RPC 2026
RIO DE JANEIRO

Towards SF_6-free RPC operation: first results from the RPC ECOGas@GIF++ Collaboration

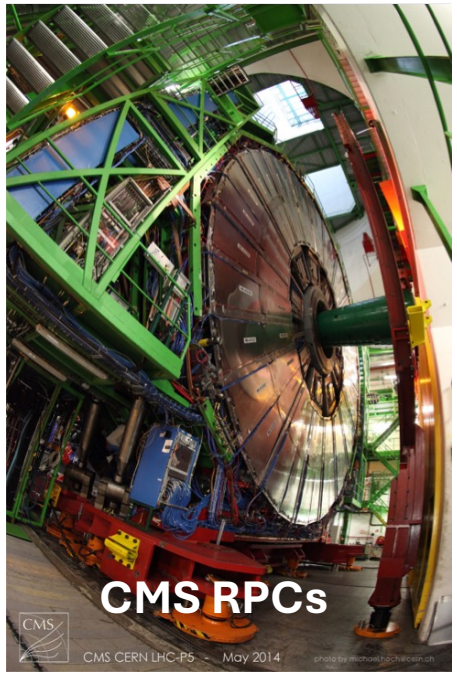
Luca Quaglia[1], on behalf of the RPC ECOGas@GIF++ collaboration

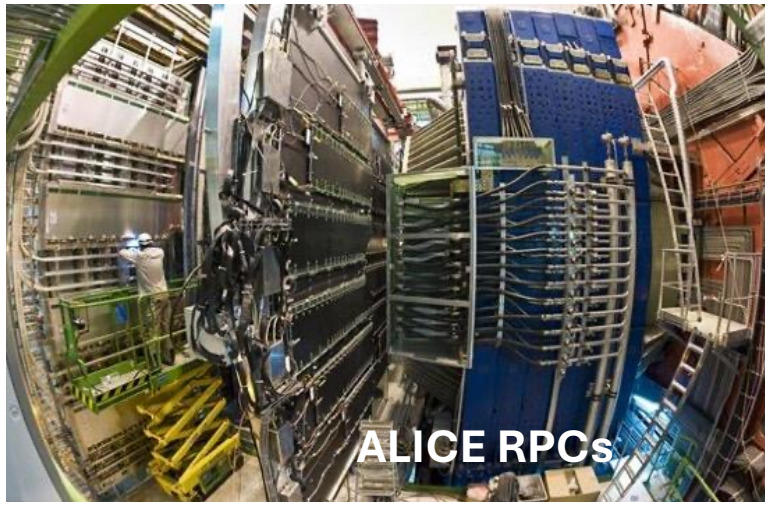
[1]Università degli Studi di Torino, INFN Sezione di Torino, ETH Zurich

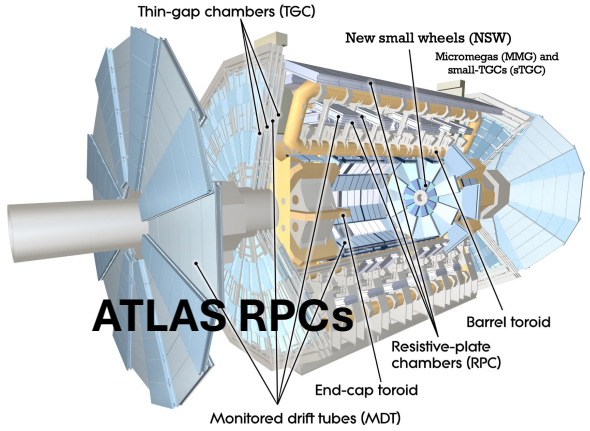
Overview

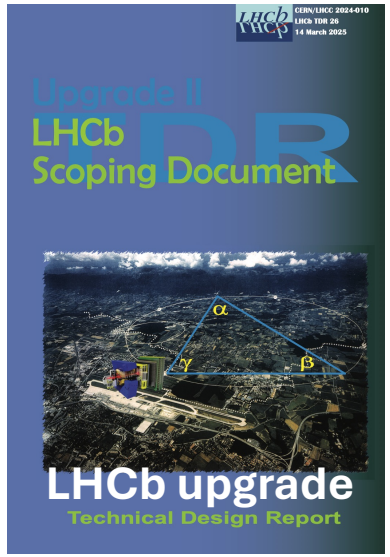
- RPC detectors at CERN
  - ➢Issues with the RPC gas mixture
- The RPC ECOGas@GIF++ history
  - ➢HFO-1234ze as an R134a alternative
- HFO-1233zd as SF6 substitute
- What if we go flammable?
- Conclusions and outlook

Resistive Plate Chambers at CERN









- Resistive Plate Chambers (RPCs)
  - ➢ Widely employed in High Energy Physics experiments at CERN
- For muon detection
- Relatively cheap
  - ➢ Large area coverage
- Fast response
  - ➢ Used for muon triggering and identification

Issues with the currently employed gas mixture

Standard (STD) gas mixture

GWP ~ 1400

$C_2H_2F_4$ (freon, R134a) ≥ 90%
- Provides primary ionization
- **GWP ~ 1400**

i-C_4H_{10} (isobutane) 5÷10%
- Photon quencher
- GWP ~ 3

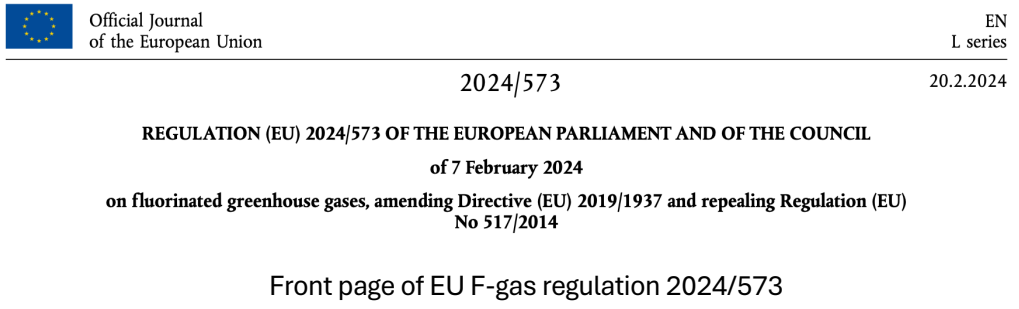
SF_6 (sulphur hexafluoride) 0.3%
- Limits avalanche size
- **GWP ~ 23000**

GWP = global warming potential = measure of GHG effect on atmosphere
- Relative to CO2 -> CO2: GWP = 1
- CERN: Aim to limit GHG emission

➢ Most emission comes from particle detectors and cooling systems

- EU: increasing regulations

➢ **Need for alternative gases**



Official Journal of the European Union — EN L series

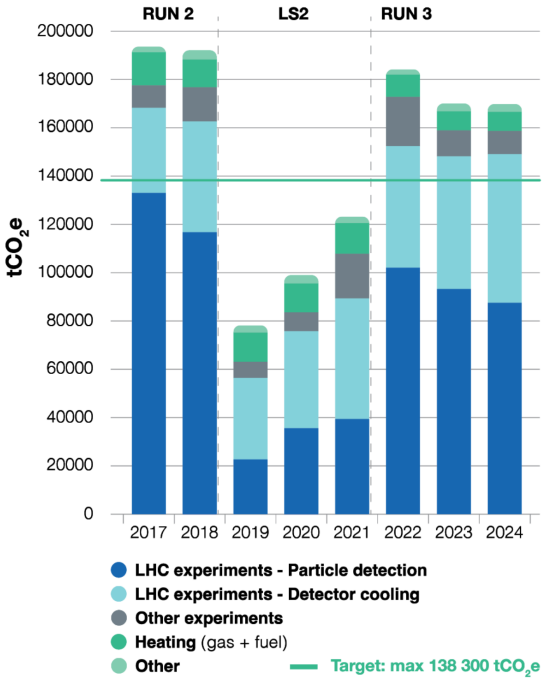
2024/573 — 20.2.2024

REGULATION (EU) 2024/573 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 7 February 2024

on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014

Front page of EU F-gas regulation 2024/573



F-gases emissions at CERN in LHC Run 3

RPC ECOGas@GIF++ collaboration

- First efforts undertaken by RPC ECOGas@GIF++ collaboration
  - ➢ Cross-experiment collaboration between ALICE, ATLAS, CMS, LHCb/SHiP and CERN EP-DT group

*All results in Marcello's talk

RPC ECOGas@GIF++ collaboration created — 2018
HFO-1234ze identified as promising R134a alternative

AIDA Innova project start — 2021
First measurements under irradiation at GIF++

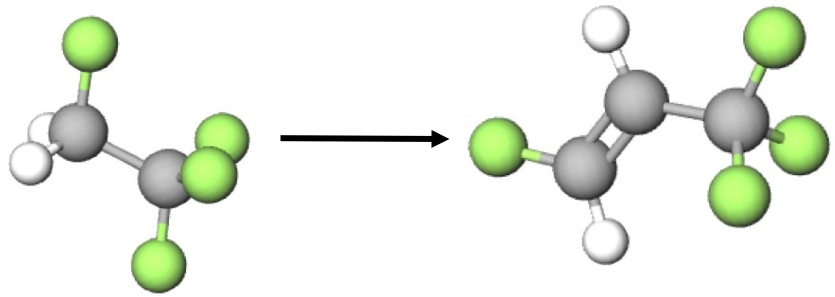
AIDA Innova final report — 2024
Long term aging test with HFO-1234ze based mixture

HFO-1234ze validation* — 2025

Studying SF_6 alternatives — 2026
Measurements under irradiation at GIF++

Main goal: find eco-friendly gas alternatives for RPC operation
- HFO-1234ze ($C_3H_2F_4$) (+ CO_2) as R134a alternative
- Short- and long-term tests
- Now: Continue tests, but with SF6 alternative

Most promising HFO-1234ze based gas mixture: ECO2
60% CO_2, 30% HFO-1234ze, 4% i-C_4H_{10}, 1% SF_6



