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Performance studies of RPC detectors operated with ECO-friendly gas mixtures

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Summary. — Resistive Plate Chamber (RPC) detectors are widely employed at the CERN LHC experiments. During Run 2 85% of CERN's greenhouse gas emissions were caused by RPCs due to leaks at detector level. RPCs operate with fluorinated gases, which exhibit high values of Global Warming Potential and are therefore prohibited from the European Union. It is of paramaount importance to find alternative eco-fiendly gas mixtures that ensure both optimimal performance and low greenhouse gas emissions.

1. – Introduction

RPCs are gaseous detectors [1] that find a great use at the CERN LHC experiments for muon trigger and identification purposes, due to their excellent time and spatial resolution of 1 ns and few mm, respectively. They are suitable to cover large surfaces thanks to their low production costs. Currently they are operated with a greenhouse gas (GHG) mixture, containing $C_2H_2F_4$ (R134a) and SF_6. These gases exhibit a high Global Warming Potential (GWP) value, meaning that they trap large amounts of heat in the atmosphere raising Earth's temperature. GHGs are subject to European Union regulations which limit their availability on the market, increasing their market price [2]. The goal of this work is to study the performances of RPC detectors operated with eco-friendly gas mixtures. The detectors were tested at the CERN Gamma Irradiation Facility (GIF ++), which provides a high energy muon beam combined with an intense gamma radiation source, allowing to simulate the background radiation expected at the High Luminosity LHC Phase (HL-LHC) [3].

Low GWP gas mixtures based on CO_2 and the new Hydro-Fluoro-Olefin (HFO) were selected for these studies [4, 5]. The data obtained were analyzed and performance were compared with the RPC gas mixture recently in use at ATLAS, CMS and ALICE experiments, to find the gas mixture with the best trade-off between GWP and good detectors performances.

2. – Experimental setup

The dedicated set up for the studies was built in the GIF++ irradiation area and represents a small replica of an LHC-like system. Three single-gap 70 cm x 100 cm x 2 mm High Pressure Laminate (HPL) RPC detectors were installed on a moving metal frame. The signal induced by the particle's interaction is collected on seven 2.5 cm wide and 100 cm lenght copper strips, terminated on a 50 Ω resistance and directly read with a CAEN digitizer v1730. A gas sysem placed in a dedicated area inside the facility provides the gas flushed in the detectors, which is remotely controlled by an electronic system. The GIF++ provides a 12.5 Tbq ^{137}Cs source combined with a high energy muon beam of 100 GeV/c from the H4 North Area line, to simulate the condition foreseen for the HL–LHC. The gamma radiation intensity is regulated through several lead filters ranging from few Hz/cm^2 to 600 Hz/cm^2 of gamma hit rate in the particular position where the set up was placed. The trigger for the beam test is obtained by the coincidence of four scintillators, two of which were placed inside the GIF++ bunker, while the others were installed outside.

3. – Test beam results and analysis

The eco-friendly alternatives selected for the studies include the substitution of the R134a with HFO-1234ze (HFO), the raise of CO_2 concentration up to 30% and 40%, the replacement of SF_6 with different concentrations of the alternative gas NOVEC 4710. The gas mixture employed in CMS RPCs, referred to as the Standard (STD) Gas Mixture was firstly tested in order to have a reference for the detectors perfomance. It is composed of 95.2% R134a, 4.5% i-C_4H_{10}, 0.3% SF_6 and 0.7% of humidity by volume of water. The analyzed parameters are the efficiency, avalanche and streamer charge, streamer probability (SP), cluster and detector currents at different gamma rates. They are evaluated at the efficiency knee (95% of the maximum efficiency value from fit) and at working point (WP), defined as the efficiency knee +150 V. In the following table the GWP values for each considered gas component.

3·1. *HFO-1234ze alternative to R134a.* – The R134a is the main contributor to the GHG emissions, due to its high concentration in the standard gas mixture. The total replacement of the $C_2H_2F_4$ with the HFO, plus the addition of CO_2, are considered.

Figure 1 shows the efficiency curves and streamer probability at the applied voltage on the top, the currents and cluster size *versus* rate on the bottom. With respect to the reference values, the R134a/CO_2 based gas mixture shows a WP value lower than 950

TABLE I. – *GWP values for each considered gas component.*

Gas component	GWP
R134a	1430
i-C_4H_{10}	3.3
SF_6	22800
R1234ze	6
Novec 4710	2100

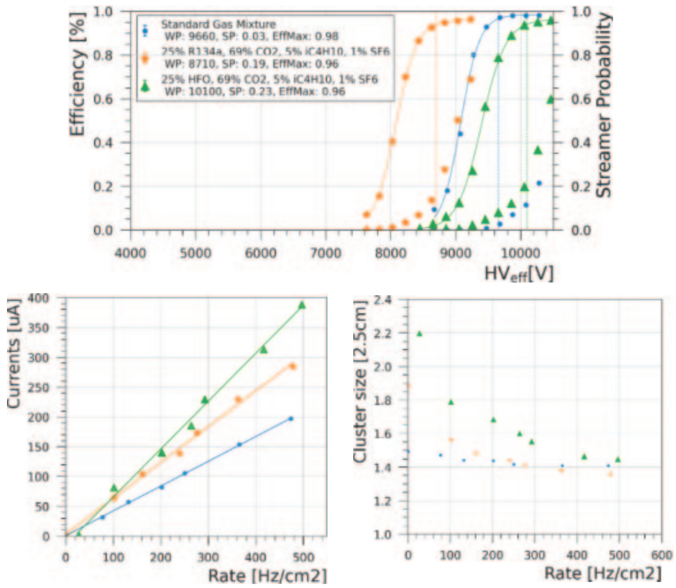

Fig. 1. – On the top the efficiency and SP curves for the STD, the 25% R134a–69% CO_2 based gas mixtures and 25% HF0–69% CO_2 based one. On the bottom the trends of current and cluster size *versus* rate.

