Studies to Mitigate Greenhouse Emissions in High-Energy Physics Particle Detectors

Mattia Verzeroli

Supervisors: Imad Laktineh, Beatrice Mandelli

2nd Year PhD Series
18/04/2024

EP-DT
Detector Technologies

Outline

- Greenhouse gases emissions at CERN;
- Research on alternative gas mixtures:
  - Introduction;
  - Laboratory tests: CO_2 based gas mixture;
  - Irradiation campaign: CO_2 based gas mixture;
  - Alternative to SF_6;
- Monitoring of Gas Recirculation and Recuperation Systems:
  - CMS CSC case;
- Optimization of current gas system technology:
  - ALICE MID gas analysis rack case;
- Conclusion.

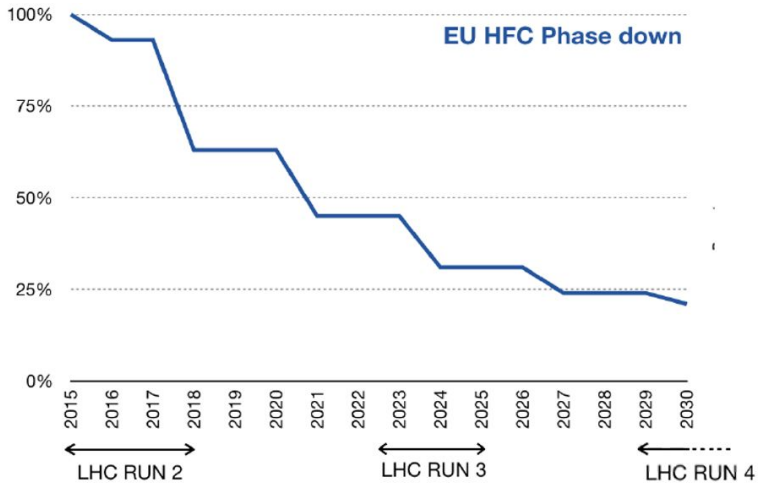
Greenhouse gas emissions at CERN

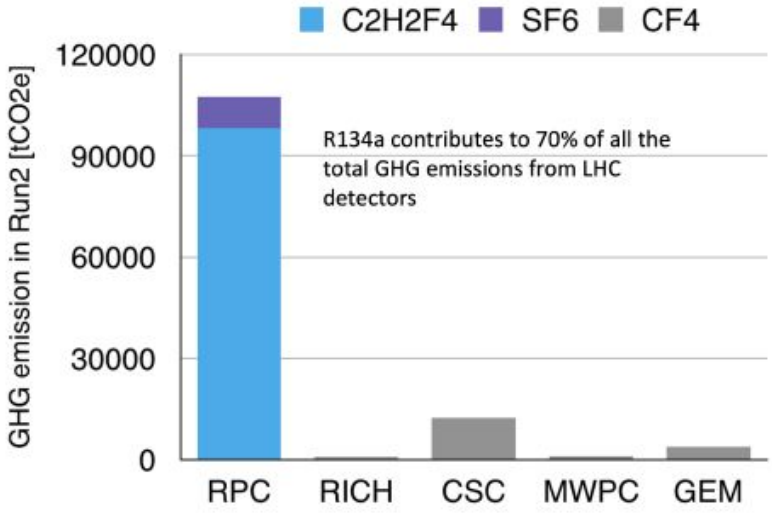
CERN Environment Report:

- Reduce GHG emissions by 28% by the end of 2024;

EU fluorinated gases regulation (2014):

- Reducing products availability of fluorinated GHGs;
- This regulation already affected fluorinated gases prices.

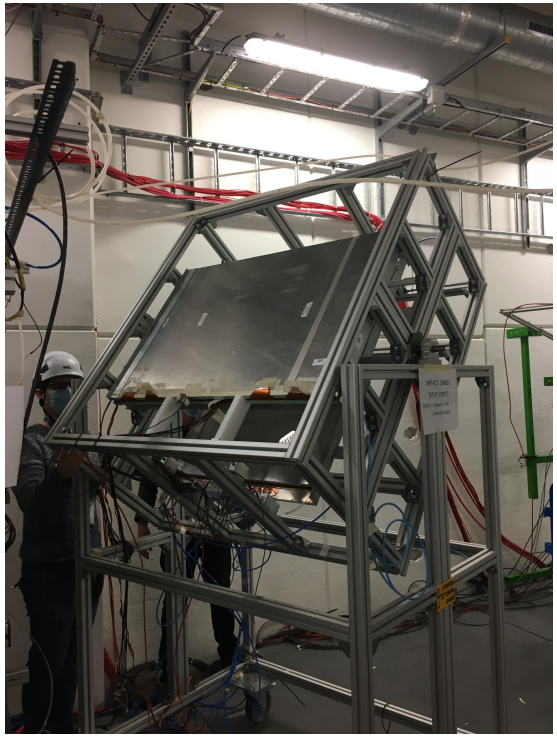


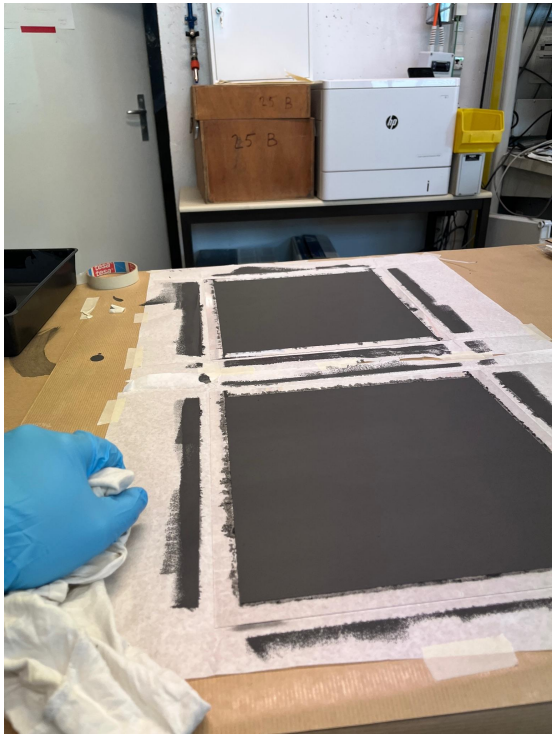


CERN gas team developed different strategies to reduce GHG emissions:

- Research on alternative eco-friendly gases;
- Development of gas recirculation systems;
- Optimization of current gas systems technologies.

Research on Alternative Gas Mixture

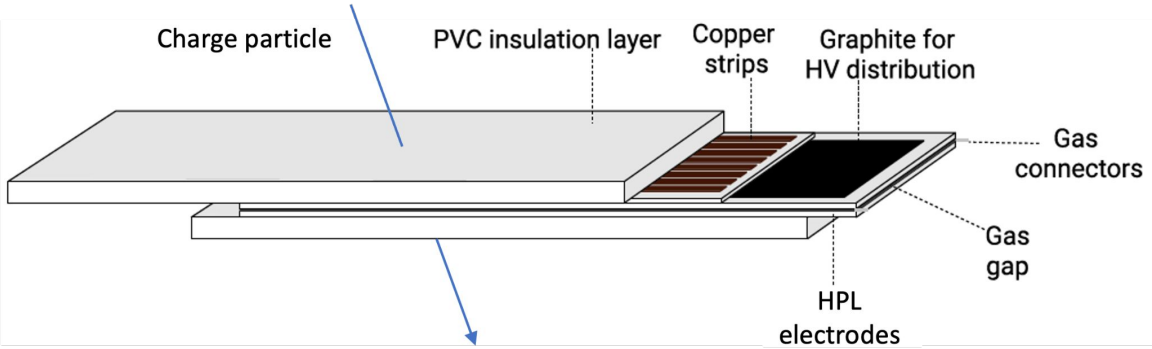


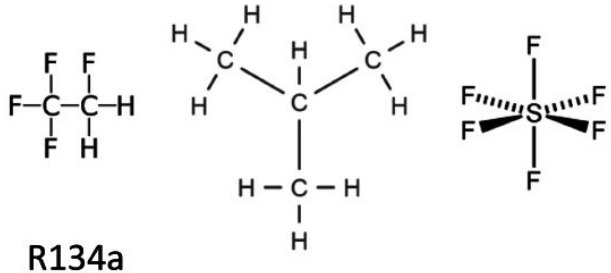


Introduction: RPC detectors

RPCs dominate CERN GHG emissions :

- Large area (5000 m^2 /experiment);
- Large volume (15 m^3 /experiment);
- Gas leaks at detector levels;
- High GWP mixture:





R134a
$C_2H_2F_4$
95.2%
GWP: 1430

iC_4H_{10}
4.5%
GWP: 3.3

SF_6
0.3%
GWP: 22800

Standard Gas Mixture

Structure:

- Planar resistive electrodes made of HPL;
- Electrodes separated by spacers;
- Gas gap between the electrodes filled with gas mixture;
- Copper strips for signal readout.

Operating principle:

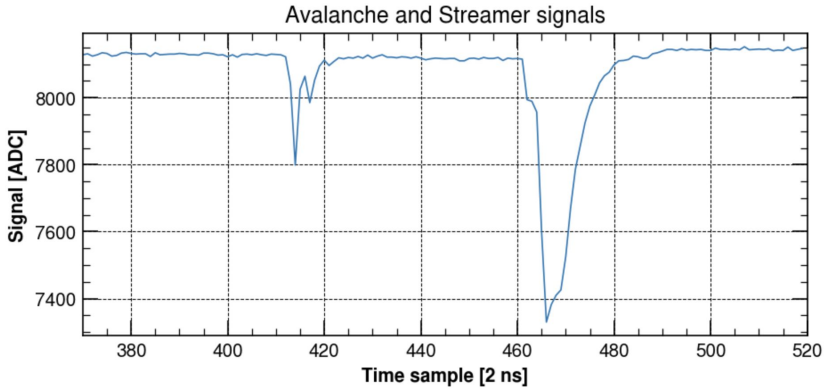
- High voltage applied to the electrodes;
- Gas ionization inside the gap;
- Charge multiplication;
- Charge induction on readout strips

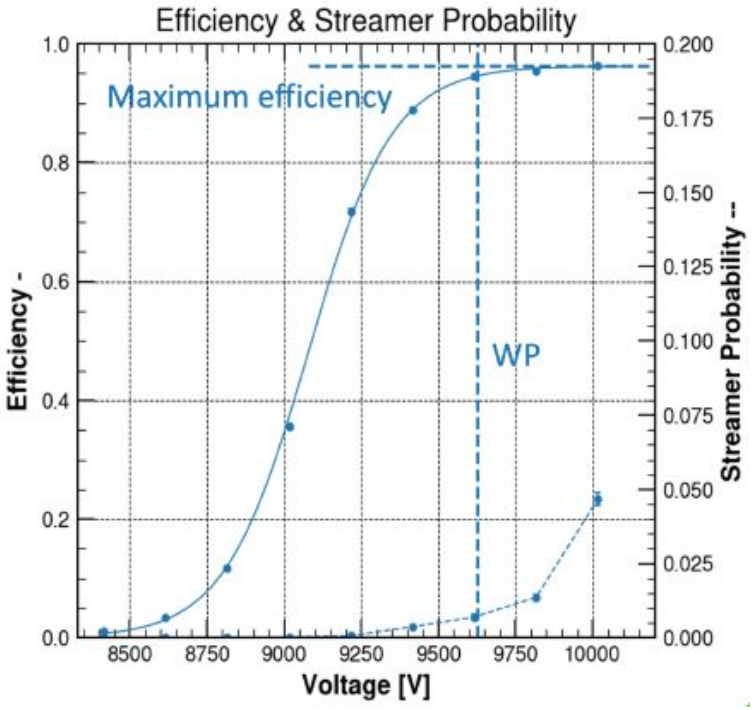
Introduction: RPC detectors

Foremost parameters:

- Detector currents;
- Prompt charge:
  - Avalanche (<10^8 e^-);
  - Streamer (>10^8 e^-);
- Streamer probability:
  - N. streamers/N. signals;
- Efficiency;
- Working point: voltage where the efficiency reach 95% of its maximal values, plus 150 V.