R134a
GWP ~ 1400

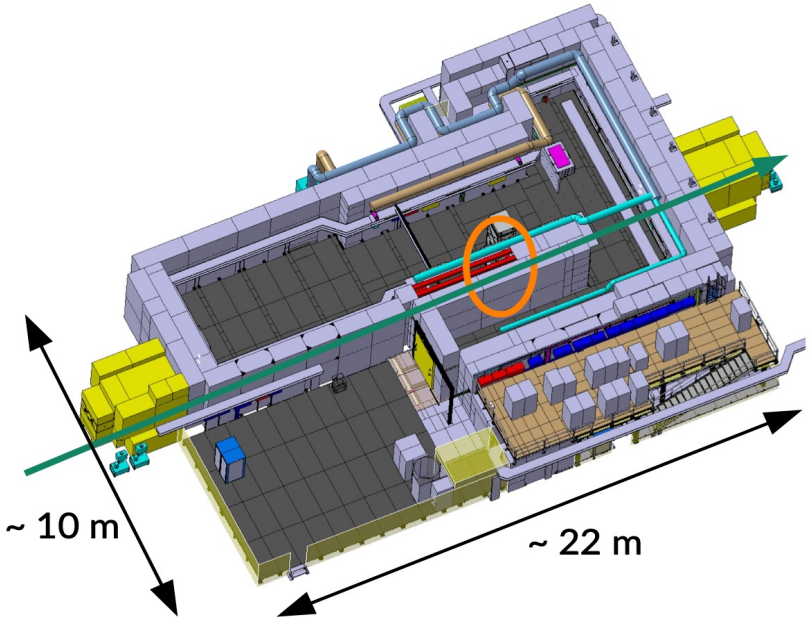
HFO-1234ze
GWP ~ 6

The GIF++ @ CERN

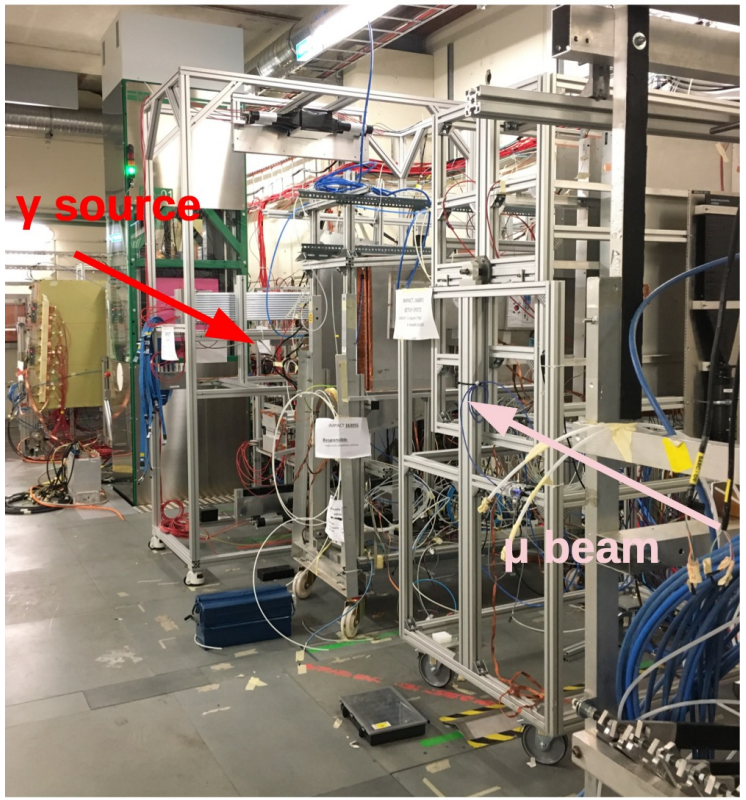
- **Gamma Irradiation Facility (GIF++):** experimental facility located on the H4 SPS beam line @ CERN

- **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



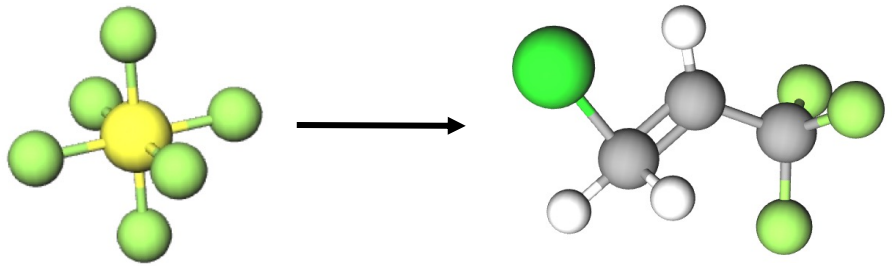
GIF++ facility layout



RPC ECOGasGIF++ detectors in the GIF++ bunker

Studies on SF6 alternatives

- Following HFO-1234ze validation as R134a substitute
  - Study of **SF_6** replacement
  - Candidate studied: **HFO-1233zd** ($C_3H_2ClF_3$), in combination with **HFO-1234ze**



SF6

GWP ~ 23000

HFO-1233zd

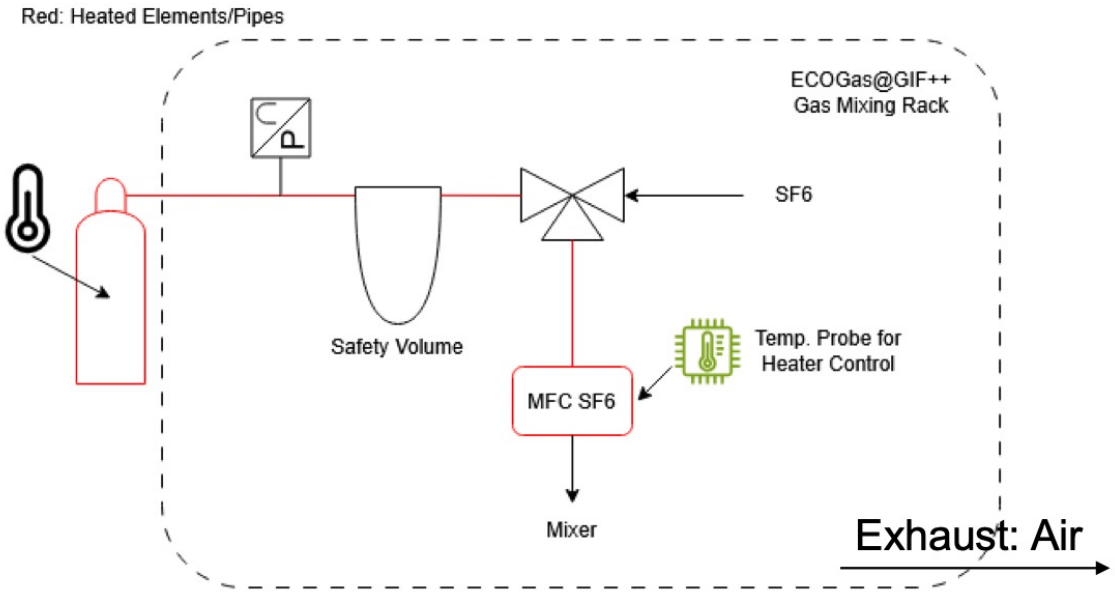
GWP ~ 4

- **HFO-1233zd is liquid at room temperature**
  - Major modifications to the gas system to include heating and pressure control on the zd line
  - Presence of Cl requires careful studies of long-term stability

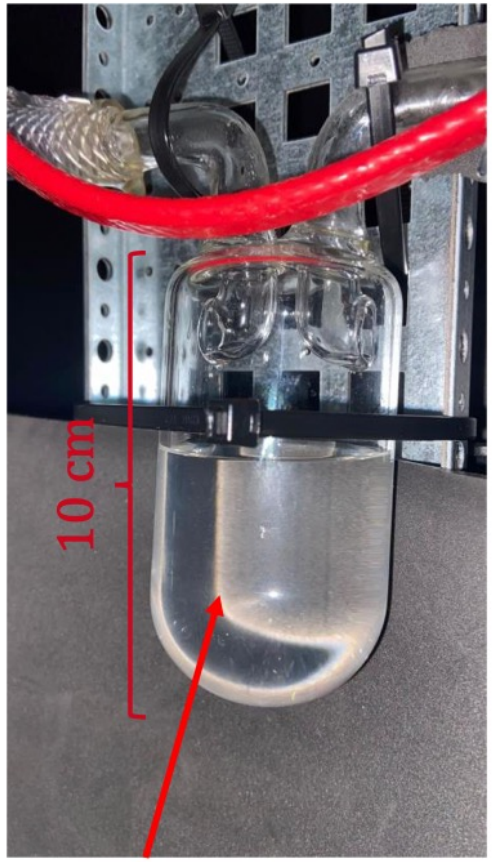
Gas system upgrades

- SF6 mass flow controller used to flush the zd
  - ➢ Calibration with *drycal* provided by EP-DT-GD

- Safety volume installed upstream of the mass flow controller to trap any liquid zd



Simplified scheme of heated pipes and pressure monitoring



Liquid R1233zd
In safety volume



Safety volume and heated piper for HFO-1233zd

May 2026 test beam

- First studies carried out in May 2026 with several RPCs and different mixtures tested

Chamber	Area (cm^2)	Gaps (mm)	Number of strips	Strip pitch (mm)	Readout
ALICE	50x50	1 x 2	24+24 (2D readout)	21	FEE + TDC
CMS iRPC*	70x100	2 x 1.4	16	50	FEE + TDC
EP-DT-GD	70x100	1 x 2	7	21	Digitizer
LHCb/SHiP	70x100	1 x 1.6	32+32 (2D readout)	10	FEE + TDC

*awaiting CMS approval

Mixture	R134a	HFO-1234ze	HFO-1233zd	$i\text{-}C_4H_{10}$	CO_2	SF_6	GWP
STD	95.2	-	-	4.5	-	0.3	1488
ECO2	-	35	-	4	60	1	482
ECO2 1% zd*	-	35	1	4	60	0	~4
ECO2 0.5% zd*	-	35	0.5	5	59.5	0	~3.9
ECO2 2% zd*	-	20	2	5	73	0	~3

Reference mixtures

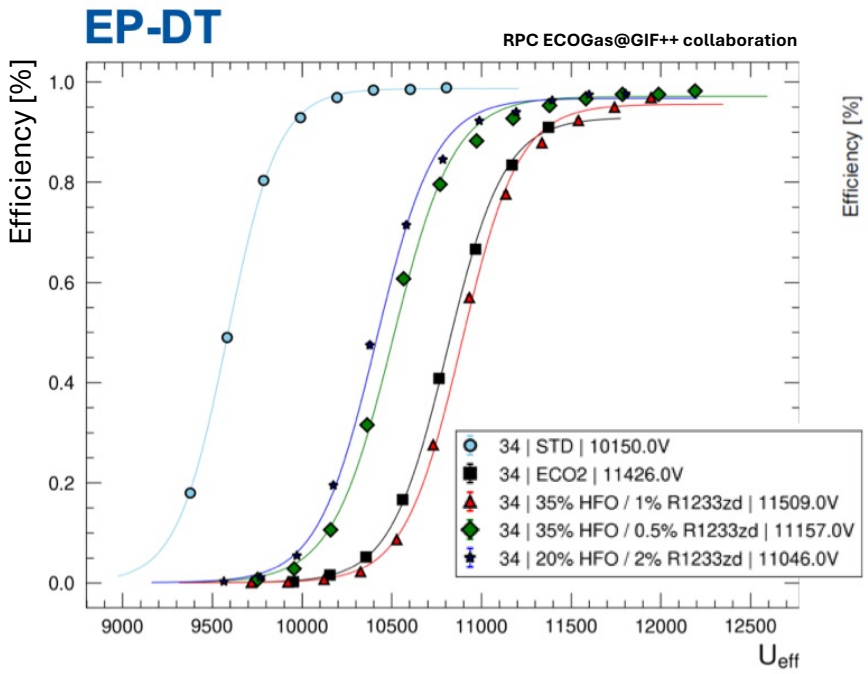
*Never tested before

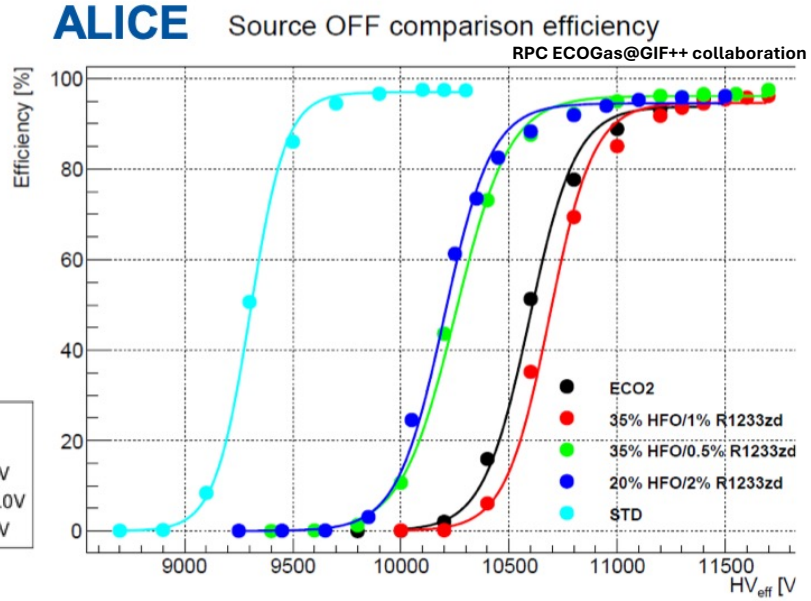
Baseline performance (May 2026)

