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Joao Pedro Gomes Pinheiro, Mehar Ali Shah, Lucia Eiriz Sanchez, for the CMS Collaboration

Abstract

Resistive Plate Chamber (RPCs) detectors in the Compact Muon Solenoid (CMS) experiment operate with a gas mixture comprised of 95.2pct of C2H2F4, that provides a high number of ion-electron pairs, 4.5pct of iC4H10, that ensures the suppression of photon-feedback effects and 0.3pct of SF6, used as an electron quencher to further operate the detector in streamer-free mode. C2H2F4 is known to be a Greenhouse gas with a global warming potential (GWP) of 1430. Several ECO-friendly alternatives to C2H2F4 have been studied in the last few years. In this context, one short-mid term approach for the next years of the Large Hadron Collider (LHC) operation could be to focus on reducing the GWP of the RPC gas mixture by adding CO2 in the place of C2H2F4. The studies are done at CERN Gamma Irradiation Facility (GIF++) in the North Area of SPS, where a 13.6TBq radiation source and a muon beam from SPS are used to mimic the conditions of Phase-II of LHC. This work will present the performance of a 1.4mm gap RPC chamber with three different CO2 based mixtures (30pct and 40pct) with a high gamma background, as well as the perspectives to start the aging campaign for the best mixture.

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Performance of new CO2 based mixture in CMS Improved Resistive Plate Chambers in HL-LHC environment

João Pedro Gomes Pinheiro[a], Mehar Ali Shah[b], Lucía Eiriz Sánchez[c], on the behalf of CMS Muon Group

[a]*Rio de Janeiro State University, Rio de Janeiro, Brazil*
[b]*Universidad Iberoamericana, Mexico City, Mexico*
[c]*University of Dundee, Dundee, Scotland*

Abstract

Resistive Plate Chambers (RPCs) detectors in the Compact Muon Solenoid (CMS) operate with a gas mixture composed of 95.2% of $C_2H_2F_4$, which provides a high number of ion-electron pairs, 4.5% of iC_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. Consequently, several ECO-friendly alternatives to $C_2H_2F_4$ have been investigated in recent years. In this context, a short-mid term approach for the upcoming years of Large Hadron Collider (LHC) operation could be to focus on reducing the GWP of the RPC gas mixture by replacing $C_2H_2F_4$ with CO_2. The studies are conducted at the CERN Gamma Irradiation Facility (GIF++) in the North Area of the Super Proton Synchrotron (SPS), where a 13.6 TBq radiation source and a muon beam from SPS mimic the conditions of Phase-II of the LHC. This paper presents the performance of a 1.4mm gap RPC chamber with three different CO_2 based mixtures (30% and 40%) under high gamma background conditions with the perspectives for the longevity campaign.

Keywords: Gaseous detectors, Resistive-plate Chambers, eco-friendly gas mixtures

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1. Introduction

The Muon System of the Compact Muon Solenoid (CMS) comprises three types of detectors: Drift Tubes (DTs) in the barrel, Cathode Strips Chambers (CSC) in the endcaps, and Resistive-Plate Chambers in both regions, covering up to $|\eta| = 1.9$ in pseudorapidity (1). With over a thousand chambers, CMS RPCs feature double gap detectors operating in avalanche mode, where each gap consists of two 2 mm wide gas gaps between two high resistive High-Pressure-Laminate (HPL) electrodes with a 2 mm thickness. The high voltage applied to the HPL electrodes is responsible for the electrons shower from the gas ionization. The showering induces a current in the strip plane positioned between the gaps for signal readout (2). In view of the Phase-II Upgrade of the LHC, new improved RPC (iRPC) chambers and Gas Electron Multiplier (GEM) detectors will be installed in the forward region of CMS, as shown in Figure 1, increasing the pseudorapidity region up to $|\eta| = 2.8$. These iRPC chambers also feature double-gap designs, but with a narrower 1.4 mm gas gap and HPL electrodes measuring 1.4 mm in thickness, accompanied by a new Front-End boards enabling a charge threshold of up to 30 fC (3). The new iRPCs boast timing resolution superior to their predecessors ($< 150ps$) and are equipped with double readouts on both strip ends, enhancing granularity in the η direction (4).

