Nuclear Inst. and Methods in Physics Research, A 1049 (2023) 168088

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Performance studies of RPC detectors operated with $C_2H_2F_4$ and CO_2 gas mixtures

Gianluca Rigoletti *, Roberto Guida, Beatrice Mandelli

CERN, Switzerland

ARTICLE INFO

Keywords:
Gaseous detectors
Resistive-plate chambers
Greenhouse gases
Environmental-friendly gases
Gas systems and purification

ABSTRACT

Resistive Plate Chambers detectors are largely employed at the CERN LHC experiments thanks to their excellent trigger performances and contained costs. They are operated with a gas mixture made of 90%–95% of $C_2H_2F_4$, that provides a high number of ion–electron pairs, about 5% of i-C_4H_{10}, that ensures the suppression of photon-feedback effects, and 0.3% of SF_6, used as an electron quencher to further operate the detector in streamer-free mode. $C_2H_2F_4$ is known to be a Greenhouse gas, with a global warming potential (GWP) of 1430. CERN has identified several strategies to reduce the consumption of greenhouse gas emissions from particle detectors at LHC experiments. One research line is focused on the study of alternatives to $C_2H_2F_4$. In this context, a conservative approach for the next years of LHC operation could be to focus on reducing the GWP of the RPC gas mixture by only adding CO_2 and not using new gases, whose effects on detector long-term operation have to be studied. The RPC performance with standard gas mixture with the addition of 30%–50% of CO_2 (and SF_6 concentration between 0.3 and 0.9%) were studied both in laboratory set-up and at the CERN Gamma Irradiation Facility in presence of muon beam and gamma background radiation. Encouraging results were obtained showing that the addition of CO_2 to the standard gas mixture can represent a mid-term solution to reduce emissions and lower operational costs by keeping stable detector performance and safe long-term operation.

1. Introduction

Resistive Plate Chamber detectors are particle gaseous detectors [1] widely employed in the muon systems of the ALICE, ATLAS and CMS experiments. Trigger RPCs are made of High Pressure Laminate material. The electrode thickness is 1.8 mm for the ATLAS chambers and 2 mm for the ALICE and CMS ones [2–4]. The gas gap is 2 mm for all detectors currently installed at the LHC experiments. RPCs are operated with a three component gas mixture and 40% relative humidity. The major component is $C_2H_2F_4$, also known as R-134a, in a fraction of 95% (90% for ALICE MID) that is necessary to provide a high number of primary ion–electron pairs and therefore to ensure high detection efficiency for the detectors. An amount of about 5% (10% for ALICE MID) of i-C_4H_{10} is added to the detector as a photon quencher to reduce photon-feedback effects from primary avalanches. A small amount of 0.3% of SF_6 is added to the gas mixture to suppress the presence of streamers and operate the detector in avalanche mode. Both R-134a and SF_6 are known to be greenhouse gases, with a Global Warming Potential (GWP) over 100 years (GWP_{100}) of respectively 1430 and 22,800 [5]. To reduce emissions of these gases, RPCs are operated with gas recirculation systems at 90% [6]. However, during LHC Run 2 ATLAS-RPC and CMS-RPC experiments accounted for 87% of CERN Greenhouse gases (GHG) emissions of particle detectors due to the presence of leaks at detector level [7].[1]

The European Union (EU) set a (EC) No. 517/2014 F-gas (fluorinated-gas) regulation starting from the 1st of January 2015 that can be summarized in the following points [8]:

- Limiting the total amount of the 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.

The F-gas industry response led to a decrease on the availability and an increase of price of high-GWP fluorinated gases [9]. The reduction of GHG consumption is a fundamental research activity for the next

* Corresponding author.
E-mail address: gianluca.rigoletti@cern.ch (G. Rigoletti).

[1] A campaign of leaks reparation was conducted during LS2 and it is currently performed during planned LHC technical stops.

[2] This applies for ATLAS and CMS RPC systems but not for the ALICE MID system where there is already in use a flammable gas mixture.

https://doi.org/10.1016/j.nima.2023.168088
Received 24 September 2022; Received in revised form 23 January 2023; Accepted 23 January 2023
Available online xxxx

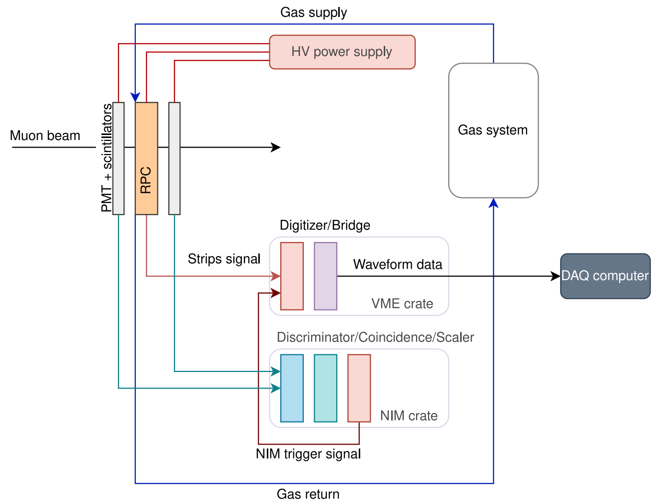

Fig. 1. Schematic view of the experimental set-up.

decades of CERN operation, as well as applications for future gaseous detectors.

