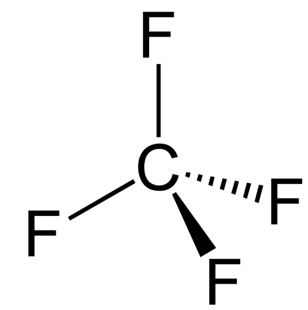
Resistive Plate Chamber (RPC)



SF_6

GWP 22800

- **Electronegative: limiting charge development**



CF_4

GWP 7390

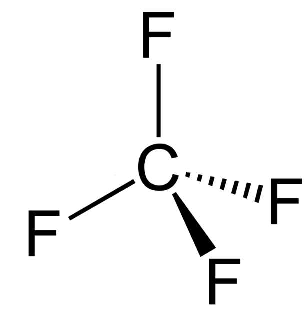
- **time resolution**

Gas Electron Multiplier (GEM)

- **Mitigation of aging phenomena**

Cathode Strip Chamber (CSC)

Multi Wire Proportional Chamber (MWPC)



C_4F_{10}

GWP 8860

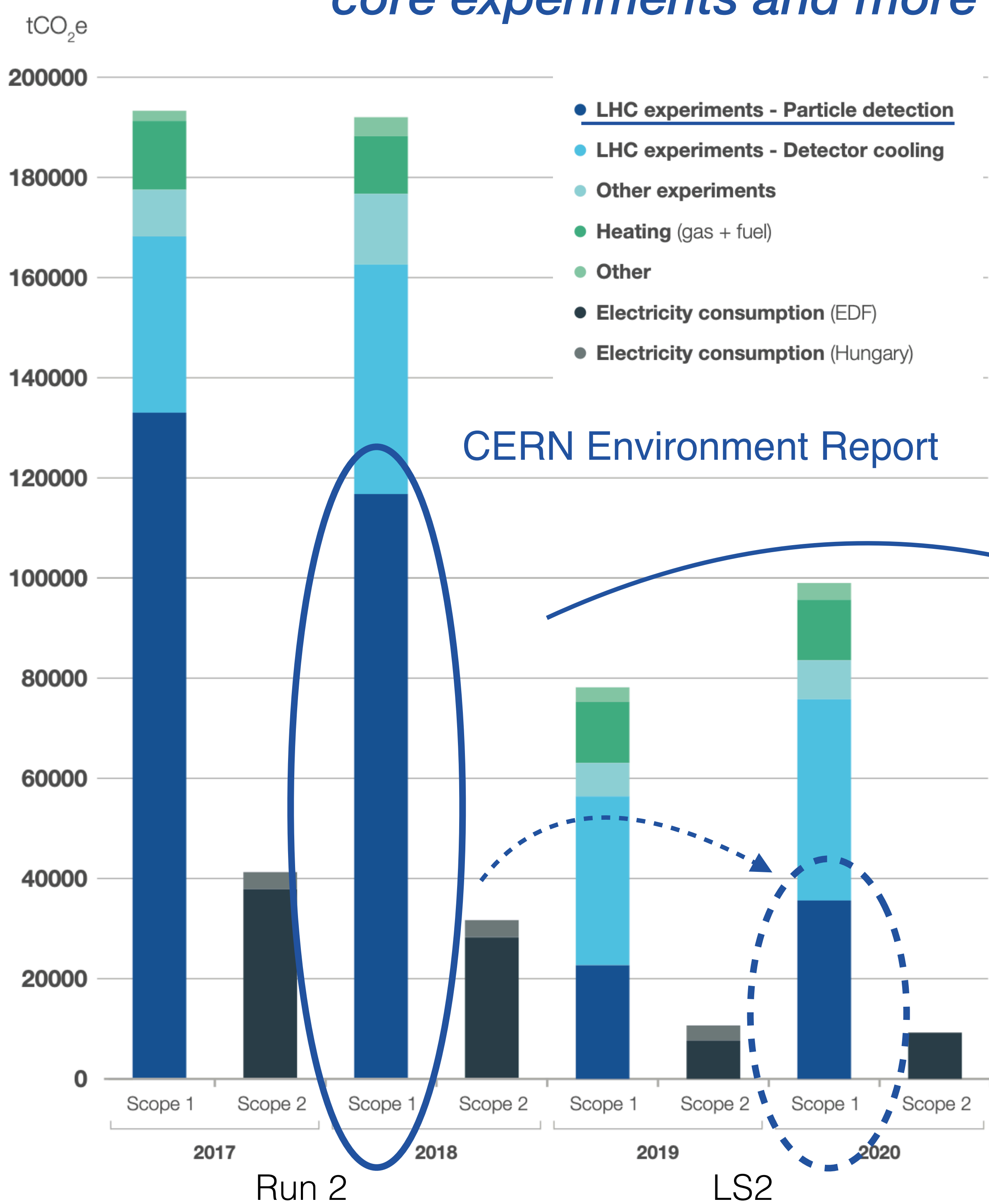
- **Cherenkov radiator**

Ring-imaging Cherenkov detector (RICH)

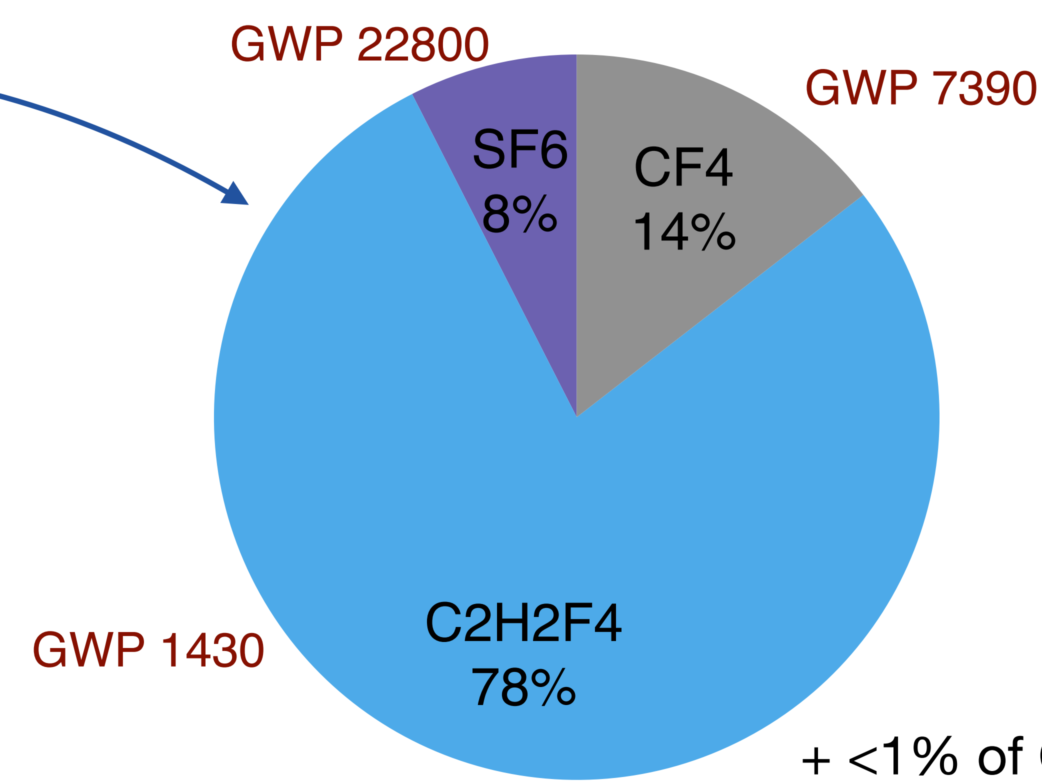
- ~20-30 years ago, it was the time to get rid of ODP gases
- There was not the awareness on the use of GHGs
  - Many gaseous detectors were conceived with use of GHGs
- Now it is time to address the usage of GHG worldwide, including particle detectors

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



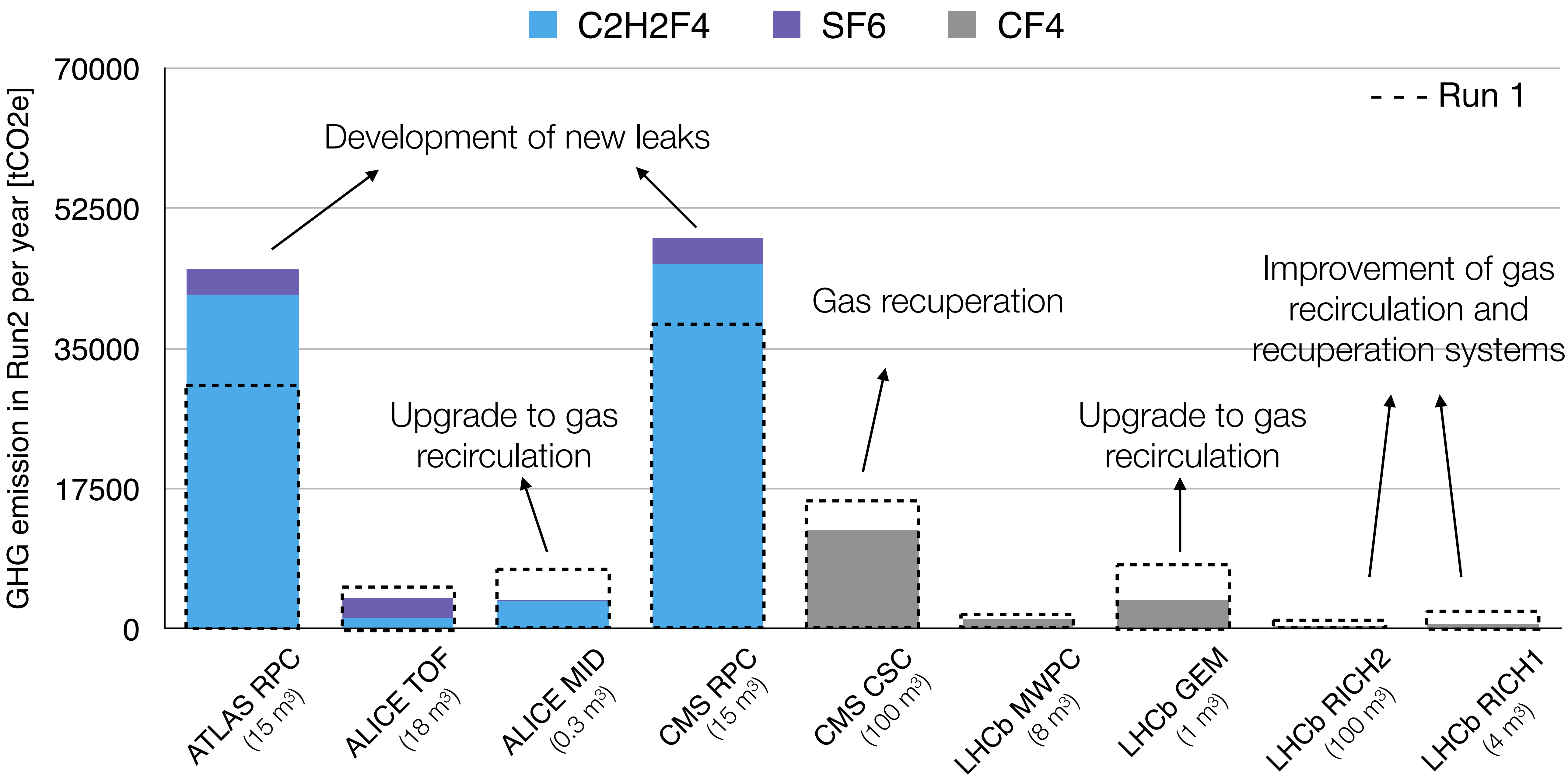
- ~90% of emissions related to large LHC experiments
- Most emissions from particle detection
- Drastic reduction of GHG emissions from particle detection during LS2



+ <1% of C_4F_{10}

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

GHGs for particle detection at LHC: Run 2

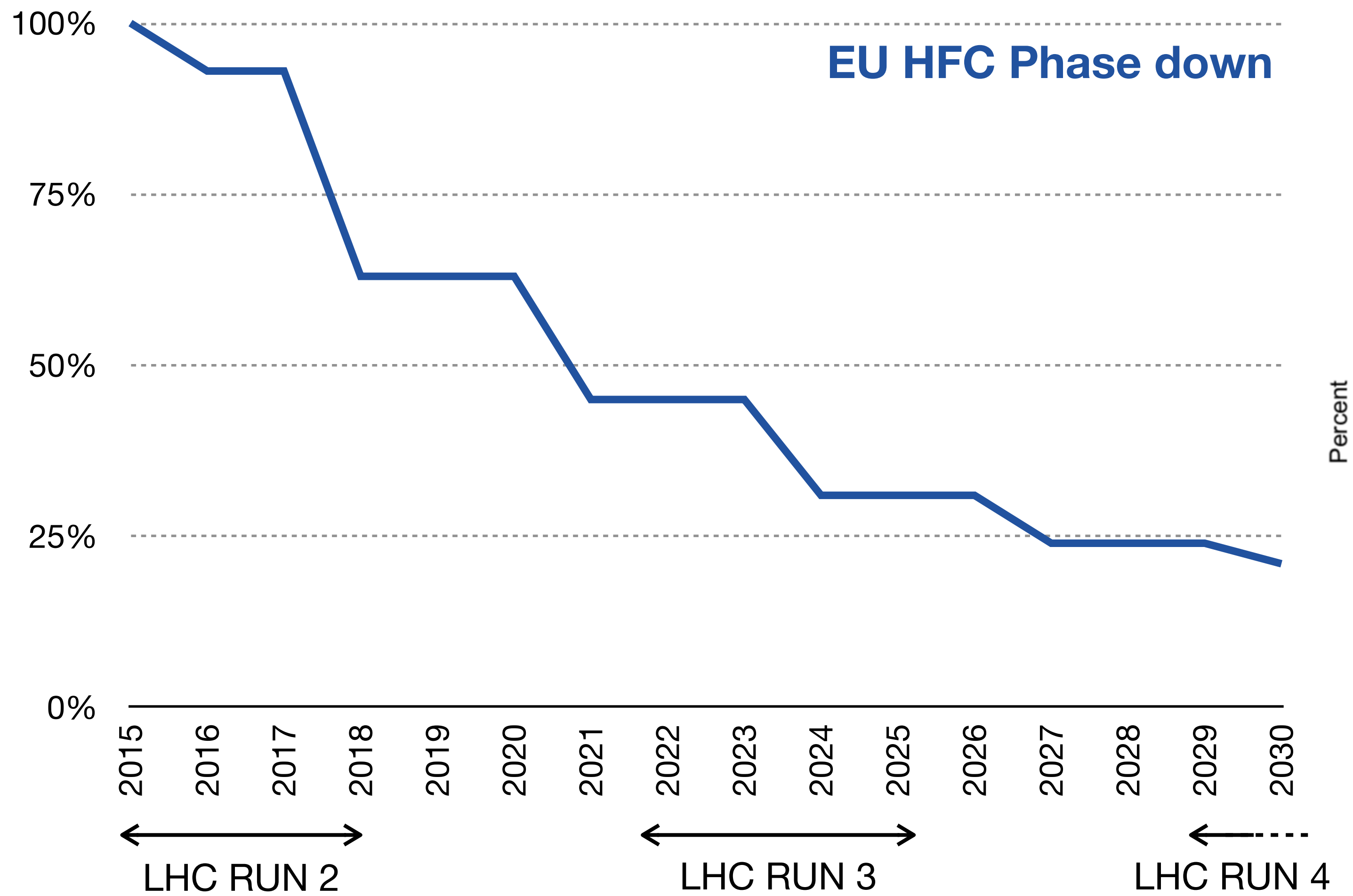


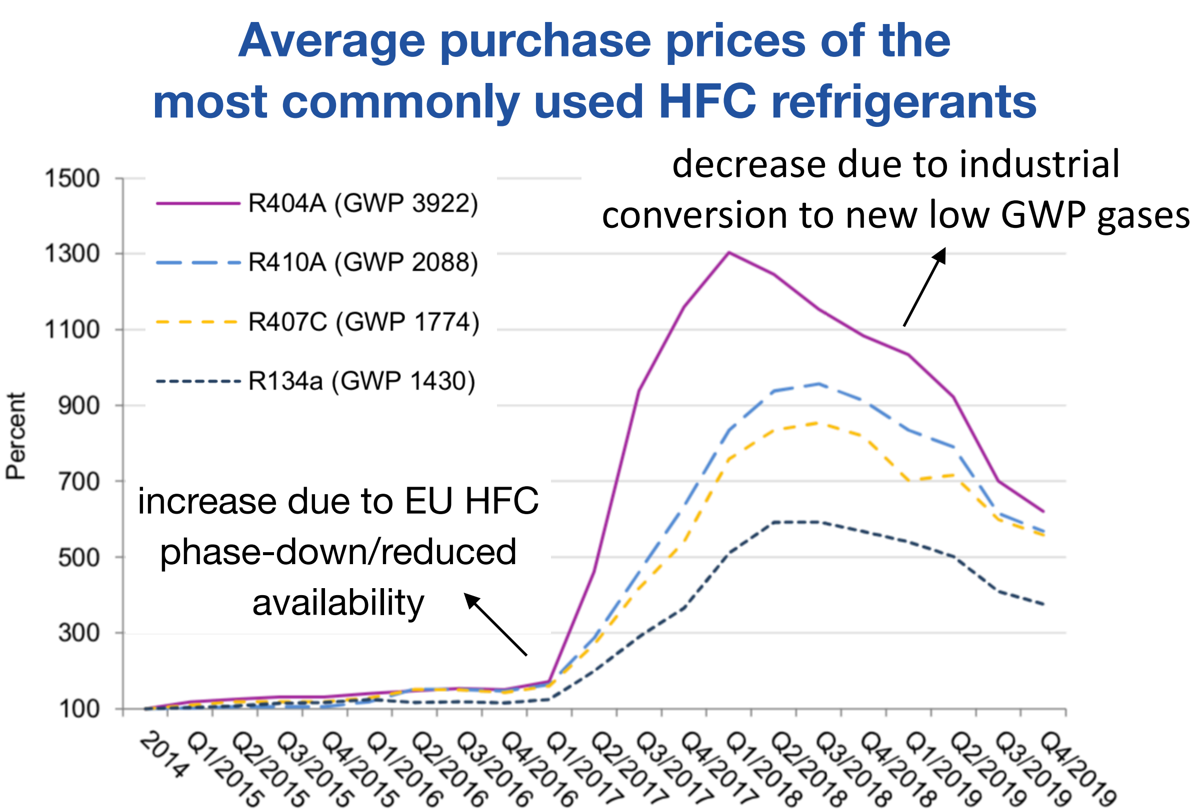
- **-40% GHG emissions** from Run 1 to Run 2 excluding ATLAS and CMS RPC systems
- ATLAS and CMS RPC systems: **+35% increase** of GHG emissions due to development of **new leaks**
- All other detector systems: decrease of GHG emissions from -20% to -80% from Run 1 to Run2
  - Thanks to the different gas system upgrades and a major attention on the use of GHGs
- **GHG emissions during LS2** reduced by 75% with respect to Run 2

The EU HFC Phase down policy

European Union "F-gas regulation"

- **Limiting the total amount** of the most important F-gases that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030.
- **Banning the use** of F-gases in many new types of equipment where less harmful alternatives are widely available.
- **Preventing emissions** of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment's life.



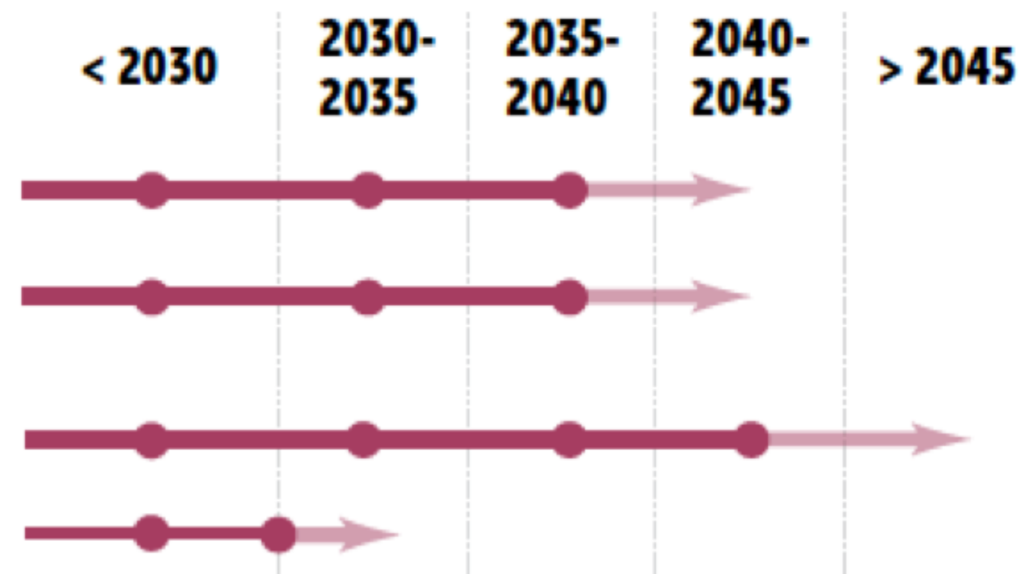


European Environment Agency, Fluorinated greenhouse gases 2019 report
Öko Recherche report, March 2020 J. Kleinschmidt et al.

Prices are increasing in EU and availability in the future is not known.
Reduction of the use of F-gases is fundamental for future particle detector applications

The ECFA Roadmap and DRD1 collaboration

Detector Research and Development Themes (DRDT)



DRDT 1.1 - Improve time and spatial resolution for gaseous detectors with long-term stability

DRDT 1.2 - Achieve tracking in gaseous detectors with dE/dx and dN/dx capability in large volumes with very low material budget and different read-out schemes.

DRDT 1.3 - Develop environmentally friendly gaseous detectors for very large areas with high-rate capability.

DRTD 1.4 - Achieve high sensitivity in both low and high-pressure TPCs.

→ ***These main activity areas correspond to the major drivers from future facilities***

General strategic recommendations have been made of which:
GSR 4 - International coordination and organisation of R&D activities → New Detector R&D (DRD) Collaboration
GSR 6 - Establish long-term strategic funding programmes

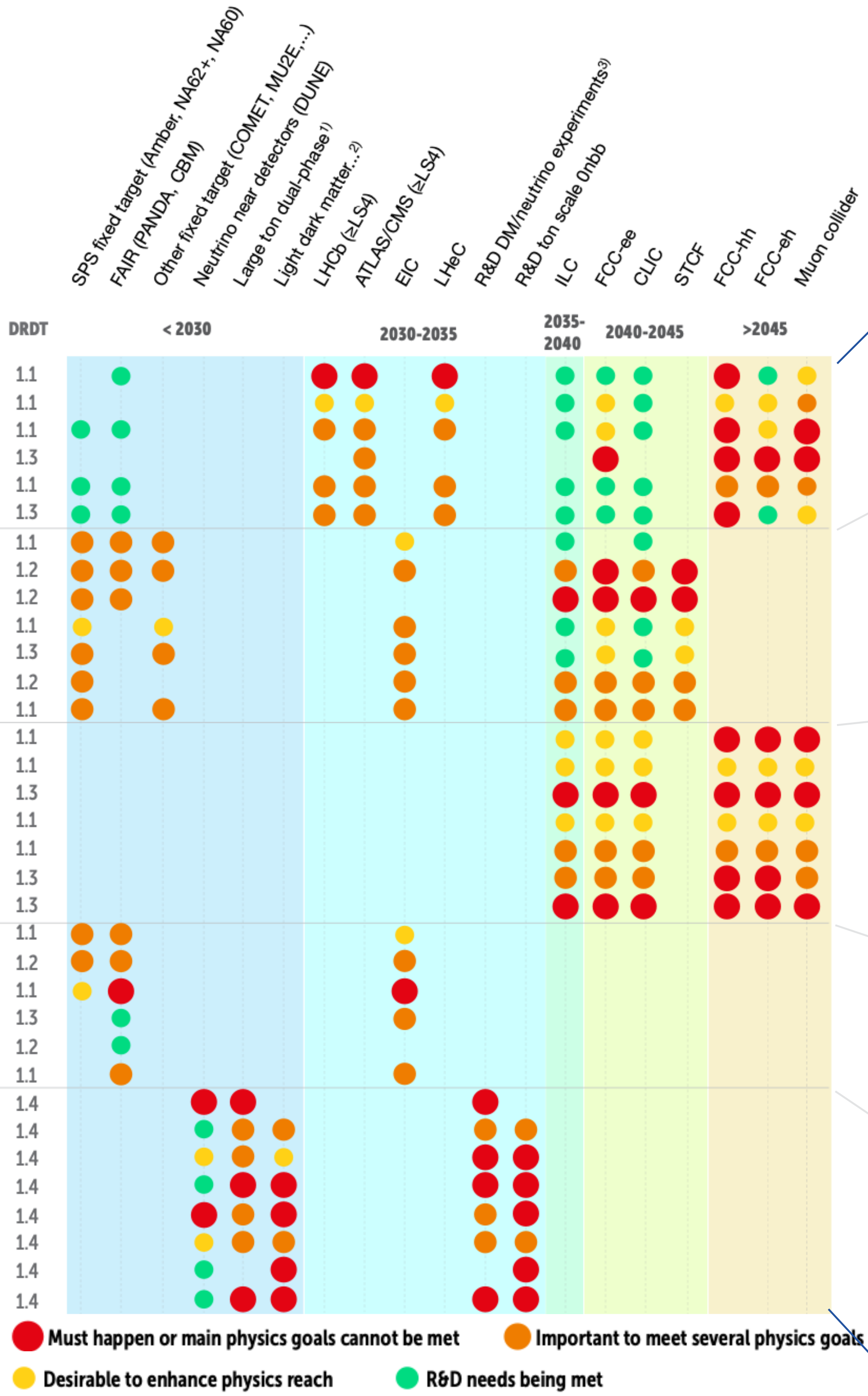
DRD1: Gaseous Detectors

- WG1: Technologies
- WG2: Applications
- WG3: Gas and material studies
- WG4: Detector physics, simulation and software tools
- WG5: Electronics for gaseous detectors
- WG6: Detector production
- WG7: Common test facilities
- WG8: Training and dissemination

Within the topics, also the **eco-gases searches**

More info: https://indico.cern.ch/event/1245751/

The ECFA roadmap and DRD1 collaboration



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DRDT 1.3 Develop environmentally friendly gaseous detectors for very large areas with high-rate capability

DRDT 1.4 Achieve high sensitivity in both low and high-pressure TPCs

Muon system

Proposed technologies: RPC, Multi-GEM, resistive GEM, Micromegas, micropixel Micromegas, μRwell, μPIC ...

