AIDA-2020-MS93

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Advanced European Infrastructures for Detectors at Accelerators

Milestone Report

RPC Performance results with ecofriendly gases and use of recirculation gas systems

Giulio Aielli (INFN) *et al*

01 April 2019

The AIDA-2020 Advanced European Infrastructures for Detectors at Accelerators project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

This work is part of AIDA-2020 Work Package **13: Innovative gas detectors**.

The electronic version of this AIDA-2020 Publication is available via the AIDA-2020 web site `<http://aida2020.web.cern.ch>` or on the CERN Document Server at the following URL: `<http://cds.cern.ch/search?p=AIDA-2020-MS93>`

Grant Agreement No: 654168

AIDA-2020

Advanced European Infrastructures for Detectors at Accelerators

Horizon 2020 Research Infrastructures project AIDA-2020

MILESTONE REPORT

RPC PERFORMANCE RESULTS WITH ECOFRIENDLY GASES AND USE OF RECIRCULATION GAS SYSTEMS

MILESTONE: MS93

Document identifier:	AIDA2020-MS93
Due date of milestone:	End of Month 44 (December 2018)
Report release date:	01/04/2019
Work package:	WP13: Innovative gas detectors
Lead beneficiary:	INFN
Document status:	Final

Abstract:

In this document, we will review the most relevant achievement in the search and validation of an eco-compatible gas mixture for RPCs. Most of the tested candidates are based on HFO (hydrofluoroolefins), the industrial replacement of R134A, presently used as the main component of the RPC gas mixture.

The Advanced European Infrastructures for Detectors at Accelerators (AIDA-2020) project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168. AIDA-2020 began in May 2015 and will run for 4 years.

Delivery Slip

	Name	**Partner**	**Date**
Authored by	Giulio Aielli, Do-Won Kim, Barbara Liberti	INFN	30/03/2019
Edited by	G. Aielli	INFN	30/03/2019
Reviewed by	G. Aielli S.DallaTorre I.laktineh	INFN INFN CNRS	01/04/2019
Approved by	Paolo Giacomelli	INFN	01/04/2019

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Executive summary

The established RPC gas mixtures, mostly used in the LHC experiments, are largely based on R134A (C2H2F4), the present industrial standard for refrigeration systems. Due to its high Global Warming Power (GWP) of 1430 with respect to CO2, the industry will phase it out progressively in the next years, making the gas procurement progressively difficult and expensive. A large R&D effort is currently ongoing to find and validate a new RPC gas mixture, based on suitable gases with a much lower GWP, affordable and industrially produced. A potential replacement candidate is the new industrial standard for refrigeration, the HFO (hydrofluoroolefin).

*The present requirements for a suitable RPC gas mixture are quite stringent: it must guarantee a stable avalanche up to a large charge (5*107 electrons), without developing streamers, which would harm the detector longevity and rate capability.*

The most relevant achievements in the search and validation of eco-compatible RPC gas mixtures are based on HFO as replacement of TFE. The HFO has features similar to TFE, even if it presents two major disadvantages, when compared to TFE:

- *HFO requires a higher operative electric field, by about 30%, in order to obtain the same gain*
- *The difference between the electric field for the standard gain and the electric field at which streamers appear, namely the avalanche to streamer separation, is narrower.*

Several strategies are tested, consisting in adding secondary components to HFO (CO2, SF6, various hydrocarbons, etc.), to overcome or mitigate the above-mentioned limitations.

It is important to underline that the typical gain at which standard RPCs are operated can be changed in novel detectors. It must be clear that the avalanche to streamer separation does not have an absolute physical meaning since the set working point depends on the avalanche signal transfer efficiency, from the gas to the pickup electrodes, and on the front-end amplifier signal to noise ratio. Therefore, an alternative approach for future operation of RPC detectors, is to redesign both the gas gap and the front-end electronics to make them able to efficiently operate at lower average charge, in order to establish a sufficiently large avalanche to streamer separation. Such performance has been demonstrated within the task 13.2.3, where a new generation of RPCs designed for the LHC upgrades, is conceptually capable of coping with a variety of Eco-compatible mixtures, however a direct demonstration, including the long-term performance is still ongoing. A further optimization of eco-compatible gas mixtures is also necessary to ensure future operation of the presently existing RPC systems of ATLAS and CMS, which do not benefit from the new RPC generation performance.