V, but an increasing SP by 16% at the WP and a 30% currents increase at 500 Hz/cm^2. The replacement of HFO-1234ze determines the growth of the cluster size at different rates respect to both the STD and the R134a based gas mixtures. This shows that the HFO-1234ze alternative does not have good tracking properties at low rate.

3˙2. *30%–40% CO_2 based gas mixtures.* – In fig. 2 on the left, the presence of CO_2 in the gas mixture leads to a lower value of the working point and the efficiency curves show similar performances to the Standard ones. In fig. 2 on the right, an increase of 15% in currents evaluated at 400 Hz/cm^2 in comparison with the standard values is observed, deducing that a reduced CO_2 amount reduces the currents.

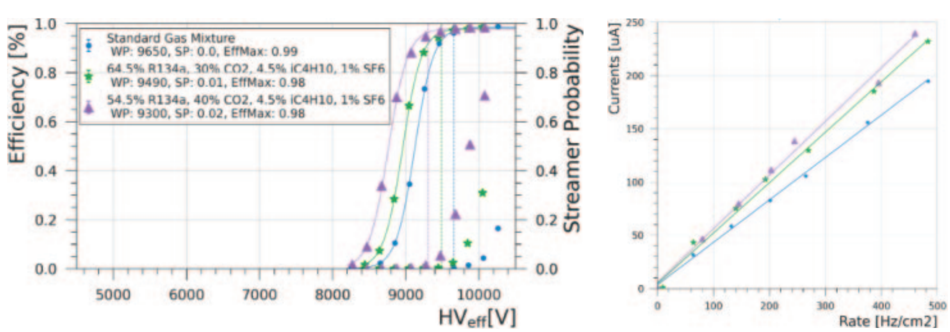

Fig. 2. – On the left the efficiency and SP curves for the STD, the 30% and 40% based gas mixtures. On the right the current trends for each one.

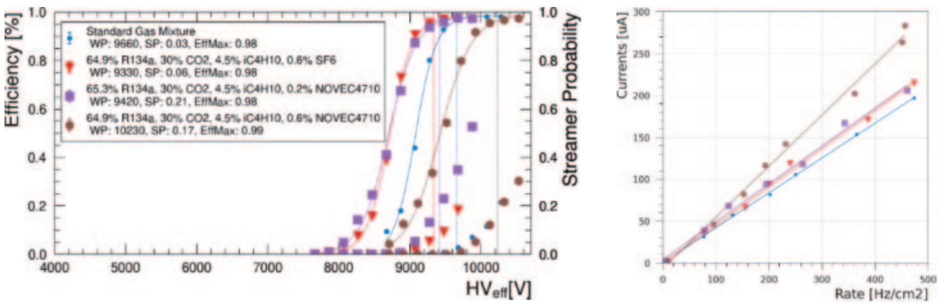

Fig. 3. – On the left the efficiency and SP curves for the STD, the 0.2%–0.6% Novec4710 based gas mixtures and 0.6% SF_6 based one. On the right the current trends.

3˙3. *SF_6 alternatives based gas mixtures*. – Different concentrations of NOVEC 4710 based gas mixtures with the addition of 30% CO_2 were tested as an alternative to SF_6. The 30% CO_2, 0.6% SF_6 gas mixture is set as reference.

Figure 3 on the left shows that the 0.2% and 0.6% Novec4710 based gas mixtures result in a higher working point, respectively of 90 V and 900 V than the 0.6% SF_6 based gas mixture. Furthermore the presence of Novec4710 increases the SP percentage respect to the reference value. In fig. 3 on the right, the comparison between the current amplitudes is evaluated at 400 Hz/cm^2. The presence of 0.2% Novec4710 shows a behavior similar to the 0.6% concentration of SF_6 gas. Increasing up to 0.6% Novec4710 the current amplitude is 15% higher than the reference value. The raising trend is due to the electronegative nature of the Novec4710, that traps free electrons producing negative ions. They slowly move to the electrodes, where they are collected contributing to the macroscopic currents measured inside the gap.

4. – Conclusions

The HFO/CO_2 based gas mixture shows higher WP and current values than the R134a/CO_2 one. The 0.2% Novec4710/CO_2 based gas mixture provides similar results respect to the STD one. However this gas may react with water molecules inside the detector, therefore further investigations are needed. Reducing the CO_2 concentration good detectors performances are obtained, allowing to reduce the R134a amount. For this reason the 30% CO_2 based gas mixture was selected by the EP-DT gas team and the ATLAS group at CERN for the aging tests and it has started to be used in ATLAS RPCs at LHC experiments since August 2023.

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