CERN has defined several strategies to reduce GHG emissions from particle detectors at LHC experiments [10]. One of the main research branches is the study of alternative gases to R-134a, SF_6 and CF_4. The search for an eco-friendly gas mixture plays a fundamental role to reduce GHG emissions and contain operational costs. However, several requirements must be met for a new gas mixture for the LHC experiments. High voltage cables and electronics, as well as the detector themselves, cannot be changed in the LHC experiments and therefore the RPCs performance with the new gas mixtures has to match or to be very similar to that the current gas mixture. Furthermore, due to safety requirements, the gas mixture must not be flammable[2] and should not be toxic.

2. Experimental set-up and data analysis

The detector performance tests were carried out on three High Pressure Laminate (HPL) RPCs with a 2 mm HPL-plate thickness, 2 mm gas gap and a surface area of 70×100 cm^2. Each detector was equipped with a set of copper strips for signal readout, with a pitch 2.5 cm. The detectors were installed at the CERN Gamma Irradiation Facility (GIF++) [11] to evaluate the performance in the presence of both muon beam and gamma background radiation, emulating the background conditions at the LHC experiments. A dedicated mixing unit was used to compose the required gas mixtures. Each chamber was flushed in order to have about one gas volume exchange per hour. A humidifier module was used to add water vapour in the gas mixture: the gas was kept at 4 °C of dew point during the tests. Two sets of scintillators were used as an external trigger system for muons, covering a surface area equivalent to around 7 RPC strips. The signal from the strip was directly read out by a CAEN Digitizer V1730, which recorded the waveform for each strip, thus allowing to measure the foremost detector parameters, such as induced prompt charge, arrival time, cluster size and time over threshold (see Fig. 1). .

2.1. Data analysis

The raw data acquired with the CAEN Digitizer V1730 consisted of a set of 520 samples recorded over a time window of 1.04 μs. For each trigger event, 7 strips of each RPCs were read out at the same time. The baseline of each waveform signal was calculated in the first 200 ns of the window, while the region from 250 ns up to the end of the window was used to detect muon signals. A threshold of 2 mV was used for muon detection to ensure a working point of 9.4–9.6 kV for the standard gas mixture, which is compatible with the working point of the current RPC systems in ATLAS and CMS [12]. For each detected signal, the prompt charge was calculated by summing the collected charge across the active strips of the detector. A threshold of 10^8 electrons was used to discriminate between an avalanche signal and a streamer one.

[2] This applies for ATLAS and CMS RPC systems but not for the ALICE MID system where there is already in use a flammable gas mixture.

Table 1
Resistivity values of the HPL plates of the three RPCs used for all measurements performed.

RPC	Rho [10^{10} Ohm cm]
7	4.2 ± 0.1
8	2.5 ± 0.1
10	1.2 ± 0.1

For each trigger event, the cluster size was computed as the maximum number of adjacent strips over which the ionizing particle was detected. The time resolution was computed as the difference of the arrival time of the muon signal with respect to the external trigger. The time over threshold was calculated as the time between the first and the last samples crossing the detection threshold. For each voltage point, 10,000 trigger events were recorded and the detector currents were read from the HV power supply module. The muon efficiency was calculated for different applied electric fields, as well as the streamer probability, defined as the number of streamers over the total number of detected events. For each run, about 10 voltage points were collected to allow to properly fit the efficiency curve with the formula:

$$\epsilon = \frac{\epsilon_{max}}{1 + e^{-\lambda(HV_{eff} - HV_{50})}} \quad (1)$$

where ϵ_{max} is the maximum efficiency, HV_{eff} is the applied voltage and HV_{50} is the voltage at 50% efficiency. From (1) the knee was defined as the voltage value at which the efficiency reaches 95% of the ϵ_{max} and the working point was defined as the knee with the addition of 150 V.

The foremost parameters described were then evaluated at the working point to compare the performance of the detector in LHC-like conditions. When operated with muon beam only, two additional parameters were computed: the first was the ΔV between the working point and the voltage at which the streamer probability reaches a value of 10%, while the second was the variation of the streamer probability when evaluated at the working point ±50 V. When operated under gamma background radiation, the hit rate was measured by counting the number of induced signals across the strips of the detector over a time window large enough to properly estimate the background rate.

3. Investigation on addition of inert gases to the RPC standard gas mixture

As a starting point, the CMS gas mixture, named standard gas mixture for simplicity and made of 95.2% $C_2H_2F_4$, 4.5% i-C_4H_{10} and 0.3% SF_6, with 40% of relative humidity[3] was used to evaluate the initial performance of each detector and have a reference set of parameters to be used for relative performance comparison against different gas mixtures. The electrical resistivity of the HPL material of each RPC was measured before the conducted tests as a different resistivity could imply different detector performance. The values of the resistivity are reported in Table 1. The performance of the three RPCs were found to be consistent between each other. For this reason, in the following sections the performance are reported only for one detector.

[3] The ATLAS gas mixture has 5% of i-C_4H_{10} for which the charge development dynamics should not significantly differ from the CMS gas mixture.