- Rad-hard/longevity
- Time resolution
- Fine granularity
- Gas properties (eco-gas)
- Spatial resolution
- Rate capability

Inner/central tracking with PID

Proposed technologies: TPC+(multi-GEM, Micromegas, Gridpix), drift chambers, cylindrical layers of MPGD, straw chambers

- Rad-hard/longevity
- Low X_o
- IBF (TPC only)
- Time resolution
- Rate capability
- dE/dx
- Fine granularity

Preshower/ Calorimeters

Proposed technologies: RPC, MRPC, Micromegas and GEM, μRwell, InGrid (integrated Micromegas grid with pixel readout), Pico-sec, FTM

- Rad-hard/longevity
- Low power
- Gas properties (eco-gas)
- Fast timing
- Fine granularity
- Rate capability
- Large array/integration

Particle ID/TOF

Proposed technologies: RICH+MPGD, TRD+MPGD, TOF: MRPC, Picosec, FTM

- Rad-hard (photocathode)
- IBF (RICH only)
- Precise timing
- Rate capability
- dE/dx
- Fine granularity

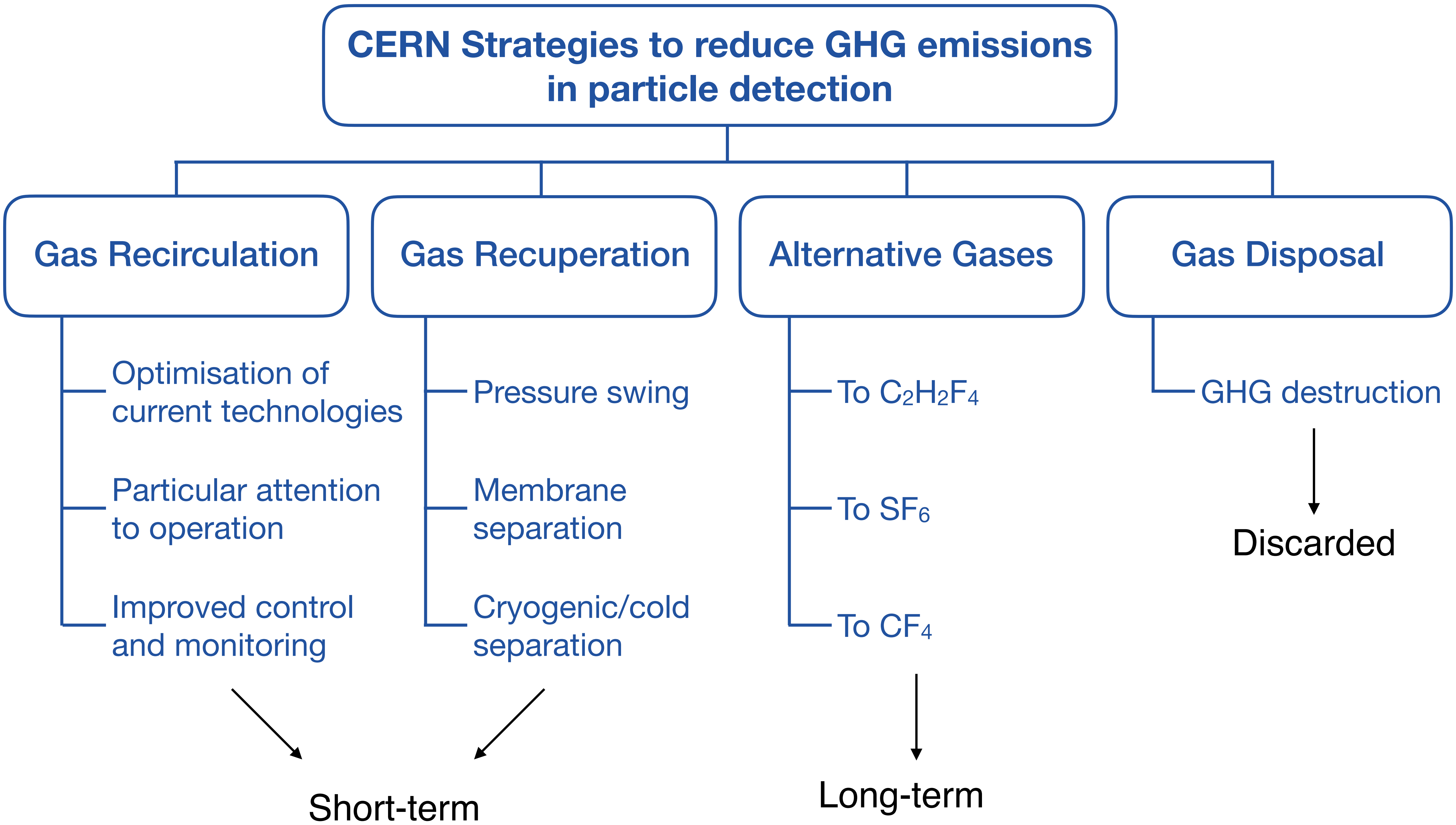
TPC for rare decays

Proposed technologies: TPC+MPGD operation (from very low to very high pressure)

- Low power
- Fine granularity
- Large array/volume
- Higher energy resolution
- Lower energy threshold
- Optical readout
- Gas pressure stability
- Radiopurity

More info here: 10.17181/CERN.XDPL.W2EX

CERN strategies for GHG reduction



CERN strategies for GHG reduction

CERN Strategies to reduce GHG emissions in particle detection

- **Gas Recirculation**
  - Optimisation of current technologies
  - Particular attention to operation
  - Improved control and monitoring
- Gas Recuperation
  - Pressure swing
  - Membrane separation
  - Cryogenic/cold separation
- Alternative Gases
  - To $C_2H_2F_4$
  - To SF_6
  - To CF_4
- Gas Disposal
  - GHG destruction

Short-term

Long-term

Discarded

Gas systems at the LHC experiments

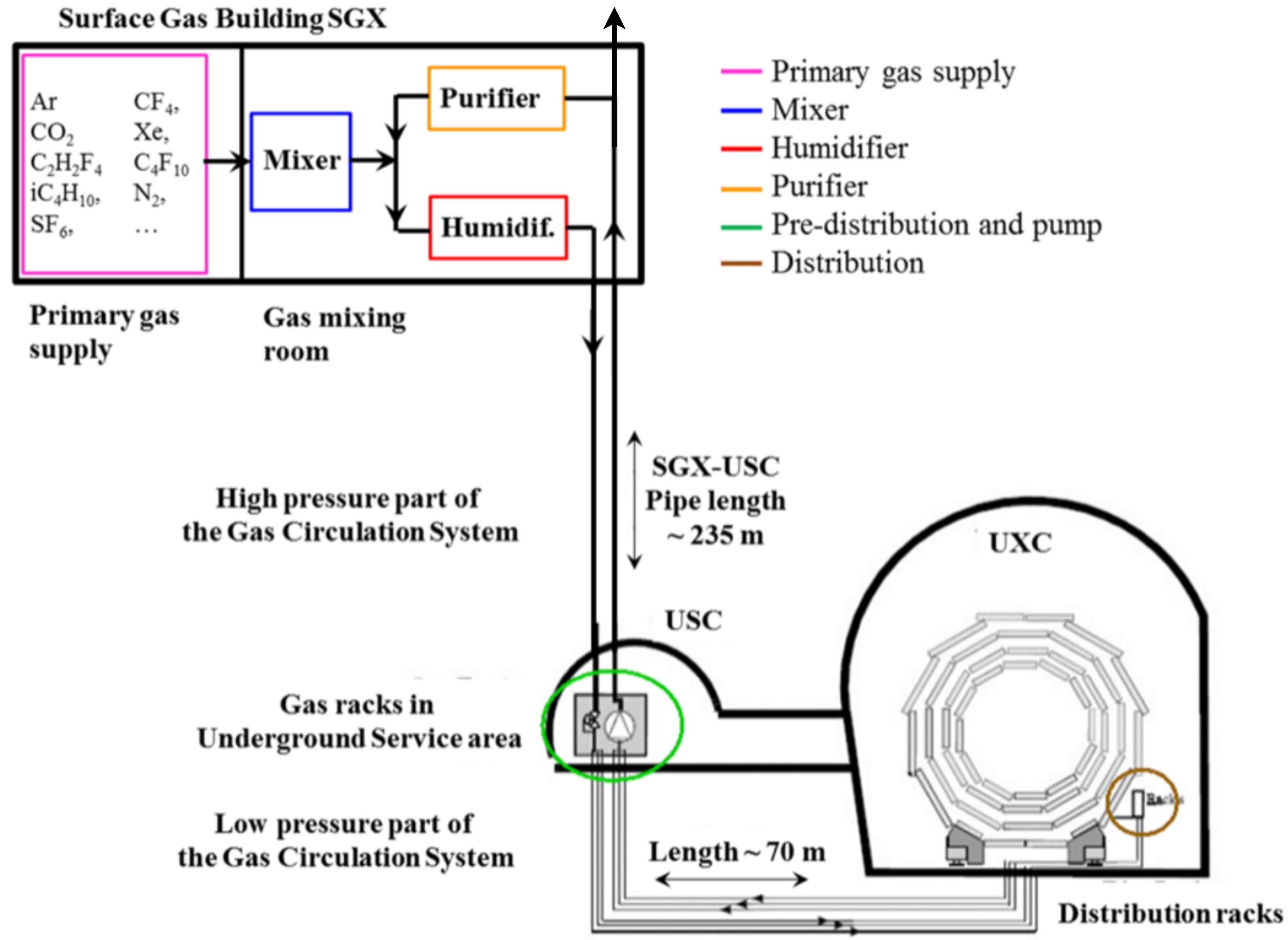
*The gas systems are complex apparatus that have to ensure an extremely high reliability in terms of **stability** and **quality** of the gas mixture delivered to the detectors*

20 Gaseous Detector Systems at LHC

- 10 different types of gaseous detector technologies
- Several gases used
  - Ar, CO_2, CF_4, C_4F_{10}, iC_4H_{10}, SF_6, $C_2H_2F_4$, nC_5H_{12}, H_2, O_2, CH_4, Xe, Ne, N_2
- More than 20 gas mixtures

28 Gas Systems at LHC

- 300 modules all over CERN
  - 60 PLCs, >10k sensors
  - Hundreds km of pipes
- Huge detector systems
  - Thousands of m^2, up to 800 m^3
- Gas recirculation up to 100%



If greenhouse gases used: gas recirculation system

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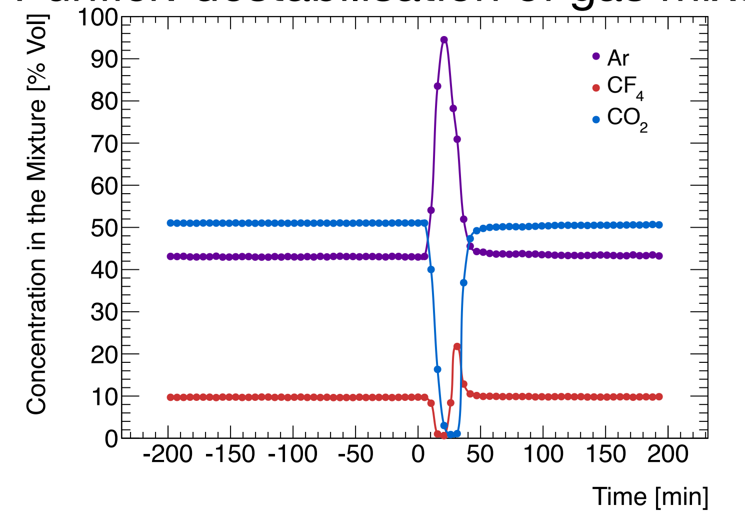
Thanks to gas recirculation: GHG emission already reduced by >90%!!!

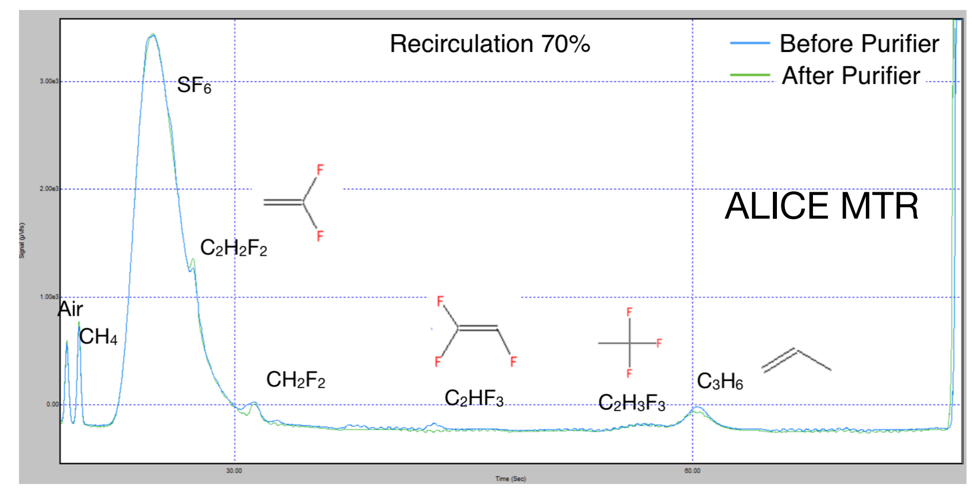
(Without gas recirculation systems, GHG emissions would be 10 times more!)

Complexity of gas recirculation systems

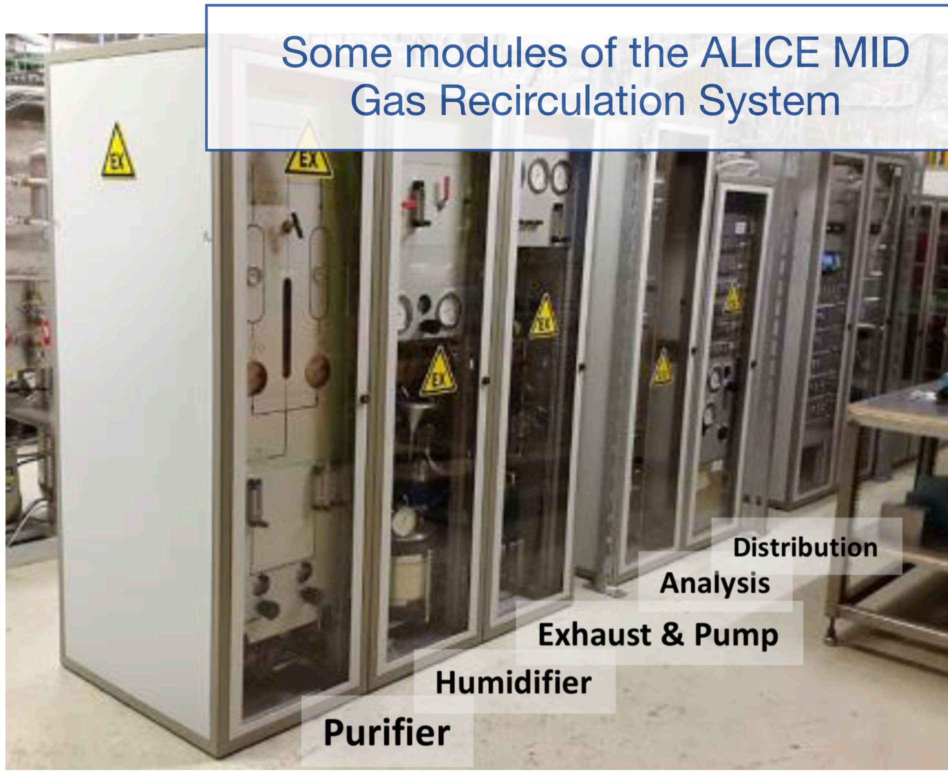
- Gas recirculation system can be very complex
  - Pressure and flow fluctuations, etc
  - Gas distribution
  - Stability of gas mixture composition
- Creation of impurities
  - They could accumulate in the gas system
  - Their concentration depends on luminosity and recirculation fraction
  - They could affect long-term detector operation
- Compulsory use of cleaning agents
  - Needed to absorb impurities
  - Destabilisation of gas mixture composition

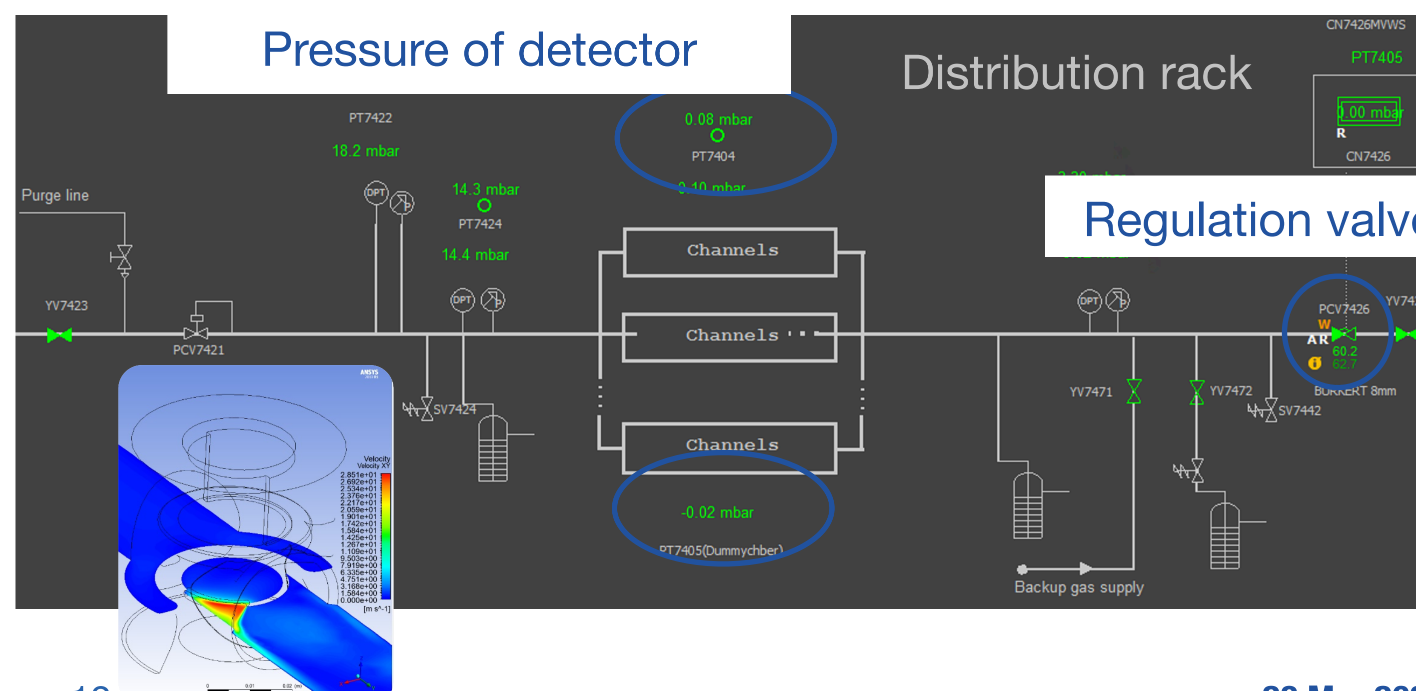
Purifier: destabilisation of gas mixture





Some modules of the ALICE MID Gas Recirculation System





Recirculation systems for laboratories

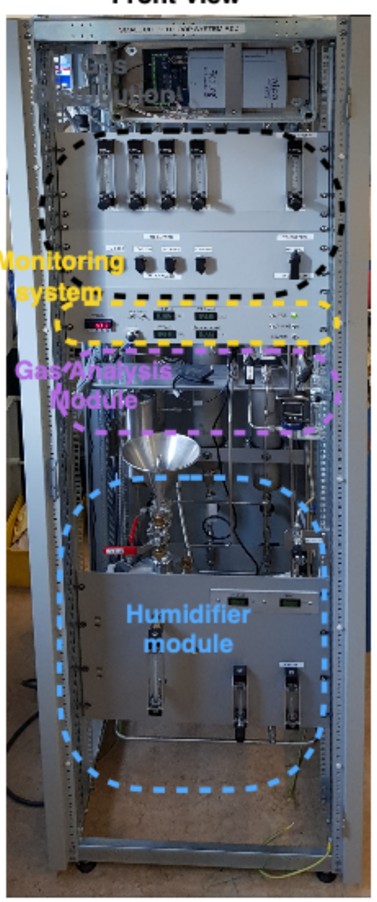
- At CERN 5-10% of emissions are coming from small experiments, testing facilities and laboratories
- In last years, it often more and more difficult to get F-gases
- F-gas prices are also increasing

↓

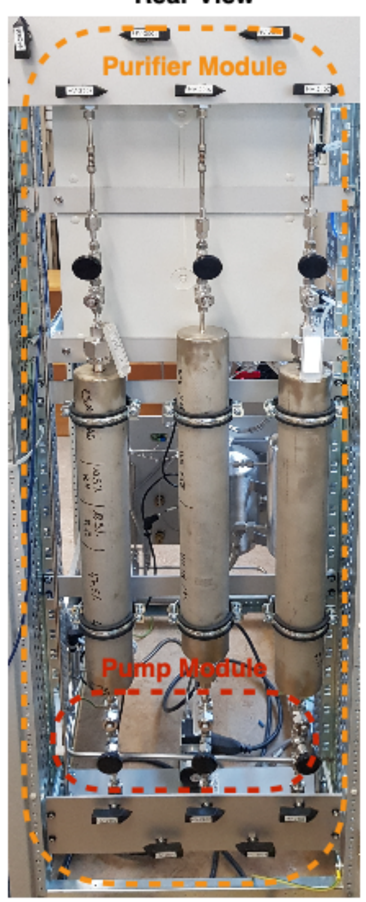
Development of small gas recirculation systems designed for small experiments and laboratories

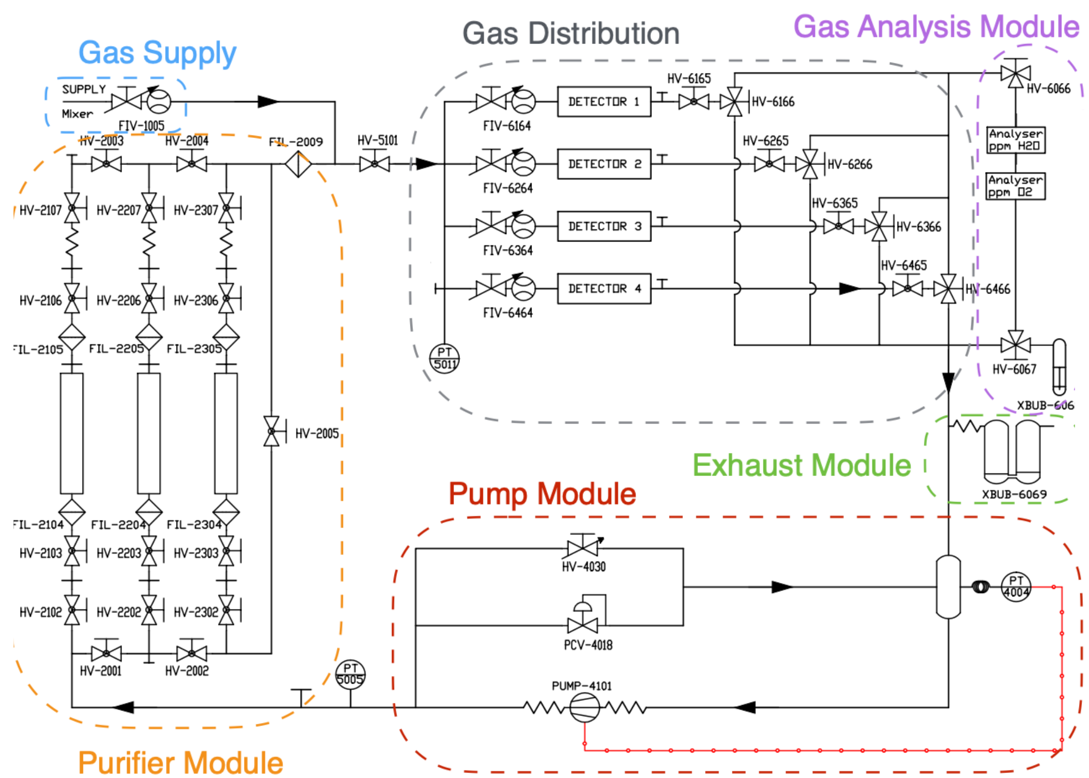
Small gas recirculation system

Front View



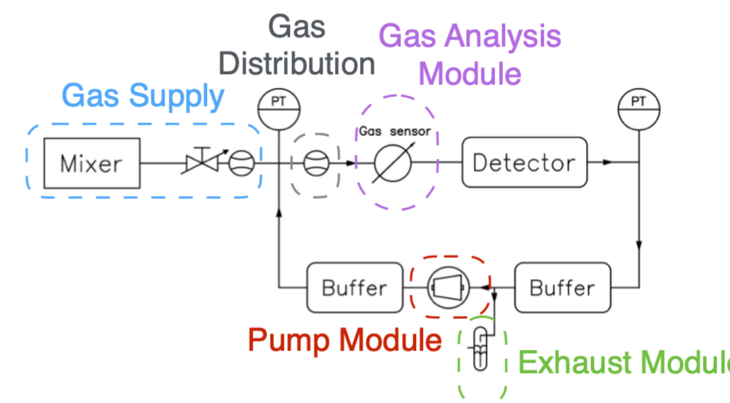
Rear View





https://doi.org/10.1088/1748-0221/12/10/T10002

Micro gas recirculation system



For medium/small experiments and facilities

Tens of detectors, hundreds of litres, ~20 kEURO

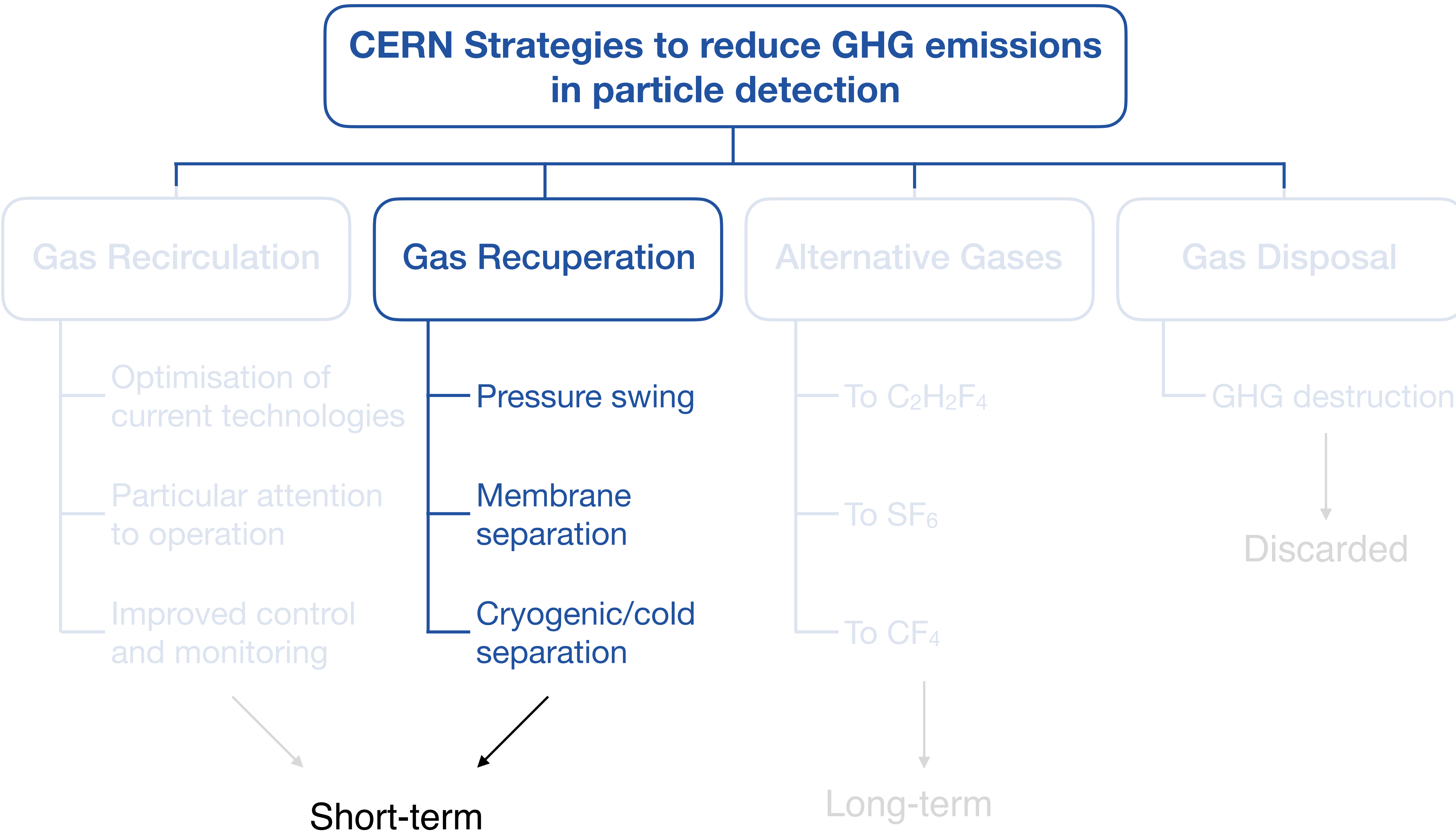
- Control system and monitoring based on simple PLC
- Possible to have some parameters controlled remotely
- Presence of sensors for pressure, flow, humidity, O_2

For laboratory set-ups

Few detectors, Few of litres, ~1 kEURO

- Control system based on RaspBerry PI
- Manual (optional remote) control
- Limited number of electronic sensors and cheap components

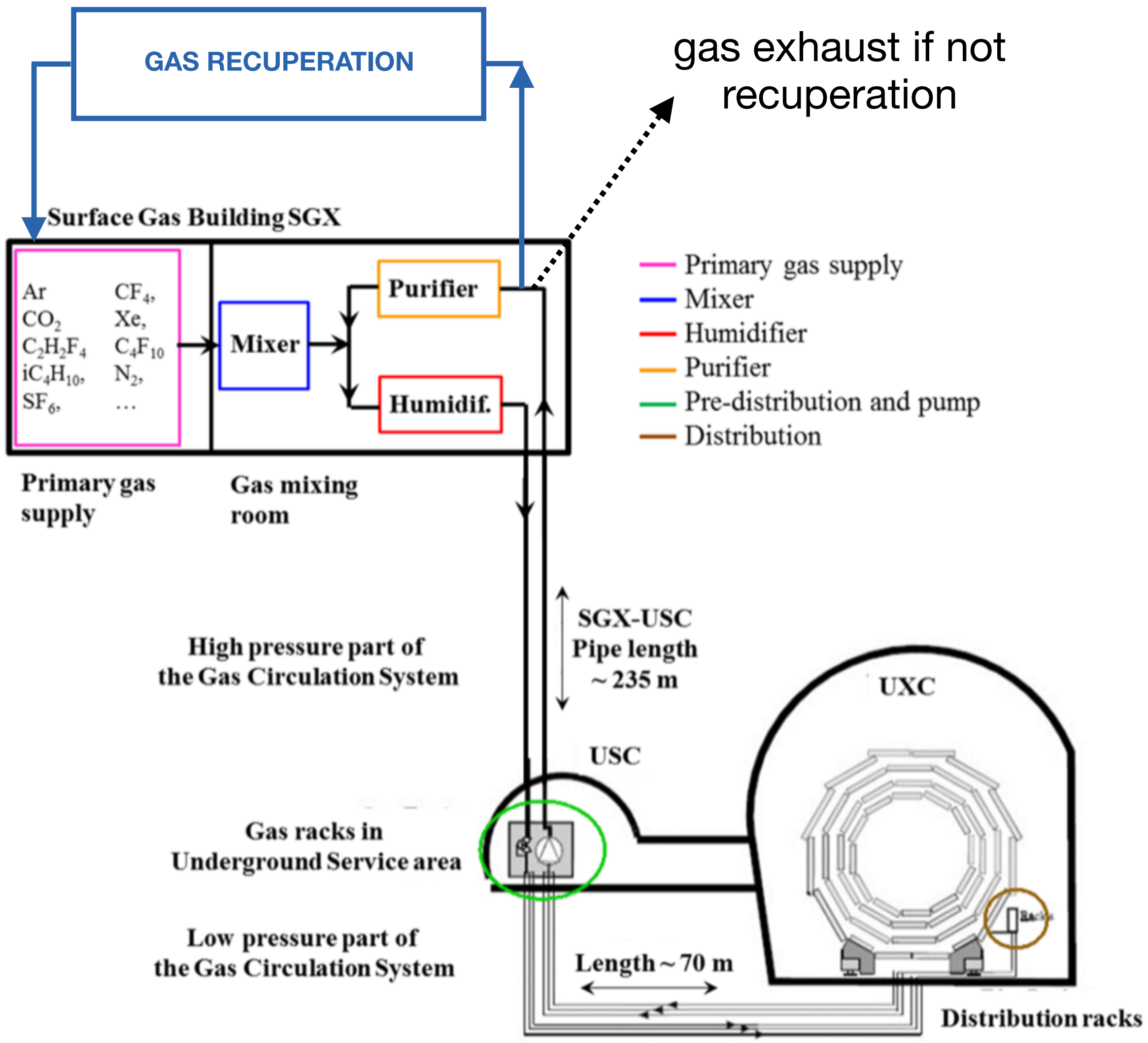
CERN strategies for GHG reduction



Gas Recuperation systems at LHC experiments

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



Advantages:

