Performance studies of HPL RPC detectors operated with alternatives to R-134a and SF6

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15/09/2026

CERN | EP-DT Detector Technologies



Outline

- RPCs at the LHC
- Alternatives to SF_6
- Reducing or replacing R-134a
- Conclusions

Gas use and emissions from LHC RPCs

LHC RPC mixtures contain 65–95% R-134a

R-134a use during LHC runs

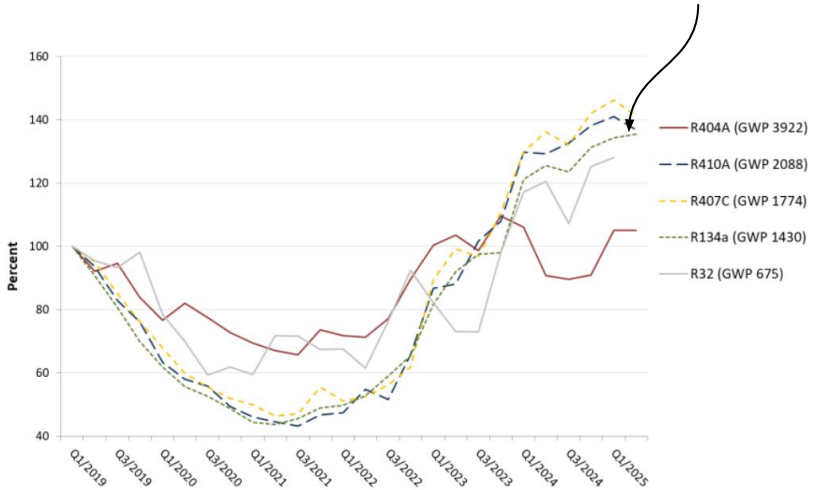
Run 2 emissions: approximately 100,000 t CO_2e/year

