



Towards sustainable RPC detectors: Exploring CO₂-based gas mixtures for CERN LHC experiments

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ABSTRACT

Resistive Plate Chamber detectors at the CERN LHC experiments use a Freon-based gas mixture containing R-134a and SF₆, high global warming potential greenhouse gases. To minimize greenhouse gas emissions and expenses and optimize RPC performance, it is crucial to research new environmentally friendly gas mixtures. This study aims to understand the properties of adding CO₂ to the standard gas mixture as a medium-term solution to reduce greenhouse gas emissions. The gas mixtures tested were chosen to be compatible with the current CERN HPL RPC systems. Detector performance, operational costs, and emissions are key characteristics considered in this research, focused on the potential use of CO₂-based gas mixtures in the ATLAS RPC system during LHC Run 3. This research is conducted at the CERN Gamma Irradiation Facility, where a 12 TBq ¹³⁷Cs source and a muon beam allow emulating the background radiation experienced in the LHC experiments. The set up consists of five, 2 mm single-gap HPL RPCs located on three different positions, placed respectively outside the irradiation bunker, at 5 m and 12 m from the gamma source.

The detectors inside the bunker are continuously irradiated for long-term performance studies, aiming to reach the integrated charge expected for ATLAS RPC detectors in LHC Run 3 and for the future High Luminosity LHC phase. Monitoring is performed with various metrics: gas analysis, oxygen, humidity, dose, environmental parameters, and flow measurements to ensure the correct operation of the gas system. Throughout the study, three test beam periods are used to evaluate the muon performance parameters for the targeted gas mixtures: efficiency, current, streamer probability, mean prompt charge, cluster size, and time resolution. Preliminary aging tests with the addition of 30% CO₂ show performances closely aligned with the Standard Gas Mixture. In addition to long-term studies, muon beam performance was evaluated with higher amounts of CO₂ in the mixture, aiming at further reducing the consumption of R-134a.

1. Introduction

The High-Pressure Laminate (HPL) Resistive Plate Chambers (RPC) detectors used at the CERN LHC experiments are operated with a gas mixture made of 90%–95% of R-134a, about 5% of i-C₄H₁₀ and 0.3% of SF₆. In addition to the gases, about 7000 ppm of water vapour are added to ensure a constant electrode resistivity. R-134a and SF₆ are known to be potent Greenhouse gases (GHG) [1]; in particular, R-134a is subjected to the European regulation on fluorinated gases [2], which aims at limiting the placement of high Global Warming Potential gases on the market. RPCs during LHC Run 2 accounted for about 87% of the GHG emissions from particle detector at CERN. Therefore, the search for alternative gas mixtures to reduce the emission of high-GWP gases

is one of the strategies identified by the CERN Gas Group and by the RPC detector communities. Several works were done in the past to look for replacements of R-134a and SF₆ [3–5]. Adding a new gas to the RPC requires several long term tests to be done, some of which were started [6]. As a possible medium term solution, the addition of an inert gas to the standard gas mixture was investigated [7]. In particular, the addition of 30%–40% of CO₂ and an increase of SF₆ was found to be a viable path for reducing the GHG emissions in the short-medium term. Tests were conducted by looking at the muon detection performance under different LHC-like background conditions. In this work, an experimental campaign was conducted to assess the long-term performance of the detectors when operated with a selected CO₂-based

