Signal shape studies and rate dependence of HFO-based gas mixtures in RPC detectors

Luca Quaglia[1] on behalf of the ALICE and RPC EcoGas@GIF++ **collaborations**

[1]INFN Torino

Overview

- RPCs and their gas mixture
  - The need for an eco-friendly gas mixture
  - HFO-1234ze as a possible replacement for R134a
- The RPC EcoGas@GIF++ collaboration
  - Experimental setup
  - Timeline of the collaboration activities
- Experimental results
  - Selected digitizer beam test results
  - Performance evolution throughout aging
- Conclusions and outlook

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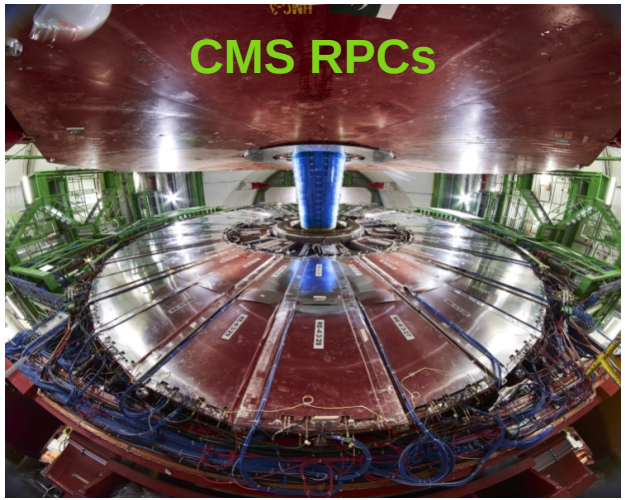
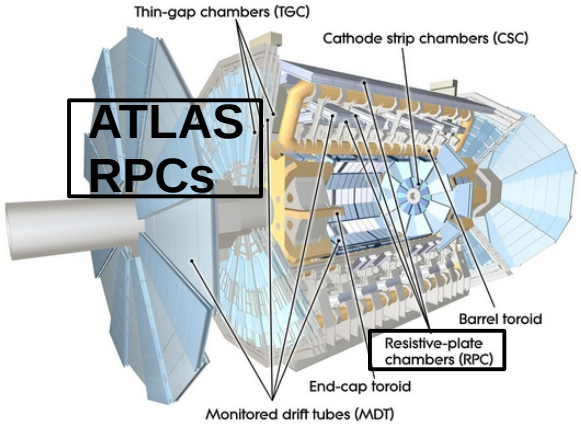
RPCs in High Energy Physics





- **Resistive Plate Chambers** (RPCs)
  → Widely employed in HEP
- For **muon detection**
- Relatively cheap
  → **Large area coverage**
- Fast response
  → Used for **muon triggering** and **identification**

Issues with current gas mixture

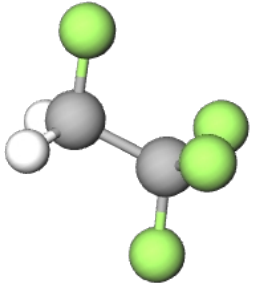
- Currently employed gas mixture in HEP (standard gas mixture/**STD** in the following)

  → Combination of **$C_2H_2F_4$, i-C_4H_{10} and SF_6** in different concentrations with **~ 90% $C_2H_2F_4$**

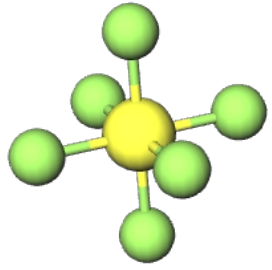
- Operated in avalanche mode

  → Time resolution **~ 1 ns** and space resolution **~ mm** ✓

  → $C_2H_2F_4$ and SF_6 are **fluorintated greenhouse gases** (F-gases) with a high GWP[1] **X**



GWP ($C_2H_2F_4$) ~ 1430



GWP (SF_6) ~ 22800

GWP of the standard gas mixture: 1350 ÷ 1430

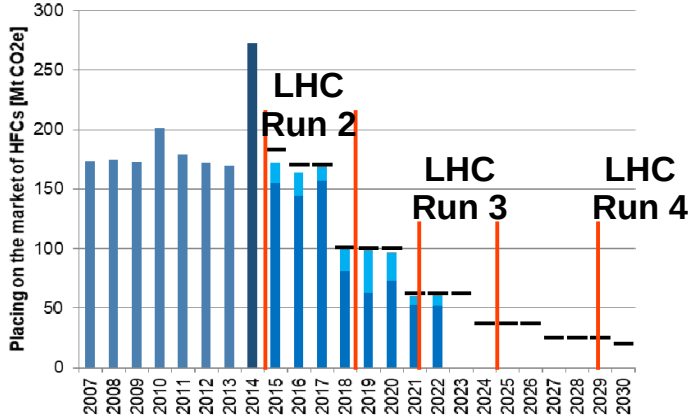
→ Is this a problem? Yes!

[1]GWP = global warming potential = measure of the heat trapped in the atmosphere by a ton of a given gas, if compared to a ton of CO_2 (GWP(CO_2) = 1)

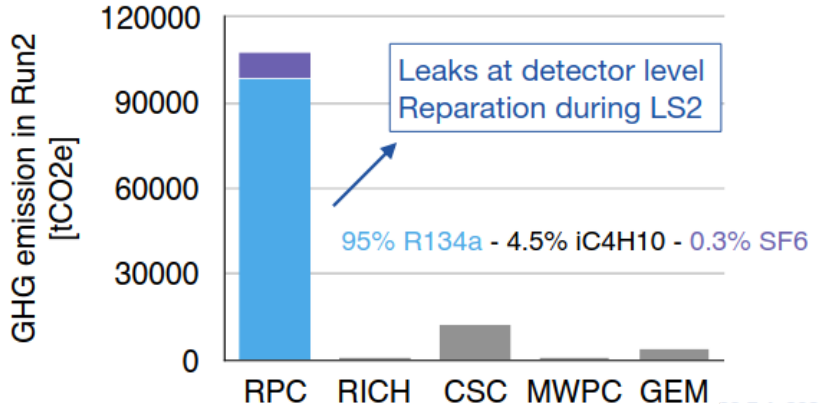
The need for an eco-friendly gas mixture

- EU regulations imposed a progressive phase down in the production and use of F-gases
  - → Phase down of the production and consumption of such gases
  - → Ban of the gases if a more eco-friendly alternative is available
  - → Reduction of emissions from existing equipment

Increase in cost and reduction in availability



F-gases placing on the market (POM) plan, from ETC CM Report 2023/04



B. Mandelli VCI 2022

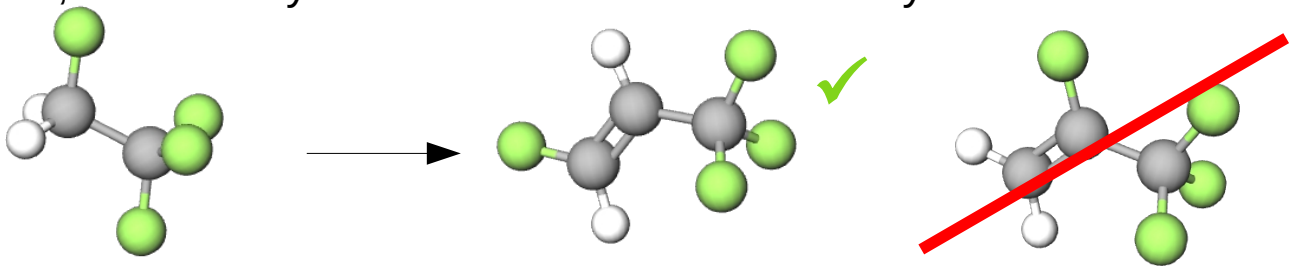
- RPCs are the main source of F-gases emissions at CERN (mainly due to gas leaks)
  - → Need to find a more eco-friendly gas mixture

- Many laboratory studies using new gases have been carried out with cosmics
  - → Now: **beam test** studies and **long-term performance evolution** under irradiation(aging tests)

Experimental approach

- First efforts of LHC RPC groups focused on R134a replacement

- **Industrial use:** from **R134a** to **hydro-fluoro-olefine** (HFO) family of gases
  → Similar chemical structure as R134a but lower Global Warming Potential
  → Among all HFOs, HFO-1234yf and HFO-1234ze are currently used



GWP ($C_2H_2F_4$) ~ 1430 | GWP (HFO-1234ze) ~ 6 | GWP (HFO-1234yf) ~ 4

- 1:1 replacement of R134a with HFO not possible
  → Lower effective first Townsend coefficient
  → Working voltage of the detectors moves to over 15 kV

- HFO has to be diluted with other gases
  → Studies with cosmic muons by different LHC RPC groups [1-4]
  → CO_2 found to be the most promising candidate for dilution
  → **In-depth studies on RPCs long-term behavior with eco-friendly alternatives needed**

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The RPC EcoGas@GIF++ collaboration

- Cross-experiment collaboration

  → It includes **CMS, ALICE, ATLAS, ShiP/LHCb** and the **EP-DT** group of CERN

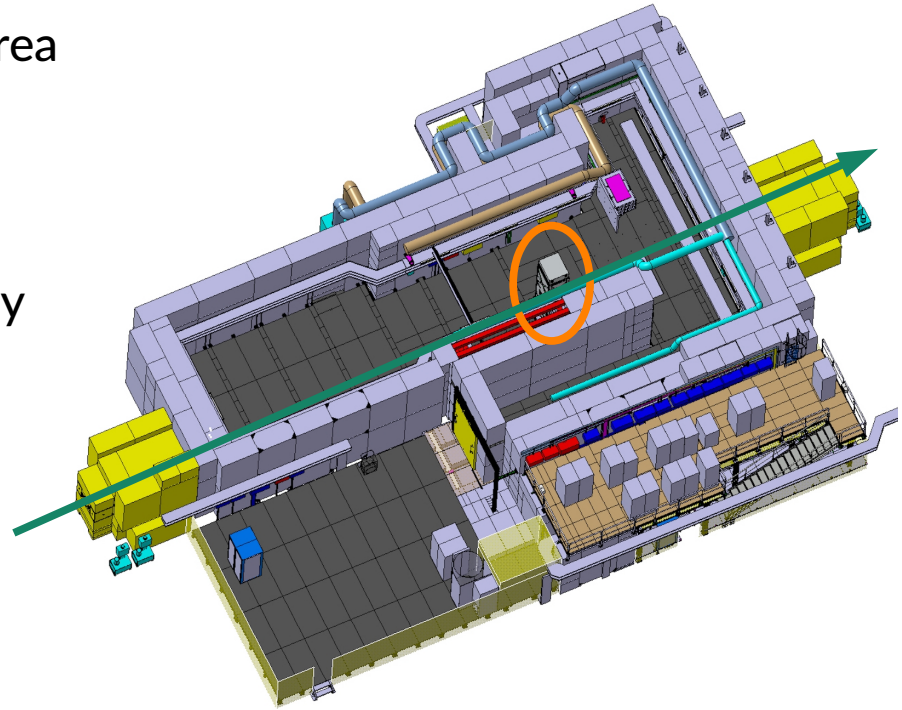
- Studies carried out at the CERN Gamma Irradiation Facility (GIF++)

  → Experimental facility located at the CERN North Area

- 12.5 TBq ^{137}Cs source, high activity allows one to simulate long operating periods in much shorter time spans (aging studies) – irradiation can be modulated by means of attenuation filters

- High energy (100 GeV/c) **muon beam** in dedicated beam time periods

→ Combination of muon beam with source: rate capability studies



GIF++ facility layout

Experimental setup - 1

- Each group provided an RPC prototype to be tested with eco-friendly gas mixtures
  → Installed on two setups, one at 3 m from the source and one at 6 m