- further reduction of gas consumption

Disadvantages:

- higher level of complexity
- dedicated R&D
- gas mixture monitoring

Gas recuperation systems for GHGs at CERN:

CF_4: CMS Cathode Strip Chambers and LHCb RICH2

- Both systems operational

$C_2H_2F_4$ and **SF_6**: Resistive Plate Chambers (RPC)

- First system will be operational in ~1month

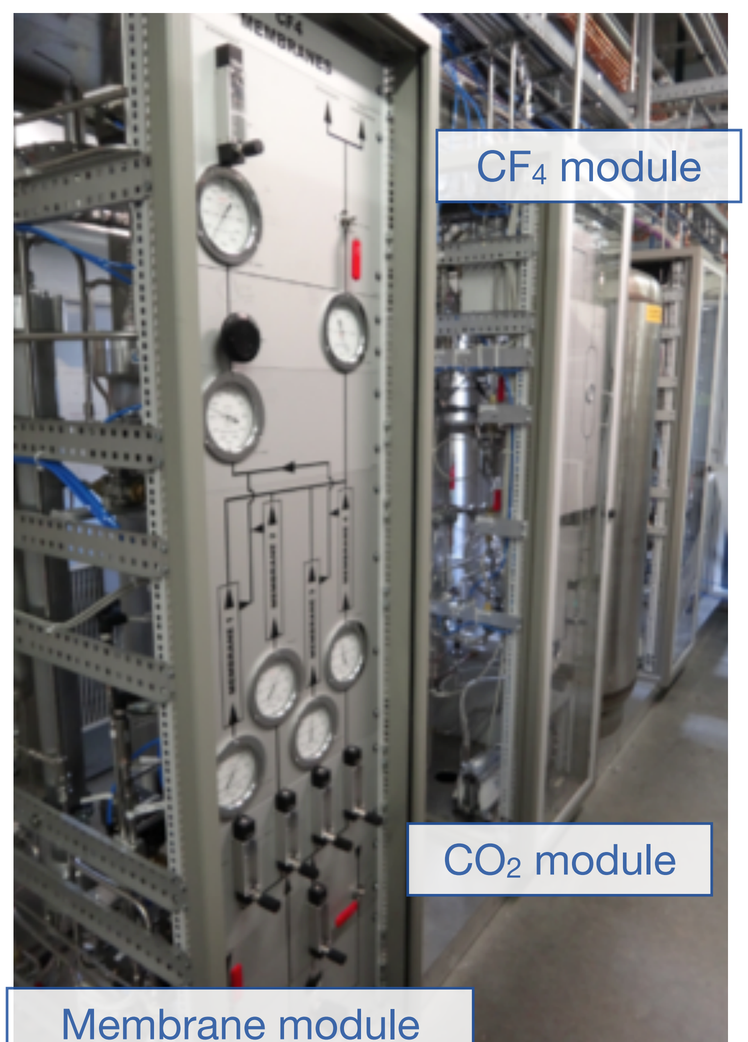
C_4F_{10}: LHCb RICH1

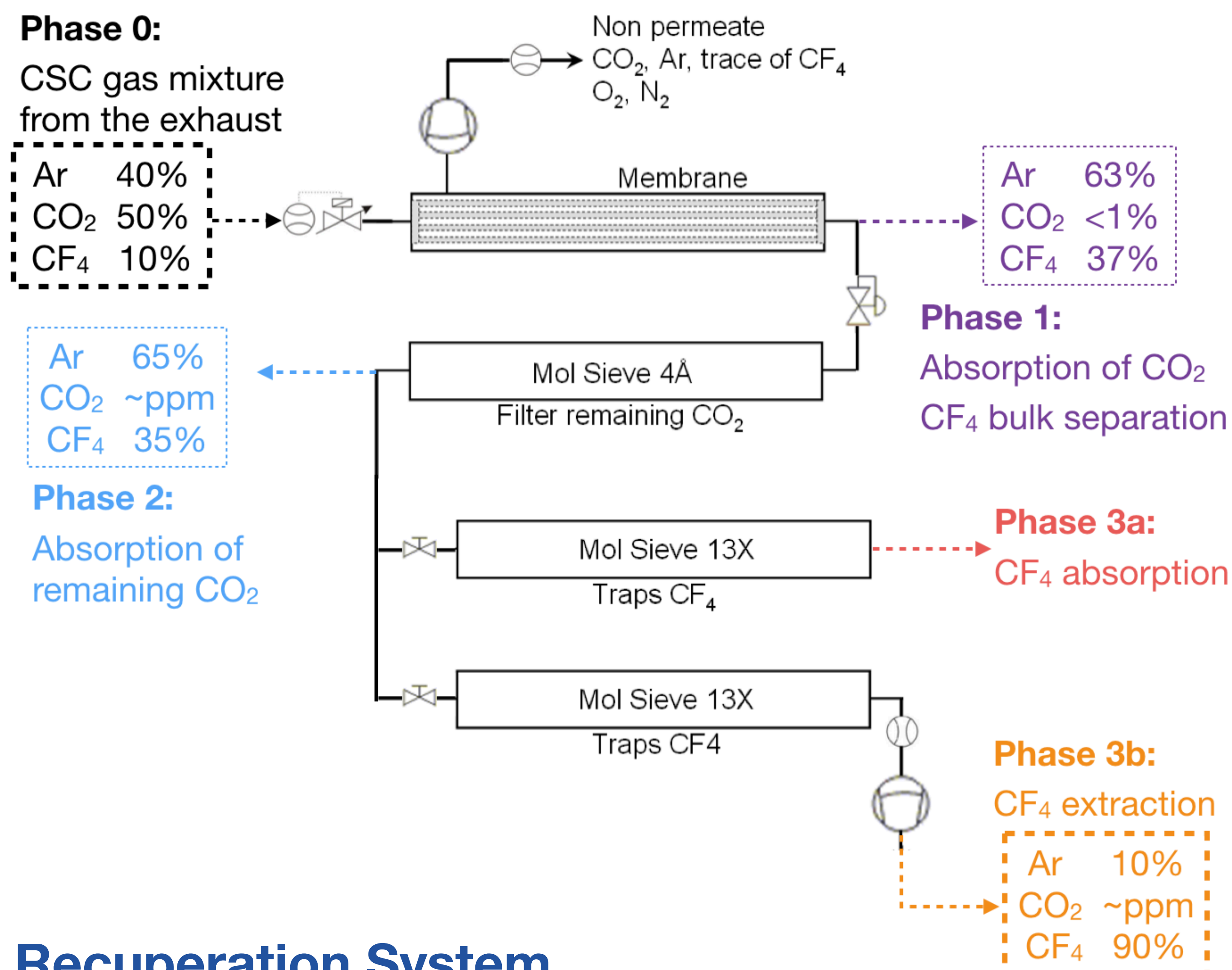
- Old system operational new under design

The CF_4 recuperation system for CMS CSC

CSC Gas System

- Detector volume ~90 m^3
- Gas mixture:
  50% CO_2, 40% Ar, **10% CF_4**
- Gas recirculation: 90%
  - Limited by detector permeability to Air
- ~800 l/h at exhaust:
  —> 80 l/h of CF_4 for recuperation





CF_4 Recuperation System

- Recuperation of CF_4 with warm separation
  - 3 phases needed and several parameters affect recuperation efficiency
  - Recuperated CF_4 quality to monitor
- CSC detectors operated with recuperated CF_4 during Run 2
  - No change in the CSC performance observed
- Current recuperation efficiency ~65%

The R134a recuperation system for RPCs

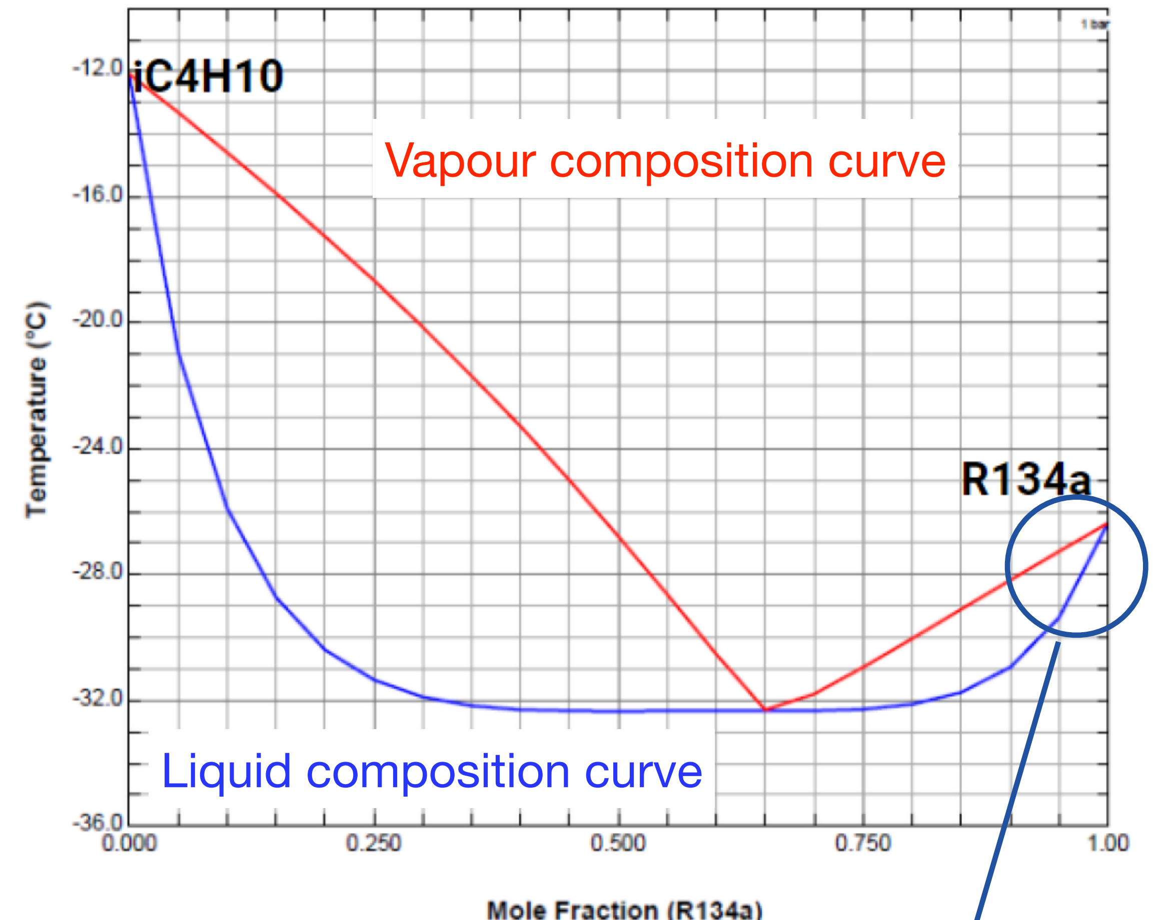
ATLAS and CMS RPC Gas Systems

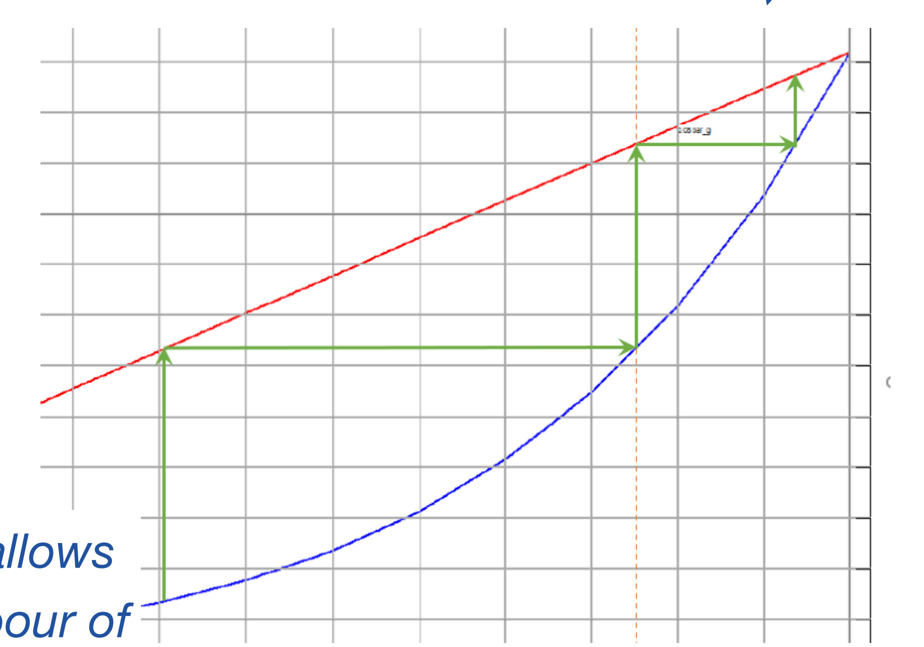
- Detector volume ~15 m^3
- Gas mixture: ~95% **$C_2H_2F_4$**, ~5% iC_4H_{10}, 0.3% **SF_6**
- Gas recirculation: ~90%
  - maximum recirculation validated for RPC detectors
- Fundamental to repair detector leaks
  - To have the gas at the exhaust (600-1000 l/h)

RPC Recuperation System

- Not convenient to recuperate the gas mixture
- Cold separation for R134a
  - Thermodynamic phase transitions
- **R134a and *i*C_4H_{10} form an azeotrope**
  - A mixture of liquids whose proportions cannot be altered or changed by simple distillation
  - Intramolecular force of same-species is much higher than the reciprocal attraction separation by quasi-static increase of temperature

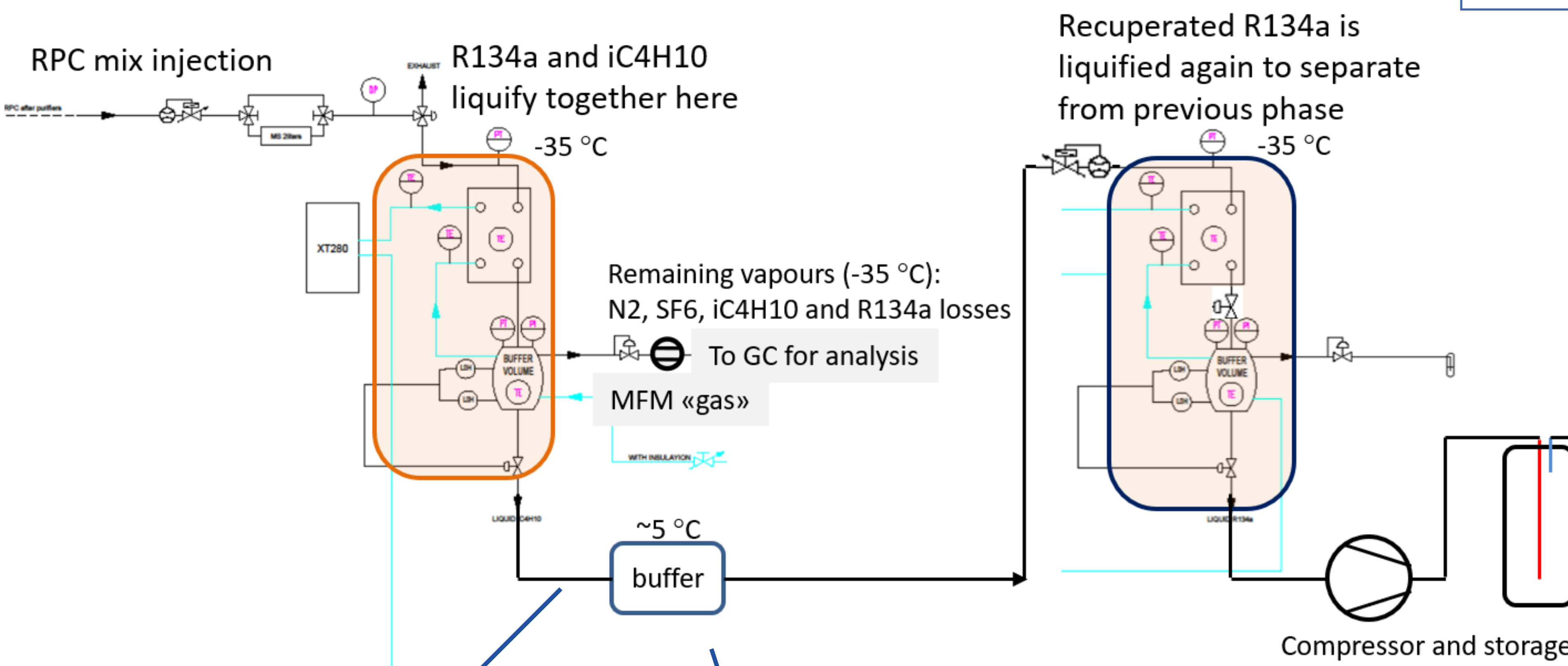
Non-ideal minimum azeotrope

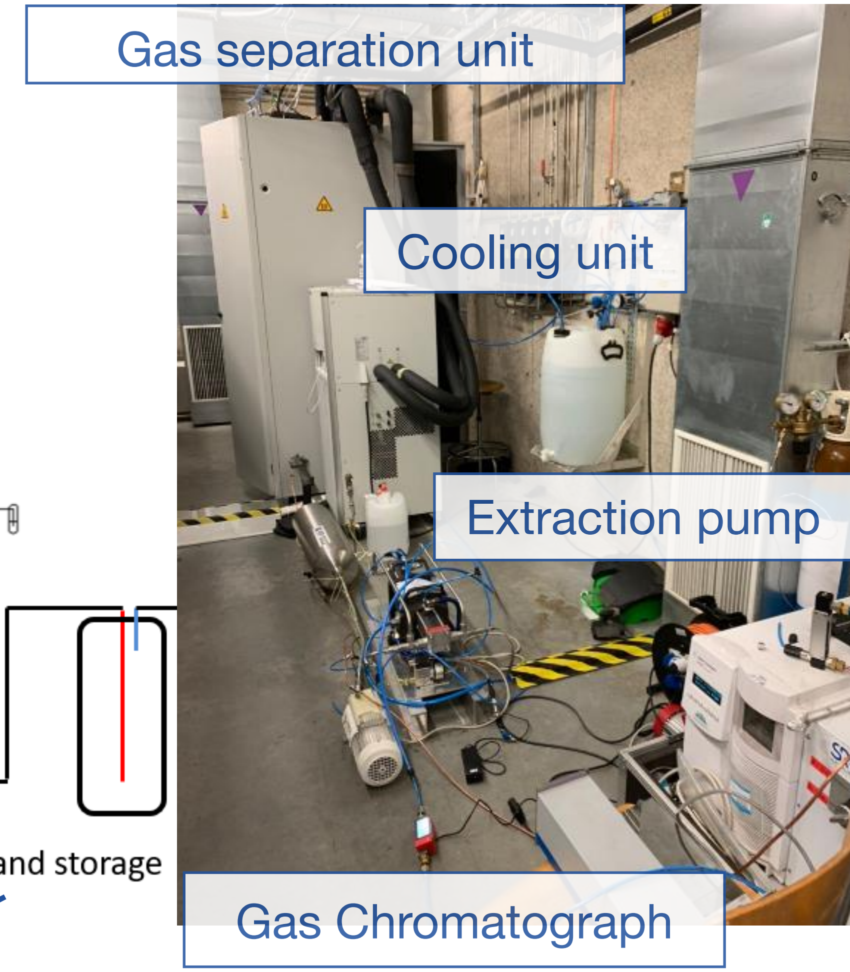




Slow heating of the liquified azeotrope allows to enrich the liquid of R134a and the vapour of iC_4H_{10}, obtaining the separation

The R134a recuperation system for RPCs





Phase 1

- Removal of N_2/SF_6 by simple distillation
  - Gas mixture in buffer 1 cools down at -35 °C
  - N_2/SF_6 in vapour phase

Phase 2

- Detachment of R134a from iC_4H_{10}
  - Liquid heats up and vapour is made of azeotrope
  - Vapours go back in buffer 1
  - Liquid R134a go in buffer 2

Phase 3

- Compression of R134a
  - Vapour is compressed in liquid storage

Recuperation efficiency ~80%

First $C_2H_2F_4$ recuperation system under construction: installation foreseen beginning of 2023 in CMS experiment

CERN strategies for GHG reduction

CERN Strategies to reduce GHG emissions in particle detection

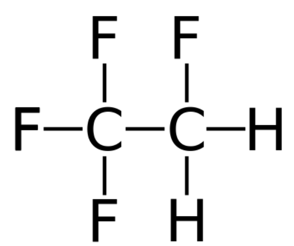
- Gas Recirculation
  - Optimisation of current technologies
  - Particular attention to operation
  - Improved control and monitoring
- Gas Recuperation
  - Pressure swing
  - Membrane separation
  - Cryogenic/cold separation
- **Alternative Gases**
  - To $C_2H_2F_4$
  - To SF_6
  - To CF_4
- Gas Disposal
  - GHG destruction → Discarded

Gas Recirculation, Gas Recuperation → Short-term

Alternative Gases → Long-term

Possible alternatives to GHG gases

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



R134a

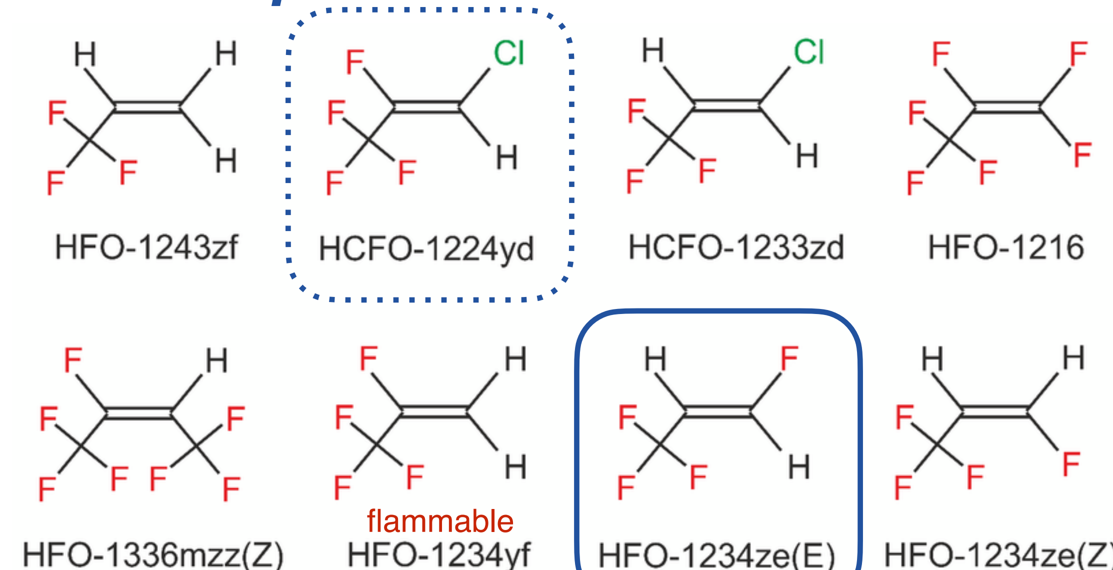
($C_2H_2F_4$)

GWP 1430

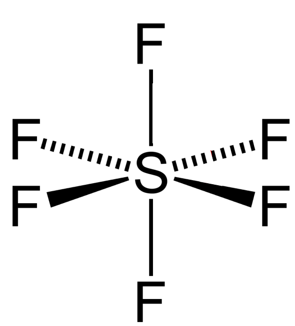
→

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

GWP <10



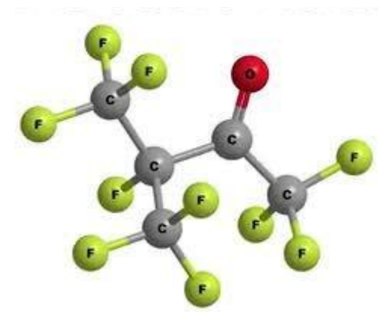
($C_3H_2F_4$)



SF_6

GWP 23900

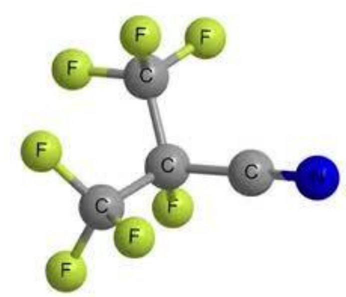
→



3M™ Novec™ 5110

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

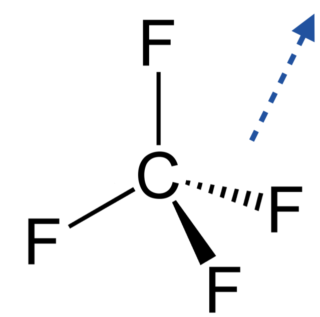
GWP <1



3M™ Novec™ 4710

($(CF_3)_2$ CFCN)

GWP 2100

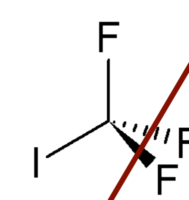


R14

(CF_4)

GWP 5700

→ ?



~~**CF_3I**~~

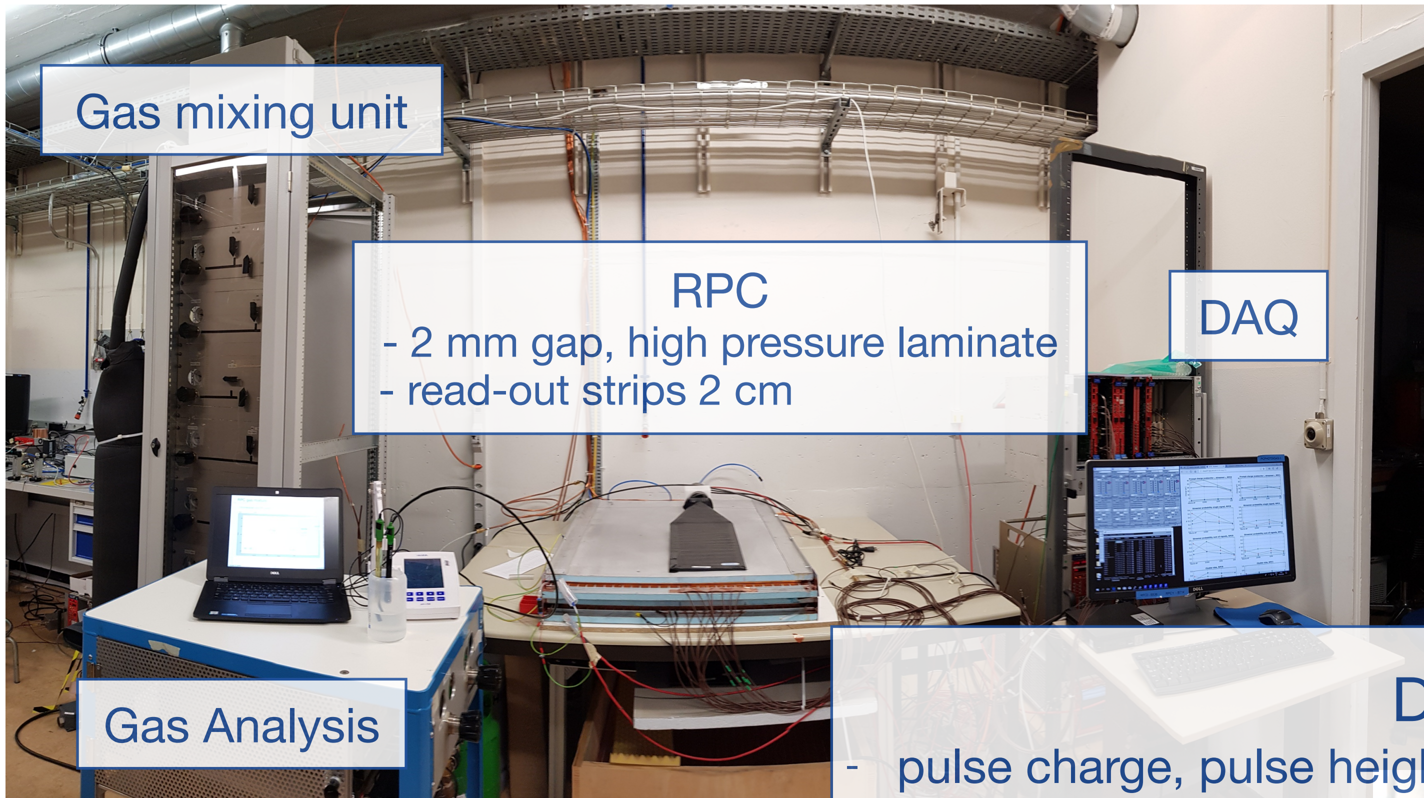
~~**GWP 0.4**~~

toxic

<u>The new eco-friendly gas mixtures have to fulfil several requirements for their use in LHC Experiments</u>

- ➡ Detector performance similar to current ones
- ➡ No change of FEB electronics, HV system, etc
- ➡ Long-term operation (to evaluate possible aging issues)
- ➡ No flammability or toxicity of the gas mixture