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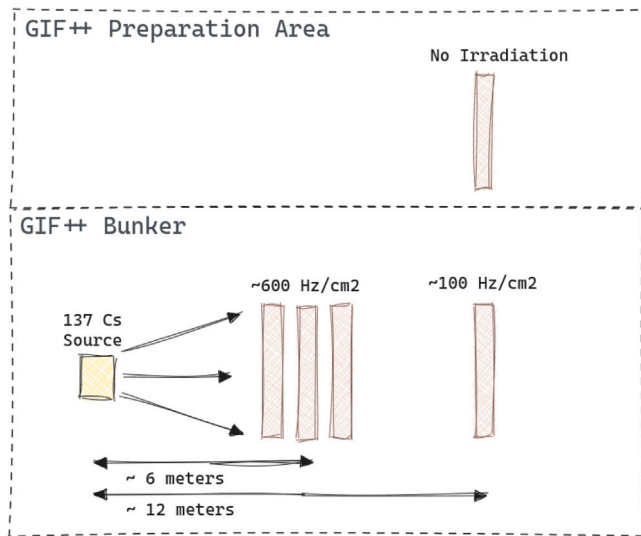


Fig. 1. Position of the installed RPCs with respect to the GIF++ irradiation area. Three detectors were installed at 6 m from the source, one at 12 m and one outside the irradiation area.

gas mixture and gamma background radiation.

2. Experimental set up

The tests were conducted at the CERN Gamma Irradiation Facility (GIF++) [8]. A gamma source of ^{137}Cs with a set of Lead filters can be used to emulate the background conditions of LHC. The facility is installed on the H4 line of the North Area, where a muon beam is provided a few weeks a year. Five High Pressure Laminate (HPL) RPCs were employed. All of them were produced by the KODEL university, with an electrode thickness of 2 mm, a gas gap of 2 mm and size of $70 \times 100 \text{ cm}^2$. Three detectors were installed on a mechanical support along the muon beam line and at a distance of about 5 m from the GIF++ ^{137}Cs source, where the gamma hit rate, measured by counting background hits on the readout strips at different irradiation filter conditions, was ranging from 400 to 600 Hz/cm^2 , depending also on the shielding of the set ups upfront. One detector was installed at about 12 m from the source, where the estimated gamma hit rate was 100 Hz/cm^2 . One RPC was instead installed in the preparation area outside the irradiation bunker, and it was used as a reference detector for the tests conducted. Fig. 1 reports a schema of the detectors and their set up. Each detector was flushed with about 2 ln/h of fresh gas, corresponding to about 1.3 gas volumes exchange per hour. During both the irradiation and muon beam periods, the environmental pressure, temperature and humidity were recorded. The detectors currents were recorded from a CAEN HV SY5527 [9] power supply. During the muon beam period, CAEN V1730 and DT5730 [10] digitizers were used to read out the prompt signals on 7 strips of each detector. Most of RPCs foremost parameters were evaluated at their working point, defined in this work as 95% of the maximum efficiency with the addition of 150 V. A set of 4 plastic scintillators was used to provide an external trigger signal for the recording of the raw waveform signals. Due to cable length constrains, the detectors muon beam performance was tested only at 5 m from the source.

3. Tests with different CO_2 and SF_6 concentration

In the past work [5], several CO_2 and SF_6 concentrations were tested. It was observed that the addition of 30% of CO_2 and the increase to 0.9%–1% of SF_6 in the mixture resulted in acceptable detector performance in terms of efficiency, currents, working point, cluster size

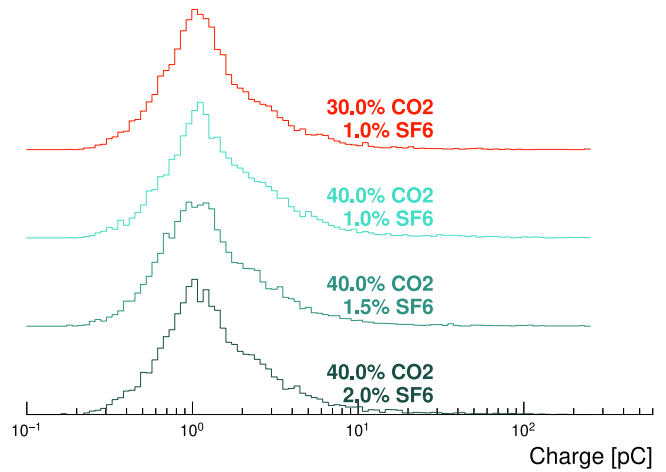


Fig. 2. Charge distribution of 30% of CO_2 with 1% of SF_6 and 40% of CO_2 with 1%, 1.5% and 2% of SF_6 . The charge spectra are taken at detector working point.