Detector leaks motivate leak-repair campaigns

Economic motivation

R-134a price ≈ 8× its 2015 level

R-134a price trend 2019–2025

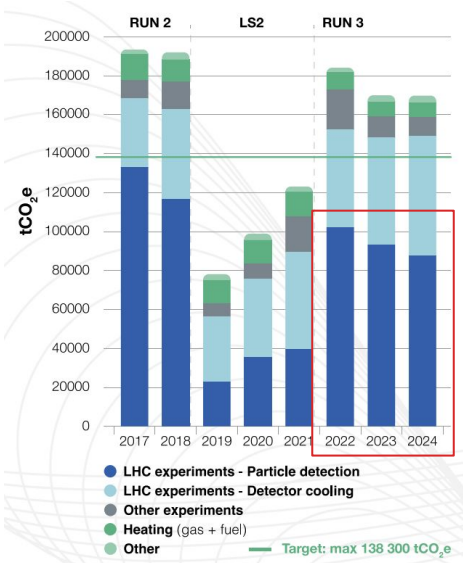


Run 3 measures

ATLAS: operation with 30% CO_2

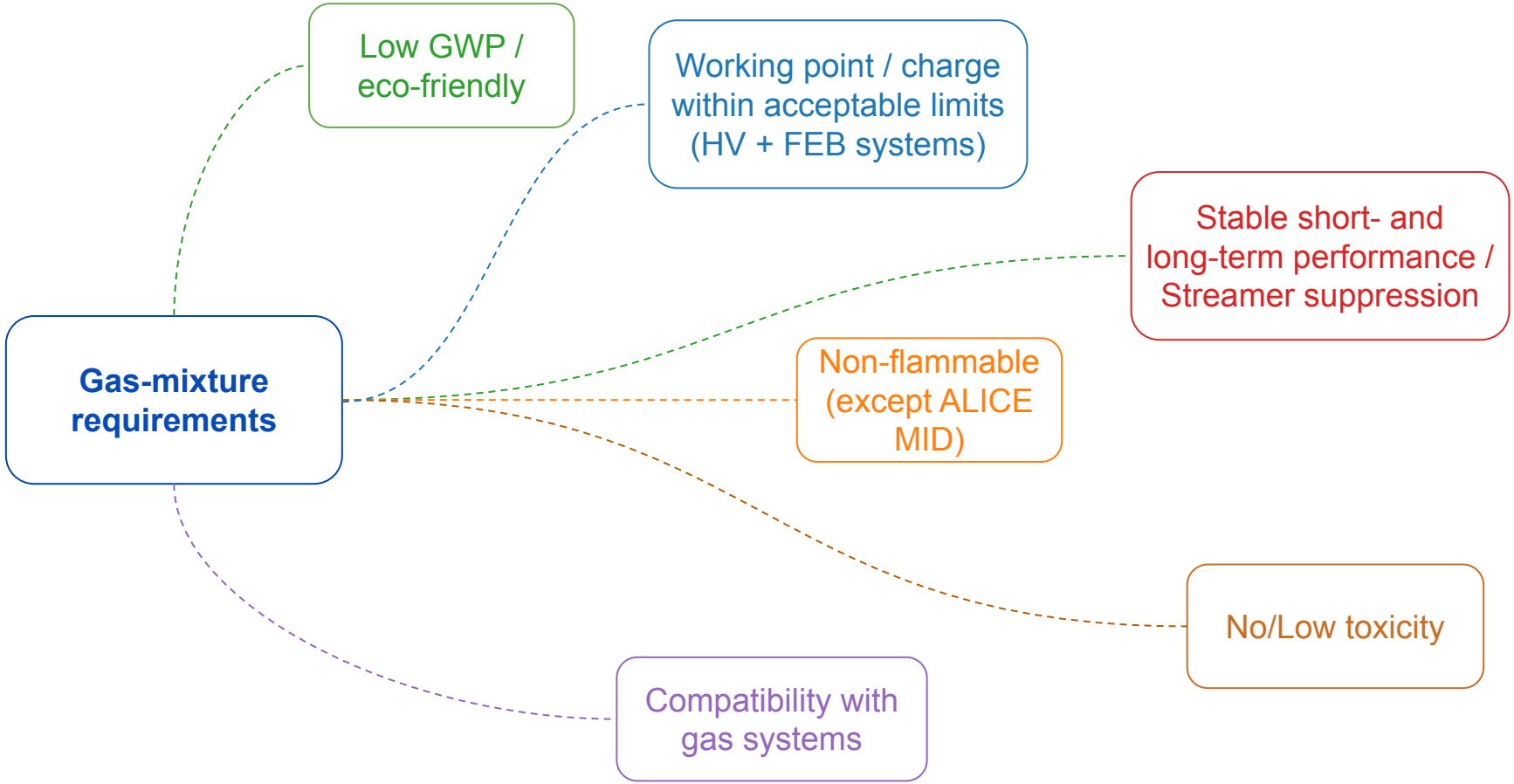
CMS: recovery of most R-134a

Consumption is below Run 2 levels, but overall emissions remain above target

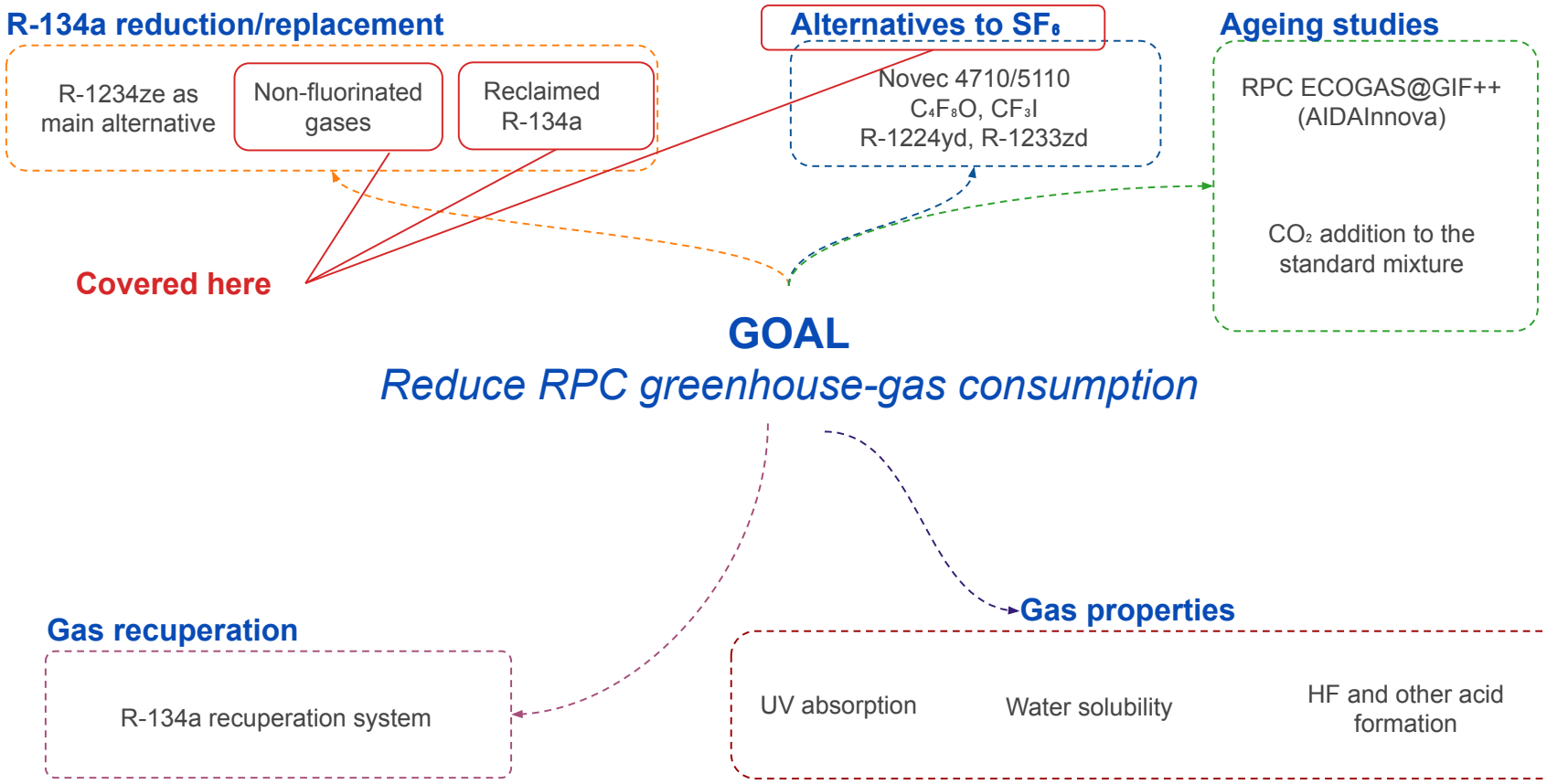


Source: CERN Environment Report 2025

Gas-mixture requirements for LHC RPCs



Scope of alternative-gas studies

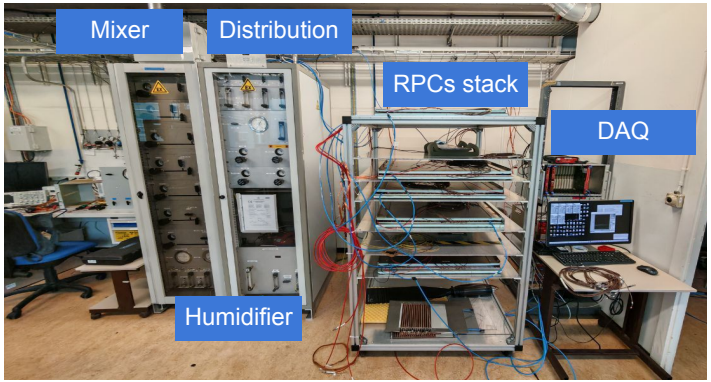


Setup

Experimental setup

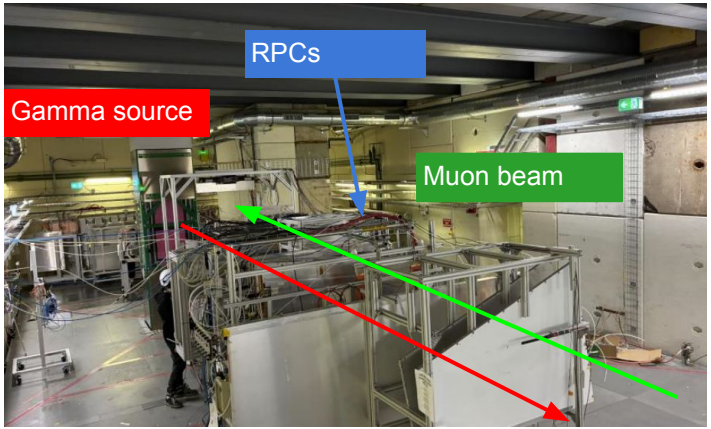
Laboratory setup

- Single-gap HPL RPCs: 2 mm electrodes, 2 mm gas gap, 80 × 100 cm²
- Candidate screening and mixture optimisation
- Up to six components, 0.01% mixing precision
- Low-rate cosmic-muon measurements
- Waveforms: efficiency, streamer probability, cluster size, timing and prompt charge



GIF++ setup

- Muon beam and ^{137}Cs gamma source
- Mixture validation at different background rates using absorption filters
- Long-term current stability
- Additional cosmic-muon measurements