Group	Dimension (cm^2)	# of gaps	Gap/electrodes Thickness (mm)	Readout	# of strips
ATLAS	500	1	2 / 1.8	Digitizer	1
CMS	4350	2	2 / 2	TDC	128
CMS Upgrade	7000	2	1.4/1.4	TDC	32
EP-DT	7000	1	2 / 2	Digitizer[1]	7
ALICE	2500	1	2 / 2	Digitizer[2]	7
ShiP/LHCb	7000	1	1.6 / 1.6	TDC	64

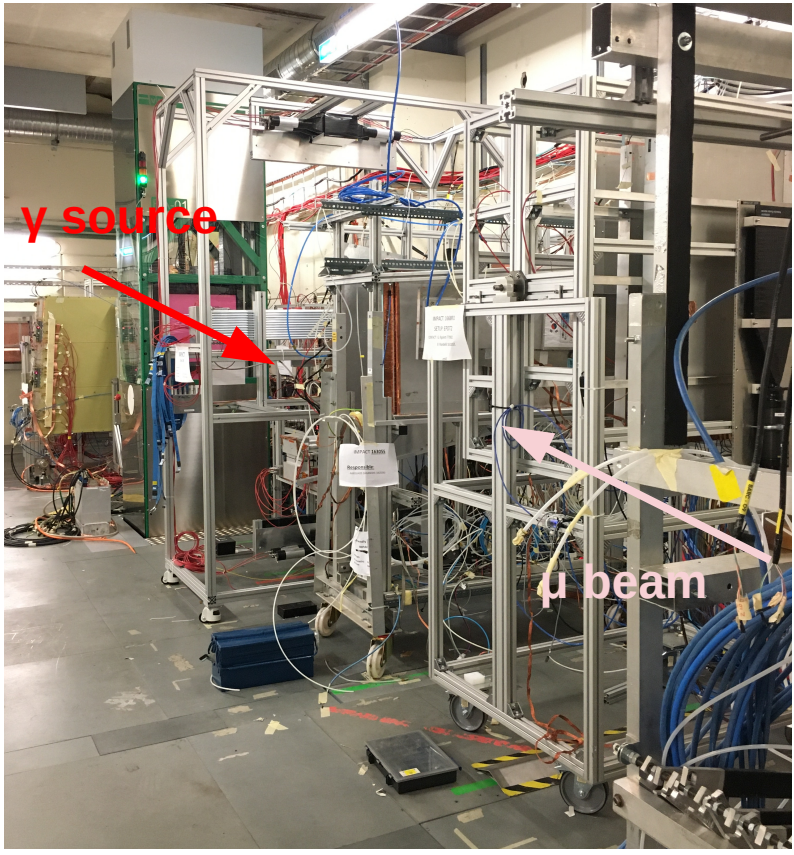
Summary table of all the RPCs of the collaboration

- Two different readout methods for the different RPCs
  1) Front-end electronics + TDCs
  2) Digitizer

Subject of this presentation*

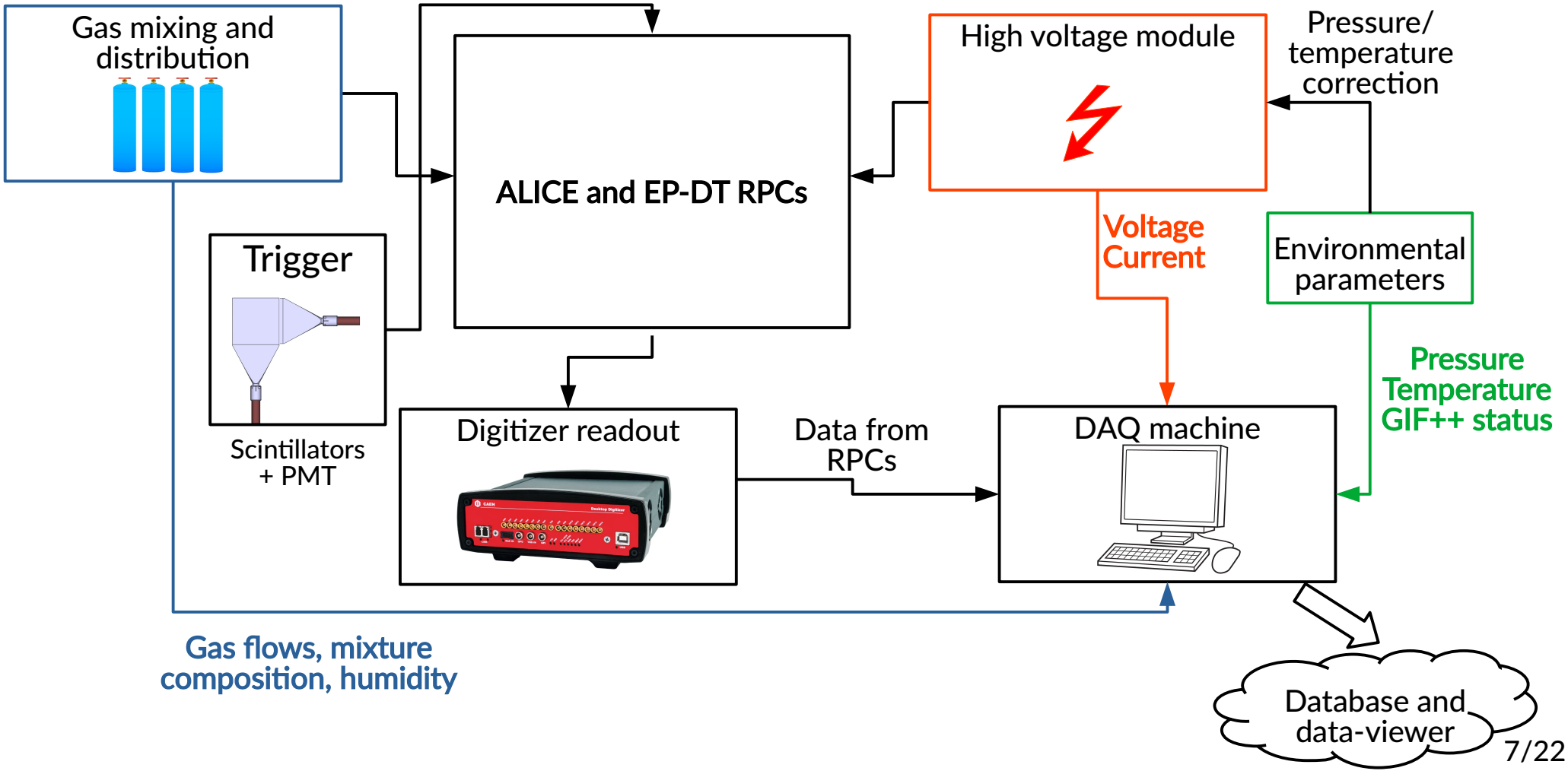
*Results from other detectors in M. Abbrescia's talk today @ 11:50 am

[1]CAEN model V1730, 14-bit at 500 Ms/s, V_{pp} = 1 V
[2]CAEN model DT5742, 12-bit at 1-5 Gs/s, V_{pp} = 1 V

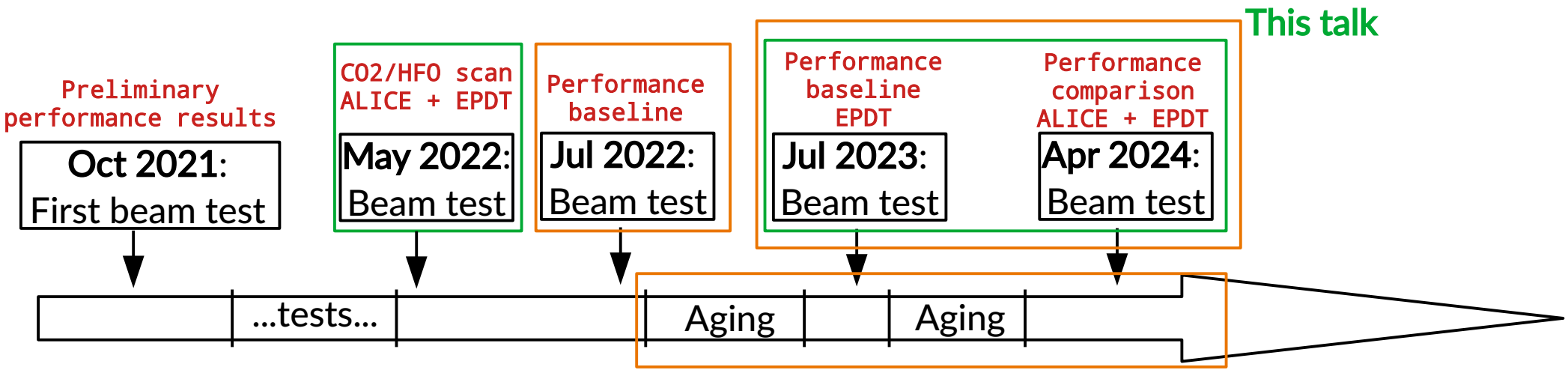


View of the setups inside the GIF++ bunker

Experimental setup - 2



Timeline of collaboration activites



Marcello Abbrescia's talk today @ 11:50 am

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Beam test measurements

- Mixtures with different ratios of HFO/CO_2 have been tested (from 0 up to 40% HFO)
- Study the interplay between these two gases and comparison to current gas mixture

Mixture	$C_2H_2F_4$ %	HFO %	CO_2 %	i-C_4H_{10} %	SF_6 %	GWP
STD	95.2	0	0	4.5	0.3	1488
MIX0	0	0	95	4	1	730
MIX1	0	10	85	4	1	640
MIX2	0	20	75	4	1	560
(ECO3) MIX3	0	25	69	5	1	529
MIX4	0	30	65	4	1	503
(ECO2) MIX5	0	35	60	4	1	482
MIX6	0	40	55	4	1	457

CO_2 concentration decreases

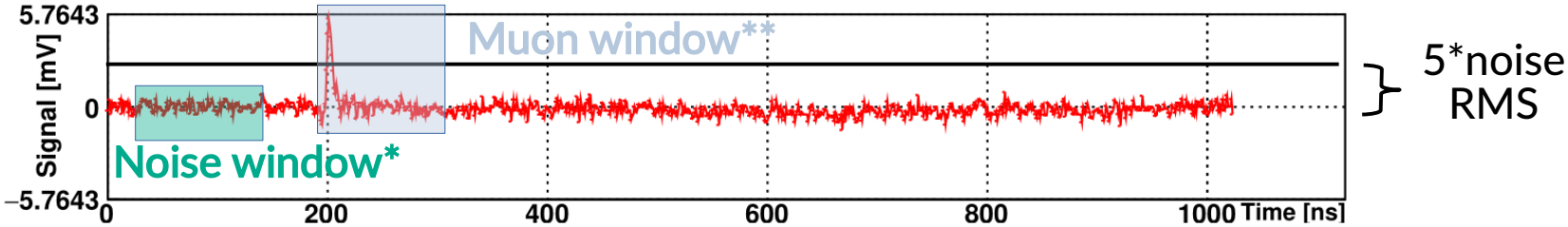
- Two readout methods employed:
  1) Detectors front-end electronics + TDCs
  → Realistic measurements of efficiency and cluster size

  2) Digitizer
  → Waveform/charge studies

- Goal of beam tests: measure RPC performance (using a muon beam) in terms of efficiency, cluster size, prompt charge, streamer contamination and rate capability

Digitizer data analysis - 1

- Access to the waveform of each signal enables in depth characterization of RPC response