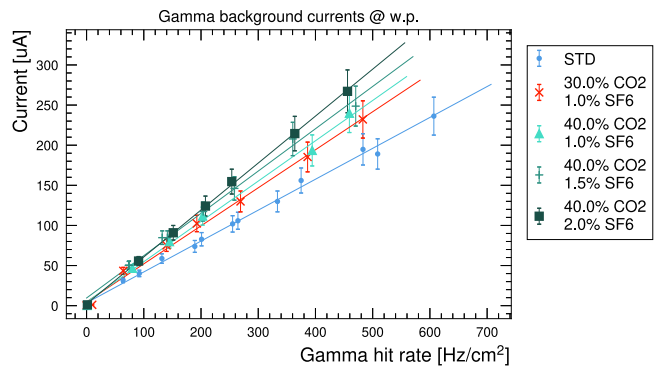


Fig. 3. Gamma background currents of 30% of CO_2 with 1% of SF_6 and 40% of CO_2 with 1%, 1.5% and 2% of SF_6 . The currents were measured at fixed detector efficiency conditions.

and time resolution. In the present work, the addition of 40% of CO_2 was also tested with increased concentration of SF_6 , up to 2%. The prompt charge distribution measured at working point is reported in Fig. 2, which shows a slight increase in the variance when moving from 30% to 40% CO_2 . No significant differences can be observed in the charge region above 10 pC, indicating that adding more than 1% of SF_6 does not significantly affect the induced signal size.

When looking at the detector currents taken at working point and different irradiation conditions as in Fig. 3, an increase can be observed both when moving from the standard gas mixture to increasing CO_2 concentration and when increasing the SF_6 concentration with fixed amounts of CO_2 . The first effect can be explained by the assumption that, with respect to the standard gas mixture, an increase in the prompt charge of the CO_2 based gas mixtures corresponds to an increase in the ionic charge. The latter effect can be explained instead by the electron attachment coefficient of SF_6 which becomes very effective at capturing free electrons when space charge effects in the avalanche occur [11]. The process leads to an increasing amount of negative ions which contributes to the currents flowing through the electrode and measured by the HV power supply.

The gas mixture with 64% R-134a, 30% CO_2 , 5% $i\text{-C}_4\text{H}_{10}$, 1% SF_6 was chosen to perform the long term irradiation tests reported in the following section.

4. Long term irradiation tests

A dedicated experimental campaign was set up to study the performance of the RPCs and understand if there were any possible aging

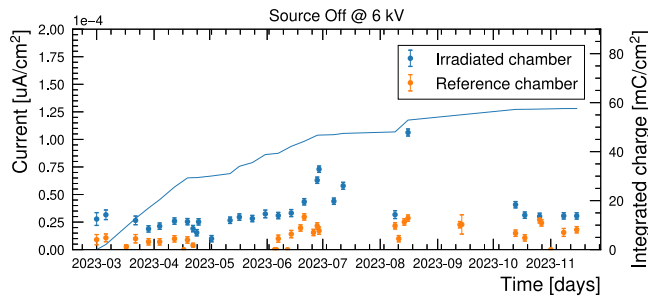


Fig. 4. Ohmic currents for an irradiated and reference chamber versus time. The currents were interpolated at 6 kV during source off scans. The solid line represents the charge integrated by the irradiated detector. The errors represent the statistical error due to the reading of the currents from the power supply.

effects. The goal of the experimental campaign was to firstly integrate about 30 mC/cm², roughly corresponding to the expected integrated charge of the ATLAS RPC system during Run 3. The second goal, for which the data taking is still ongoing, consisted instead in evaluating the performance of the detector after integrating the amount of charge expected in the highest intensity sectors of the CMS and ATLAS RPC systems during the High-Luminosity LHC phase. One detector was found to have an inborn defect, while the remaining two showed no significant differences between each other. For simplicity, the experimental results will be reported for the detector at the closest position to the source.

