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Study of environment-friendly gas mixtures for the Resistive Plate Chambers

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The standard gas mixture for the Resistive Plate Chambers (RPC), composed of $C_2H_2F_4$/i-C_4H_{10}/SF_6, has a high Global Warming Potential (GWP ~ 1430) mainly due to the presence of $C_2H_2F_4$. This gas is not recommended for industrial uses anymore, therefore it will be problematic to use it in the next future. We report the performance of the RPC working with new environment- friendly gases which could replace the standard mixture. The new gaseous components have the Global Warming Potential (GWP) at very low level. In this work the standard mixture main component, the $C_2H_2F_4$ (GWP~1300), is replaced by a proper mixture of CO_2 (GWP = 1) and Tetrafluoropropene ($C_3H_2F_4$, GWP~6). The other high-GWP component, the SF_6 (GWP ~ 23900), is replaced by a new molecule, the Chloro-Trifluoropropene ($C_3H_2ClF_3$, GWP ~ 5) never tested in the RPC detectors. The mixtures studied have a total GWP~ 10. We report, for several eco-gas mixtures, the detection efficiency, streamer probability, electronic and ionic charge as a function of the high voltage. Moreover the timing properties are studied and the detector time resolution is measured. We also focus the attention on a new category of signals having intermediate properties between avalanche and streamer, called "transition events". This category is negligible for the standard gas mixture but relevant for HFO based gas mixtures. We show a direct comparison between SF_6 and $C_3H_2ClF_3$ to study in depth the possibility to replace an industrially very important molecule like SF_6.

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1. Search of an environment-friendly gas mixture for Resistive Plate Chambers

The Resistive Plate Chambers (RPC)[1] are planar gaseous detectors working with a uniform electric field generated by two parallel plates of high-bulk resistivity electrodes. The uniform field makes them very fast detectors with an excellent time resolution (<1 ns), suitable for timing measurements and for triggering. Experiments which work in high radiation environments, like those operating at the Large Hadron Collider, require the RPC operation in avalanche mode in order to guarantee modest working current, good rate capability and long term operation. The operation in pure avalanche mode with a large high-voltage range streamer-free is achieved thanks to the standard gas mixture, composed of $C_2H_2F_4$/i-C_4H_{10}/SF_6. This gas mixture has a high Global Warming Potential (GWP), due to the $C_2H_2F_4$ and SF_6. These gases are not recommended for industrial uses anymore, therefore their availability will be increasingly difficult over time and the search of an eco-friendly gas mixture is currently a crucial research for the usage of RPC in present and future experiments. In this work the $C_2H_2F_4$ is substituted with a proper mixture of $C_3H_2F_4$ and CO_2, while the highest-GWP molecule, the SF_6, is replaced by $C_3H_2ClF_3$, never tested in RPC detectors. This gas mixture has a GWP of the order of few units, to be compared to that of the standard one equal to 1430.

2. Experimental setup and analysis strategy

The test chamber is a small-size RPC, 55×10 cm^2 area, with 2 mm gas gap and 1.8 mm thick electrodes. The not-amplified electronic signal is read on both sides of a single strip line with an oscilloscope with analog bandwidth of 4 GHz and sampling rate of 20 Gs/s. On one side of the strip the signal is read on the scope using the maximum sensitivity in order to improve the efficiency measurement, while on the other side a variable scale is used to study the charge content avoiding saturation effects which can occur in presence of very wide signals. The ionic signal, which represents the best approximation of the total charge delivered inside the gas, is read on a 10 kΩ resistor connecting the graphite electrode to ground. Cosmic rays tracks are selected using triple coincidences among three 2 mm gas gap RPCs and a 0.5 mm gas gap RPC used also as time reference for timing measurements.
For each acquired signal the efficiency, streamer probability, transition event probability and prompt and ionic charges are measured.
A signal is considered efficient if it crosses an amplitude threshold equal to 0.8 mV (5 times the Root Mean Square of the background amplitude). The charge is measured integrating the signal over the entire time window acquired, which is 180 ns for the electronic signal and 80 μs for the ionic one. The criteria for discriminating avalanches from streamers and transition events [2] are summarized in Table 1. The time resolution is measured with the Time of Flight (TOF) method, using the 0.5 mm RPC as time reference ($\sigma_{0.5mm}$ < 500 ps).

The mixtures under studied are composed of $C_3H_2F_4/CO_2$/i-$C_4H_{10}/C_3H_2ClF_3$ with GWP ~ 10. During the test the $C_3H_2F_4$/i-C_4H_{10} proportions are fixed at 15/7, while the $CO_2/C_3H_2ClF_3$ ratio varies, exploring a $C_3H_2ClF_3$ (Cl-HFO in the following) range from 0 to 6%.

Table 1: Avalanche, streamer and transition event criteria. The exceeding charge is defined as the charge integrated over the tail of the signal, excluding therefore the avalanche contribution.

