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Studies on RPC detectors operated with environmentally friendly gas mixtures in LHC-like conditions

Gianluca Rigoletti *, Roberto Guida, Beatrice Mandelli

CERN, 1, Esplanade des particules, Geneva, Switzerland

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ABSTRACT

Resistive Plate Chambers (RPC) are gaseous detectors employed at CERN LHC experiments thanks to their trigger performance, timing capabilities and contained production costs. High Pressure Laminate RPCs are operated with a three-component gas mixture, made of 90%–95% of $C_2H_2F_4$, around 5% of i-C_4H_{10} and 0.3% of SF_6. Due to the presence of leaks at detector level and to the greenhouse characteristics of $C_2H_2F_4$ and SF_6, RPCs in ATLAS and CMS were accounting for about 87% of CO_2 equivalent emissions during LHC Run 2. The addition of some amount of CO_2 into the RPCs gas mixture was explored as a possible short-to-medium term solution to lower the total greenhouse gases emissions and reduce the usage of $C_2H_2F_4$. A dedicated data taking campaign was performed at the Gamma Irradiation Facility at CERN, where RPCs detectors performance were studied with muon beam and gamma background. The detectors were operated with the addition of 30% and 40% of CO_2 to the standard gas mixture, together with an increased fraction of SF_6. In addition, the performance with two different amount of i-C_4H_{10} were evaluated in order to assess the compatibility of the gas mixture with the CMS and ATLAS requirements. Results on the muon beam performance of RPCs operated with the aforementioned gas mixtures are reported in this work.

1. Introduction

Resistive Plate Chambers (RPC) detectors are gaseous detectors [1] widely employed at CERN LHC experiments thanks to their excellent muon detection performance and production costs. High Pressure Laminate (HPL) RPCs are installed in the muon systems of the ALICE, ATLAS and CMS experiments. They are operated with a gas mixture made of 90%–95% of $C_2H_2F_4$, also known as R-134a, 4.5%–10% of i-C_4H_{10}, 0.3% of SF_6 and 7000–8000 ppm of water vapour. Both R-134a and SF_6 are known to be greenhouse gases, with a global warming potential (GWP) of 1430 and 22800 respectively [2], with a gas mixture GWP of around 1490.

In order to reduce Greenhouse Gases (GHG) consumptions and emissions and to align with the European strategies to reduce the placement of high-GWP fluorinated gases [3], CERN identified different strategies. One of the main research lines is focused on the study of alternative gases for particle detectors.

Since RPCs at LHC accounted for about 87% of GHG emissions due to the presence of leaks at detector level, the search for an alternative gas mixture to reduce or replace R-134a usage is highly advisable.

When looking for an alternative gas mixture, several requirements must be met for the gas mixture in order to be compatible with the current RPC systems at LHC: for safety reasons, the gas mixture must not be flammable[1] and should not be considered toxic. The working point of the detector should not exceed the maximum voltage allowed by the high voltage system and the charge developed in the gap should be high enough to be detected by the currently installed front-end electronics. Furthermore, in view of High-Luminosity LHC (HL-LHC), the gas mixture should not affect the detectors rate capability. For this reason, the RPCs should be operated with the least amount of streamers.

2. Experimental setup

The tests were conducted using three High Pressure Laminate (HPL) RPCs with an electrode thickness of 2 mm and a gas gap of 2 mm. The dimensions of the three RPCs were 70 cm x 100 cm and the resistivity measured by means of a plasma Argon were found to be 1–5 10^{10} Ω cm. Each RPC was equipped with a set of 7 copper strips of 2.5 cm x 100 cm on which the induced signal can be read. The detectors were installed at the Gamma Irradiation Facility (GIF++) [4] of the CERN's Prevessin site, where a gamma source of ^{137}Cs can be used to emulate the background conditions of LHC. During few weeks of the year a muon beam is also provided to the facility, allowing to evaluate the muon efficiency of the detectors. The signal induced on the strip was read using a CAEN V1730 digitizer, which recorded the raw

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

[1] The flammability constraint applies for the ATLAS and CMS RPC systems but not for the ALICE MID system.