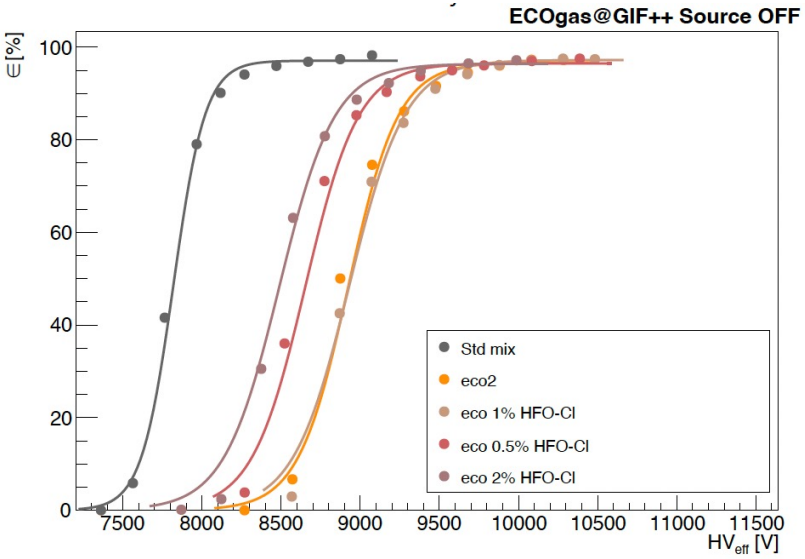
- No background efficiency vs HV_{eff} (source OFF) similar for all RPCs:
  - 1:1 replacement of SF6 with **HFO-zd** = no increase in WP
  - **HFO-zd** ↓ = WP reduction + slight beam-induced current increase
  - **HFO-ze** ↓ and **HFO-zd** ↑= no WP shift + slight beam-induced current decrease

$$\varepsilon(HV_{eff}) = \frac{\varepsilon_{Max}}{1 + e^{-\lambda(HV_{eff} - HV_{50})}}$$

$$\mathrm{WP} = \mathrm{HV}(\varepsilon = 0.95\varepsilon_{\mathrm{Max}}) + 150\ \mathrm{V}$$

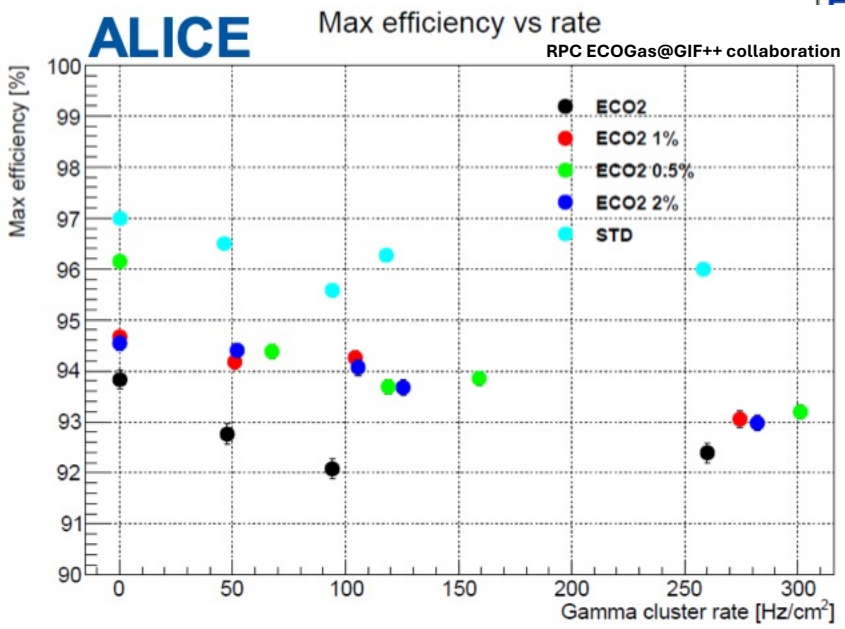


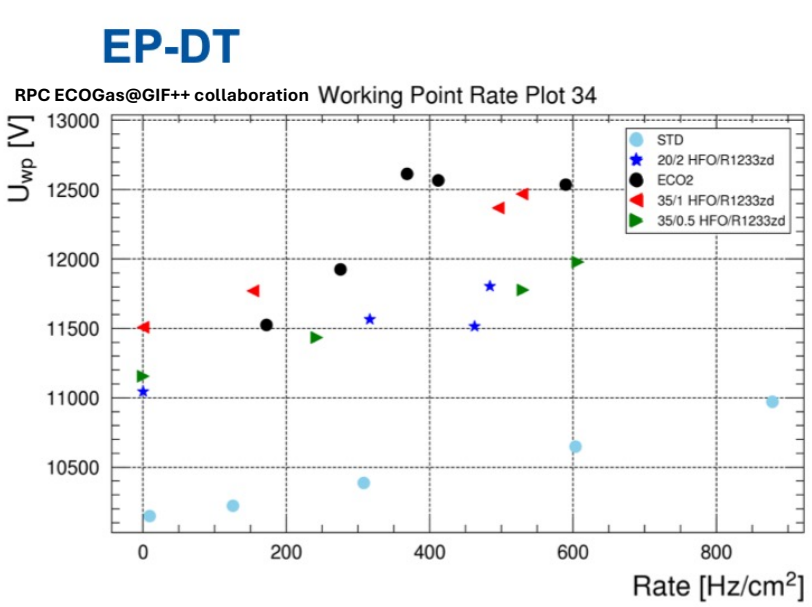


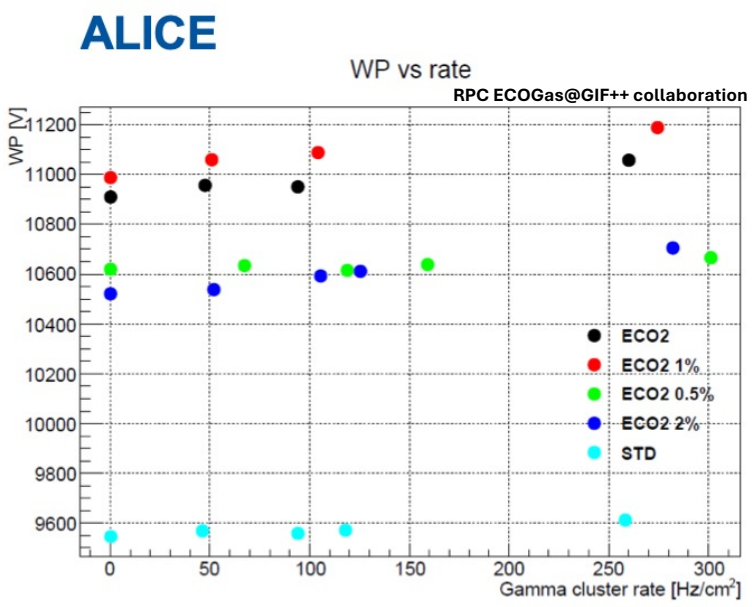


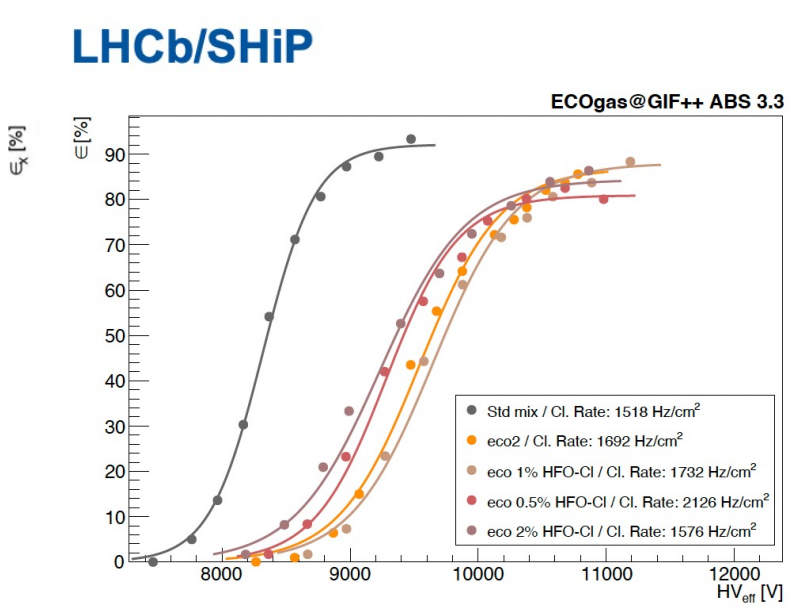
Results under irradiation

- Increase WP under increasing background rate
  - ➢ Depends stronger on **HFO-ze** than **HFO-zd** content
- Maximum efficiency decrease
  - ➢ Higher for HFO-based mixture compared to STD
- At 300 Hz/cm^2 γ background rate: all new mixtures 89% – 94%







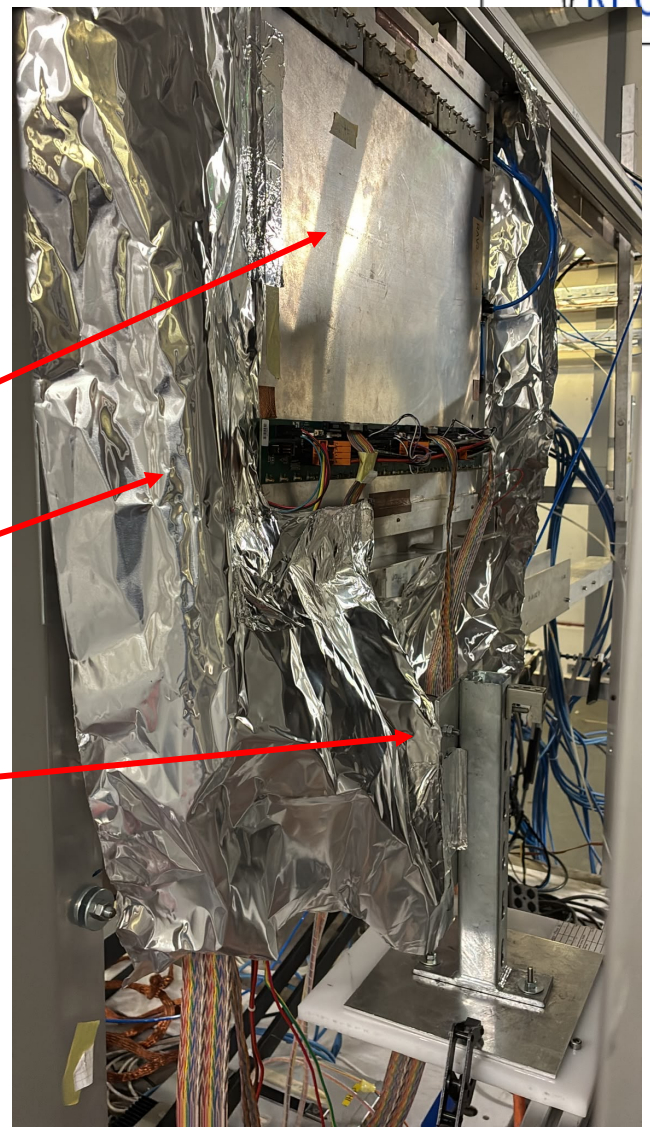


What if we go flammable?