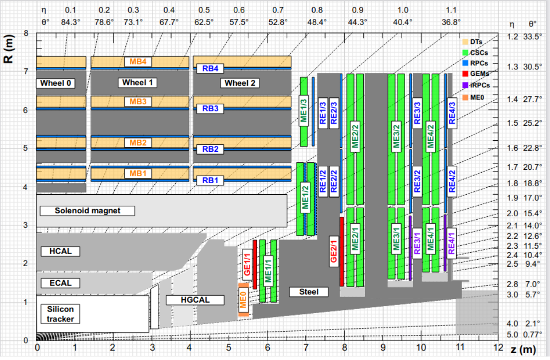

Figure 1: Muon System of the Compact Muon Solenoid for the Phase-II Upgrade of LHC. Existing RPCs are represented in blue. The new iRPC chambers to be installed in the stations RE3/1 and RE4/1 are represented in purple (1).

In the CMS experiment, RPCs operate using a three-component gas mixture with a relative humidity of 40%. The gas mixture used in CMS is composed of 95.2% $C_2H_2F_4$, that provides a high number of ion-electron pairs, 4.5% of iC_4H_{10}, that ensures the suppression of photon-feedback effects, and 0.3% SF_6, used as an electron quencher to further operate the detector in streamer-free mode. Both $C_2H_2F_4$ and SF_6 are known as greenhouse gases due to their high Global Warming Potential (GWP). Since the European Union issued new regulations on the use of Fluoridated-gases due their high Global Warming Potential, the price of $C_2H_2F_4$ is increasing and its future availability is unclear (5). Consequently, at CERN, extensive research is underway to explore alternative gas mixtures aimed at reducing F-gas emissions, which are crucial for the future of particle detector applications (6). Significant studies have been conducted on replacing $C_2H_2F_4$ with alternative gases like Hydrofluro-Oleofins (HFO) (7). These results

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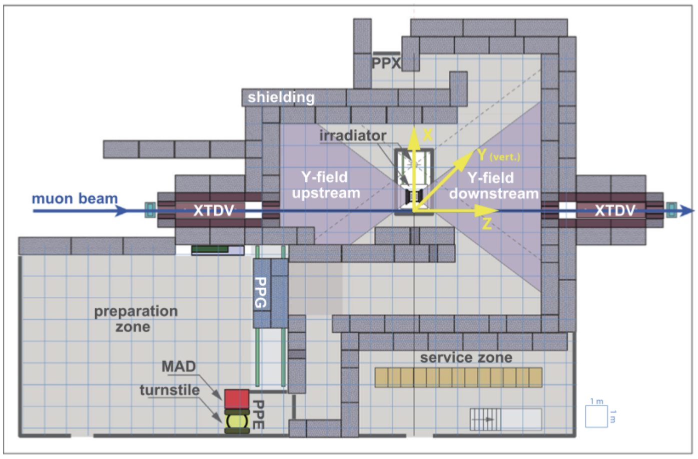

Figure 2: Floor plan of the Gamma Irradiation Facility GIF++. CMS-RPC chambers are strategically positioned in the upstream area. The high voltage supply and signal readout mainframe are situated on the first floor of the service zone, while the gas mixer is located on the second floor of the service zone (9).

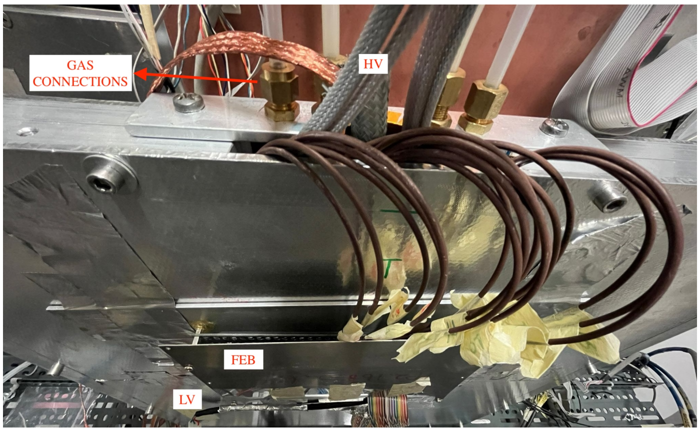

Figure 3: Chamber prototype placed in the upstream area of GIF++ bunker. The chamber has high voltage connections (HV), low voltage (LV) to power the Front-End board and gas connections for the gaps (supply and return for each gap).