During the irradiation period, the detectors in the trolley closer to the source were kept at about 9 kV, while the detector at 12 m from the source and the one in the preparation area were kept at about 9.4 kV, corresponding to the working point.

The detectors inside the bunker were irradiated when the GIF++ source was on and a voltage scan was performed when the source was put off for weekly access. The currents were then evaluated by interpolation at 6 kV, where no charge multiplication happens and the current flow is only due to the resistive components of the detector such as the spacers or the borders of the frame. In addition, the current at working point was also evaluated: in this case, the current was interpolated at about 9400 V and the ohmic current was subtracted.

Fig. 4 shows the behaviour of the ohmic current density versus time for one of the chambers closest to the source. The integrated charge is reported to show that about 60 mC/cm² were accumulated. In addition, the currents of the reference chamber in the preparation area are reported in the plot. It could be observed that until about 100 days and 30 mC/cm² the current behaviour was constant. After 100 days a slight increase of the currents was observed for both detectors, although the irradiated chamber showed a more significant increase. One hypothesis could be due to some impurities or pollutants that entered in the chamber during its operation, since mechanical interventions were performed over that period. The chamber was kept on at 6 kV for several days and a decrease of the currents was observed. The ohmic currents of the detector after 250 days and 60 mC/cm² were comparable with the ones of the initial days of test, suggesting no aging effects are observed.

Fig. 5 shows instead the currents evaluated at detectors working points, from which the ohmic current component was subtracted. Both detectors showed stable behaviour until 100 days of irradiation. After that period, both the reference chamber and the irradiated one started showing an increase in the currents. This behaviour is under investigation; the increase of currents in the reference RPC at the same time of the irradiated RPC suggests that external factors such as the gas quality or non-monitored environmental parameter affected both detectors.

The performance of the detectors were also evaluated throughout the irradiation campaign by measuring the muon beam efficiency, the maximum efficiency reached by the detectors at different gamma rates and the detectors currents at different backgrounds.

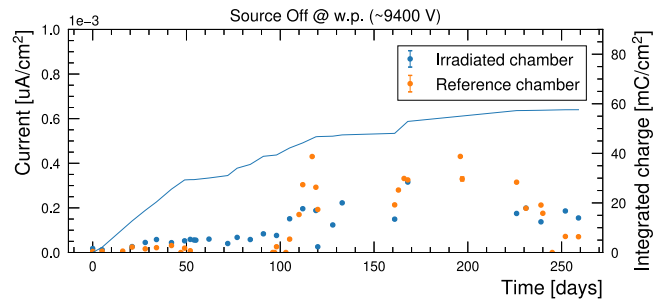


Fig. 5. Physics currents for an irradiated and reference chamber over time. The currents were interpolated at working point of about 9.4 kV during source off scans. The solid line represents the charge integrated by the irradiated detector. The errors represent the systematics due to the reading of the currents from the power supply crate.

Fig. 6 shows that the muon efficiency and the working point of the detector were constant over the irradiation campaign. A slight difference in the low efficiency region can be observed: the alignment of the detector sensitive area was different during the different beam periods. When looking at the maximum efficiency extracted as a parameter of the sigmoid fit, no significant differences were found between the different muon beam periods. Concerning the currents obtained at working point versus different background conditions, no significant differences were observed, except for the ones taken during the last irradiation campaign, where the currents at 300 Hz/cm² are about 6% higher than the ones taken during previous beam periods. Future muon beam campaign will allow to confirm if such behaviour is a sign of detector performance degradation or if other systematics errors were contributing to the data and were not considered.