Setup modifications

- Increasing i-C_4H_{10} in the mixture could mitigate the absorbed current
  - ➢ 5% is the flammability limit at CERN
- Setup modifications to go flammable:
  - ➢ Leak test + detection head and envelope installation
- **Only ALICE detector** was used for the studies with flammable gas mixtures in July 2026
  - ➢ Front-end electronics (190 fC threshold) + TDCs
- Installation of new copper pipes from the mixer all the way to the detector
  - ➢ Humidifer and rotameters **not** ATEX-rated
  - ➢ Humidifier bypassed and gas flow directly controlled at mixer level

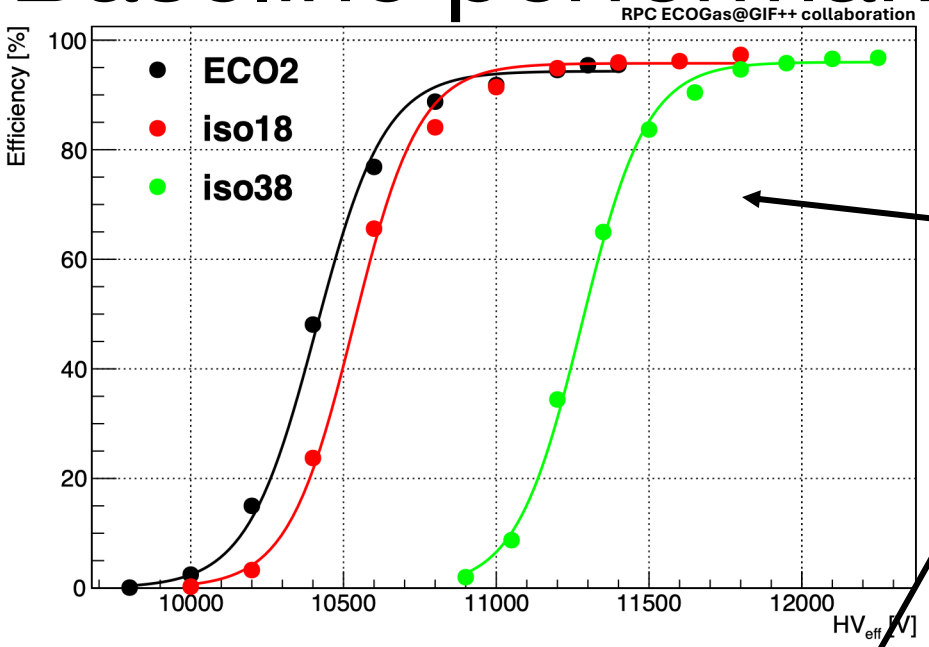


Gas mixtures tested

Mixture	R134a	HFO-1234ze	HFO-1233zd	i-C_4H_{10}	CO_2	SF_6	GWP
ECO2	-	35	-	4	60	1	482
iso18	-	20	2	18	60	0	~3.3
iso38	-	20	2	38	40	0	~3.55
iso28	-	10	2	28	60	0	~2.72
iso38_co2_50	-	10	2	38	50	0	~2.88
iso48_co2_50	-	0	2	48	50	0	~2.22
iso58_co2_40	-	0	2	58	40	0	~2.40
iso48_co2_49	-	0	3	48	49	0	~2.28

- All mixtures (**but ECO2**) are flammable
- Systematic scan of **HFO-ze** content and isobutane with **HFO-zd** fixed to 2% (best compromise from previous data)

Baseline performance (20% HFO-1234ze)



- **ECO2**, **60/18/2**, **40/38/2** CO_2/i-C_4H_{10}/HFO-1233zd

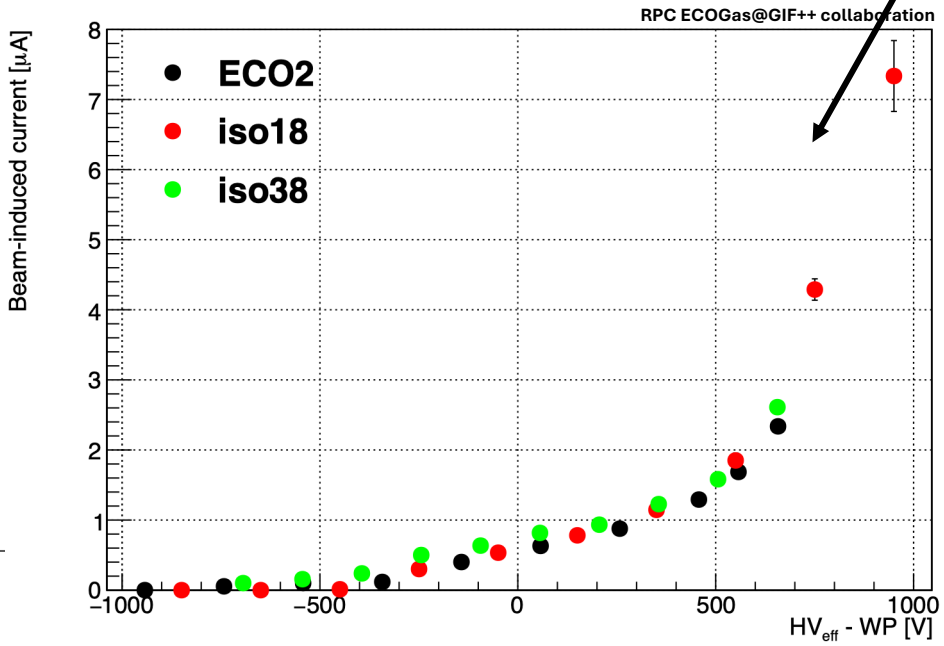
Higher WP wrt ECO2

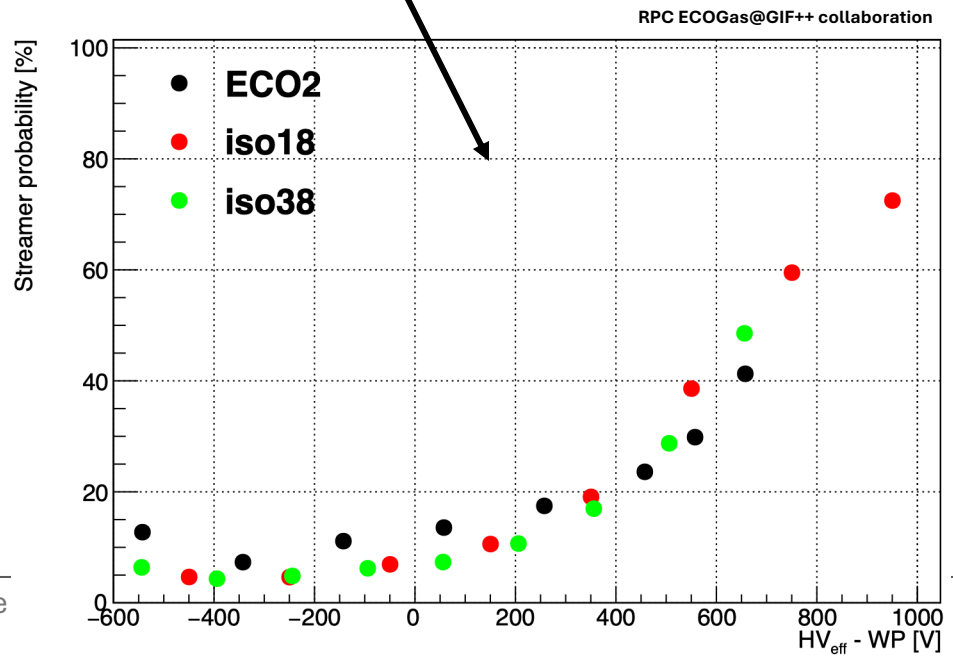
Similar beam-induced current @ source OFF

Events tagged as “streamers” if cluster size > 2.5 strips

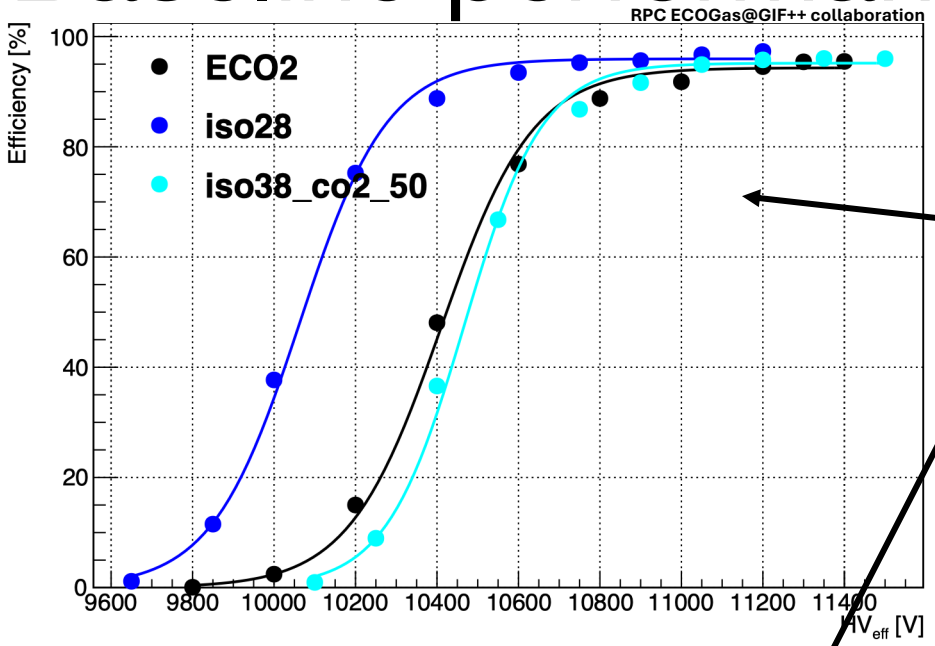
- Slight reduction of streamers if i-C_4H_{10} content is increased