The **goal** is to find an eco-friendly gas mixture that is compatible with the current LHC RPC systems (HV supply, FEB electronics, gas systems…) and that allows to have a good detectors performance.





Introduction: Research overview

R134a Alternatives

- ➔ He
- ➔ HFO1234ze
- ➔ R32
- ➔ N_2
- ➔ Ar…

\+ market available

(Rigoletti, Guida, Mandelli, 2023)

selected → CO_2 based gas mixture 30-60%

- Reduction of the tCO2e emissions
- Laboratory Studies to fine-tune the concentration.

based on performance → **30% CO2 + 64% R134a + 5% iC4H10 + 1% SF6**

- Constant monitoring of the detector status
- Periodic Test Beam Monitoring

SF_6 alternatives

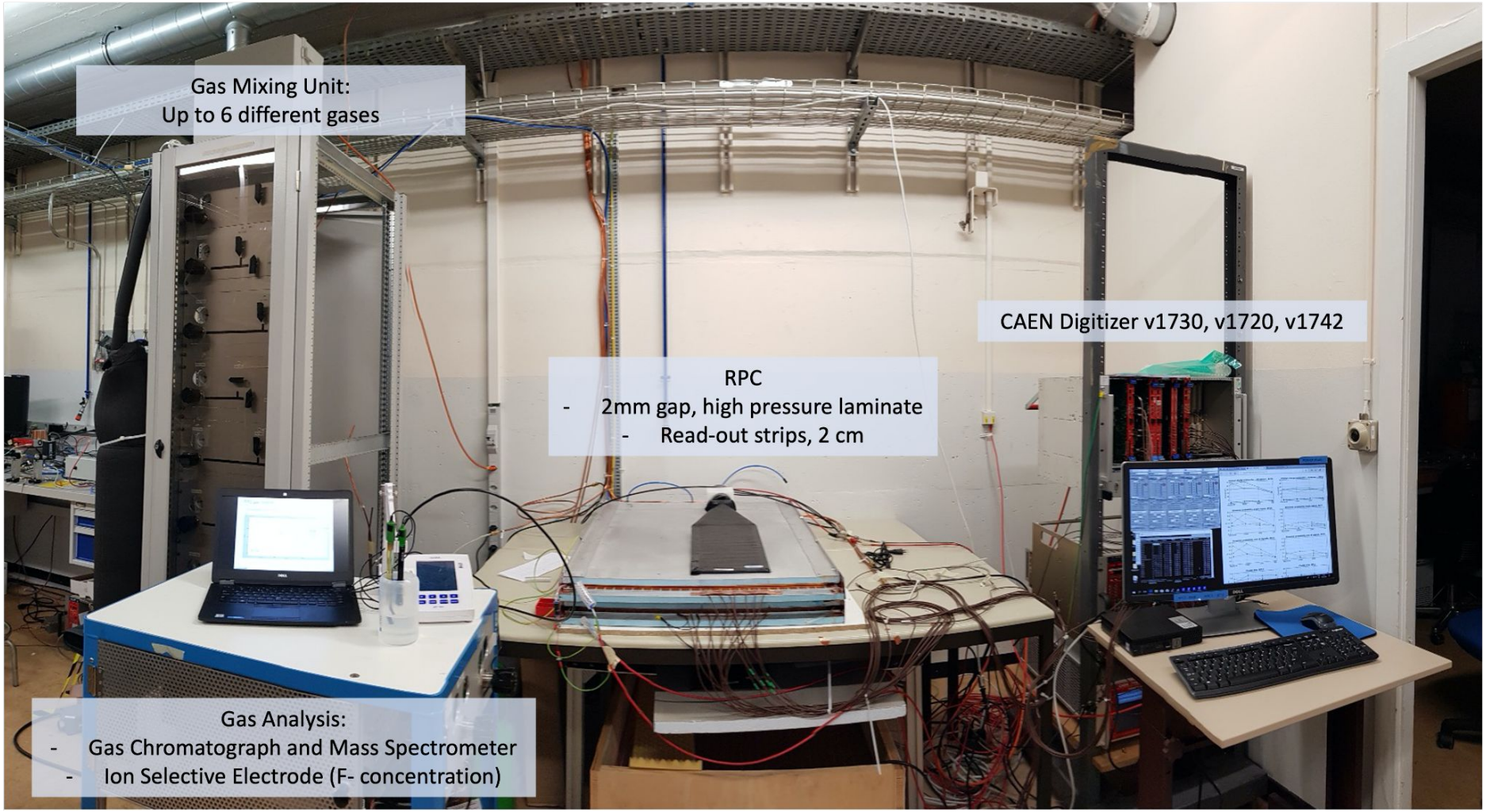
- ➔ Amolea 1224yd
- ➔ Novec 4710

laboratory studies → **0.5% Amolea 1224yd**
0.1% Novec 4710

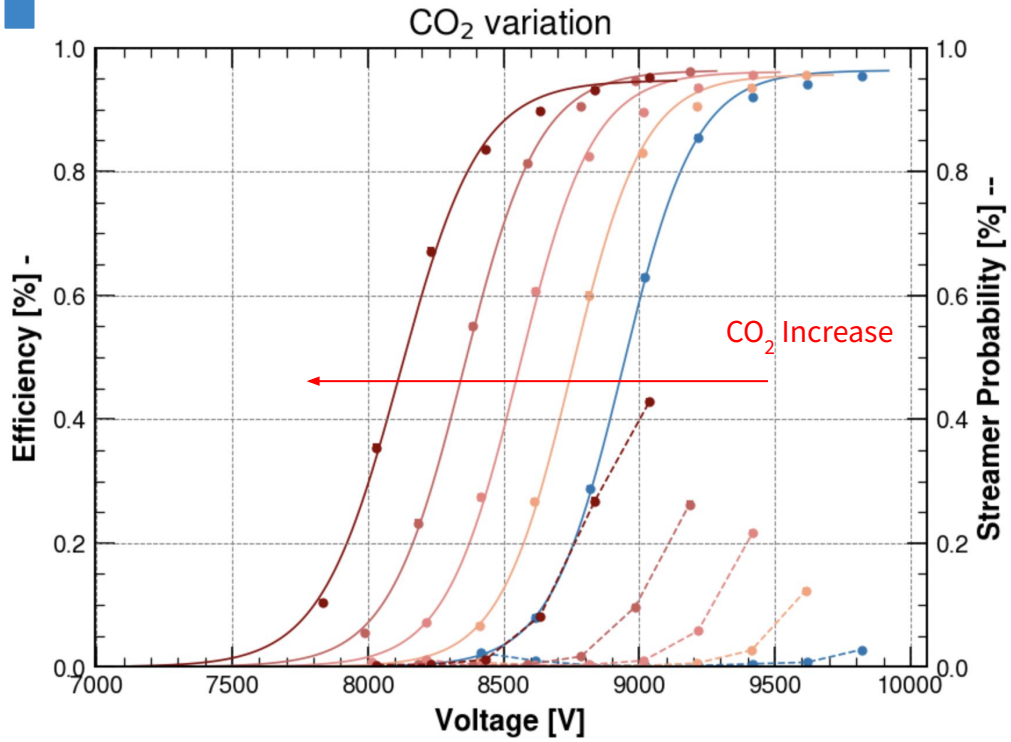
→ study on going also for glass MGRPC

Laboratory setup

EP-DT
Detector Technologies



STD mixture with the addition of CO_2



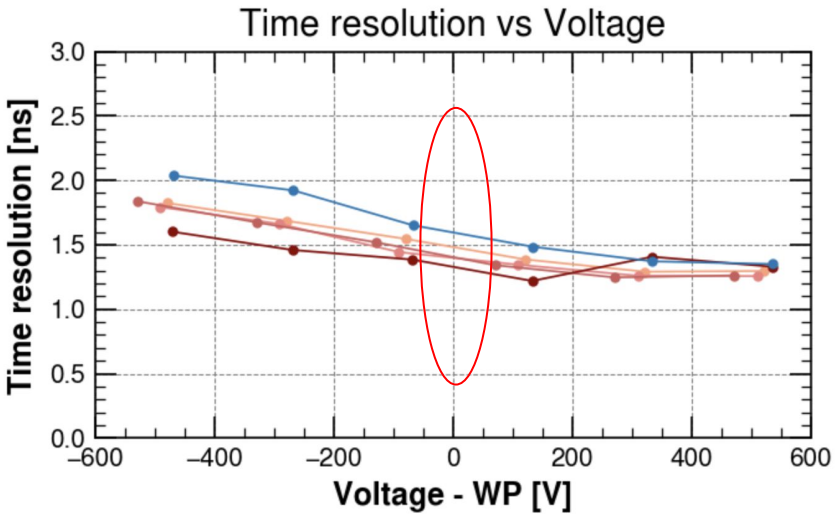
STD	$R134a/iC_4H_{10}/SF_6$ - 95.2/4.5/0.3
30% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 30/64.0/5.0/1
40% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 40/54.0/5.0/1
50% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 50/44.0/5.0/1
60% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 60/34.0/5.0/1

- +10% CO2 -> WP -200 V;
- Maximum efficiency similar to STD;
- Time resolution at WP lower than STD.

