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Performance of eco-friendly alternative gas mixtures in CMS iRPC detectors in the HL-LHC environment

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The Resistive Plate Chamber (RPC) detectors in the CMS experiment operate with a gas mixture made of 95.2% $C_2H_2F_4$, known to be a greenhouse gas. Several eco-friendly alternatives to $C_2H_2F_4$, such as HFO, have been studied in the last few years in order to find an alternative mixture with low Global-Warming Potential (GWP), while maintaining the performance of the RPC chambers. Another way to improve the RPC standard gas mixture GWP could be replacing between 30% and 40% of the $C_2H_2F_4$ with CO_2. Studies of eco-gas and CO_2 based mixtures are carried out at the CERN Gamma Irradiation Facility (GIF++), where the LHC Phase-2 conditions are mimicked by a 11.5 TBq radiation source and a muon beam. This study presents the performance of two 1.4 mm gap RPC chambers with several alternative gas mixtures in a high gamma background environment, as well as future perspectives of aging studies.

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1. Introduction

The Compact Muon Solenoid (CMS) [1] is one of two general-purpose experiments at the Large Hadron Collider (LHC) at CERN. The muon system's Resistive Plate Chambers (RPCs), which are gaseous detectors in the barrel and endcaps (1,056 chambers in total), operate in avalanche mode for position and timing measurements. For the Phase-2 upgrade of CMS, 72 improved RPC (iRPC) detectors [2] will be installed in the forward region of the Muon System, as shown in Fig. 1, in stations 3 and 4 in order to increase the $|\eta|$ region from 1.9 to 2.4. The background radiation in this region is ~700 Hz/cm^2. The iRPCs also have a double gap design; both the electrodes and gaps have a narrower width of 1.4 mm instead of 2 mm (as RPCs operating at CMS). These features and new electronics [3] will give them a superior intrinsic timing resolution of 0.5 ns compared to their predecessors of 1.5 ns. Furthermore, thanks to the double readout in both sides of the strips, the space resolution in η is ~1.5 cm.

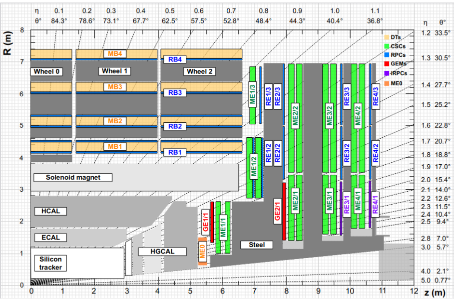

Figure 1: CMS muon detector.

Mixture	$C_2H_2F_4$	HFO	CO_2	iC_4H_{10}	SF_6	GWP_{mix}
STD	95.2	0	0	4.5	0.3	1485
MIX1	64	0	30	5	1	1529
MIX2	54	0	40	5	1	1353
MIX3	64.5	0	30	5	0.5	1337
ECO2	0	35	60	4	1	476
ECO3	0	25	69	5	1	527
GWP	1430	7	1	3	22800	-
$\rho(g/L)$	4.68	5.26	1.98	2.69	6.61	-

Figure 2: Alternative gas mixtures tested in RPC detectors.

The gas mixture (standard, STD) used in CMS is composed of 95.2% $C_2H_2F_4$, which provides a high number of ion-electron pairs; 4.5% iC_4H_{10}, which 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). Alternative gas mixtures are being studied at the CERN Gamma Irradiation Facility (GIF++), which simulates LHC Phase-2 conditions with an 11.5 TBq radiation source and muon beam. This study presents the performance of two 1.4 mm double-gap iRPC chambers with various alternative gas mixtures in a high gamma background and discusses future aging studies. Due to the unavailability of official Front-End Boards (FEBs) for iRPCs in CMS, a customized FEB with a 60 fC charge threshold is used.

2. Alternative Gas Mixtures for RPC detectors

The alternative gas mixtures can be grouped into two sets. The first set (MIX in Fig. 2) partially replaces $C_2H_2F_4$ with CO_2, representing a mid-term plan, as ATLAS has been using MIX1 since 2023 with no efficiency degradation [4]. In this case, the SF_6 component is increased up to 0.5-1% to maintain the cluster size and streamer probability within requirements, as shown in previous studies [5]. The GWPs of the mixtures are equivalent to the standard one, but the CO_2 equivalent exhaust is 15-26 % lower and price is also reduced by 30-40%. The second set (ECO in Fig. 2) completely replaces $C_2H_2F_4$ with HFO-1234ze, a low-GWP alternative gas used in the industry as well as for this purpose. SF_6 is also increased for the same reasons, and CO_2 is added to lower the working point (which is defined as the high voltage value where the efficiency is 95% + 150 V), as shown in previous studies [6].

3. HFO/CO_2 mixtures

For all ECO mixtures tested, the efficiency at the working point shows about 2% reduction when HFO/CO_2 replaces $C_2H_2F_4$ in the absence of background and we observed similar efficiency drops as gamma background intensity increases, due to electronics dead time (~80 ns) and not mixture related. However, the efficiency is kept >90% even for background radiation three times higher than what is expected for the HL-LHC phase, as shown on left of Figure 3. The working point was found to be higher for HFO/CO_2-based mixtures with respect to the standard one. The presence of HFO and SF_6 increases the working point due to the ionization characteristics of HFO and free electron suppression of SF_6 due to the high electronegativity molecule, while the addition of CO_2 holds it to lower values, as demonstrated in past studies. The muon cluster size at WP is similar for all mixtures studied, as shown on right of Figure 3; with the addition of SF_6 the detector maintains operation in avalanche mode indicating that SF_6 is performing the expected function of preventing streamer modes. The current density is shown to be around 40% higher for the ECO mixtures tested.