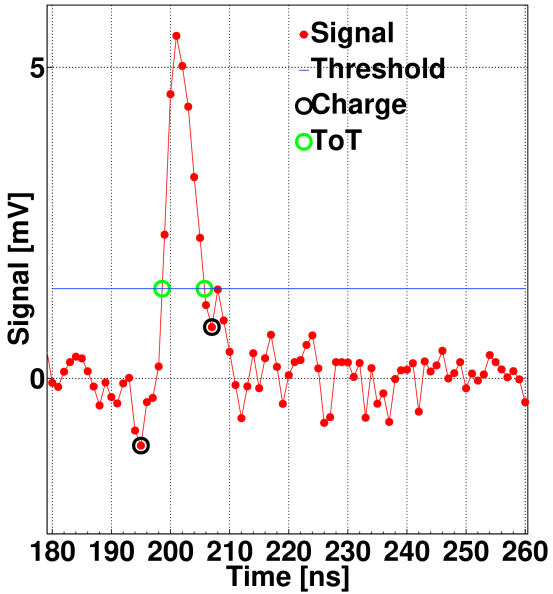
Example of RPC response when readout with digitizer – ALICE RPC

- **Analysis procedure** developed to

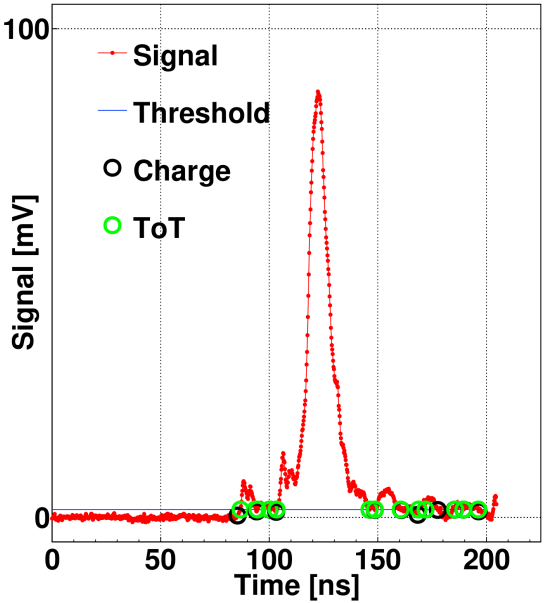
1) Identify "efficient" strips for further processing
ALICE: threshold = 5*RMS of the noise window. **EP-DT**: threshold = 2 mV
→ Reflection signals are identified and discarded (see backup)
2) Find integration interval for prompt-charge calculation
3) Compute streamer probability
4) Compute time-over-threshold
5) Analyze run globally (efficiency, streamer probability… vs high voltage)

*** Time window where NO muon signal is expected**
** Time window where muon signal is expected

Digitizer data analysis - 2



Single-peak signal typical of STD – ALICE RPC

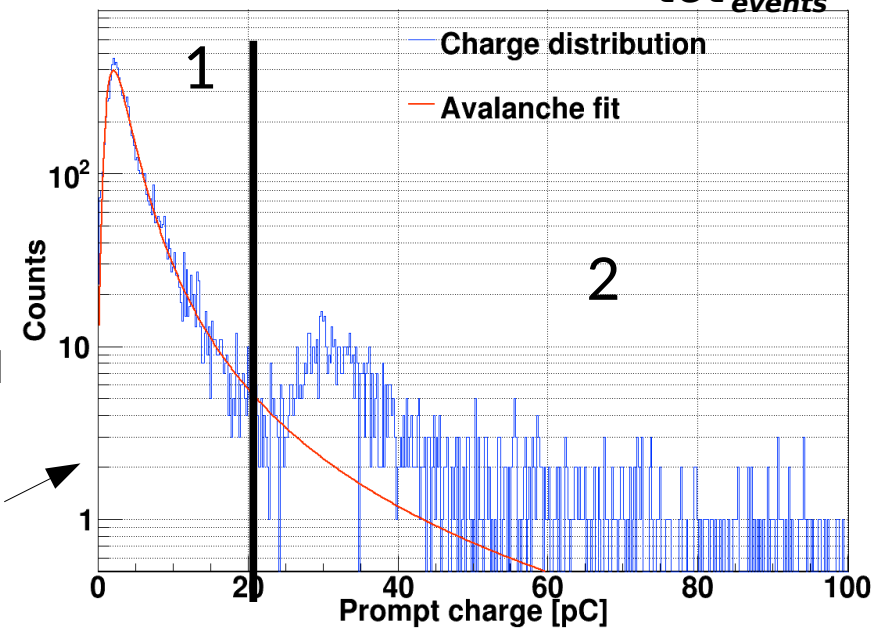


Multi-peak signal in HFO-based mixtures ALICE RPC

- Two populations: 1) **avalanches** and 2) **streamers**
- Two regions are separated at ~ 20 pC → Events with prompt charge > 20 pC tagged as streamers

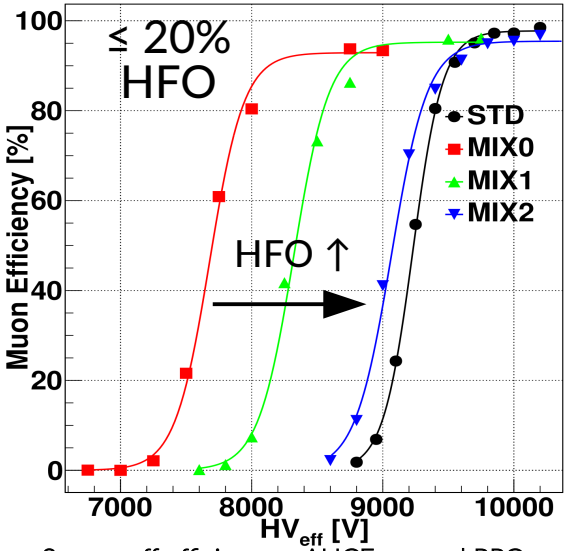
$$\textbf{Streamer probability} = \frac{\textbf{charge} \geq \textbf{20 pC}}{\textbf{tot}_{\textbf{events}}}$$

- Examples of **signal integration and time over threshold** calculation intervals
- For a fixed high voltage value, prompt charge distribution example

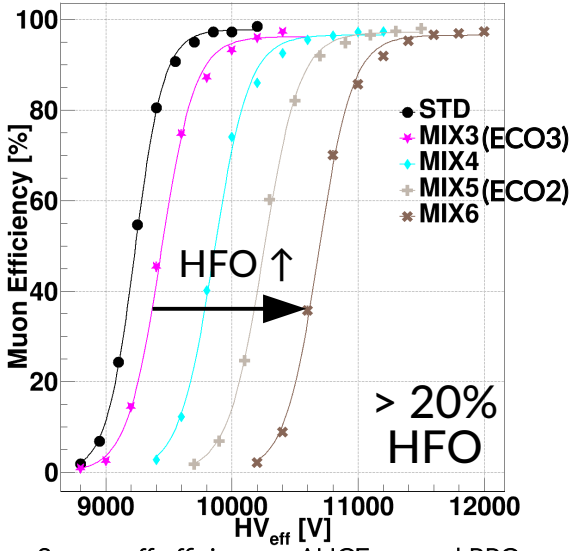


Prompt charge distribution at max efficiency - STD – ALICE RPC

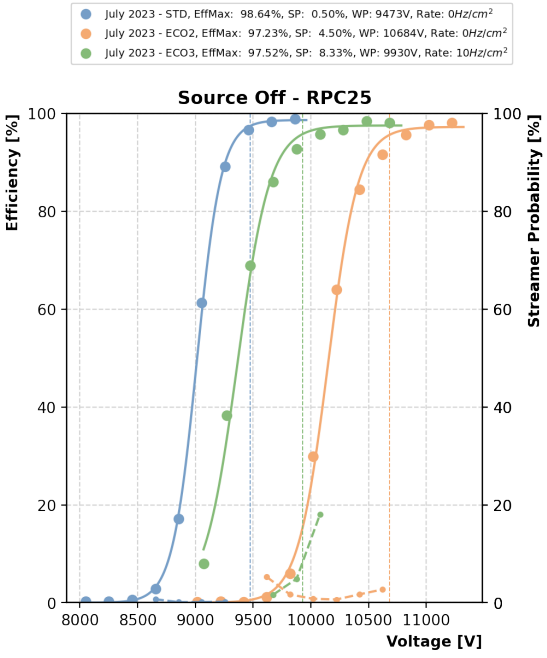
Efficiency vs HV at source off



Source off efficiency – ALICE unaged RPC



Source off efficiency – ALICE unaged RPC

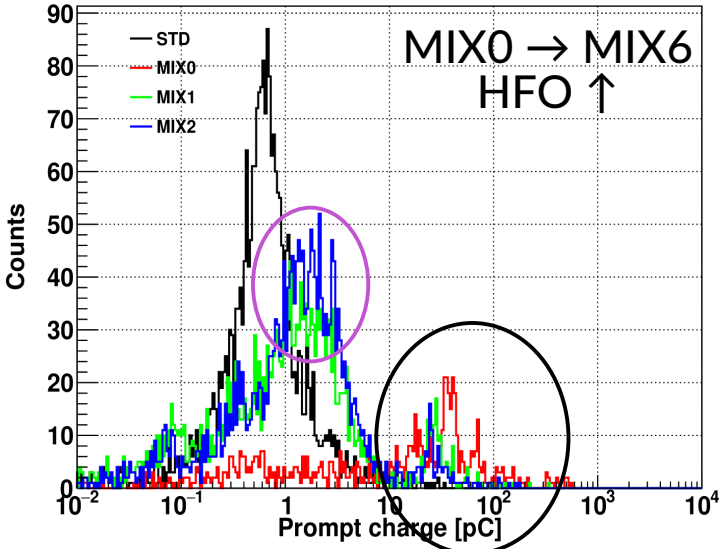


Source off efficiency – EPDT unaged RPC

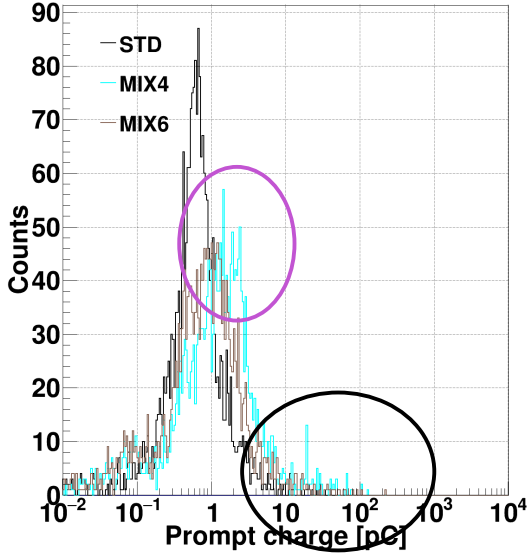
- **Trigger** provided by coincidence of 4 scintillators coupled with PMTs
- Efficiency curves fitted with logistic function to extract
  Working Point (WP) = knee (voltage where efficiency is 95% of its maximum) + 150 V
- Increasing value of maximum efficiency as the HFO concentration increases (denser mixture)
- Increase of WP by ~1 kV for every 10% HFO added to the mixture is observed in both detectors
- Differences between ALICE and EP-DT can be explained by the different threshold

Source-off prompt charge distribution

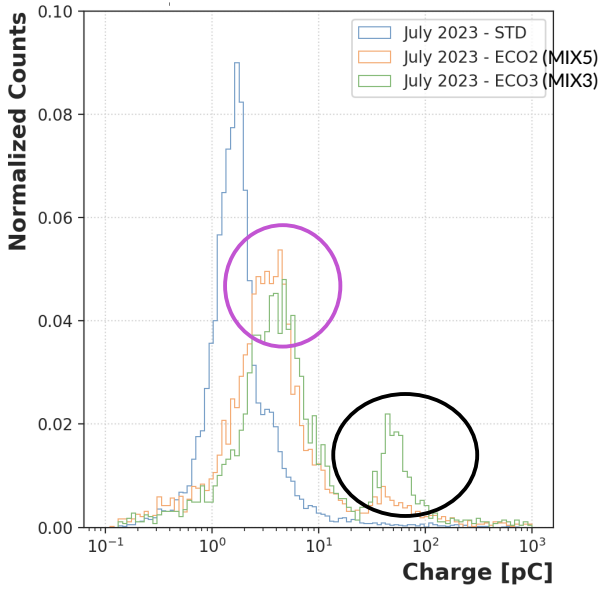
- Spectra shown correspond to the HV closest to the estimated WP