4.1. Resistivity measurements

One key parameter in High-Pressure-Laminate RPCs is the bulk resistivity of the electrodes. A constant resistivity ensures the desired rate capability. In the past, signs of performance loss of the detectors were studied and correlated with the resistivity of the bakelite plates and graphite coatings [12]. Different methods were used to have an estimated value of the resistivity. A common approach is to fill the detector with Argon and perform voltage-currents scans. Above a certain breakdown voltage, Argon behaves as a conducting plasma and the current behaviour is mostly ohmic, giving an estimate of the bulk resistivity of the detector. A second approach was to estimate the resistivity by observing the shift in the efficiency curves when operating the detector at different background conditions. The voltage in the gap can be expressed as $HV_{gap} = HV_{eff} - R_{bulk} * I$, where HV_{eff} is the effective applied voltage to the electrodes, R_{bulk} is the bulk resistivity and I is the current flowing through the RPC.

Table 1 shows the comparison between the two methods of resistivity measurements. It can be observed that before the beginning of the tests the resistivity measured with Argon was around $4.5 \cdot 10^{10} \Omega \text{ cm}$. After 30 mC/cm² the two measured resistivities gave results compatible within the experimental errors and showed a general increase in the resistivity: a possible explanation could be related either to a wrong initial estimation of the resistivity due to an incorrect conditioning of the detector, or to an effective increase of the resistivity of the detector. However, after about 57 mC/cm² the resistivity of the RPC went back to the initial measured values, suggesting that some uncontrolled parameters such as the environmental humidity may have contributed to a temporary change of the resistivity in the first periods of the irradiation campaign.

A high rate model [13] was used to fit the voltage-current curves of the irradiated detectors at nominal background radiation. The fit function used can be expressed as

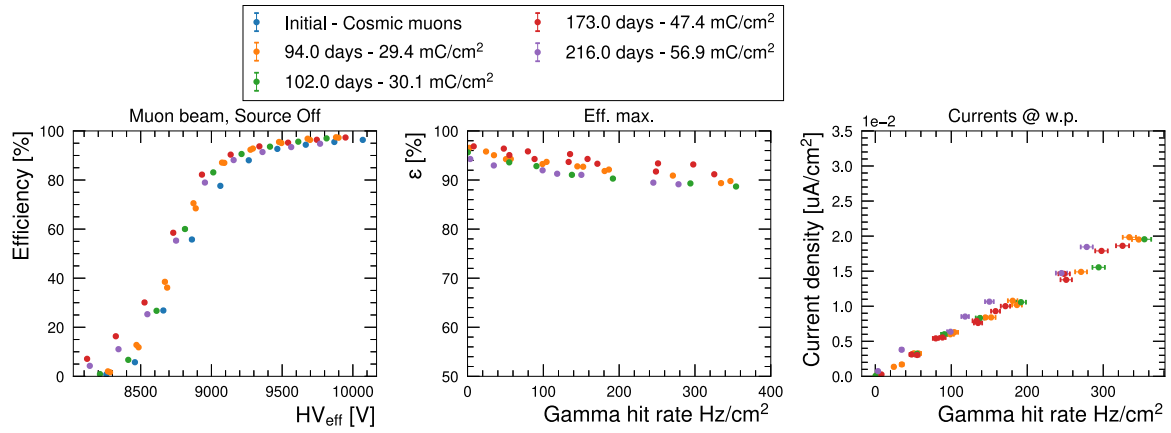


Fig. 6. On the left, efficiency curves versus effective voltage taken at different periods of the experimental campaign for one of the irradiated detectors. In the middle: maximum efficiency obtained from the fit of the efficiency curve of the detector versus gamma hit rate. On the right: gamma background currents evaluated at working point versus rate for the same detector and taken at the same periods of the irradiation campaign.

Table 1

Resistivity measurements taken with different methods. Empty cells are displayed where no data was taken with the mentioned technique.