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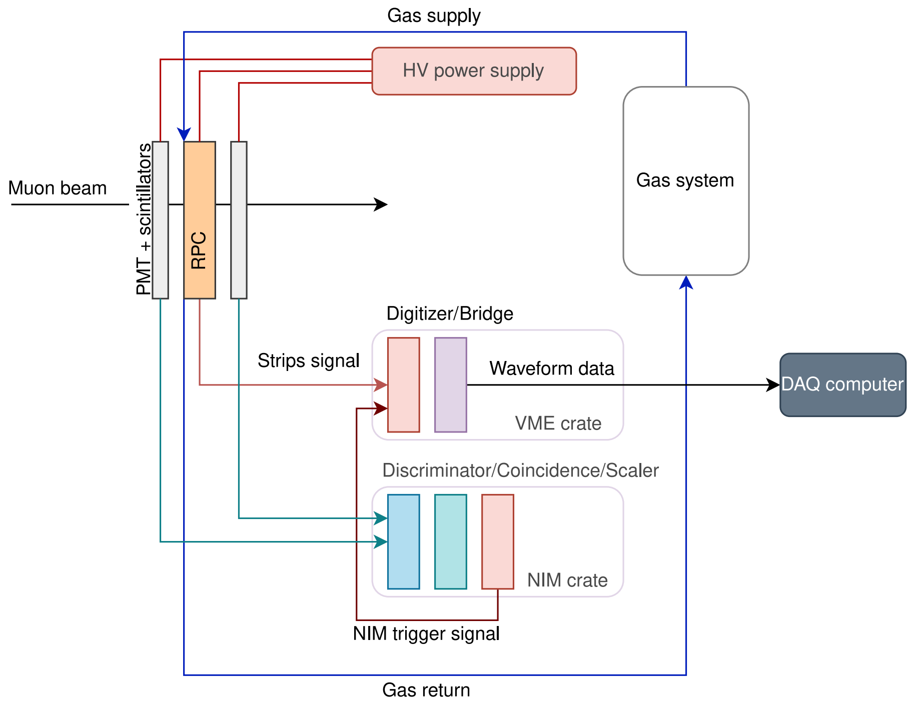

Fig. 1. Schematic view of the experimental set-up at GIF++.

waveforms, thus allowing to perform pulse shape analysis and evaluate RPC's foremost parameters such as efficiency, prompt charge, cluster size, time resolution, signal duration (see Fig. 1).

The muon efficiency was calculated using a height threshold on the raw signal of 2 mV, from which the working point was then defined by fitting the efficiency–voltage curve with a sigmoid and taking 95% of the maximum efficiency + 150 V. The computed working point resulted to be around 9600–9800 V, compatible with the current values used in the ATLAS and CMS experiments [5,6]. A threshold on the prompt charge of 10^8 electrons, similar to the Raether's limit [7], was used to discriminate between avalanche and streamer signals. The cluster size was computed as the maximum number of adjacent firing strips for a given trigger acquisition. The time resolution was estimated by taking the time difference between the falling edge of the external trigger minus the arrival time of the muon signal. The time over threshold was instead defined as the time between the first and last sample recorded above the efficiency threshold. The parameters defined above were computed for different gas mixtures and with different background conditions, ranging from muon beam only to a gamma hit rate of about 600 Hz/cm^2.

3. Addition of non fluorinated gases to the standard gas mixture

A possible replacement of R-134a was mainly identified in R-1234ze, an HydroFluoroOlefin (HFO) with a GWP of 7, designed to be used in the refrigerant industry. However, the properties of the gas in terms of ionization are still under study. Experimental works were conducted to evaluate the possibility of using HFO-based gas mixtures with LHC-like background conditions [8,9]. Long term studies were started with HFO-based gas mixtures, but the identification of the gas mixture, as well as the studies of possible aging effects of the detector are still being investigated.

A possible short-to-medium term solution to reduce the consumption of R-134a at LHC experiments is to add to the standard gas mixture some amount of a fourth gas that does not significantly affect the detector performance.