Data acquisition and analysis

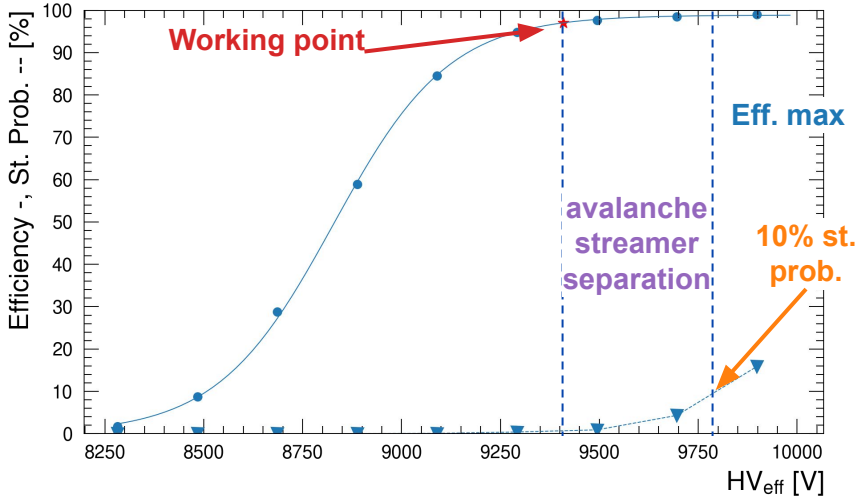
Data acquisition

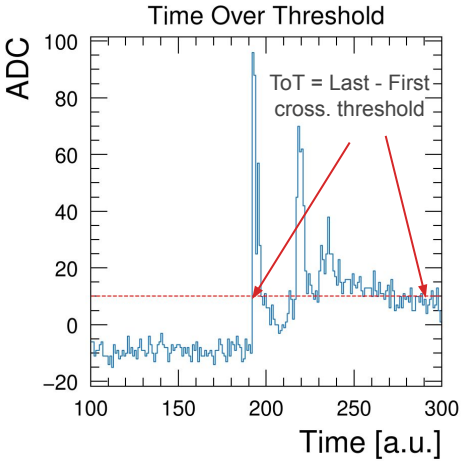
Digitised waveforms for efficiency, charge, pulse shape and timing

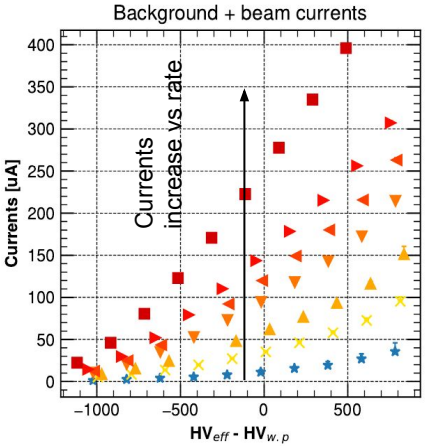
HV scans: approximately 10^4 triggers per point

Data analysis

- Sigmoid fit to the MIP efficiency
- Working point (WP): HV at 95% of maximum efficiency + 150 V
- Streamer threshold: 16 pC, approximately 10^8 electrons
- Test each mixture at different gamma-background rates
- Compare performance at the WP for each rate







Alternatives to SF_6

Screening SF_6 alternatives

Laboratory screening

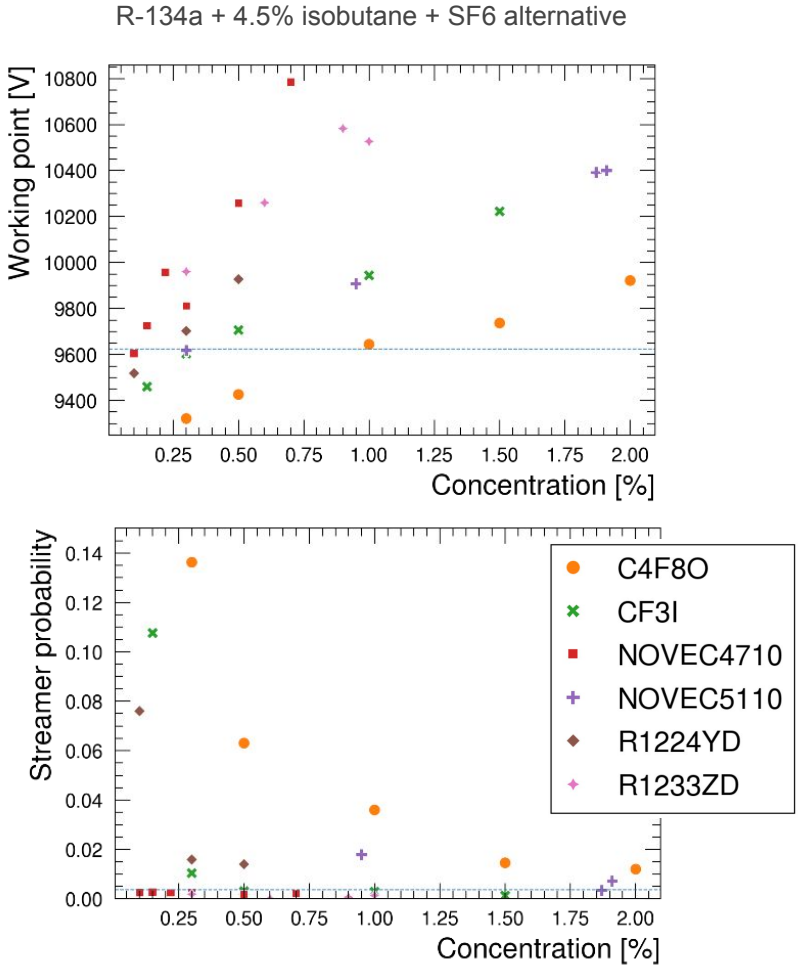
C_4F_8O and Novec 5110: performance limitations

CF_3I: good performance, but toxicity concerns

Novec 4710: good performance, but water-compatibility concerns and GWP ≈ 2400

Candidates for further study

R-1224yd and R-1233zd: chlorinated fluoroolefins selected for detector-performance and gas-compatibility tests

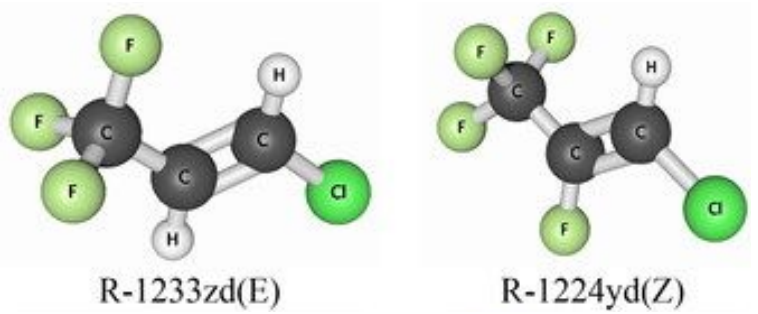


Gianluca Rigoletti

SF_6 alternatives: R-1224yd and R-1233zd

Shared properties

- Chlorinated fluoroolefins (HCFOs), low GWP
- **Boiling** points near **room temperature**
- Similar C=C structures, differing by H/F substitution



Decomposition products

R-1224yd: **TFA** and **HF** pathways

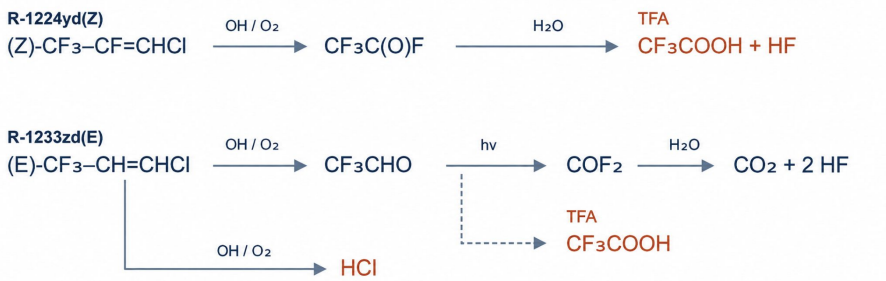
R-1233zd: **HF** and **HCl** pathways

These lists are not exclusive: R-1233zd can also form TFA

*Studying the **production of breakdown products** in RPCs is fundamental to understand long-term effects on detectors*