Source off prompt charge spectrum for MIX0 – MIX2 ALICE RPC



Source off prompt charge spectrum for MIX4 and 6 - ALICE



Source off prompt charge spectrum for ECO2 and ECO3 - EPDT

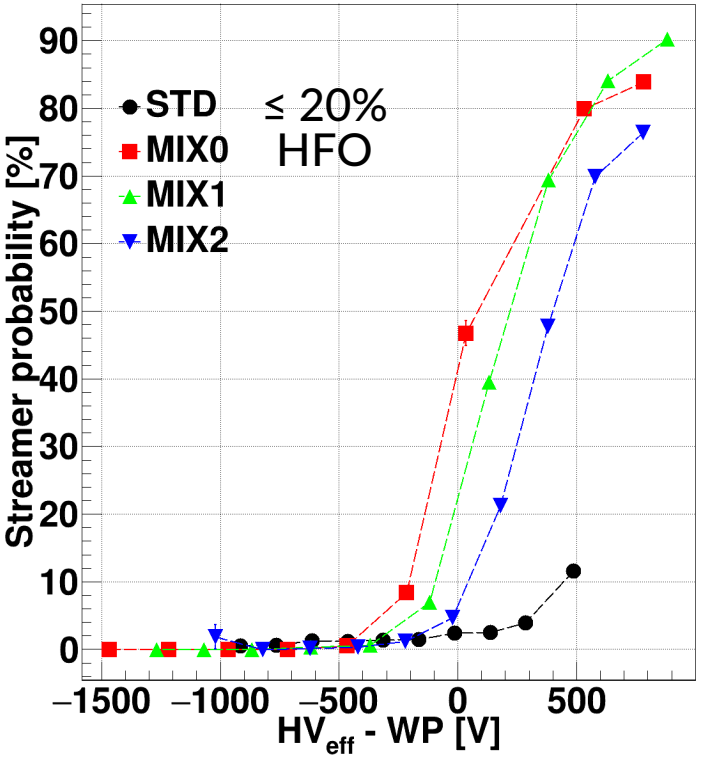
- For all HFO-based mixtures, avalanche peak shifted towards higher values wrt STD
  → Higher absorbed current

- Streamer peak generally more populated than with STD
  → # of streamers decreases as CO_2 concentration decreases (quenching effect of more HFO)
  → Same observations for ALICE and EP-DT RPCs

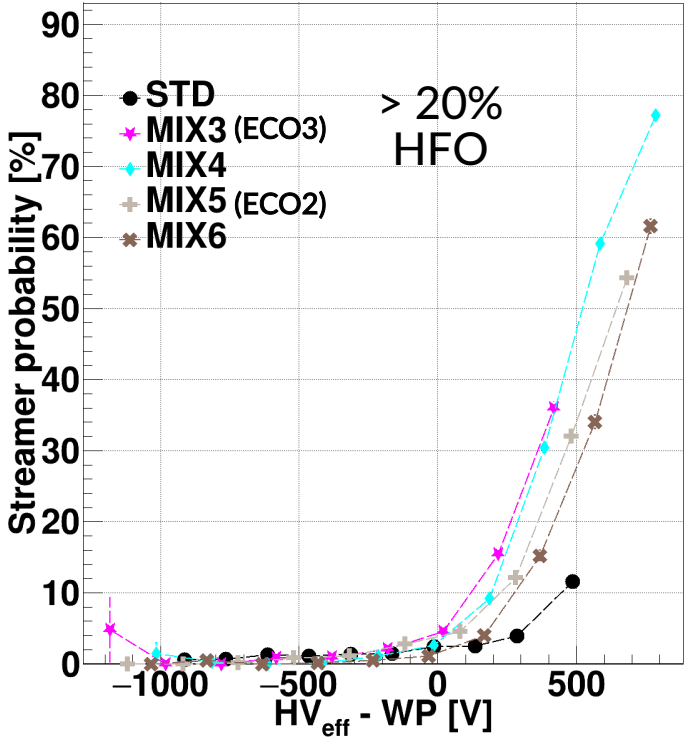
- Small differences between ALICE and EPDT can be explained by the different threshold

Source-off streamer contamination

- Streamer contamination at source off, as a function of (HV - WP) for each mixture
- **STD** gas mixture:
  1) Streamer probability < 5% at WP
  2) Still < 10% 500 V above WP



Source off streamer probability (HV), MIX 0-2, ALICE

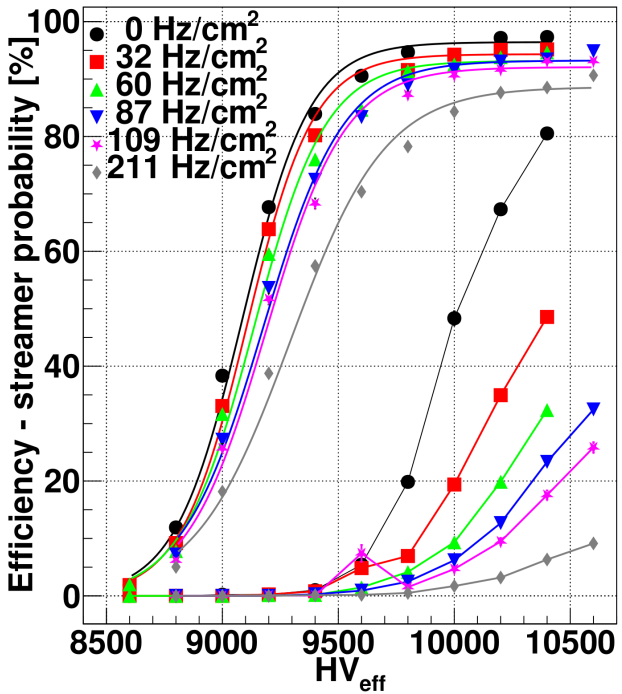


Source off streamer probability (HV), MIX 3-6, ALICE

- Streamer contamination at WP improves with increasing HFO content
- MIX5 (35% HFO) has similar contamination as STD at WP
- Steep rise of the curve for voltages above the WP (35% contamination 500 V above WP for MIX5)

Efficiency under irradiation

- RPC response to the muon beam was studied in combination with the ^{137}Cs source (source on) to study the rate capability
  → Results shown in terms of gamma cluster rate measured using a random trigger to periodically sample the RPC response



RPC response with source on and MIX2 (HFO/CO_2 20/75)

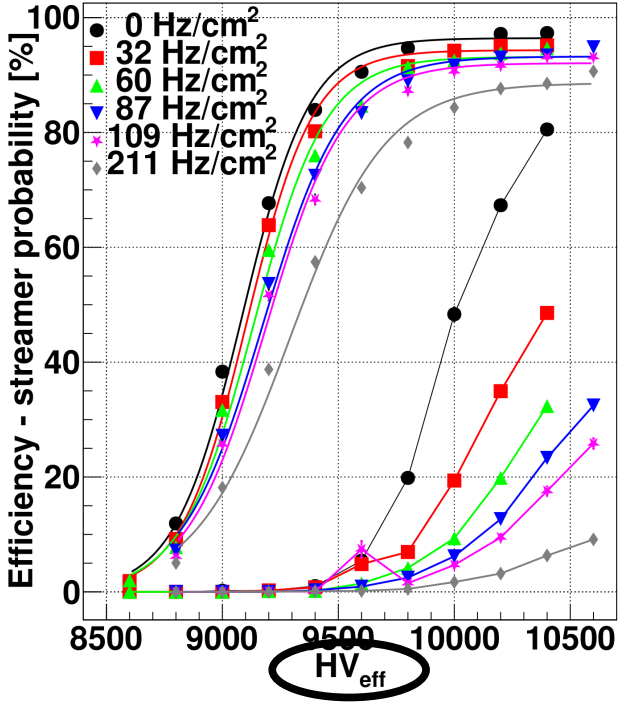
- MIX2 (HFO/CO_2 20/75) shown as an example but similar results with all mixtures

- Three effects under irradiation:
  1) Efficiency curves shift to higher voltages
  2) Maximum value of efficiency reaches lower values
  3) Reduction of streamer contamination

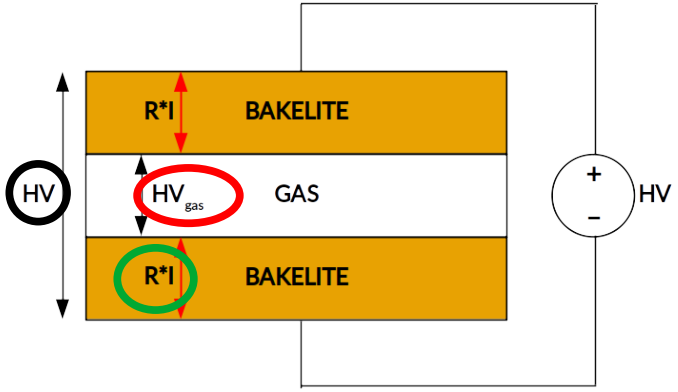
Efficiency under irradiation

N.B. This works only up to rates ~ 250/300 Hz/cm²

- When gamma rate increases, current also increases
- Current flowing through the Bakelite electrodes leads to a voltage drop ($\Delta V_{electrode}$)
  → Can be calculated as the product of electrode resistance and current

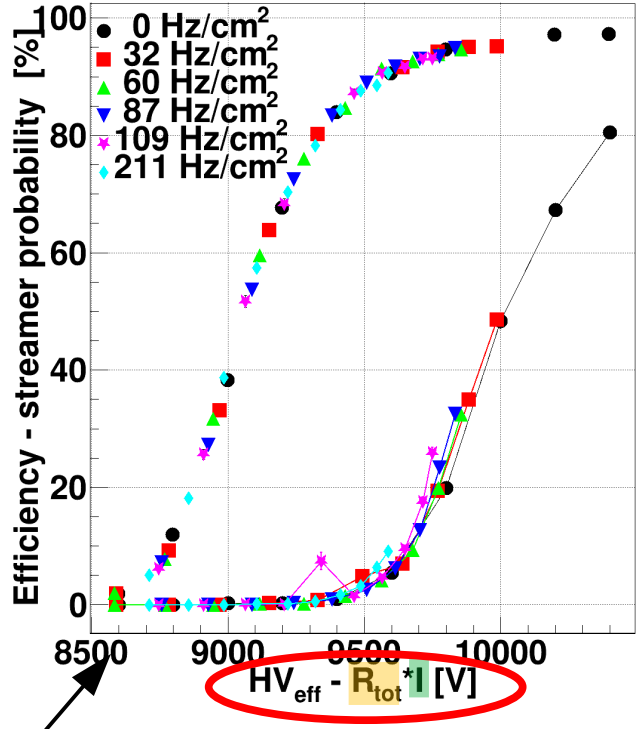


RPC response with source on and MIX2 (HFO/CO_2 20/75)



$$HV_{eff} = HV_{gas} + 2*\Delta V_{electrode}$$

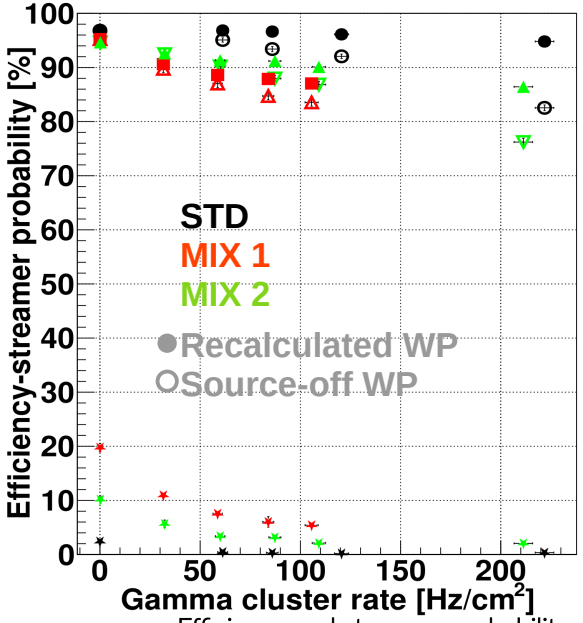
- Current is known, resistance can be measured with Ar method
- Current-induced voltage drop ($\Delta V_{electrode}$) can be calculated
  → Plot of efficiency vs HV_{gas} shows that all curves align