Time	Integrated charge	ρ (measured from efficiency curves)	ρ (measured with Argon, T=21 °C)
Initial	0 mC/cm ²		$4.5 \pm 0.5 \cdot 10^{10} \Omega\text{cm}$
94 days	29.4 mC/cm ²	$8 \pm 0.5 \cdot 10^{10} \Omega\text{cm}$	$8.5 \pm 0.5 \cdot 10^{10} \Omega\text{cm}$
102 days	30.1 mC/cm ²	$7.5 \pm 0.5 \cdot 10^{10} \Omega\text{cm}$	
173 days	47.4 mC/cm ²	$6.0 \pm 1.0 \cdot 10^{10} \Omega\text{cm}$	$5.0 \pm 1.0 \cdot 10^{10} \Omega\text{cm}$
216 days	57 mC/cm ²	$5 \pm 0.5 \cdot 10^{10} \Omega\text{cm}$	

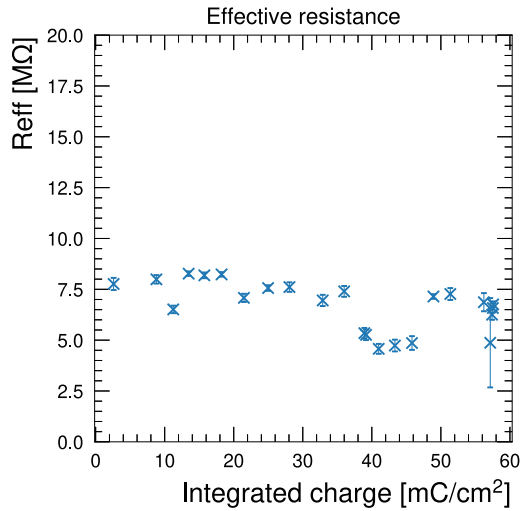


Fig. 7. Calculated value of R_{eff} from the voltage scans taken at fixed source on conditions.

$$I(V) = \frac{1}{R_{eff}} \left(\frac{\sigma_t}{\sqrt{2\pi}} \cdot e^{-\frac{1}{2} \left(\frac{V-V_t}{\sigma_t} \right)^2} + \frac{1}{2} \cdot (V - V_t) \cdot \left(1 + \operatorname{erf} \left(\frac{V - V_t}{\sqrt{2} \cdot \sigma_t} \right) \right) \right)$$

where R_{eff} is a fit parameter giving an indication of the electrode and gas resistivity at high particle fluxes, σ_t describes the spread of the knee of the curve, and V_t is a threshold voltage at which the background particle flux start to contribute to the charge multiplication in the gas gap.

Fig. 7 shows no significant trends in the effective value of R_{eff} . At about 40 mC/cm², R_{eff} seems to drop from 7.5 to 5 MΩ, although the values comes back to 7.5 MΩ at 50 mC/cm², suggesting that the change could be related to variation on the irradiation conditions, such as the shielding due to the detector between the source and the detector.

5. Conclusions

Several alternative gas mixtures were tested to evaluate the possibility of reducing the consumption of R-134a from HPL RPCs at the CERN LHC experiments. The addition of CO₂ to the Freon-based gas mixture was identified as a possible short-to-medium solution to mitigate the emissions. 30% and 40% of CO₂ were added to the standard gas mixture, with the SF₆ concentration tested in concentrations up to 2%. Of all the tested alternatives, a conservative gas mixture with 30% CO₂ and 1% SF₆ was chosen for long term studies. About 60 mC/cm² were integrated and several parameters were studied to understand about possible aging effects. No signs of performance loss or aging were observed on the detectors, indicating that the CO₂-based gas mixture could be a suitable mid-term solution for LHC Run 3 and beyond. For the High Luminosity LHC phase, the detector will have accumulated several times more integrated charge than what was achieved with the current tests. For this reasons, the longer term studies are required and are currently ongoing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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