1. INTRODUCTION

The RPC generation designed for LHC (including ATLAS, CMS and Alice) uses a mixture mostly based on R134A ($C_2H_2F_4$): for instance, 94.7 % [R134A] 5 % [C_4H_{10}] 0.3% SF_6 in the ATLAS case. It was chosen because of the following features:

- High efficiency
- Large avalanche stability plateau up to $5*10^8$ electrons
- Controllable ageing effects
- Non flammable
- Non Ozone-depleting behaviour
- Industrial standard for refrigeration (easy to procure and stable price).

Due to its high Global Warming Power (GWP) of 1430 with respect to CO_2, companies will progressively phase it out in the next years, therefore making the gas procurement more and more difficult and more expensive. An extensive R&D effort is currently ongoing to find and validate a new RPC gas mixture, based on suitable gases with a much lower GWP, industrially produced and available at affordable costs.

The requirements for a gas mixture suitable for the standard RPC already in operation are quite stringent; in fact, it must allow stable avalanche mode up to a large charge ($5*10^7$ electrons), without developing streamers, which would harm the detector longevity and rate capability. A potential replacement candidate is the new industrial standard for refrigeration: HFO (hydrofluoroolefin).

1.1. TEST ON 2 MM SINGLE GAP RPCS WITH NO SF6

Single gap RPCs are formed by a single gas gap, 1 to 2 mm wide, that must ensure a sufficient amount of primary ionization to reach full efficiency. The standard RPCs used as key trigger elements in ATLAS and CMS have 2 mm gaps. This section is dedicated to the effort of identifying an eco-compatible gas mixture that can preserve the performance of these standard RPCs.

The difficulty in finding an eco-compatible replacement of the present gas mixture stays in the many features required to a candidate mixture. HFO, namely the most promising TFE replacement candidate, when used in standard RPCs, exhibits two major drawbacks:

- it requires a higher operative electric field, by about 30%, in order to obtain the same gain;
- the difference between the electric field for the standard gain and the electric field at which streamers appear, namely the avalanche to streamer separation, is narrower.

Specific and systematic tests have been carried out in order to measure these two quantities in comparison to the standard mixture. Additional components such as CO_2, SF_6, Ar, and several different hydro-carbons (Ethylmethylketone [MEK], Methyl tert-Butyl ether [MTBE], Dimethyl Sulfide have been used trying to mitigate the problems mentioned above .

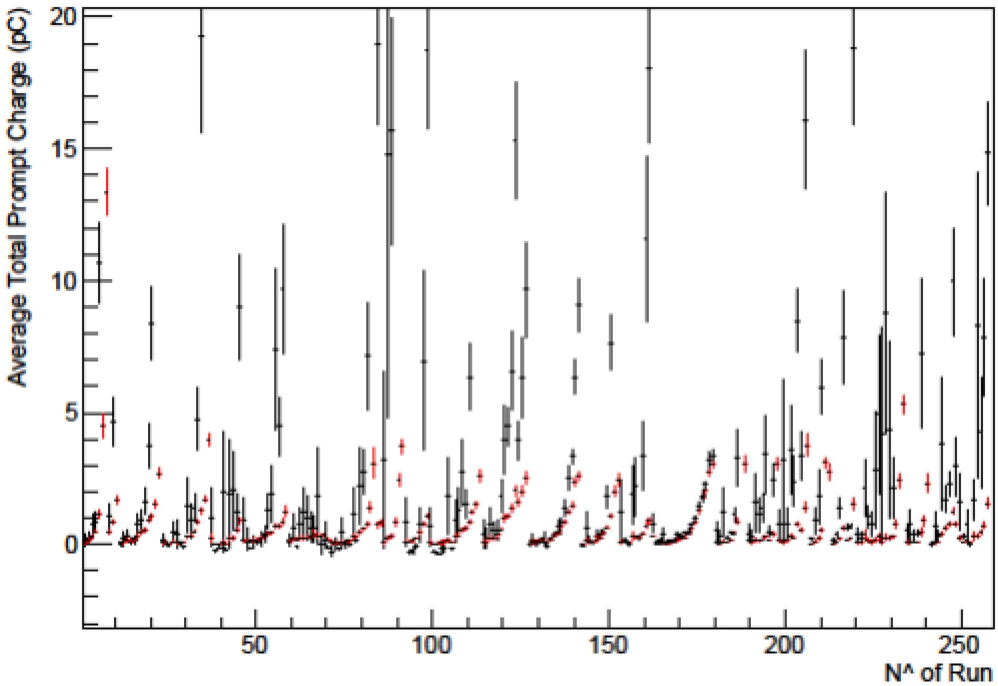

Figure 1- Summary of 260 test performed with 20 different gas mixtures. The total prompt charge for different HV is plotted in black along with the prompt charge relative to the first avalanche.