Set-ups: laboratory and irradiation facility



Laboratory

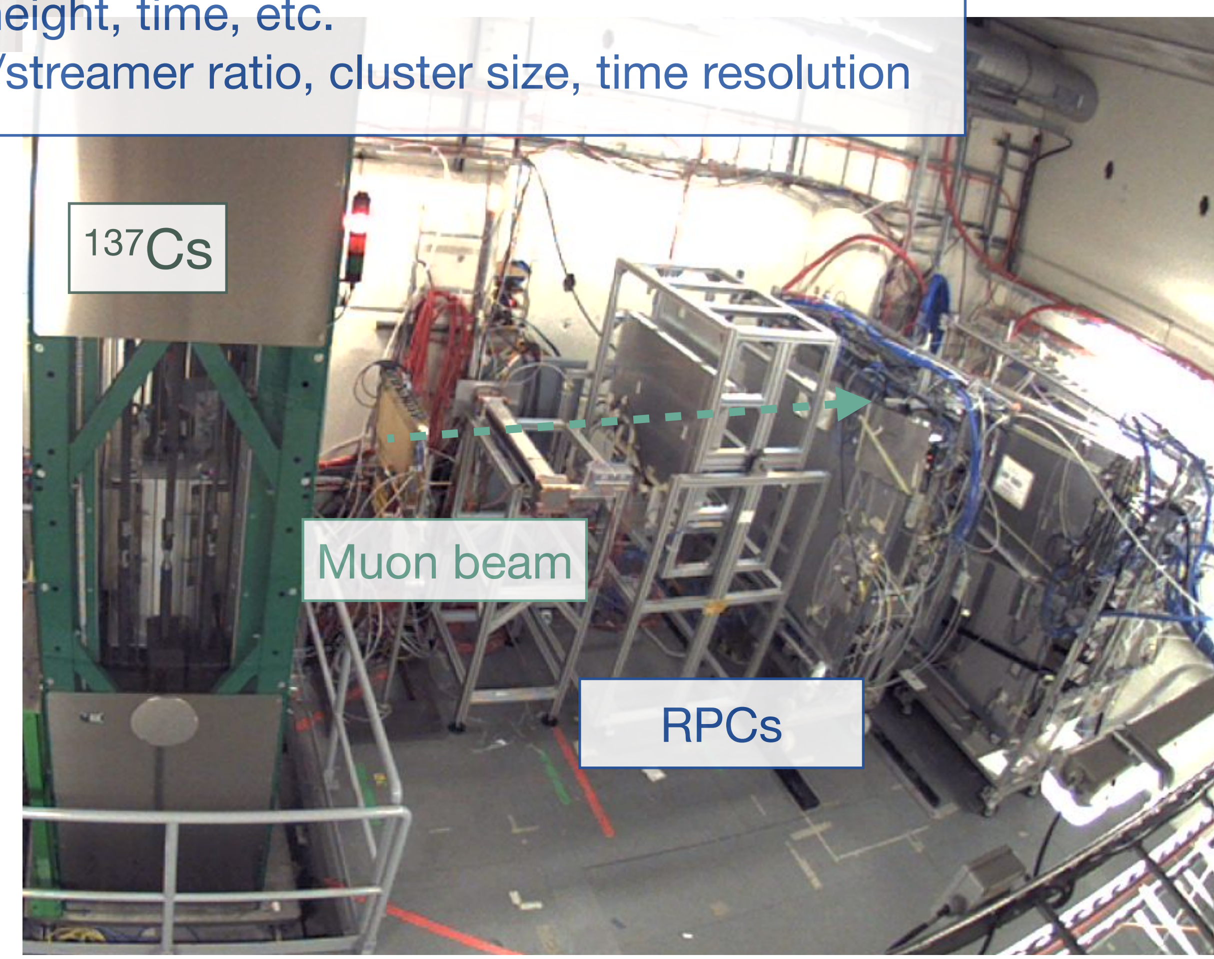
- Gas mixing unit
  - Gas mixture up to 6 components
- DAQ
  - CAEN Digitizer V1730: resolution 0.24 mV, sampling 500 MS/s
- Gas analysis
  - GC, MS and ISE

Data analysis

- 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



Resistive Plate Chamber (RPC) Detectors

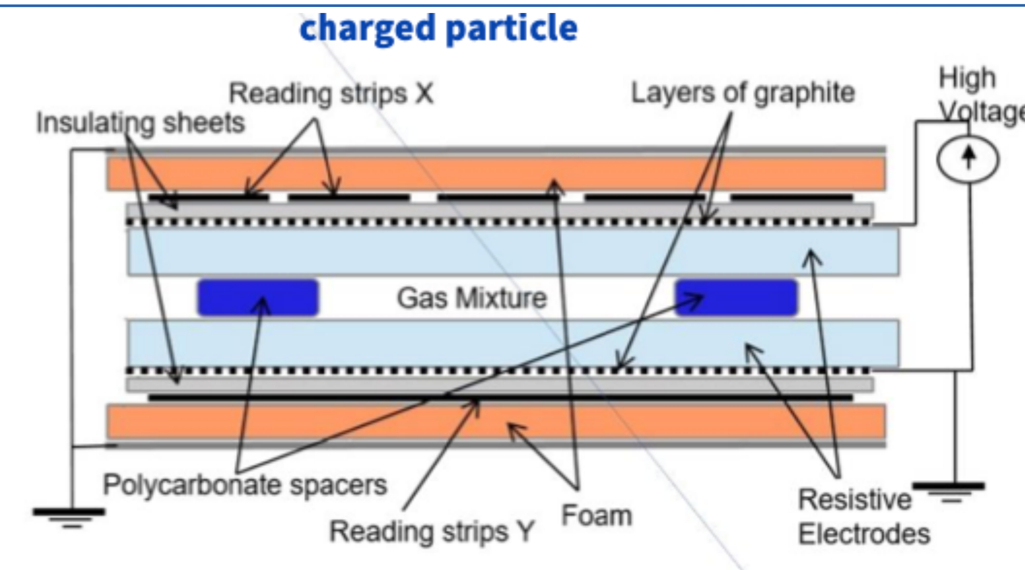
RPC main features

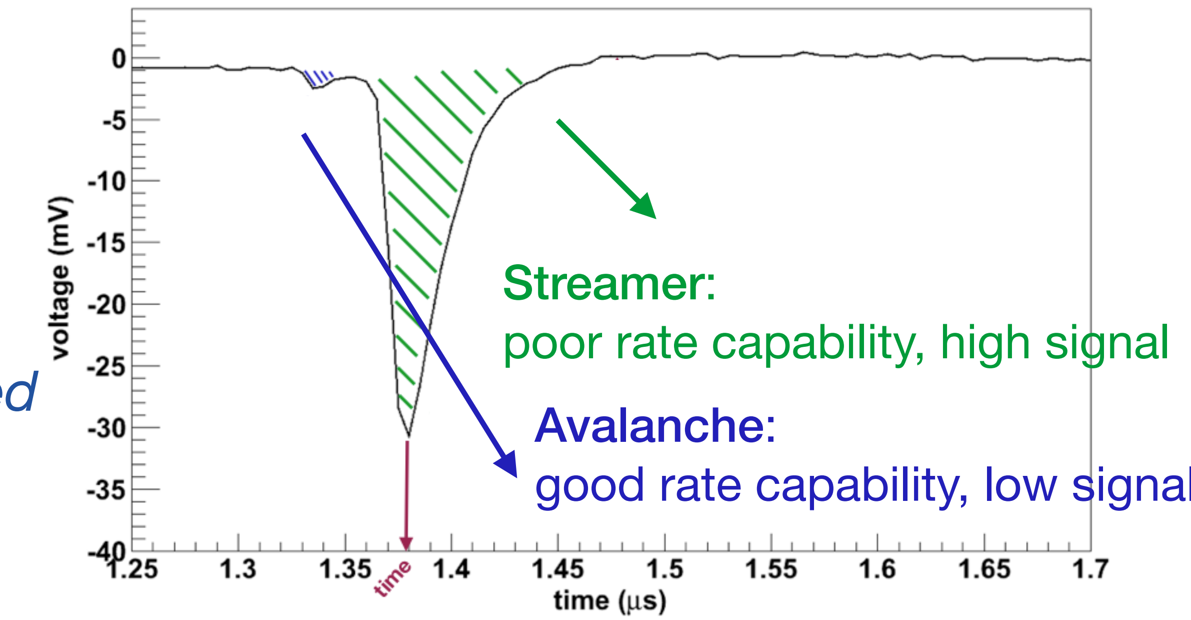
- Planar geometry, uniform electric field
  - ~ 5kV/mm
- Ionisation region = multiplication region
  - No drift (good time resolution)
- Induced charge movement read on pick-up strips
- Resistive electrodes
  - ~10^{10} Ohm*cm (High Pressure Laminate)
- Operation in avalanche mode
  - Signal of few pC, good rate capability
- Single, double or multi-gap RPC
- Used at LHC experiments
  - ALICE, ATLAS, CMS as trigger
  - ALICE as TOF system

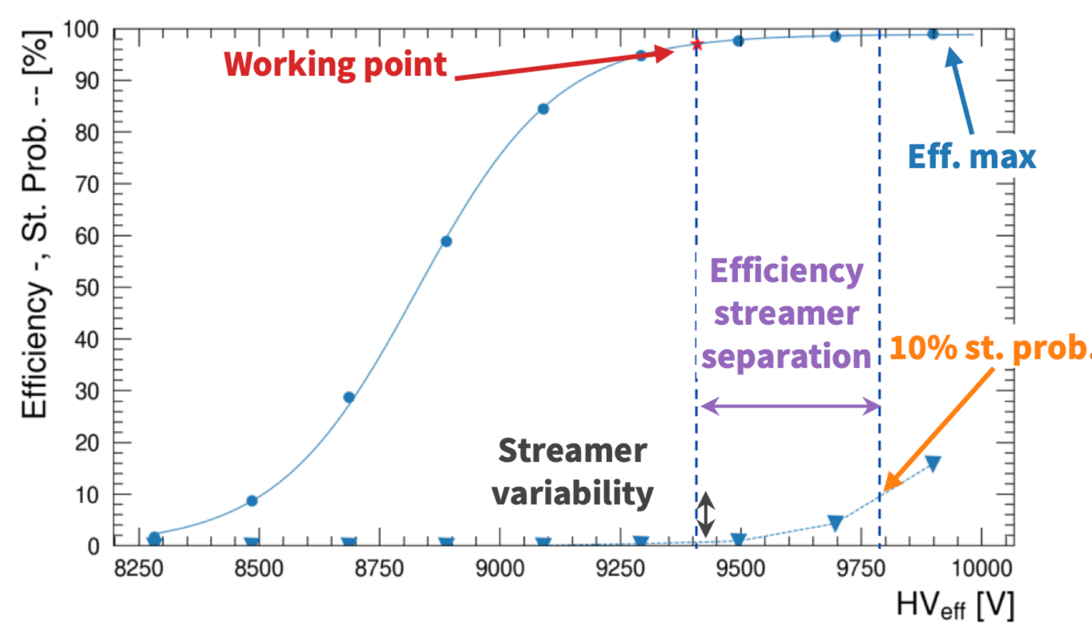
Parameters extracted from the signal: pulse height, integrated charge, time

Foremost parameters of an RPC

- Efficiency and efficiency plateau
- Time resolution
- Cluster size
- Avalanche to streamer (> ~16pC) ratio
- Streamer fraction
- Currents flowing through the electrodes







Addition of He or CO_2 to std gas mix

1:1 R134a substitution with HFO doesn't work for 2mm RPC

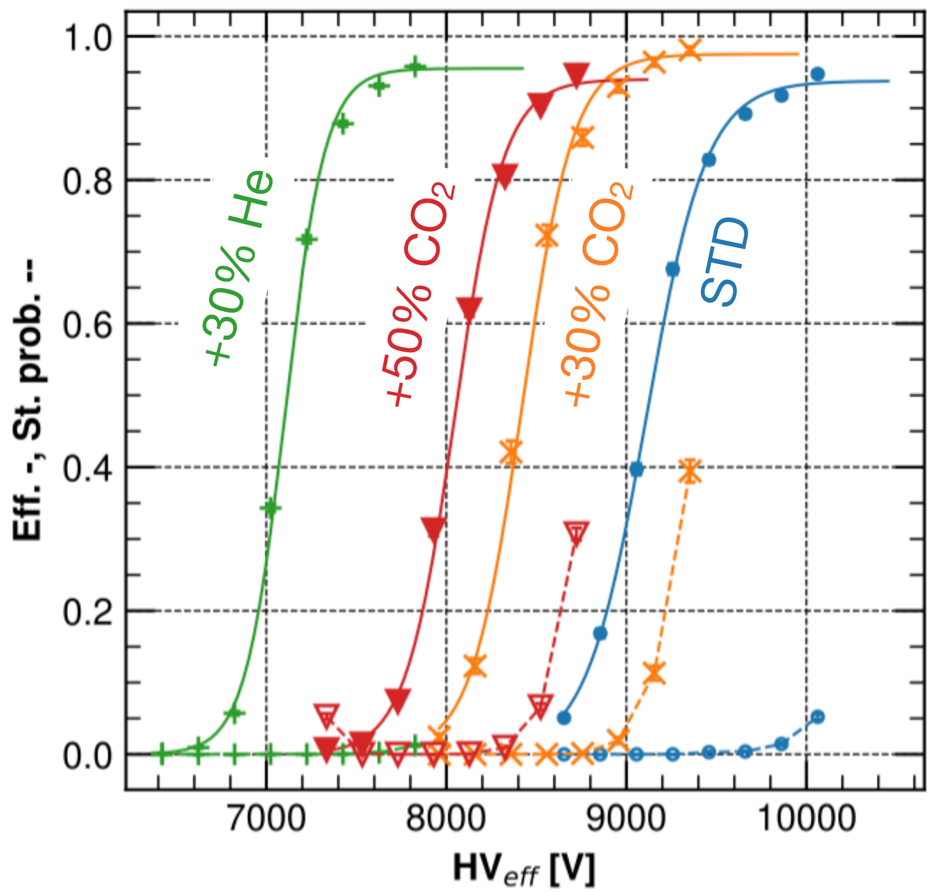
↓

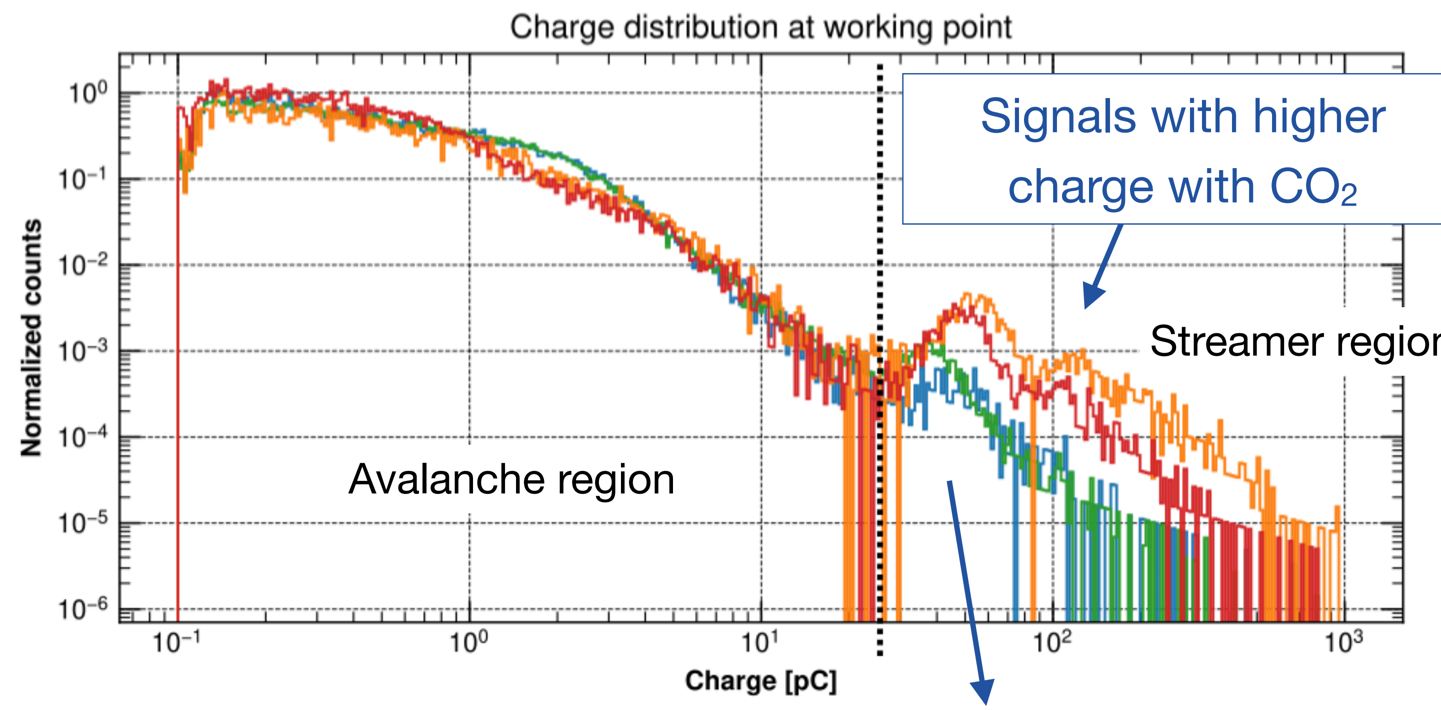
Necessary to add a gas to lower working point (and GWP!)

N.B. As it is today, He cannot be used in CMS and ATLAS

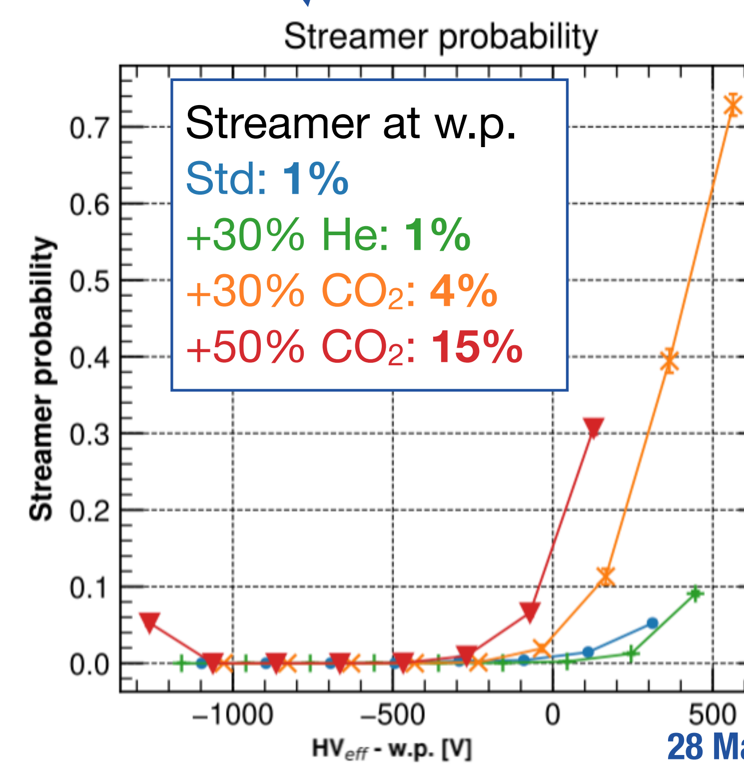
+10% CO_2 —> -200 V

+10% He —> -600 V





R134A/IC4H10/SF6 95.2/4.5/0.3
R134A/HE/IC4H10/SF6 65.2/30/4.5/0.3
R134A/CO2/IC4H10/SF6 65.2/30/4.5/0.3
CO2/R134A/IC4H10/SF6 50/45.2/4.5/0.3

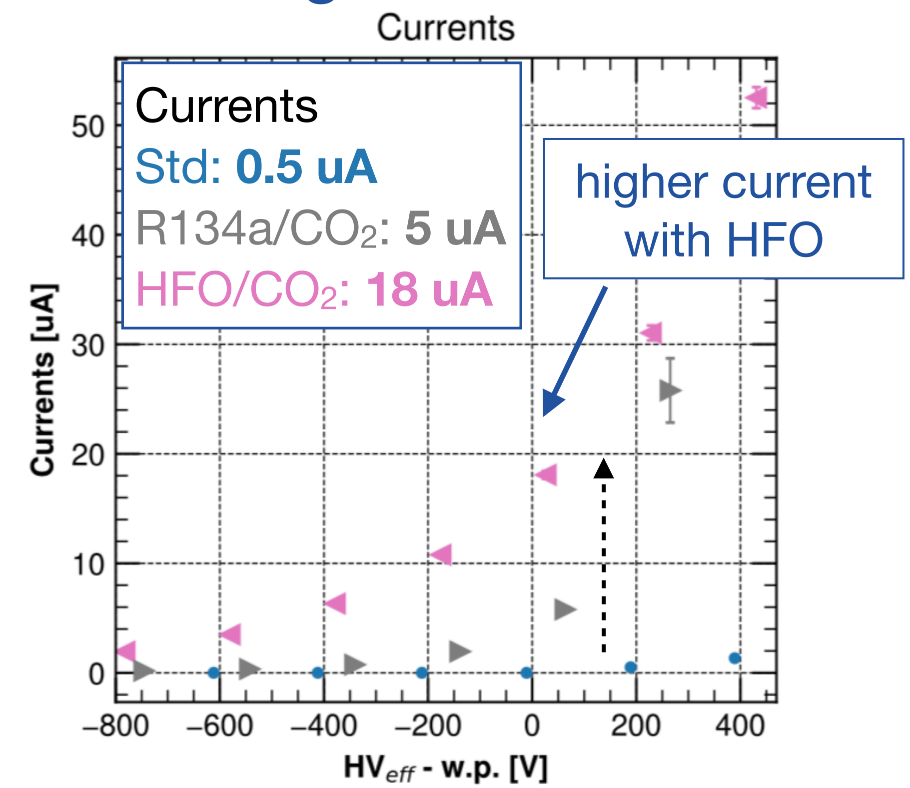


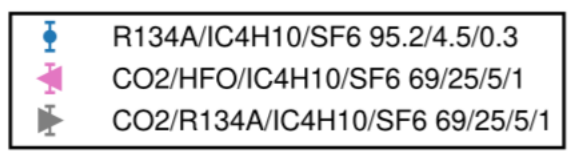
- Addition of He or CO2 to lower the working point
- Streamer probability increases with addition of CO_2
  - Increase of drift velocity and decrease of attachment coefficient
- With 30% CO_2, ~1% SF_6 needed to have same streamer probability of standard gas mixture (0.3%)
  - but detector currents increase of ~20% under high irradiation

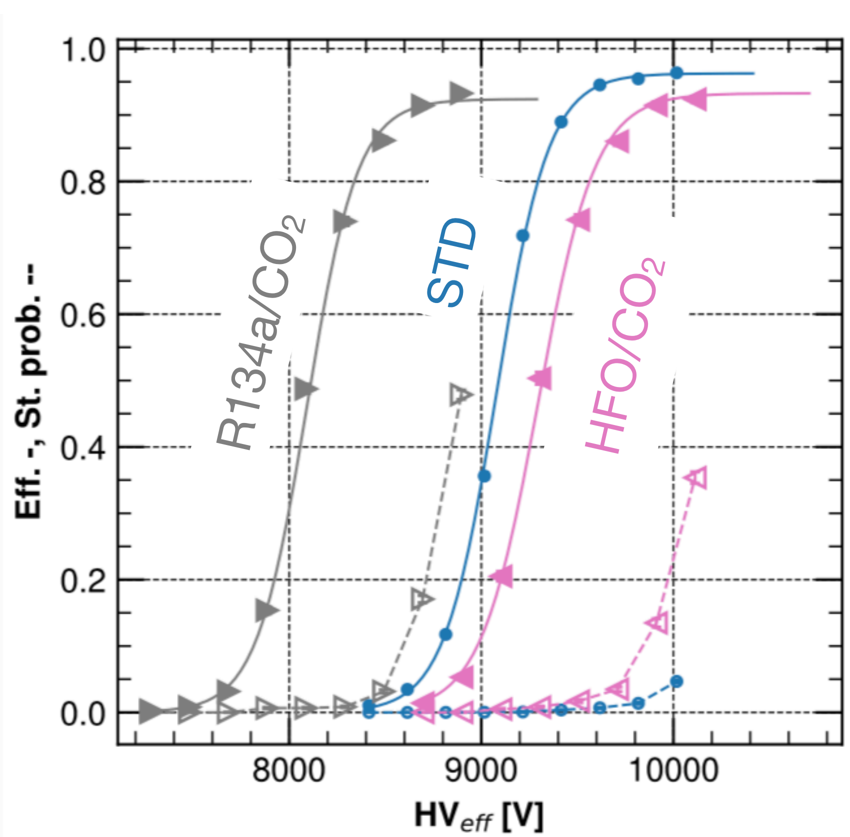
HFO as replacement of R134a

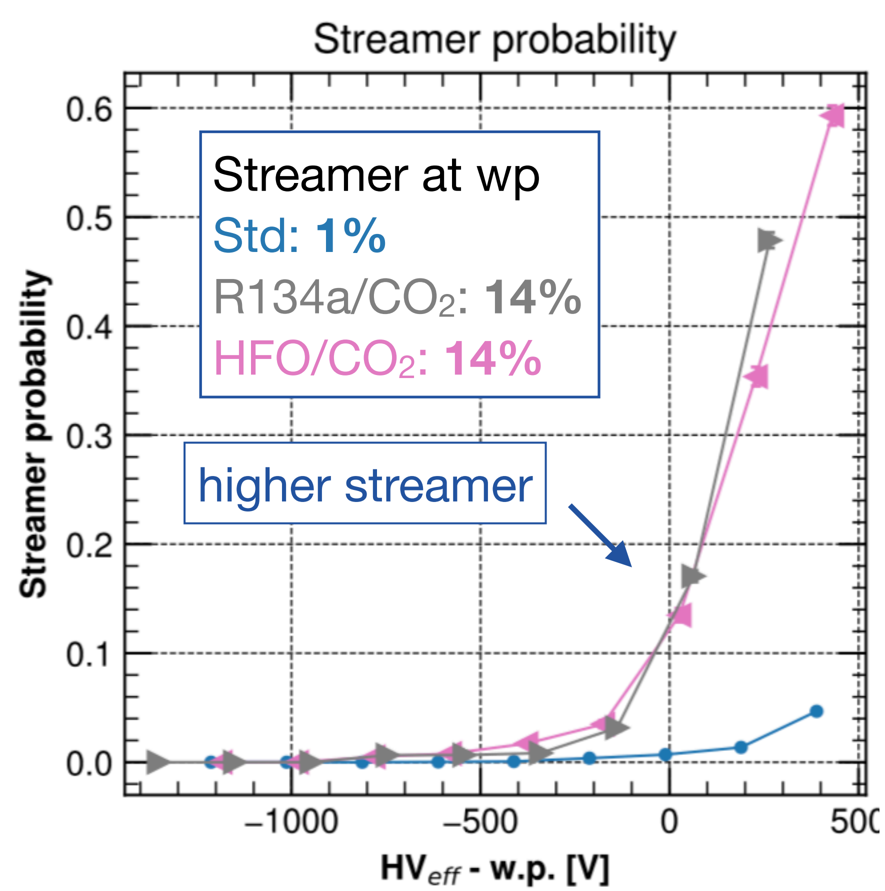
70% CO_2 needed with HFO to keep same wp of standard gas mixture

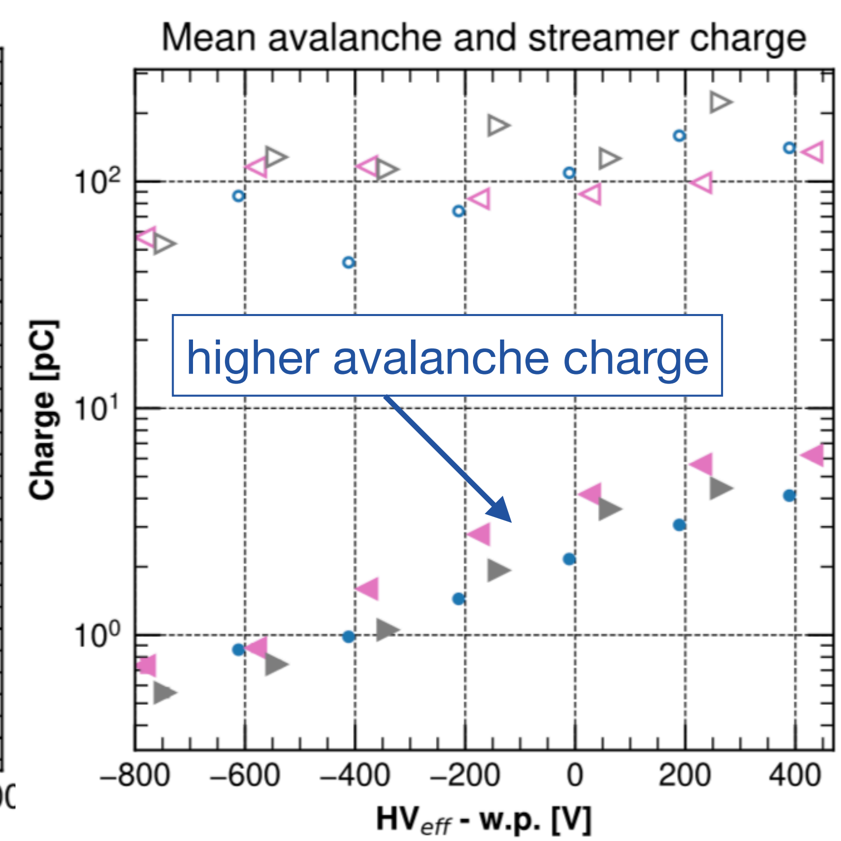
- Streamer probability ~15% with both CO_2 gas mixtures
  - Already with 1% of SF_6
  - It seems HFO doesn't contribute so much to streamer
- CO_2/HFO gas mixture has higher currents and avalanche charge signals
  - It seems HFO has a clear effect in detector currents
  - Also visible at high gamma rates