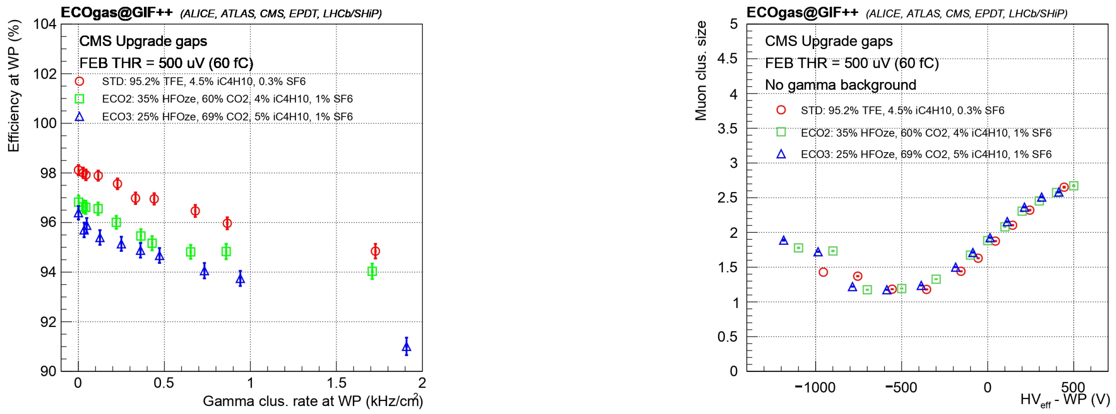

Figure 3: Efficiency as a function of background gamma rate (left) and muon cluster size for standard gas mixtures and different HFO-based mixtures (right).

4. $C_2H_2F_4$ /CO_2 mixtures

As expected, for CO_2 based mixtures with the presence of $C_2H_2F_4$ the working point is raised by adding SF_6 but lowered by adding CO_2, resulting in a lower WP for all the alternative gas mixtures tested with respect to the standard one, as shown on left of Figure 4. None of the tested mixtures showed dramatic efficiency degradation at the WP for 800 Hz/cm^2 (the expected background rate for HL-LHC), confirming what was shown in previous initial studies [7]. The gamma cluster size at 800 Hz/cm^2 is similar for all the mixtures tested, which can also be related to the addition of SF_6

to the mixture, as shown on the right of Figure 4. No difference was observed between mixtures with 0.5% and 1.0% of SF_6, indicating that, for a 1.4 mm gap, the SF_6 value can be kept at 0.5% (lower GWP). However, the resolution of this prototype is ~1.8 cm, instead of the 1 cm of the real iRPC chamber. Further studies are needed to thoroughly investigate the impact of this gas mixture. The current density is shown to be around 20% higher for the ECO mixtures tested.

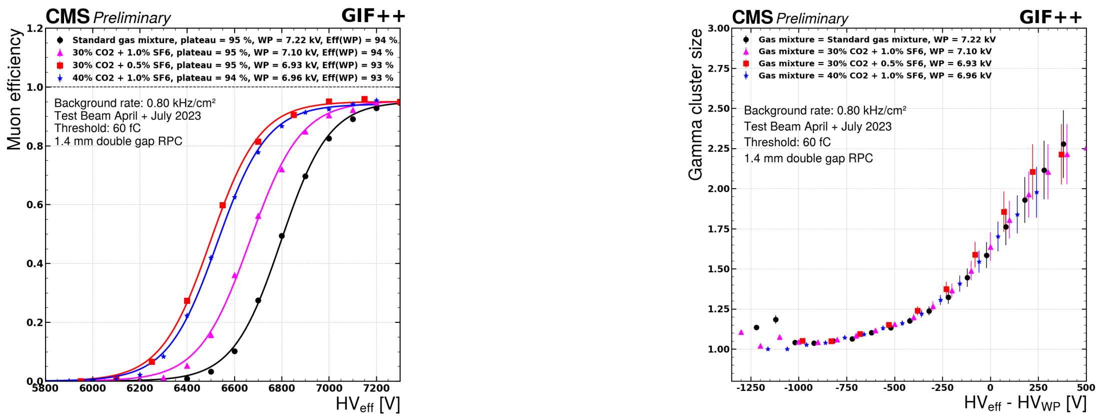

Figure 4: Efficiency curve for standard gas mixtures and different CO_2 based gas mixtures with a background rate ~800 Hz/cm^2 (left) and the gamma cluster size for the same rate (right).

5. Conclusion

The results summarized here represent the initial performance evaluation of alternative gas mixtures for iRPC operation in CMS during the High Luminosity LHC Phase. Among the proposed eco-friendly HFO/CO_2-based mixtures, the mixture with 35% HFO (ECO2) showed the most promise based on its efficiency, despite having a relatively high, but not excessive, working point compared to the standard mixture. Additionally, similar muon cluster size and efficiency drops were observed. The $C_2H_2F_4/CO_2$-based mixtures showed good performance, comparable with the STD in terms of efficiency curves; however, further research is needed to understand the implications of higher current density, observed during the study of both sets of mixtures, in the acceleration of the aging process. Both prototypes began an irradiation campaign in September 2023 using ECO2 and MIX1 for extended longevity studies. The charge integrated so far represents 4% of what is expected for HL-LHC and no degradation in the performance has been observed so far.

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