show an increase in the working point of the mixture, and the present approach is to test the performance of RPC chambers by adding CO_2 in the HFO mixtures, in order to compensate for the change in the working point (8). Another strategy concerning the reduction of the GWP of the mixture, presented in this paper, consists of a mid-term plan to partially replace the $C_2H_2F_4$ with CO_2, a gas renowned with GWP of 1 and cost-effectiveness. This paper showcases initial endeavors to study the performance of an iRPC with various CO_2-based mixtures under a high radiation environment, conducted at the Gamma Irradiation Facility (GIF++) at CERN, along with future prospects for longevity studies.

2. Gamma Irradiation Facility (GIF++) and experimental setup

The Gamma Irradiation Facility (GIF++) in the North Area of the SPS combines a ^{137}Cs source with two sets of adjustable filters to vary the intensity, and a high-energy muon beam (100 GeV/c) from the secondary SPS beamline H4 in EHN1 (9). The floor plan of GIF++ is shown in Figure 2. This facility is widely used by LHC experiments to test the detectors under a high gamma rate, as the typical energy of the neutron-induced background radiation at experiments like CMS approximately matches the energy spectrum of the ^{137}Cs source, consisting of primary 662 keV photons and lower energy scattered photons.

In early 2023, a prototype iRPC chamber was placed inside GIF++ in order to conduct measurements with different CO_2-based gas mixtures. The chamber configuration consists of two gaps measuring 50 x 50 cm^2, each with a width of 1.4 mm, and 16 strips positioned between the gaps for signal readout. Due to the unavailability of official Front-end Boards specifically designed for iRPC in CMS, a customized FEB is utilized. This adapted FEB features a current-sensitive design with an input impedance of 20 Ω, an amplification gain of 200, a LVDS width of 60 ns, and a charge threshold set at 60 fC. Signals from the FEB are sent to a CAEN multihit TDC V1190A. Additionally, a system comprising four scintillators (two located externally and two within the bunker) is employed to trigger the TDC, enabling the recording of the signals for further analysis.

The muon window is determined through a Gaussian fit applied to the muon signal region, yielding a width of 75 ns. In a scenario without gamma background, the efficiency is straightforwardly defined as the ratio of recorded events to muon triggers. However, in the presence of gamma gamma background, the gamma contribution within the muon window is mitigated using Bayesian probability, as described in the equation below:

$$\epsilon_{muon} = \frac{\epsilon_{total} - \epsilon_\gamma}{1 - \epsilon_\gamma} \tag{1}$$

where ϵ_{muon} is the muon efficiency, ϵ_{total} is the efficiency taking into account all hits inside the muon window, and ϵ_γ is the efficiency of gamma events in a time window with same range but outside the muon window.

The gamma source within GIF++ incorporates a sophisticated filter system, allowing independent control over the gamma rate in both the upstream and downstream areas. Given that the expected background rate for HL-LHC period is around 600 Hz/cm^2, the data taking is conducted at GIF++ with filter ranging from few Hz/cm^2 up to 2 kHz/cm^2, aiming to cover the expected value of HL-LHC within a safety factor of 3.

The efficiency (ϵ) is calculated for different applied high voltage (HV_{eff}) in order to obtain the S-curve. This curve is derived through a fitting procedure utilizing the following Equation:

$$\epsilon = \frac{\epsilon_{max}}{1 + e^{-\lambda(HV_{eff} - HV_{50\%})}} \tag{2}$$

where ϵ_{max} is the maximum efficiency, λ is a multiplication factor and $HV_{50\%}$ is the high voltage where $\epsilon = 50\%$. These are the parameters to be fitted.

The chamber's working point is determined based on the fit above, defined as the high voltage at which the efficiency reaches 95%, with an additional 150 V margin to ensure that the plateau in the efficiency curve is reached.