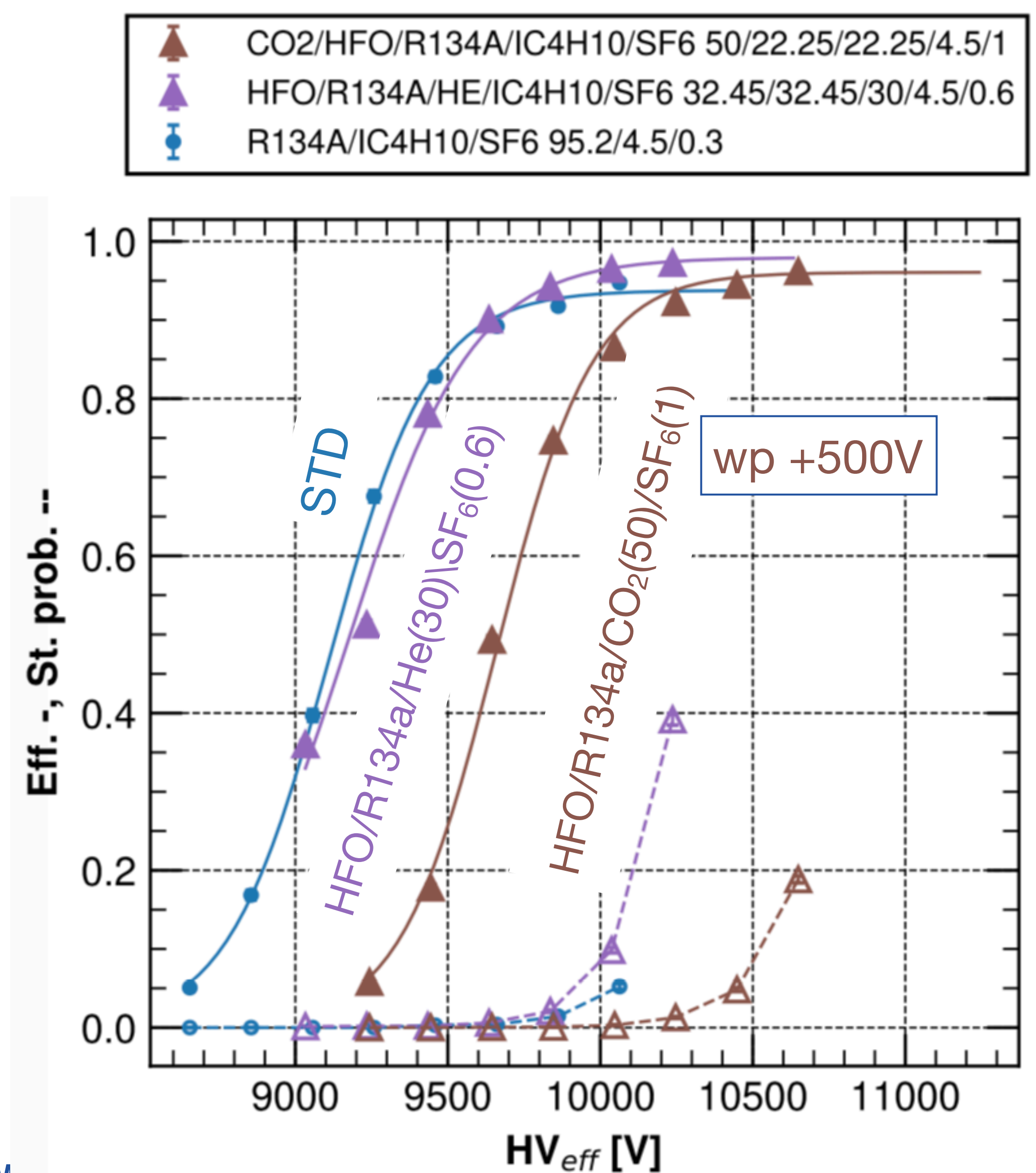


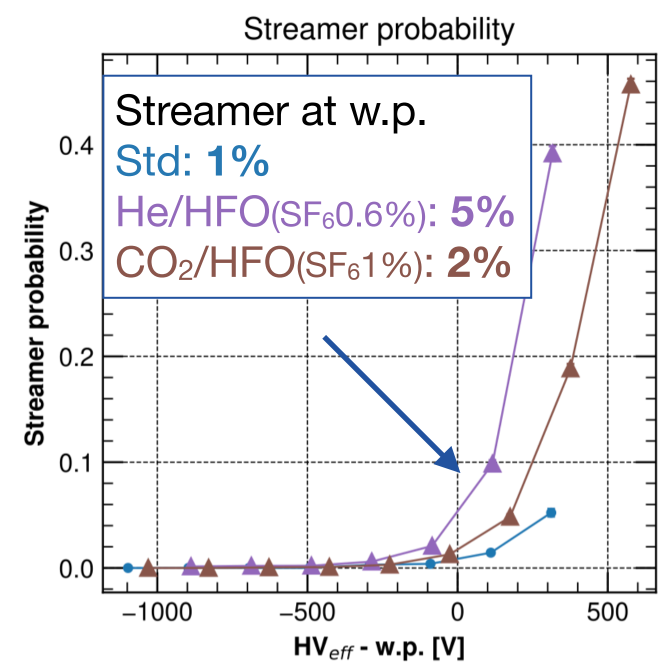


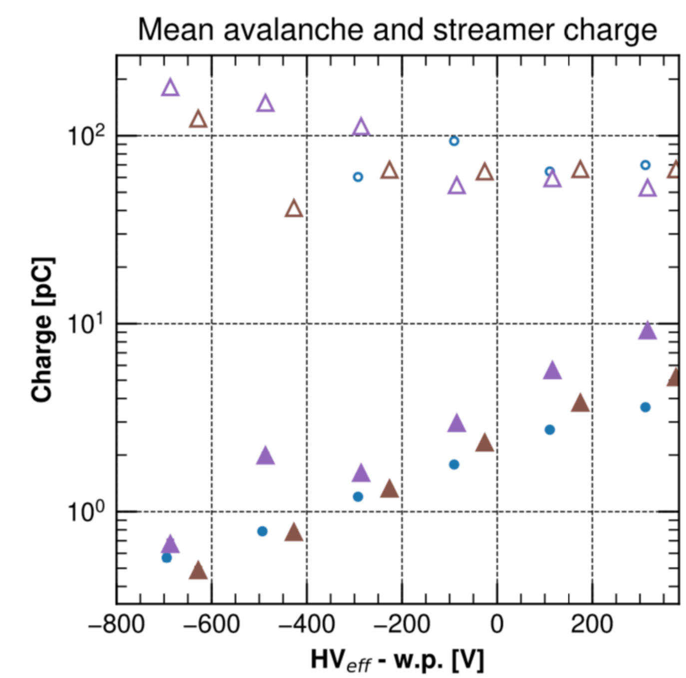
HFO/R134a based gas mixtures with CO_2 or He

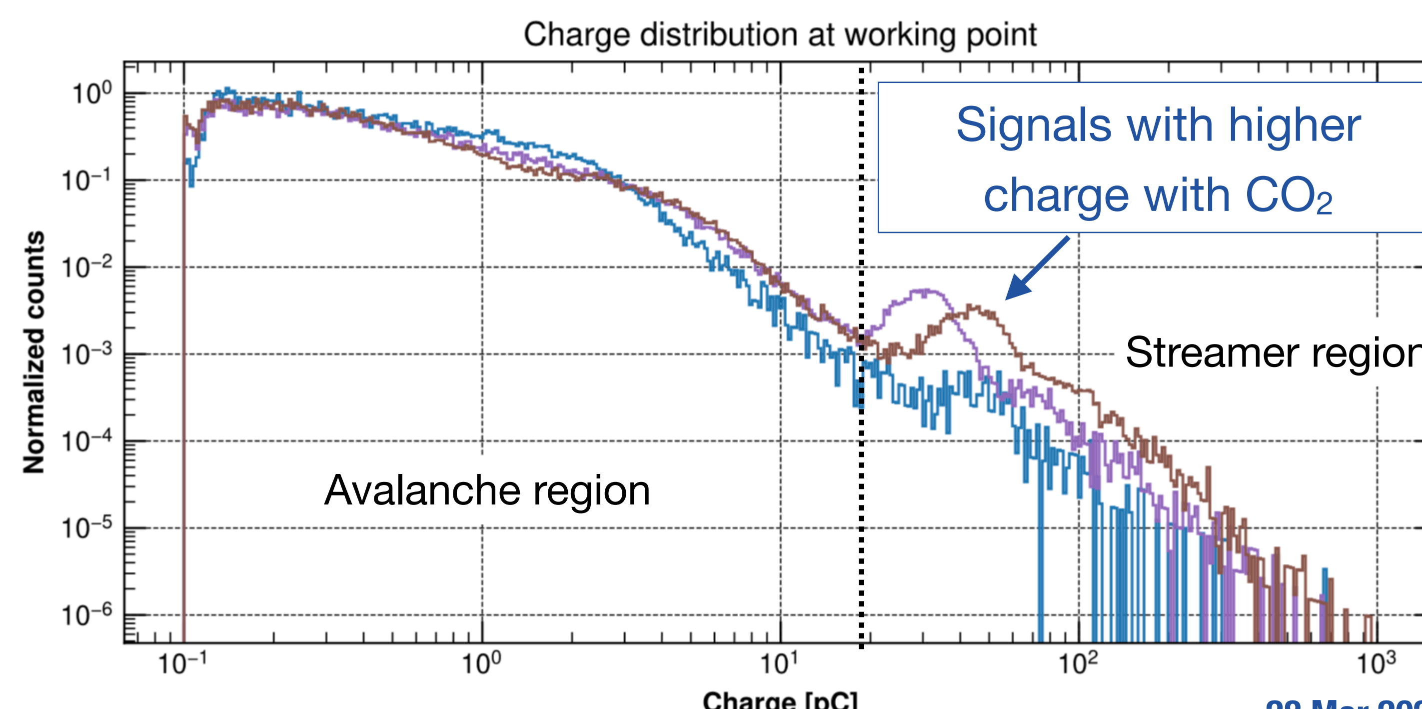
A small fraction of R134a is kept to lower currents and charge

- To have good working point: CO_2 at 50% and He at 30%
  - Necessary to increase the SF_6 concentration to lower streamer probability
- In CO_2 based gas mixture: higher streamer charge and wp but lower streamer probability
  - Higher charge because higher CO_2
  - Lower streamer because higher SF_6









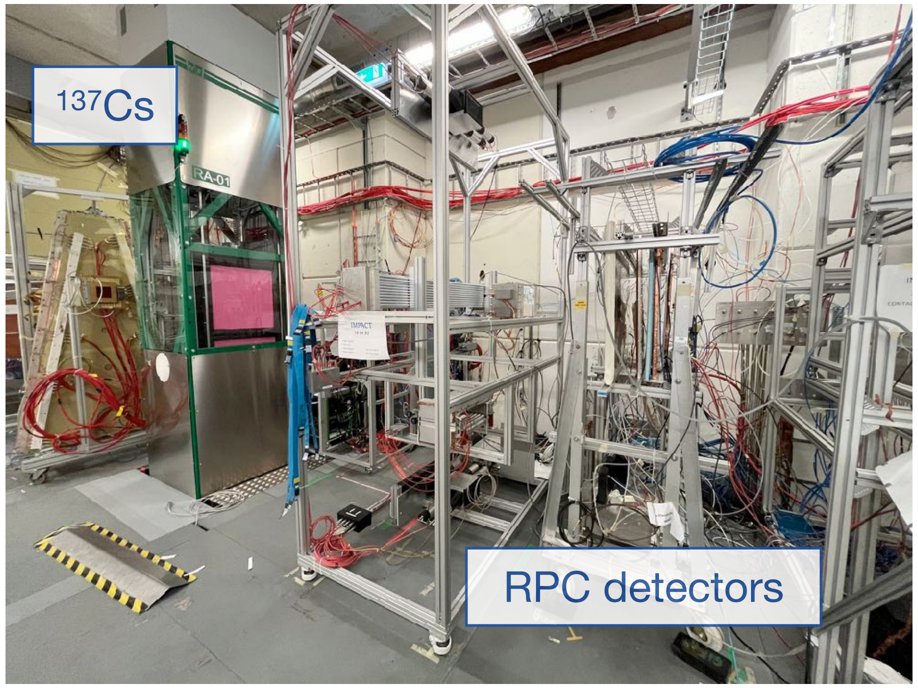
Long-term studies with HFO gas mixtures

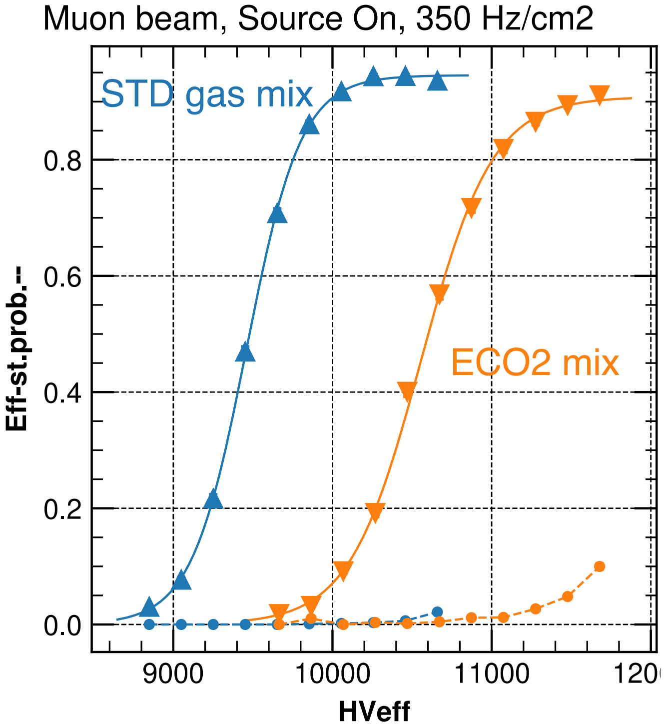
RPC long-term operation with eco-friendly gas mixtures
under high background radiation and possible ageing effects must be investigated

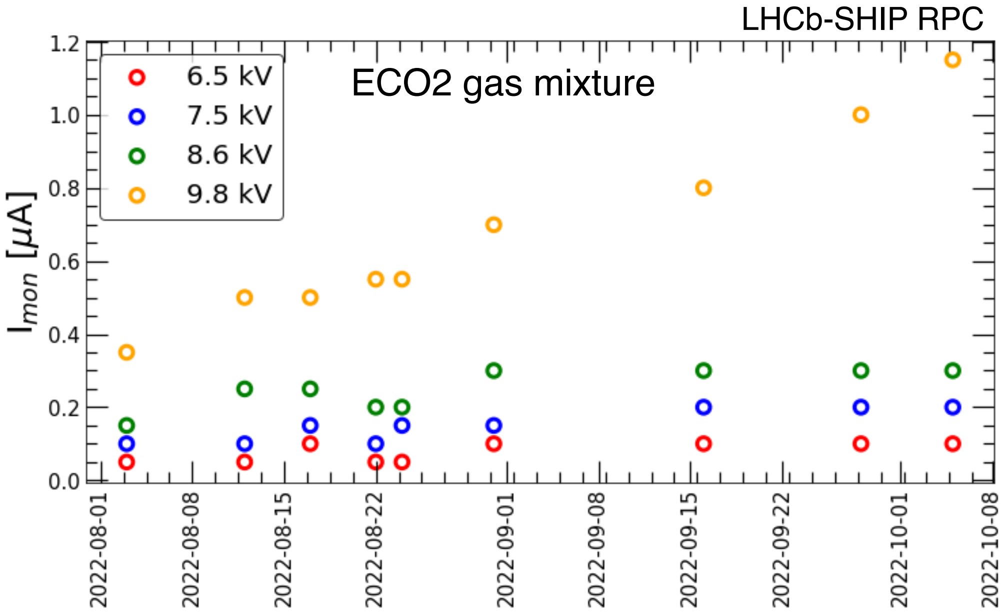
↓

Creation of the ECOGAS@GIF++ collaboration:
a joint effort between CERN Gas Team, ALICE, ATLAS, CMS, LHCb-SHIP RPC communities

- Set-up at CERN Gamma Irradiation Facility (**GIF++**)
  - 12.2 TBq ^{137}Cs and H4 SPS beam line
- Several RPCs under test from different experiments
- Detector **performance studies**
  - At different back-ground radiations
  - For different gas mixtures and for different types of RPCs
- **Long-term** performance studies
  - Irradiation of RPCs to accumulate an **equivalent charge of the HL-LHC Phase**
  - Fundamental for the validation of new eco-friendly gas mixtures
- Three gas mixtures under study
  - CO_2 50-70% + HFO 45-25% with~5% iC_4H_{10} and 1% SF_6



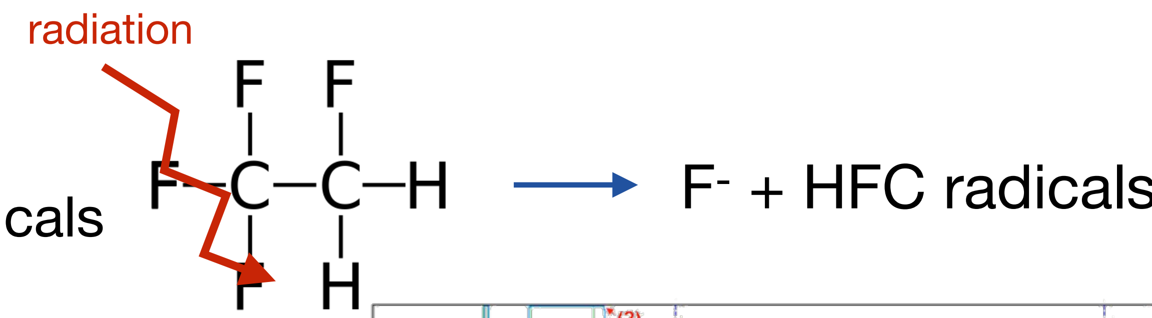


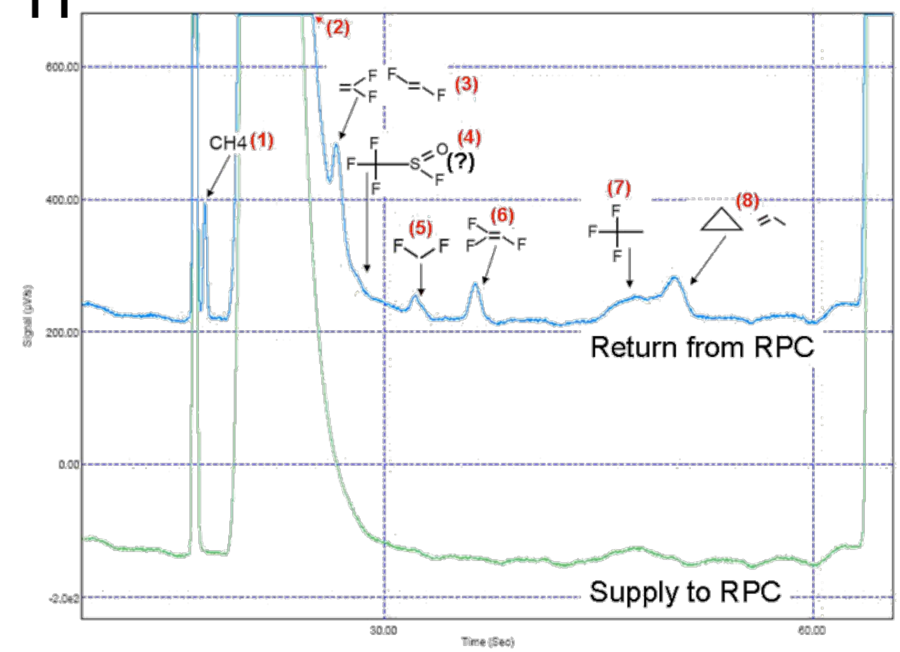


Creation of impurities under irradiation

Impurities created from $C_2H_2F_4$ breaking

- Under the effects of high background radiation and electric field, $C_2H_2F_4$ molecule breaks into fluorine radicals
  - Creation of F^- radical free: very chemical reactive
  - Sub-products in the order of hundreds ppm
  - Accumulation in case of closed loop system
- Creation of these impurities also present in the RPCs at LHC experiments in Run 2
  - Not well know the maximum limit for safety of the detector

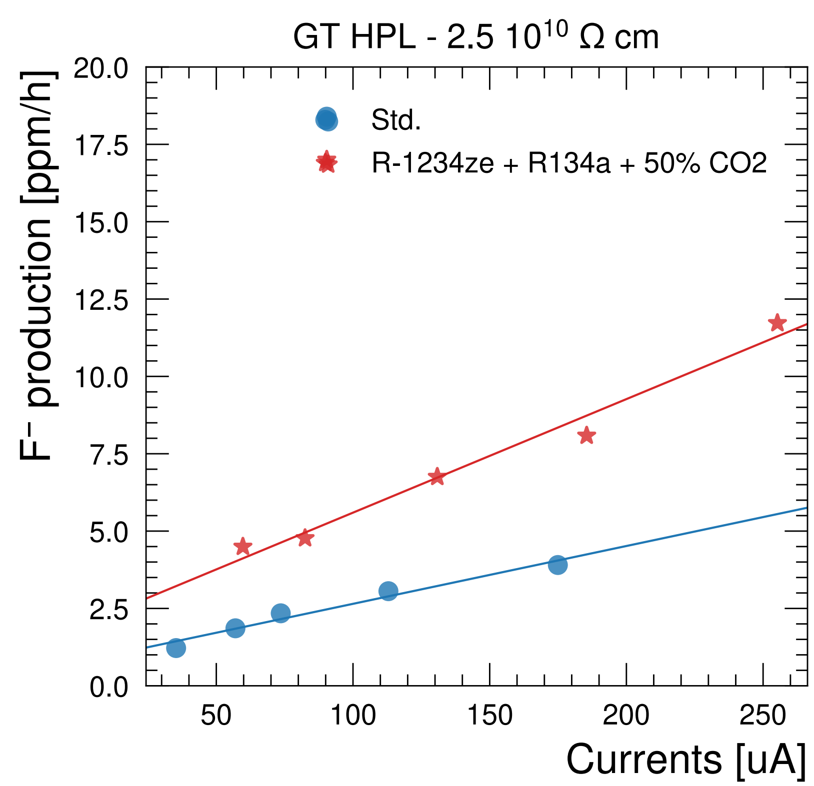


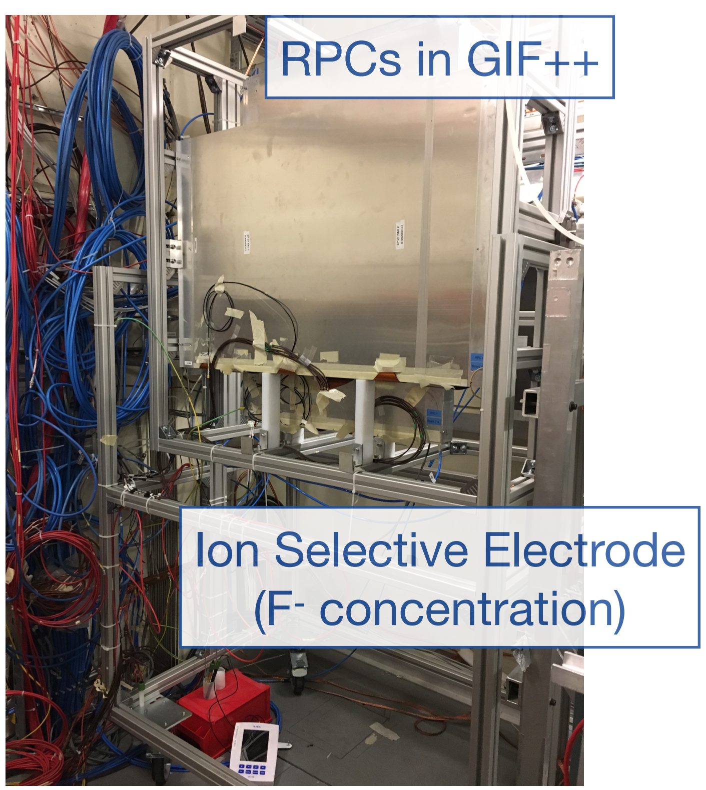


What about HFOs?

- HFOs have a very short atmospheric lifetime
  - They are destroyed easier than $C_2H_2F_4$
- RPC operated with HFO-based gas mixture have higher currents with respect to std gas mixture

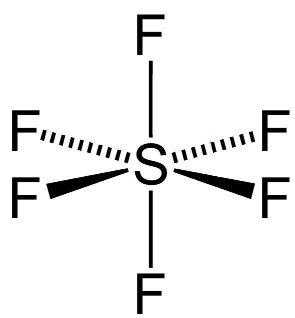
F^- production is higher in presence of HFO at same detector current





Alternatives to SF_6

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

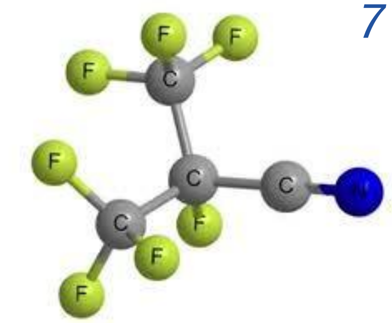
3M™ Novec™ 5110

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

GWP <1

Atm. lifetime 15 days

7 F



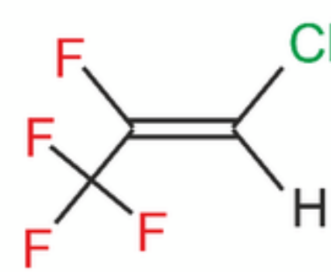
3M™ Novec™ 4710

$((CF_3)_2CFCN)$

GWP 2100

Atm. lifetime 30 years

4 F



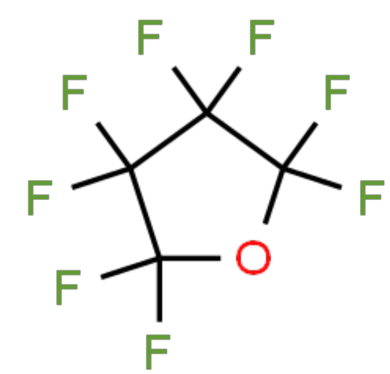
AMOLEA™ HFO-1224yd

$(CF_3\text{-}CF{=}CHCl)$

GWP <1

Atm. lifetime 20 days

8 F

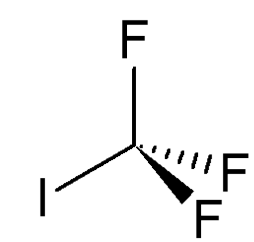


C_4F_8O

GWP 8700

Atm. lifetime >3000 years

3 F



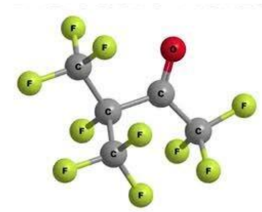
CF_3I

GWP 0.4

Atm. lifetime 6 days

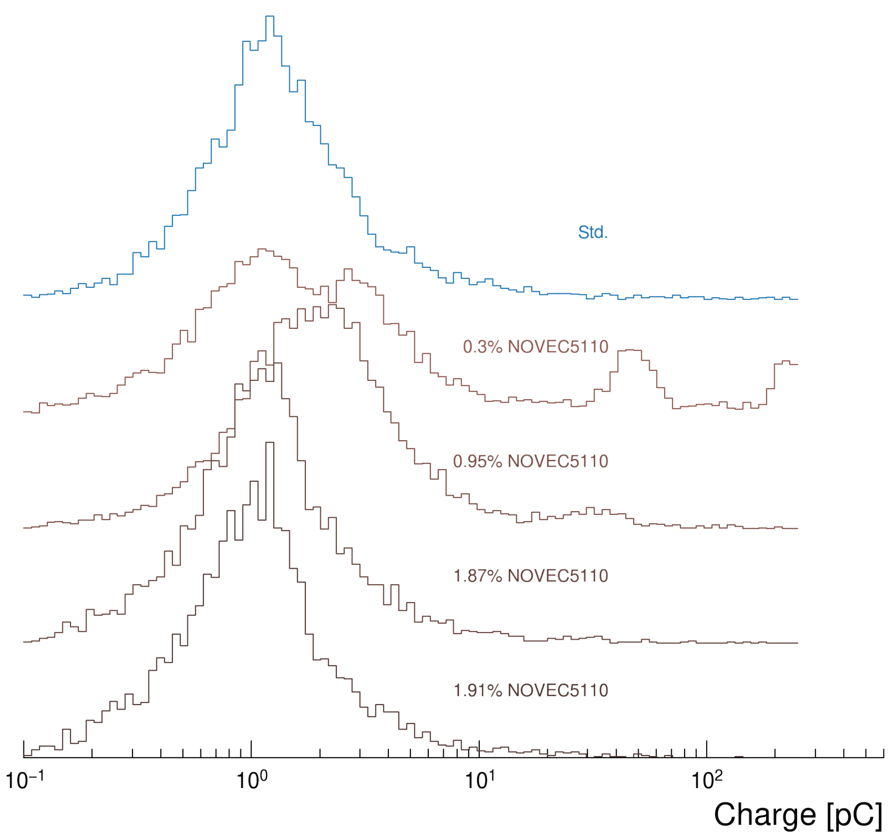
Performance with NOVEC gases

NOVEC 5110



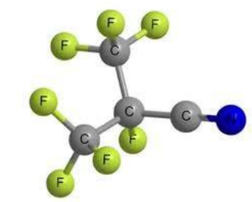
PRO
- Very low GWP: <1
- Application in industry
- High dielectric strength