T.J. Wallington et al.
doi:10.1016/j.chemosphere.2014.06.092

Simplified atmospheric pathways



SF_6 alternatives in std. gas mixture

Avalanche–streamer separation

At 0.3% **R-1224yd** or **R-1233zd**: approximately 375 V

At 0.9% R-1233zd: 450 V, compared with 590 V for the standard mixture

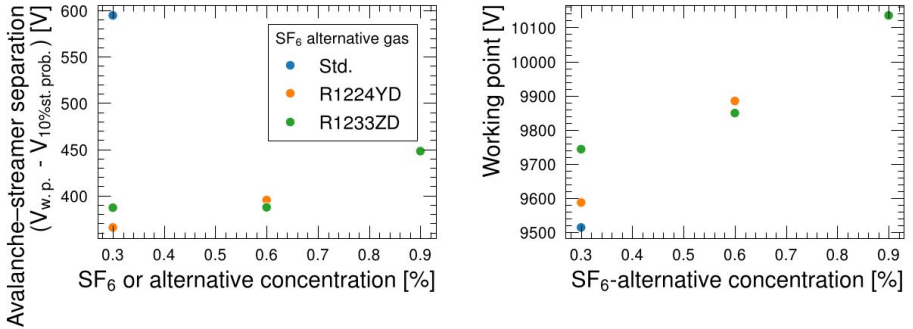
Working point

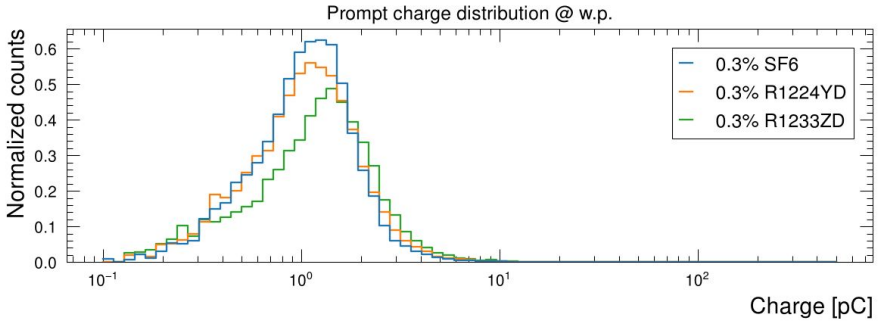
At 0.3%, R-1224yd is close to SF_6; **R-1233zd** requires a **higher voltage**

Increasing R-1233zd from 0.3% → 0.9% raises the WP by almost 500 V

The two alternatives give **comparable performance** results in terms of charge content/streamer suppression

Muon beam performance





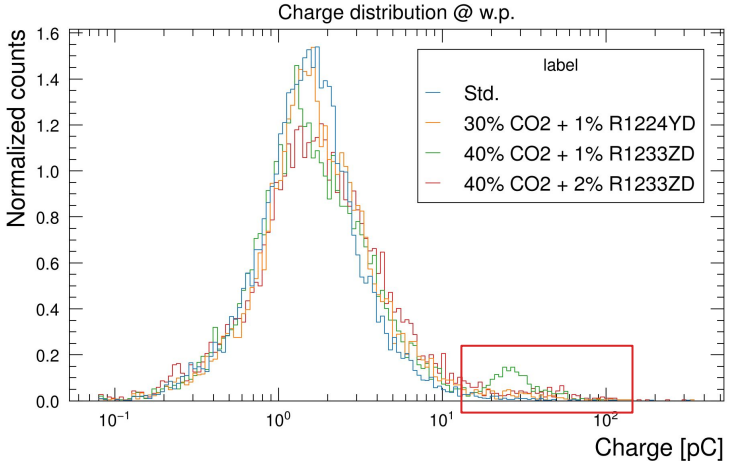
Effect of CO_2 and quencher concentration

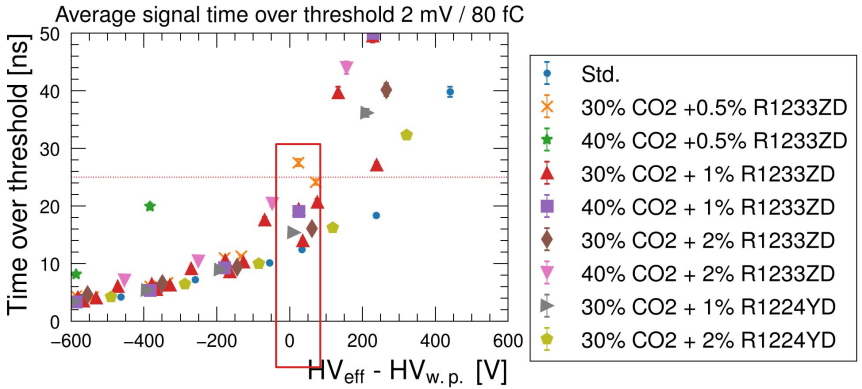
30% CO_2 + 1% R-1224yd/R-1233zd: wide avalanche–streamer separation and approximately 1% streamer contamination. R-1233zd has wider avalanche streamer separation than R-1224yd

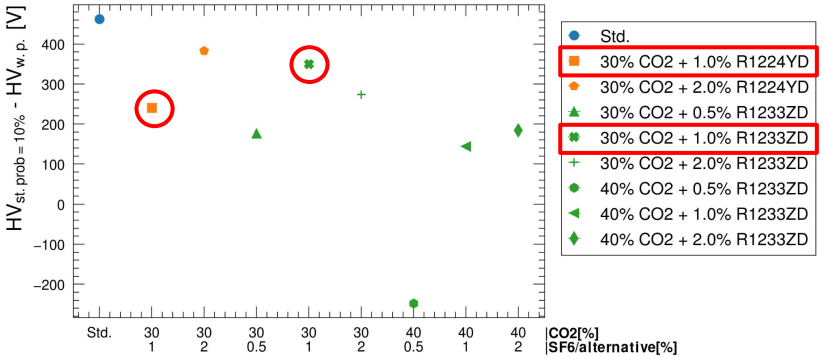
40% CO_2 + 1% R-1233zd: observed higher prompt charge content

40% CO_2 + 2% R-1233zd: separation ≈ 200 V, with no streamers observed at the WP

Mean time over threshold is generally within 25 ns at the WP







Performance under background irradiation

Current

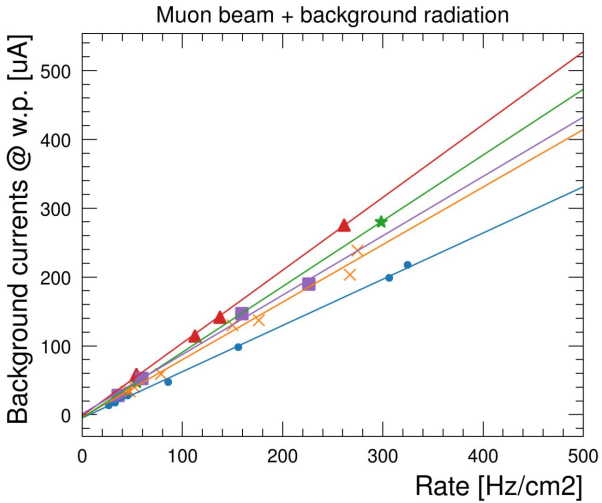
Under gamma irradiation, higher CO_2 and R-1233zd fractions increase current