Mixtures	$C_2H_2F_4$	CO_2	i-C_4H_{10}	SF_6	CO_2^{equiv}
STD	95.2%	0	4.5	0.3	664
MIX1	64%	30%	5%	1%	565
MIX2	54.5%	40%	5%	1%	500
MIX3	64.5%	30%	5%	0.5%	494

Table 1: Table displaying the composition of the gas mixtures utilized, alongside the standard RPC gas mixture in CMS. The final column shows the equivalent emissions in tons of CO_2, which are around 15-26% lower for the alternative CO_2-based mixtures examined in this study.

3. Alternative CO_2-based mixtures

Three different gas mixtures were selected for testing, as outlined in Table 1. Initially, experimentation aimed to explore mixtures containing 30% and 40% of CO_2 as substitutes for $C_2H_2F_4$. Previous research indicates that CO_2 concentrations beyond this range may compromise efficiency, particularly in high background rates (10). Moreover, past studies have demonstrated that elevating CO_2 levels can increase the streamer probability, potentially impacting detector response under intense gamma background conditions (11). To mitigate these effects, mixtures 1 and 2 incorporate a percentage of SF_6 up to 1%. Given SF_6's significantly higher GWP compared to $C_2H_2F_4$ and its greater molecular weight, the overall GWP of the mixture is primarily influenced by the SF_6 percentage. For this reason, the performance of a third mixture was also investigated, with 0.5% of SF_6. It's worth noting that substituting $C_2H_2F_4$ with CO_2 in all three mixtures results in a cost reduction of approximately 30-40%, since CO_2 is cheap, and a corresponding decrease in CO_2 emissions by approximately 15-26% compared to the standard gas mixture.

4. Results and discussion

The data collection took place during the test beams conducted in April and July of 2023 at the GIF++ facility. The efficiency curve for each mixture in Table 1 was obtained to assess the performance at the working point under varying background rates. As illustrated in Figure 4, in the absence of gamma background, the efficiency at the WP is consistent for all mixtures (98%), and the working point is driven by the different concentrations of CO_2 and SF_6. The working point (7.25 kV) and efficiency (98%) for the standard gas mixture is consistent with previous iRPC studies (3). Upon comparing mixtures 1 and 2, it becomes apparent that the inclusion of 10% CO_2 results in an 80V decrease in the working point. Similarly, when contrasting mixtures 1 and 3, the addition of 0.5% SF_6 leads to an approximate 90V increase in the working point. Consequently, mixtures 2 and 3 exhibit similar working points due to CO_2 and SF_6 compensations.

As shown in Figure 5, for a background hit rate of approximately 1.5 kHz/cm^2, the efficiency remained consistent at 94% for both the standard gas mixture and mixture 1. This finding is consistent with previous research, underscoring the importance of limiting the CO_2 percentage to no more than 40%. Conversely, the results justify further exploration of tests incorpo-

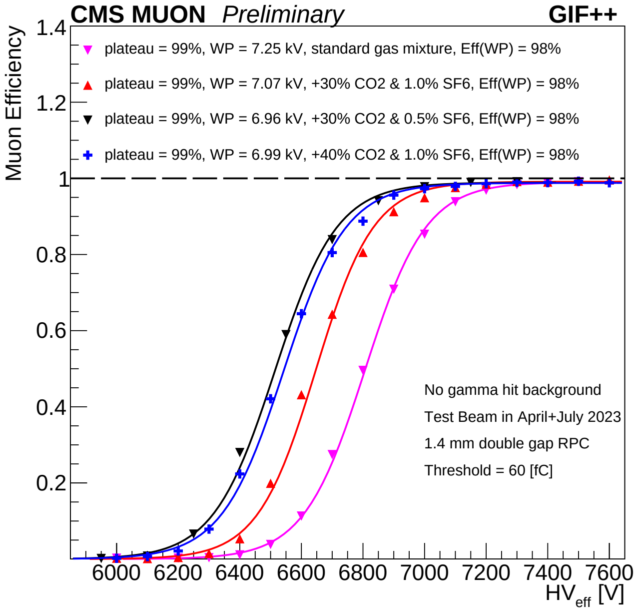

Figure 4: Efficiency curve without gamma background rate at working point (WP) for the standard gas mixture of CMS-RPC, replacing 30% and 40% of the $C_2H_2F_4$ for CO_2 and changing the concentration of SF_6 between 0.5% and 1%. The different concentrations of CO_2 and CO_2 shift the WP as expected. The efficiency in the working point with no gamma background is 98% for all tested mixtures, showing no degradation in the efficiency in the absence of gamma background.