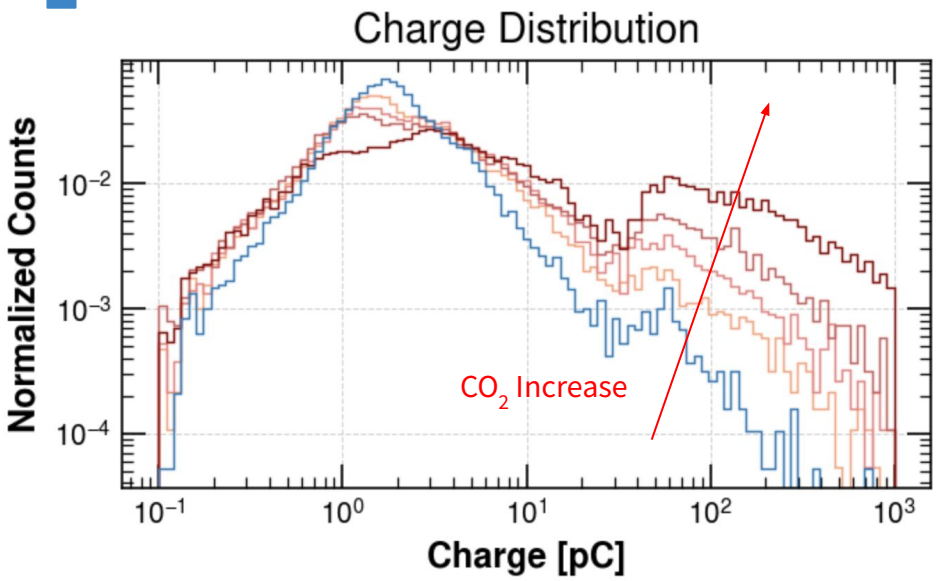
- Higher streamer probability:

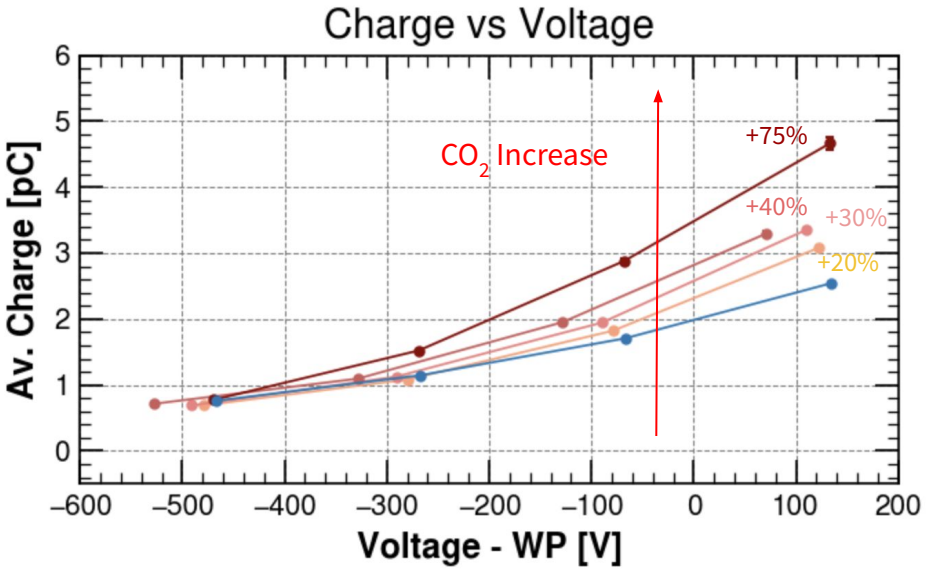
STD = 0.5%
30% CO2 < 1.5%
40% CO2 < 3.5%
50% CO2 < 7%
60% CO2 < 15%

1% SF_6 selected in precedent studies to mitigate the streamer probability.



STD mixture with the addition of CO_2





STD	$R134a/iC_4H_{10}/SF_6$ - 95.2/4.5/0.3	
30% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 30/64.0/5.0/1	-15% GWP
40% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 40/54.0/5.0/1	-25% GWP
50% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 50/44.0/5.0/1	-34% GWP
60% CO_2	$CO2/R134a/iC_4H_{10}/SF_6$ - 60/34.0/5.0/1	-44% GWP

- Higher avalanche charge wrt STD:
  30% CO_2 -> +20% 40% CO_2 -> +30%
  50% CO_2 -> +40% 60% CO_2 -> +75%

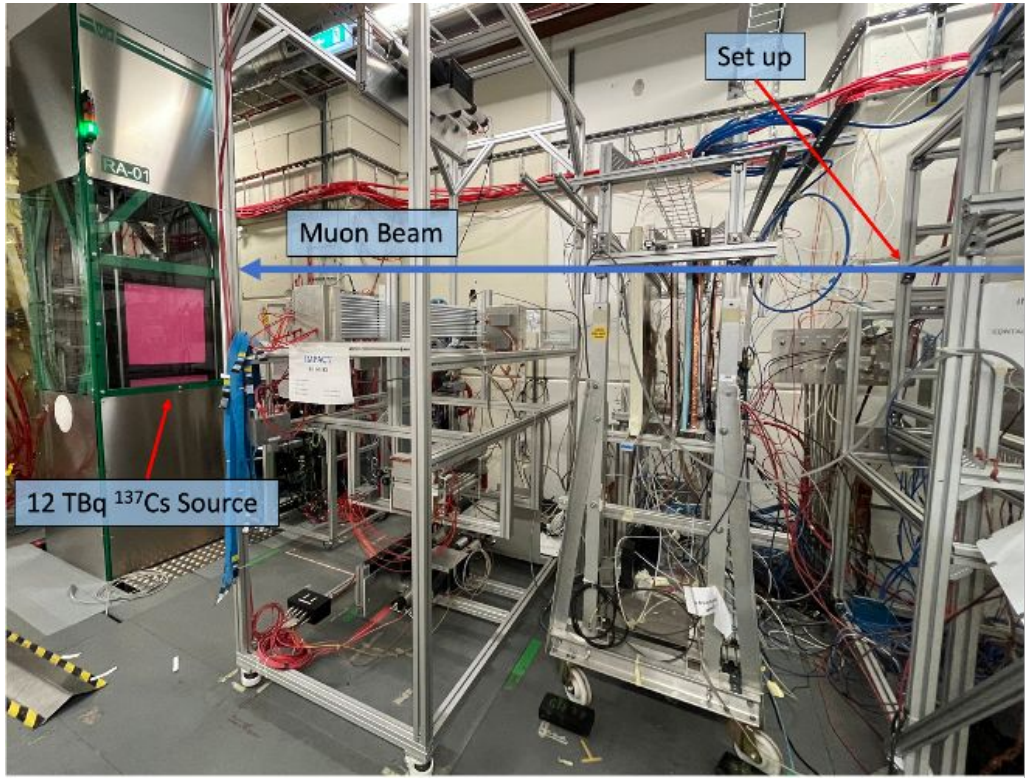
- Higher Streamer probability and Streamer Charge

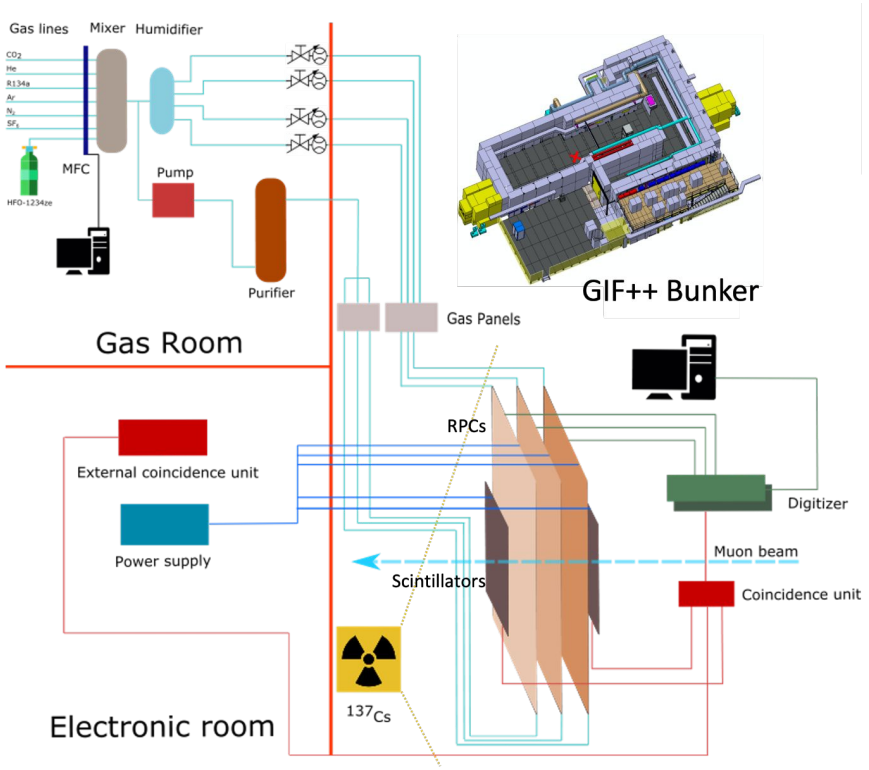
Due to its good performances, 30% CO_2 gas mixture was selected for long term aging at the Gamma Irradiation Facility (GIF++) at CERN:

-> Collaboration with ATLAS RPC and CMS RPC groups

Possibility to further study also 40% CO_2 gas mixture.

Long-Term study: GIF++ setup





Attenuation factor (ABS): from 69 to 2.2 (~20 Hz/cm^2 to ~500 Hz/cm^2)

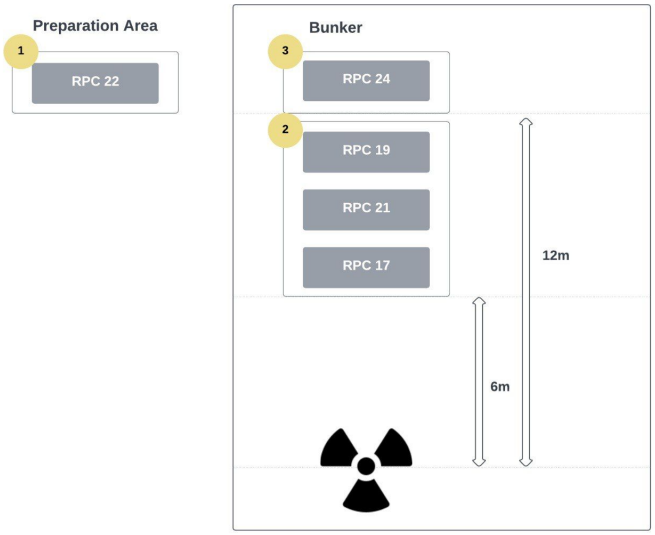
Long-Term study: Irradiation

Starting date: 1st March 2023

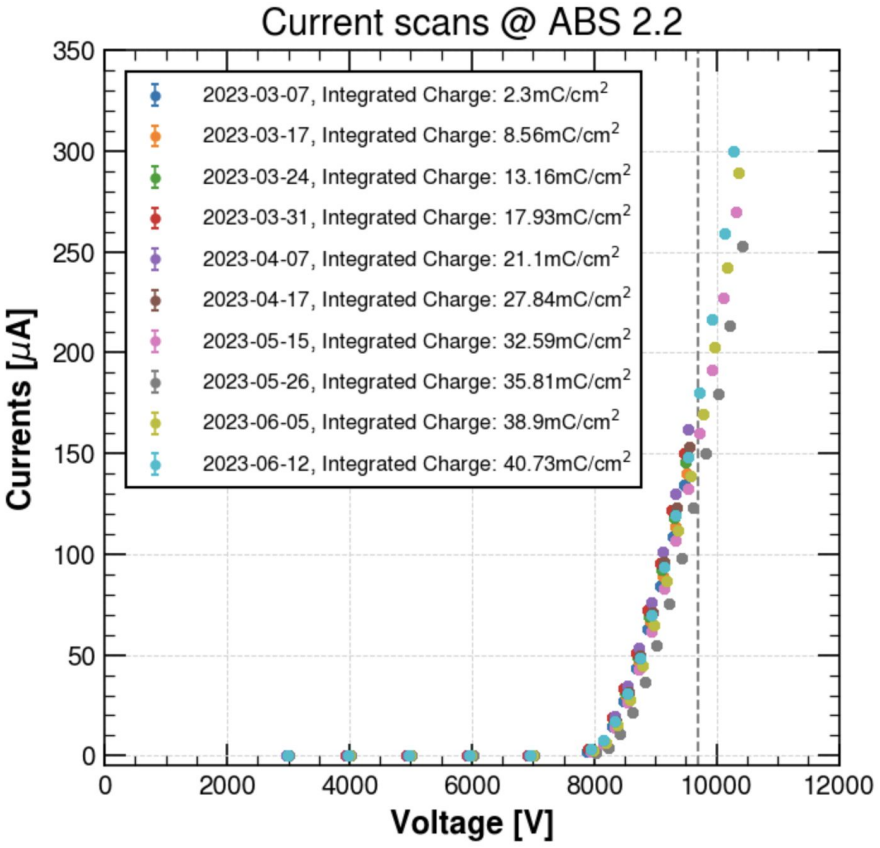
Gas Mixture: **30% CO_2** [CO_2/R134a/iC_4H_{10}/SF_6 - 30/64.0/5.0/1]

