Performance studies of RPC detectors with new environmentally friendly gas mixtures in presence of LHC-like radiation background

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Outline

**Overview** on the Resistive Plate Chambers *gas mixtures* and possible alternatives

**Characterization** of RPCs with new eco-friendly gas mixtures

RPC *operation* with new environmentally friendly gas mixtures at CERN Gamma Irradiation Facility (GIF++)
Greenhouse Gases in RPC operation

RPC gas mixture at LHC
→ Made out of three components
→ High Global Warming Potential due to presence of SF6 and R134a

\[
\begin{align*}
&\text{GWP 1430} + \text{GWP 3.3} + \text{GWP 22800} \\
&\sim 95\% + 4-5\% + 0.3\%
\end{align*}
\]

GHG emissions
→ The main contribution is from R134a
→ R134a and SF6 due to leaks at detector level at ATLAS and CMS RPCs
→ A campaign of leaks reparation is currently ongoing

European Union F- regulation
→ Limit the total amount of F- gases that can be sold → Phase down process
→ Banning the use of F- gases where eco friendly alternatives are present
→ Preventing emissions by requiring proper checks and servicing of the gases and recovery of the gases

HFC phase down schedule by Linde Group
RPC gas mixtures

First gas mixtures for RPCs were Ar and/or R13B1

R13B1 was then replaced with R134a + small quantities of iC4H10 and SF6

GWP 6900 - ODP 10

R134a (C2H2F4)

GWP 1430 - ODP 0

Refrigerant industry started using HFO gases as replacement of R134a

Hydro-Fluoro-Olefin (HFO)

Contains C=C bound

Contains Fluorine

Contains Hydrogen

Thermodynamical characteristics are known for HFOs but studies on ionization properties have just started

HFO-1234ze (C3H2F4)

GWP 6

HFO-1234yf (flam) (C3H2F4)

GWP 4

Goal: find and eco-friendly gas mixture compatible with the current ATLAS and CMS RPC systems (i.e. requires no change in the HV cables, FE electronics, gas system etc.)
Experimental setup for cosmic muons

Gas Mixing Unit
- Up to 6 different gases
- Gas system component validation

RPC
- 2 mm gap, high pressure laminate
- Read-out strips 2 cm

CAEN Digitizer V1730
- 16 Channels
- Resolution: 0.12 mV/adc
- Sampling: 500 MS/s

Gas Analysis
- Gas Chromatograph and Mass Spectrometer
- Ion Selective Electrode (F- concentration)

Off-line data analysis
HFO based gas mixtures

Initially, R134a was completely replaced by HFO
- Results indicate higher working voltage (>12kV) → Related to C=C bound
- Avalanche signals smaller compared to Standard Gas Mixture

An addition of a gas to lower the working point is required
- Promising results with +20-30% of He
  The use of He + presence of leaks may affect LHC operation
- Use of CO₂ as inert gas: +10 % CO₂ → - 800V
  The streamer probability increases → CO₂ different quenching properties w.r.t. to iC₄H₁₀
  Need to keep a small amount of R134a and increase SF₆ concentration
**Selected HFO based gas mixtures**

**Over 50 different gas mixtures tested**
Tested 3, 4 and **5 components** gas mixtures

**HFO based gas mixture**
Performed best together with \( \text{CO}_2 \) and \( \text{R}134a \)
\( \text{HFO} + \text{CO}_2 + \text{R}134a + 4.5\% \text{iC}_4\text{H}_{10} + 1\% \text{SF}_6 \)

**Fine tuning of HFO gas mixtures**
Two candidates that can compete with the standard gas mixture

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>GWP</th>
<th>Knee (95% effmax) [V]</th>
<th>Streamer probability %</th>
<th>Avalanche/Streamer charge [pC]</th>
<th>( \Delta V ) (eff-str)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard gas mixture</td>
<td>1430</td>
<td>9450</td>
<td>1.4</td>
<td>0.90 / 8.7</td>
<td>1000</td>
</tr>
<tr>
<td>HFO + 50% ( \text{CO}_2 )</td>
<td>550</td>
<td>10150</td>
<td>9.9</td>
<td>1.35 / 17.1</td>
<td>950</td>
</tr>
<tr>
<td>HFO + 40% ( \text{CO}_2 )</td>
<td>620</td>
<td>10550</td>
<td>8.3</td>
<td>1.20 / 16.3</td>
<td>980</td>
</tr>
</tbody>
</table>
CERN Gamma Irradiation Facility (GIF++)