Signal type	Prompt charge	Time over threshold	exceeding charge
avalanche	≤5 pC	<12	-
streamer	> 30 pC	>30 ns	-
transition event	5 ≤ q (pC)<30	≥ 12 ns	> 0.21

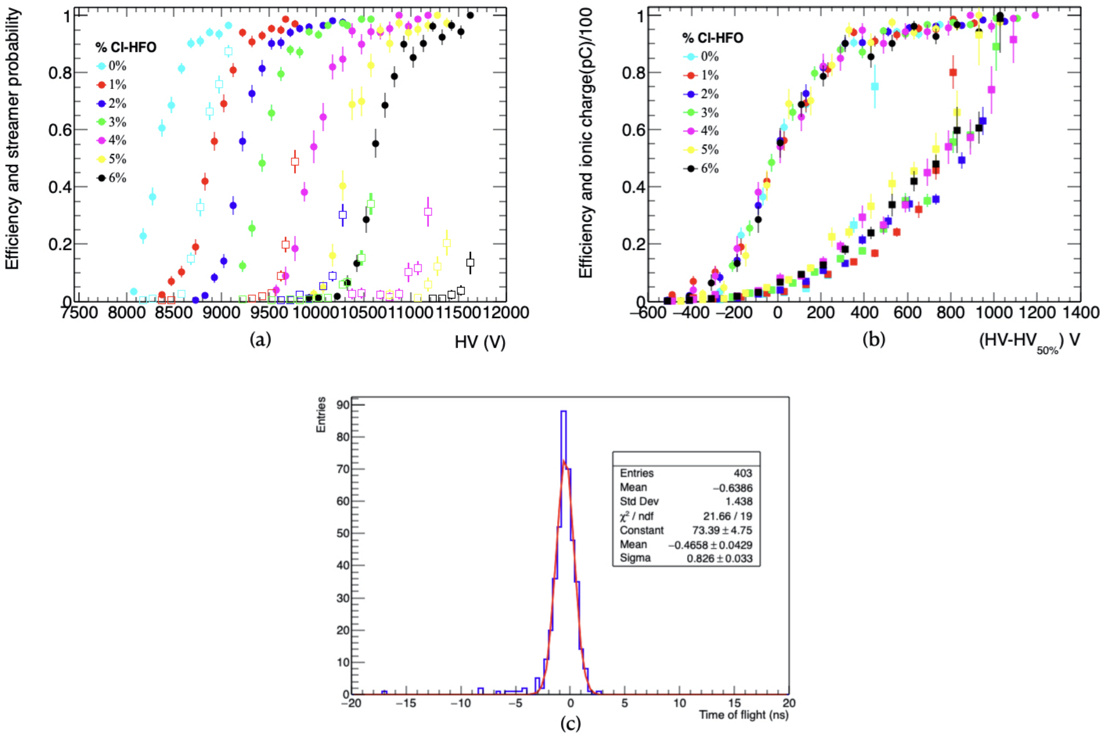

Figure 1: Efficiency with (a) streamer probability and (b) ionic charge as a function of the high voltage for Cl-HFO concentrations varying in the range (0-6)%. (c) Time resolution measured with the mixture with 2% Cl-HFO concentration.

3. Results

Figure 1.a shows the efficiency and streamer probability as a function of the high voltage for several Cl-HFO concentrations. The efficiency plateau is above 95% for all the gas mixtures, with a shift in high voltage which increases at the rate of ∼ 400 V/1% Cl-HFO. The streamer probability trend shows that the Cl-HFO has strong quenching properties: adding only 1% of this gas the RPC operation moves from the full streamer mode at plateau (0% Cl-HFO) to avalanche mode with 400 V of separation between the two regimes.

The contamination of transition events at plateau is below 25% for all the gas mixtures with Cl-HFO concentration different from zero. The charge contribution from avalanches, transition and streamer events is taken into account in the ionic charge measurement, shown in Figure 1.b. The ionic charge is drastically reduced thanks to the Cl-HFO, moving from 75 pC at plateau, obtained