Several non-fluorinated gases were tested by adding 10% of them to the standard gas mixture in favor of R-134a. O_2, Ne, CO_2, N_2, He, N_2O, Ar were tested. Fig. 2 shows the efficiency and streamer probability curves of the standard gas mixture together with the gas mixtures with 10% of the candidates added. It was observed that the performance with O_2 were similar to the standard gas mixture. However, due to the oxidizing nature of O_2, higher currents were observed. Furthermore, the flammability of the gas mixture is not known and should be further investigated. The performance with Ne were acceptable, but the gas was discarded for further tests due to the current unavailability on the market. CO_2 tests showed good performance, decreasing the working point of about 190 V and making the gas the selected one for further tests. The addition of He was also showing very good performance, but due to the presence of leaks in the RPC detectors and the presence of PMTs in the experimental caverns of LHC, the gas was discarded. N_2O performance were showing interesting results, but the working point of the gas mixture was increased of about 350 V. This would mean that higher concentration may result in higher working point. Finally, Ar was also tested, showing good performances, but with a significantly increased charge content at detector's working point.

4. Studies on the addition of CO_2 to the standard gas mixture

CO_2 was added in concentrations of 30%, 40%, 50% to the standard gas mixture by reducing the equivalent amount of R-134a. When looking at the prompt charge distribution at detector's working point, it was observed an increase of streamers with a mean charge of 50 pC. The streamer populations was observed to increase with the increase of CO_2. Furthermore, Fig. 3 shows the development of two population in the region [0.8-2] pC. Investigation on the appearance of these signals is under investigation.

When looking at the duration of the signals, it was observed a significant increase of the mean time over threshold with the increase of CO_2. Fig. 4 shows that with concentrations higher than 30% of CO_2, the time over threshold goes above 25 ns, corresponding to the LHC bunch crossing time.

Table 1
Time resolution and cluster size measured at working point for different background conditions. For each gas mixture, the mean value and standard deviation are reported.

Gas mixture	Time Resolution [ns] Source Off [ns]	Cluster Size [2.5 cm^{-1}]	Time Over Threshold Source Off [ns]
Standard	1.64 ± 0.03	1.29 ± 0.02	11.3 ± 0.2
Std. (4.5% iso.) + 30% CO_2 + 1% SF_6	1.52 ± 0.02	1.31 ± 0.03	14.6 ± 0.4
Std. (5% iso.) + 30% CO_2 + 1% SF_6	1.60 ± 0.10	1.30 ± 0.03	14.8 ± 0.4

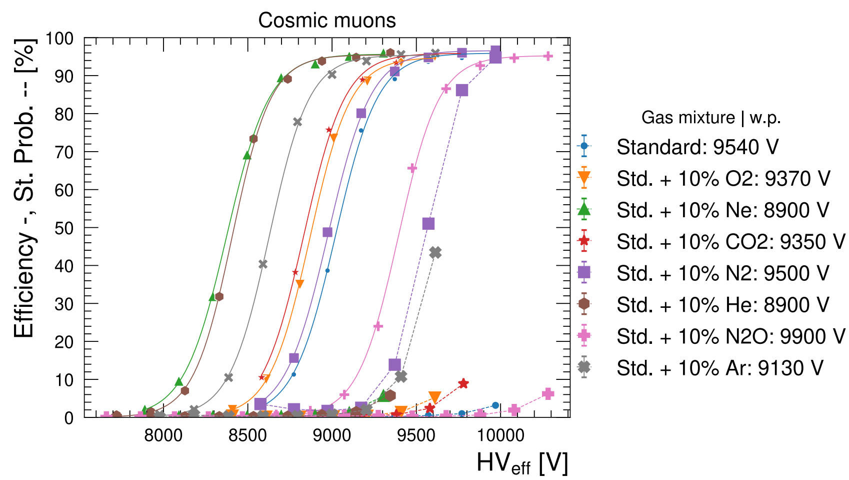

Fig. 2. Schematic view of the experimental set-up.

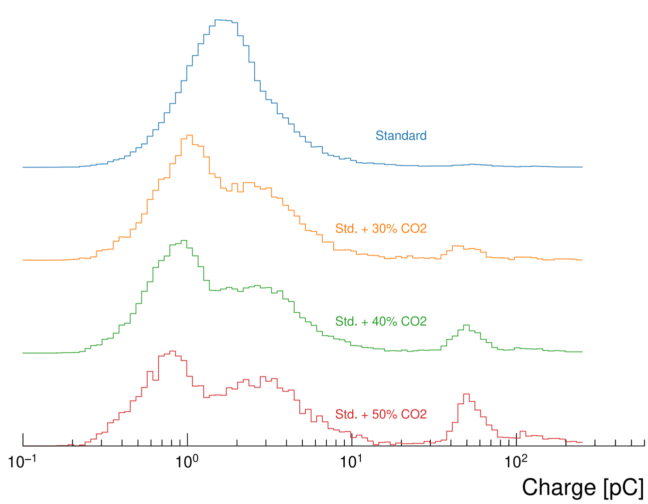

Fig. 3. Prompt charge distribution for the standard gas mixture and the standard gas mixture with the addition of 30%, 40%, 50% of CO_2. All distributions are taken with muon beam and at detector's working point.

