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ICHEP 2024 PRAGUE
ichep2024.org
42nd International Conference on High Energy Physics
18-24 July · 2024 · Prague · Czech Republic

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Performance and ageing studies on Eco-Friendly Resistive Plate Chamber detectors

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on behalf of RPC EcoGas@GIF++ Collaboration

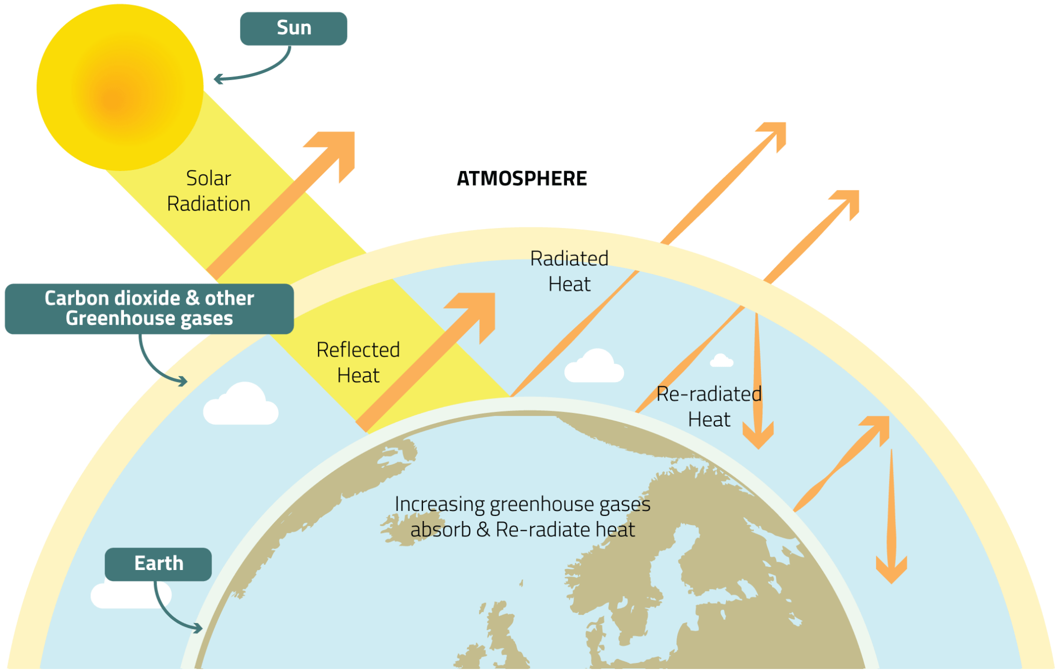
RPCs in High Energy Physics experiments

Fast response: used for triggering and identification purposes, widely employed in **High Energy Physics** experiments
High efficiency and **time resolution**
Relatively cheap to cover large areas

Gaseous detectors

Global Warming Potential (GWP) and GHG emissions at LHC

Greenhouse Gases (GHGs) are gases in the earth's atmosphere that trap heat.



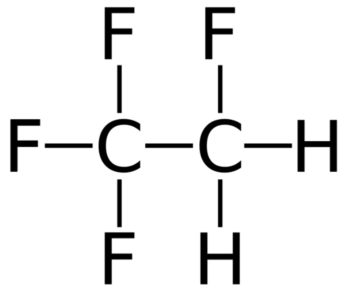
Global warming potential (GWP) is an index to measure of how much infrared thermal radiation a GHG would absorb over a given time. It is expressed as a multiple of the radiation that would be absorbed by the same mass of carbon dioxide, which is taken as a reference gas.

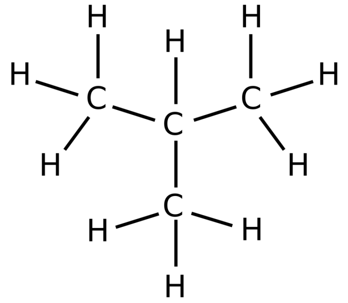
Gas	Atmospheric lifetime	$GWP_{100\ years}$
CO_2	50-200 years	1
R-134a	14 years	1430
CF_4	50,000 years	7390
C_4F_{10}	2600 years	9200
SF_6	3200 years	22800

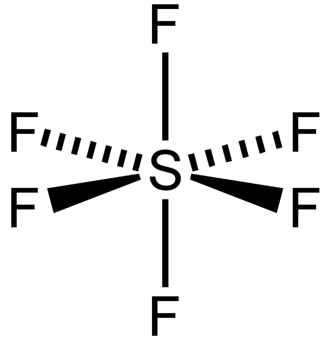
Gases used at CERN with high GWP

Gaseous mixture for RPC operation at CERN

TFE ($C_2H_2F_4$) ~ 95% + iC_4H_{10} ~ 4-5% + SF_6 < 1%





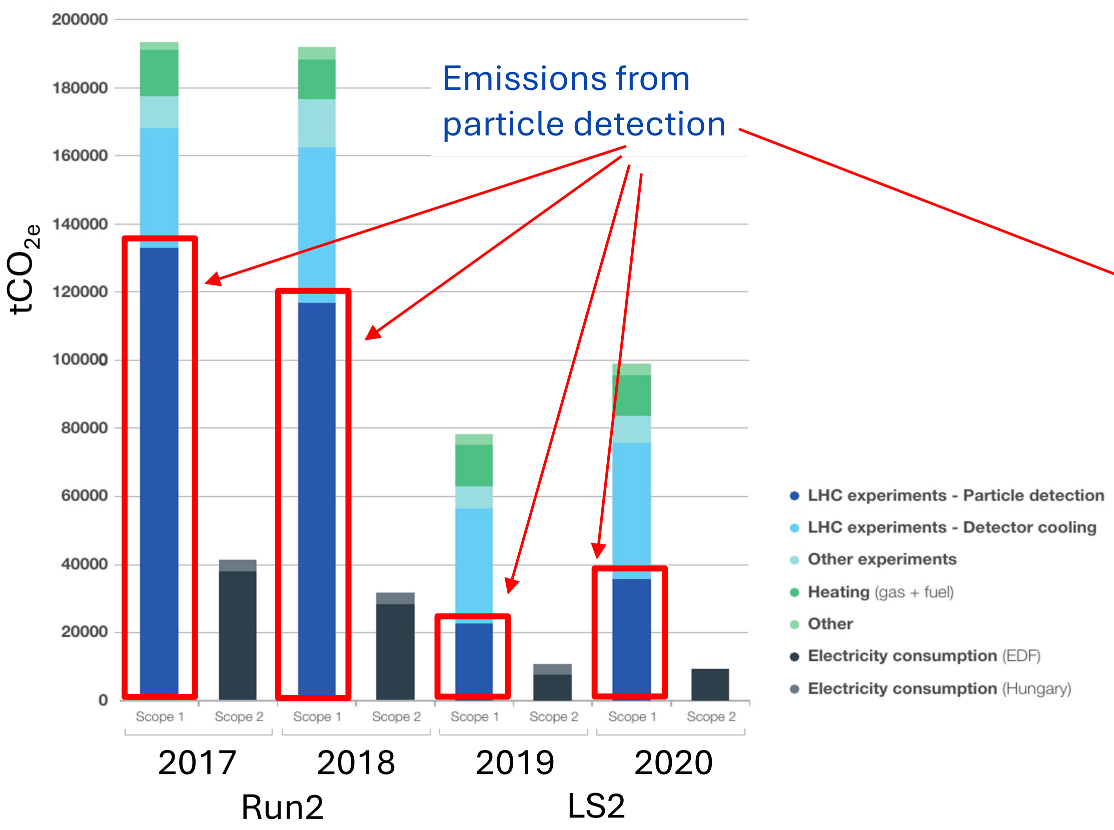


- High density of primary ion-electrons pairs → high RPC efficiency
- Good quenching properties and electronegativity → very low streamer probability
- High rate capability

Nowadays increased attention on GHGs emissions: F-gas regulation aims in limiting emissions, GHGs availability, price, **GHGs are used because needed to achieve specific detector performance and/or long-term stability**

Greenhouse gas usage at CERN (1)

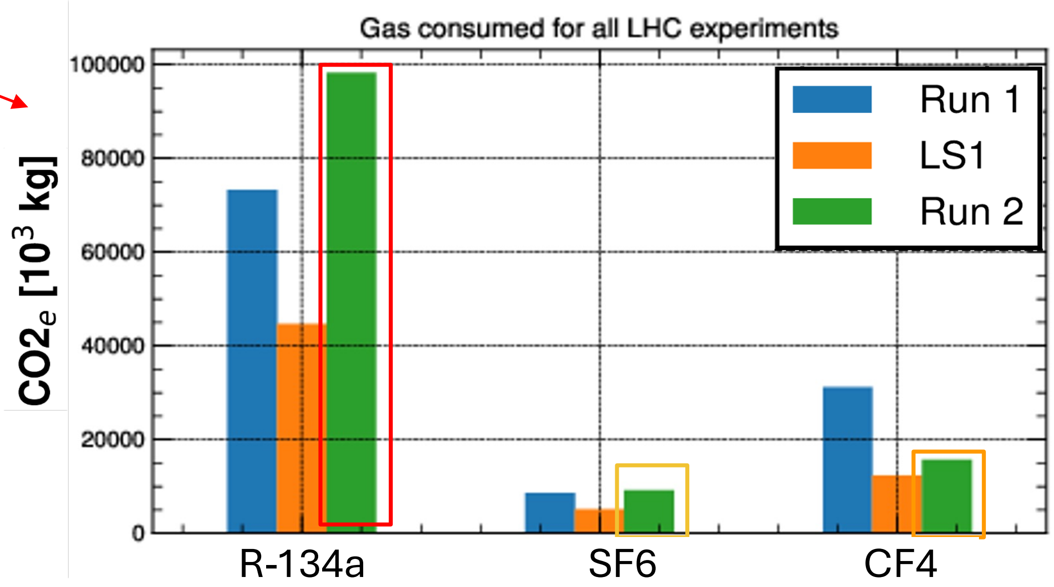
- [CERN Environment Report 2019-2020]
- [2021: CERN's Year of Environmental Awareness.]
- [CERN Environment workshop: 12 and 13 October 2022]
- [CERN Environment Report 2021-2022]