A summary of measurements performed with more than 20 gas mixtures based on HFO, in combination with various additional components, is reported in Figure 1. The tests are performed using a standard 2mm gas gap similar to the ones used for the ATLAS and CMS RPCs. The red points are the average prompt charge of the first useful signal, the black points are the corresponding total prompt charge collected per event, including also the unwanted after-pulses and streamers appearing after the first avalanche. For each gas mixture several measurements are performed at increasing HV. The black and red points should be close to each other also at HV beyond the limit of the efficiency plateau, in order to account for a reasonable safety margin. Looking at Figure 1, the runs between 160 and 180 report the results with the the standard gas mixture: they are the only ones satisfying the requirement. It must be concluded that none of the tested gas mixtures show a safety margin comparable to that of the standard mixture. Moreover, the novel mixtures impose to operate at a HV between 10% and 40% higher.

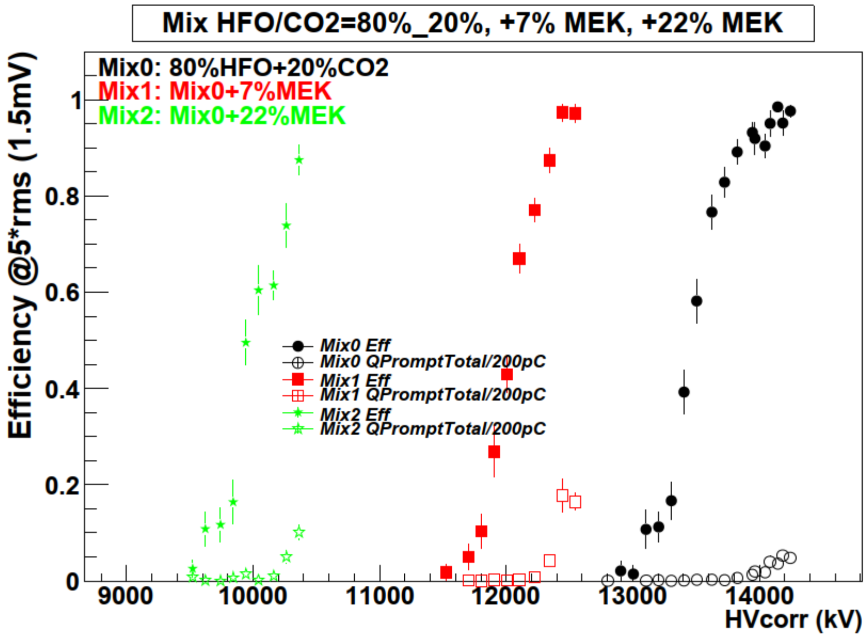

Figure 2 Efficiency (full) and streamer estimator (empty) versus high voltage for Mix8020 = 80%HFO − 20%CO_2 (black), and Mix8020= 80%HFO − 20%CO_2 + 7%MEK (red) and Mix8020= 80%HFO − 20%CO_2 + 22%MEK (green).

In Figure 2 some of the most significant results are reported, relative to the addition of MEK (butanone, also known as methyl ethyl ketone) to a base binary mixture HFO-CO_2 [80%-20%]. MEK has proved to lower the high voltage working point, proportionally to its concentration and the more efficient the higher is the HFO percentage in the binary mixture. Nevertheless, the average total prompt charge increases when the same efficiency provided by the traditional gas mixture is required.

1.2. TEST USING 2 MM SINGLE GAS GAPS WITH SF_6

Further tests are reported in this section to assess the performance of 2 mm gap RPCs. Using the mixture CO_2/HFO =20/80, the efficiency plateau knee is reached at 13.6 kV, with a very clear avalanche-streamer separation, ~ 300 V, at full efficiency. The advantage is a GWP as low as 6 and the disadvantage is the very high operating voltage.

The addition of small amounts of SF_6 to the binary mixture CO_2/HFO mixtures increases the detector performance at the cost of a significant increase of the GWP (Figure 3).

The best result is obtained with mixture CO_2/HFO = 50/50 with 4.5% of SF_6 which has a good working point at 11.8 kV, with an avalanche-streamer separation of ~ 300 V. The GWP of this mixture is increased to ~ 700.