$$S.P. = \frac{\#\text{ of events with CS} > 2.5}{\#\text{ of detected muons}}$$





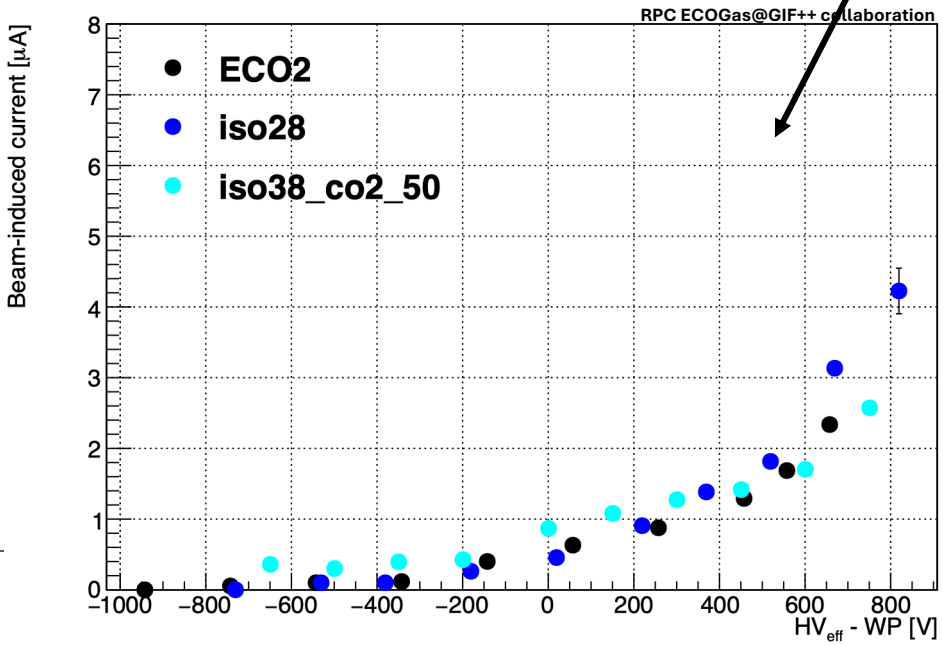
Baseline performance (10% HFO-1234ze)



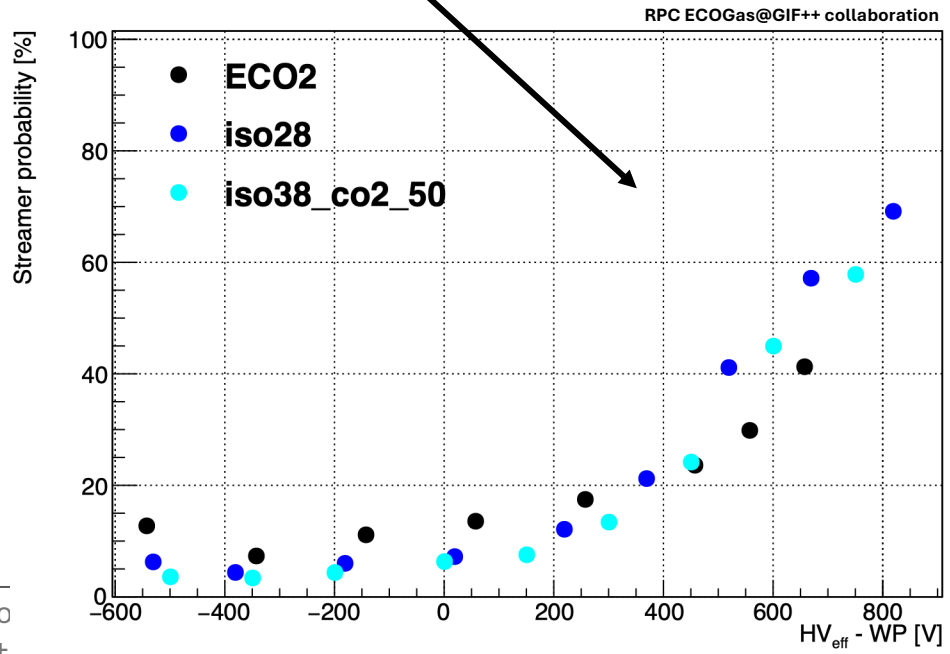
- **ECO2**, **60/28/2**, **50/38/2** CO_2/i-C_4H_{10}/HFO-1233zd

Lower and similar WP wrt ECO2

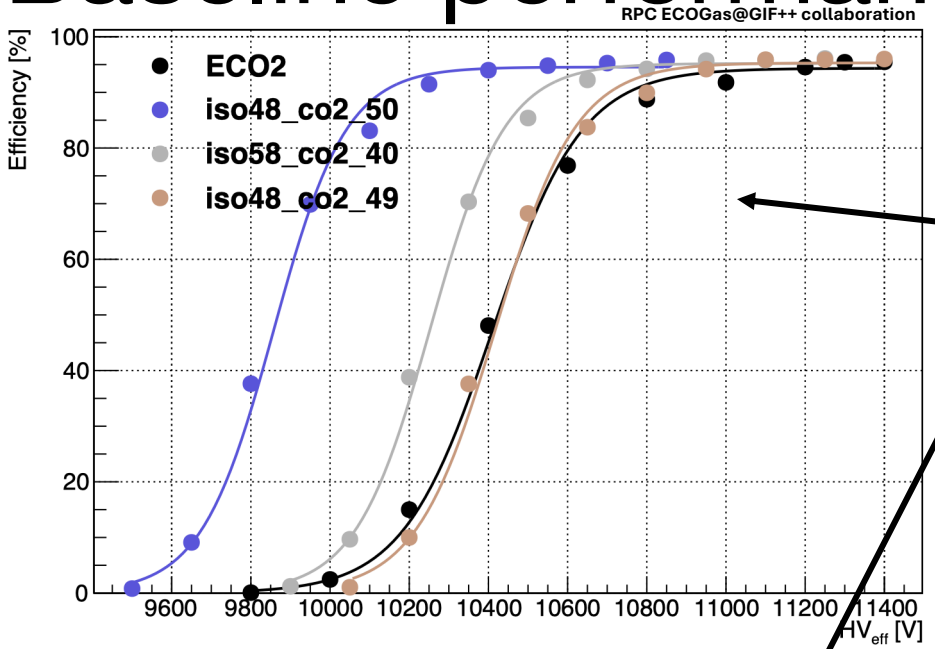
Beam-induced current is lower wrt 20% HFO-1234ze mixtures and more similar to ECO2



Same results for streamer probability



Baseline performance (0% HFO-1234ze)

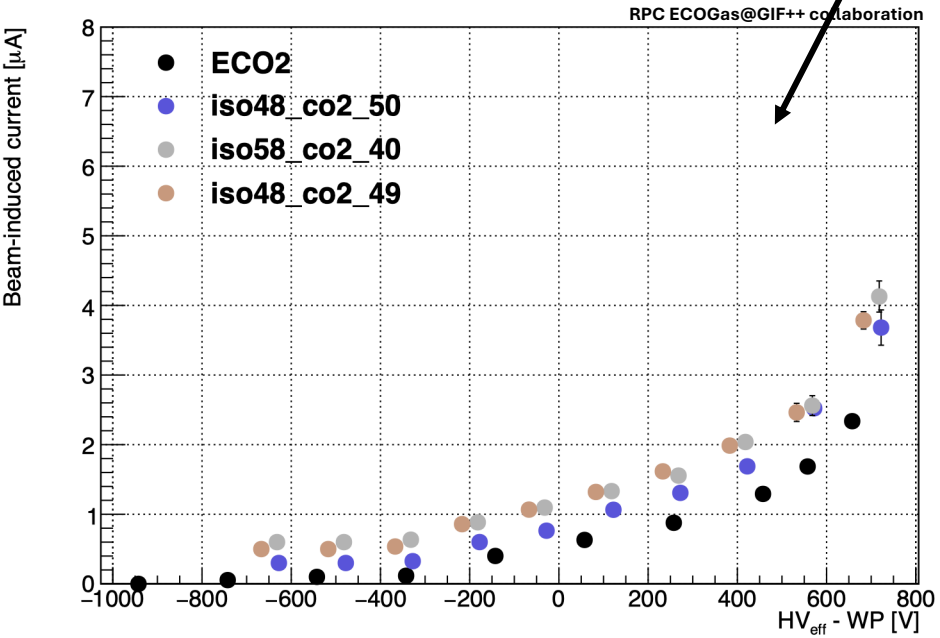


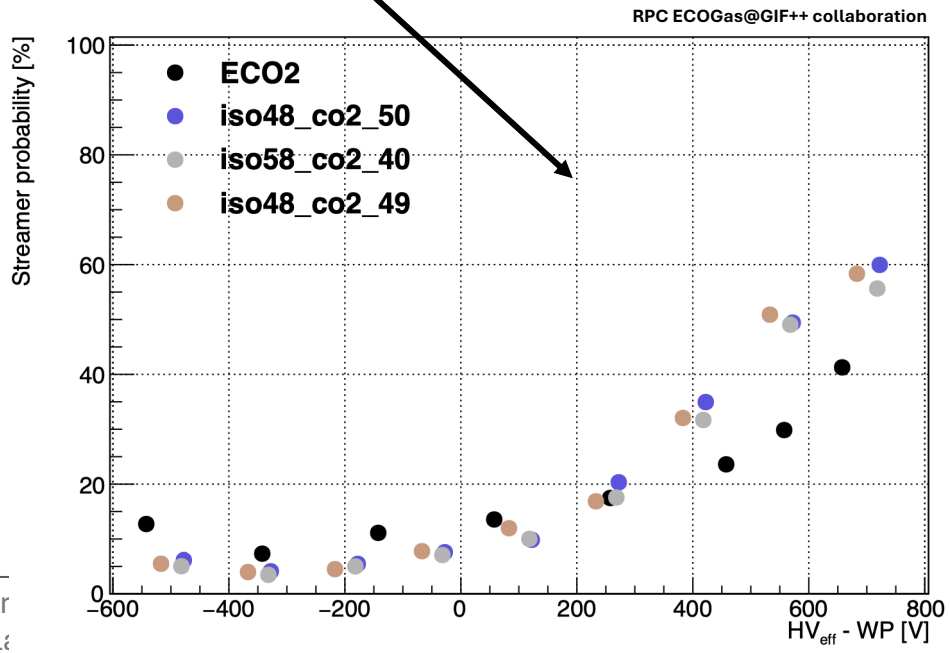
- **ECO2**, **50/48/2**, **40/58/2**, **49/48/3** CO_2/i-C4H10/HFO-1233zd