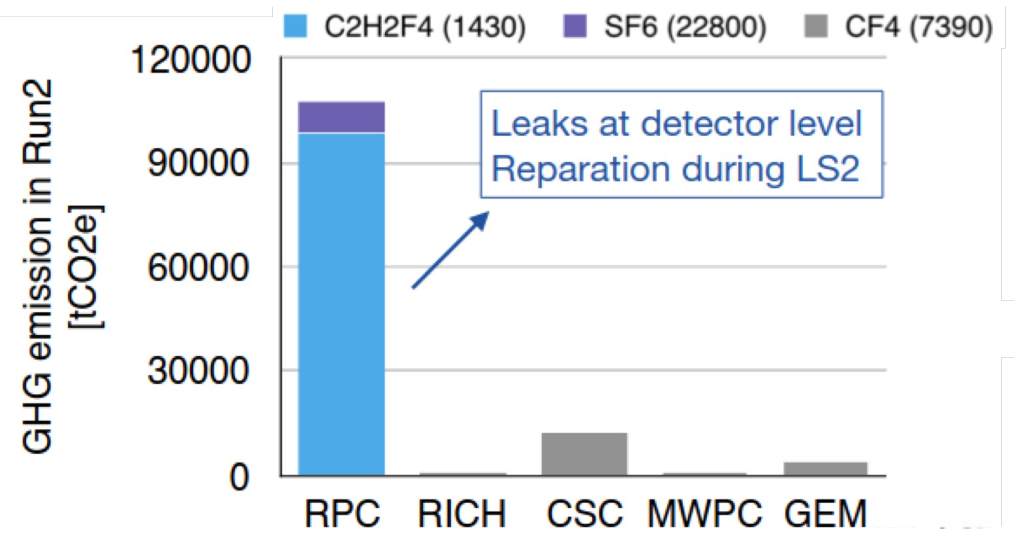
Total CERN emissions during 1 year of Run 2 ~ **200 000 tCO2e**

~ 50% from particle detectors

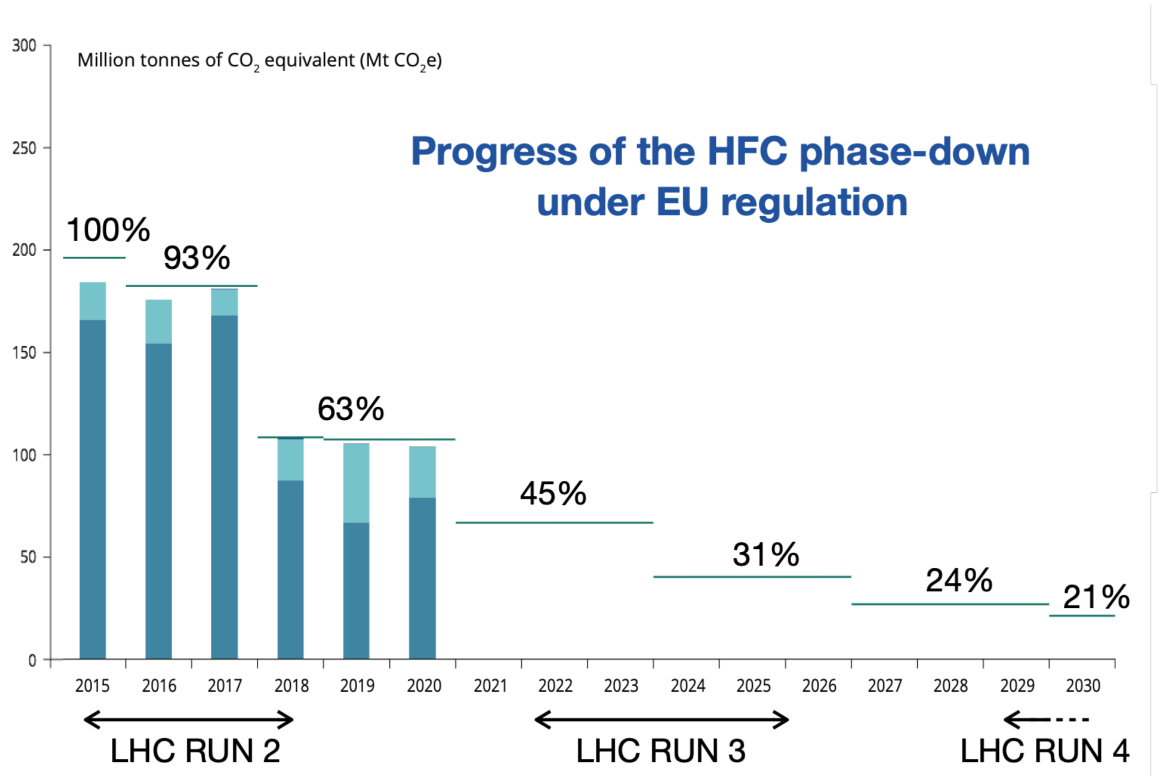
- **$C_2H_2F_4$/R-134a** biggest contributor → leaks from RPC detector, used for ALICE, ATLAS and CMS systems
- **CF_4** → due to operation of CSC and RICH systems
- **SF_6** → Related to RPCs as R-134a



Greenhouse gas usage at CERN (2)



Limiting the total amount of the most important F-gases that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030.
Banning the use of F-gases where less harmful alternatives are widely available.
Preventing emissions of F-gases from existing equipment by requiring checks, proper servicing and recovery

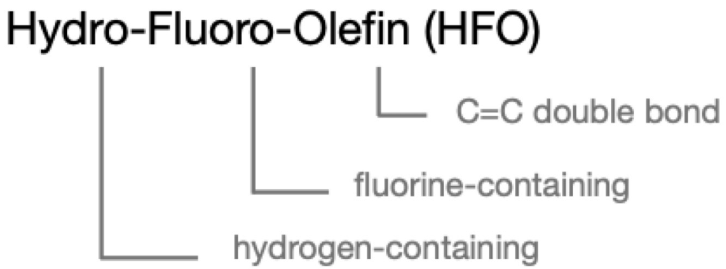


New gaseous mixtures candidates

- Requirements: low GWP, low toxicity, not flammable and detector performance comparable with standard one

In industrial applications $C_2H_2F_4$ is being replaced with HydroFluoro-Olefins (HFOs)

- the replacement of C2H2F4 with HFO moves the operating voltage at much higher values (es. >13kV for 2mm gap)
- the addition of CO2 helps in decreasing the WP



	TFE (%)	HFO-1234ze (%)	CO_2 (%)	iC_4H_{10} (%)	SF6 (%)	GWP	CO_2e (g/l)
STD	95.2	-	-	4.5	0.3	1485	6824
ECO2	**-**	**35**	**60**	**4**	**1**	**476**	**1522**
ECO3	**-**	**25**	**69**	**5**	**1**	**527**	**1519**
Density (g/l)	4.68	5.26	1.98	2.69	6.61	-	-
GWP	1430	7	1	3	22800	-	-

GWP with respect to CO2, and their CO2e, in grams, for one litre of mixture
Values mainly driven by SF6

ECOGas at GIF++ collaboration timeline

EcoGas@GIF++ Collaboration

AidaInnova startup

Irradiation at GIF++ for aging studies

2018

2021

Test Beam 2021

Test Beam 2022

Test Beam 2023

Test Beam 2024

Setup of the system and first HFO-CO2 mixtures tested under irradiation at GIF++

ECO1: CO_2 50%, HFO 45%, iC_4H_{10} 4%, SF_6 1%
High current increase of dark current After ~ 20 mC/cm2 integrated charge

ECO2: CO_2 35%, HFO 60%, iC_4H_{10} 4%, SF_6 1%

ECO3: CO_2 25%, HFO 69%, iC_4H_{10} 5%, SF_6 1%

STD, ECO2 and ECO3 mixtures under performance test and irradiation

ECOGas@GIF++ collaboration timeline

Transversal collaboration to find an ecological gas mixture replacement for RPC operation at CERN
Beam tests and irradiation campaigns, performance analysis of chambers from each experiment

CMS CERN ALICE ATLAS EXPERIMENT LHCb

startup

2018

2021

Test Beam 2021

Setup of the system and first HFO-CO2 mixtures tested ... irradiation at GIF++

STD, ECO2 a...

CO₂ 50%, HFO 45% ... F₆ 1%

er ~

1%

1%

Around 24 universities, institutes and research centers!!!

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Many colleagues, PhDs, students and technicians!!!

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Some papers!!!