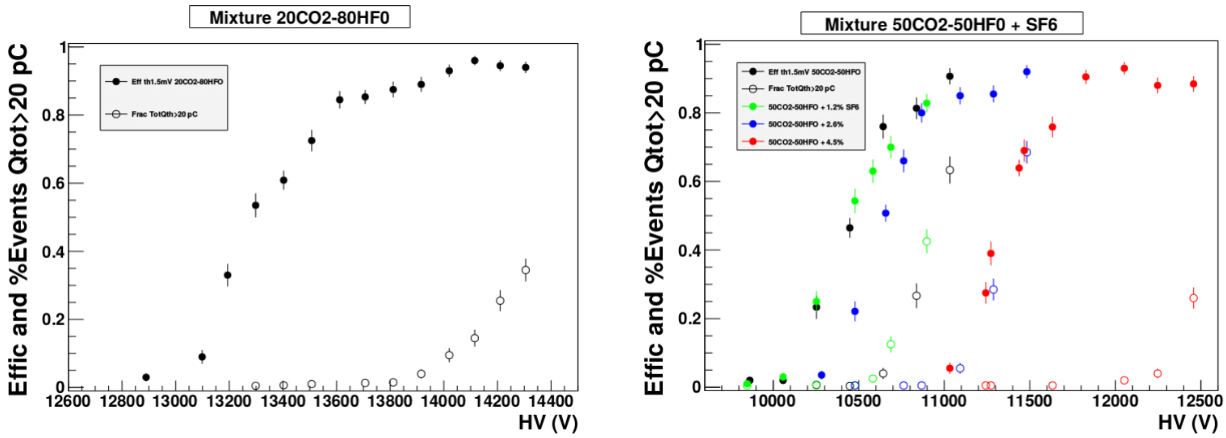

Figure 3 Left: efficiency (full dots) and the fraction of prompt charge respect to the total charge (open circles) versus the applied voltage using 20%-80% CO_2 – HFO. Right: the same using 50%-50% CO_2 – HFO added by different fractions of SF_6.

1.3. TEST ON 1 MM SINGLE GAS GAPS WITH PURE HFO

RPCs with 1 mm gas gap are relevant because they represent the baseline for the ATLAS Phase1 and Phase2 upgrades and allow to reach higher electric field for a given applied voltage.

While it is not possible to test pure HFO in the 2 mm gap RPCs because the working voltage would exceed the 15 kV limit of the available power supply, tests have been performed on gas gaps of 1 mm, with both standard resistive electrodes (1.8 mm) and thinner electrodes (0.8 mm), with the new front-end electronics for the amplification of the signals.

Efficiency figures versus high voltage are compared in Figure 4. For thin electrodes gas gap, with

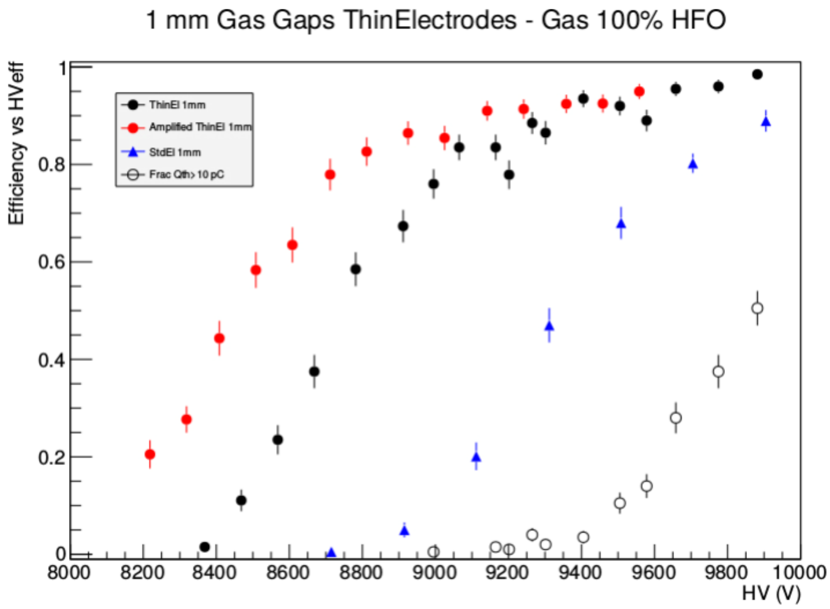

Figure 4 - Pure HFO tested with 1 mm gas gap in different configurations:1.8 mm thick electrodes (black), 1.8 mm thick electrodes and signal amplification by FE electronics (red), 0.8 mm thick electrodes (red), fractional charge >10 pC (open circles) [COMMENT: this I do not understand].

front-end amplifier, the avalanche-streamer separation from the plateau knee at 8.9 kV is ~ 500 V.