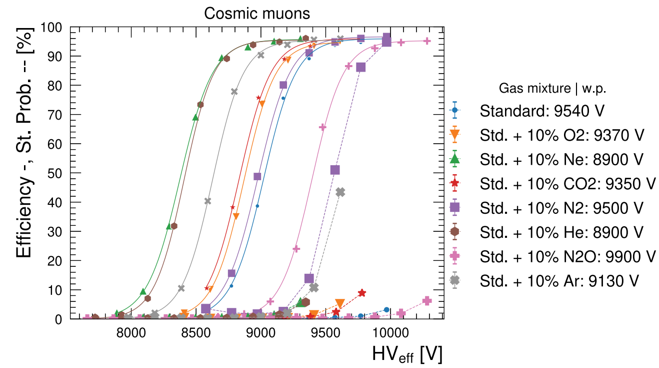

Fig. 2. Efficiency (full lines) and streamer probability (dashed lines) curves for the addition of seven different gases in a concentration of 10% to the standard gas mixture: N_2, O_2, CO_2, Ne, He, Ar and N_2O.

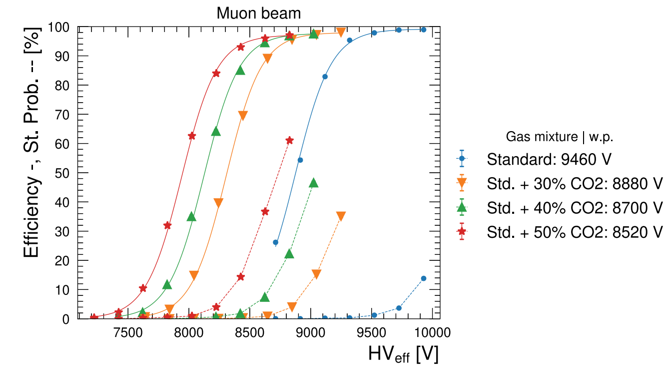

Fig. 3. Efficiency (full lines) and streamer probability (dashed lines) curves of the standard gas mixture and the gas mixture with the addition of 30%, 40%, 50% of CO_2.

The aim of the current work was to lower the GWP of the gas mixture by maintaining very similar or same detector performance as the standard gas mixture. In particular, the current research was focused on the addition of a possible inert gas to the standard gas mixture that results in performances as close as possible to the standard gas mixture. The idea was to check if the gas added could affect detector performance and if not until what concentration. Ar, CO_2, He, Ne, O_2, N_2 and N_2O were chosen as possible candidates. An initial amount of 10% for each gas was added to the standard gas mixture. Fig. 2 shows the efficiency curves and the streamer probability obtained with cosmic muons for the different gas mixtures.

The gas chosen is CO_2 because, even if it is used as quenching gas for wire chambers and Multi-Pattern Gaseous Detectors, it shows a different energy range of photon absorption when compared to i-C_4H_{10} [13,14]. Helium was discarded because it cannot be used in LHC experiments due to the presence of photomultipliers [15] but otherwise it could be considered as a good alternative. The addition of 10% of Ne was found to lower the working point by about 700 V. However, the gas was not considered for further testing due to its current restricted availability and high market price. O_2 also showed performance similar to CO_2 in terms of working point and streamer contamination. However, O_2 is a comburant, thus it lowers the flammability limits of the standard gas mixture, possibly making it not suitable for LHC operation. Also, the currents of the detector during data taking were observed to have a slow drift trend: one possible explanation could be related to the high number of oxidation reactions taking place in the detector when operated at full efficiency. Also N_2 was investigated but even 10% was enough to get 35% of streamers at working point and therefore it was discarded. N_2O was tested, showing relatively stable performance, but the working point of the gas mixture was around 300 V higher than the standard one, making the candidate difficult to be used in higher concentrations.

4. RPC performance using standard gas mixture with the addition of CO_2

The RPC performances with the addition of CO_2 were evaluated in comparison with the standard gas mixture. The studies on the addition of CO_2 to the RPC standard gas mixture were conducted in two steps. Initially, 30%, 40% and 50% of CO_2 was added to the standard gas mixture to study the foremost parameters of the detectors. A second test was performed and detailed in Section 5 to investigate if the resulting performance loss from increasing CO_2 concentration could be mitigated by increasing the SF_6 amount in the gas mixture: for each CO_2 concentration, the SF_6 was tested in concentrations of 0.3%, 0.6% and 0.9%. Fig. 3 shows the efficiency and the streamer probability curves for the standard gas mixture and the three CO_2 based gas mixtures.

The working point of the CO_2-based gas mixture is shifted towards lower voltages with respect to the standard gas mixture: each addition of 10% CO_2 implies 190 V of shift of working point. It can be noted that the streamer fraction is higher for the CO_2 based gas mixtures, and even better visible in Table 2 where the streamer probability at working point is reported for the different CO_2 concentrations.