High-rate tests on resistive plate chambers operated with eco-friendly gas mixtures

Preliminary results on the long term operation of RPCs with eco-friendly gas mixtures under irradiation at the CERN Gamma Irradiation Facility

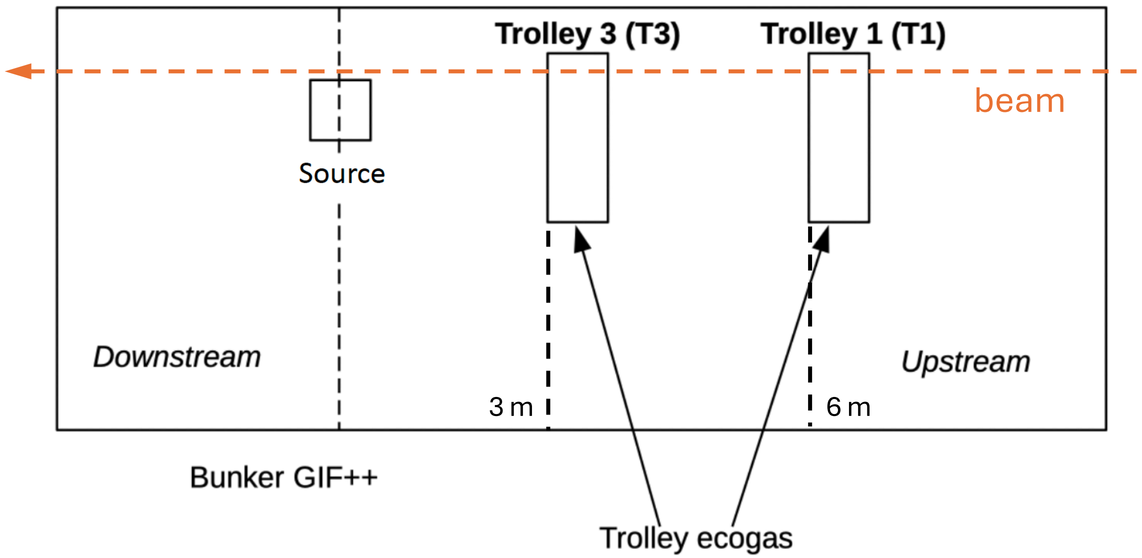
Performance of thin-RPC detectors for high rate applications with eco-friendly gas mixtures

Setup at GIF++

- 12.2 TBq ^{137}Cs + H4 SPS beam line
- Radiation intensity attenuated by combination of filters

Gas mixer unit to provide up to 4 component gas mixture (humidified)

- $C_2H_2F_4$, iC_4H_{10}, SF_6, CO_2, Ar, HFO



RPCs: Alice (2 mm), EP-DT (2 mm), CMS (2mm), CMS_KODEL (1.4 mm), LHCb/SHIP (1.6 mm), ATLAS (2 mm)

Aging studies

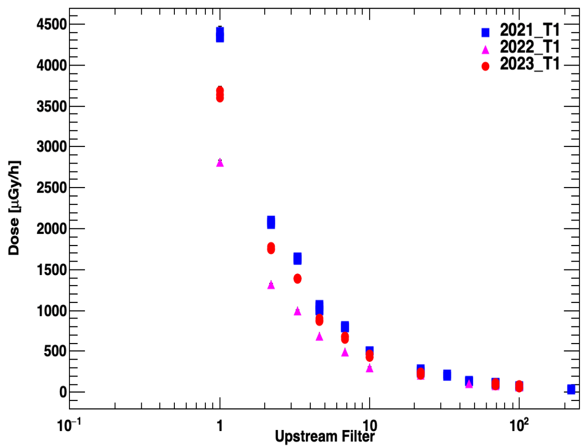
Monitoring of currents

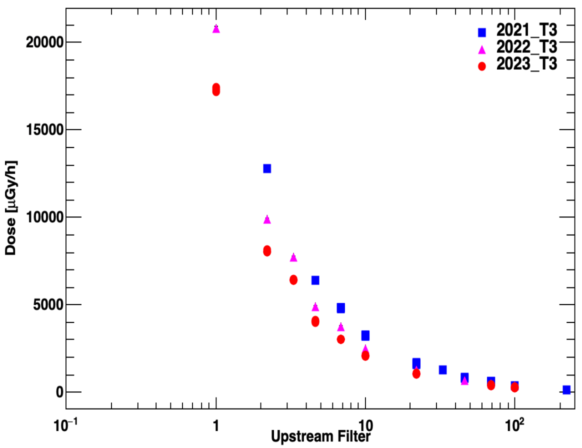
Detector performance (test-beam)

CMS FEB for CMS RPC

ALICE FEB FEERIC for ALICE and LHCb/SHIP RPCs

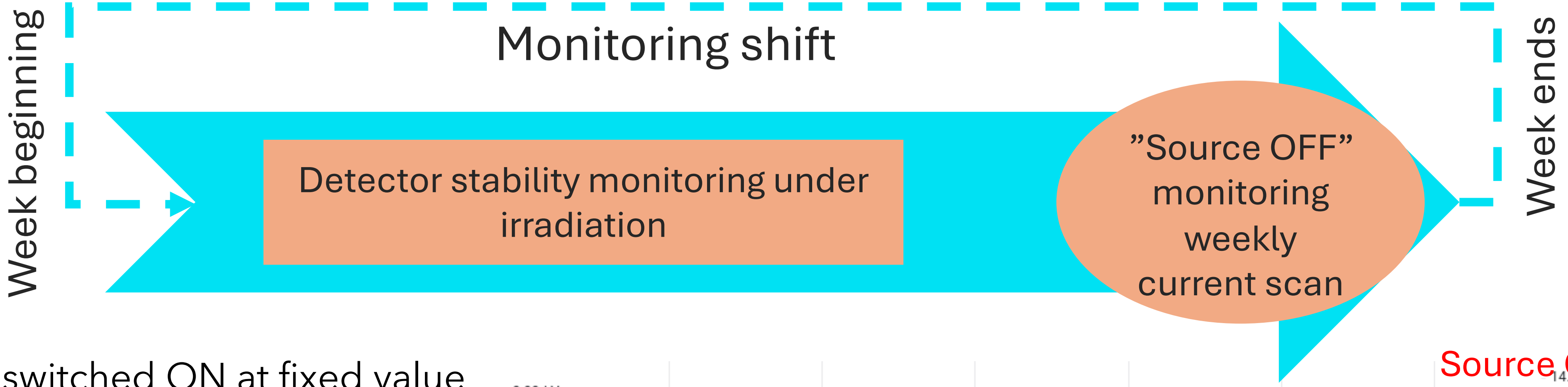
Dedicated digitizer for EP-DT and ATLAS RPCs





Aging studies

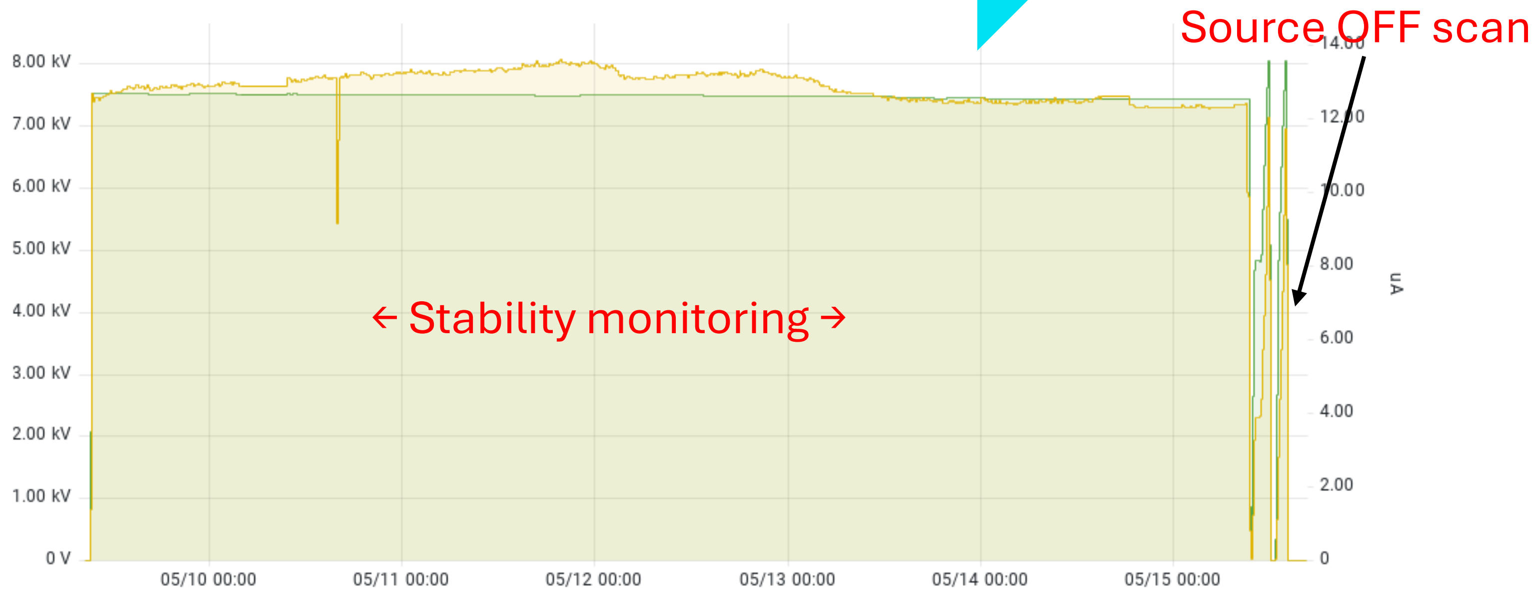
How our aging program works?



- Detector HV switched ON at fixed value for hole week → Stability monitoring
- HV is corrected every minute

$$HV_{app} = HV_{eff}\left[(1-\alpha)+\alpha\frac{P}{P_0}\frac{T_0}{T}\right]$$

- Detectors are exposed to the γ flux from the ^{137}Cs source → current and voltages are monitored by shifts



How our aging program works?