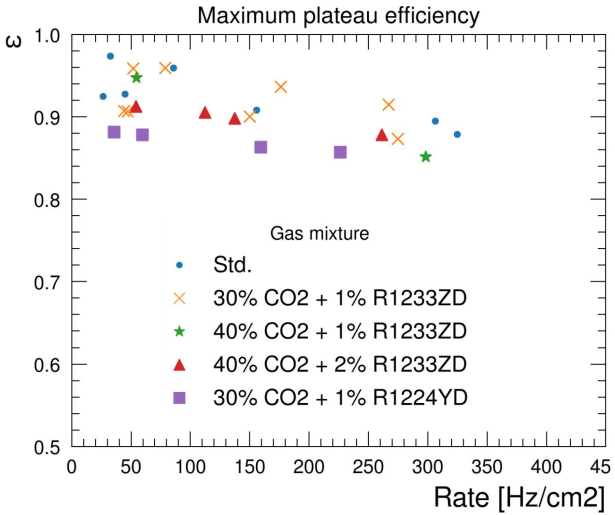
Plateau efficiency

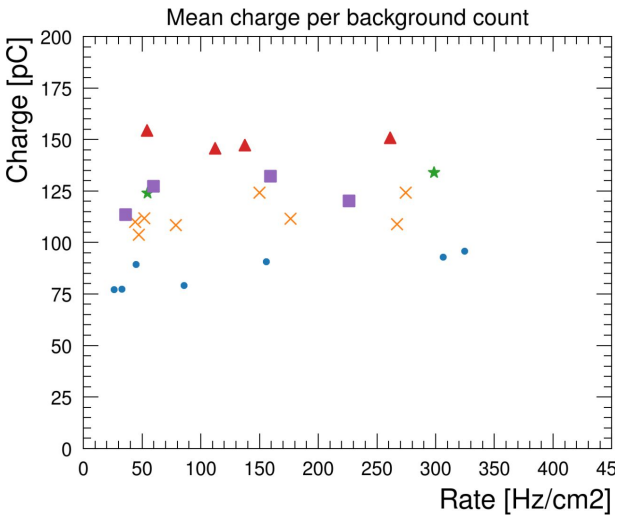
No significantly steeper efficiency loss with rate than for the standard mixture

Charge per background count

40% CO_2 + 2% R-1233zd gives almost twice the **standard-mixture** charge







Reducing or replacing R-134a

Approaches to reducing R-134a

Current research lines and approaches

- RPC ECOGAS: R-1234ze/CO_2 mixtures, see M. Abbrescia's talk on RPC2026
- ATLAS and CMS: CO_2 addition to the standard mixture
- ALICE MID already uses a flammable mixture

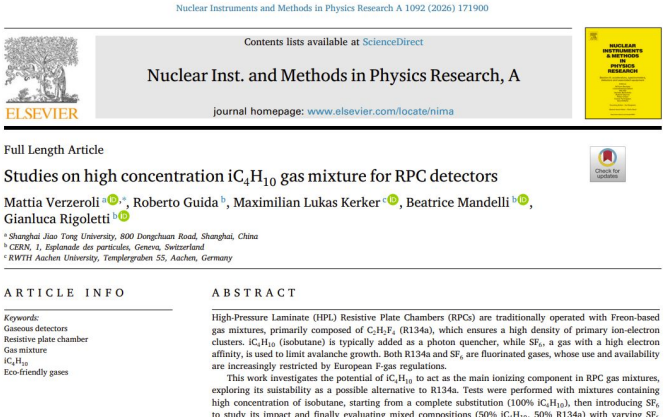
Future mixtures for large RPC installations

Accommodating flammability may be more feasible than relaxing toxicity or GWP requirements

This can motivate studies on hydrocarbons-based gas mixtures for future RPCs applications

Isobutane-based gas mixtures tests

- Pure isobutane, with and without SF_6
- 50:50 R-134a/isobutane base mixture, with and without SF_6
- Isobutane/CO_2 with SF_6



Nuclear Instruments and Methods in Physics Research A 1092 (2026) 171900

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Full Length Article

Studies on high concentration iC_4H_{10} gas mixture for RPC detectors

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ARTICLE INFO

Keywords:
Gaseous detectors
Resistive plate chamber
Gas mixture
iC_4H_{10}
Eco-friendly gases

ABSTRACT

High-Pressure Laminate (HPL) Resistive Plate Chambers (RPCs) are traditionally operated with Freon-based gas mixtures, primarily composed of $C_2H_2F_4$ (R134a), which ensures a high density of primary ion-electron clusters. iC_4H_{10} (isobutane) is typically added as a photon quencher, while SF_6, a gas with a high electron affinity, is used to limit avalanche growth. Both R134a and SF_6 are fluorinated gases, whose use and availability are increasingly restricted by European F-gas regulations.

This work investigates the potential of iC_4H_{10} to act as the main ionizing component in RPC gas mixtures, exploring its suitability as a possible alternative to R134a. Tests were performed with mixtures containing high concentration of isobutane, starting from a complete substitution (100% iC_4H_{10}), then introducing SF_6 to study its impact and finally evaluating mixed compositions (50% iC_4H_{10}, 50% R134a) with varying SF_6