When using 30% of CO_2 the streamer probability is about 6%, while for the standard gas mixture is 1%. When 50% CO_2 is added to the standard gas mixture, the streamer fraction is more than 20%. The avalanche and streamer signal formation was also studied in detail. Fig. 4 shows the charge distribution of the four gas mixtures at working point. It could be observed that when adding CO_2, two, avalanche-sized populations are present: the first distribution shows a peak around 1 pC, while the second has a peak at 2–3 pC. Furthermore, the first avalanche peak slightly shifts towards lower charge values with the increase of CO_2 concentration. Investigation of the phenomenon are under study, although simulations on this gas mixture may be required to better understand the dynamics of the signal formation. The mean streamer charge distribution for the 30% CO_2 is around 70 pC, similar to the standard gas mixture. When 50% CO_2 is added to the standard gas mixture, signals of more than 100 pC are present. For this reason the 50% CO_2 gas mixture was discarded. The time resolution was carefully investigated and it was observed that it is slightly enhanced with the CO_2 gas mixtures. This could be explained by a higher electron mean free path that is increasing due to the lower amount of fluorine in the gas mixture, resulting in signals with a faster rise time. Concerning the cluster size, an increase of 0.25 cm was observed for each addition of 10% of CO_2, as reported in Table 2. Fig. 5 shows the mean value of the time over threshold distribution versus the effective voltage relative to the working point. The mean time over threshold for CO_2 gas mixtures is significantly increasing with the amount of CO_2. Concentrations above 40% of CO_2 show signals with a mean time over threshold at working point higher than 25 ns, a value corresponding to the bunch crossing period of the LHC beam [16].

5. RPC performance with CO_2 and different SF_6 concentrations

Three concentrations of SF_6 were tested to investigate if this gas could help suppress streamers signals related to the mobility of free electrons. For each concentration of CO_2, 0.3%, 0.6% and 0.9% of SF_6 was added to the gas mixture. Fig. 6 shows the ΔV between the working point and the voltage at which the streamer probability is 10% for all gas mixtures tested. The standard gas mixture shows the best avalanche–streamer separation performances, while the 30% of CO_2 with 0.6% and 0.9% of SF_6 and the 40% of CO_2 with 0.9% show the highest separation among the gas mixtures tested, suggesting that an increased amount of SF_6 could help suppress the fraction of streamer signals.

Table 2
Foremost parameter values for the addiction of 30, 40, 50% of CO2 to the standard gas mixture.

Gas mixture	Time resolution	Cluster size [2.5 cm]	Time over threshold	Streamer probability	Mean avalanche charge	Mean streamer charge
Standard	1.8 ns	1.3	13.3 ± 0.3 ns	0.8% ± 0.1%	1.9 ± 0.01 pC	70.4 ± 0.4 pC
30% CO2	1.6 ns	1.4	29.6 ± 0.7 ns	6.1% ± 0.2%	2.5 ± 0.01 pC	72.4 ± 0.5 pC
40% CO2	1.6 ns	1.5	51.0 ± 1.0 ns	13.5% ± 0.3%	2.7 ± 0.01 pC	86.1 ± 0.7 pC
50% CO2	1.6 ns	1.7	91.1 ± 1.4 ns	24.9% ± 0.4%	3.2 ± 0.1 pC	119.9 ± 1.3 pC

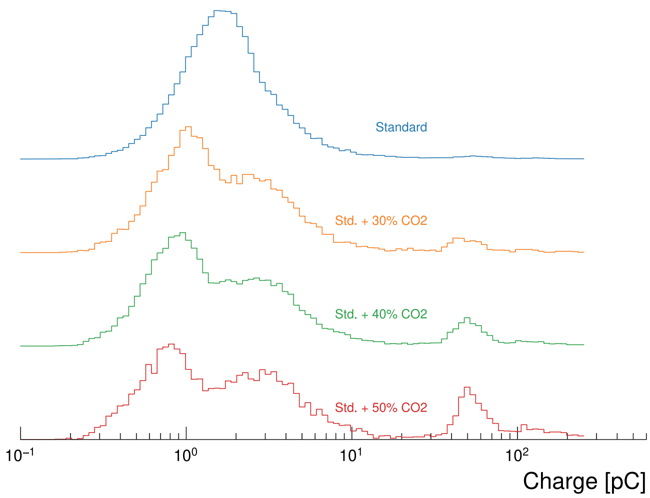

Fig. 4. Prompt charge distribution for the standard gas mixture compared with the addition of 30, 40, 50% of CO_2 at detector's working point.

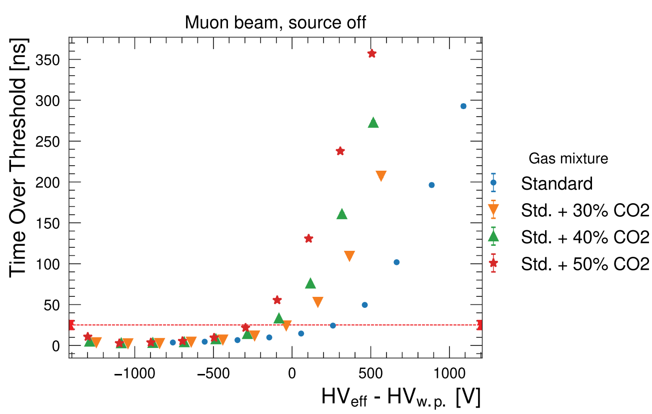

Fig. 5. Mean Time Over Threshold versus the effective voltage subtracted by the HV working point for the standard gas mixture and gas mixtures with 30, 40, 50% of CO_2 added.