Week beginning

Monitoring shift

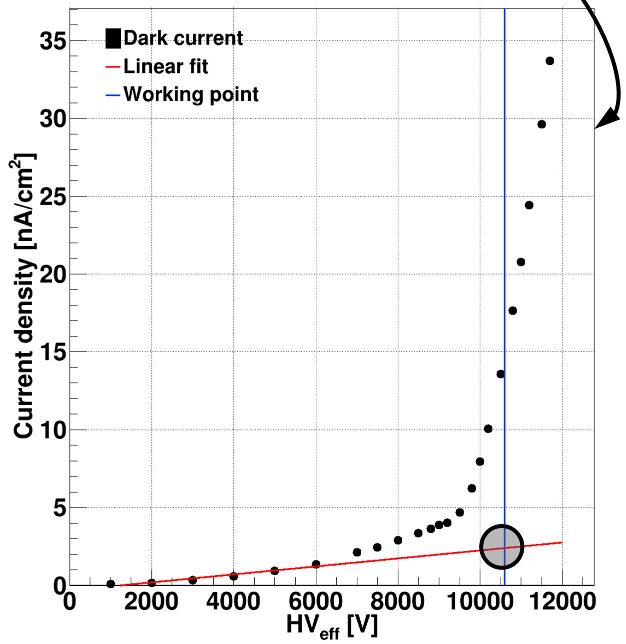
Detector stability monitoring under irradiation

”Source OFF” monitoring weekly current scan

Week ends

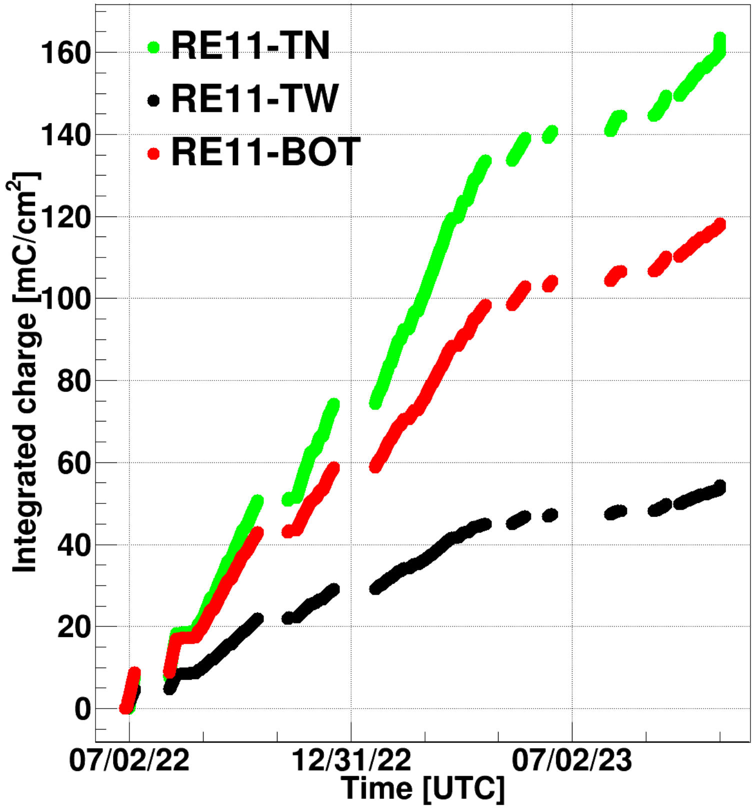
Linear fit between 0 and 5 kV to extrapolate Ohmic component of the dark current at the irradiation voltage
→ This current does not necessarily flow through the gas
→ Subtracted from the current absorbed under irradiation to calculate the integrated charge density

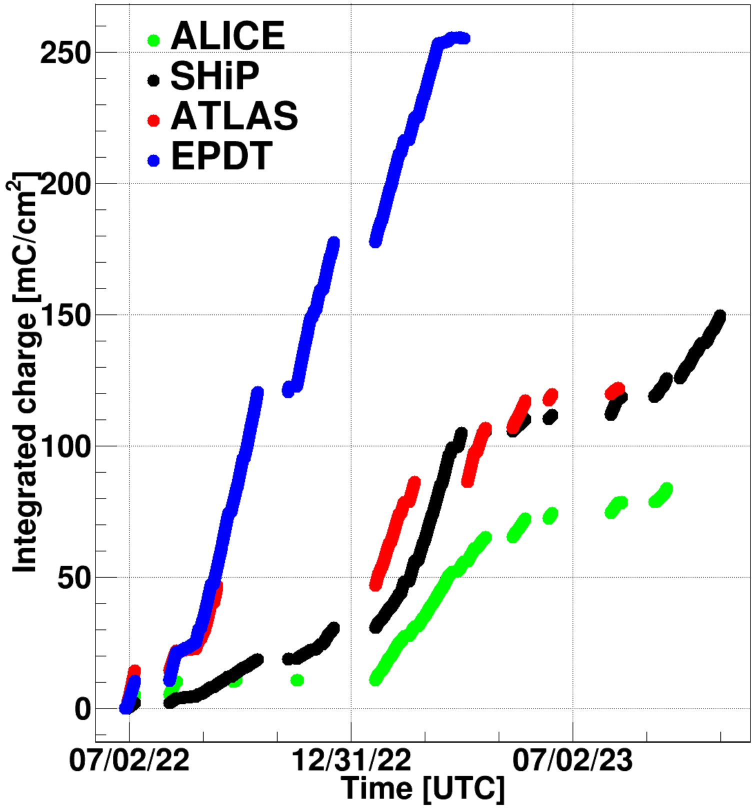
Current density monitoring over time as function of integrated charge density

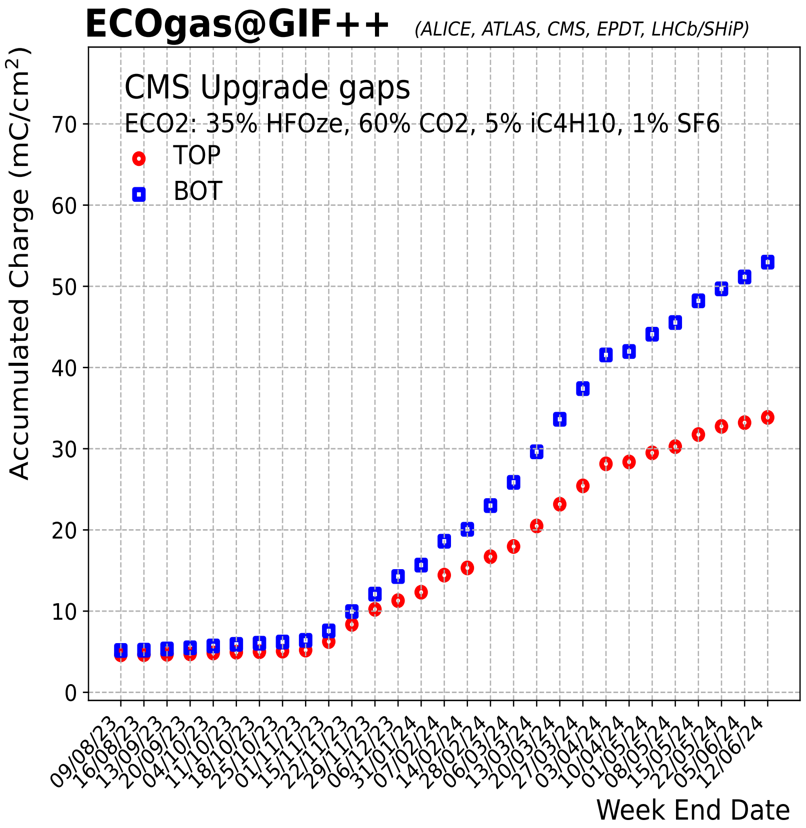


Integrated charge on time

BY flushing all detectors with ECO2







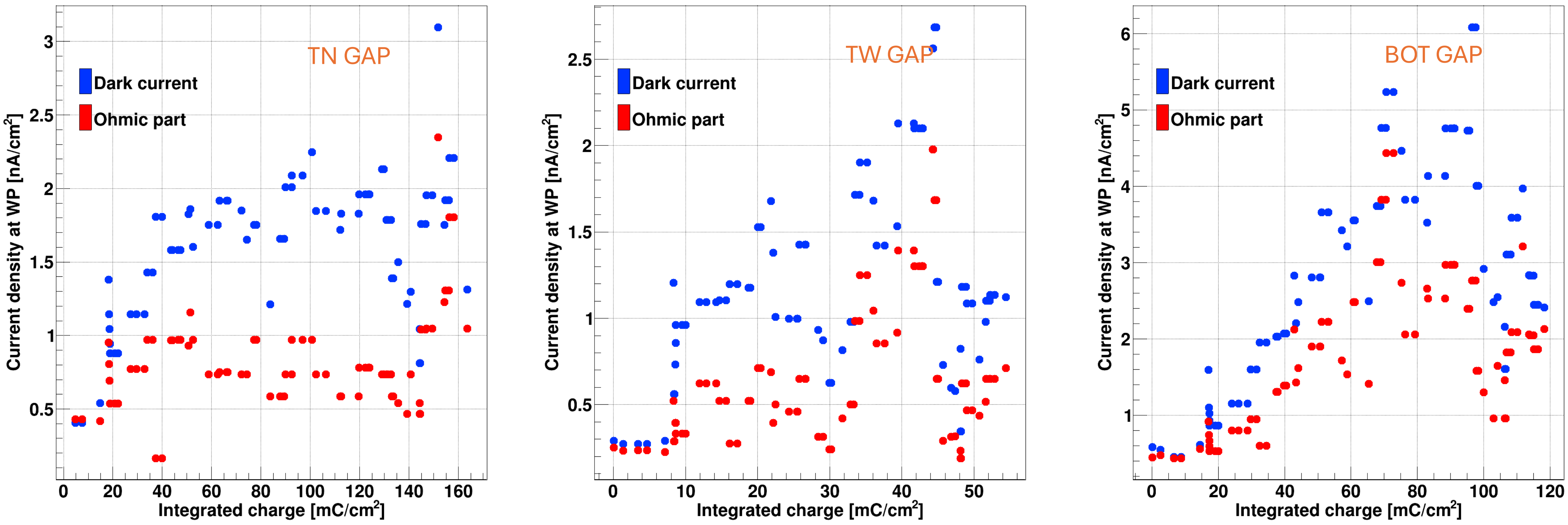
Different maximum values of integrated charge reached by the different RPCs

→ Efficiency corresponding to irradiation voltage is not the same on all detectors + different distances from the Cs source

Aging studies results (1)

CMS RPC

Total and Ohmic dark currents at working point



- After initial increase followed by some stability for TN and TW gap, while less stable and increase trend BOT gap.

