Performance studies of RPC operated with alternatives to R-134a in the presence of LHC-like background radiation

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Outline

● RPCs at LHC
  ○ R-134a consumption

● Alternative gases to R-134a
  ○ R-1234ze as alternative to R-134a
  ○ Addition of alternative, non fluorinated components

● Addition of CO2 as a possible mitigation of R-134a consumption
  ○ Muon beam + Gamma background tests

● Conclusions
RPCs at LHC: R-134a consumption

RPCs at LHC are operated with 90-95% of R-134a

R-134 consumption during LHC Runs
Run 2: \(~100,000\,\text{tCO}_2e/\text{year}\) emitted from R-134a consumption
Early Run 3 estimates: \(~90,000\,\text{tCO}_2e/\text{year}\) of R-134a

Environmental + Economical factors
R-134a price increased of about \(2.5\) times w.r.t to 2015

\[90\,\text{kT CO}_2e\]

\[\Rightarrow\,3.5\%\,\text{of Geneva CO}_2e\,\text{emissions (2019)}\]

\[\Rightarrow\,0.23\%\,\text{of Switzerland CO}_2e\,\text{emissions (2018)}\]

Goal

Replace or reduce R-134a without changing the current RPC infrastructure
(no change in FEB, HV, Gas system)
**Experimental setup**

**Laboratory setup**
- Single gap, 2 mm electrodes + 2 mm 80x100 cm² gap HPL
- Tests of new gases
- Gas mixtures fine tuning: up to 6 components, 0.01% precision
- Low rates, cosmic muons
- Raw waveform analysis: efficiency, st. prob., cluster size, time resolution, prompt charge

**GIF++ setup**
- Muon beam + $^{137}$Cs gamma source
- Gas mixtures validation:
  - Muon beam at different background rates (ABS filters)
  - Long term studies: currents stability
  - Cosmic muons measurements

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*Image showing experimental setup and GIF++ setup diagram.*
Data acquisition and analysis

Data acquisition
- **Raw waveform** digitizing: efficiency, charge, shape, time analysis of signals
- 7 strips readout / RPC
- 2-3 RPC for **result consistency**
- HV scans: \(\sim 10\) HV points, \(10^4\) waveforms for each HV point \(\rightarrow O(10^5-10^6)\) waveforms analyzed per run

Data analysis
- Efficiency fitting with sigmoid function
- Working point definition: \(HV(95\% \text{ of } \epsilon_{\text{max}}) + 150\) V
- Avalanche / Streamer threshold: \(10^8\) electrons \(\sim 16\) pC
- **Efficiency-streamer separation**: \(\Delta V_{\text{w,p}} - \Delta V_{\text{10% st.prob.}}\), **streamer variability**: (w.p. \(\pm 50\) V)
- **GIF++ tests**: foremost parameters evaluated at working point for each ABS filter
  - Tested up to 500-600 Hz/cm²
Alternative gases: R-1234ze

R-1234ze identified as possible replacement to R-134a
- Extremely low GWP (~7)
- Increasingly wider adoption in refrigerant industry
- However, market price and availability not yet comparable to R-134a → Honeywell patented
- Cannot replace 1:1 R-134a → w.p. too high → CO2/He required to lower w.p.
- Long term effects still under investigation

R-1234ze performance with CO2 (+ R-134a) with cosmic muons
- 45% HFO + CO2 (ECO1) ⇒ w.p. too high (~11.6 kV)
- 25% HFO + CO2 (ECO3) ⇒ low GWP, high charge content ⇒ higher currents. Currently being tested by RPC ECOGAS collaboration
- 22% HFO + 22% R-134a + CO2 ⇒ higher GWP, lower charge content than HFO only. Possible compromise between performance and environment
Waveforms of Std vs. HFO vs. HFO + R134a gas mixtures

- HFO only → higher charge content: bigger and longer signals
- HFO + R-134a only: lower charge content and faster signals decay times

Waveforms with cosmics muons @ w.p.
R-134a + R-1234ze: two gas mixtures at high rates (1 CO2 50%, 1 He 30%):

- CO2 + R-1234ze gas mixtures have slightly higher efficiency drop (-2 %)
- He gas mixture has slightly lower currents than CO2 equivalent

He gas mixture has lower working point than CO2 one

Muon beam + gamma background

![Graphs showing working point, max. eff., and background currents vs. gamma hit rate]
HFO flammability tests

Safety concerning HFO usage

- R-1234yf classified as mildly flammable → Focus on R-1234ze

R-1234ze + i-C4H10 + 40% RH flammability test conducted:

ISO 1056 standard flammability test (detachment + flame propagation criteria) performed by external company

Results

- **Mixture with 1% i-C4H10 + R-1234ze is flammable**
- Water vapour plays an important role

HFOs alone + i-C4H10 is flammable → Effects of the CO2 on the mixtures to be understood/checked

![Illustration of a flame detachment with flame propagation over a distance of at least 100 mm as criterion for flammability](https://edms.cern.ch/document/2463340/1)