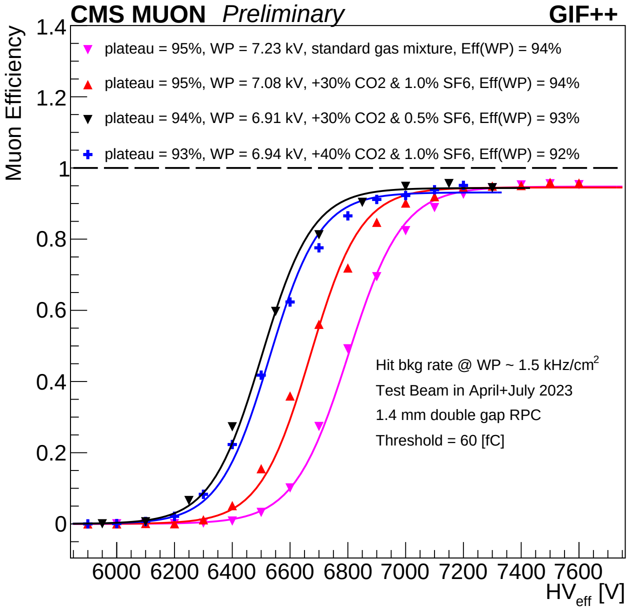

Figure 5: Efficiency curve illustrating the performance at the working point (WP) under a background hit rate of approximately 1.5 kHz/cm^2, using the standard gas mixture of CMS-RPC, with substitutions of 30% and 40% of $C_2H_2F_4$ for CO_2, and adjustments in SF_6 concentration between 0.5% and 1%. Variations in CO_2 and SF_6 concentrations result in expected shifts in the working point (WP). The efficiency remains consistent at 94% for both the standard gas mixture and mixture 1. However, a slight decrease in efficiency is observed for mixture 2 (-2%) and mixture 3 (-1%).

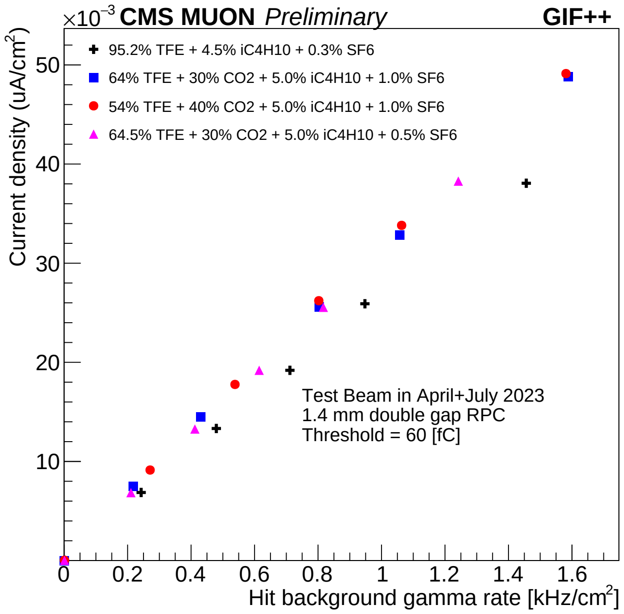

Figure 6: Current density (current-to-gap active area ratio) at the working point for varying background gamma hit rates with different gas mixtures. The chamber's active area measures 45.5 x 45.5 cm^2. Notably, the rate of increase in current density for all CO_2-based mixtures is approximately 20% higher compared to the standard gas mixture.

rating 0.5% SF_6, as evidenced by mixture 3's remarkable efficiency performance. Despite containing only half the amount of SF_6 compared to mixtures 1 and 2, mixture 3 demonstrated a minimal 1% efficiency drop, suggesting promising potential for further studies.