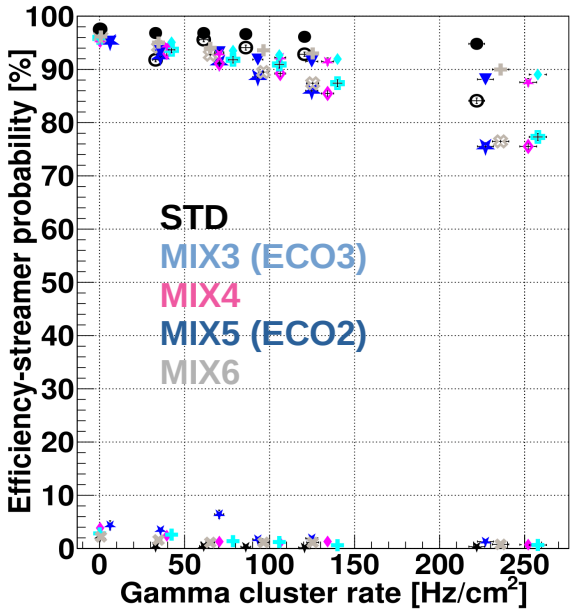


RPC response with source on and MIX2 vs HV_{gas}

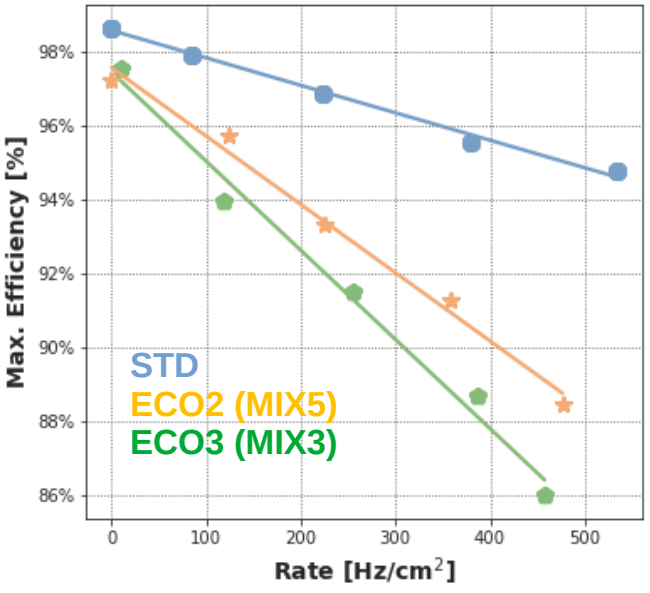
Beam test results – under irradiation

- Evolution of the efficiency and streamer probability estimated at the working point (recalculated for each value of gamma cluster rate) as a function of the gamma cluster rate





Efficiency and streamer probability at WP vs gamma cluster rate – ALICE RPC



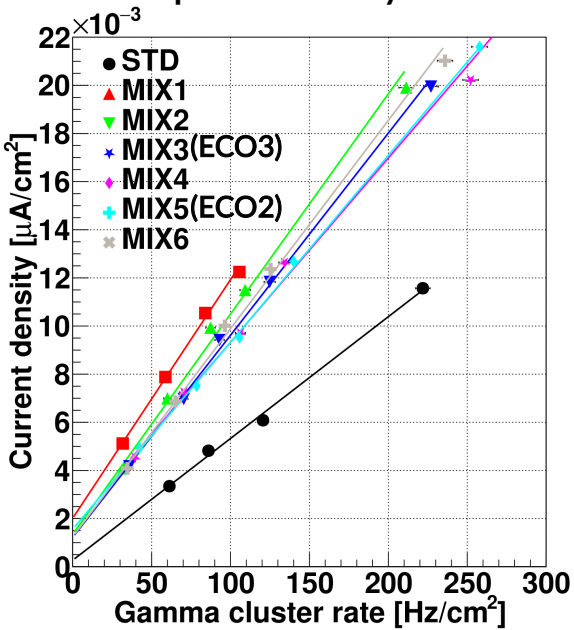
EP-DT RPC

- Open markers in the plot refer to the quantities measured at the source-off working point
- Efficiency drop at recalculated WP and ~ 100 Hz/cm^2 cluster rate (RUN3/4 ALICE)
  1) **STD ~ 1** percentage points (pp)
  2) **Eco-friendly alternatives**: from ~ **8 pp** (lowest HFO concentration) to ~ **3 pp** (highest HFO concentration)
- Observed also in EP-DT: increase of HFO in the mixture leads to smaller maximum efficiency drop at fixed rate

Average charge per gamma cluster

- Total charge per hit = total charge released by ionizing particle in the gas

- If RPC exposed to photon flux
  → Absorbed current (minus its dark component) is proportional to the rate of detected photons
  → Proportionality factor is the average charge per hit



Current density vs gamma cluster rate - ALICE

Current density

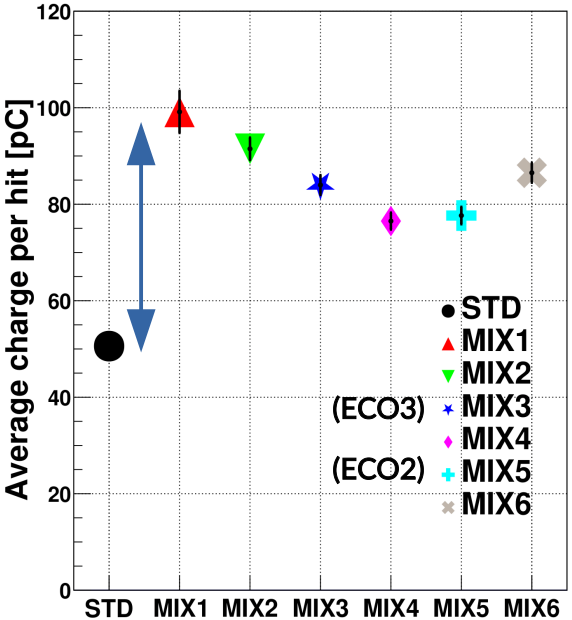
Gamma cluster rate

$$\frac{I}{A} = \langle Q \rangle \cdot \frac{N_{\gamma-detected}}{A\,\Delta t} + DCD$$

Average charge per hit

Dark current density

Linear fit



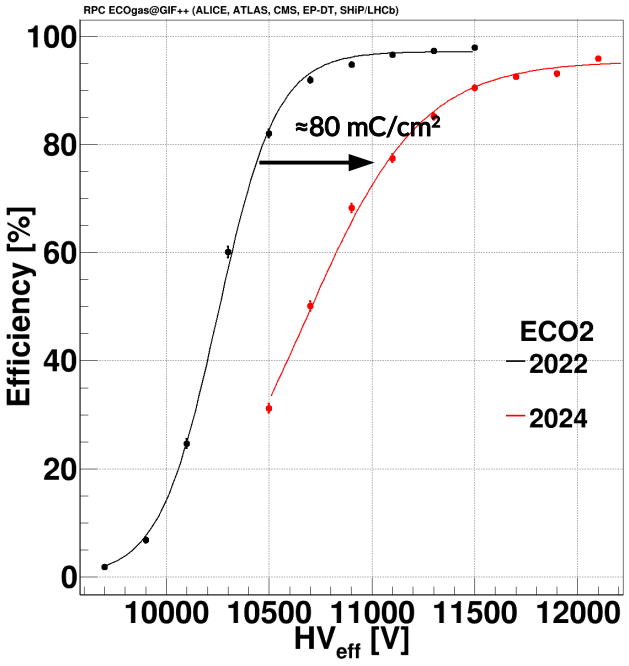
Average charge per gamma cluster - ALICE

- Current at given rate is 1.6/1.7 times higher for all the eco-friendly alternatives wrt STD gas mixture

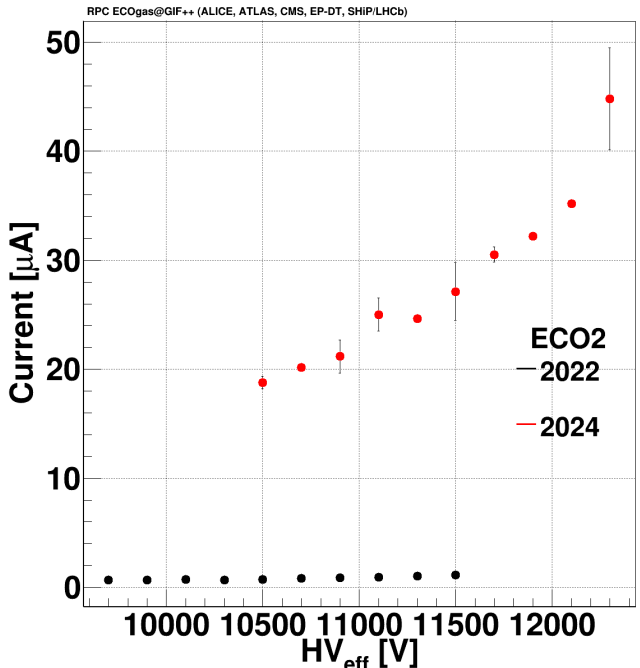
- Same result obtained for the average charge per hit

RPC response evolution during aging - 1

- **Aging test with ECO2 gas mixture** ongoing since 2022[1]
- Periodic beam test campaigns performed during the aging campaign allow one to measure RPC performance evolution as a function of the integrated charge



ALICE RPC source off efficiency - ECO2



ALICE RPC source off current - ECO2

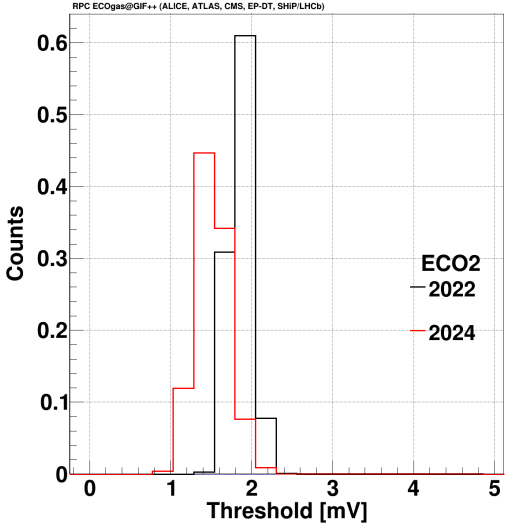
- Comparison **at source OFF** with **ECO2**
- **Shift of the WP** by ≈ 700 V

  → Readout on the same RPC region, same signal polarity and same data analysis
- **Increase in absorbed current**
- **Slight decrease in maximum efficiency**

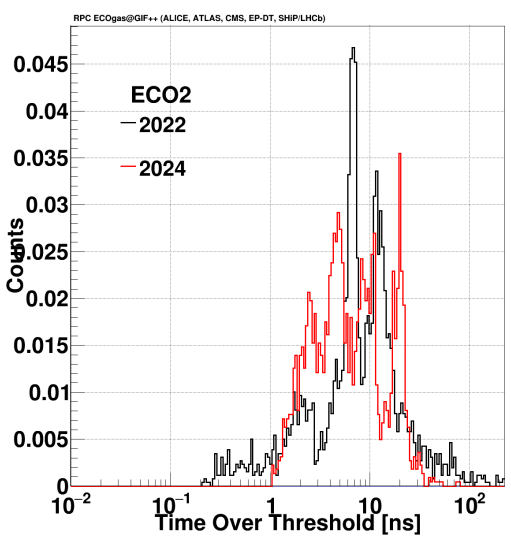
[1]See Marcello Abbrescia's talk today @ 11:50 am