This test shows that a 1 mm gas gap with thinner electrodes and a new generation amplifier, as the one adopted as a baseline for the present Task 13.2.3, is capable to reach a relatively safe operating voltage also with pure HFO. Further tests are ongoing to further improve the 1 mm gas gap working point and avalanche to streamer separation by means of appropriate additional components.

2. TEST ON MULTI-GAP RPCS

2.1. INTRODUCTION AND SETUP

The Multigap Resistive Plate Chambers (MRPC) are used as timing device in several collider experiments and cosmic ray experiments thanks to the excellent timing performance. The typical gas mixtures of RPC-type detectors at current experiments are based on the gases $C_2F_4H_2$ (95%) and SF_6 (5%). The performances of MRPC have been measured with two different gas mixtures; $C_2F_4H_2$ based gas mixtures and the eco-friendly $C_3F_4H_2$ (HFO-1234ze). A small MRPC was used for the tests. It has a sensitive area of 20 × 20 cm^2 and it has 6 gaps of 220 µm. The operating voltage with the standard mixture is 15 kV. In standard operation, the strong space charge created within the gas avalanche limits the avalanche's growth. SF_6 plays an important part in the process due to its high attachment coefficient at low electric fields. Therefore, it is necessary to find a replacement gas that has a similar attachment coefficient. CF_3I is a possible candidate. Tests were performed with this gas added to $C_3F_4H_2$.

2.2. EXPERIMENTAL RESULTS

2.2.1. Efficiency vs. HV and Rate

Measurements of efficiency vs. HV and particle rate, obtained for various gas mixtures, are reported in Fig.5. The MRPOC operation with $C_3F_4H_2$ mixtures requires a voltage increase of 4 kV with respect to operation with $C_2F_4H_2/SF_6$ gas mixtures. The plateau efficiencies obtained for the

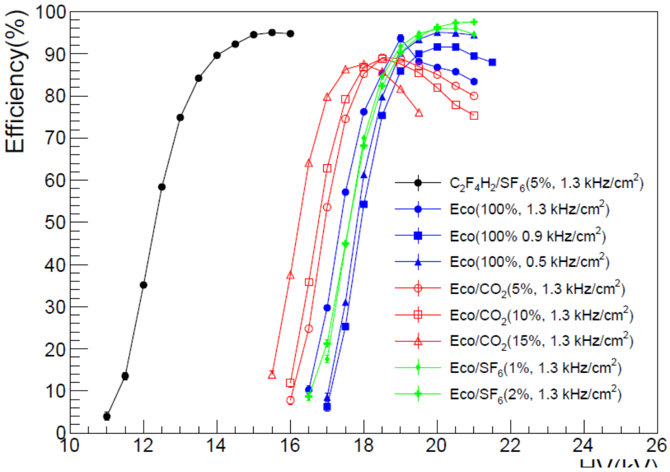

Figure 5 Efficiency measured with various gas mixtures at 1.3 kHz/cm^2 particle rate. For C3F4H2 additional particle rates of 0.5 and 0.9 kHz/cm^2 have been tested.

efficiency plateau are 95% for $C_2F_4H_2/SF_6$ and 88% for $C_3F_4H_2$ at the same particle flux of 1.3

kHz/cm^2 . At a lower flux, for pure $C_3F_4H_2$, the efficiency increases and the plateau becomes longer, as clearly visible for the data collected at 0.5 kHz/cm^2.

The tests reported in Fig. 6 focus on the use of CF_3I as replacement of SF_6. The expected increase of operating voltage is there; apart from this aspect, the results obtained are very comparable.

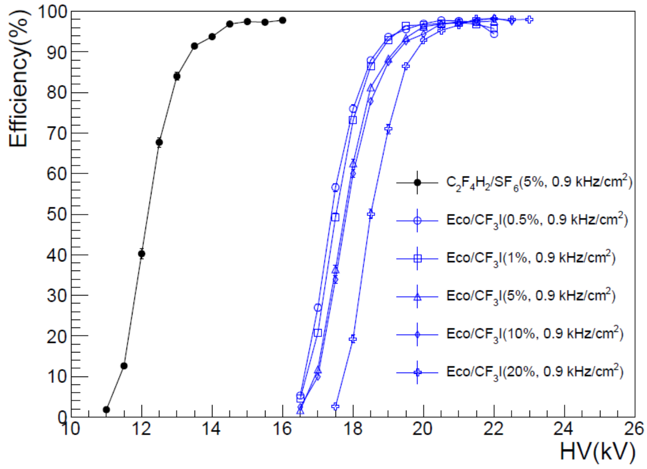

Figure 6 Efficiency measured different fractions of CF_3I as replacement of SF_6.