CONS
- High boiling point: 27 C
- Sensitive to UV radiation



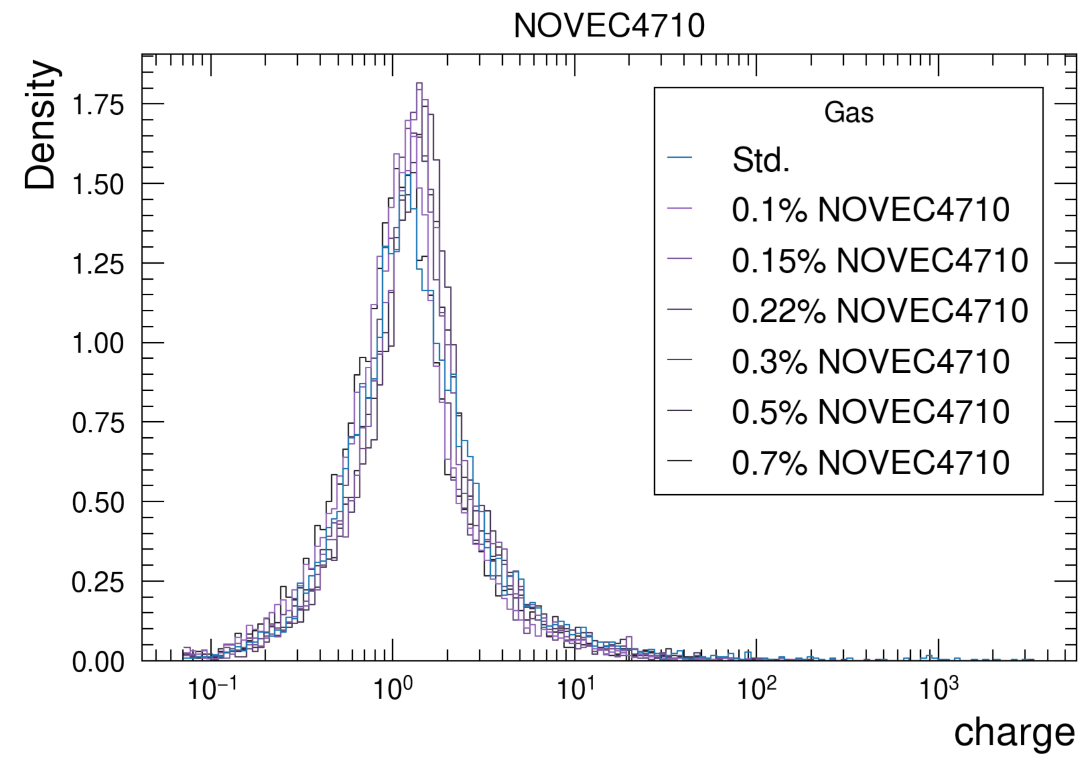
- High concentration (~2%) of NOVEC 5110 needed to obtain good streamer suppression
  - Suspect that NOVEC 5110 breaks inside RPC
- Higher working point for concentrations > 0.3%
- Avalanche and streamer charge similar of std gas mixture from 0.9%
  - At 0.3% very large avalanche signals

NOVEC 4710



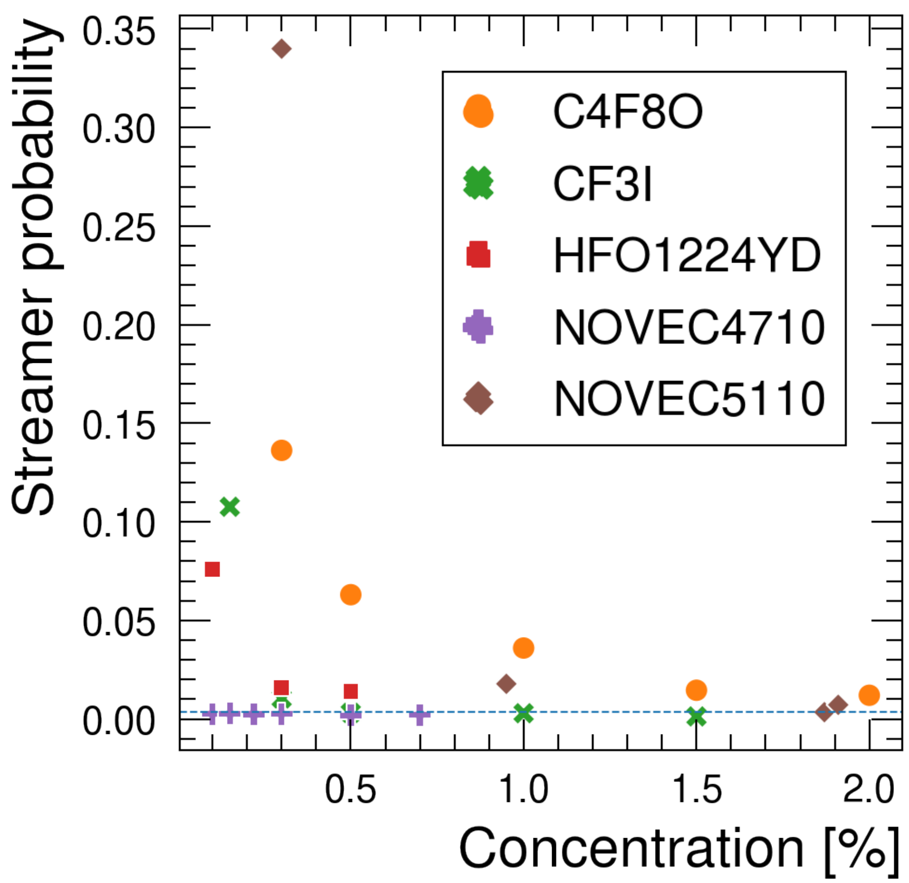
PRO
- Good vapour pressure
- Application in industry
- High dielectric strength

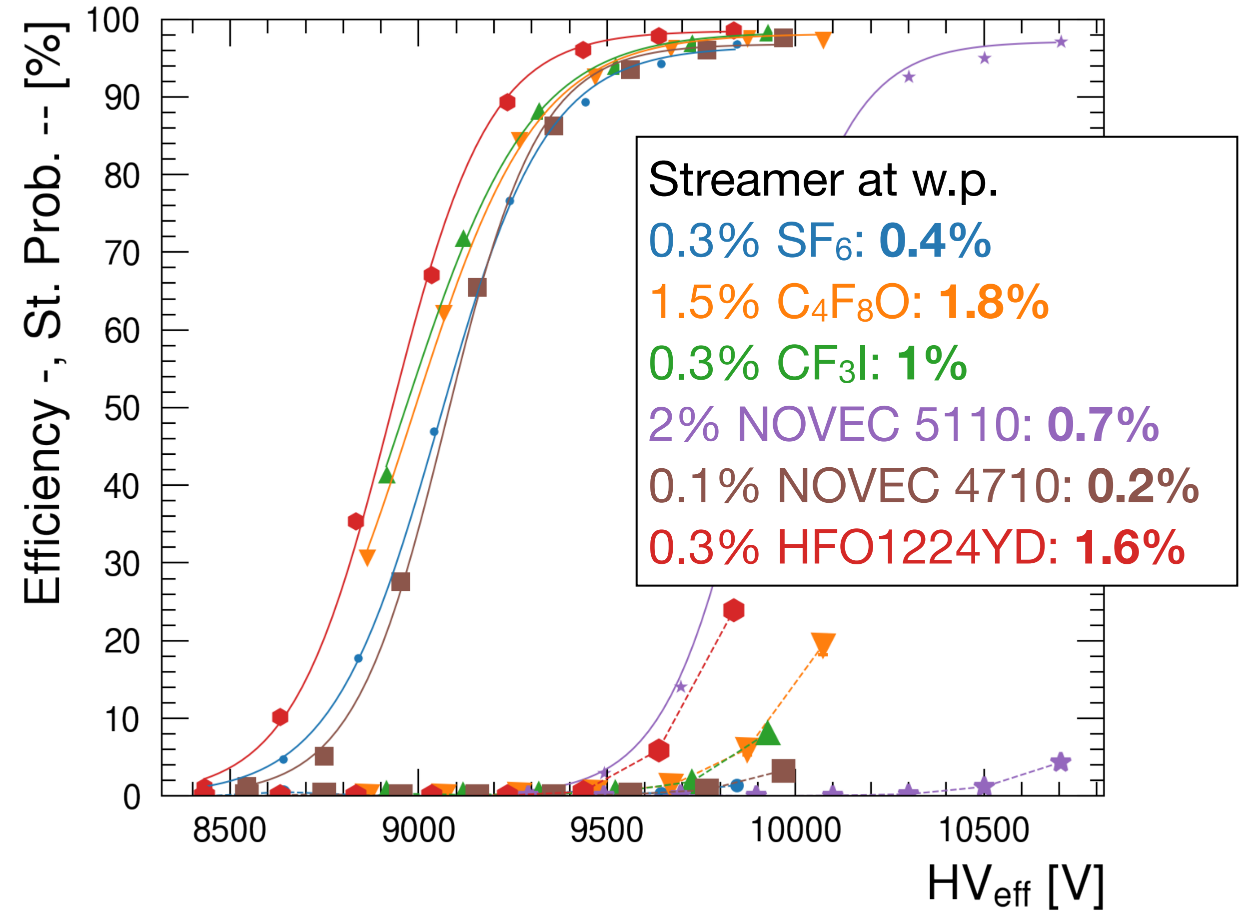
CONS
- GWP of 2200
- It may react with H_2O



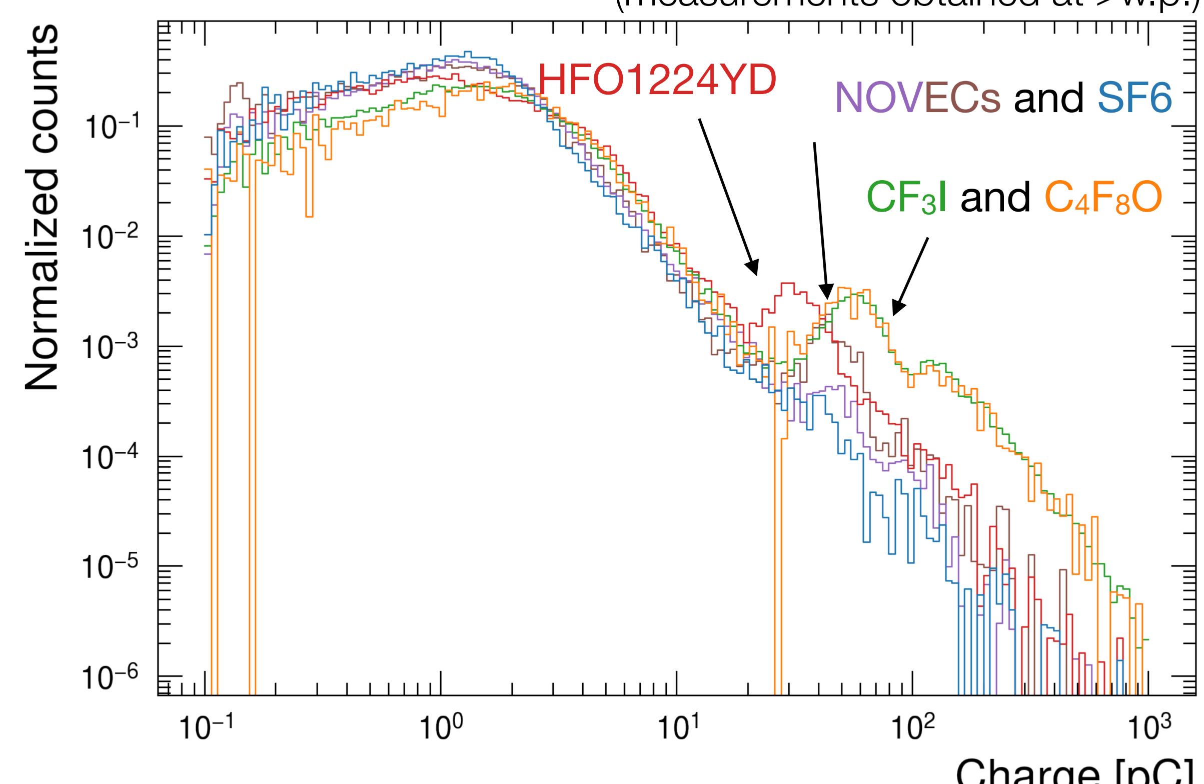
- Streamer probability always lower than std gas mixture
  - 0.1% of NOVEC 4710 already enough!
- Avalanche charge and cluster size lower than std gas mixture
- Higher working point for concentrations > 0.1%

Comparison of all tested gases





(measurements obtained at >w.p.)



- 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 performances....

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

↓

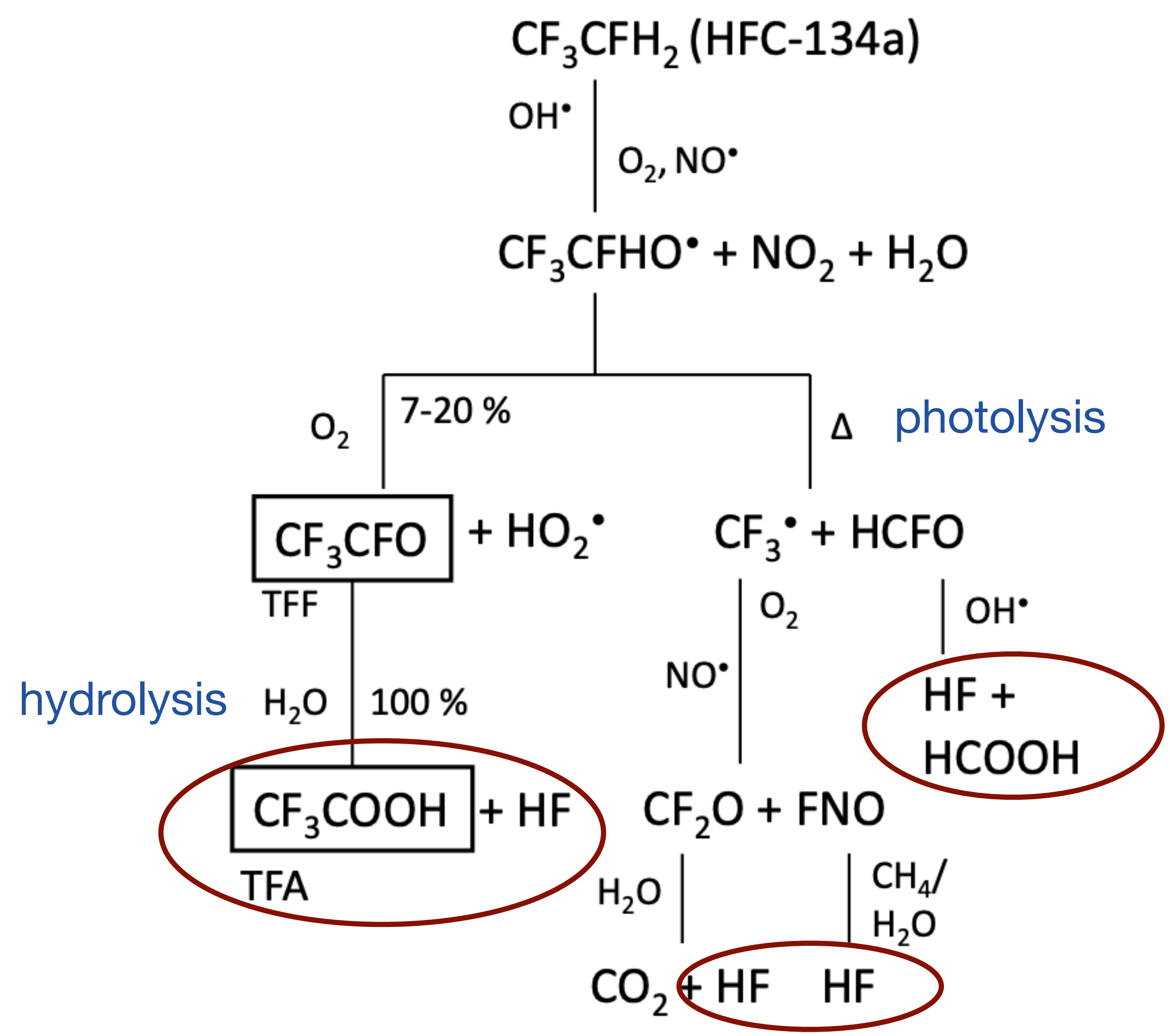
The lower are the GWP and the lifetime, the easier is the creation of sub-products

↓

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

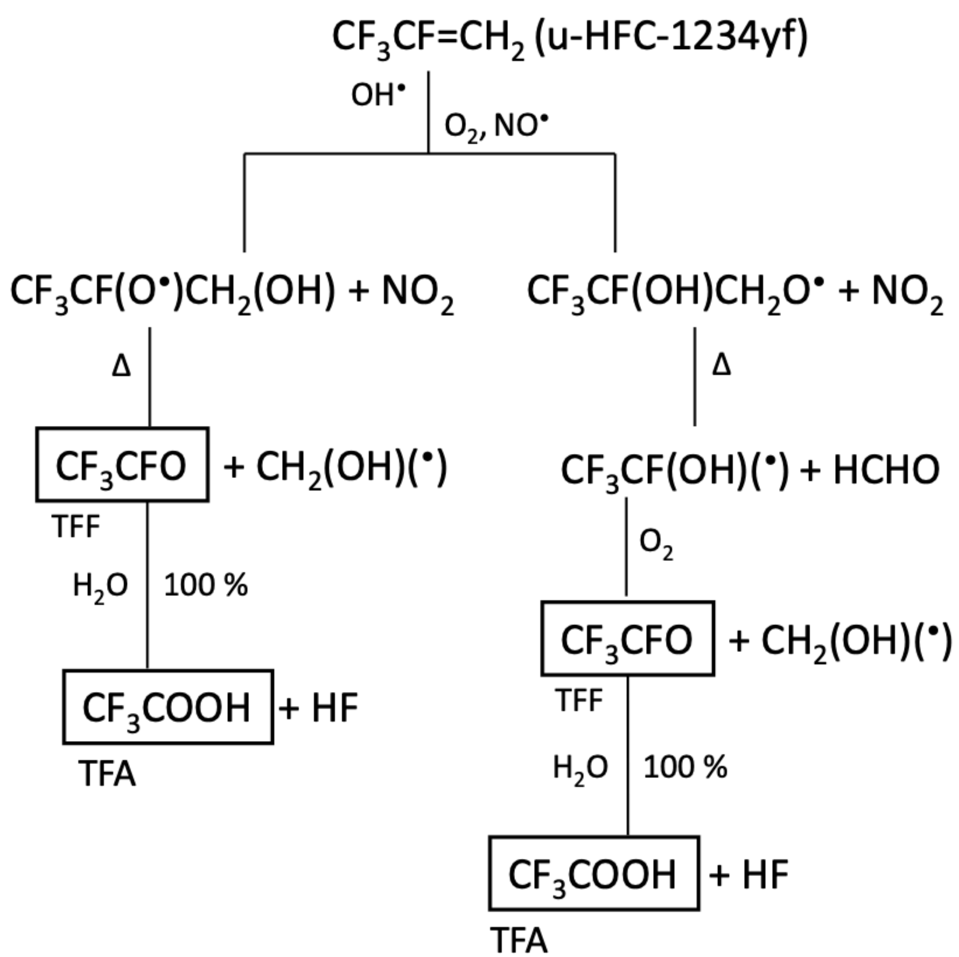
Three factors determine the atmospheric lifetime

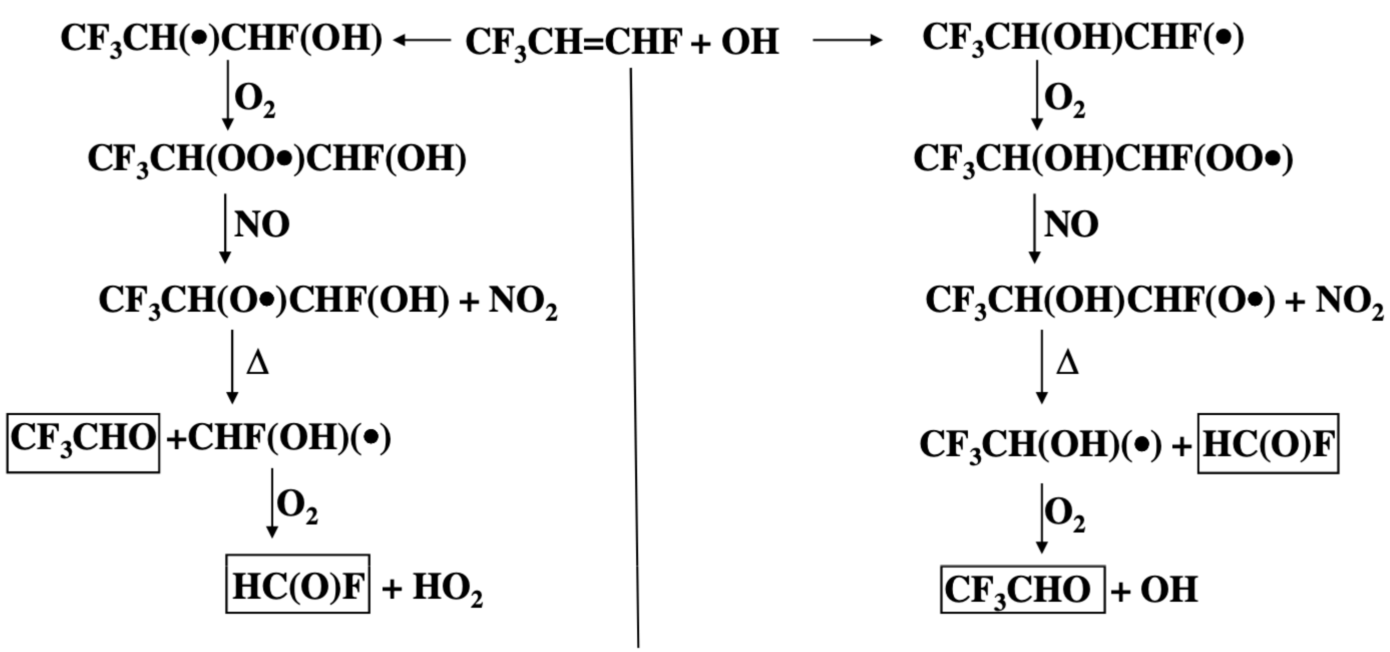
Rain out	→	Water solubility
Oxidation	→	Reactivity with OH
Photolysis	→	UV absorbance



HFO degradation

Atmospheric lifetime of HFO1234yf is 11 days
Atmospheric lifetime of HFO1234ze is 18 days ⟷ **Atmospheric lifetime of R134a is 500 years**





Hydrofluoric Acid (HF)

- It has already been measured that 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

NOVEC degradation

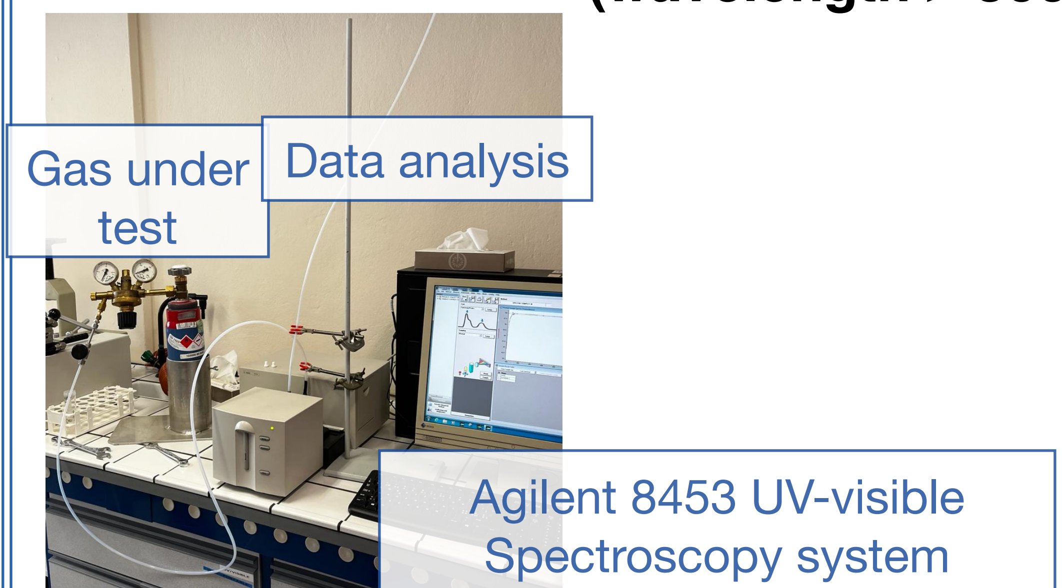
NOVEC 5110

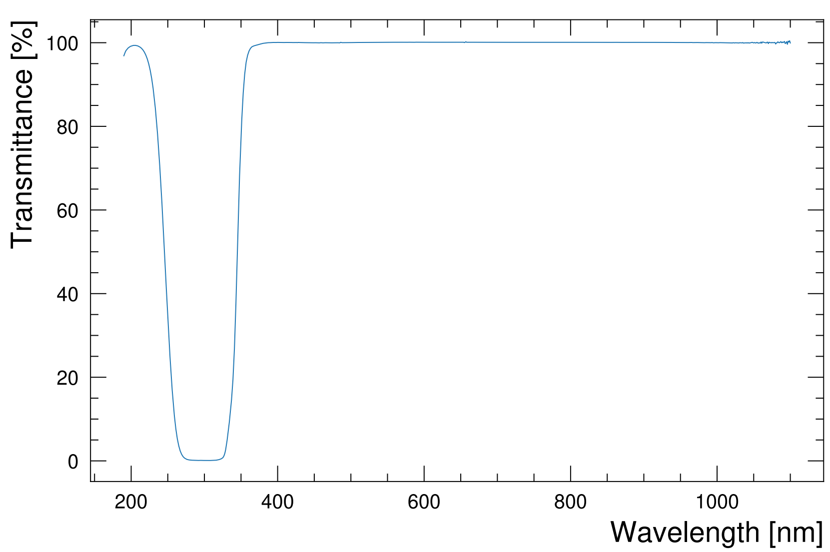
$(CF_3)_2CFC(=O)CF_3$

Rain out → water solubility (1ppmw)

Oxidation → unreactive with OH

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





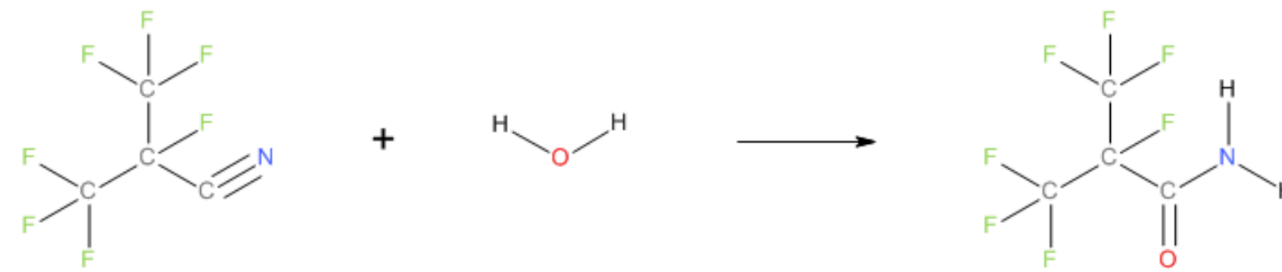
NOVEC 4710

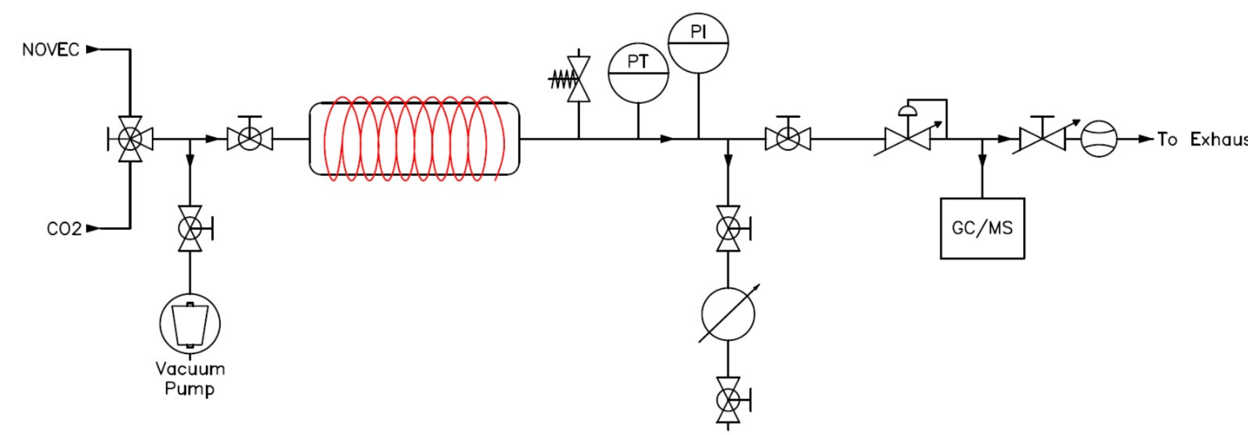
$(CF_3)_2CFC\equiv N$

Rain out → Water solubility (272 ppbw)

Oxidation → reactivity with OH radicals

Photolysis → transparent in near UV





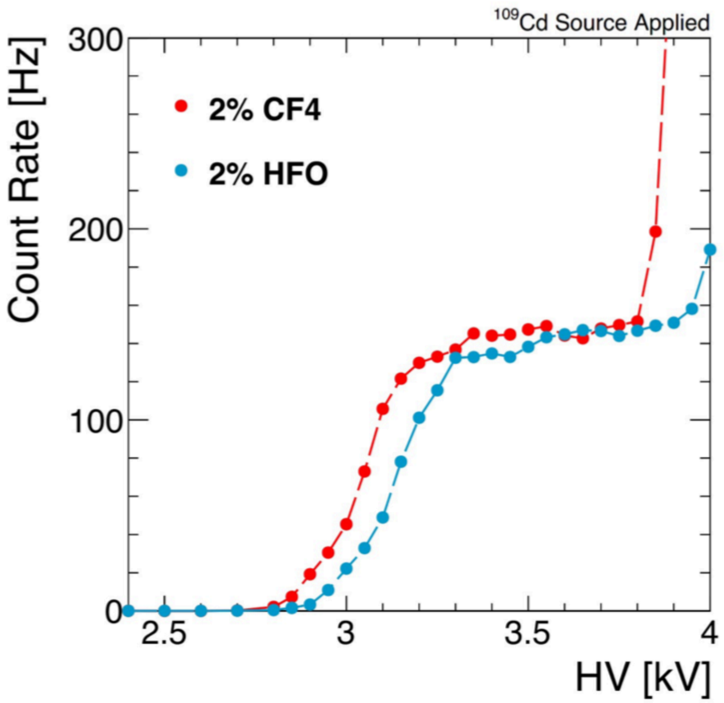
- Bakelite RPCs use 40% relative humidity
- Production of an amide from NOVEC 4710 + H_2O
  - Sub-products in the order of ppb
  - Solid at room T with a melting point of 49°C
  - The amide has appreciable vapour pressure at 60°C, it remains in gas phase at low concentrations
- Tests on-going in laboratory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