RPC response evolution during aging - 2

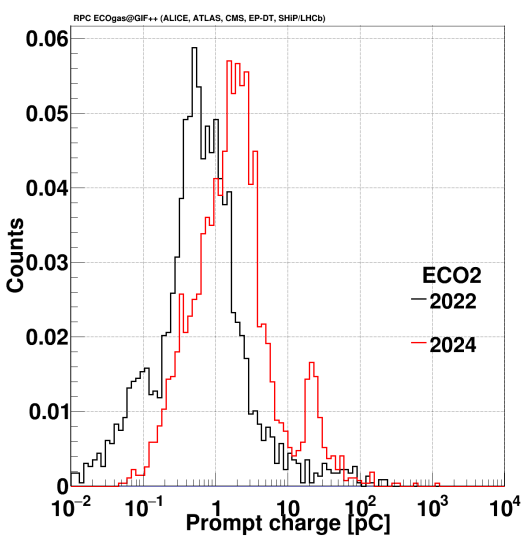
- Comparison of RPC response between 2022 and 2024
  → Taken at 90% efficiency (different HV but same gas gain)



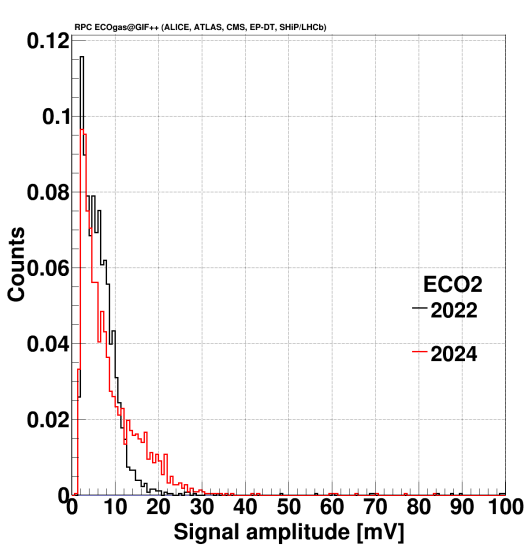
ALICE RPC threshold distribution at 90% efficiency – ECO2



ALICE RPC time over threshold distribution at 90% efficiency - ECO2



ALICE RPC prompt charge distribution at 90% efficiency - ECO2

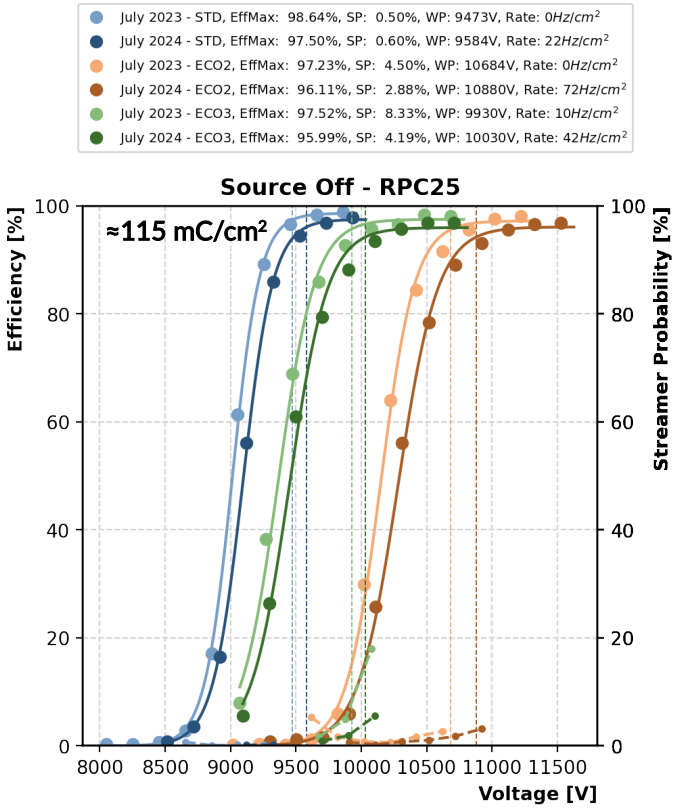


ALICE RPC signal amplitude at 90% efficiency - ECO2

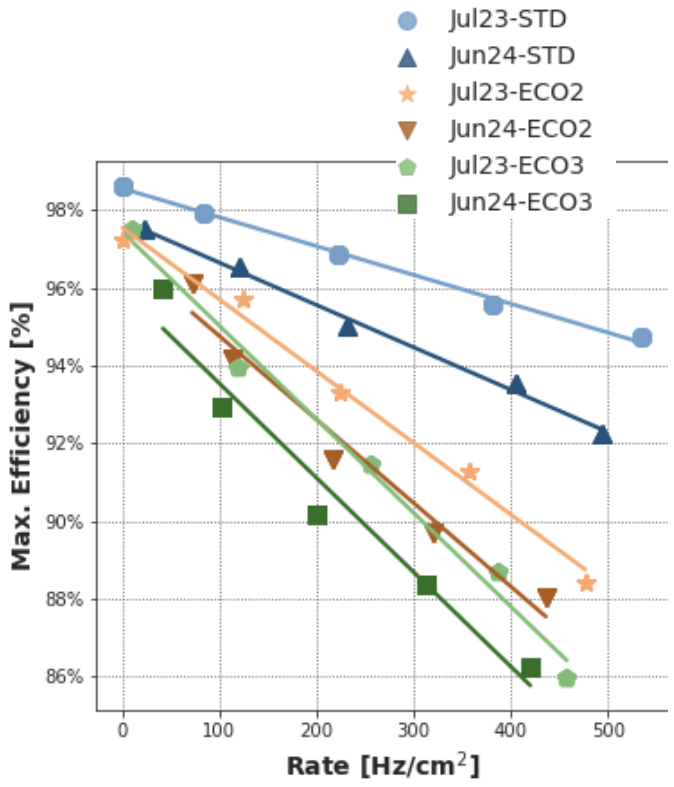
- **Threshold** is similar between 2022 and 2024
- **Larger prompt charge in 2024**
  → Together with larger fraction of streamers
- Can be explained by **larger average signal amplitude and time over threshold**

RPC response evolution during aging - 3

- Comparison of performance for EPDT RPC before and after the aging studies with ECO2



EP-DT RPC source off efficiency vs HV curves. Comparison between 2023 and 2024

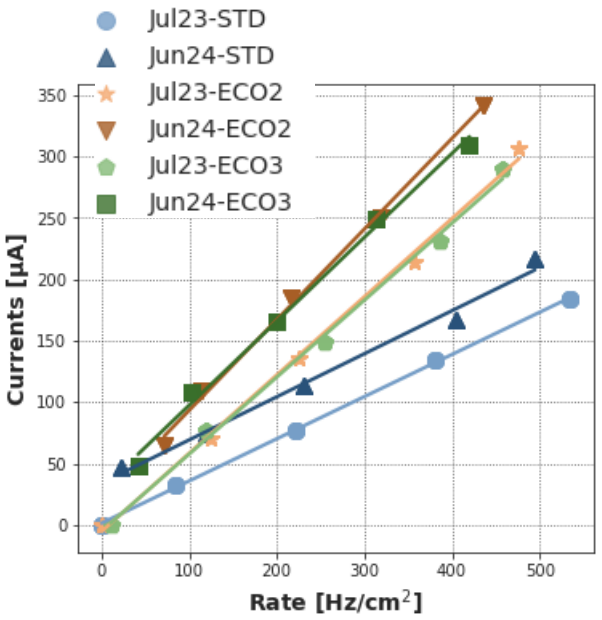


EP-DT RPC maximum efficiency vs background rate. Comparison between 2023 and 2024

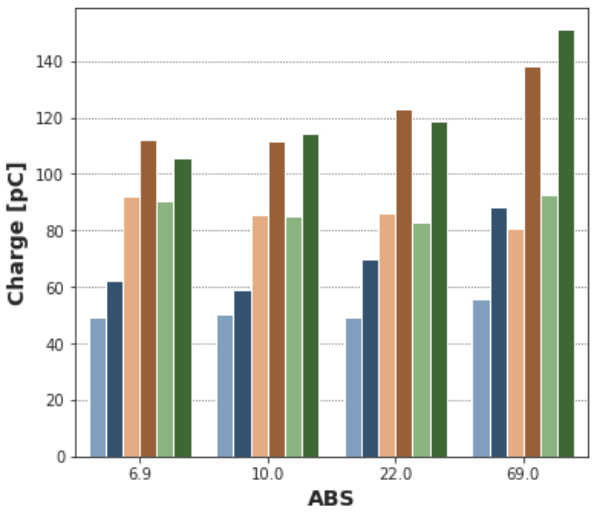
- **Integrated charge** ~115 mC/cm²
- **WP increased** in 2024 wrt 2023, yet (~+100 V for STD, ~+200 V for ECO2 and ~+150 V for ECO3)
- Max **source off efficiency** decreases maximum by ~2% (could be due to alignment)
- Source off **streamer probability reduced** for all the mixtures
- **Max efficiency under irradiation** for same background reduced in 2024 vs 2023 for all mixtures (~2% for all mixtures)

RPC response evolution during aging - 4

- **Currents under irradiation** slightly higher in 2024 wrt 2023
  → Visible for all mixtures
- Increase of dark current
  → Could be related to electrode degradation
  → Chemical analyses needed
- **Ratio between current and rate**
  → Estimation of total charge per gamma hit
  → Higher in 2024 wrt 2023
  → For all mixtures and for all ABS tested @ GIF++
  → Partly explained by higher dark current in this detector



EP-DT RPC source on current vs rate at WP.
Comparison between 2023 and 2024 TB



EP-DT RPC average charge per gamma hit for different GIF++ ABS filter.
Comparison between 2023 and 2024 TB

Overview

- RPCs and their gas mixture
  - The need for an eco-friendly gas mixture
  - HFO-1234ze as a possible replacement for R134a
- The RPC EcoGas@GIF++ collaboration
  - Experimental setup
  - Timeline of the collaboration activities
- Experimental results
  - Selected digitizer beam test results
  - Performance evolution throughout aging
- Conclusions and outlook

Conclusions and outlook

- **RPC ECOgas@GIF++** collaboration is performing beam tests and aging studies on RPCs where the **R134a** is fully replaced using different concentrations of **HFO and CO_2**

- **RPC response** studied using a **digitizer** with ALICE and EPDT RPCs:
  - In general:
    → More HFO in the mixture, better performance (but higher WP)
  - **Average charge** per gamma cluster **increases** by 1.6/1.7 times wrt R134a-based mixtures

- Following the **aging** campaign:
  - **ALICE** RPC: integration of ~80 mC/cm^2
    → Increase in absorbed current, muon prompt charge, ToT and signal amplitude

  - **EPDT** RPC: integration of ~ mC/cm2
    → Slight increase of WP and decrease of maximum effciency under irradiation
    → No significant performance degradation