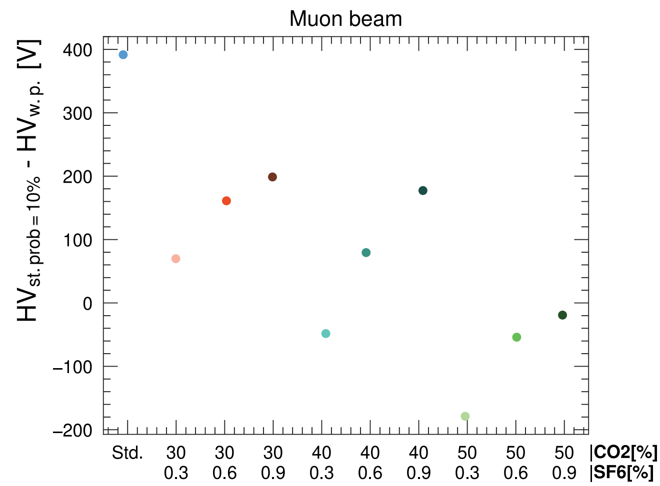

Fig. 6. Avalanche-streamer separation with muon beam for the standard gas mixture and the gas mixture with 30%, 40%, 50% of CO_2 in combination with 0.3%, 0.6%, 0.9% of SF_6.

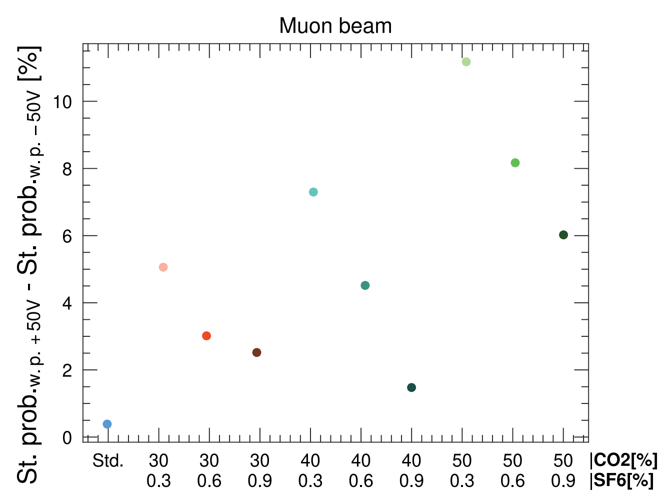

Fig. 7. Streamer probability variation with muon beam for the standard gas mixture and the gas mixture with 30%, 40%, 50% of CO_2 in combination with 0.3%, 0.6%, 0.9% of SF_6.

Fig. 7 shows the streamer variability for all the gas mixtures. Similarly to the efficiency–streamer separation, the best gas mixture remains the standard gas mixture while the addition of CO_2 increases these streamer variability. Also in this case, the gas mixtures closer to the standard gas mixture are the ones with 30% CO_2 and 0.6 and 0.9% SF_6 and with 40% CO_2 and 0.9% SF_6.

For these selected gas mixtures, the charge distribution was plotted in Fig. 8 to check for possible differences with different CO_2 and SF_6 concentrations. It is for example visible that by increasing the SF_6 concentration from 0.6% to 0.9% in the 30% CO_2 gas mixture, the difference between the two avalanche peaks is less pronounced and the first peak shifts towards the same values of the standard gas mixture. The 40% CO_2 gas mixture with 0.9% of SF_6 shows instead a similar charge distribution to the 30% CO_2 gas mixture with 0.6% of SF_6.

The mean time over threshold of the three selected gas mixtures is reported in Fig. 9. As it can be observed, both the 30% CO_2 and 40% CO_2 gas mixtures shows an average time less than or equal to 25 ns, making the gas mixture suitable for an LHC-like environment.

Due to the mentioned foremost parameters, the gas mixtures with 30% of CO_2 and 0.6%, 0.9% of SF_6 together with the gas mixture with 40% and 0.9% of SF_6 were further studied with muon beam and gamma background in Section 6. Table 3 reports the foremost parameters observed for the selected gas mixture in muon beam only conditions. The time resolution is around 0.2 ns lower for the CO_2-based gas mixtures, while the cluster size does not show any significant difference from the standard gas mixture. The mean time over threshold and streamer probability values are higher for the three selected gas mixtures, with a tendency to decrease when increasing the SF_6 amount. The mean avalanche and streamer charges were also found to be 10% to 20% higher with respect to the standard gas mixture.

Table 3
Foremost parameter values for the selected gas mixtures operated at working point and with muon beam only.

Gas mixture	Time resolution	Cluster size [2.5 cm]	Time over threshold	Streamer probability	Mean avalanche charge	Mean streamer charge
Standard	1.8 ns	1.3	13.3 ± 0.3 ns	0.8% ± 0.1%	1.9 ± 0.01 pC	70.4 ± 0.4 pC
30% CO2 + 0.6% SF6	1.6 ns	1.4	26.3 ± 0.7 ns	3.9% ± 0.2%	2.4 ± 0.01 pC	102.5 ± 1.1 pC
30% CO2 + 0.9% SF6	1.6 ns	1.3	24.6 ± 0.7 ns	2.9% ± 0.2%	2.4 ± 0.01 pC	99.9 ± 0.9 pC
40% CO2 + 0.9% SF6	1.6 ns	1.3	23.5 ± 0.6 ns	3.0% ± 0.2%	2.1 ± 0.1 pC	86.0 ± 0.8 pC