Verzeroli et al. *10.1016/j.nima.2026.171900*

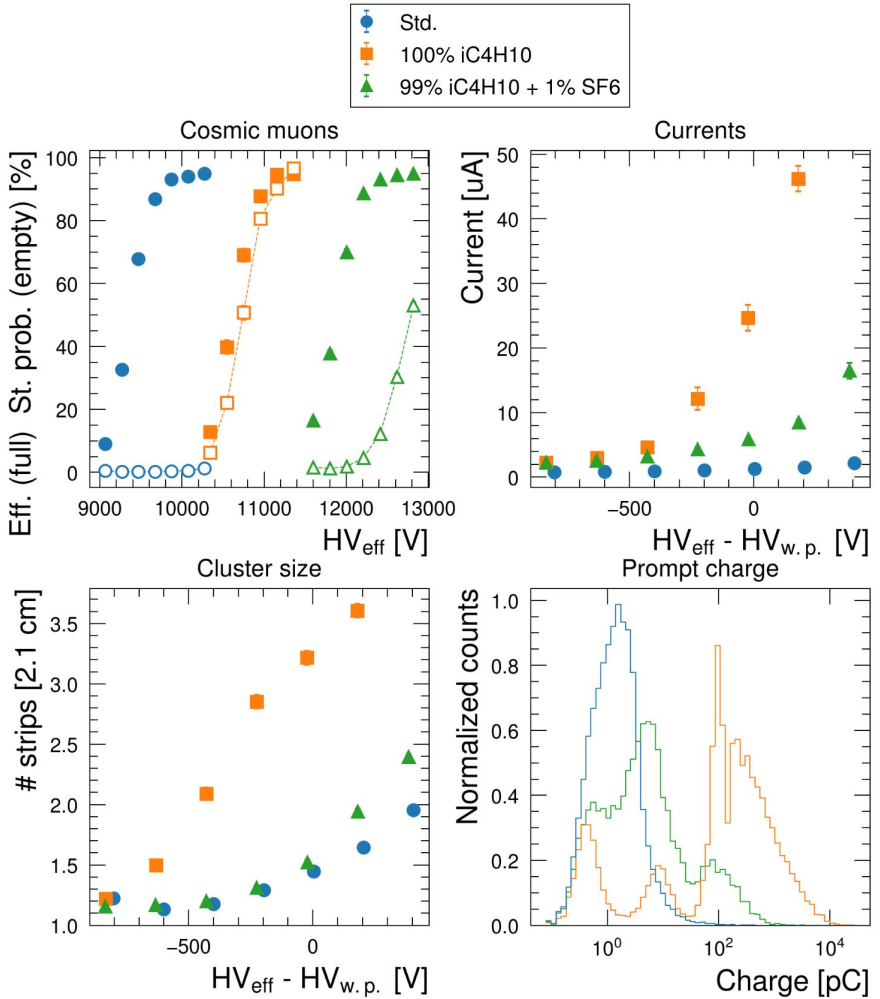
Isobutane with and without SF_6

Pure isobutane

- WP ≈ 2 kV above the standard mixture
- No streamer-free avalanche regime observed
- Large prompt charge, current and cluster size

99% isobutane + 1% SF_6

- WP ≈ 3 kV above the standard mixture
- Lower charge and current than pure isobutane, but streamers persist



R-134a/isobutane mixtures

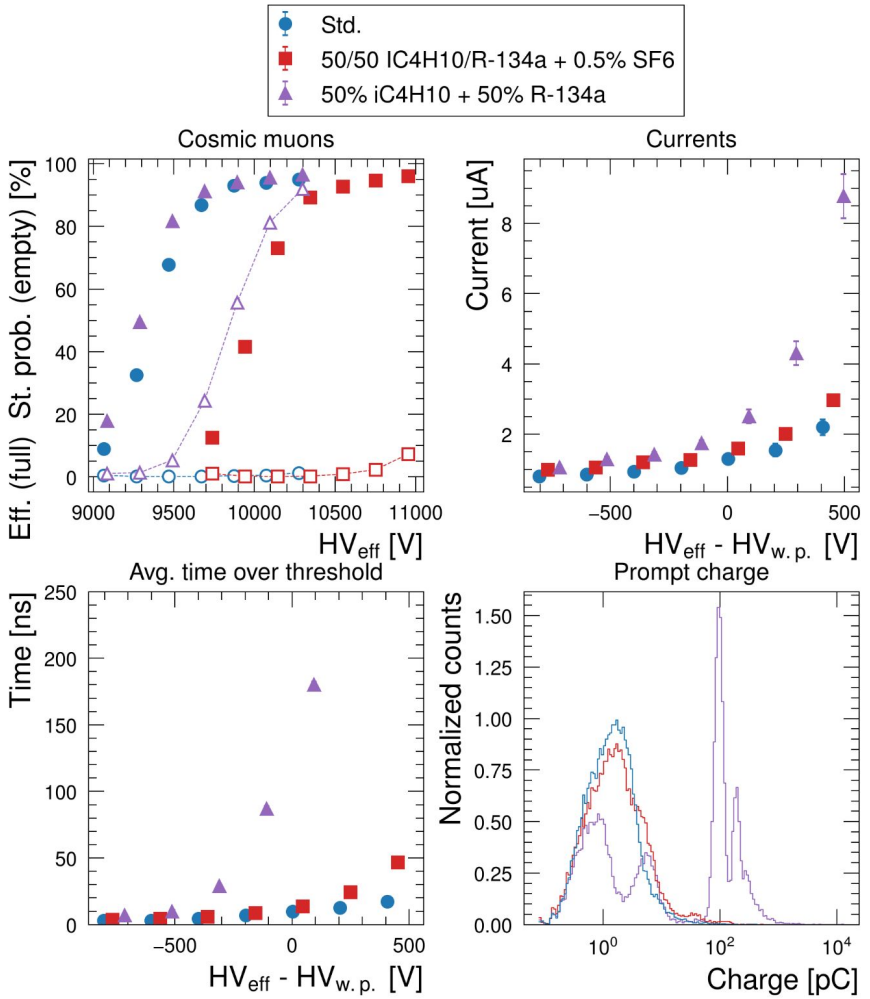
50:50 R-134a/isobutane base mixture

Without SF_6

- WP close to the standard mixture
- Significant amount of streamers @ w.p. (~30-40%)

With 0.5% SF_6

- WP approximately 700 V higher
- Other measured performance parameters are comparable to the standard mixture



Isobutane/CO_2 with 1% SF_6

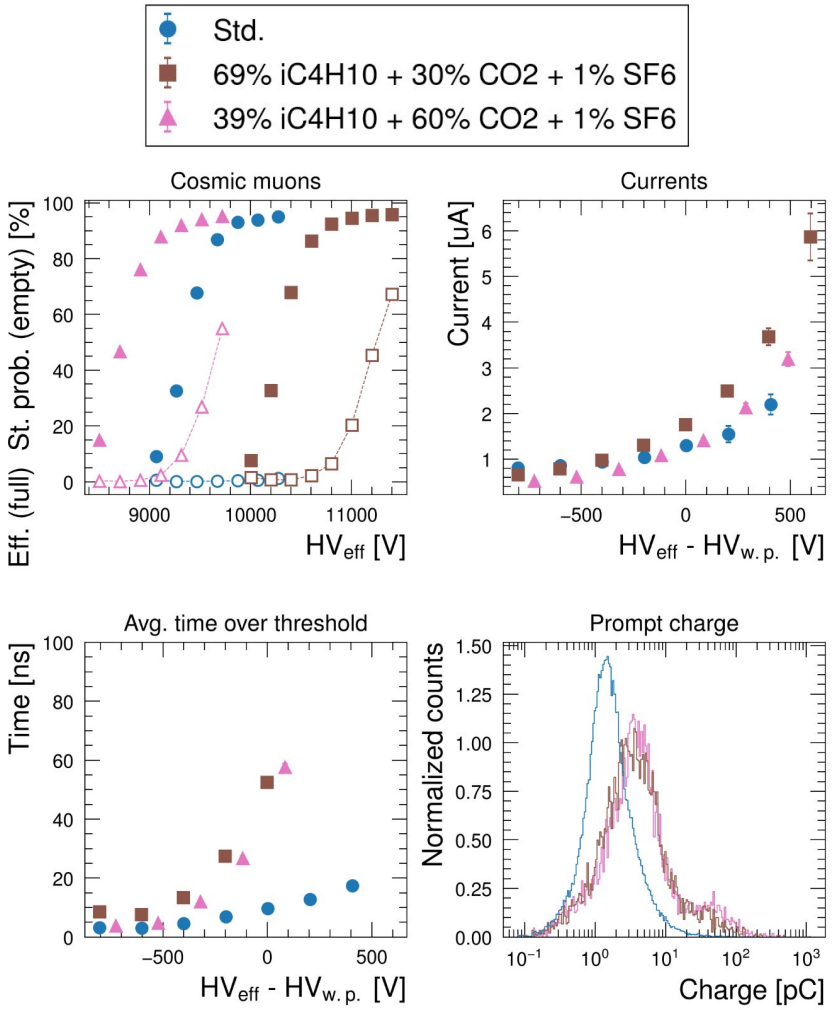
Mixtures without R-134a

- Increasing CO_2 to 60% lowers the WP by approximately 400 V
- Higher isobutane content gives slightly higher current