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<th>fraction of air including 2.25 mol% water in mol%</th>
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https://edms.cern.ch/document/2463340/1
Alternative gases: reduction of R-134a consumption

Reduction of R-134a in the standard gas mixture by addition of a 4th, non-fluorinated gas

O₂: good performance but highly reactive → lower flammability limit, higher currents due to oxidation reactions

Ne: good performance but no availability on the market

CO₂: good performance → selected as main candidate for GIF++ tests

N₂: high streamer contamination at low concentrations

He: good performance but problematic for PMTs in LHC caverns

N₂O: discrete performance but increased working point of ~ 300 V

Ar: slightly high streamer probability
Studies on CO2 impact when added to the standard gas mixture: 30%, 40%, 50%
- Tests performed with muon beam and gamma background
- w.p. decreases of ~ 190 V / 10% CO2
- GWP reduction of 30-50%
- Current increase of +10-15% @ 500 Hz/cm²
- Streamer fraction increases
- Two avalanche populations when using CO2 and R-134a → under investigation
Addition of CO2 to the standard gas mixture

Addition of 30%, 40%, 50% of CO2 gas mixture as mid-term solution to mitigate R-134a. Muon beam studies

1. Average prompt charge slightly increasing (+10-15%)
2. Cluster size increases with CO2 amount
3. Average signal times over threshold increase with CO2
4. Time resolution of CO2 gas mixtures is lower than std. one

Adjustment of SF6 needed to further suppress streamers
SF6 adjustment in CO2 + R-134a gas mixture

Combination (30%, 40%, 50%) CO2 x (0.3%, 0.6%, 0.9%) SF6

- Higher efficiency-streamer separation for 30%/40% CO2 + 0.9% SF6 or 30% CO2 + 0.6% SF6 → selected gas mixtures
- Lower variation of streamer probability for the same gas mixtures

Streamerviability. Muon beam only

Charge distribution @ w.p.
Selected CO2-based gas mixtures

**Selected CO2/SF6 gas mixtures**
- **30% CO2 + 0.6% SF6**: overall good performance
- **30% CO2 + 0.9% SF6**: best performance but higher SF6 consumption
- **40% CO2 + 0.9%**: slightly worse performance (cluster size, ToT) but higher R-134a reduction

**Observed performance**
1. Efficiency drop similar to std. gas mixture up to 500 Hz/cm\(^2\)
2. Mean time over threshold below 25 ns for 30% CO2 gas mixtures
3. Currents at fixed ABS around 15-20% higher
Conclusions

Alternatives to R-134a

R-1234ze current main fluorinated alternative
- Needs to be used with a 4th gas to keep “low” working point
- SF6 concentration needs to be increased to ~ 1%
- Market availability and price still a matter of concern
- Still requires understanding of its effects on long term operation of RPC

Non fluorinated alternatives
- Several gas tested: N2, N2O, O2, Ne, He, CO2, Ar
- They cannot replace R-134a but mitigate its consumption
- CO2 selected: availability, price, good performance, known effects on other detectors

Addition of CO2 to mitigate R-134a consumption
- 30%, 40%, 50% of CO2 added to the standard gas mixture: good performance but SF6 concentration needs to be increased
- 0.3%, 0.6%, 0.9% of SF6 tested for each CO2 concentration: few combinations selected
- Foremost parameters of selected CO2 + SF6 gas mixture similar to standard gas mixture
  - Only background currents found to be 15-20% higher probably due to avalanche mean prompt charge

30-40% CO2 + 0.6%-0.9% SF6 are promising short to mid-term gas mixtures for RPC @ LHC experiments
Thank you
Backup
GWP calculation

GWP for a single gas is well defined: it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO2).

Gas mixture is expressed in fractions of normal volume → proportional to number of moles → molecular weight.

GWP of gas mixture: \( \frac{\sum GWP_i \times M_i \times f_i}{M_{CO2}} \), where \( M \) is molecular mass and \( f \) the amount of the gas in the mixture.

Example:

Suppose RPCs are operated with 1000 ln/h of CO2. After one year the tons of CO2 are:

\[
1000 \text{ ln/h} \times 8760 \text{ h} / 22.4 \text{ l/mol} \times 44 \text{ g/mol} = 17.2 \text{ tons}
\]

Suppose RPCs are operated with 70% R-134a and 30% CO2. If we simply do the proportion we would get: 1430 * 0.7 + 1 * 0.3 = 1001 of GWP → wrong estimation.

After one year the equivalent tCO2e are:

- **CO2**: 300 ln/h * 8760 h / 22.4 l/mol * 44 g/mol = 5.2 tons
  \( \Rightarrow 39.9 \text{ ktCO2e} \quad \Rightarrow \text{GWP}_e = 39.9 \text{ ktons} \)

- **R-134a**: 300 ln/h * 8760 h / 22.4 l/mol * 102 g/mol * 1430 = 39.9 kTons / 17.2 tons = 2320 GWP_e

This results are because detectors and gas systems are operated using normal volume units and not mass of the gases.
Gamma charge per count

CO2 at 50%, ABS = 2.2

Charge [pC] vs. HV - HVw.p.
Gas coefficients