Lower and similar WP wrt ECO2

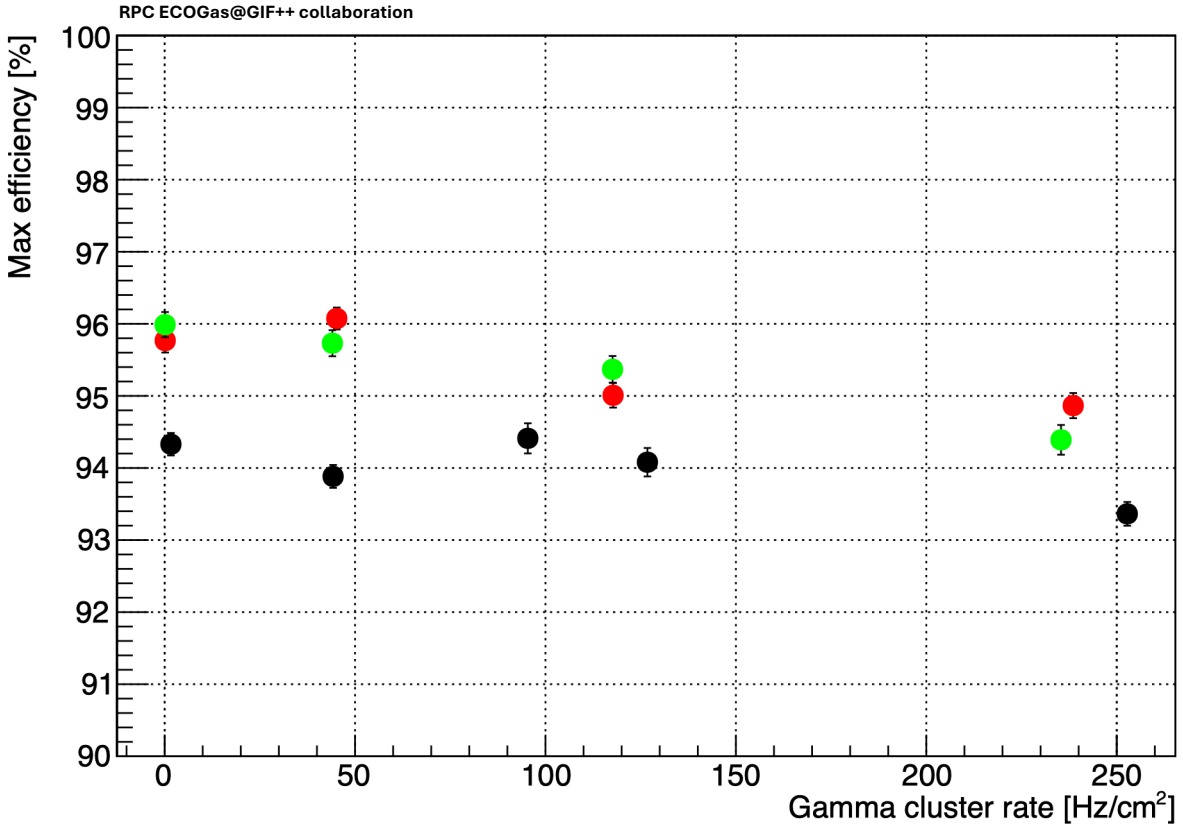
Slightly higher beam-induced wrt ECO2

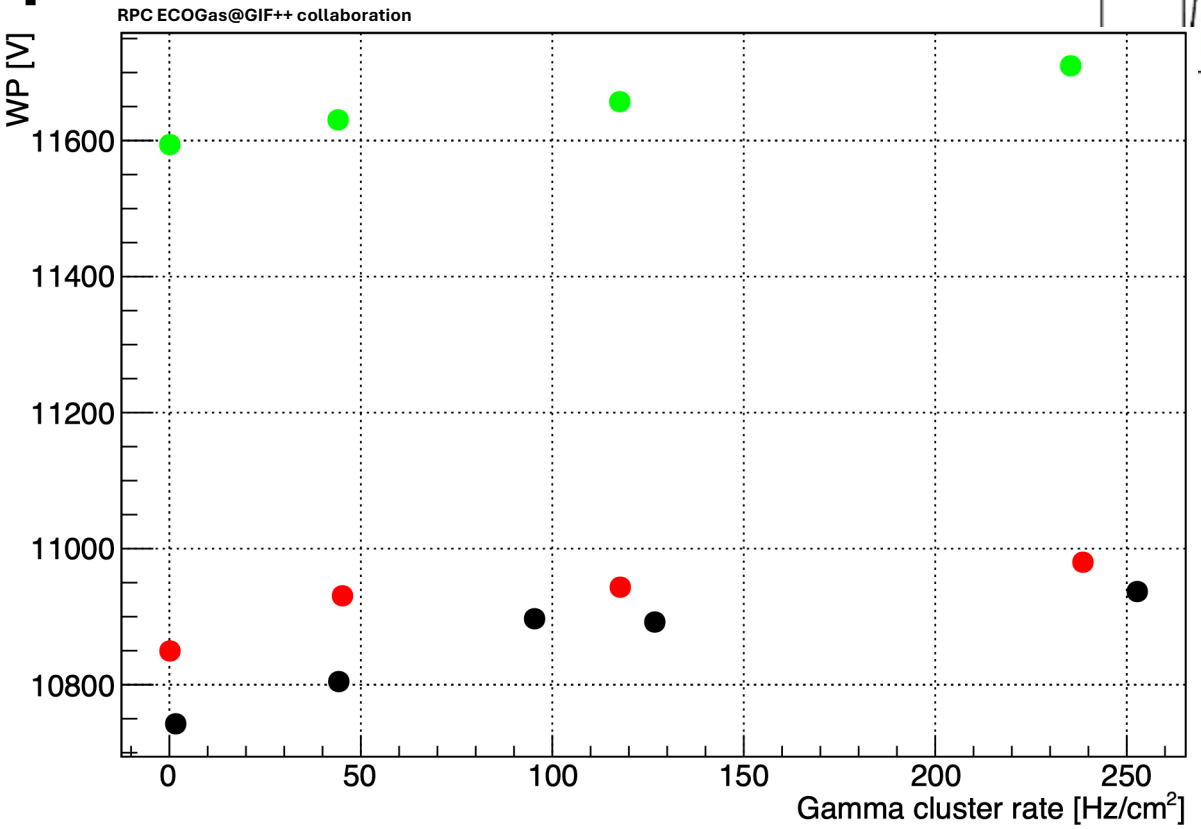
Same for streamer probability





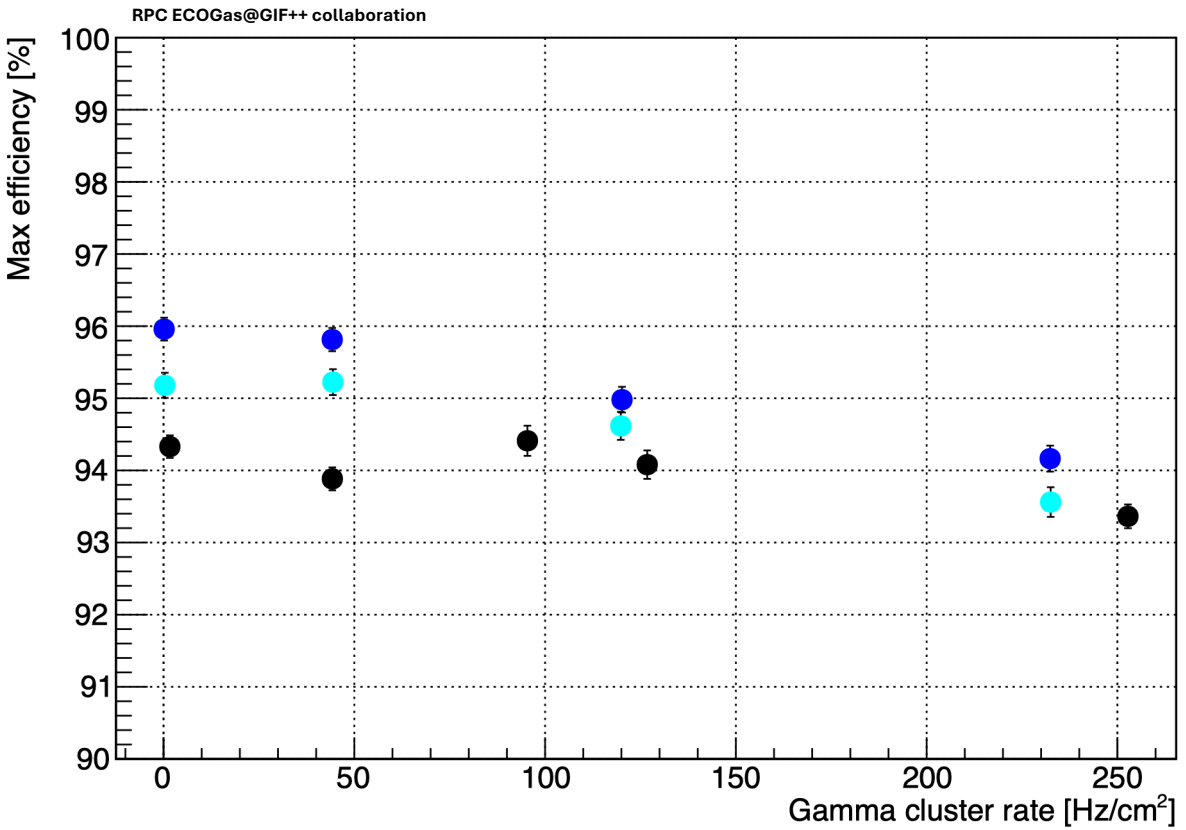
Results under irradiation

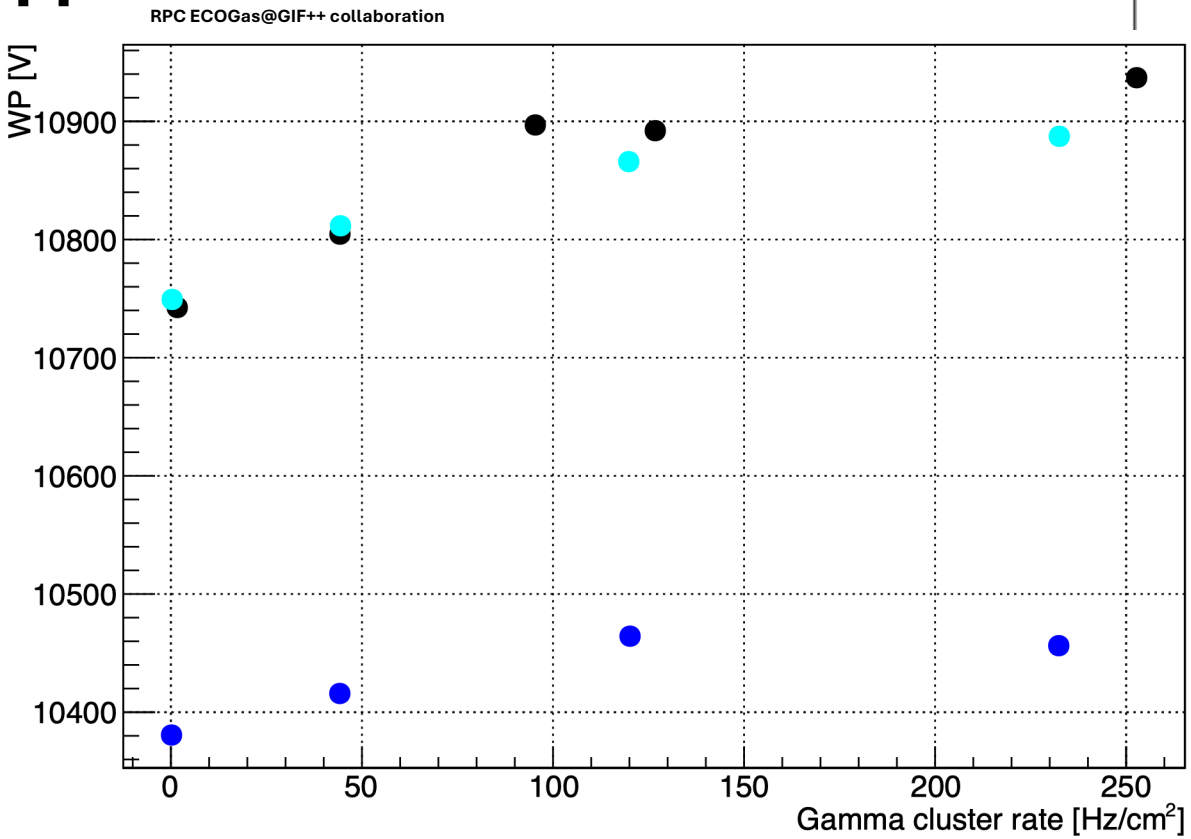




- WP and maximum efficiency (from fit) under increasing background radiation
  - **ECO2**
  - **60/18/2**, **40/38/2** CO_2/i-C_4H_{10}/HFO-1233zd (20% HFO-1234ze)