Aging studies results (2)

LHCb/SHiP RPC

Total and Ohmic dark currents at working point

Effective high voltage of SHiP RPC moved in steps up to 9.8 kV
→ Only RPC of the collaboration to reach full efficiency

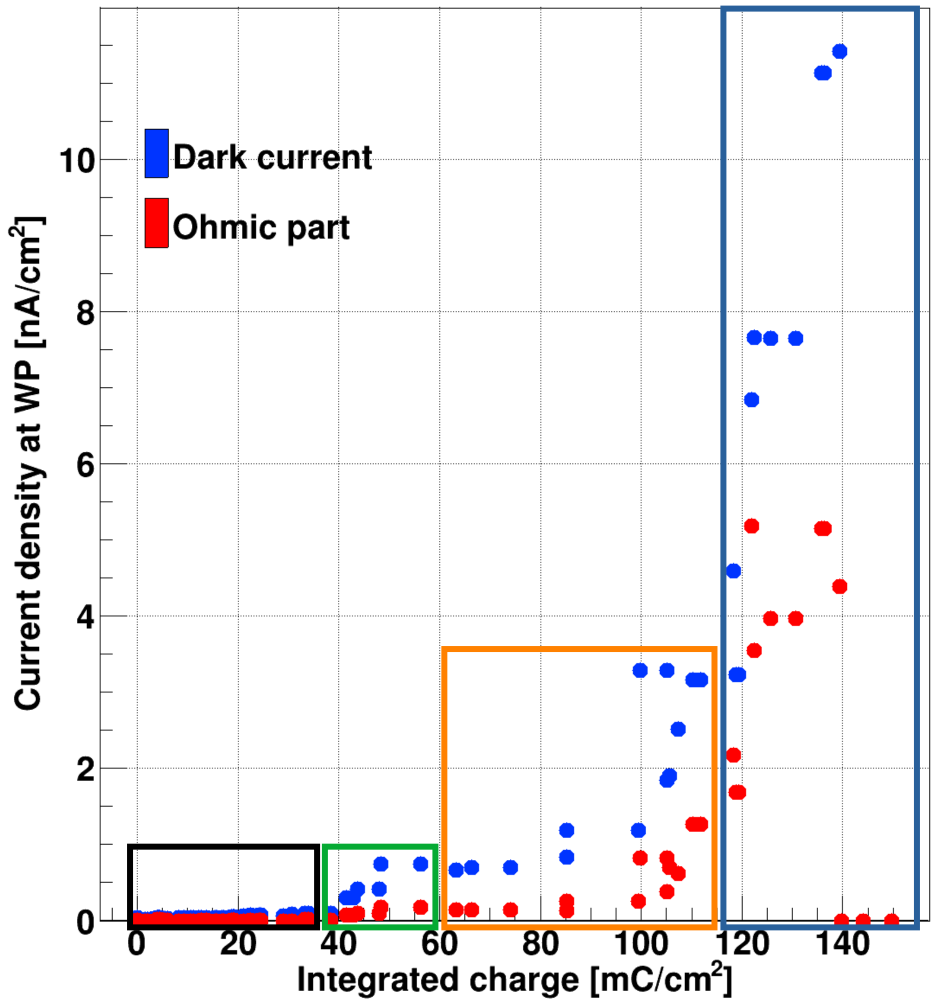
- For lower HVs

→ Current trend stable over time

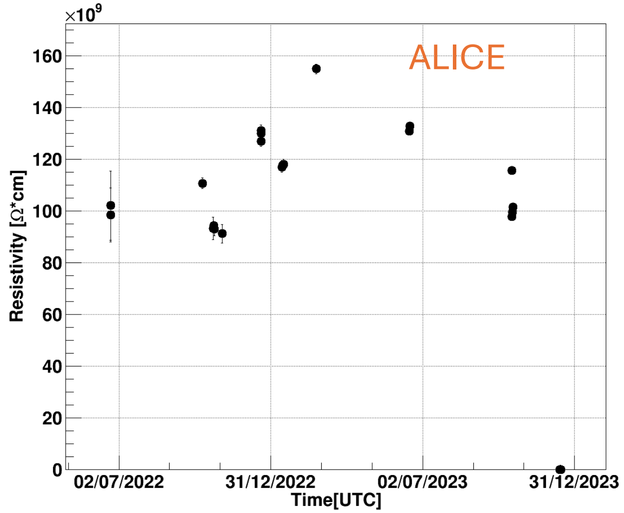
- When HV increased

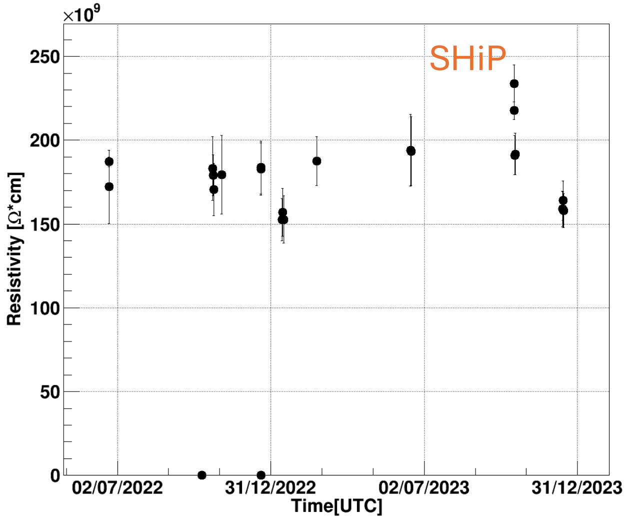
→ Current increase + appearance of instabilities (under investigation)

Similar trend for dark current
HV: 8.8 kV
HV: 9 kV
HV: 9.8 kV
HV: 8.8 kV (3 m from source)

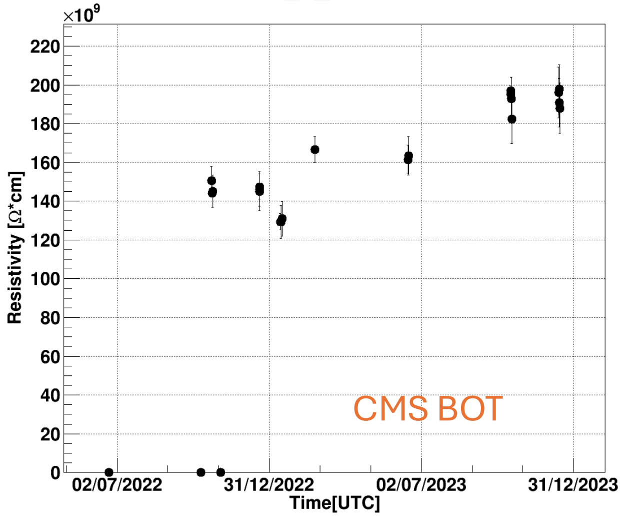


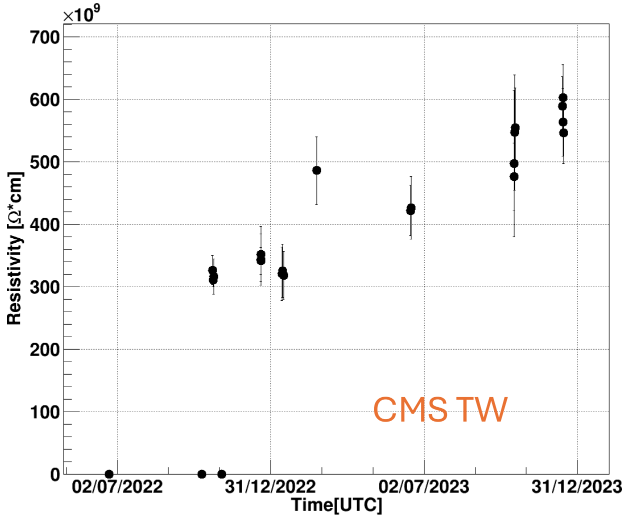
Resistivity trend

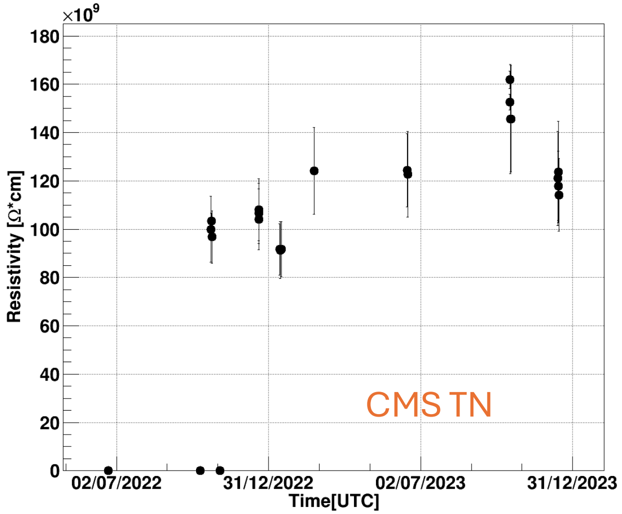




- Resistivity monitoring by Ar scan (see backup slides)
- Slightly increase trend for CMS top RPCs while more constant behavior for the others
- Possible not uniform response in all detectors (under discussion, electrodes materials??)