4.1. SFF_6 variation in CO_2 based gas mixtures

To suppress the streamers and decrease the possibility of after pulses, several tests were conducted by increasing the amount of SF_6 in the gas mixtures with 30%, 40%, 50% of CO_2. In particular, for each 50% of CO_2 concentration, 0.3%, 0.6% and 0.9% of SF_6 were tested. To evaluate the performance improvement, the difference between the working point and the voltage at which the streamer fraction reaches 10% were calculated for each gas mixture. In Fig. 5 it can be noticed that the standard gas mixture has the highest separation, indicating the operation in streamer-free mode. The addition of a higher amount of SF_6 helps increasing the separation, although with 50% of SF_6 the separation is always negative, which indicates a significant presence of streamers.

Higher concentration of SF_6 were tested on a different beam period and with a different detector. Results are shown in Fig. 6. 1% of SF_6 with 30% of CO_2 showed the highest separation, while 1%, 1.5% and 2% SF_6 showed increasingly higher separations but always lower than the gas mixture with 30% of CO_2.

4.2. i-C_4H_{10} variation on selected CO_2 gas mixtures

The gas mixture with 30% of CO_2 and 1% of SF_6 was compared with 4.5% and 5% of i-C_4H_{10}, in order to evaluate the possibility of using the gas mixture both in the CMS and ATLAS experiments. Fig. 7 shows the efficiency and streamer probability curves of the two gas mixtures. Both show a working point slightly lower than the standard gas mixture and not significantly different between each other. Also, the streamer fraction is similar between the two gas mixtures, suggesting that i-C_4H_{10} is not significantly affecting the muon beam performance on the short term.

The selected gas mixtures were also evaluated with different gamma source intensities. The maximum tested irradiation was around 600 Hz/cm^2, corresponding to the maximum hit rate foreseen for High Luminosity LHC (HL-LHC) on the CMS endcap RPCs, with a safety factor 3 [10].

The drop of maximum efficiency reached by the detector as a function of the rate is reported in Fig. 8. No significant difference was observed up to rates of 500 Hz/cm^2, while a difference of about 2% starts to be noticeable when the detector are reaching 500 Hz/cm^2.

Fig. 9 shows that when evaluating the background currents as a function of the gamma hit rate, the two CO_2-based gas mixtures show an increase of about 20% in the currents with respect to the standard gas mixture. However, no significant difference was observed between the gas mixture with 4.5% and 5% of i-C_4H_{10}, suggesting that the developed charge per gamma hit of the two gas mixtures is similar.

The results for the measured time resolution and the cluster size are reported in Table 1. The two parameters were observed to be stable at

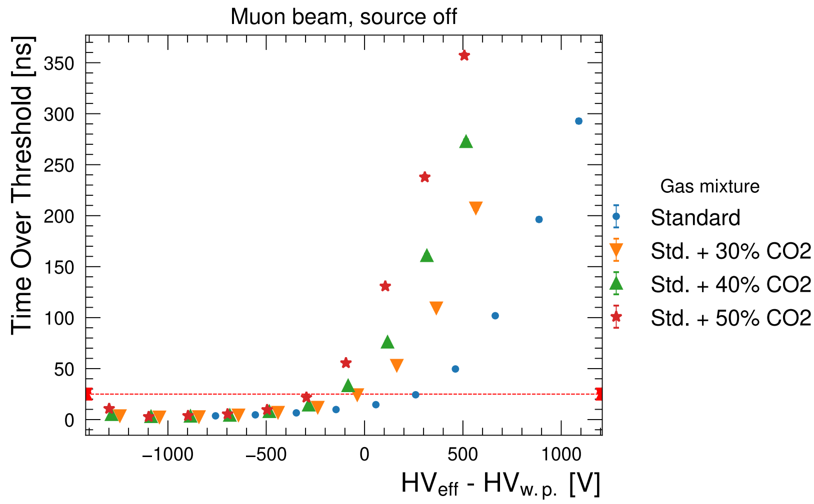

Fig. 4. Mean time over threshold of the standard gas mixture and the standard gas mixture with the addition of 30%, 40%, 50% of CO_2 versus the effective voltage subtracted by the detector's working point. The 0 indicates the RPC's working point.