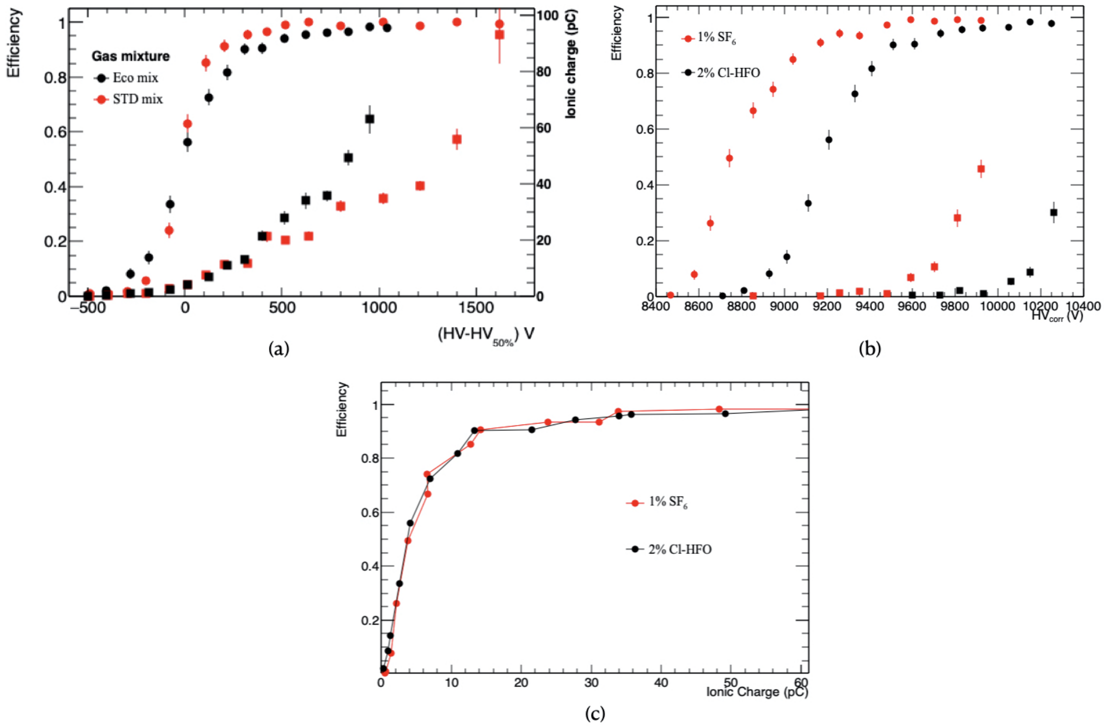

Figure 2: (a) Efficiency and Ionic charge as a function of the high voltage for the standard gas and eco-gas with 2% Cl-HFO. (b) Efficiency and streamer probability as a function of the high voltage for the mixture: $C_3H_2F_4/CO_2/i\text{-}C_4H_{10}/C_3H_2ClF_3$=(15/76/7/2)% and $C_3H_2F_4/CO_2/i\text{-}C_4H_{10}/SF_6$=(15/77/7/1)%. (c) Efficiency as a function of the ionic charge for the mixture : $C_3H_2F_4/CO_2/i\text{-}C_4H_{10}/C_3H_2ClF_3$=(15/76/7/2)% and $C_3H_2F_4/CO_2/i\text{-}C_4H_{10}/SF_6$=(15/77/7/1)%

with the mixture without Cl-HFO, to ~ 30 pC with the addition of only 1% of Cl-HFO. Among the Cl-HFO proportions studied, the one with 2% shows the lowest ionic charge and the larger avalanche-streamer separation, therefore it has been selected as the best gas mixture for further analysis. This choice strongly depends on the threshold used for the test.
The usage of CO_2 as the main gas component provides improvements of the timing properties of the detector. Indeed, the drift velocity is higher in CO_2 than in $C_2H_2F_4$, resulting in a better time resolution, shown in Figure 1.c. The time resolution with the eco-gas is 826 ps to be compared to $\sigma_{STD} \sim 1.1$ ns.

On the other hand, the total charge delivered inside the gas, even if it assumes low values, has a steep rise in the eco-gas with respect to the standard gas, as shown in Figure 2.a.
The possibility to replace a very important molecule like SF_6 with the Cl-HFO is strongly supported by the plots shown in Figure 2.b and 2.c. In these plots the efficiency, streamer probability and the ionic charge are shown comparing the gas mixture composed of 15%$C_3H_2F_4$/76%CO_2/7%i-C_4H_{10}/2%$C_3H_2ClF_3$ with the mixture composed of 15%$C_3H_2F_4$/77%CO_2/7%i-C_4H_{10}/1%SF_6. Figure 2.b shows that the two gas mixtures reach the same efficiency plateau and the one with Cl-HFO shows a slightly larger range of separation between avalanche and streamer regimes. Figure 2.c shows that the two gas mixtures have the same ionic charge at the same efficiency value, demon-

strating that the Cl-HFO can substitute at all the SF_6 in these gas mixtures.

4. Conclusions

In this work possible substitutes of the standard gas mixture for RPC have been studied, with the aim of replacing both the high-GWP molecules which compose the standard gas : the $C_2H_2F_4$ and the SF_6. The former has been substituted with a proper mixture of CO_2 and $C_3H_2F_4$, while the latter has been replaced with the $C_3H_2ClF_3$ never tested before in RPCs. The gas mixtures under study have GWP ~ 10, to be compared to the one of the standard gas which is 1430. The tests show excellent performance results in terms of efficiency, separation between avalanche and streamer regimes, total charge delivered inside the gas and time resolution.
Despite a time resolution which is 24% better than the one obtained with the standard gas, the performance of eco-gases is not yet at the same level of the standard one. However, this is the first time that an excellent performance is achieved with an RPC operated with a totally eco-friendly gas mixture.

References

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[2] "On a new environment-friendly gas mixture for Resistive Plate Chambers", G.Proto et al., JINST 17 (2022) 05, P05005, DOI:10.1088/1748-0221/17/05/P05005