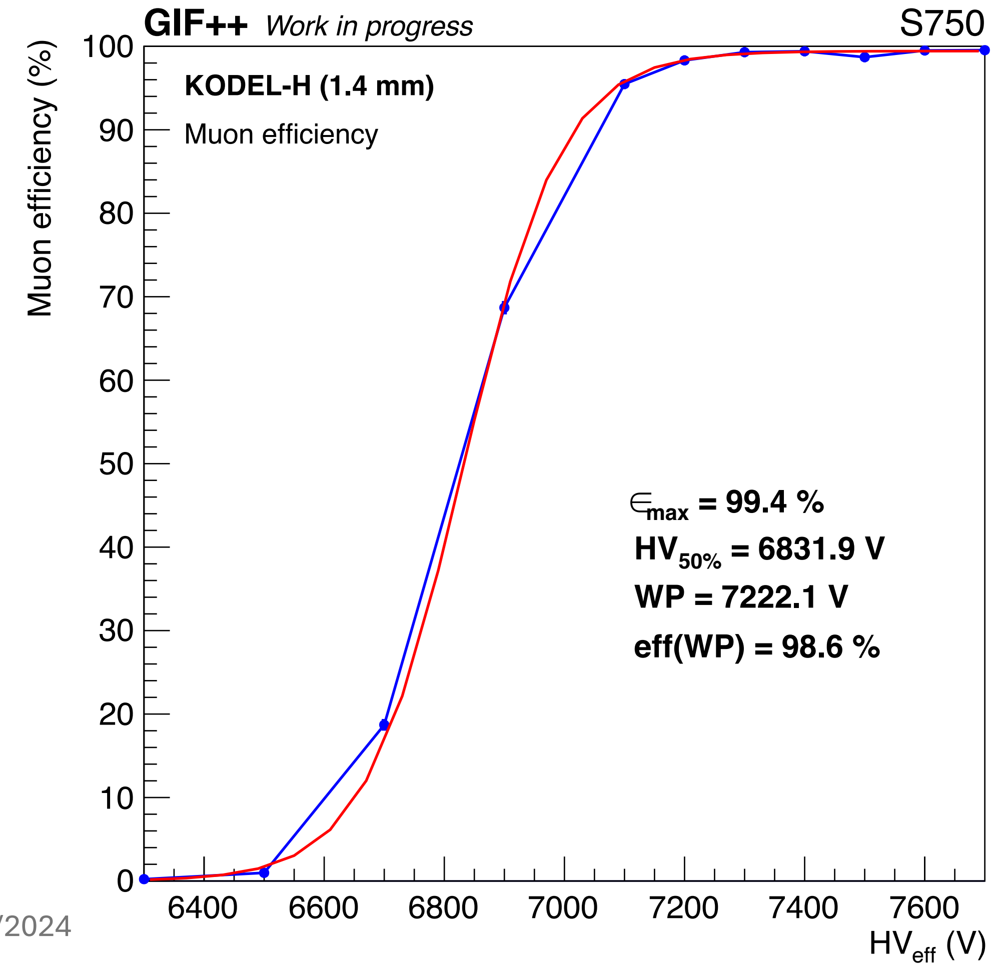




Performance verification

Some definitions

Example of high voltage scan with CMS_KODEL chamber in absence of gamma background



Logistic function for efficiency fit

$$\varepsilon(HV) = \frac{\varepsilon_{max}}{1 + e^{-\beta(HV - HV_{50})}}$$

Working point

$$\mathrm{WP} = \frac{\log 19}{\beta} + HV_{50} + 150\ \mathrm{V}$$

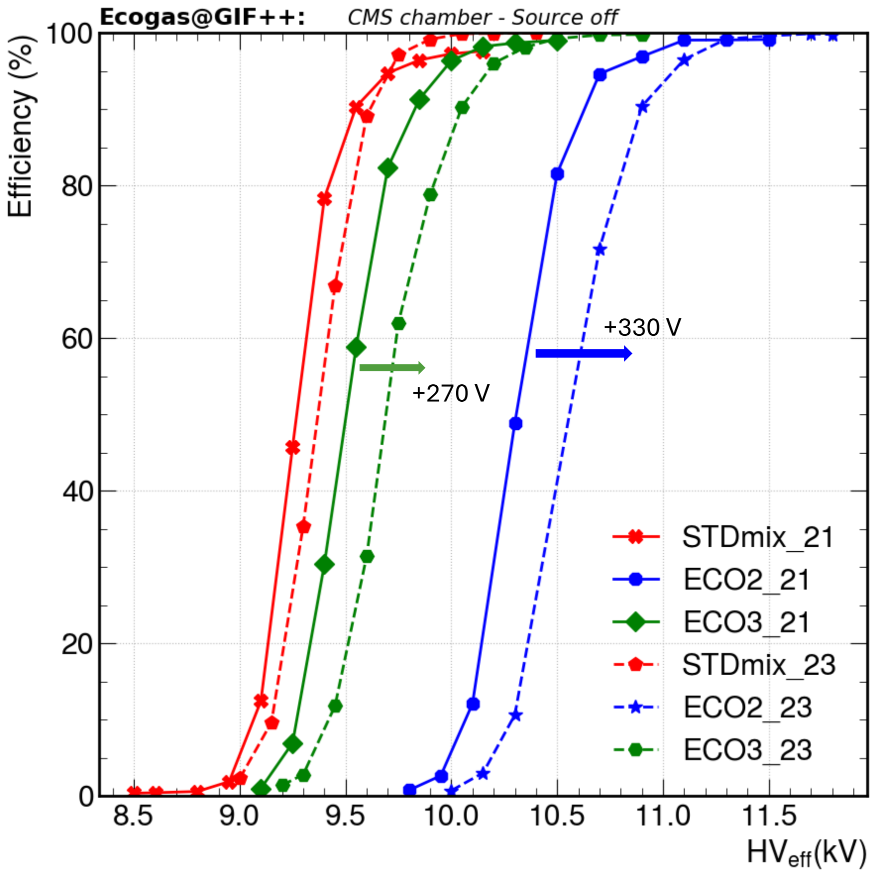
Effective high voltage corrected to be applied

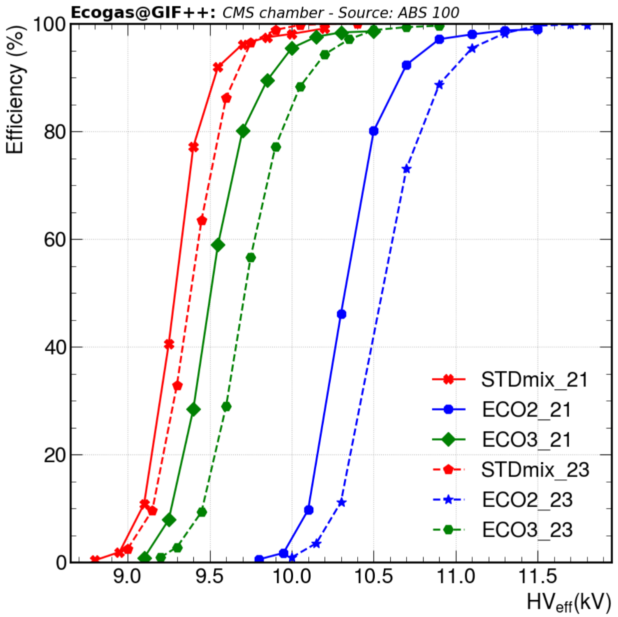
Environmental correction to the high voltage also applied during irradiation (see slide 12)

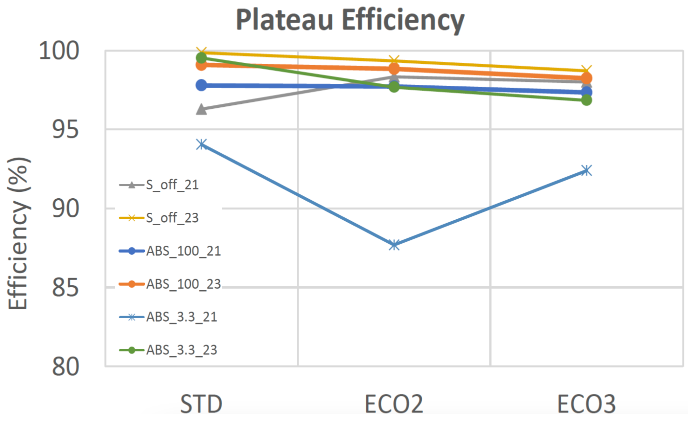
Performance verification (1)

2021 – 2023 CMS RPC

Efficiency





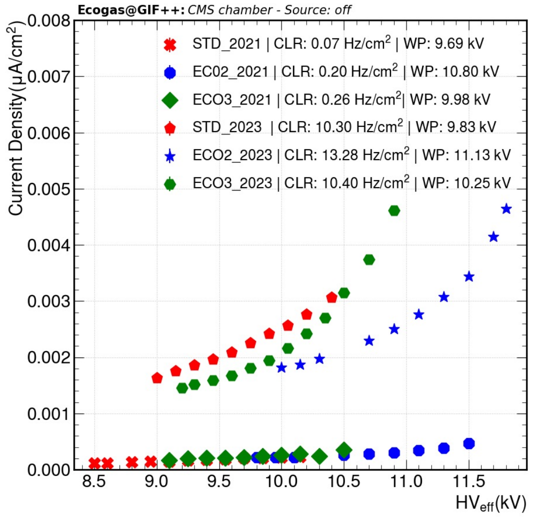


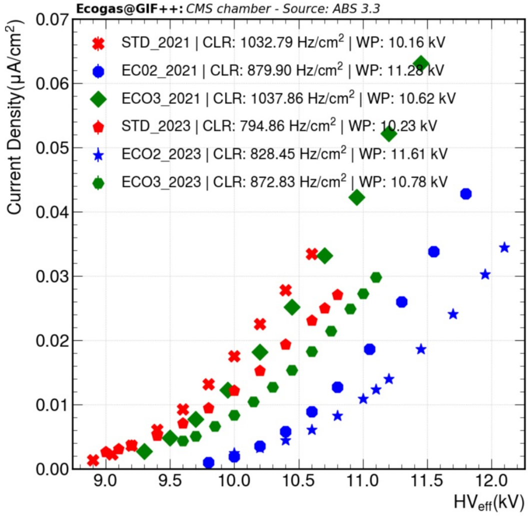
- It was **not observed a drop in the plateau efficiency** at source OFF and lower rates
- The **working point is increased** for all the mixture after irradiation
- ECO2 shows a higher increase in working point than ECO3
- Measurements at ABS 3.3 still to be analysed to understand efficiency drops

Performance verification (2)