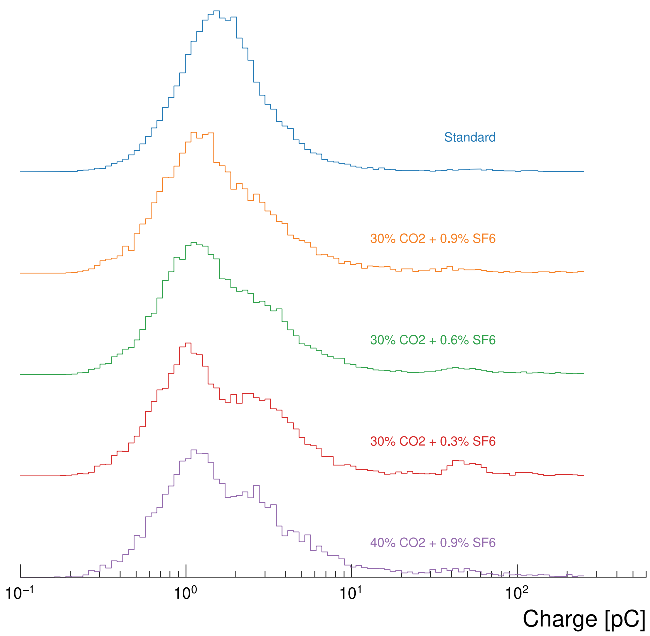

Fig. 8. Prompt charge distribution for the standard gas mixture and the selected CO_2 gas mixture with the 0.6% and 0.9% of SF_6.

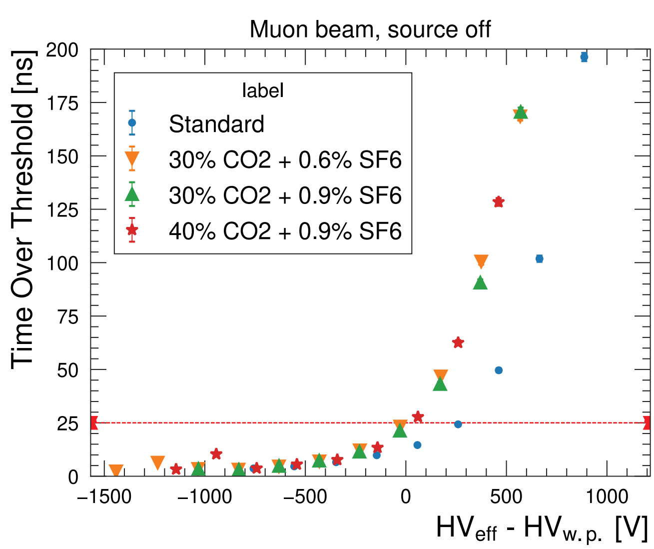

Fig. 9. Mean time over threshold of the standard and selected CO_2 gas mixtures. An horizontal red dash line is set at the LHC collision period of 25 ns.

6. Evaluation of RPC performance in presence of LHC-like background radiation for the selected CO_2-based gas mixtures

As this research was mainly focused on alternative gas mixtures for RPC detectors at LHC experiments, it was fundamental to evaluate detector performance in presence of LHC-like background radiation. RPCs parameters were evaluated for all the different gas mixtures at GIF++ in presence of muon beam and with different background

Table 4
Measured gamma hit rates for the different tested GIF++ ABS filters.

ABS filter	Min. rate [Hz/cm^2]	Max. rate Hz/cm^2
2.2	540	600
3.3	490	530
4.6	330	390
10.0	200	230
22.0	110	120

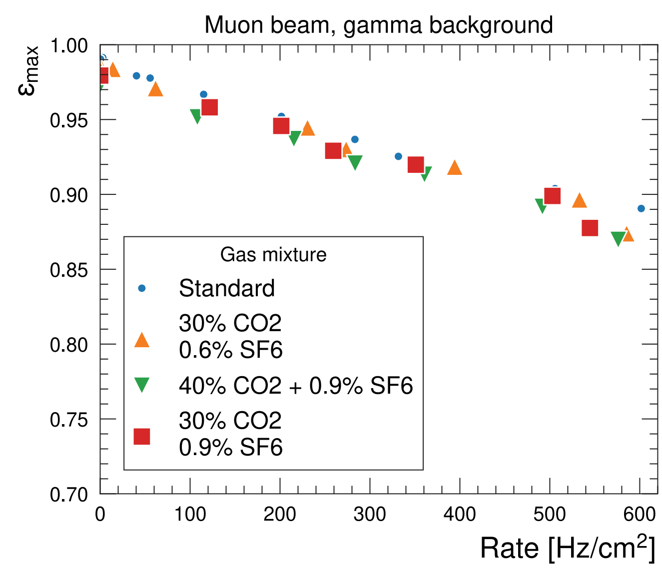

Fig. 10. Maximum muon efficiency versus gamma hit rate for the standard gas mixture and the three selected CO_2 gas mixtures.

radiations, up to a gamma rate of 600 Hz/cm^2, which is the maximum rate foreseen in CMS RPC Endcap region for the High Luminosity LHC Phase [17,18].

The measured minimum and maximum gamma hit rate for each ABS factor is reported in Table 4. The highest ABS 22 corresponded to a measured gamma rate of 110–120 Hz/cm^2 while ABS 2.2 resulted in a gamma rate of 540–600 Hz/cm^2. . Table 5 reports the maximum efficiency, gamma hit rate, background currents, cluster size and time resolution of the selected gas mixtures measured with highest irradiation settings.