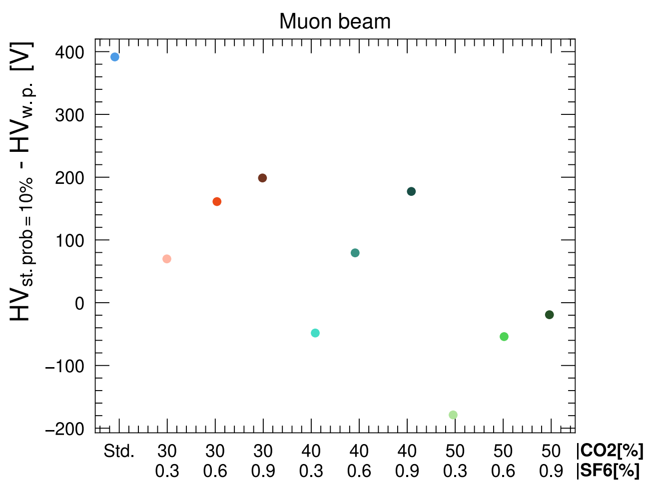

Fig. 5. Working point separation from the voltage at which the streamer probability reaches 10%. The gas mixtures were tested in the presence of muon beam.

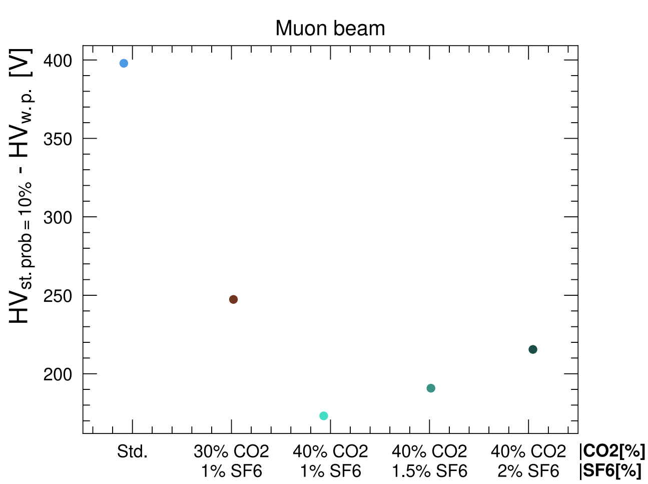

Fig. 6. Working point separation from the voltage at which the streamer probability reaches 10%. The gas mixtures were tested in the presence of muon beam.

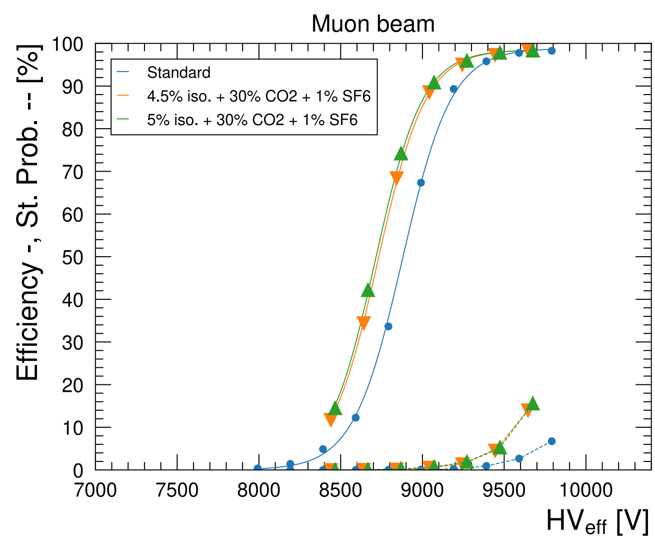

Fig. 7. Efficiency curves in solid lines and streamer probability curves in dashed lines for the standard gas mixture and the selected CO_2-based gas mixture with 1% of SF_6 and respectively 4.5% and 5% of i-C_4H_{10}.

different background conditions. The CO_2-based gas mixtures showed similar or slightly lower time resolution compared to the standard gas mixture, while the cluster size tends to be slightly higher, but within the error of the measurement. The time over threshold was also measured with muon beam only. The average value obtained at working point shows about 11 ns for the standard gas mixture and about 14.5–15 ns for the CO_2-based gas mixtures, the two being compatible with each other.