Monitoring the current between the gaps at the working point emerges as a crucial parameter in our investigative efforts. The current is related to the gamma background rate and serves as a direct indicator of the gas mixture's potential to accelerate ageing phenomena within the HPL electrodes (12). Given the diverse range of studies conducted with chambers of varying gap sizes, we define current density as the ratio between the current and the active area of the gap. As shown in Figure 6, the current density exhibits a linear proportionality with the gamma hit rate, as expected. Notably, across all CO_2-based mixtures, the rate of increase in current density is approximately 20% higher compared to the standard gas mixture.

Transitioning towards ageing investigation, an understanding of the average gamma charge induced for different gamma rates is paramount. With the current density denoted as I_d, we proceed to define the average gamma charge as follows:

$$\bar{q} = \frac{I_d}{(R/\gamma_{CLS})} \tag{3}$$

where R is the gamma hit rate and γ_{CLS} is the gamma cluster size, defined in this analysis as the number of hits in adjacent strips inside a time range of 30 ns.

Figure 7 illustrates a notable increase in the average gamma charge induced within the gaps when employing CO_2-based mixtures compared to the standard mixture. This increase is consistently observed to be around 20%. Such findings imply a potential acceleration of ageing effects within the detector system. Consequently, this underscores the necessity for a comprehensive long-term longevity plan, particularly directed towards the evaluation and potential adoption of one of the newly tested mixtures.

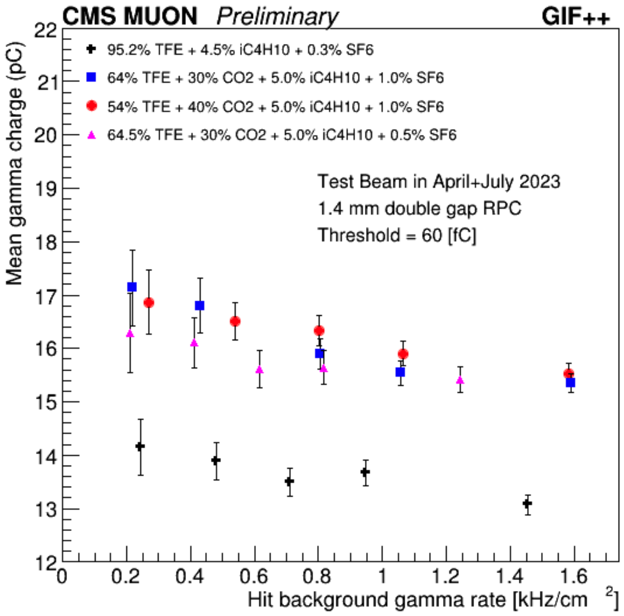

Figure 7: Average gamma charge at WP for different hit background gamma rates with different gas mixtures. The average gamma charge is calculated as in Equation 3. The average charge is approximately 20% higher for all CO2 based mixtures when compared to the standard one.

5. Summary and conclusions

In conclusion, this study presents a comprehensive evaluation of new CO_2-based mixtures in CMS iRPC under high gamma rate conditions. During the test beams at GIF++ in CERN, the efficiency, current density, and average gamma charge induced by these mixtures were investigated, aiming to assess their performance and anticipated longevity impacts.

Even if some CO_2-based mixtures present a small drop in efficiency in extremely high gamma rate environments, it cannot be considered a show-stopper. Ongoing studies focusing on parameters such as cluster size for muons and gammas, streamer probability, and timing resolution aim to provide deeper insights into potential performance disparities among the present mixtures. Additionally, the investigation into the current density and the average gamma charge induced within the gaps revealed an increase of around 20% for CO_2-based mixtures compared to the standard mixture. This increase suggests a potential acceleration of ageing effects within the detector system, highlighting the importance of implementing a comprehensive long-term longevity plan to address these concerns.

Overall, this study provides valuable insights into the performance of CO_2-based mixtures for the first time in CMS iRPC prototypes. While these mixtures offer promising potential as mid-term eco-friendly alternatives, further research is needed to address efficiency limitations and ageing concerns, ensuring the continued effectiveness and sustainability of RPC detectors in future high-energy physics experiments.

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