Integration goal: **25 mC/cm²** -> From ATLAS RPC prediction for Run 3

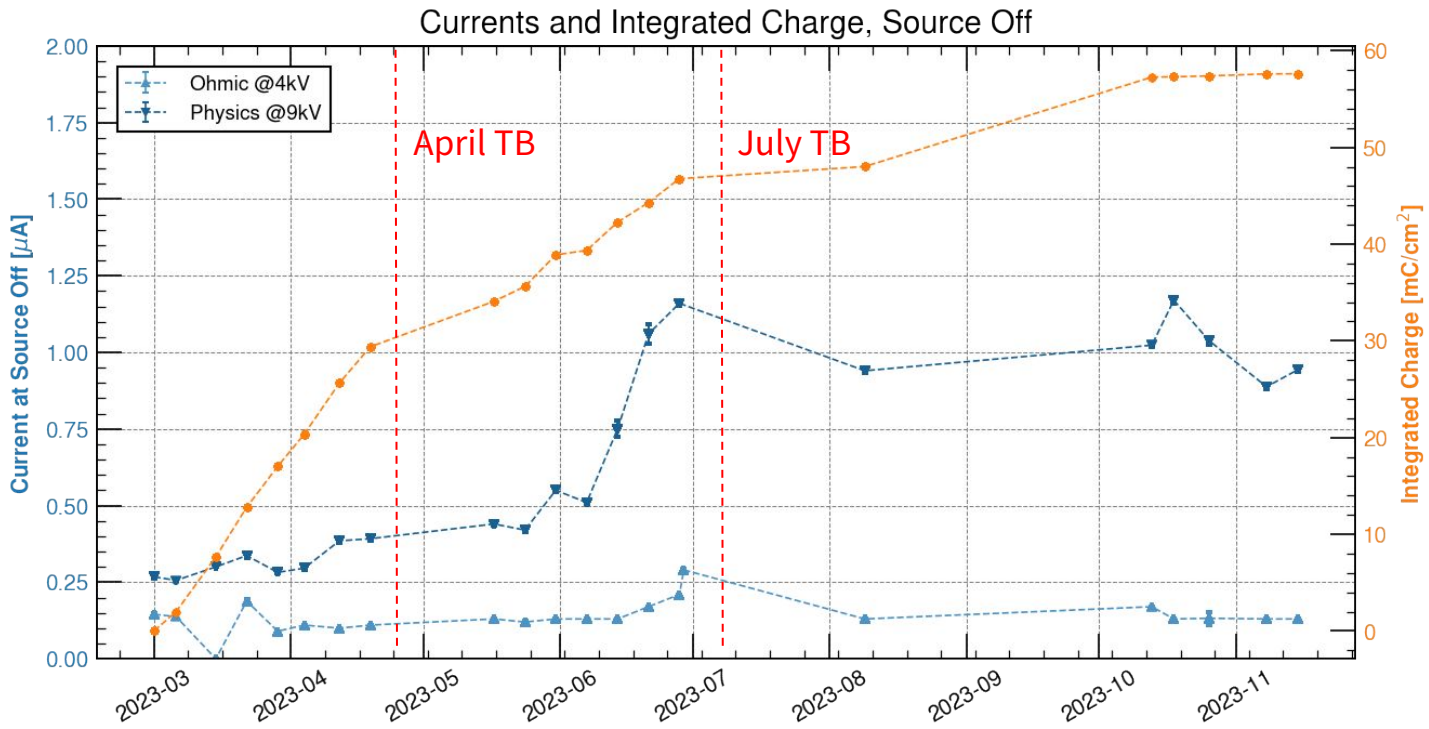
Detector hit rate: **400 Hz/cm²**, with detector at 50% of the maximum efficiency



1. Source off
2. 100 Hz/cm²
3. 400 Hz/cm²



Long-Term study: Irradiation



For Source Off:

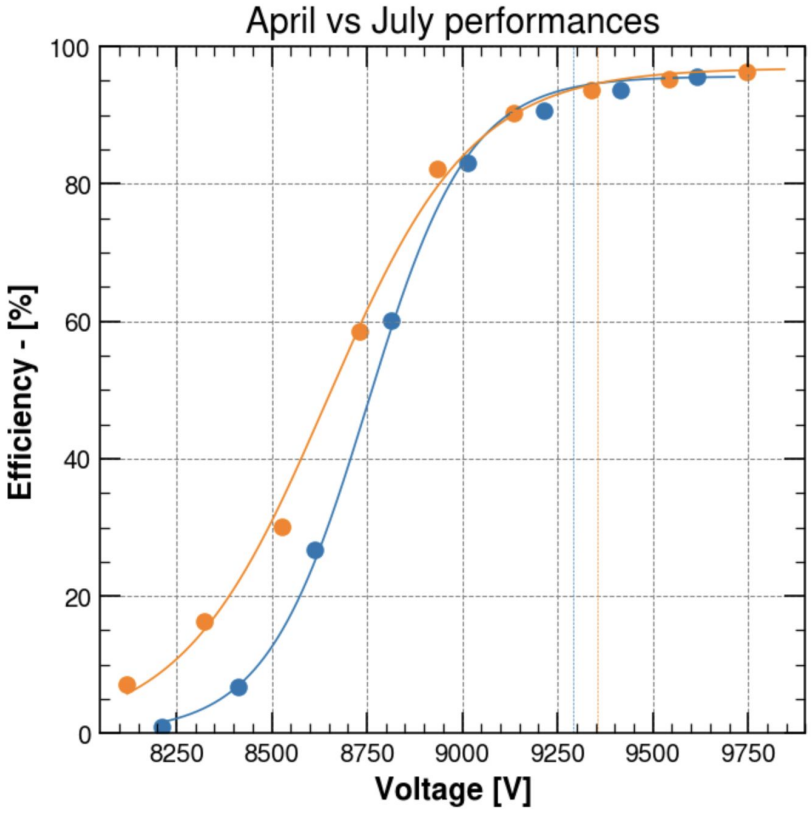
- Ohmic currents remain stable over all the irradiation period
- Physics currents start to increase after 35 mC/cm^2, then stable higher value -> under investigation
- Similar behavior in all the detectors irradiated.

Promising results obtain during ageing campaign

-> Monitoring of the detector status:
April and July test beam

Long-Term study: Test Beam

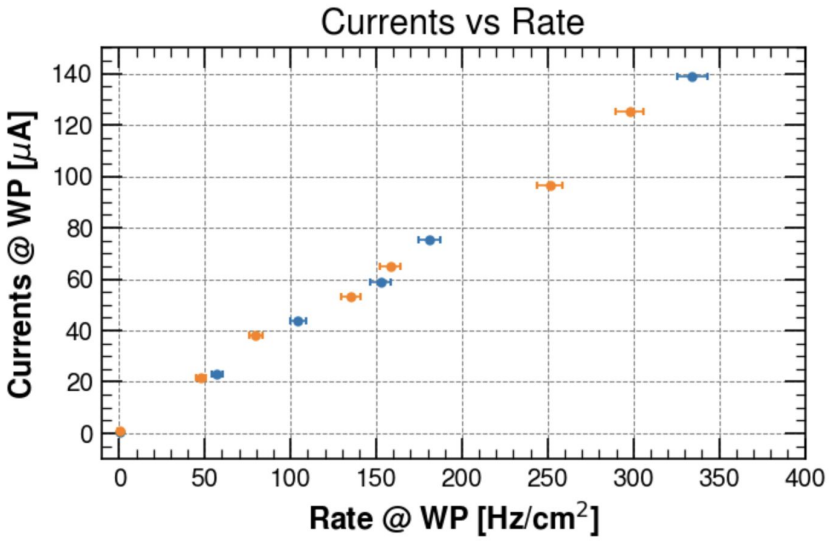
April 30% CO_2 CO2/R134a/iC_4H_{10}/SF_6 - 30/64.0/5.0/1
July 30% CO_2 CO2/R134a/iC_4H_{10}/SF_6 - 30/64.0/5.0/1



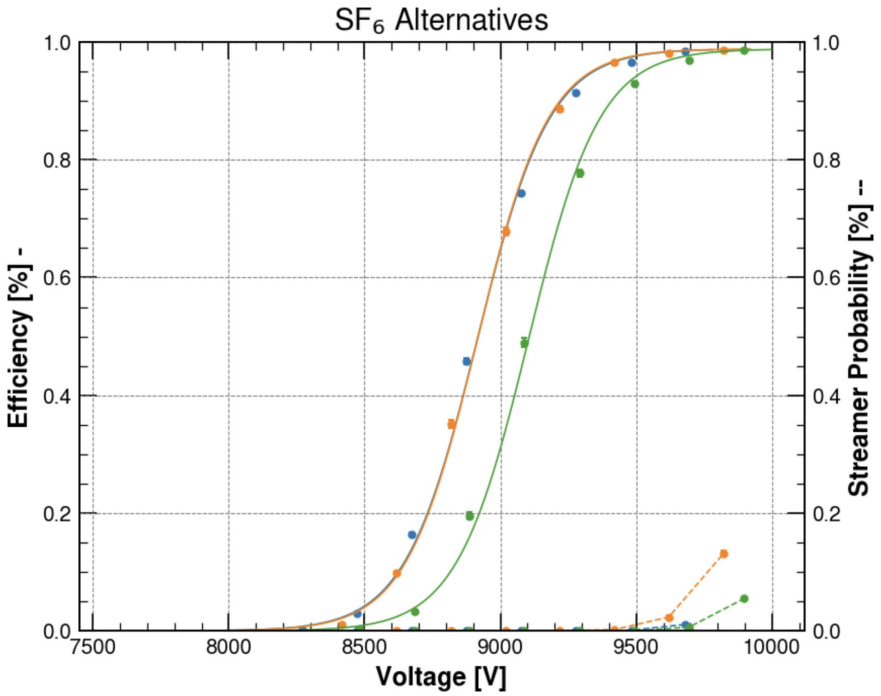
- Similar behavior between April and July test beam:
  - Similar Working Point and Efficiency;
  - Similar behavior Currents vs Rate.

No significant change between the four months of irradiation, after 35 mC/cm^2 .