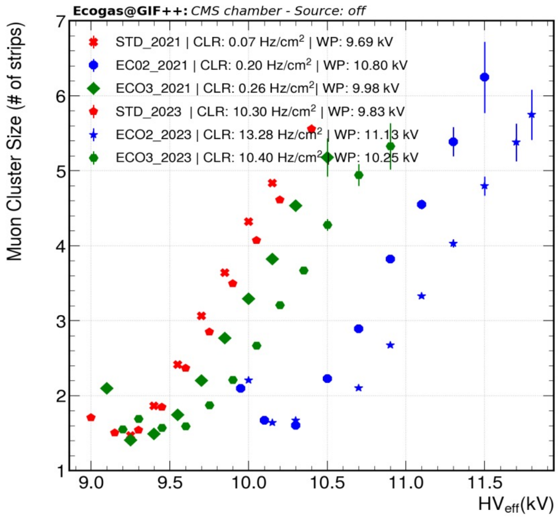
2021 – 2023 CMS RPC

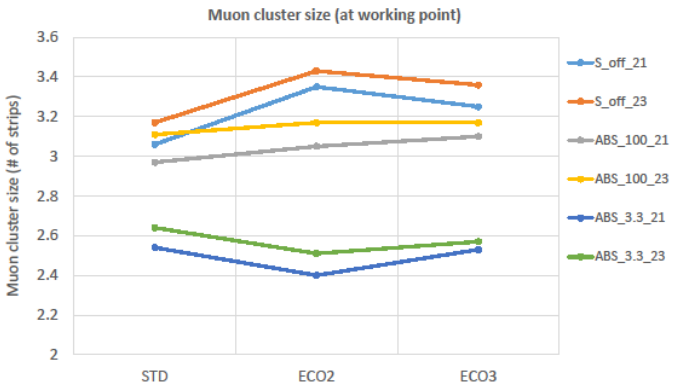
Current Density, gamma rates and muon cluster size





- The **current density rises** to 2 to 3 nA for all gas mixtures **at their working points, nearly 10 times** of the values before
- Increase values observed in agreement with increased irradiation as well as when employing ECO2 or ECO3 with respect to the STD gas mixture.



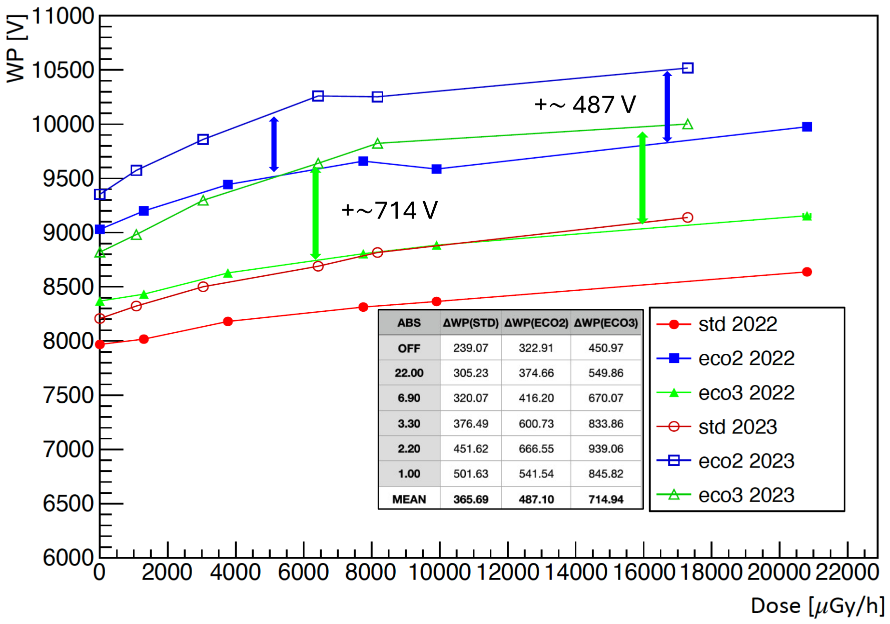


- The muon cluster size decreased as the irradiation cluster rate increased
- **Slightly increase rise in cluster size between the data from 2021 and 2023** at their working points for all gas mixtures.

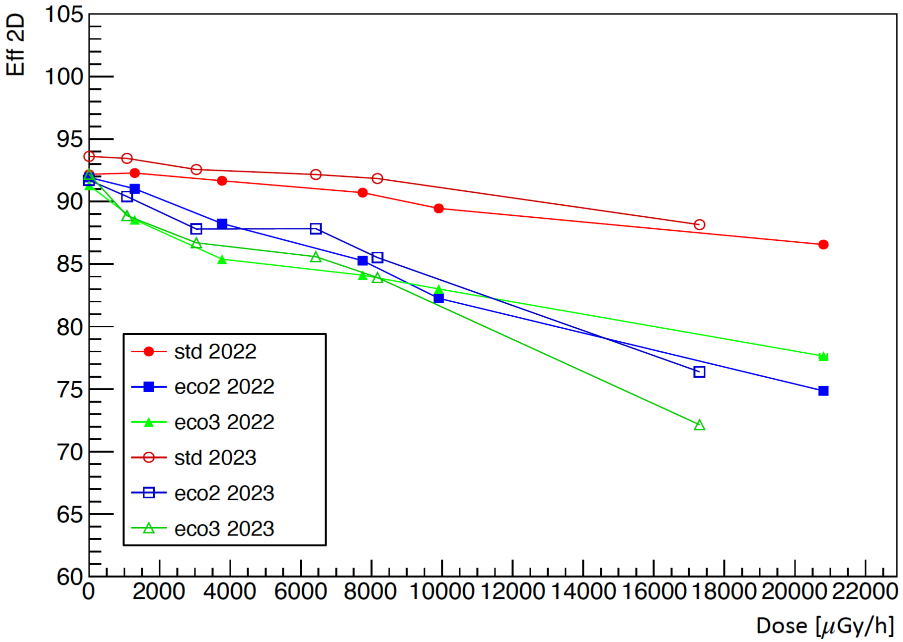
Performance verification (3)

2022 – 2023 LHCb/SHiP RPC

Efficiency and Working Point



ABS	ΔWP(STD)	ΔWP(ECO2)	ΔWP(ECO3)
OFF	239.07	322.91	450.97
22.00	305.23	374.66	549.86
6.90	320.07	416.20	670.07
3.30	376.49	600.73	833.86
2.20	451.62	666.55	939.06
1.00	501.63	541.54	845.82
MEAN	365.69	487.10	714.94

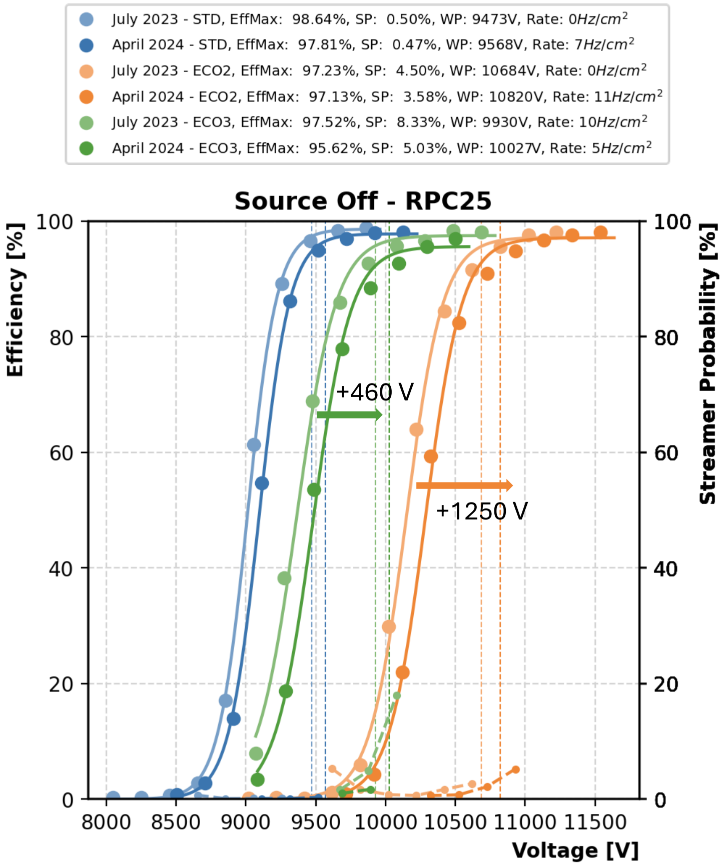


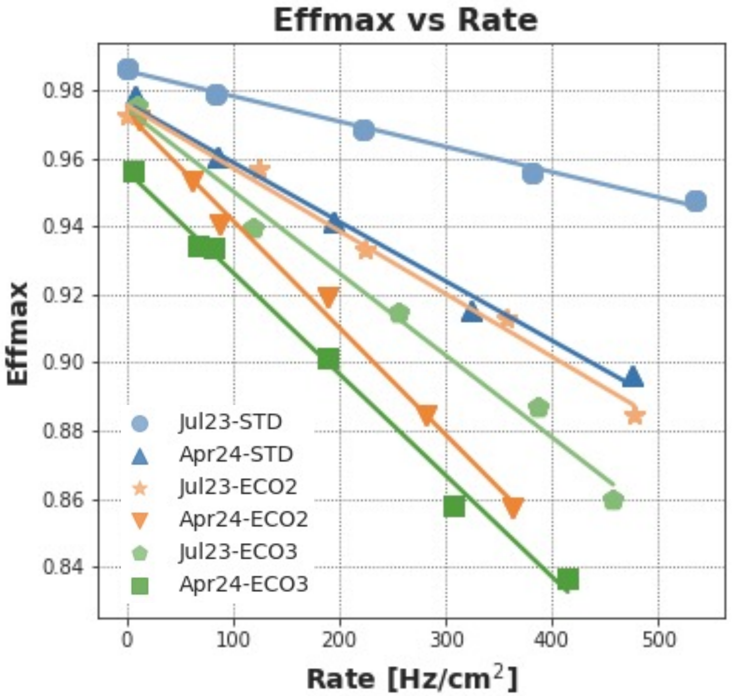
- **Increase of WP voltages** after 1 year of irradiation. In average higher increase when the operation was with ECO3, around 700 V, while with ECO2 around 500 V
- The **2D efficiency** shows similar trend for the ecological candidates and **not significant drop** is observed