Possible CF_4 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

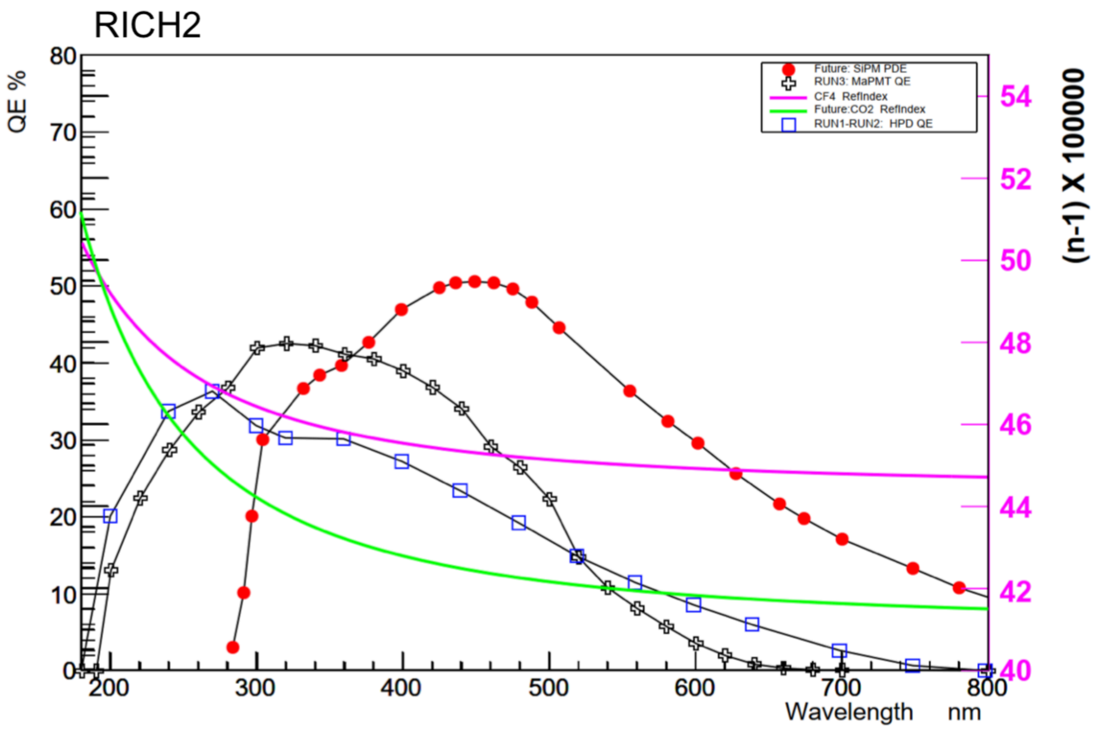
CMS CSC studies

- 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

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



Conclusions

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

Gas recirculation systems

- Gas recirculation systems are the best way to reduce GHG consumption
- All detector systems using GHGs should work under gas recirculation
- Also small laboratories could be equipped with gas recirculation units

Gas recuperation plants

- Used when not possible to recirculate 100% of the gas mixture
- Very complex and different technologies depending on the GHG to recuperate
- Suitable and affordable in medium-big experiments

Alternative gases

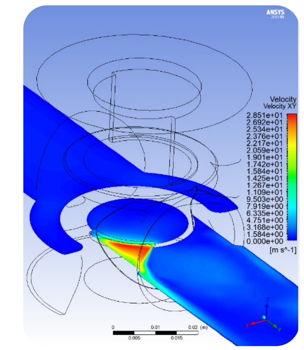
- A lot of work especially in RPC community to search for alternatives to $C_2H_2F_4$
- Not an easy task to find new eco-friendly gas mixtures for current LHC detectors
- Fundamental for future particle detectors
- Need to understand detector lifetime with new eco-friendly gases
- But often not “so friendly” as described…

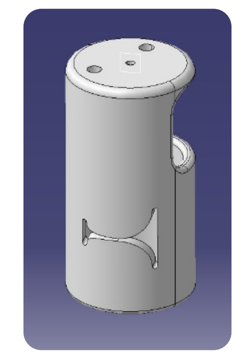
Back-up slides

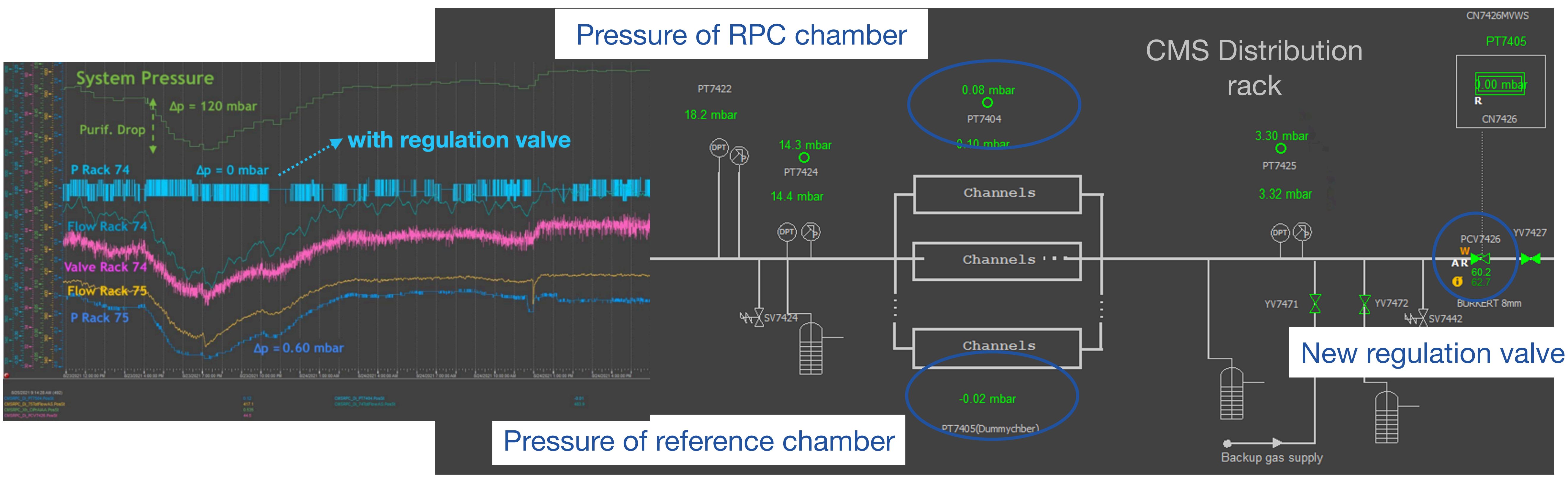
Minimization of flow/pressure fluctuations

Goal: to minimize any chamber pressure/flow fluctuations at the level of ~ 0.1 mbar

- New automated regulation valves on the return of each distribution rack to minimize any pressure changes
  - To decrease the risk of developing new leaks at the detector level
- 30 distribution racks for Barrel and Endcap divided into top and bottom
  - Different valve seats depending on pressure, flow, etc.
- Installation of reference volumes
  - To have a good reference for the regulation of the detectors pressure
- Addition of gas impedances
  - To smooth pressure and flow fluctuations at the output of distribution system, i.e. pressure and flow seen by the detectors





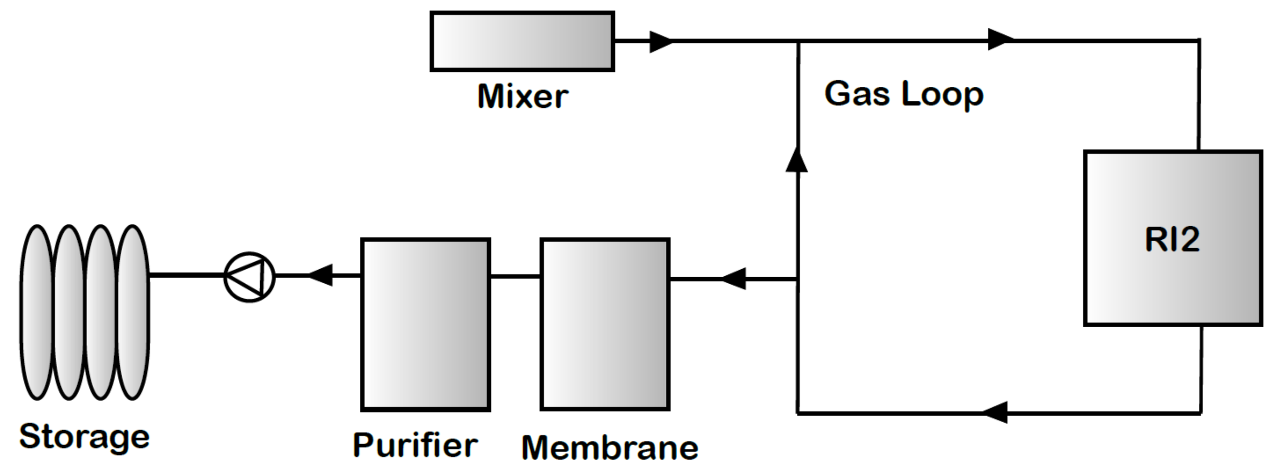


Gas recuperation: LHCb RICH2 CF_4

RICH2 Gas System

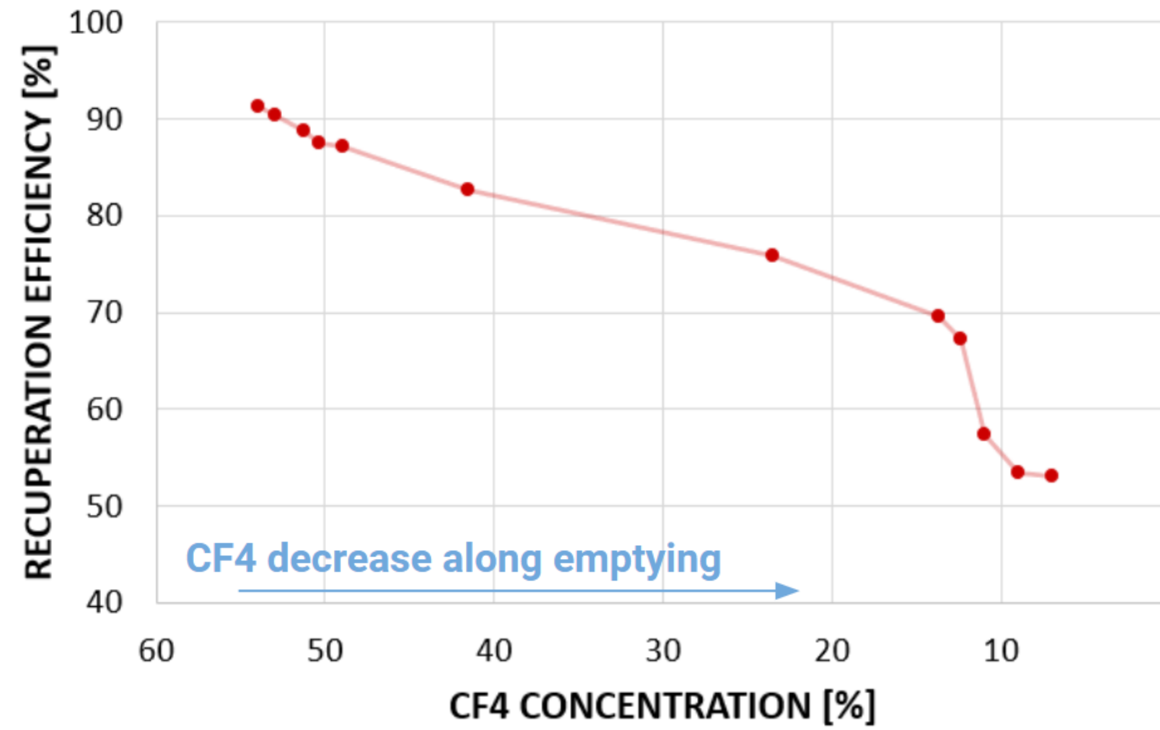
- Detector volume ~100 m^3
- Gas mixture: **92% CF_4**, 8% CO_2
- Gas recirculation: ~100%
  - Small quantity lost in leaks or for gas system operation

GHG reduction from Run1 to Run2 up to **60%**



RICH2 Recuperation System

- Two recuperation modes (warm separation)
  - During long shutdown: emptying detector
  - During Run: recuperation of small quantities otherwise lost in gas modules
- New system implemented in LS2
  - Upgrades on-going



Performance

- Recuperation efficiency ~60%
- About 30 m^3 of CF_4 recuperated in LS2
- CF_4 quality satisfactory
- CF_4 recuperated will be re-used for Run 3 operation

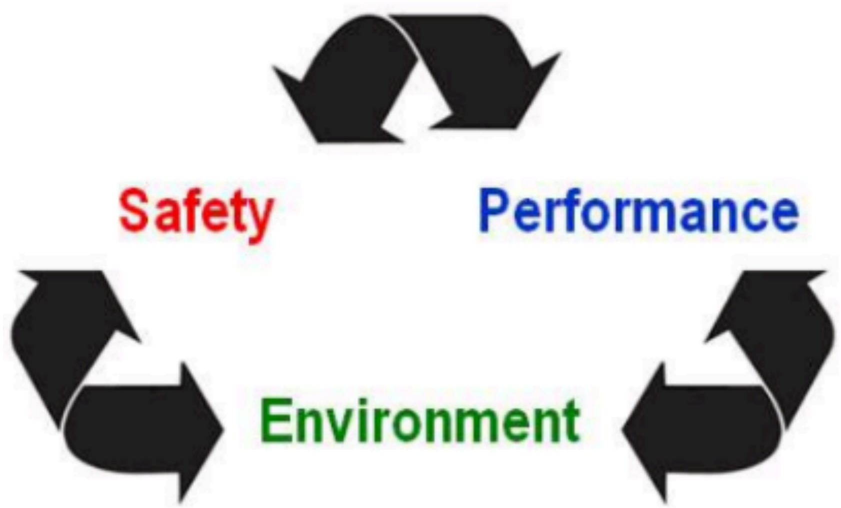
Why it is so difficult to find good GHG alternatives

When looking for alternatives eco-friendly gases, several factors have to be taken into account

Safety

Safety first for detector operations
- Gas mixture not flammable
- Gas components cannot have high toxicity levels

Tradeoff between flammability and GWP
- Replacing F with Cl or H: it shortens atmospheric lifetime BUT increase flammability limit
- Adding C=C bound: it increases reaction with O_2



Performance

GWP is related to IR absorption over time. Low GWP gases have short atmospheric lifetimes
- Water solubility —> rain out
- OH reactivity —> oxidation
- UV absorbance —> photolysis

RPC short and long term performance are affected
- Good quenching gases required
- Radiation-hard gas required
- Gases cannot heavily react with H_2O or UV radiation

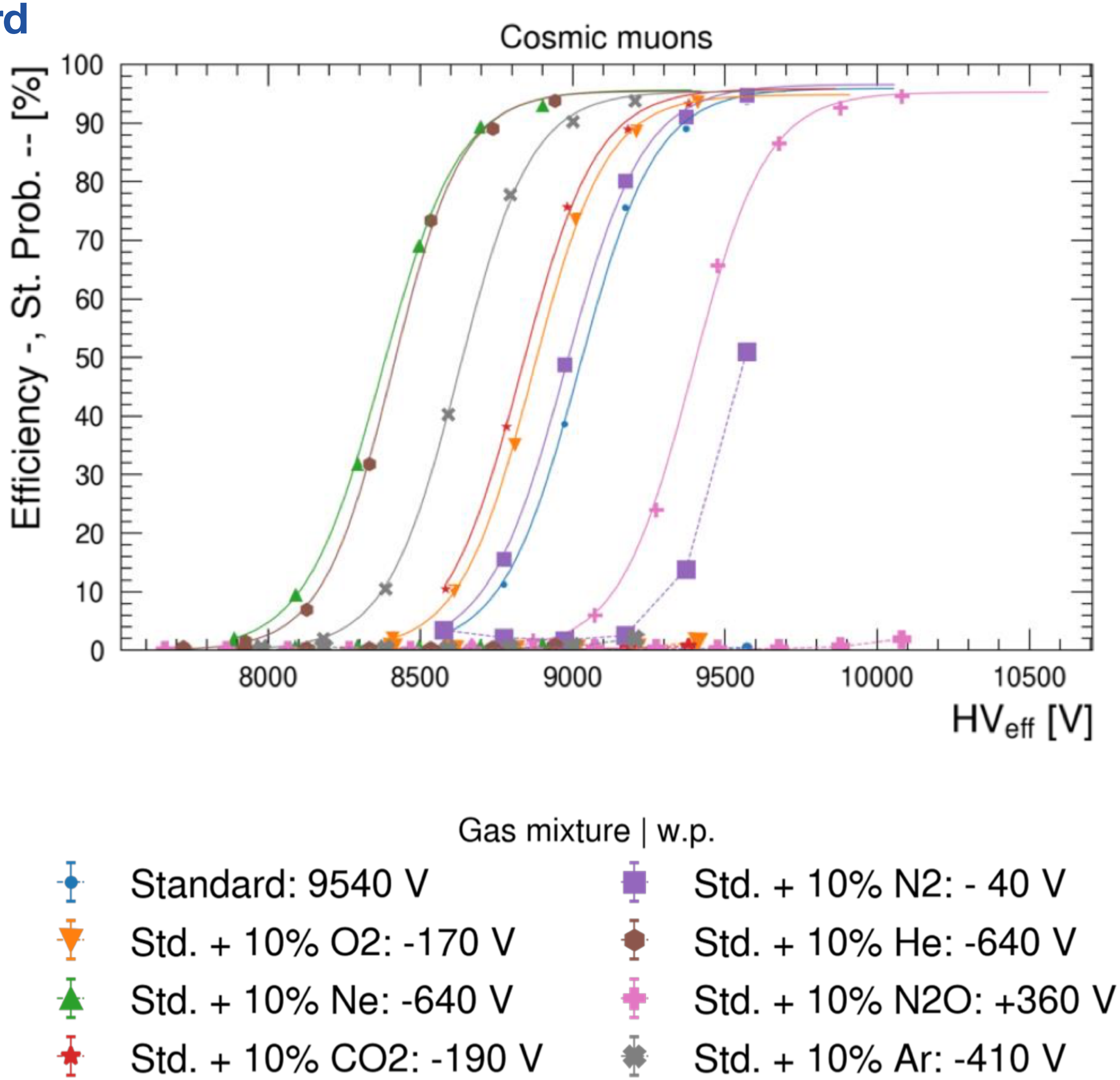
Environment

GWP represents the main environment concern

Alternatives gases to lower RPC w.p.

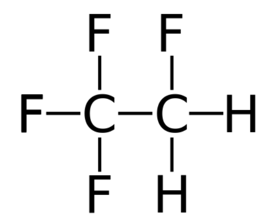
Reduction of R134a in the standard gas mixture by addition of a 4th, non-fluorinated gas

- O_2: good performance but highly reactive → lower **flammability limit**, higher currents due to oxidation reactions
- Ne: good performance but **no availability** on the market
- CO_2: good performance → selected as main candidate for GIF++ tests
- N_2: **high streamer** contamination at low concentrations
- He: good performance but problematic for PMTs in LHC caverns
- N_2O: discrete performance but **increased working point**of~300V
- Ar: slightly high streamer probability



What about other HFCs?

To investigate how RPC performance can vary by using gases containing different amounts of fluorine and carbons



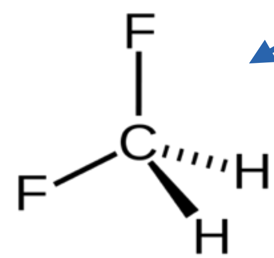
R134a

GWP 1430

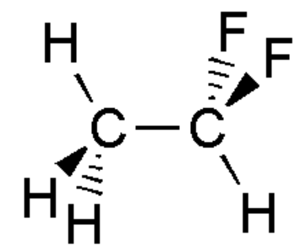
-1 C
-2 F

HFC-32 (flam)

GWP 675

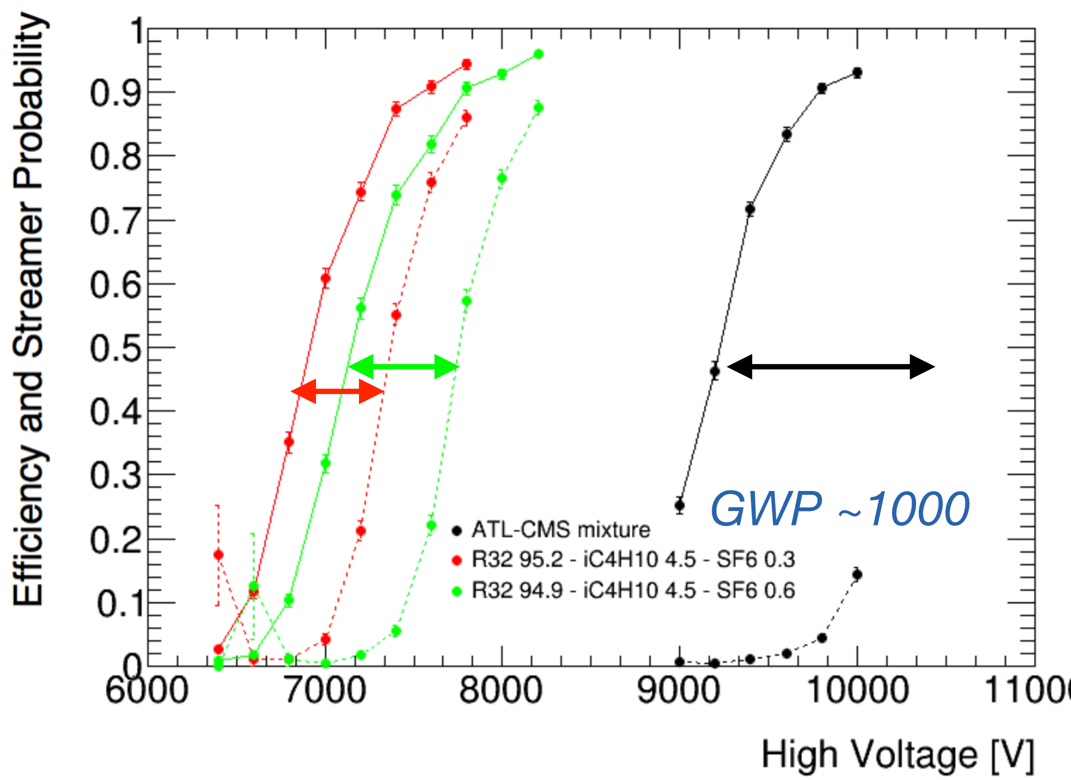


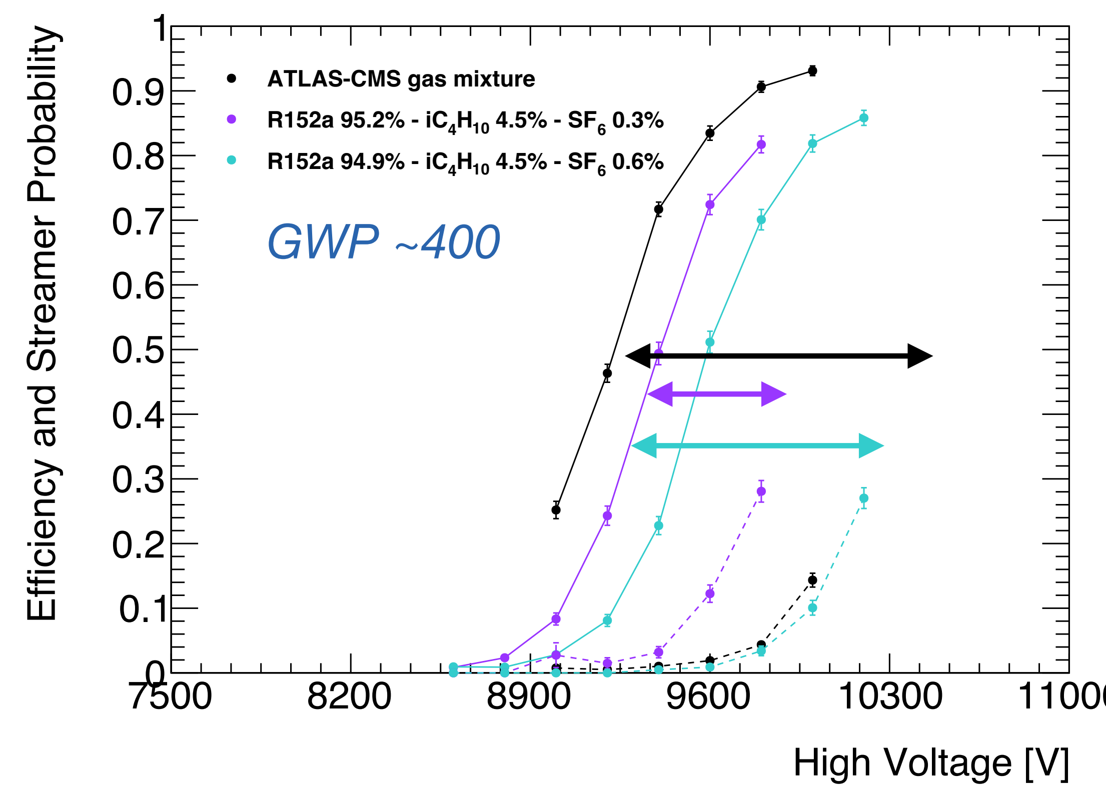
-2 F



HFC-152a (flam)

GWP 120

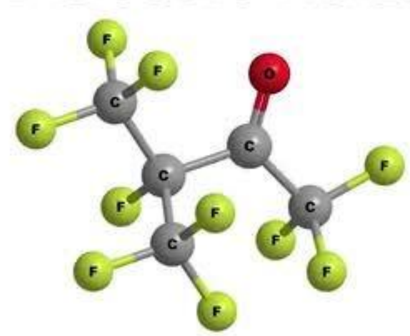




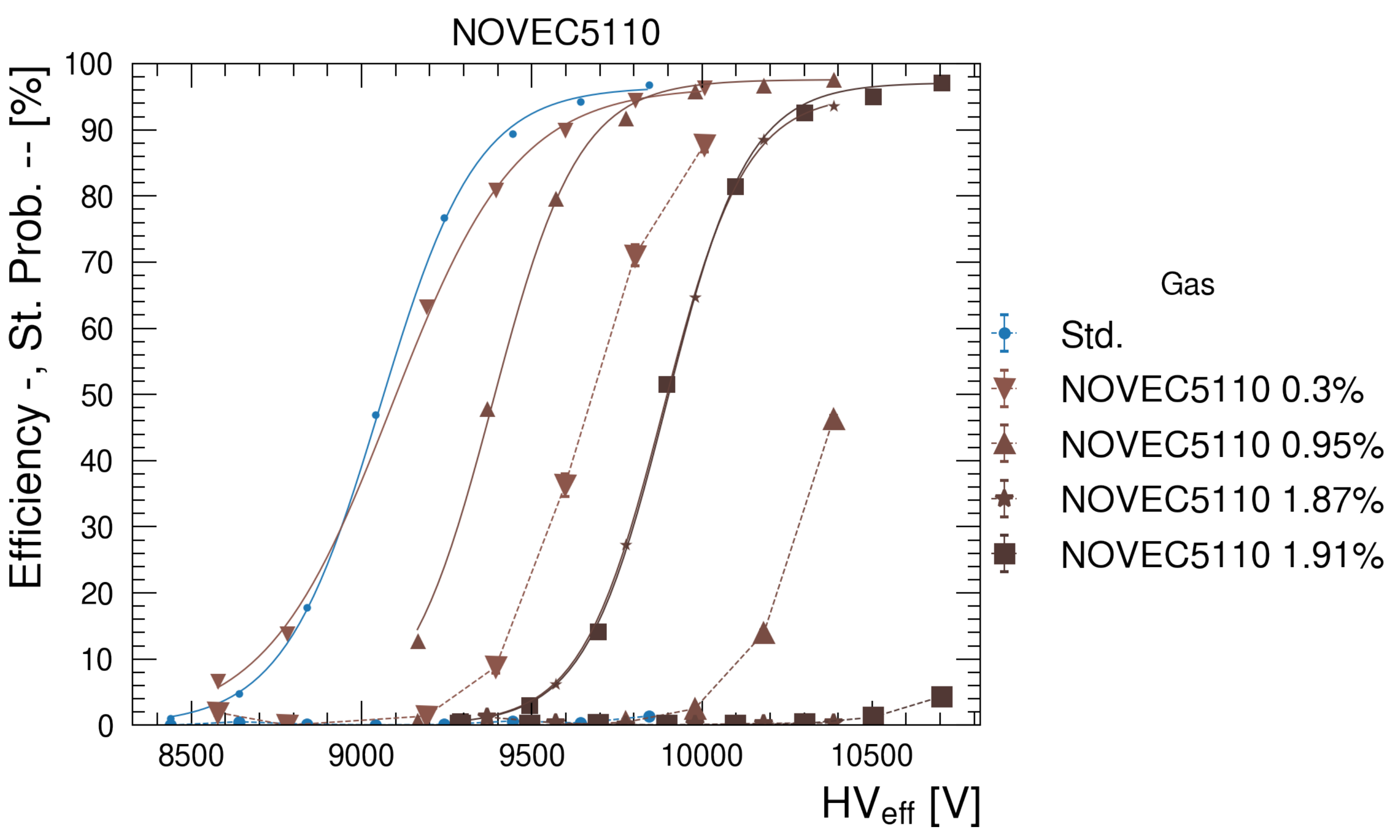
- 1 C less —> reduction of working point
- But very high streamer probability