This gas mixture was recently validated for ATLAS Run 3.
-> to continue to reach HL-LHC prevision (~300 mC/cm^2)



SF_6 Alternatives in STD mixture

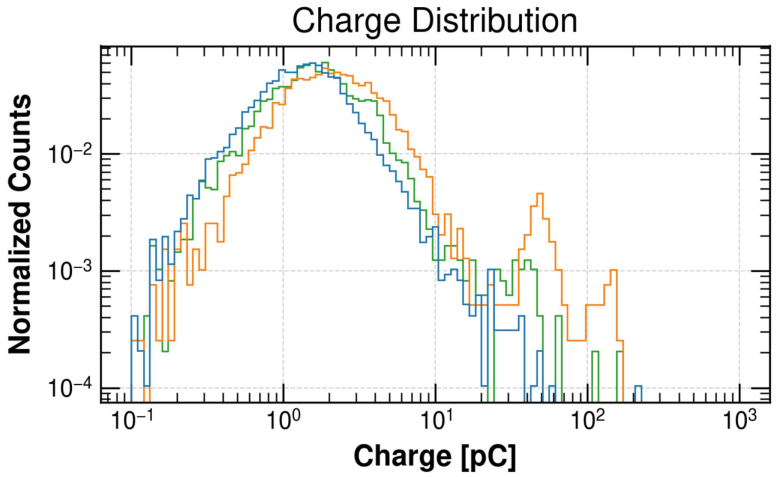


STD	$R134a/iC_4H_{10}/SF_6$	- 95.2/4.5/0.3
0.1% Novec 4710	$R134a/iC_4H_{10}$/Novec 4710	- 95.4/4.5/0.1
0.5% Amolea 1224yd	$R134a/iC_4H_{10}$/Amolea 1224yd	- 95/4.5/0.5

Tested as SF_6 Alternatives:

- Novec 4710;
- Amolea 1224yd.

Promising result for 0.1% Novec 4710 and 0.5% Amolea 1224yd substitution.



0.1% Novec 4710:

- Same STD WP
- Similar STD Streamer Probability

0.5% Amolea 1224yd:

- +200 V WP
- Similar STD Streamer Probability

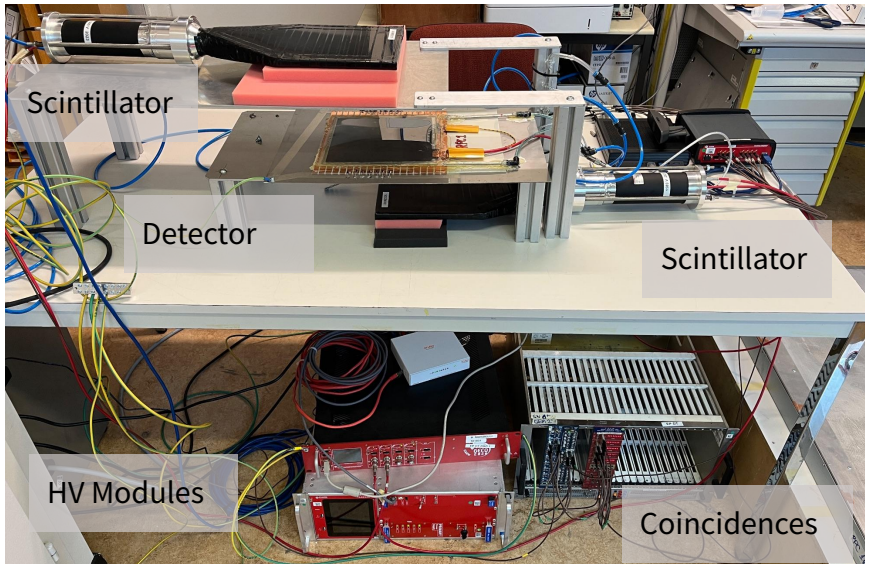
Glass MRPC Application

4-gaps 0.3 mm, 30 cm x 30 cm

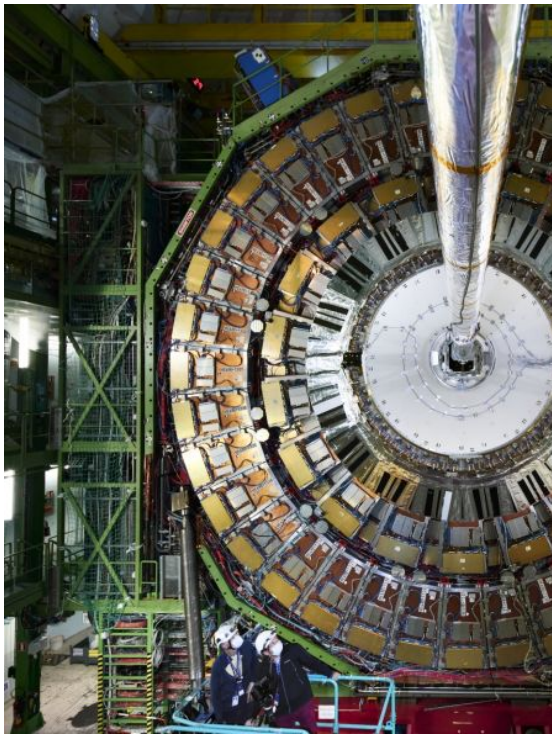
The goal is to apply the research on eco friendly gas mixture also on Glass MRPC detector, considering also time resolution measurements

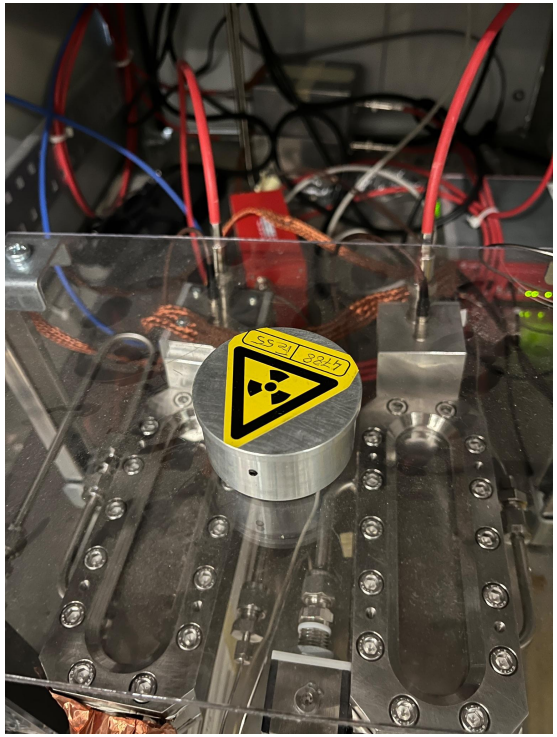
After preliminary tests, the detector are now in the construction phase:

- A complete new setup was created;
- The detectors construction is ongoing



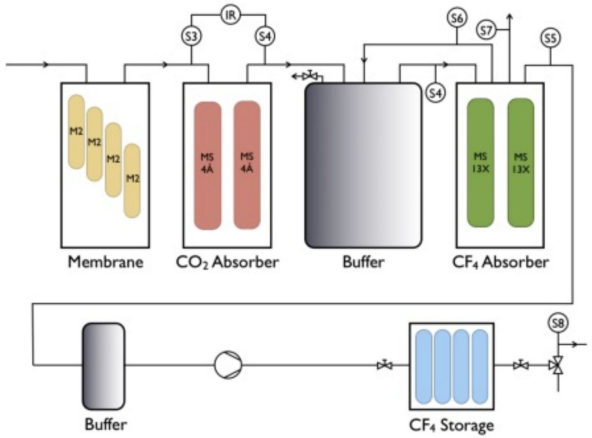
Monitoring of Gas Recirculation and Recuperation systems: CMS CSC case





Introduction: CSC gas system

- CSC gas mixture: **Ar 40%, CO_2 50%, CF_4 10%;**
- Operation in **recirculation mode;**
- **CF_4 Recovery system** in use since 2014 (450 m^3 of CF_4 recuperated);
- Usually used 50%/50% fresh/recuperated ratio.



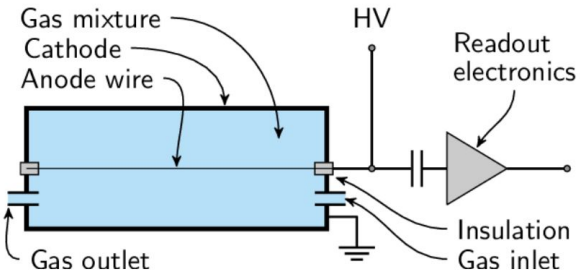
CMS CSC CF4 Recovery System: Schematic View.

Gas quality monitored by:

- Gas Chromatograph (GC);
- Single Wire Proportional Chambers (SWPC);

The geometry and materials of these SWPC are optimized to have an high sensitivities to impurities;

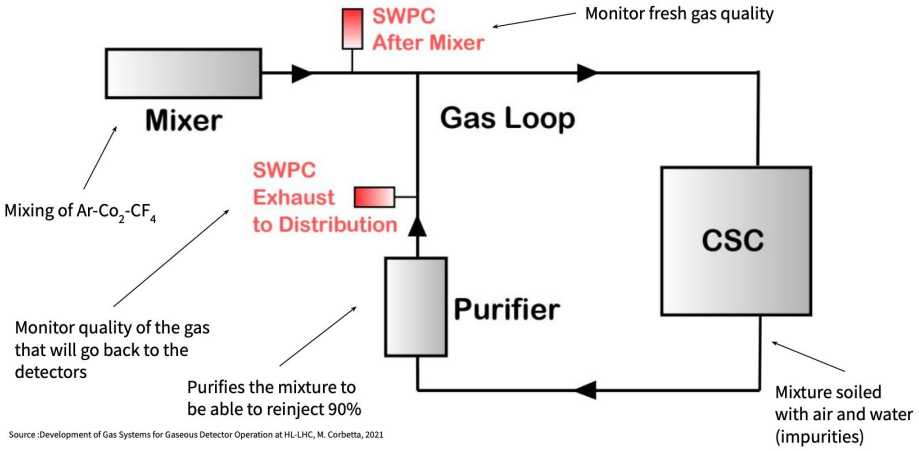
SWPC are working since the end of 2015.

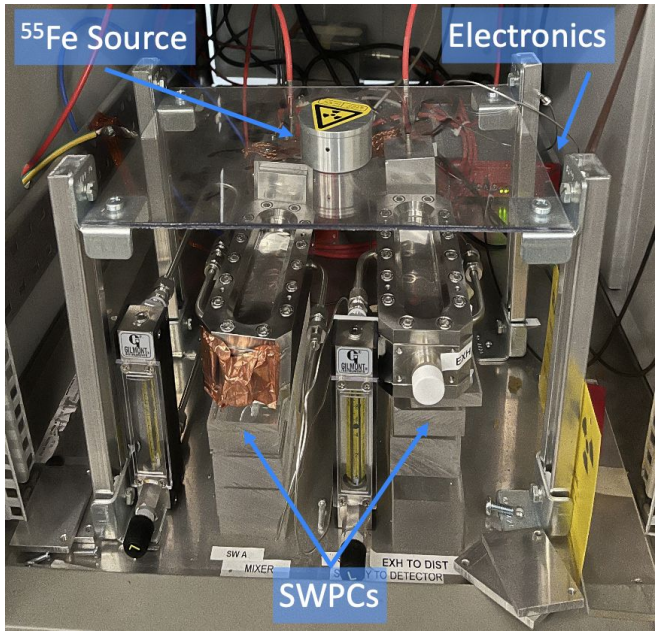


Schematic view of a SWPC detector.