Goal: study RPC performance with muon beam, gamma background and HFO based gas mixtures

GIF++ facility
- Located along SPS line, north area
- Built to emulate the background conditions of LHC

→ Gamma Source
\(^{137}\text{Cs}\) of 14 TBq → 662 KeV gamma peak background

→ Muon Beam
100 GeV, \(10^4\) muons/spill, \(10\times10\) cm\(^2\) area

Setup DAQ and DCS
- Raw waveform acquisition via v1730 digitizer
- HV control via dcs
- Online monitoring of gas parameters via influxdb + grafana
- EOS storage of data
- Offline analysis python + pandas + numpy on SWAN

<table>
<thead>
<tr>
<th>ABS</th>
<th>Gamma Rate [kHz/cm(^2)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>55.3</td>
</tr>
<tr>
<td>220</td>
<td>41.2</td>
</tr>
<tr>
<td>2200</td>
<td>3.75</td>
</tr>
<tr>
<td>22000</td>
<td>0.774</td>
</tr>
</tbody>
</table>

Muon efficiency vs. currents

- Efficiency curves are plotted against effective voltage seen by gas gap \( (HV_{\text{eff}} = HV_{\text{app}} - RI) \)
- Data is fitted with a sigmoid → Information about maximum efficiency and knee
- Currents raise of ~20% with a change of 10% of CO\(_2\)
  - \( \Delta(\text{eff} - \text{str.}) \) increases when CO\(_2\) decrease

Streamer probability at ABS 220 (counting rate ~ 250 Hz/cm\(^2\))

<table>
<thead>
<tr>
<th>Gas mixture</th>
<th>At HV knee</th>
<th>At efficiency (+150 V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard gas mixture</td>
<td>3%</td>
<td>13%</td>
</tr>
<tr>
<td>HFO + 40% CO(_2)</td>
<td>8%</td>
<td>25%</td>
</tr>
<tr>
<td>HFO + 50% CO(_2)</td>
<td>15%</td>
<td>23%</td>
</tr>
</tbody>
</table>

Streamer probability is 10% higher at working point
The mean avalanche charge is higher for the eco-friendly gas mixtures.
The mean streamer charge is lower for the eco-friendly gas mixtures.
Gas recirculation system

RPC operation must be validated under LHC like conditions

RPCs operated under gas recirculation with eco-friendly gas mixtures
Validation with selected HFO based gas mixture

Cosmics validated
Stable performance, low current

Gamma irradiation validation ongoing
Stable currents, change in detector resistivity observed

Monitoring of currents and integrated charge

High background rate

Gas recirculation

Gas mixer
- Up to 5 component
- Ar and N2 lines for flushing

Gas recirculation unit
- From 0% to 100%

Gas Analysis
- GC/MS
- ISE (F⁻ concentration)
Dark current monitoring

Observed increase of dark currents before and after irradiation
- ~10 mC/cm² accumulated

Detector were then flushed with standard gas mixture without irradiation
- Observed a recovery trend
- Dark currents almost back to before irradiation condition

It is important to understand and estimate the impurities accumulated in the detector
Creation of impurities under irradiation

Impurities created from R134a and HFO
- Under the effect of high background radiation and electric fields, Freons molecules break into fluorine radicals
- F- radicals are very reactive, especially with water → HF formation, very aggressive for linseed oil and bakelite
- Sub-products in the order of the ppm
- Accumulation in case of closed loop system

Creation of impurities observed also in RPCs at LHC experiments during Run 2
- Safety limit is still being understood

HFO gases have shorter atmospheric lifetime than R134a
- They could break more easily
- F- production depends on the current of the detector and the prompt charge size
Creation of impurities under irradiation

Radiation measurements with HFO based gas mixture

Test performed by irradiating 2 RPCs at different background rates and at different voltages
- Open mode, fixed flow and correction for environmental conditions

Gas mixture tested:
- Standard Gas mixture and selected eco-friendly
- Comparison between the production of impurities

Impurities measured with different instruments
- Gas Chromatographer / Mass spectrometer
- Ion Selective Electrodes (ISE) for F- measurements

At detector efficiency
- The production depends on the background rate
- The F- production of the selected eco-friendly gas mixture is ~4 times higher than the standard gas mixture