Signal characteristics

- Both mixtures show a prompt-charge shift
- Longer time over threshold is consistent with an afterpulse contribution; this remains a hypothesis

Unsuitable for streamer-free avalanche operation, but potentially useful at low rates



Reclaimed R-134a

Reclaimed gas

Recovered R-134a, purified and tested against new-product specifications

Supplier’s published purity specification: ≥99.5%

Supply and environmental considerations

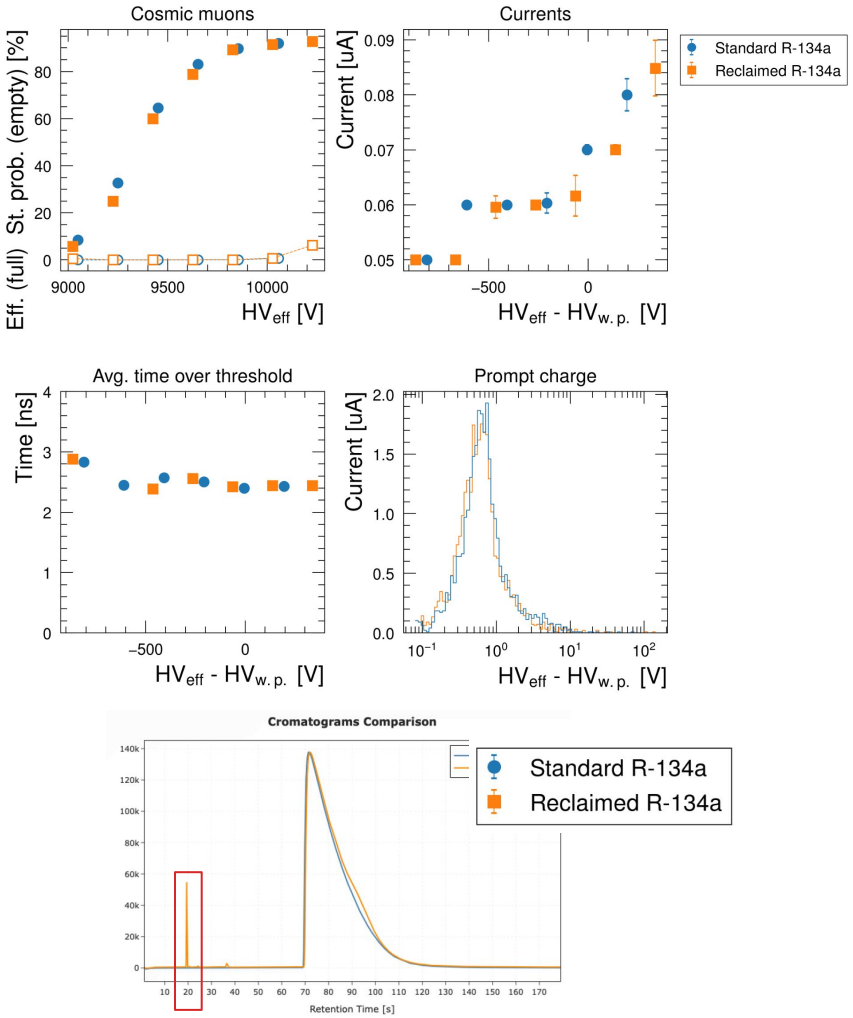
Potential alternative to fresh-gas procurement, with recovery and purification costs

Reuse reduces demand for newly produced gas; emitted R-134a retains its GWP

Measurements

Detector performance matches fresh R-134a

GC area-ratio estimate: ≈0.9% air; method accuracy is not yet quantified



Conclusions

Alternatives to SF_6

- R-1224yd and R-1233zd show promising detector performance
- Decomposition products and long-term compatibility require further study
- Additional candidates remain to be tested

Reducing or replacing R-134a

- Future detectors could accommodate flammable gases while meeting toxicity and GWP requirements
- Isobutane mixtures were tested: pure isobutane does not provide streamer-free operation
    - Combining isobutane with other gases and a quencher remains a promising approach
- Other flammable gases remain to be tested
- Reclaimed R-134a matches fresh-gas performance and could provide a temporary supply option

Thank you

Backup

Not only detector performance: gas properties studies

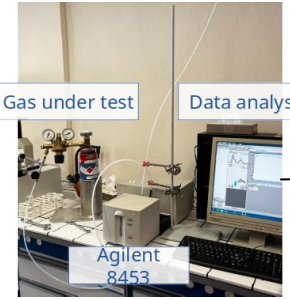
Not only detector performance

Understanding **physical** and **chemical** properties of gases is fundamental to detector operation
Environmental chemistry helps understanding pollutants formation

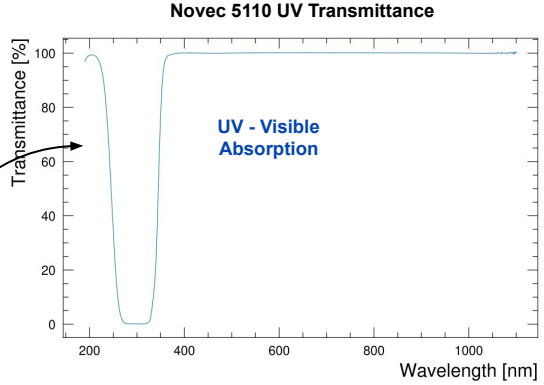
Gas molecules interaction in the atmosphere and in the detector

Rain out → Water solubility → critical for humidified gas mixtures
Oxidation → Reactivity with OH-
Photolysis → UV (wavelength < 300 nm) → quenching properties

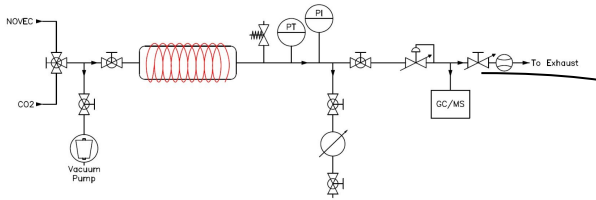
UV spectrometry

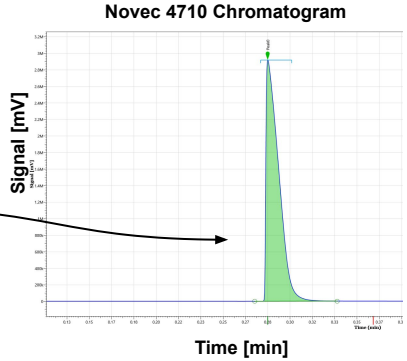


Thanks to B. Teissandier for helping in the measurements and providing the instrument