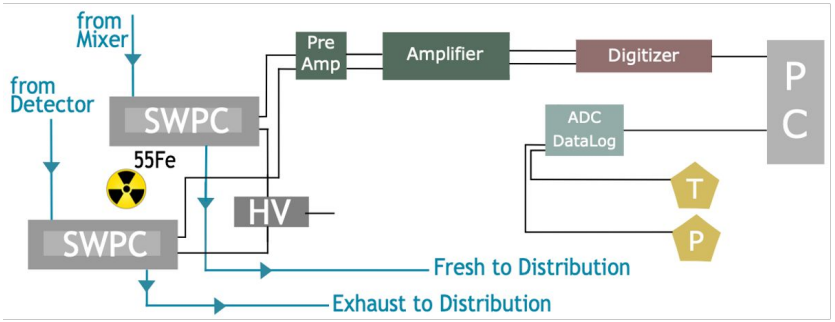
The goal is to upgrade this system in order to have a better stability during time and also to have a more reliable monitoring.

Setup



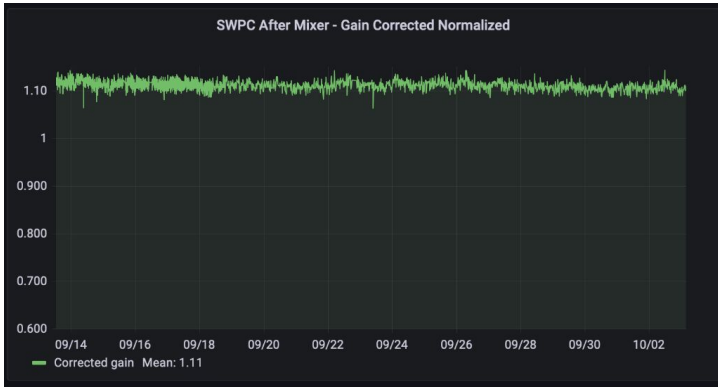


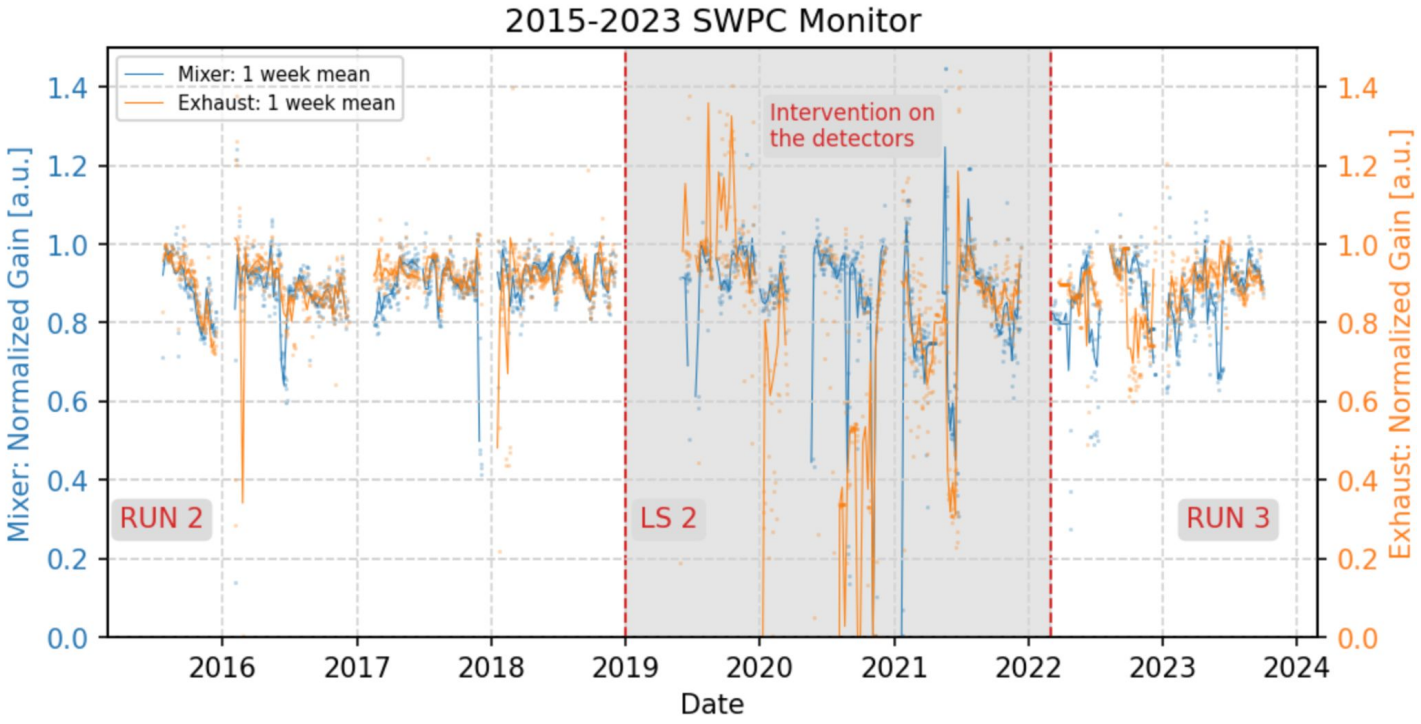
- Two SWPCs with ^{55}Fe source;
- temperature sensor inside and outside the gas rack;
- Atmospheric pressure sensors;
- Pressure sensor at the SWPC output.



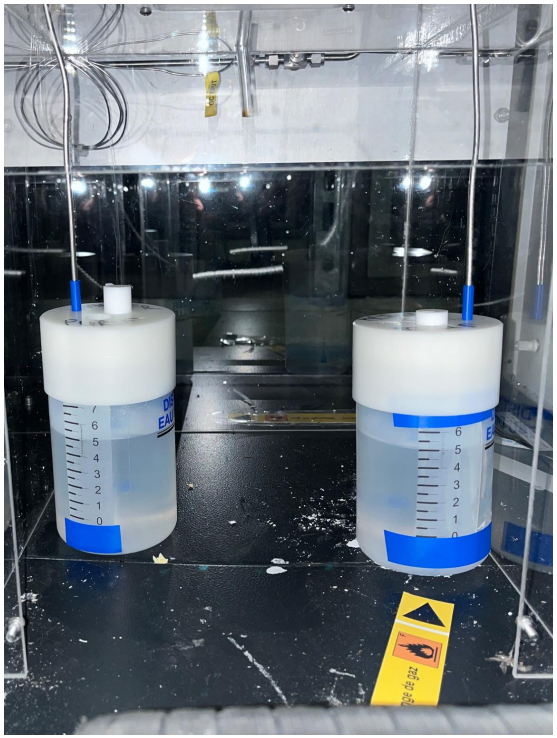
Gas System Monitoring

- 7 years of continue operations and improvements;
- SWPCs complement weekly GC analysis with real-time monitoring on the gas gain;
- All the deviation from stability have been thoroughly understood and resolved.





Optimization of current gas system technologies: ALICE MID case



New Gas Analysis Rack: History

Run 2
Installation 2016

Start to use the gas system with **Gas Recirculation**: 50% of recirculation fraction

Need to monitor Gas Quality and Impurities formation

Good results: recirculation fraction increased up to 85%

LS2

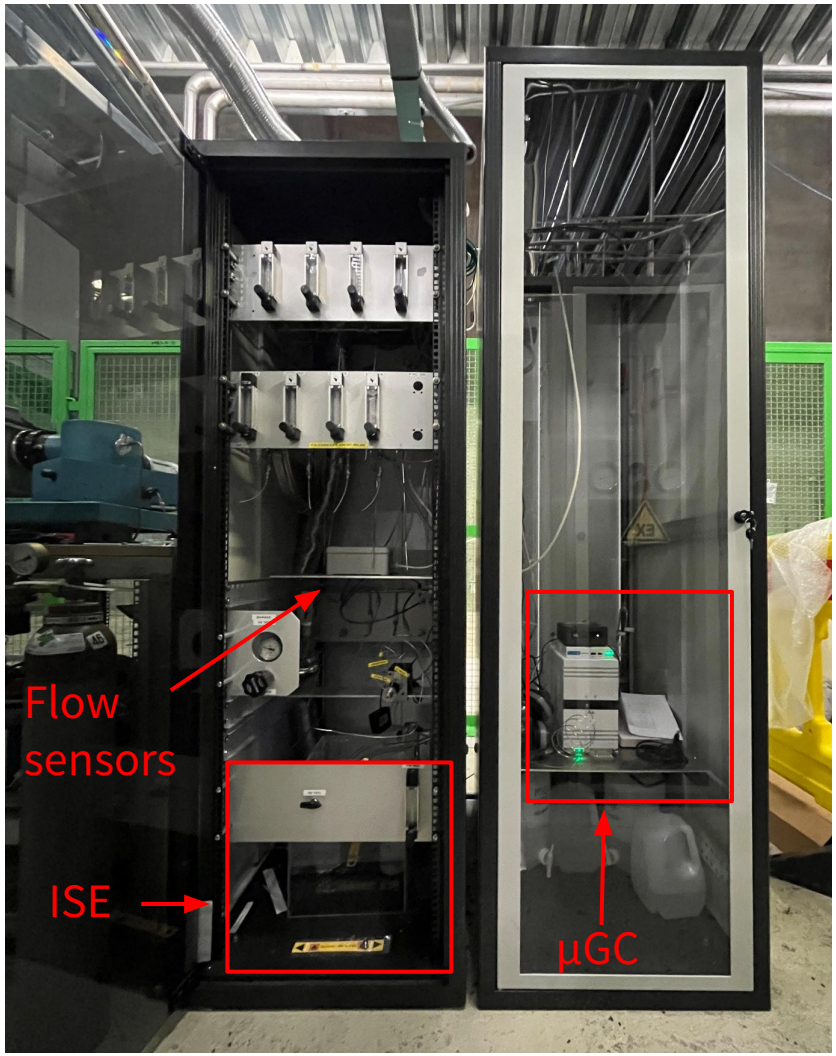
Installation of the new Gas Analysis Rack in CR5