Performance verification (4)

2023 – 2024 EP-DT RPC

Efficiency and Streamer Probability



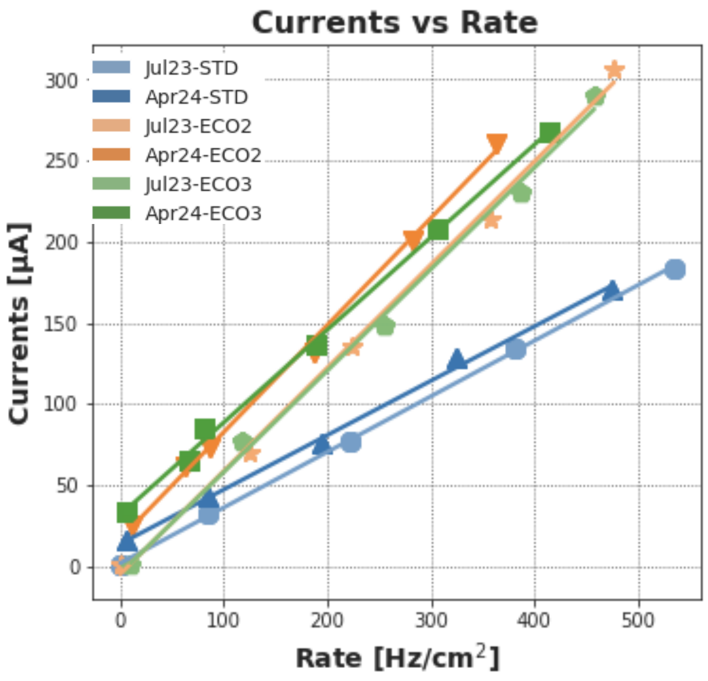


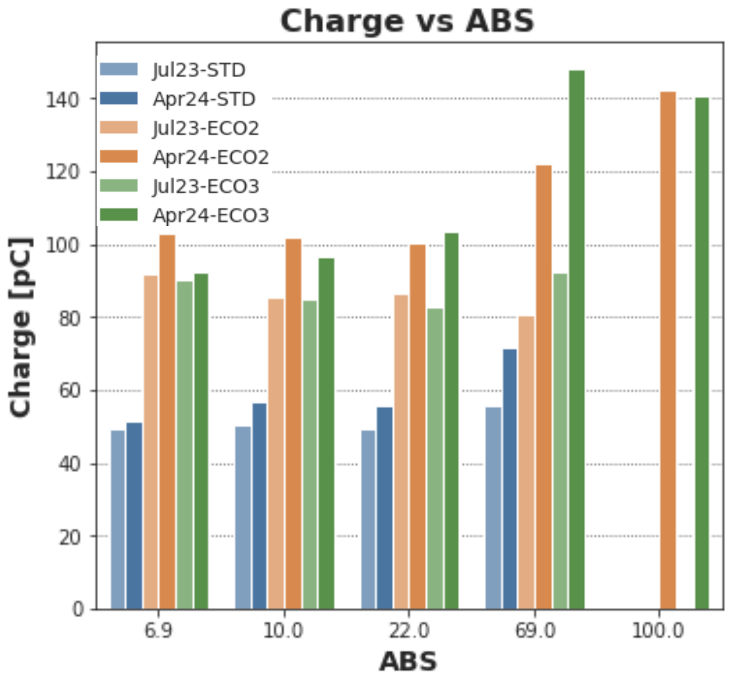
- Between the three mixtures, the efficiency drops at maximum ~2% (depending on the mixture and ABS filter) - which could result from the alignment
- The **streamer probability is reduced** for all runs for all the mixtures taken; the ECO3 shows more streamers than ECO2
- The **working point is increased**, yet the rate for all runs is consistently lower
- **ECO2 shows a higher increase** in working point than ECO3
- The **maximum efficiency has dropped** compared to the last test beam for all mixtures

Performance verification (5)

2023 – 2024 EP-DT RPC

Currents and total charge





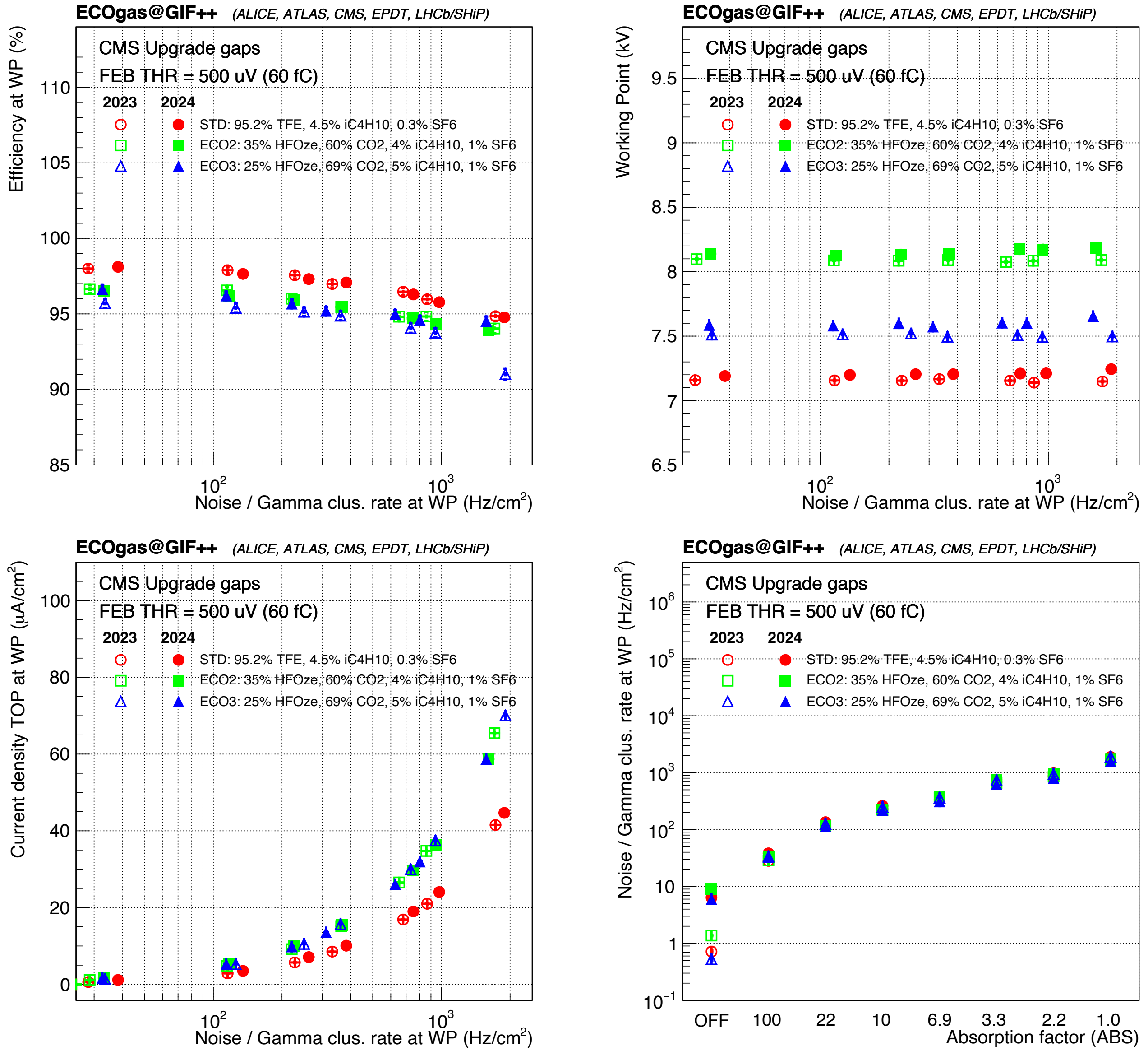
- The **currents** with respect to the rate are a **little higher than in July 2023**, ranging between ~10-25 µA for the fixed rate of 300Hz/cm2 → meaning a **10% increase irrespective of the gas mixture**
- The slopes for the STD and ECO2 are similar to the last year, only for the ECO3 mixture, the currents are slightly decreasing at higher rates.
- In terms of charge per ABS filter, it seems higher than in 2023, consistent with the higher currents and lower rate observed.
- Between the mixtures, for the STD, the charge is lower, but for ECO2 and ECO3 they are similar except for ABS 69.

Performance verification (6)

2023 – 2024 CMS_KODEL RPC

Efficiency, Working Point, Current densities and rates

- The **efficiency do not suffer drop** after 1 year of irradiation
- Slightly increase of the working point – still to control resistivity. Increase more pronounce at higher gamma rates and when the RPC is operated with ECO2
- **Not major variations on the current densities** at WP values with respect to gamma rates
- Gamma rates consistent while small increase of noise was observed (under investigation)



Summary

- Involved in the CERN phase-down of fluorinated GHG emissions, the RPC **EcoGas@GIF++ collaboration** has joined efforts to find a solution for the **environmentally friendly operation of RPCs**
- In August 2022, a systematic **irradiation campaign** started, and the performance of the detectors is annually verified during **beam tests**
- From aging studies, a **smooth increase trend of the total dark current** has been observed (also increases in ohmic contribution) → further discussion needed
- **No major degradation of the detector performance** has been verified from the beam test campaign at GIF++. **Increases in Working Point** values were observed in all RPCs after irradiation.

THANKS!

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Backup slides

Resistivity monitoring by Ar scan

Procedure

1. Linear fit to the ohmic part of the I(V) curve
2. Starting point of the fit is decided by the fit with the minimum chi square adding one point at a time
3. Function used y = a + bx, b = 1/R (R = resistance of the electrodes)

ρ(resistivity) = R*S(surface)/2d(electrode thickness) = 1/b*S/2d

Resistivity values shown in the following are normalized to T_0 = 20°C using the following formula:

$$\rho(T)=\rho(T_0)*4.4^{\frac{T_0-T}{12°C}}$$

https://doi.org/10.1016/S0168-9002(00)00979-7