Fig. 10 shows the maximum efficiency reached by the detectors as a function of the gamma hit rate for the selected gas mixtures. Up to 500 Hz/cm^2 no major degradation is visible for the CO_2 based gas mixtures with respect to the RPC standard gas mixture, suggesting that all the RPC can be operated at full efficiency under high rate conditions.

Fig. 11 summarizes the detector currents at the different used ABS filters. The RPC currents are the lowest using the standard gas mixture and about 20% higher with the CO_2 based gas mixture, with a tendency to increase together with the CO_2 concentration. The increase of current can be due to the increase of streamer signals and to the less presence of $C_2H_2F_4$ that helps in capturing free electrons. Also, the currents with SF_6 at 0.9% were slightly higher than the ones with 0.6% of SF_6. A possible explanation could be related to the relatively high electronic threshold: as the SF_6 is increased, the required electric field to detect muons is shifted towards higher values since the average

Table 5
Foremost parameters of the selected gas mixtures evaluated at working point and with ABS filter of 2.2.

Gas mixture	ϵ_{max}	Gamma rate	Currents	Cluster size [2.5 cm]	Time resolution
Std.	89.1% ± 0.2%	602 Hz/cm^2 ± 12 Hz/cm^2	245 uA ± 1 uA	1.31 ± 0.05	1.94 ns ± 0.05 ns
30% CO_2 + 0.3% SF_6	87.4% ± 0.2%	585 Hz/cm^2 ± 12 Hz/cm^2	292 uA ± 1 uA	1.34 ± 0.05	1.62 ns ± 0.05 ns
30% CO_2 + 0.9% SF_6	87.8% ± 0.2%	545 Hz/cm^2 ± 11 Hz/cm^2	284 uA ± 1 uA	1.37 ± 0.05	1.60 ns ± 0.05 ns
40% CO_2 + 0.9% SF_6	87.0% ± 0.2%	576 Hz/cm^2 ± 11 Hz/cm^2	300 uA ± 1 uA	1.31 ± 0.05	1.61 ns ± 0.05 ns

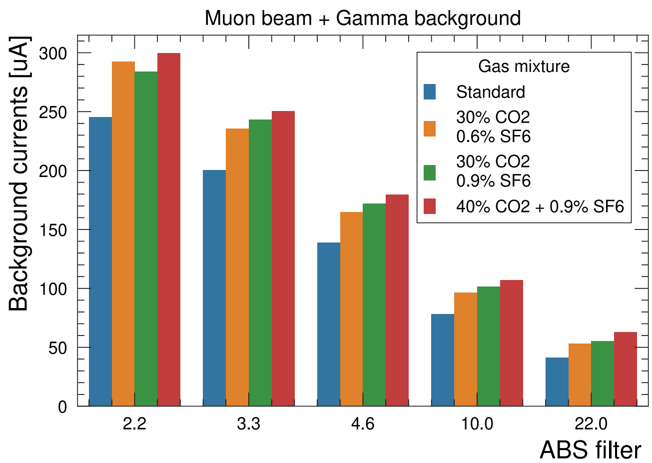

Fig. 11. Gamma background currents evaluated at working point for different ABS filters. In the present case, ABS 22 corresponds to a gamma hit rate of.

charge distribution tends to decrease. However, the recorded currents are the macroscopic effects of the charge induced by a high flux of particles, without any threshold discrimination applied. This could result in a higher-SF_6 gas mixture with a shift of working point towards voltages higher than the ones that have the same background-induced charge of a gas mixture using a lower amount of SF_6.

Concerning the cluster size, no significant differences were observed at high rates with respect to the standard gas mixture, indicating that CO_2 is not significantly affecting the transversal size development of the signal along the RPC gap. The time resolution was observed to be consistent with the muon beam only conditions, showing slightly higher values for the standard gas mixture and lower values for the CO_2-based gas mixtures.

7. Conclusions

In this work we have investigated possible alternative gas mixtures for the LHC RPC detectors as replacement of the standard gas mixture for the short–medium term period of the LHC schedule. The aim was to lower the GWP of the gas mixture, and therefore CERN GHG emissions, by maintaining very similar detector performance and by avoiding the use of new gases, like $C_3H_2F_4$, whose effects on detector longevity and ageing have to be investigated in long-term studies. The addition of a relatively inert gas to the RPC gas mixture was therefore investigated as a possible option. In particular, after studying different alternatives, CO_2 was selected as a promising candidate.

The addition of 30%, 40% and 50% CO_2 to the standard gas mixture was studied in details. The use of 50% CO_2 in RPC detectors brings to a large streamer fraction (20%) with muon beam and higher detector currents when evaluated under high gamma background rate. For this reason, 30% and 40% CO_2 gas mixtures were selected as possible candidates and the amount of SF_6 was slightly increased as it was observed it helps to contain the charge development, resulting in lower detectors currents. Although the increased amount of SF_6, the GWP_{100}, normalized by the density of the gas molecules of the selected gas mixtures, is reduced by 30%–40% with respected to the standard gas mixture, depending on the choice of the CO_2 and SF_6 concentrations. The RPCs performances with the three selected CO_2 based gas mixtures showed similar results to the standard gas mixture, suggesting that these gas mixtures can be used as possible alternatives to the standard LHC gas mixture for the ATLAS and CMS experiments.

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.

Data availability

Data will be made available on request.