2.2.2. Time resolution vs. HV and Rate

The time resolution for the tested gas mixtures is shown in fig. 7. At the voltage corresponding to the knee of the efficiency plateau the time resolution is 88 ps for both $C_2F_4H_2/SF_6$ and $C_3F_4H_2/SF_6$. The other results are between 115 and 125 ps at 1.3 kHz/cm^2. Figure 8 reports the use of CF_3I as replacement of SF6. Better resolution between 95 and 120 ps is obtained for $C_3F_4H_2$, depending on the ratio of CF_3I.

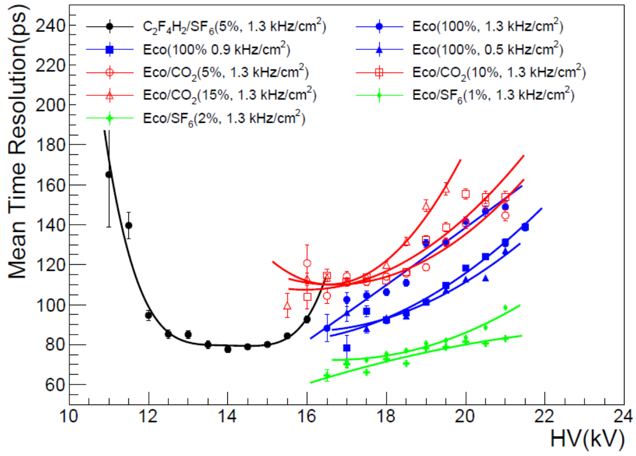

Figure 7 Time resolution measured with various gas mixtures at 1.3 kHz/cm^2 particle rate. For $C_3F_4H_2$ additional particle rates of 0.5 and 0.9 kHz/cm^2 have been tested

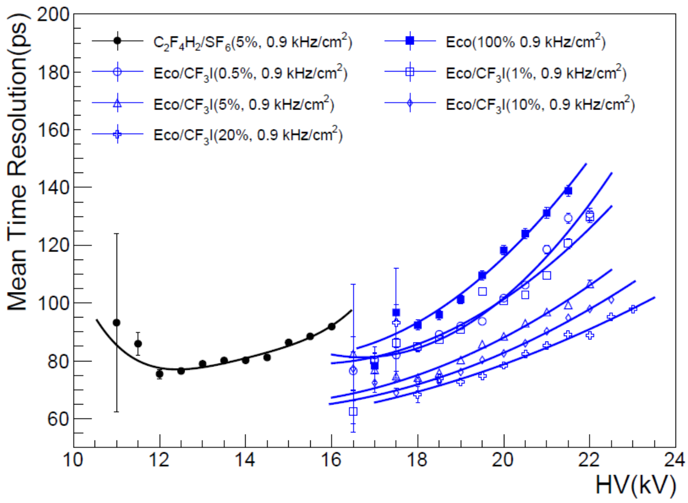

Figure 8 Time resolution for different concentrations of CF_3I

3. ONGOING ACTIVITIES: WHAT IS STILL TO BE DONE

The research dedicated to a good replacement of the standard RPC gas mixtures is pretty advanced, even if not yet exhausted. The following points are still under investigation:

- HFO is a fair candidate to replace TFE, even if the performance is not as good. Therefore, the search for a better candidate is still open.
- SF_6, which ensures stable RPC operation, has an extremely high GWP but still needs to be considered because it has no replacements in industry. However, there are already replacement candidates such as CF_3I and NovecTM 5110, the last one not yet fully explored and very expensive.

- These gases have been tested in a low and moderate rate environment but high rate and longevity tests are still to be performed. A delay to perform this last test has been accumulated due to the long time needed to setup an appropriate gas system at the GIF++ of CERN. The gas system is now available and the studies can be completed within a year.

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ANNEX: GLOSSARY

Acronym	Definition
RPC	Resistive Plate Chambers
MEK	Ethylmethylketone
HFO	Tetra-Fluor-Ethylene
TFE	Tetrafluoroethylene
GWP	Global Warming Power