Eco-friendly Resistive Plate Chamber for HL-LHC and beyond

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on behalf of the RPC ECOGAS @ GIF++ collaboration

IDTM, Innovative Detector Technologies and Methods
Lisboa, 12-14 September 2023

GAS: The most fundamental ingredient of a gaseous detector

The gas mixture of the RPC detectors is made out of:

- $C_2H_2F_4$ = tetrafluoroethane = R134a
- SF_6 = sulfur exafluoride
- C_4H_{10} = iso-butane

R134a is a kind of Freon = commercial name for many various gases used mainly for refrigeration

- it is where **most ionization and multiplication processes** take place

SF6 is used to "quench" the mixture, namely reduce (or avoid) the formation of streamers.

C4H10 is also a quencher and aging effect mitigator

They have been selected after hundreds (literally) of tests!

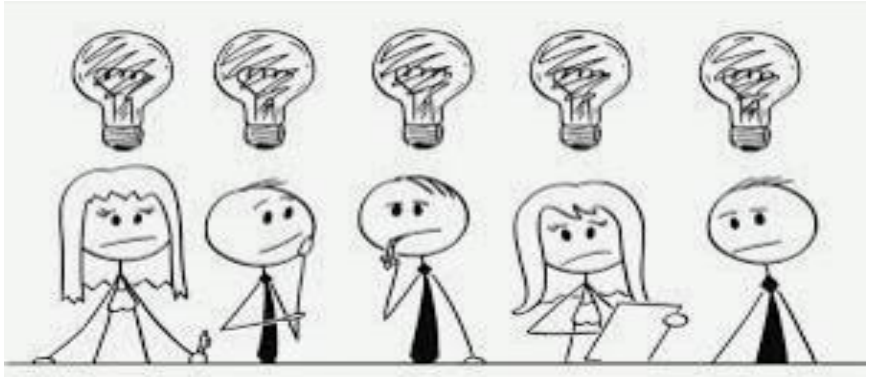
What's the problem with R134a and SF6? They are greenhouse gases, and they have an effect similar to CO_2, but much larger.

The problem

We need to replace the R134a and SF_6 with more ecological gases, namely with a much lower GWP.

Difficult problem: gases are **the core of gas-filled detectors**
-It's like I would ask you to replace silicon in electronic devices (including smartphones, computers, TV sets, etc.) with another material, BUT:

- with the **same performance**
- without **changing the electronics** (including HV)
- at the **same cost**



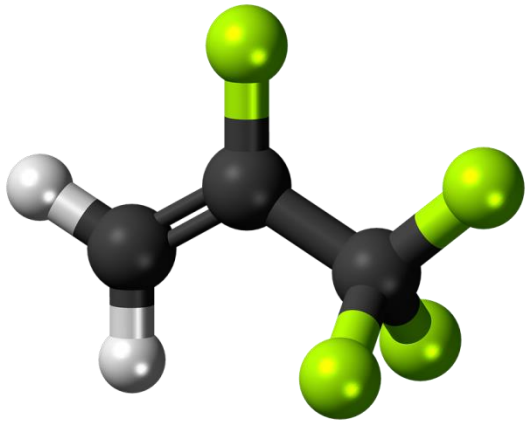
The smart (!?) idea

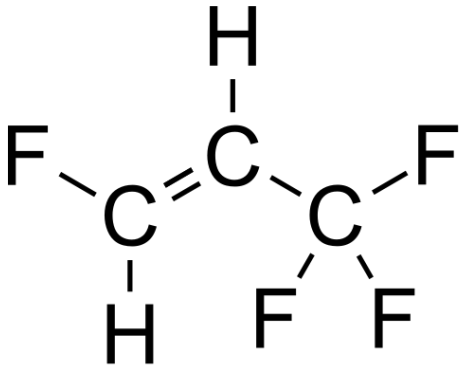
-Practically all research trendlines (with notable exceptions) are concentrated around the idea of replacing:

- $C_2H_2F_4$ (GWP=1430)→ $C_3H_4F_4ze$ (GWP=4)

  + CO_2 (GWP=1) or He (GWP<1)

He and/or CO2 are added essentially to reduce the operating voltage.





$C_3H_4F_4ze$ is the most similar molecule to $C_2H_2F_4$ but with a low GWP

Studies on the replacement of SF_6 are at an earlier stage, but an interesting solution is on the table (see later on this talk).