Commissioning of the new Rack

Run 3
2023

Restart of operation with periodical monitoring:
- µGC analysis
- ISE analysis

New Setup



Gas Quality
Radical Impurities

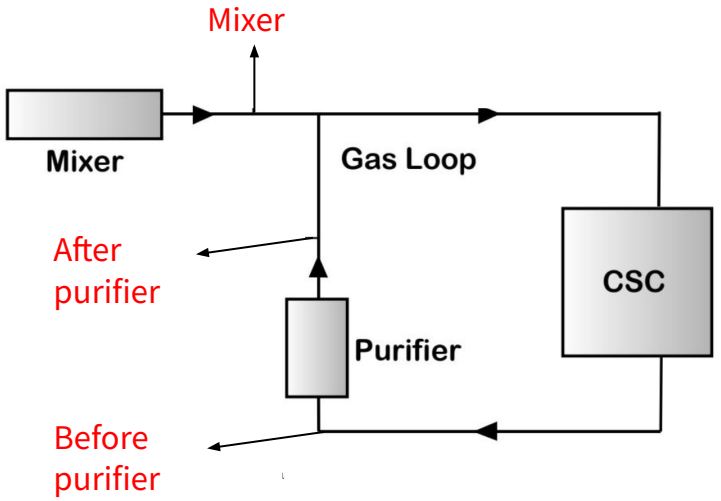
New dedicated
Gas Chromatograph

Studies of impurities formation and gas mixture composition

F- Impurities

New dedicated
Ion Selective Electrode

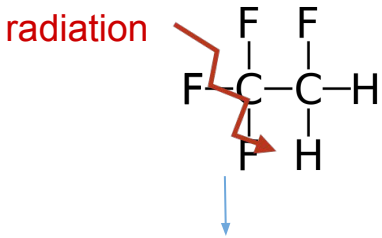
Studies of F- production



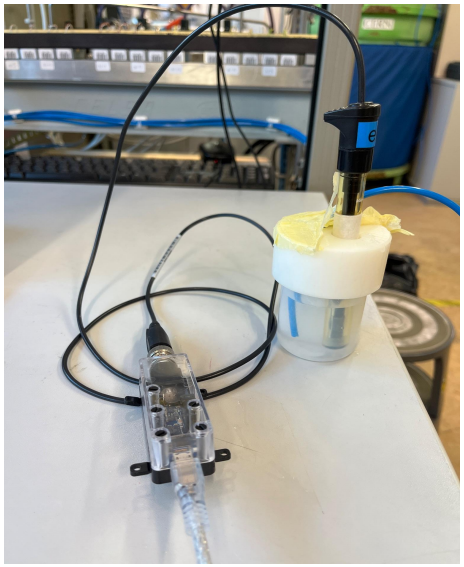
F^- Production studies

EP-DT
Detector Technologies

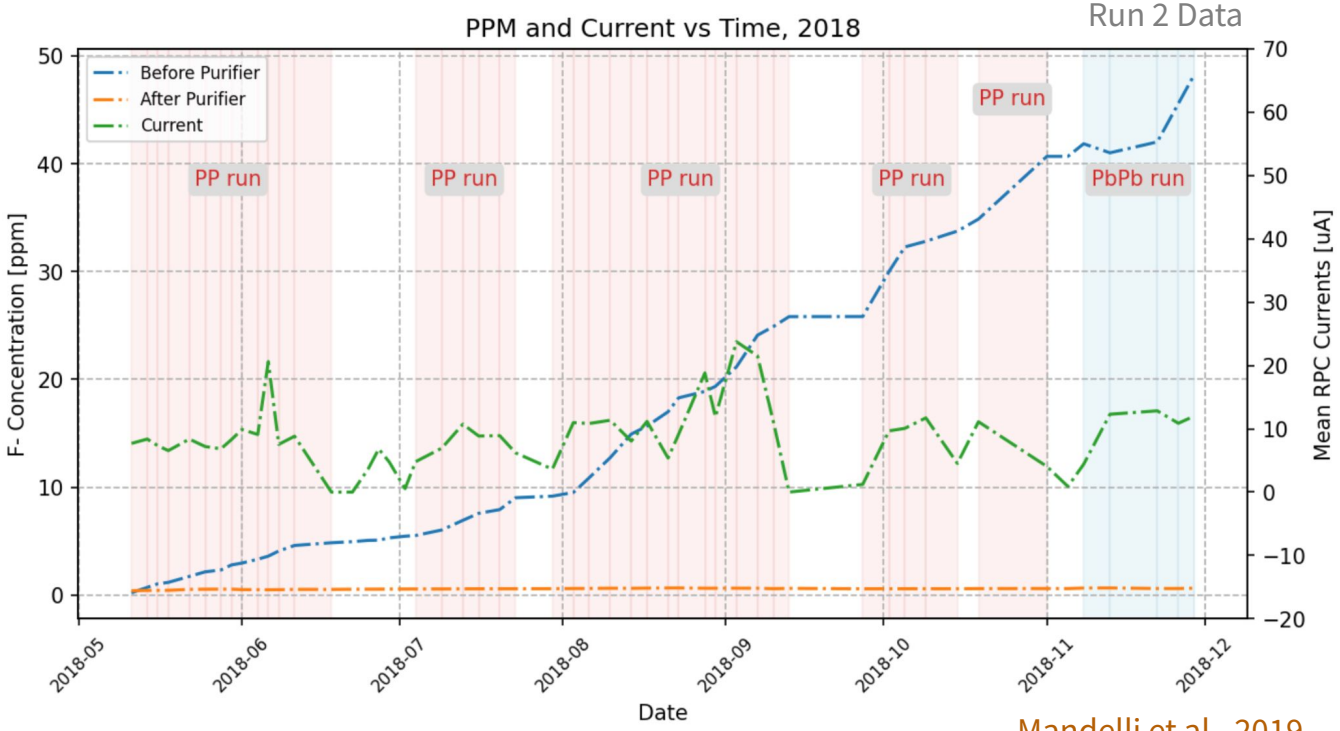
R134a: 89,7%
iC_4H_{10}: 10,0%
SF_6: 0,3%



F- + HFC radicals



Run 2 Data



Mandelli et al., 2019

- Gas left bubbled in a TISAB solution
- Electrode membrane allows to read the F- concentration inside the solution

Measurements campaign restarted in January 2024

Conclusion

Research on Alternatives Gas Mixture

R134a alternatives:

- Performances of 30% - 40% CO_2 based gas mixtures similar to the Standard Gas Mixture;
- Same Test Beam performance after 4 months of irradiation with 30% CO_2 gas mixture;
- 30% CO_2 gas mixture tested at the Gamma Irradiation Facility up to 57 mC/cm^2:
  -> In use in ATLAS since August 2023.

SF_6 Alternatives:

- Performances of 0.1% Novec gas mixture comparable to Standard Gas Mixture
  (= WP, ~ Str. Prob.);
- Performances of 0.5% Amolea 1224yd similar to Standard Gas Mixture
  (+200 V WP, ~ Str. Prob.).

Glass MGRPC studies:

- Detector construction ongoing
- Initial studies on going for SF_6 alternatives:
  - Novec 4710;
  - time resolution performances;
- R134a alternative studies foreseen.

Conclusion

CMS CSC Gas Monitoring System:

- Improved online SWPC monitoring in combination with periodic GC analysis;
- Ran continuously since September 2015, without showing any signs of aging;
- Upgrade in 2023: new temperature and pressure sensors, as well as a more efficient data analysis system.

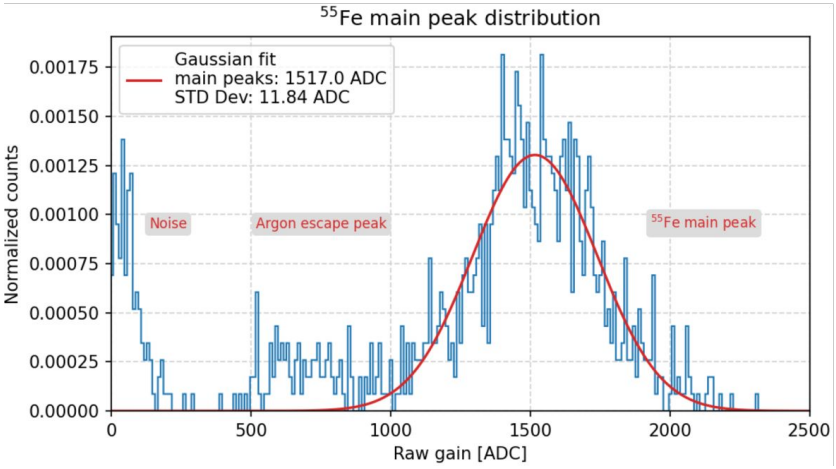
ALICE MID Gas Analysis rack:

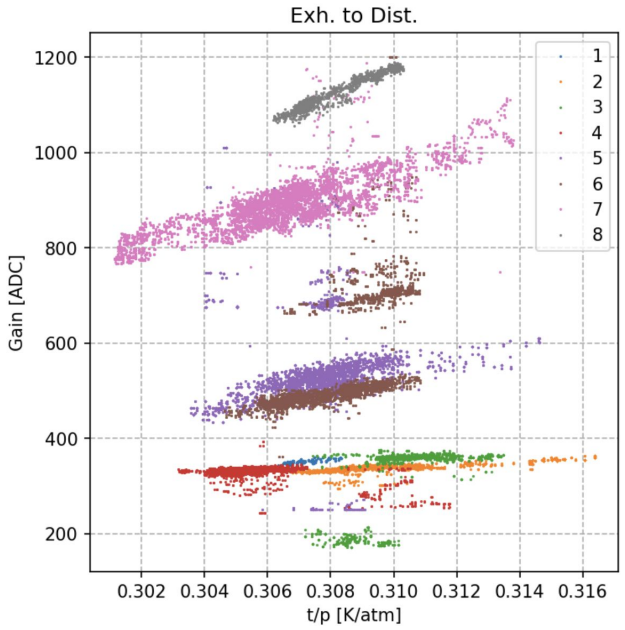
- Significant increase in recirculation fraction, from 50% to 85%;
- Periodic Analysis and Impurity Study performed to have a comprehensive system oversight;
- The analysis rack upgrade has increased system's reliability and efficiency;
- This installation also represents a starting point for a continuous improvement of the monitoring system in future years.