References

[1] R. Santonico, R. Cardarelli, Development of resistive plate counters, Nucl. Instrum. Methods Phys. Res. 187 (2) (1981) 377–380, http://dx.doi.org/10.1016/0029-554X(81)90363-3, URL https://www.sciencedirect.com/science/article/pii/0029554X81903633.
[2] J.G. Layter, The CMS Muon project: Technical design report, in: Technical Design Report. CMS, CERN, Geneva, 1997, URL http://cds.cern.ch/record/343814.
[3] ATLAS collaboration, ATLAS Muon spectrometer: Technical design report, in: Technical Design Report. ATLAS, CERN, Geneva, 1997, URL https://cds.cern.ch/record/331068.
[4] G. Martinez, The Muon spectrometer of the ALICE experiment, Nuclear Phys. A 749 (2005) 313–319, http://dx.doi.org/10.1016/j.nuclphysa.2004.12.059, arXiv:hep-ex/0410061.
[5] I.P. on Climate Change, Fourth Assessment Report: Climate Change 2007: The AR4 Synthesis Report, IPCC, Geneva, 2007, URL http://www.ipcc.ch/ipccreports/ar4-wg1.htm.
[6] M. Capeans, I. Glushkov, R. Guida, F. Hahn, S. Haider, Optimization of a closed-loop gas system for the operation of resistive plate chambers at the large Hadron collider experiments, Nucl. Instrum. Methods Phys. Res. A 661 (2012) S214–S221, http://dx.doi.org/10.1016/j.nima.2010.08.077, X. Workshop on Resistive Plate Chambers and Related Detectors (RPC 2010). URL https://www.sciencedirect.com/science/article/pii/S0168900210018516.
[7] M. Capeans, R. Guida, B. Mandelli, Strategies for reducing the environmental impact of gaseous detector operation at the CERN LHC experiments, Nucl. Instrum. Methods Phys. Res. A 845 (2017) 253–256, http://dx.doi.org/10.1016/j.nima.2016.04.067, Proceedings of the Vienna Conference on Instrumentation 2016. URL http://www.sciencedirect.com/science/article/pii/S0168900216302807.
[8] M. Schulz, D. Kourkoulas, Regulation (EU) No 517/2014 of the European parliament and of the council of 16 April 2014 on fluorinated greenhouse gases and repealing regulation (EC) No 842/2006, Off. J. Eur. Union 2014 (517) (2014) L150.
[9] K. Julia, G. Barbara, B. Stéphanie, Briefing Paper: HFC availability on the EU market, 2020, URL https://www.oekorecherche.de/en/node/276,
[10] R. Guida, B. Mandelli, R&D strategies for optimizing greenhouse gases usage in the LHC particle detection systems, Nucl. Instrum. Methods Phys. Res. A 958 (2020) 162135, http://dx.doi.org/10.1016/j.nima.2019.04.089, Proceedings of the Vienna Conference on Instrumentation 2019, URL https://www.sciencedirect.com/science/article/pii/S0168900219305716.
[11] R. Guida, GIF++: The new CERN irradiation facility to test large-area detectors for HL-LHC, in: 2015 IEEE Nuclear Science Symposium and Medical Imaging Conference, NSS/MIC, 2015, pp. 1–4, http://dx.doi.org/10.1109/NSSMIC.2015.7581874.
[12] CMS collaboration, The CMS Muon Project : Technical Design Report, Tech. Rep., CMS, CERN, Geneva, 1997, URL https://cds.cern.ch/record/343814.
[13] J.W. Au, G. Cooper, G.R. Burton, T.N. Olney, C. Brion, The valence shell photoabsorption of the linear alkanes, CnH2n+2 (n=1–8): Absolute oscillator strengths (7–220 eV), Chem. Phys. 173 (2) (1993) 209–239, http://dx.doi.org/10.1016/0301-0104(93)80142-V, URL https://www.sciencedirect.com/science/article/pii/030101049380142V.

[14] W. Chan, G. Cooper, C. Brion, The electronic spectrum of carbon dioxide. Discrete and continuum photoabsorption oscillator strengths (6–203 eV), Chem. Phys. 178 (1) (1993) 401–413, http://dx.doi.org/10.1016/0301-0104(93)85079-N, URL https://www.sciencedirect.com/science/article/pii/030101049385079N.

[15] J. Incandela, S. Ahlen, J. Beatty, A. Ciocio, M. Felcini, D. Ficenec, E. Hazen, D. Levin, A. Marin, J. Stone, L. Sulak, W. Worstell, The performance of photomultipliers exposed to helium, Nucl. Instrum. Methods Phys. Res. A 269 (1) (1988) 237–245, http://dx.doi.org/10.1016/0168-9002(88)90885-6, URL https://www.sciencedirect.com/science/article/pii/0168900288908856.

[16] O.S. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, P. Proudlock, LHC Design Report, in: CERN Yellow Reports: Monographs, CERN, Geneva, 2004, http://dx.doi.org/10.5170/CERN-2004-003-V-1, URL https://cds.cern.ch/record/782076.

[17] CMS collaboration, The Phase-2 Upgrade of the CMS Muon Detectors, Tech. Rep., CERN, Geneva, 2017, This is the final version, approved by the LHCC, URL https://cds.cern.ch/record/2283189.

[18] ATLAS collaboration, Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer, Tech. Rep., CERN, Geneva, 2017, URL https://cds.cern.ch/record/2285580.