Test to be performed

RPCs filled with the desired gas mixture have to be operated and tested in terms of:

-Efficiency (at low and high rate) and streamer fraction

-Cluster size → direct impact on tracking capabilities

-Time resolution → direct impact on triggering and TOF

-Current absorbed (at low and high rate) → good indication of possible aging effect

-Pollutants produced (e.g. HF, but NOT only HF) → direct impact on aging effect

-Charge distribution →helps explaining many things

All high energy experiments (ALICE, ATLAS, CMS, LHCb, etc.) have started an intense R&D program to find suitable gas mixtures

Typical steps to propose and test a new gas mixture

Example taken from CMS

Review of possible Gas present on the market

L. Benussi, D. Piccolo et al.
Properties of potential eco-friendly gas replacements for particle detectors in high-energy physics
JINST **13** P03012 (2018)

Laboratory tests started in 2014

A study of HFO-1234ze (1,3,3,3-Tetrafluoropropene) as an eco-friendly replacement in RPC detectors, **arXiv:1505.01648**

Eco-friendly gas mixtures for Resistive Plate Chambers based on Tetrafluoropropene and Helium
***JINST* 11 P08019 (2016)**

Preliminary results of Resistive Plate Chambers operated with eco-friendly gas mixtures for application in the CMS experiment
***JINST* 11 C09018 (2016)**

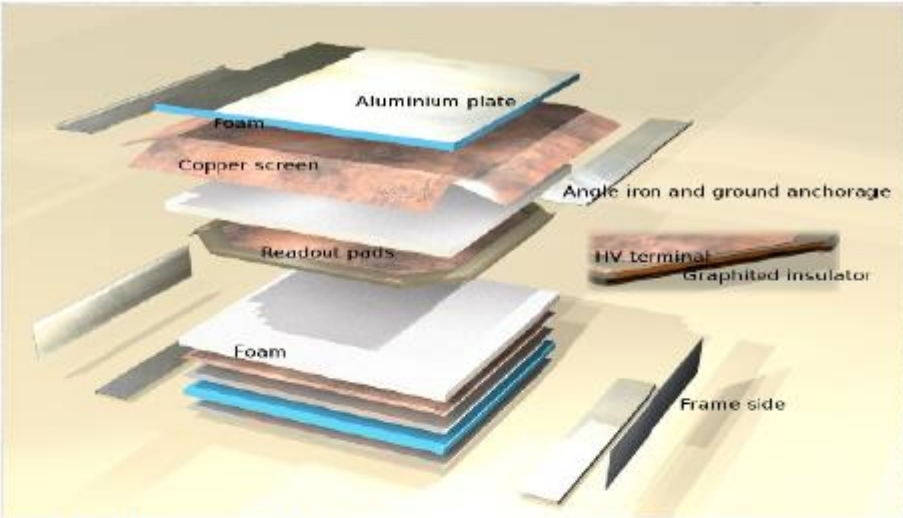
Choice of few candidate mixtures

Tests under irradiation (GIF++)

RPC ECOGAS@GIF++ Collaboration

The RPC EcoGas@GIF++ collaboration is a VERY nice example of collaboration across various experiments.

Test set-up in Frascati with cosmics for CMS



- single gap RPCs, 2 mm wide gas gap
- 50 x 50 cm^2
- Double Pad readout
  - partial cancellation on single mode noise
  - Expected about x2 induced signal charge
- Scintillator layers on top and bottom for trigger