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 CO_2 to the Freon-based gas mixture was identified as a possible short-to-medium solution to mitigate the emissions. CO_2 was added from concentrations of 10% up to 50%. It was observed an increase in the overall charge developed within the gap with the increase of $CO2_2$. For this reason, the increase of SF_6 in the gas mixture was studied as a possible solution to suppress streamer formation. Two gas mixtures were ultimately selected: one with 30% of

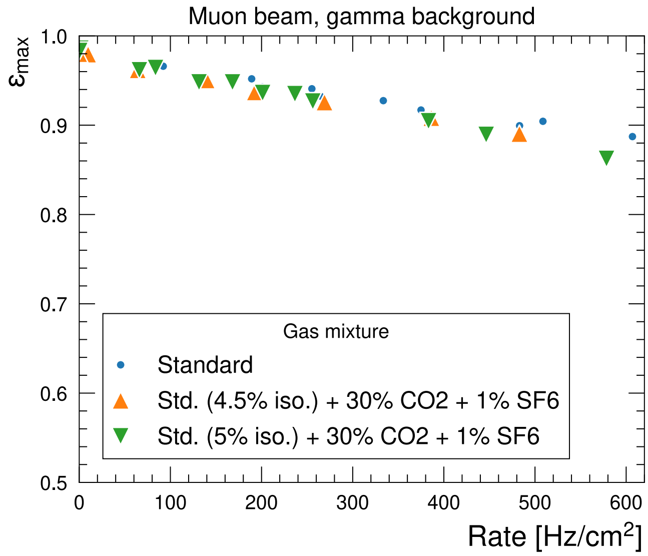

Fig. 8. Maximum efficiency of the RPCs as a function of the gamma hit rate for the standard gas mixture and the two selected CO_2-based gas mixtures.

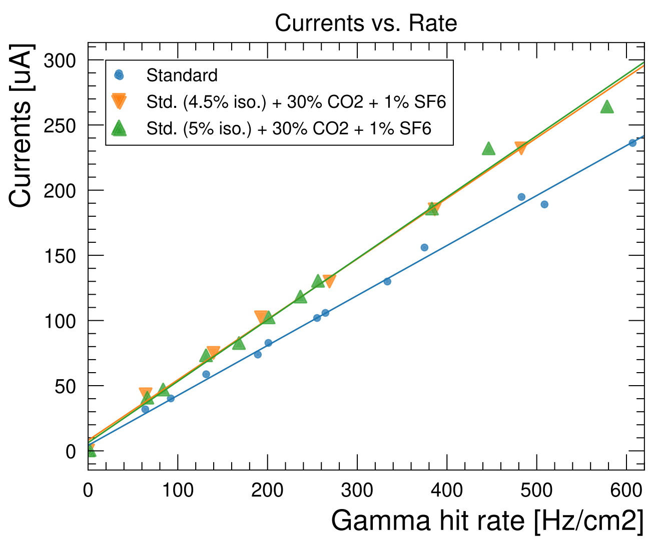

Fig. 9. Gamma background currents measured at working point as a function of the gamma hit rate for the standard gas mixture and the selected CO_2-based gas mixtures. The data were fitted with a linear function for each gas mixture.

CO_2, 1% SF_6 and 4.5% of i-C_4H_{10} and one with the same concentrations but with 5% of i-C_4H_{10} to be compatible with the ATLAS RPC system.

Both gas mixtures showed similar performance between each other and similar performance with the standard CMS gas mixture, taken as a reference. Only the gamma background current at detector's efficiency were found to be about 20% higher. The reason for this phenomenon is currently under investigation. The gas mixture with 5% of i-C_4H_{10} was selected for further tests at the GIF++ where long-term performance will be carefully studied.

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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