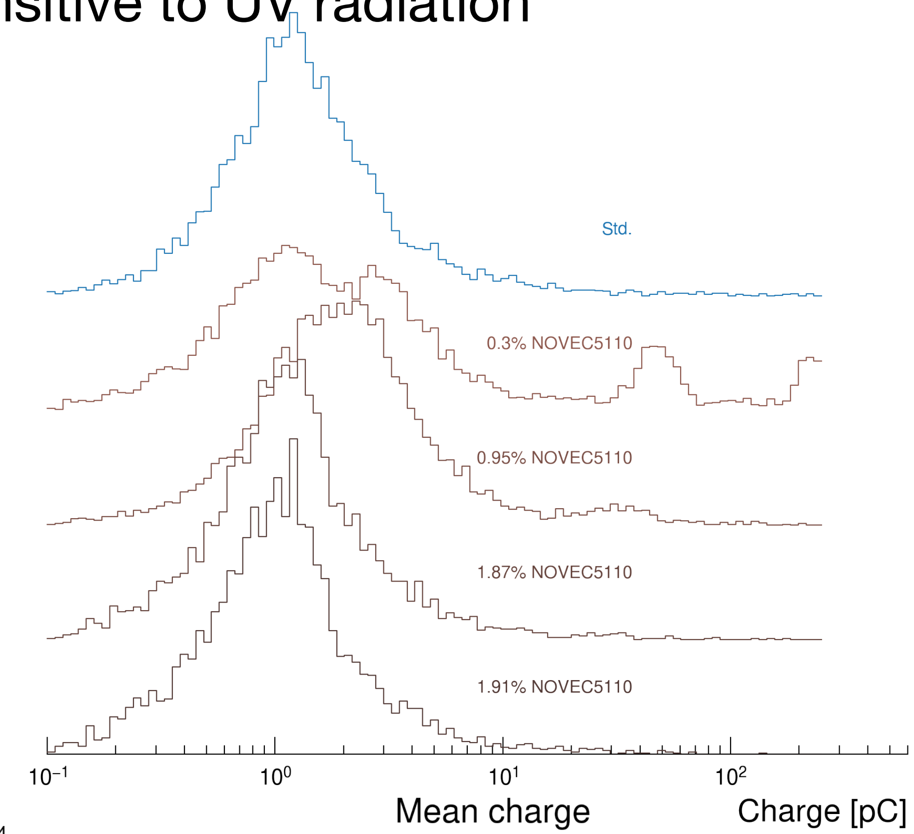
- 2 F less —> a bit higher streamer probability
- Chemical structure is equal (ethane)

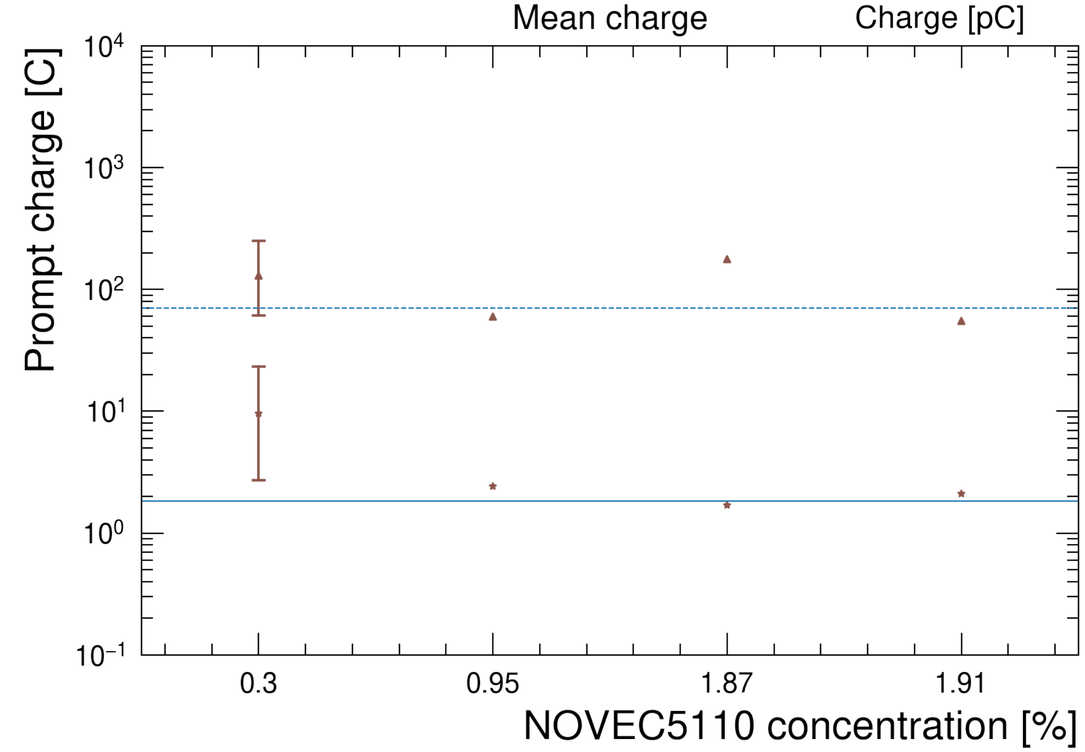
NOVEC 5110



- Very low GWP: <1
- Application in industry
- High dielectric strength
- High boiling point: 27 C
- Sensitive to UV radiation

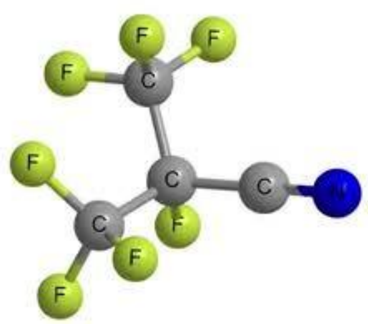






- High concentration (~2%) of NOVEC 5110 needed to obtain good streamer suppression
  - Suspect that NOVEC 5110 breaks inside the RPC
- Higher working point for concentrations > 0.3%
- Avalanche and streamer charge similar of std gas mixture from 0.9%
  - At 0.3% very large avalanche signals

NOVEC 4710

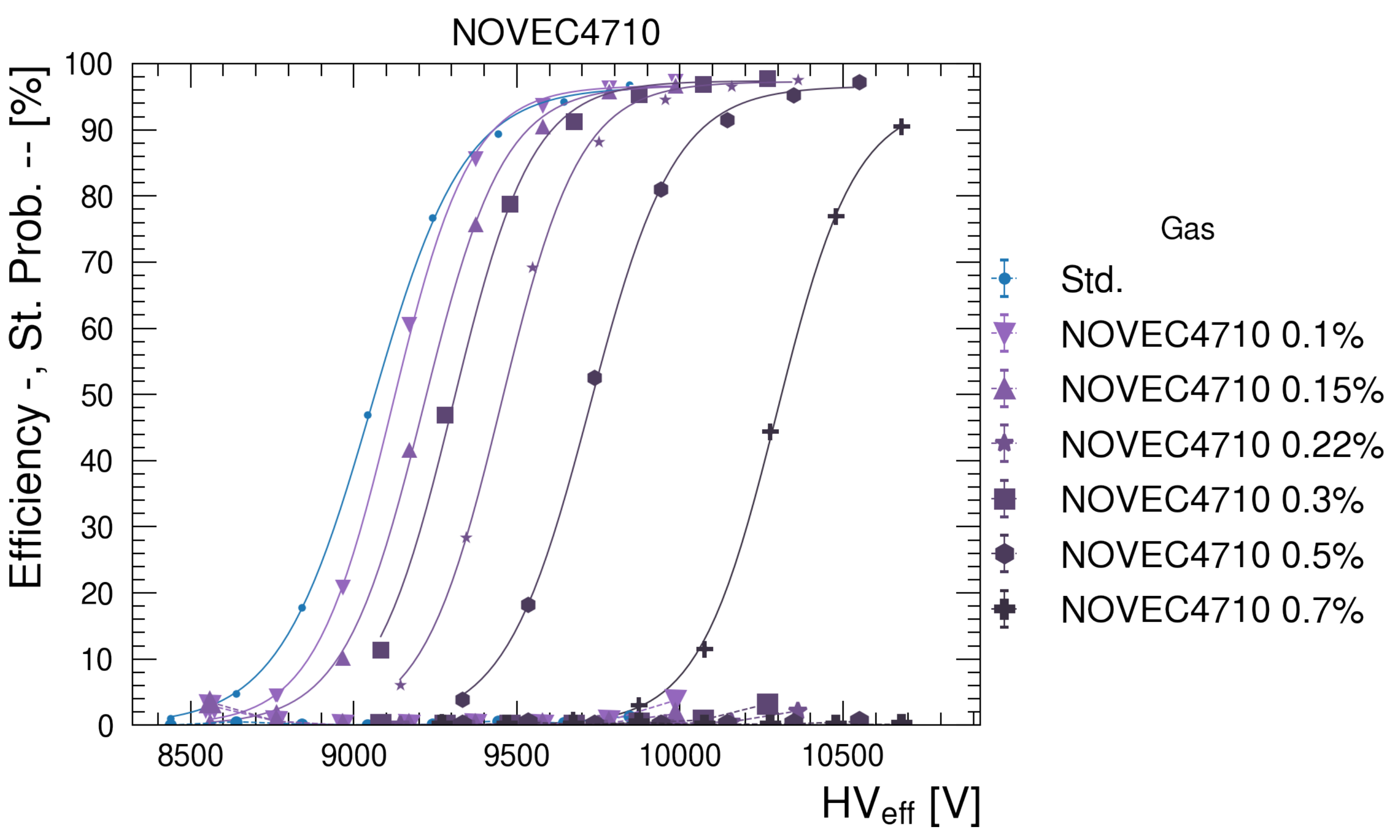


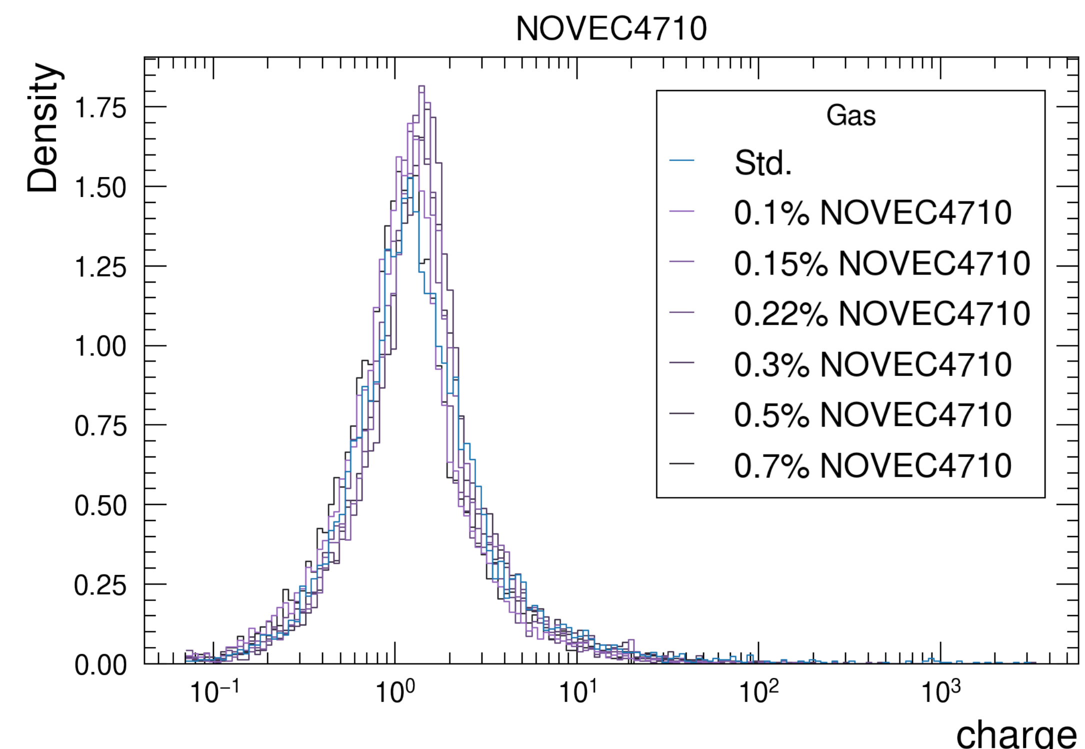
PRO

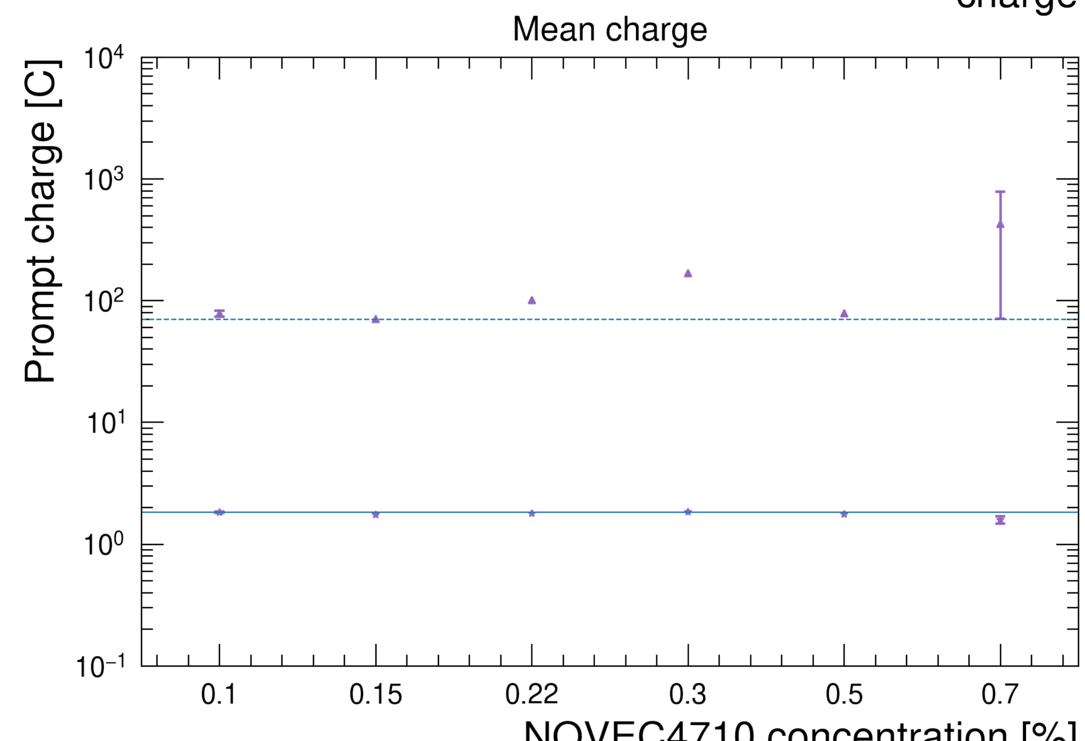
- Good vapour pressure
- Application in industry
- High dielectric strength

CONS

- GWP of 2200
- It may react with H_2O

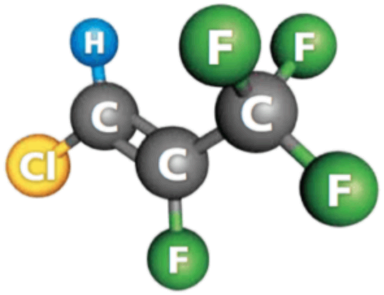






- Streamer probability always lower than std gas mixture
  - 0.1% of NOVEC 4710 already enough!
- Avalanche charge and cluster size lower than std gas mixture
- Higher working point for concentrations > 0.1%

HFO-1224yd

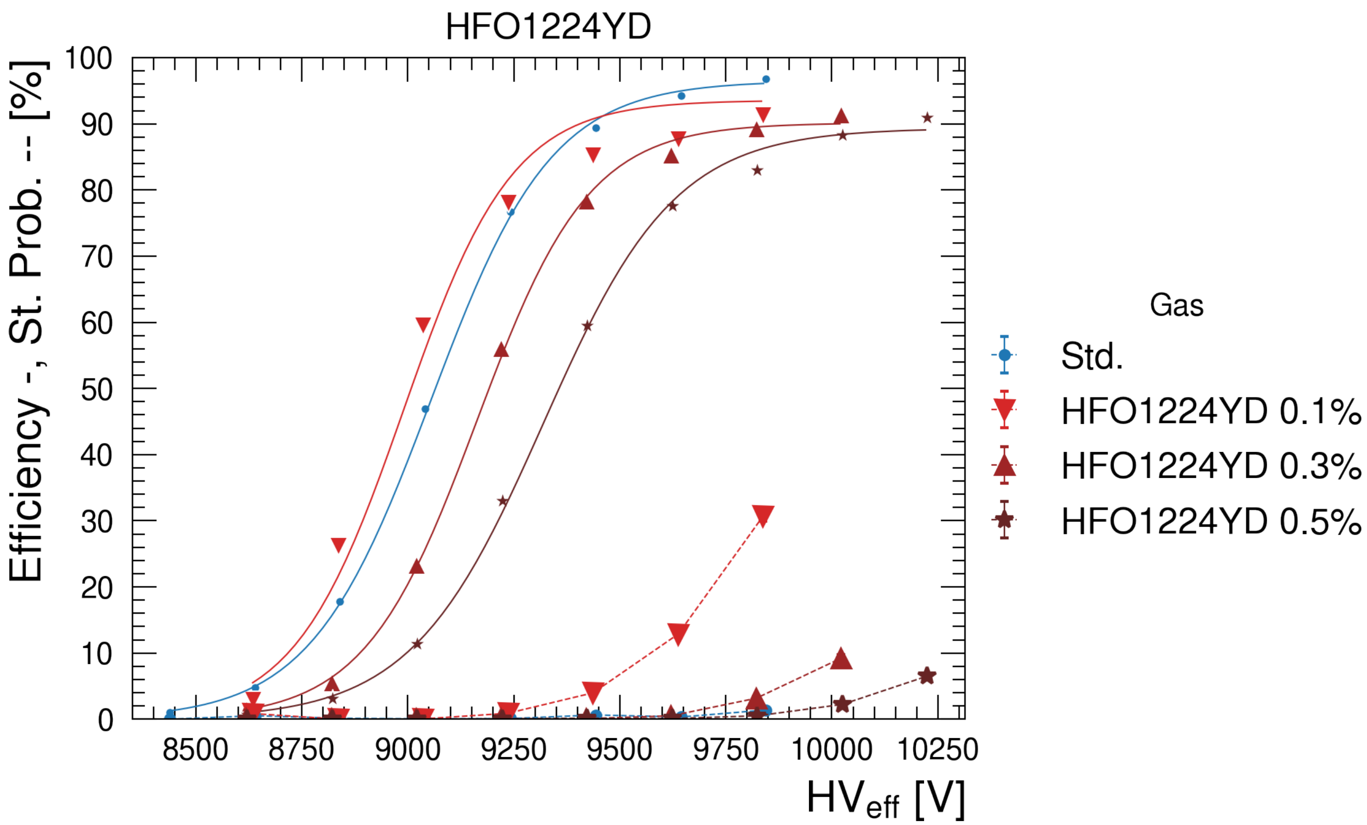


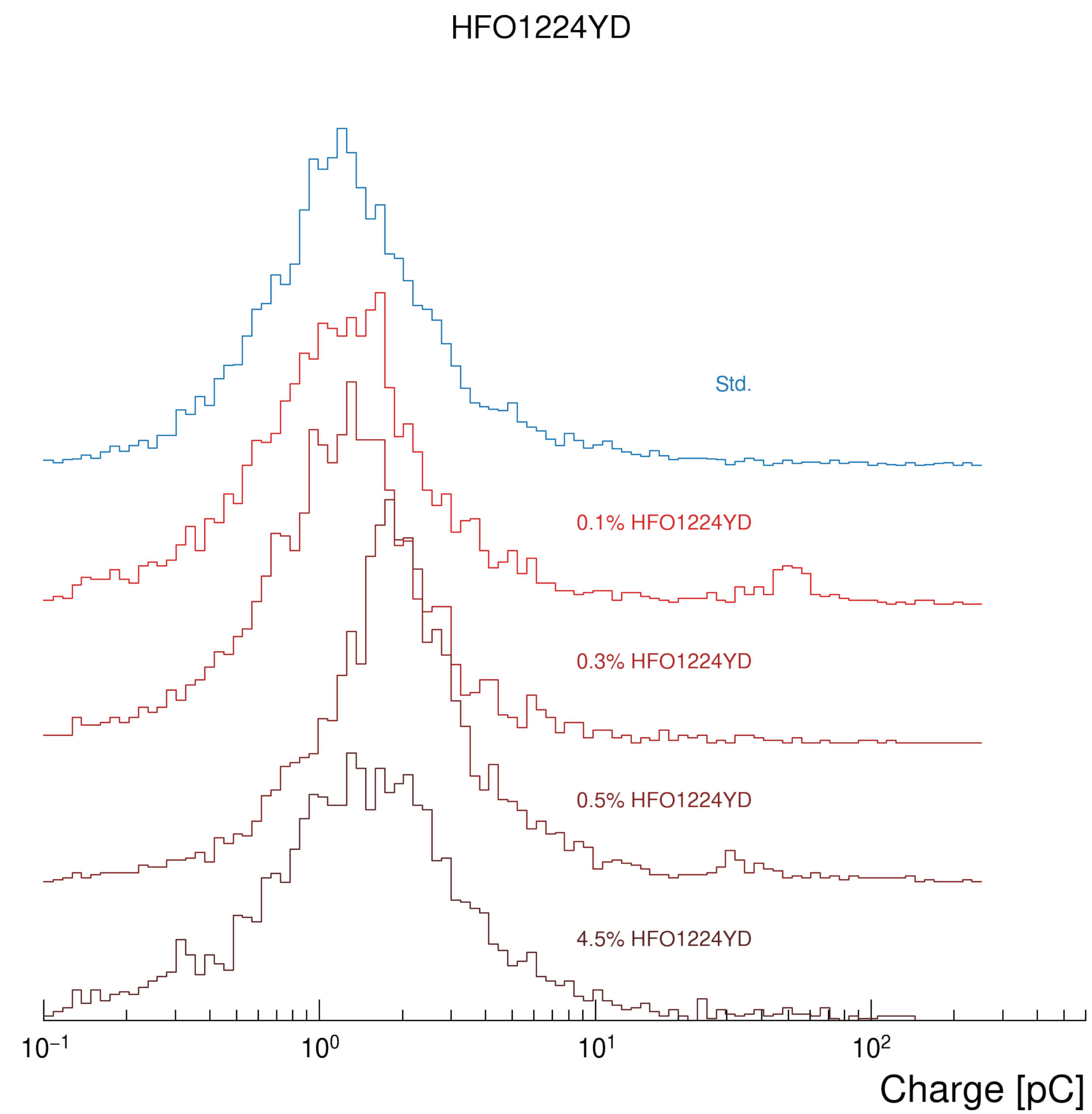
PRO

- Very low GWP: 1
- Application in industry

CONS

- Presence of Cl



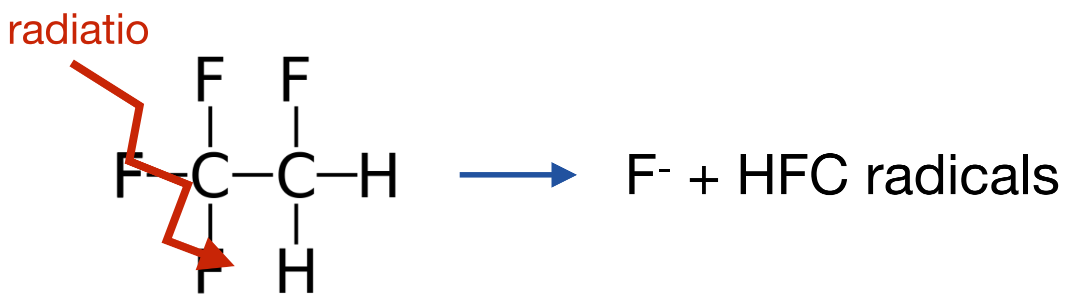


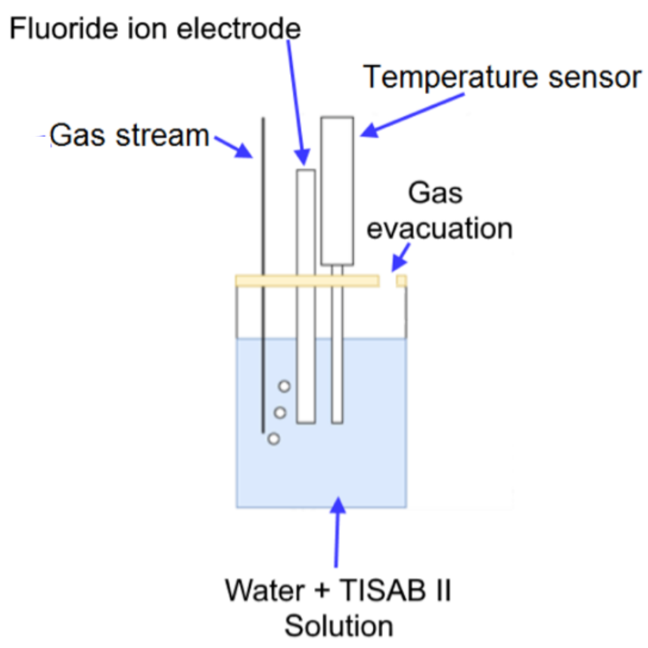
- Lower efficiency than std gas mixture
  - Under investigation
- Streamer probability acceptable from 0.5%
- Avalanche charge a bit higher than std gas mixture
- Higher working point for concentrations > 0.3%

How to measure F^- production in detectors

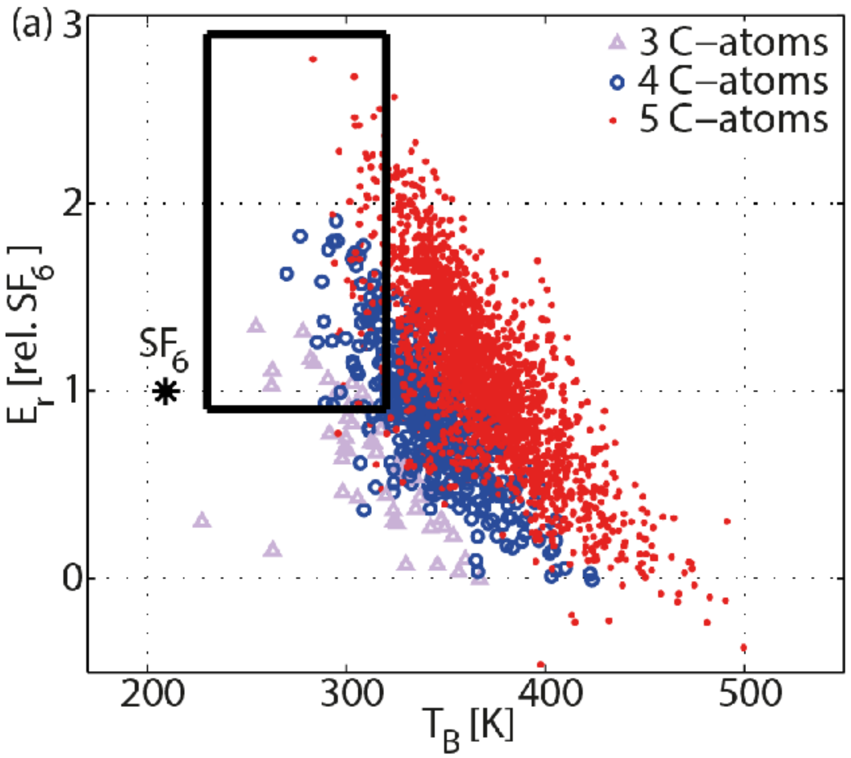
Ion Selective Electrode (ISE) station

- It measures fluoride ions in aqueous solutions
  - When the F^- sensing element is in contact with a solution containing fluoride ions, an electrode potential develops
  - The potential depends on the level of free fluorine ions in solution (Nernst equation)
- Gas mixture is bubbled in water+TISAB II solution
  - Bubbling efficiency in trapping the HF





Alternatives to SF_6: search in HV industry



	Dielectric Strength	GWP	Lifetime (year)	T_b (◦C)
SF_6	1	23900	3200	-63.8
N_2	0.36	0	-	-198
CO_2	0.3	1	300-1000	-78
CF_4	0.4	6300	50000	-128
CF_3I	1.2	0.4	6 days	-21.8
C_4F_8O	1.2	8000	>3000	-
C_4F_7N (Novec 4710)	2	1490	30	-4.7
$C_5F_{10}O$ (Novec 5110)	1.5 - 2	1	15 days	27
C_3F_4HCl (HFO1224yd)	-	0.88	20 days	15

group	$<E_r>$ [rel. SF_6]	$<T_B>$ [K]	$<z>$	n
C_3-Ketones	0.39	319	2.00	17
C_3-Aldehydes	0.56	320	1.89	18
C_3-Acyl Fluorides	0.98	293	3.15	13
C_4-Ketones	0.69	352	2.58	138
C_4-Aldehydes	0.77	345	2.39	117
C_4-Acyl Fluorides	1.14	326	3.36	110
C_5-Ketones	0.94	375	3.30	923
C_5-Aldehydes	1.00	370	2.91	685
C_5-Acyl Fluorides	1.35	356	3.85	590
SF_6	1	209 [18]	6	1

Nr	SMILES	E_r	T_B	T_B^L
	C_3–compounds			
(1)	FC(=O)C(C(F)(F)F)(F)F	1.34	255	280
(2)	O=C(C(F)(F)F)C(F)(F)F	1.03	262	280
(3)	FC(C(C(=O)F)(F)F)F	1.11	263	288
(4)	FC(=O)CC(F)(F)F	1.31	278	302
	C_4–compounds			
(5)	FC(=O)C(C(C(F)(F)F)F)(F)F	1.63	270	317
(6)	FC(C(C(F)(F)F)(C(=O)F)F)F	1.82	277	
(7)	FCC(C(F)(F)F)(C(=O)F)F	1.91	295	
	C_5–compounds			
(8)	FC(=O)C(C(F)(F)F)(C(F)(F)F)C(F)(F)F	2.77	283	303
(9)	O=C(C(C(F)(F)F)(C(F)(F)F)F)C(F)(F)F	1.93	293	310
(10)	FC(C(C(C(F)(F)F)(F)F)(C(=O)F)F)F	2.28	296	
(11)	O=C(C(C(C(F)(F)F)(F)F)(F)F)C(F)(F)F	2.01	302	322
(12)	FC(=O)C(C(C(F)(F)F)C(F)(F)F)(F)F	2.67	304	

M. Rabie, C. Franck, predicting the electric strenght of proposed sf6 replacement gases by means of density functional theory

XXX