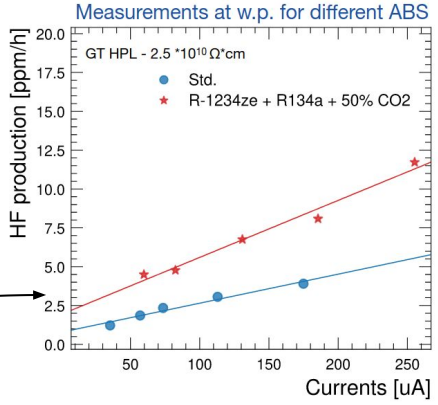


Novec 4710 water solubility setup schema



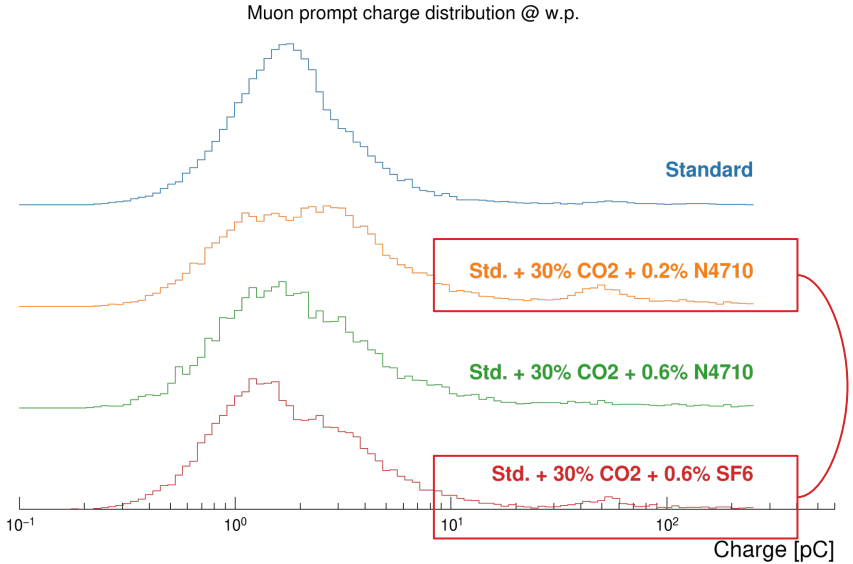


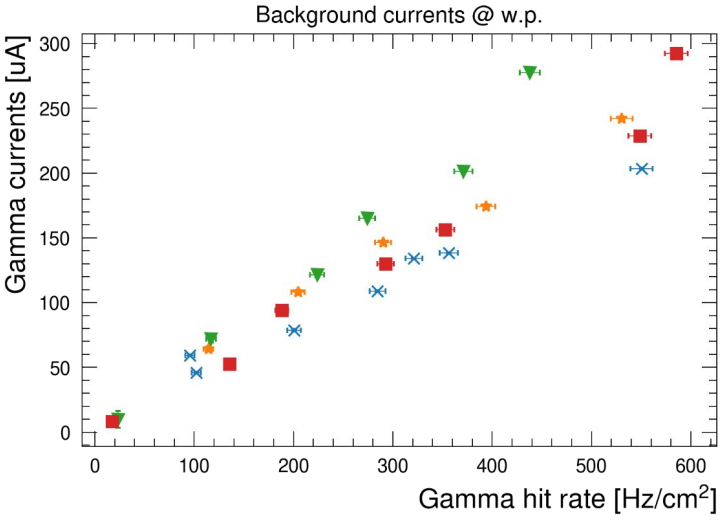




Novec 4710 with R-134a/CO2 gas mixtures

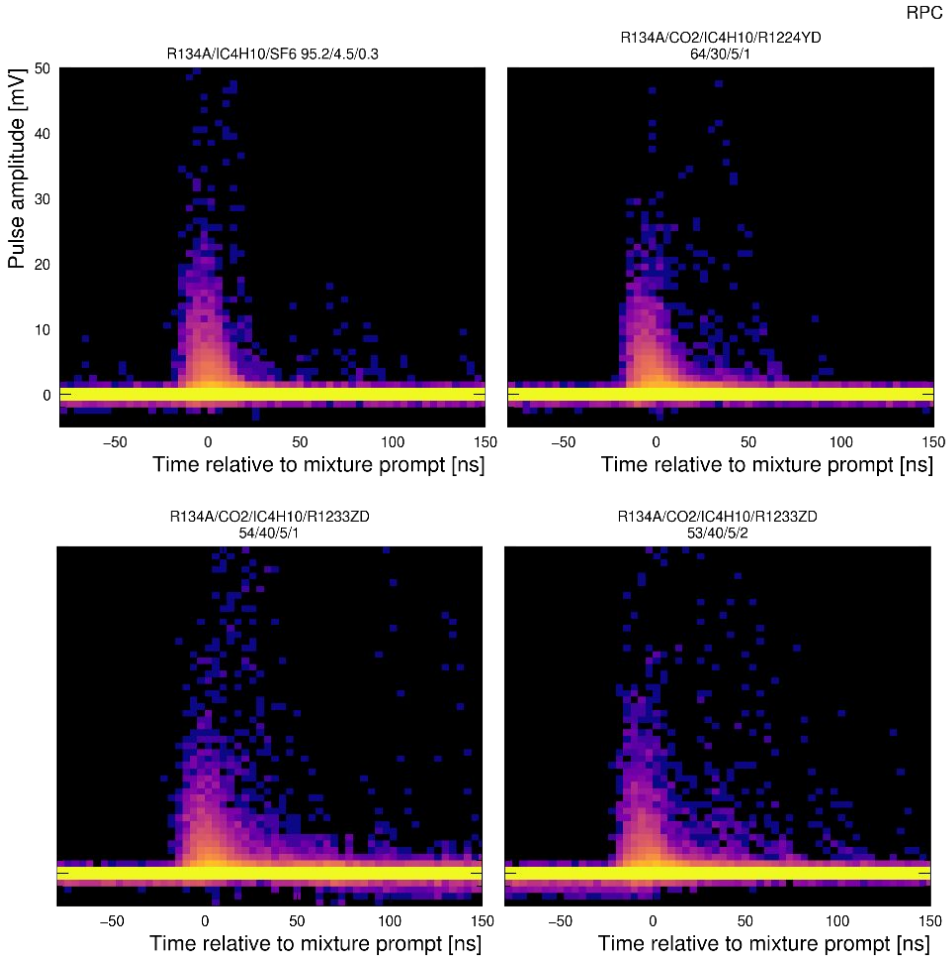
Novec 4710 + R-134a + 30% CO2 (+ 4.5% i-C4H10)
30% CO2 + 0.2% N4710 and **30% CO2 + 0.6% SF6** have similar performance (w.p., prompt charge, background currents)
30% CO2 + 0.2% N4710: lower gamma background currents
30% CO2 + 0.6% N4710: lower mean prompt charge but higher background currents → under investigation







Oscillograms of CO2/SF6 alternative gas mixtures



Impurities studies: F- measurements

2019 ⇒ Std., HFO + R-134a + 40% CO2

1. F- production does **not** depend **only** on the **currents** but also on the gap **electric field**
2. Tested **R-1234ze** gas mixture produced **4x more F-** than std. gas mixture

2022 ⇒ Std, Std + CO2 (+1% SF6), HFO + R134a + 50% CO2

3. 30% of CO2 in the standard gas mixture has the same F- production → **F- production** not **proportional** to R-134a
4. Using **1% SF6** to 30% CO2 + R-134a increases the **F- production** → under investigation
5. HFO + R134a + 50% CO2 produces **4x more F- than Std**