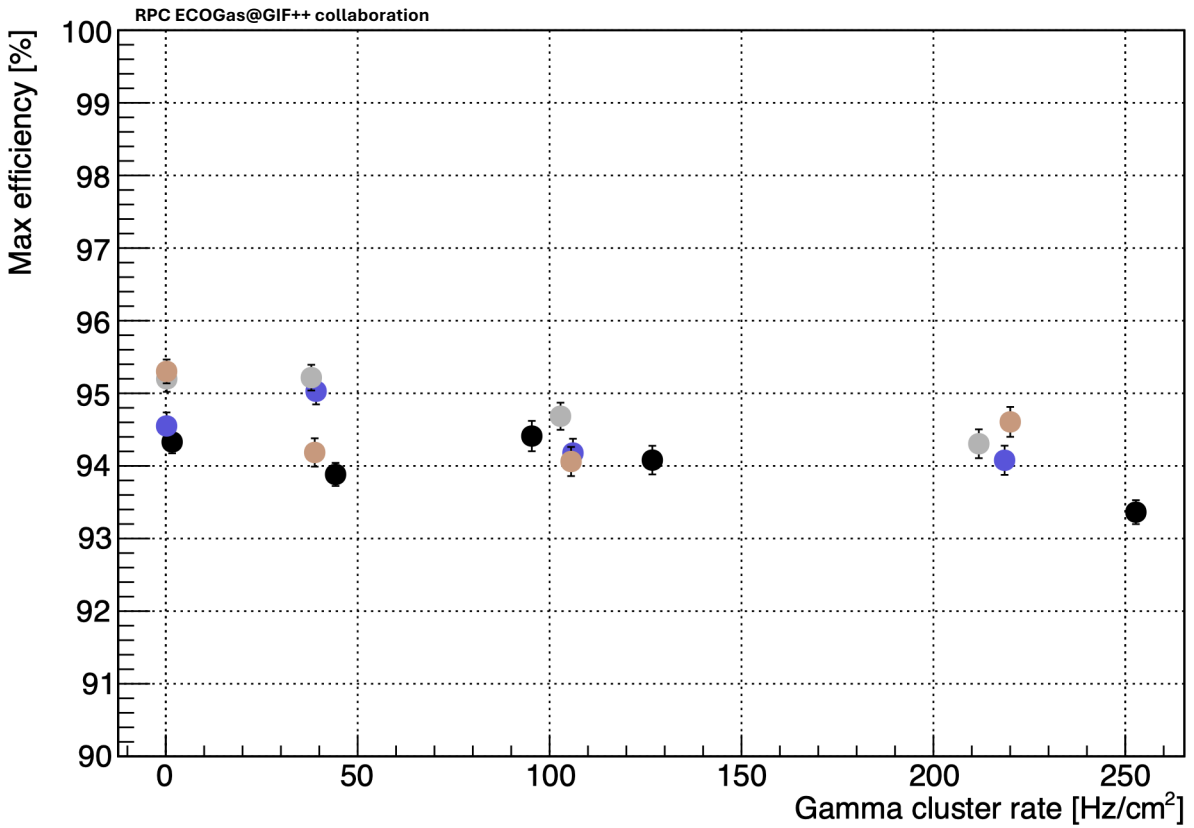
Results under irradiation

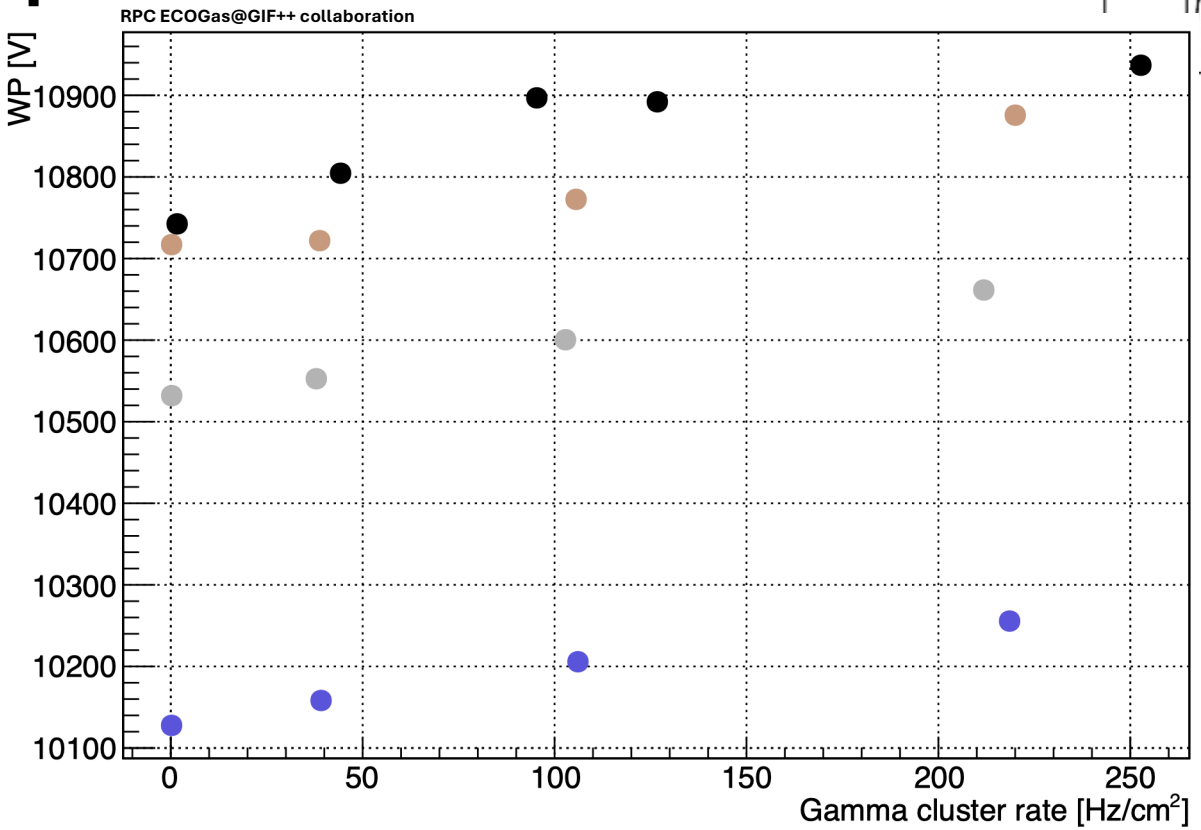




- WP and maximum efficiency (from fit) under increasing background radiation
  - **ECO2**
  - **60/28/2**, **50/38/2** CO_2/i-C_4H_{10}/HFO-1233zd (10% HFO-1234ze)