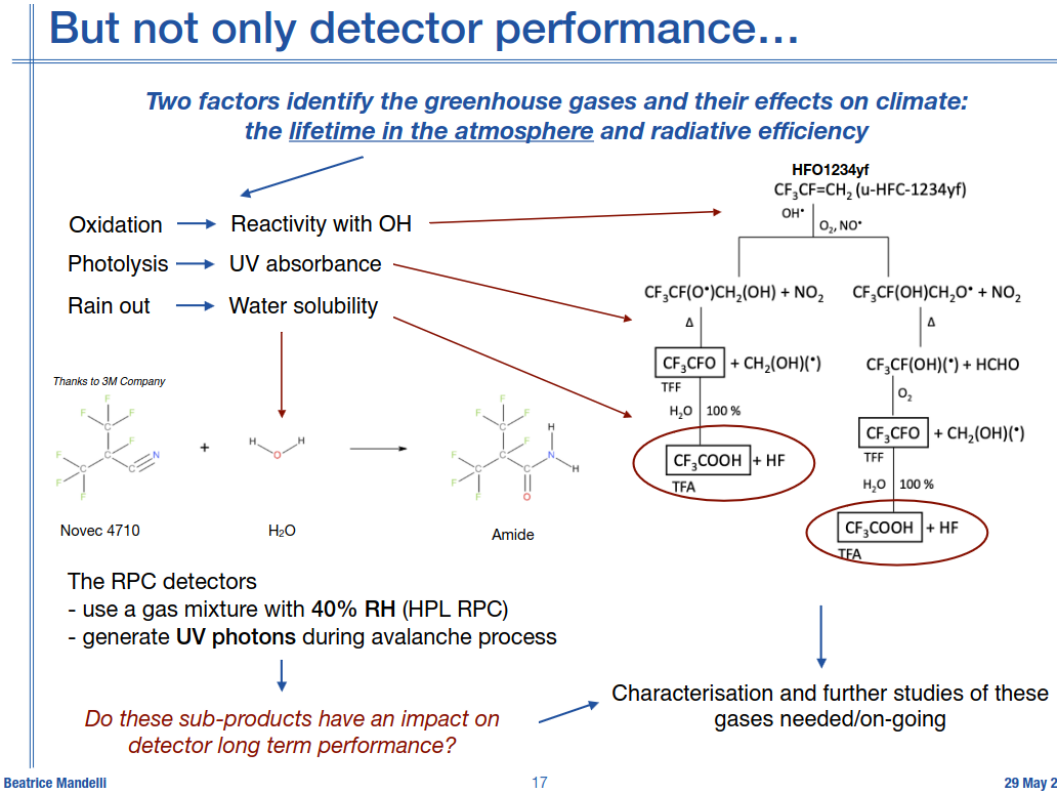
- Aging campaign continuing for the **other detectors** of the collaboration. ALICE RPC removed from irradiation and dedicated studies ongoing to further investigate the observations

Thanks for your attention!!!

Backup

On the HFO ecology - 1

B. Mandelli
https://indico.cern.ch/event/1263322/



- HFO dissociation in atmosphere might leas to the creation of TFA (toxic chemical for humans)
- Deposition on land following rain fall and consequent exposure to humans
- Studies on the matter (such as those reported in [5-7]) are not yet conclusive
- Research work on this direction is ongoing and we are studying these gases since for now they are not deemed as pollutants

On the HFO ecology - 2

B. Mandelli
https://indico.cern.ch/event/1263322/

- PFAs: Per- and polyfluoroalkalyl substances:

  - Group of synthetic substances consisting of carbon chain + fluorine

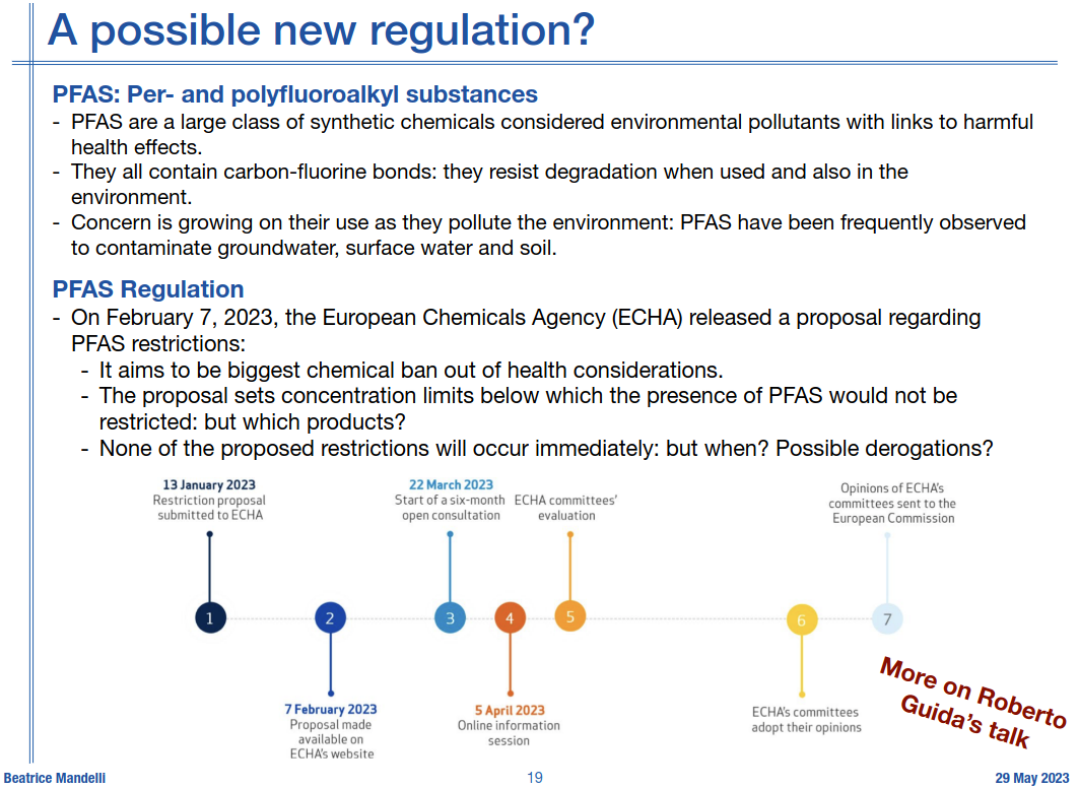
  - Widely used in the industry and can leak into water/air/soil

  - Prolonged exposure harmful for humans

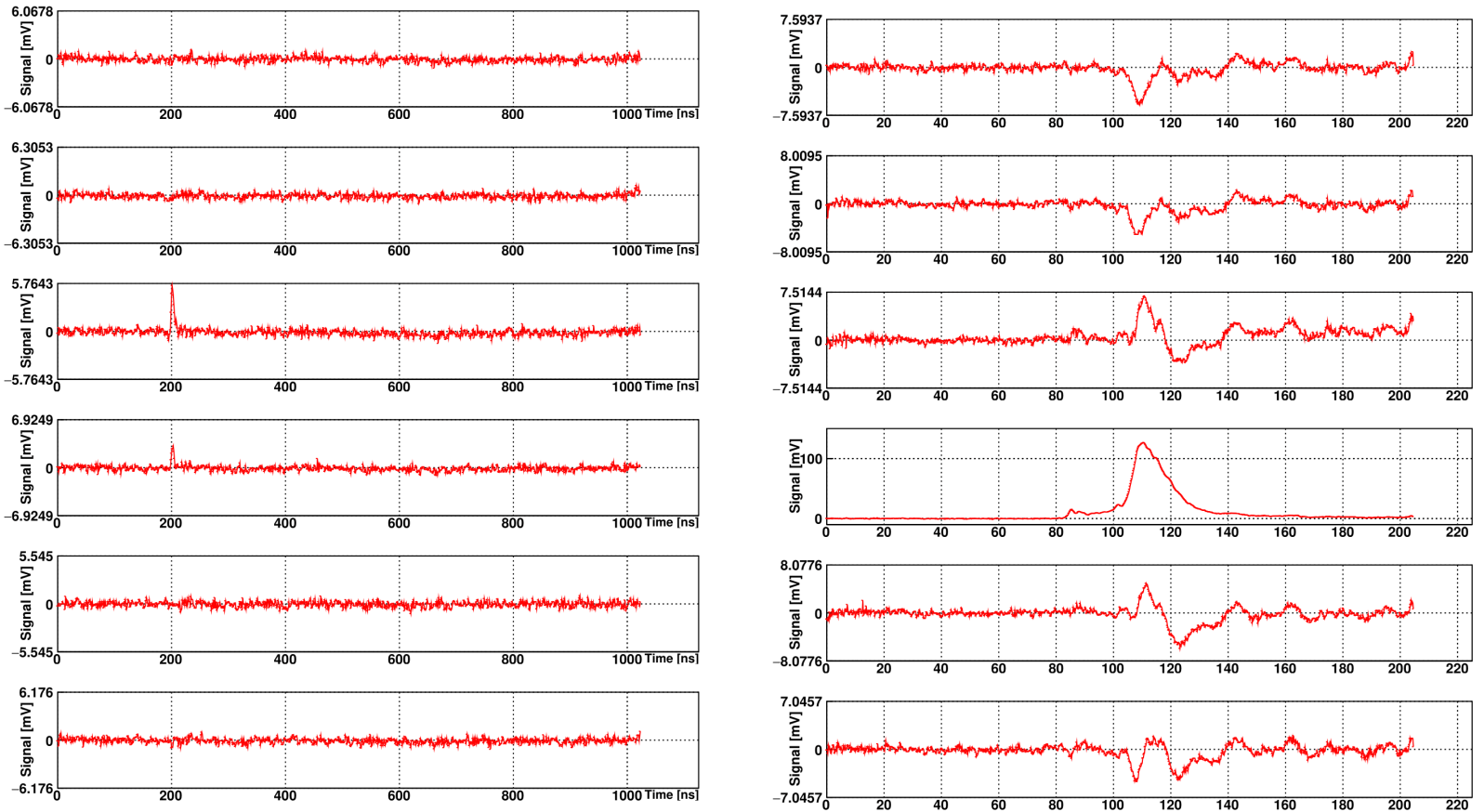
  - More than 15k PFAs identified

- Possible new regulations to ban PFAs

  - Not yet clear if HFO will be included + not clear if the ban will be immediate or if derogations are foreseen



Efficiency/charge calculation with digitizer

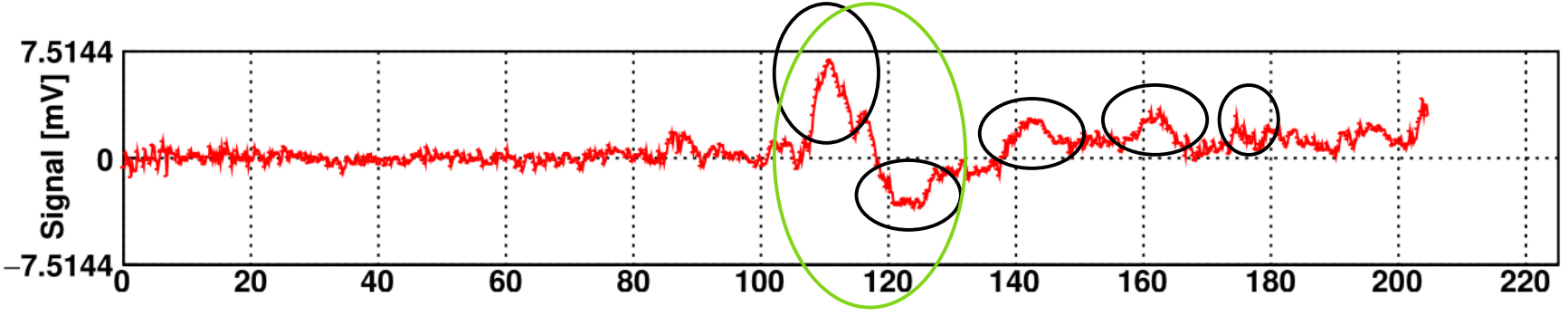


Example of signals from RPC when readout with the digitizer. Left: STD gas mixture; right: MIX0 gas mixture

- RPC response when readout with the digitizer
- Algorithm developed to discriminate efficient strips
- Would tag strips 3 and 4 in the left case
- Would tag strip 4 in the right case because other signals would be classified as reflections (see next slide)