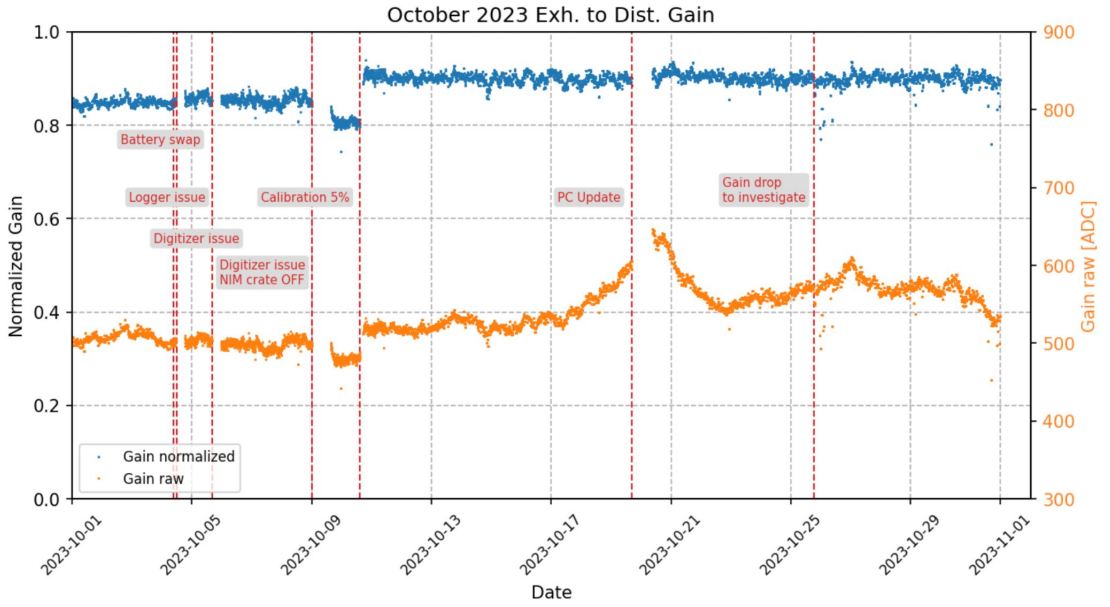
Backup

Data Acquisition

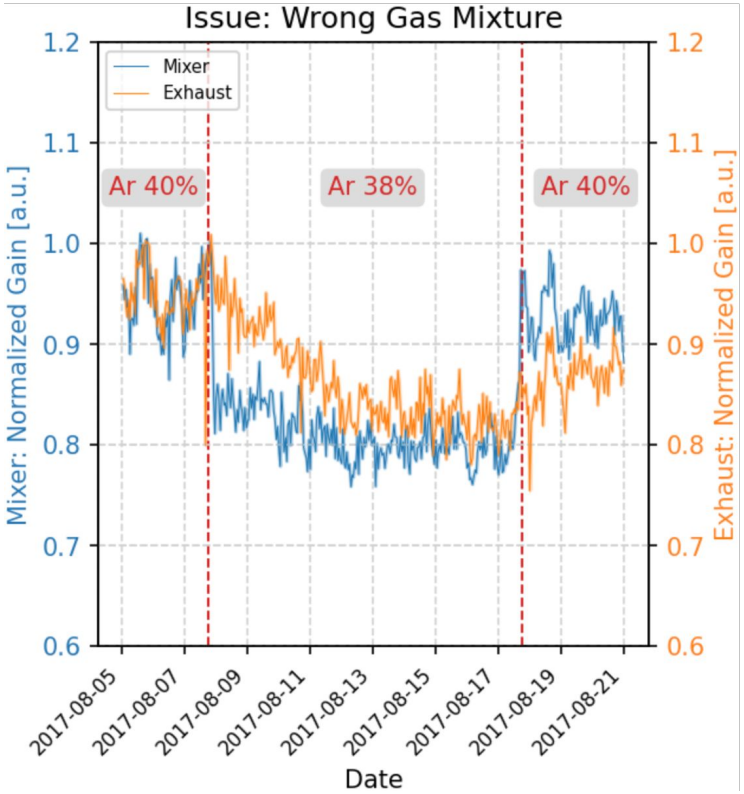
- Acquisition made with pre-amplifier, amplifier and digitizer;
- recorded 5000 signals for run, one run every 15m;
- Gaussian fit on signal peaks distribution;
- T/P correction applied to the data;
- Normalization made wrt premixed gas bottle (calibration made every 1-2 months).



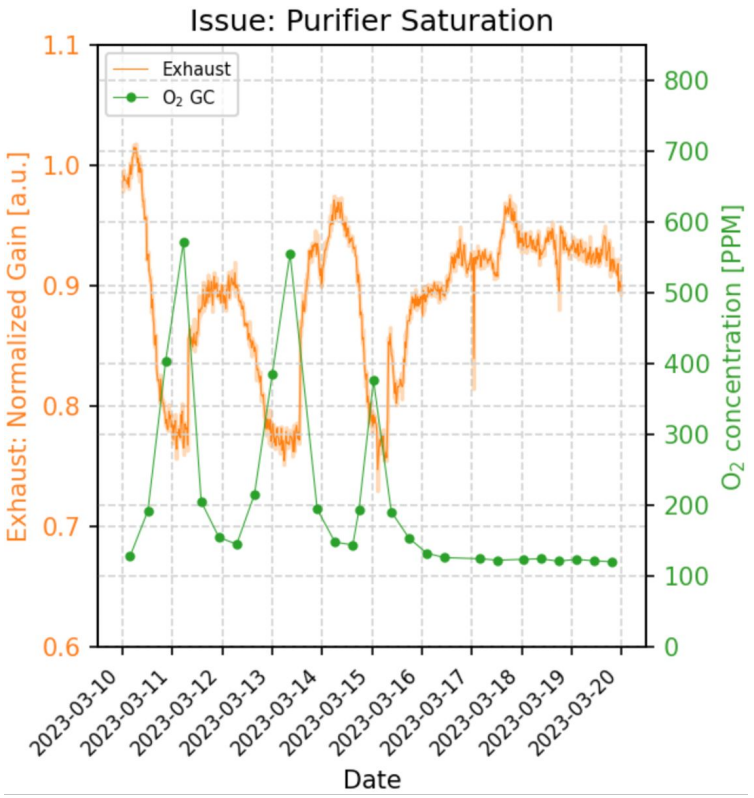




Examples of spotted issues

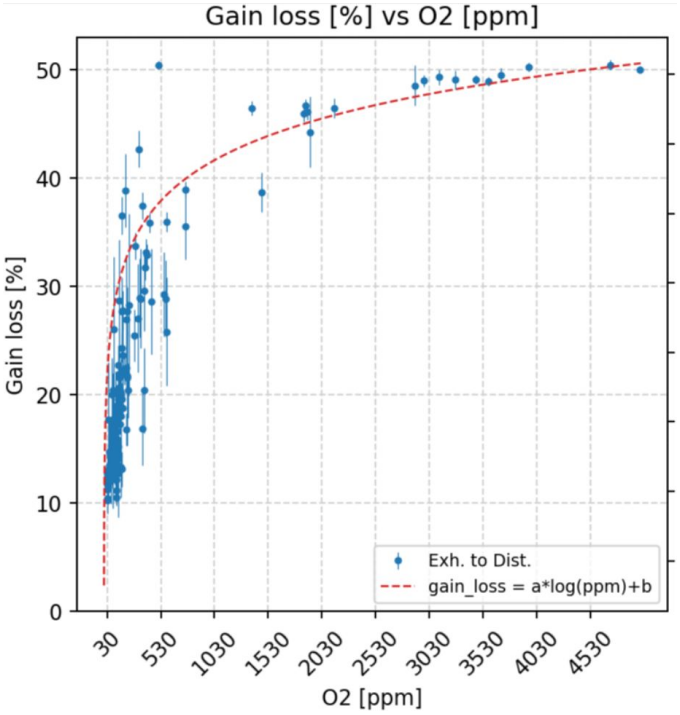


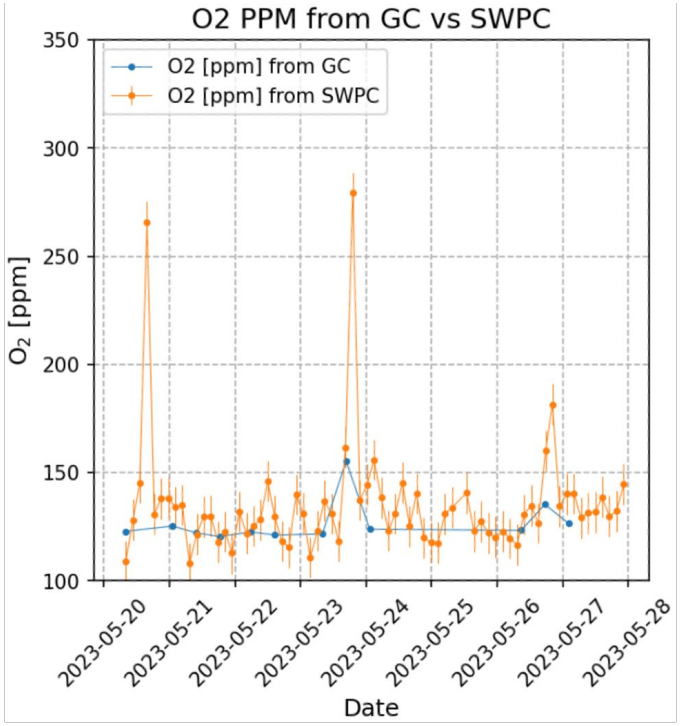
An example of an incorrect gas mixture from the mixer. An instantaneous gain change is observed in the Mixer SWPC, followed by a gain drop in the Exhaust SWPC after 1-2 days



An example of gain reduction in the Exhaust SWPC due to peaks of O_2. This is caused by the saturation of the purifier, which cannot effectively remove all the O_2 in the mixture, and need to be regenerated.

Examples of spotted issues

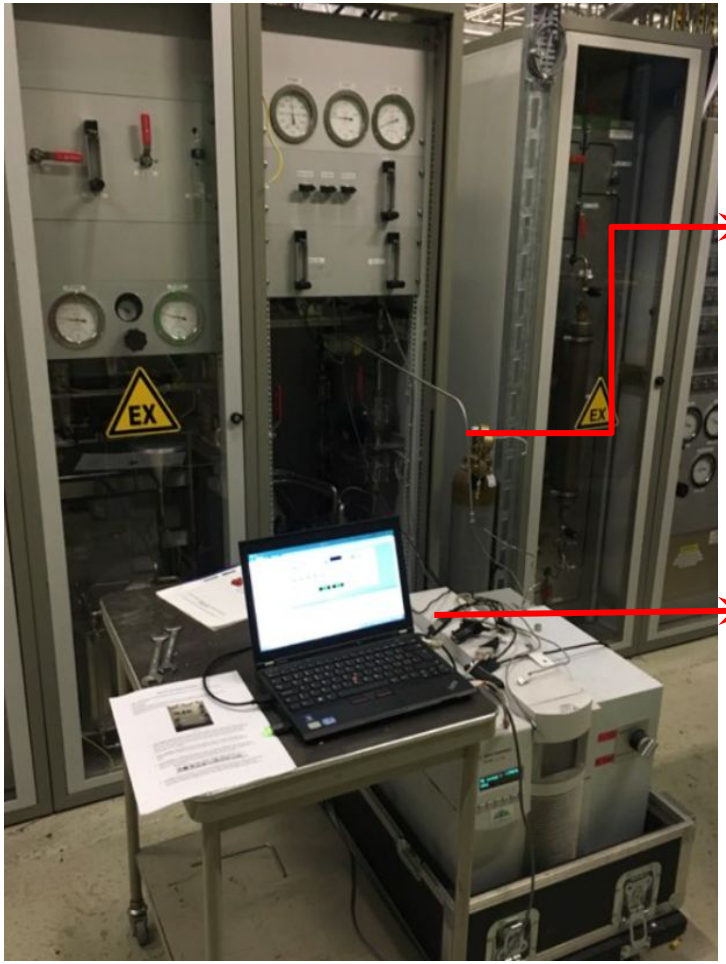




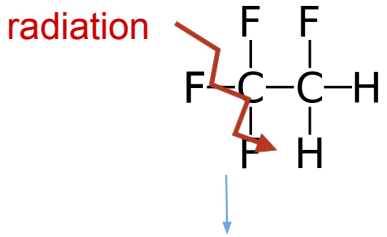
Study the effect of O_2 concentration on SWPC gain:

- Find a suitable fitting function for the gain loss vs PPM from GC analysis, simplifying the analysis by considering only O_2 as an impurity in the gas mixture;
- Compare the GC measurements with the estimates derived from the SWPC gain loss;
- **Good agreement** was observed between the two datasets, with differences falling within their respective experimental errors.

Setup Run 2



R134a: 89,7%
iC_4H_{10}: 10,0%
SF_6: 0,3%



F- + HFC radicals

Gas Quality
Radical Impurities

Gas Chromatograph
+
Mass Spectrometer:

- Before Purifier
- After Purifier

F- Impurities

Ion Selective Electrodes:

- Before Purifier
- After Purifier

ISE measurements

- The electrode can measure the F- concentration in the sampling solution
- The output of the detector is left bubbling inside the solution

- The electrode can stay in the solution for no more than 6-7 h
  -> One measurements for days
- A weekly calibration is needed