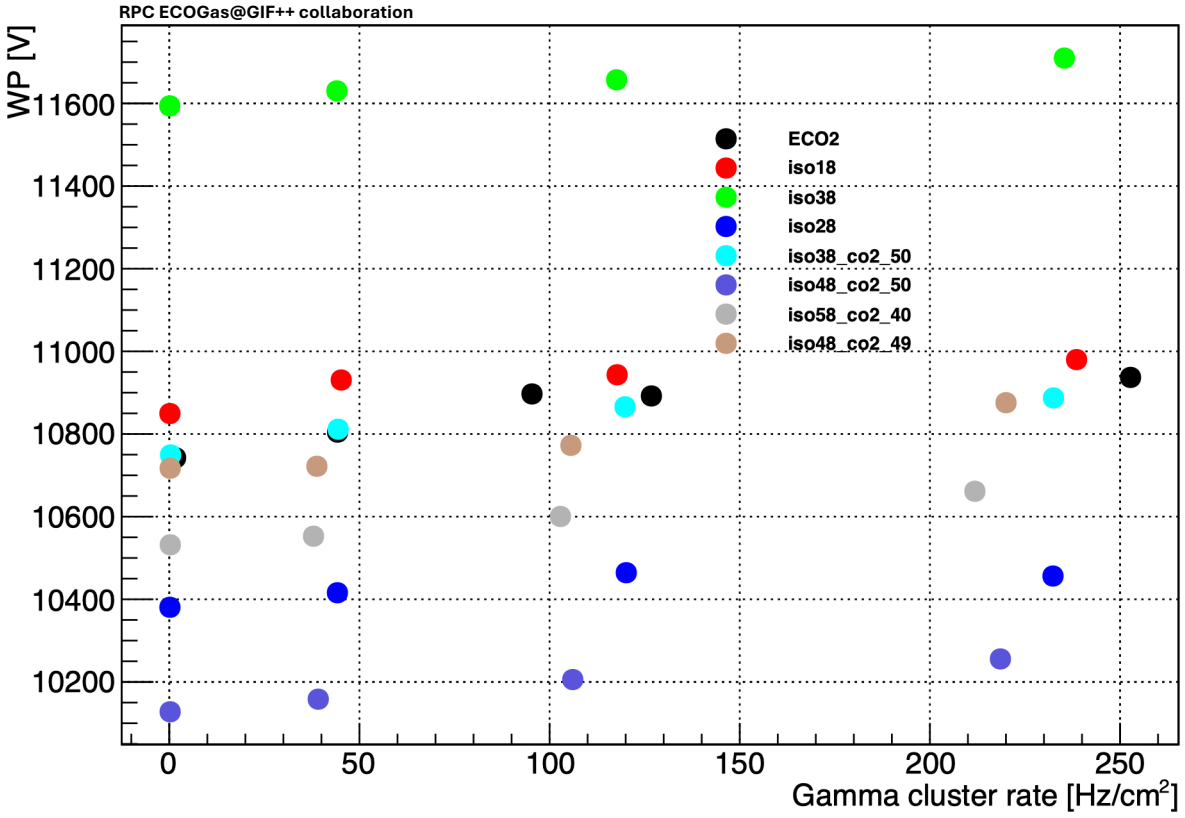
Results under irradiation

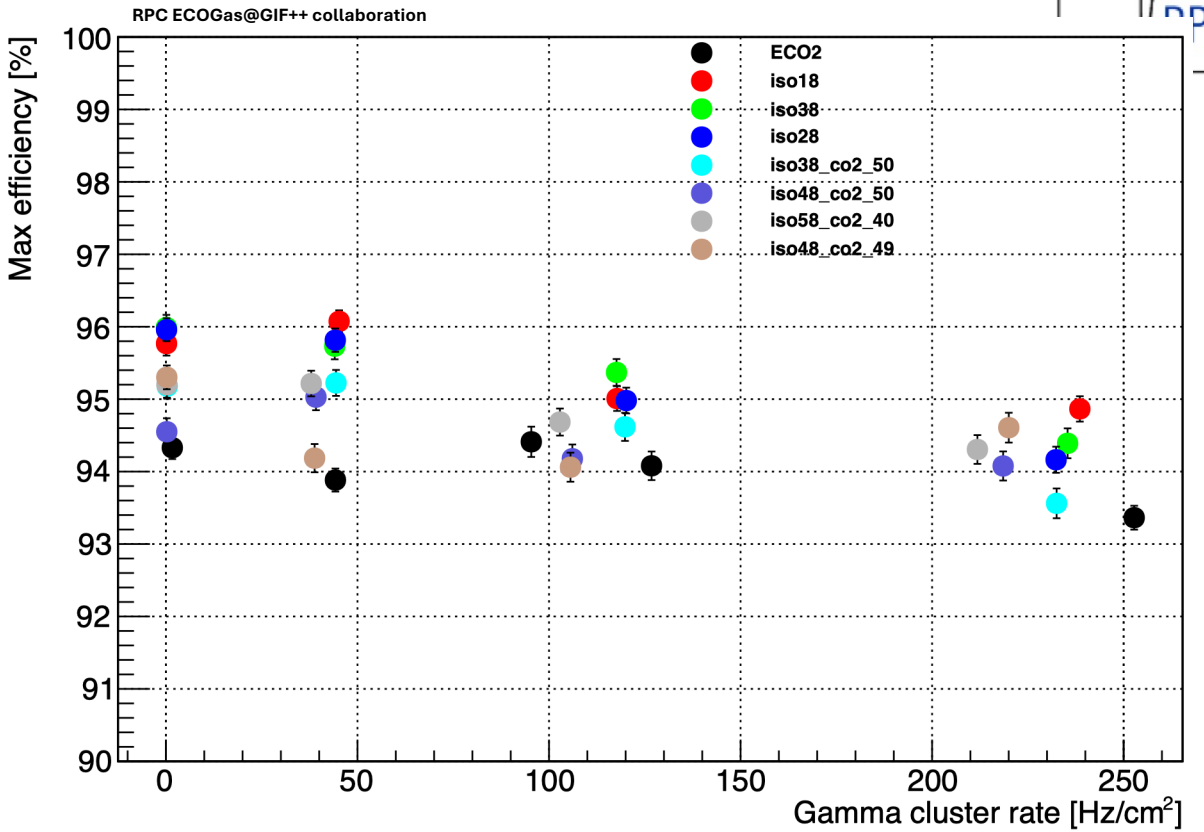




- WP and maximum efficiency (from fit) under increasing background radiation
  - **ECO2**
  - **50/48/2**, **40/58/2**, **49/48/3** CO_2/i-C4H10/HFO-1233zd (0% HFO-1234ze)

Results under irradiation

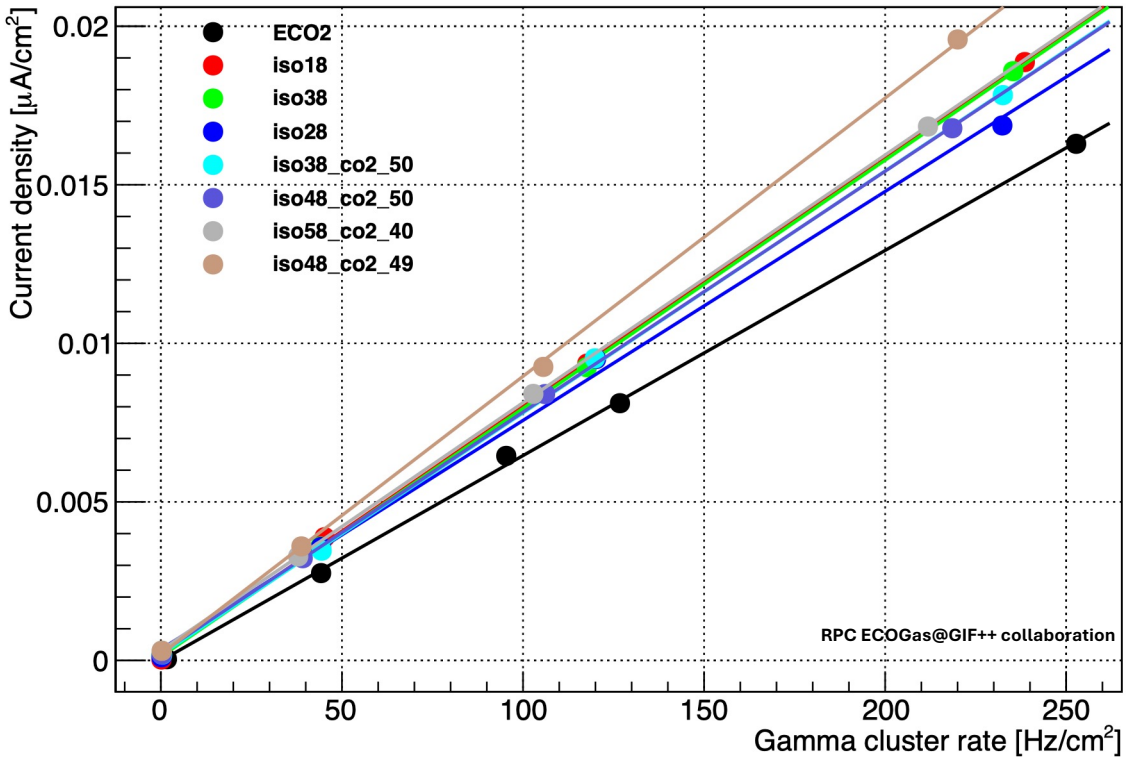


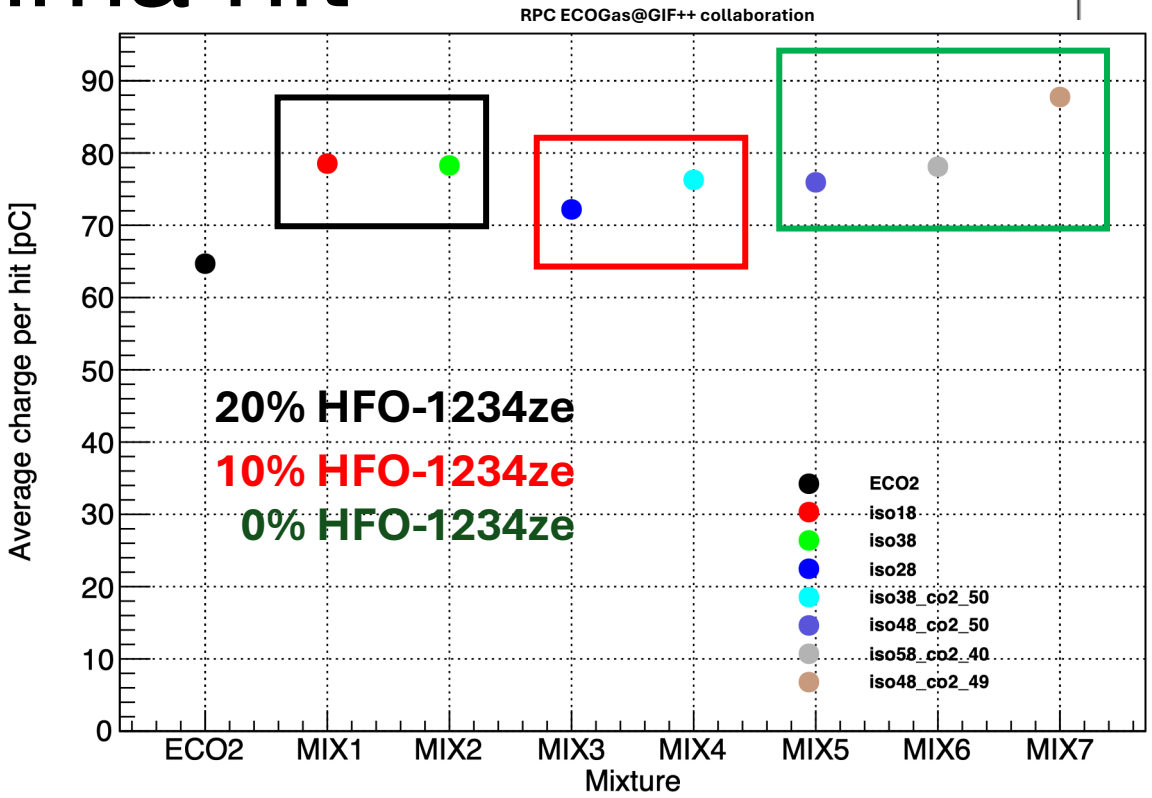


- Similar WP shift across all mixtures for increasing background rate

- Maximum efficiency increases by 2/3% if i-C_4H_{10} increases (similar values to STD)
  - Mixtures with 0% HFO-1234ze show the *worst* performance
- Efficiency drop ~2-3% at 250 Hz/cm² background rate (for STD ~1%)

Average charge per gamma hit





- The slope of the linear fit of current density vs background cluster rate provides an estimate of the mean charge per gamma hit
- Average charge per hit slightly higher wrt ECO2 for all the mixtures tested and values are similar across all mixtures

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

Conclusions & outlook

- The RPC ECOGas@GIF++ is still actively pursuing F-gas-free RPC operation
  - ➢ Summary paper in preparation for **HFO-1234ze** studies (see Marcello's talk)

- **HFO-1233zd** considered as a valuable alternative to SF6 for RPC operations

- Studies with **HFO-zd** combined with **HFO-ze** for mixtures with very low GWP
  - ➢ With and without background radiation @ GIF++

- Increasing i-C_4H_{10} and decreasing **HFO-ze** leads to very promising results
  - ➢ Most promising results obtained with 10% **HFO-ze** and 28% i-C_4H_{10}

- **What's next?**
  - Assess long term stability of detectors flushed with **HFO-zd**
  - Construct and test a gas recirculation system with an efficiency up to 100% @ GIF++
  - Part of the OTELLO proposal (sub-task 6.2) recently submitted + applied for an additional support to set-up the recirculation system within the DRD1 common funds availabilities



Thank you so much for your attention!!!

Backup