How to find “real signals” with digitizer? - 1

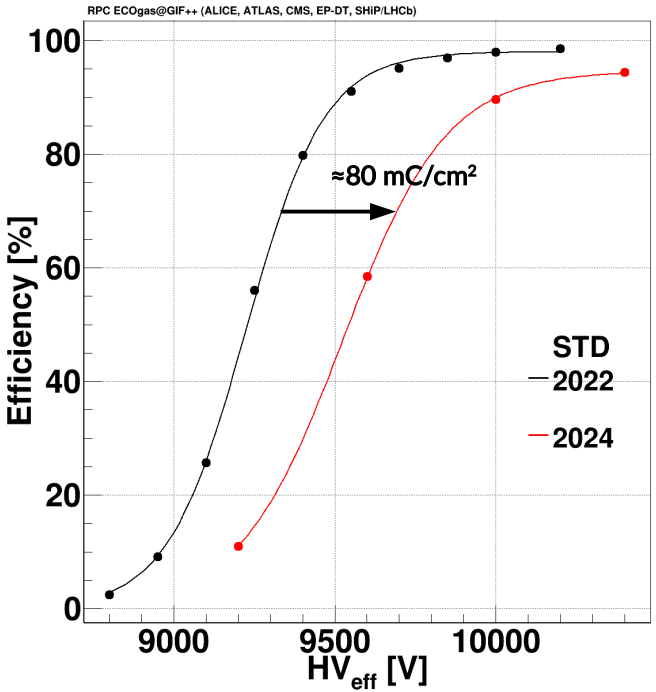
- All the strips which have a signal above 5*RMS in the muon window (arbitary window defined by looking at the muon time of arrival distribution) are deemed as potentially efficient
- The algorithm goes through all the data of the waveform (amplitude vs time with a sample every 1 or 0.4 ns (according to digitizer sampling frequency)) and it finds all the “peaks” (i.e. portions of signal above the threshold)
- If more than one peak is found, they are divided into peak-groups (if time difference between two peaks is < 40 samples)
- With eco-friendly mixtures with low HFO content, often more than one peak and many times they are due to cross-talk effects
  → These peaks are characterized by two opposite-polarity peaks with same absolute value of amplitude



RPC response evolution during aging

- Periodic beam test campaigns performed during the aging campaign allow one to measure RPC performance evolution as a function of the integrated charge

- STD gas mixture for reference

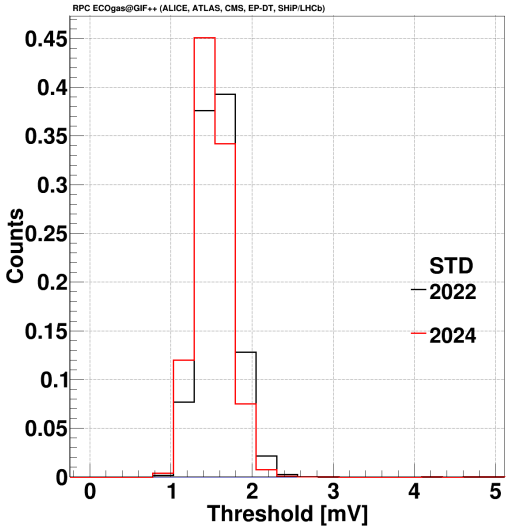


ALICE RPC source off efficiency - STD

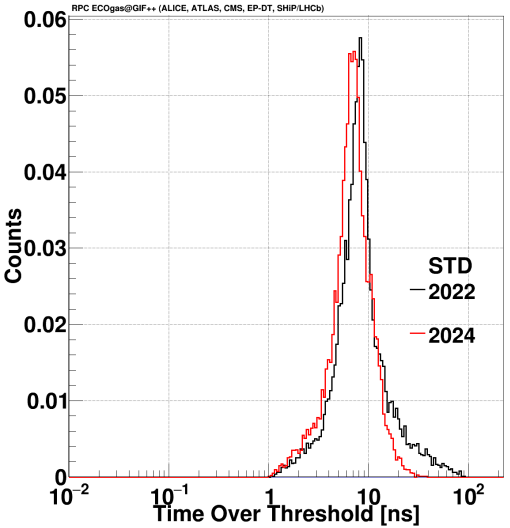
- Shift of the WP by ≈ 400 V

- Readout on the same RPC region, same signal polarity

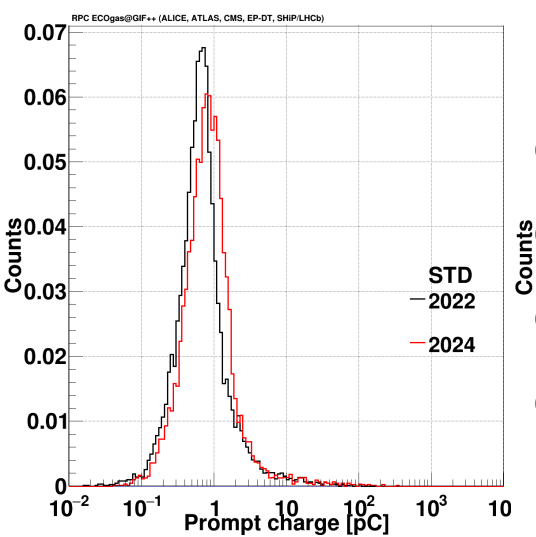
RPC response evolution during aging



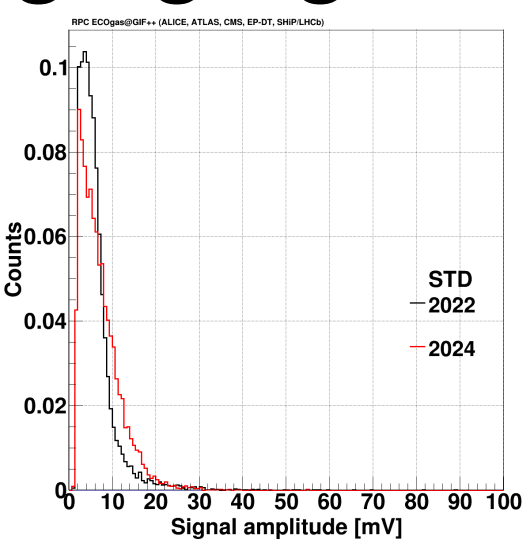
ALICE RPC threshold distribution at 90% efficiency - STD



ALICE RPC time over threshold distribution at 90% efficiency - STD



ALICE RPC prompt charge distribution at 90% efficiency - STD



ALICE RPC signal amplitude at 90% efficiency - STD

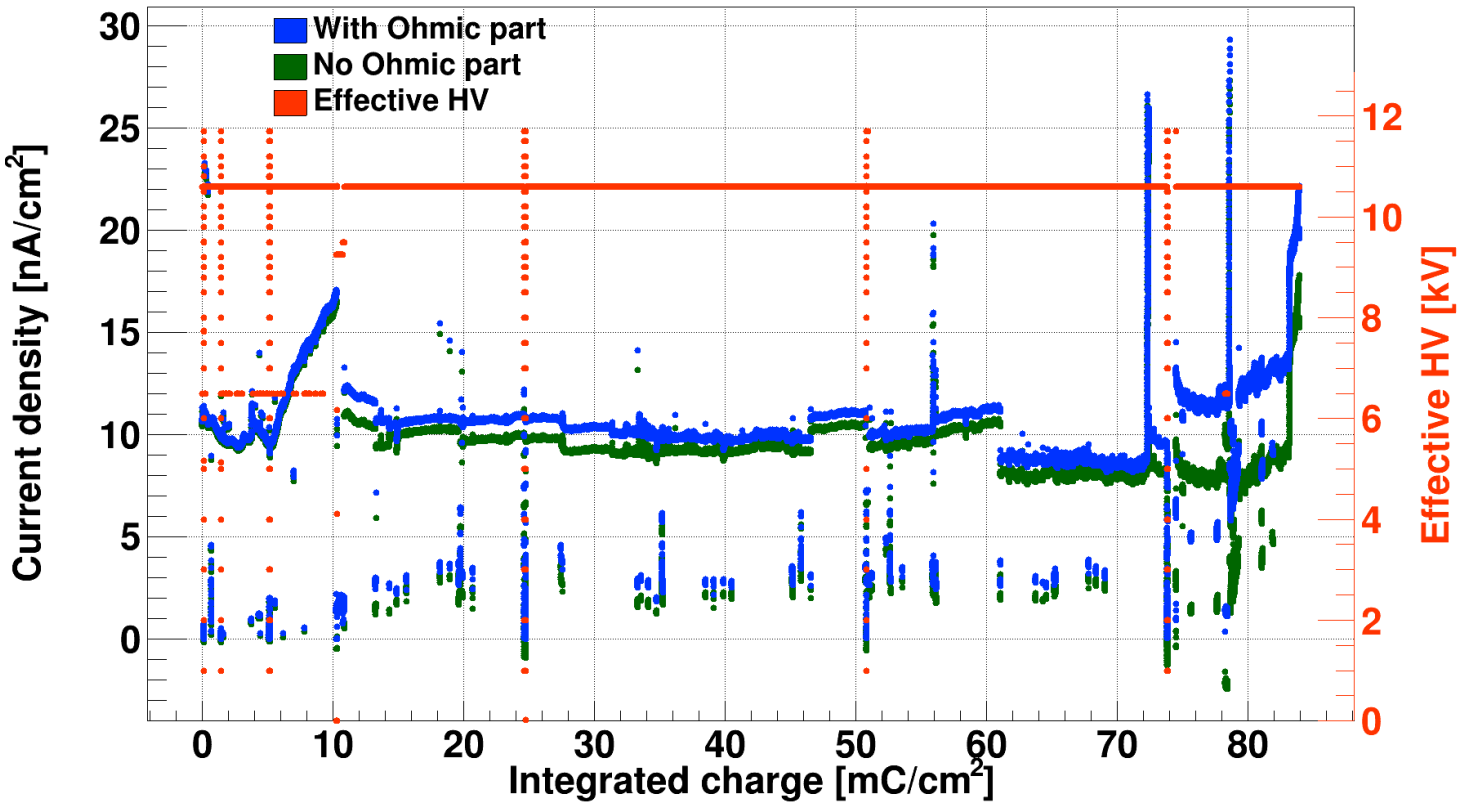
- **Threshold** is comparable between 2022 and 2024
- **Slightly larger prompt charge in 2024**
  → Together with larger fraction of streamers
- Can be explained by **larger average signal amplitude**
- **Slightly lower** average **time over threshold**

Aging campaign results - EPDT

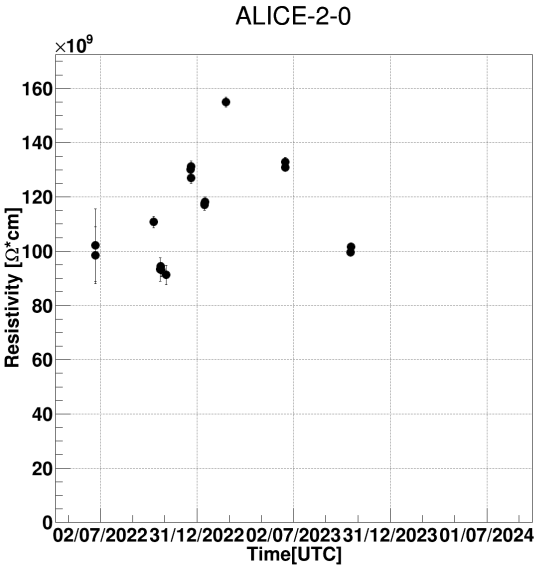
Resistivity measurements during aging – measured with the Ar method

Evolution of the absorbed current as a function of the integrated charge during the aging test

Aging campaign results - ALICE



Evolution of the absorbed current as a function of the integrated charge during the aging test



Resistivity measurements during aging measured with the Ar method