Assuming contribution from SF6 neglectable

HFO is breaking ~10 times more easily than R134a

<table>
<thead>
<tr>
<th>Mixture</th>
<th>F- rate production</th>
<th>Contribution to the mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.2% R134a</td>
<td>10 ppm/h</td>
<td>R134a = 10.5 ppm/h</td>
</tr>
<tr>
<td>27.25% R134</td>
<td>40 ppm/h</td>
<td>HFO = 136 ppm/h</td>
</tr>
<tr>
<td>27.25% HFO</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RPC1

- Standard Gas Mixture
- HFO + 40% CO2 Gas mixture

Preliminary
Conclusions

R&D goal: find an eco-friendly gas mixture compatible with the current ATLAS and CMS RPC systems

Eco friendly gas mixture for RPCs
- HFO not suitable for direct substitution to R134a
- HFO requires an inert gas to work at lower working points (<12 kV)

Characterization of RPCs with eco-friendly gas mixtures
- More than 50 different gas mixture tested
- HFO + He or CO₂ shows similar properties to the standard gas mixture

RPCs operation with eco-friendly gas mixtures under background irradiation
- RPC tested up to HL-LHC expected rate (~300 Hz/cm² counting rate)
- Streamer probability and currents are slightly higher for HFO based gas mixtures
- Long term performance studies of eco-friendly mixture are currently going on
- HFO seems to break more easily to R134a: studies ongoing on the causes and possible solutions
Thank you
Recirculation system
## Other tested mixtures

<table>
<thead>
<tr>
<th>Chemical Structure</th>
<th>GWPmix</th>
<th>HV (V)</th>
<th>Streamer (%)</th>
<th>Pulse charge (pC)</th>
<th>ΔV Eff-Stream (V)</th>
<th>Clu Size (strip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R32-iC₄H₁₀-SF₆ 0.6</td>
<td>c</td>
<td>1030</td>
<td>7500</td>
<td>0.5 / 6.5</td>
<td>600</td>
<td>1.5</td>
</tr>
<tr>
<td>R134a-iC₄H₁₀-SF₆ 0.3</td>
<td>c-c</td>
<td>1490</td>
<td>9600</td>
<td>0.5 / 6</td>
<td>1000</td>
<td>1.5</td>
</tr>
<tr>
<td>R152a-iC₄H₁₀-SF₆ 0.6</td>
<td>c-c</td>
<td>430</td>
<td>10000</td>
<td>1 / 8.5</td>
<td>760</td>
<td>1.6</td>
</tr>
<tr>
<td>R245fa-iC₄H₁₀-SF₆ 0.6-He 50</td>
<td>c-c-c</td>
<td>1260</td>
<td>6600</td>
<td>1 / 7</td>
<td>610</td>
<td>2</td>
</tr>
<tr>
<td>HFO-iC₄H₁₀-SF₆ 0.3-Ar 42.5</td>
<td>c=c-c</td>
<td>130</td>
<td>8900</td>
<td>2 / 15</td>
<td>160</td>
<td>4</td>
</tr>
<tr>
<td>HFO-iC₄H₁₀-SF₆ 0.6-He 50</td>
<td>c=c-c</td>
<td>370</td>
<td>9000</td>
<td>1.5 / 8</td>
<td>700</td>
<td>4</td>
</tr>
<tr>
<td>HFO-R134 37.45-iC₄H₁₀-SF₆ 0.6-He 20</td>
<td>c=c-c</td>
<td>890</td>
<td>10500</td>
<td>0.5 / 6</td>
<td>970</td>
<td>1.6</td>
</tr>
<tr>
<td>HFO-R134a 50-iC₄H₁₀-He 20</td>
<td>c=c-c</td>
<td>430</td>
<td>10800</td>
<td>1.5 / 8</td>
<td>400</td>
<td>2.5</td>
</tr>
<tr>
<td>HFO-R134a 22.5-iC₄H₁₀-CO₂ 50-SF₆ 1</td>
<td>c=c-c</td>
<td>560</td>
<td>10500</td>
<td>1.5 / 7.5</td>
<td>950</td>
<td>1.5</td>
</tr>
</tbody>
</table>
More details on muon efficiency

- **95.2/4.5/0.3 R134a/iC4H10/SF6**
  - Efficiency and streamer probability (dotted line)
  - Source off
  - 100
  - 220
  - 2200
  - 22000
  - Approx. 150 V

- **27.25/27.25/40/4.5/1 R134a/HFO/CO2/iC4H10/SF6**
  - Efficiency and streamer probability (dotted line)
  - Source off
  - 100
  - 220
  - 2200
  - 22000
  - Approx. 240 V