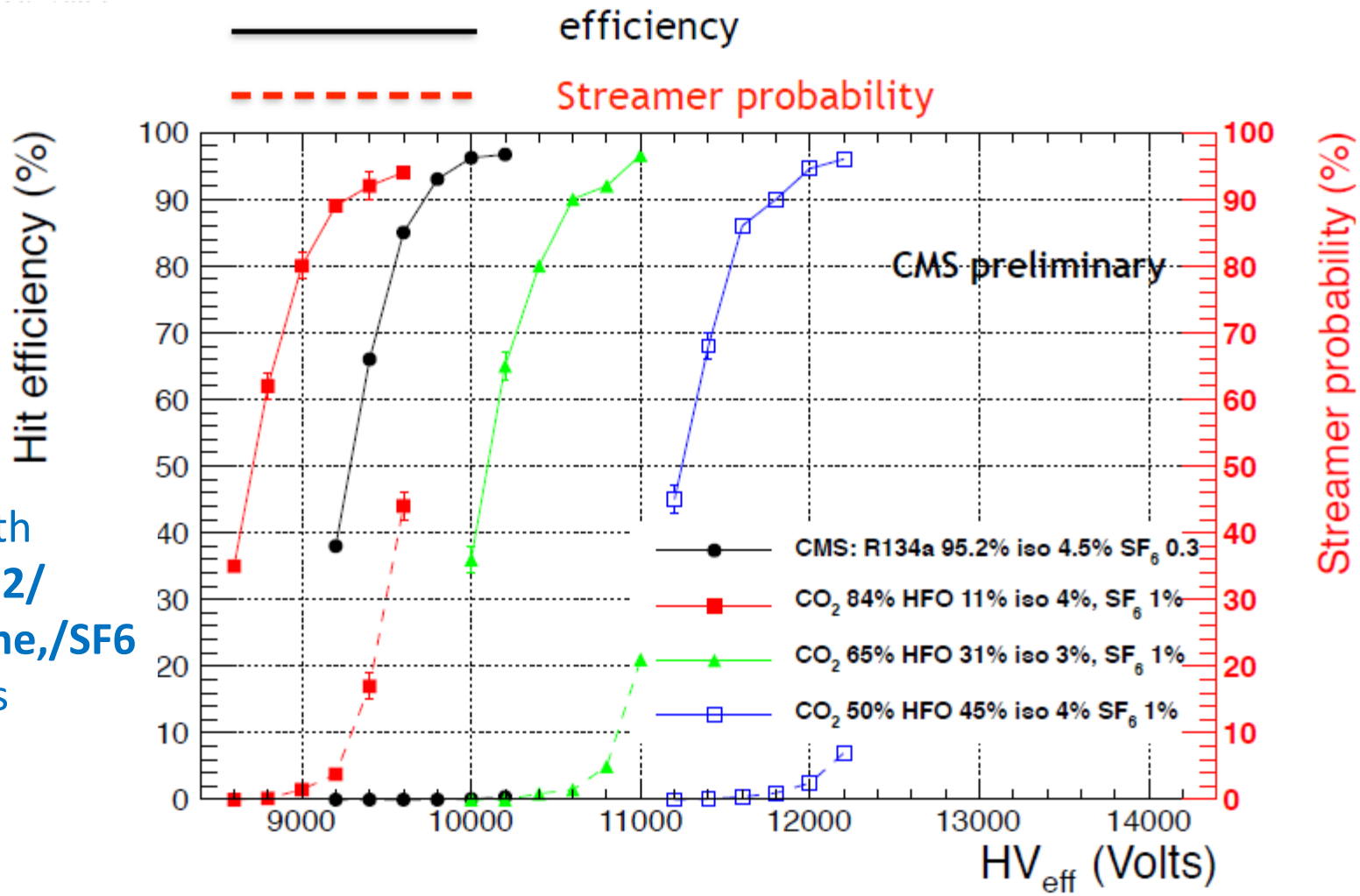
Data taken with oscilloscope

- **Gas chromatograph: for gas mixture analysis**
- 4 channels Oscilloscope lecroy104xi (5 Gsamples, 1 GHz): for signal readout
  - Full digitization of signal

Using an oscilloscope (or, in general, a digitizer) allows to extract EACH and ANY info from the detector signal.

Test set-up in Frascati with cosmics

Tests with **HFO/CO2/ isobutane,/SF6** mixtures

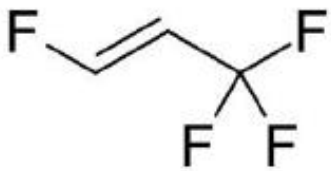


In general, encouraging results, but width of the full efficiency zone without streamers reduced wrt. “standard” mixture.

Looking for replacements for SF_6 (ATLAS)

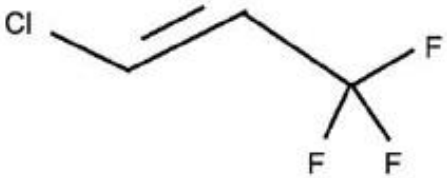
The standard gas mixture has a high Global Warming Potential (GWP)

- $C_2H_2F_4$ + i-C_4H_{10} + SF_6 → **GWP ~ 1450**



Substitute $C_2H_2F_4$ with an environment-friendly gas mixture

- CO_2 / $C_3H_2F_4$ **(HFO1234ze)** + i-C_4H_{10} + SF_6 → **GWP ~ 200**



Substitute the SF_6 with a different environment-friendly gas :the **Chloro-trifluoropropene** $C_3H_2ClF_3$ (HFO1233zd)

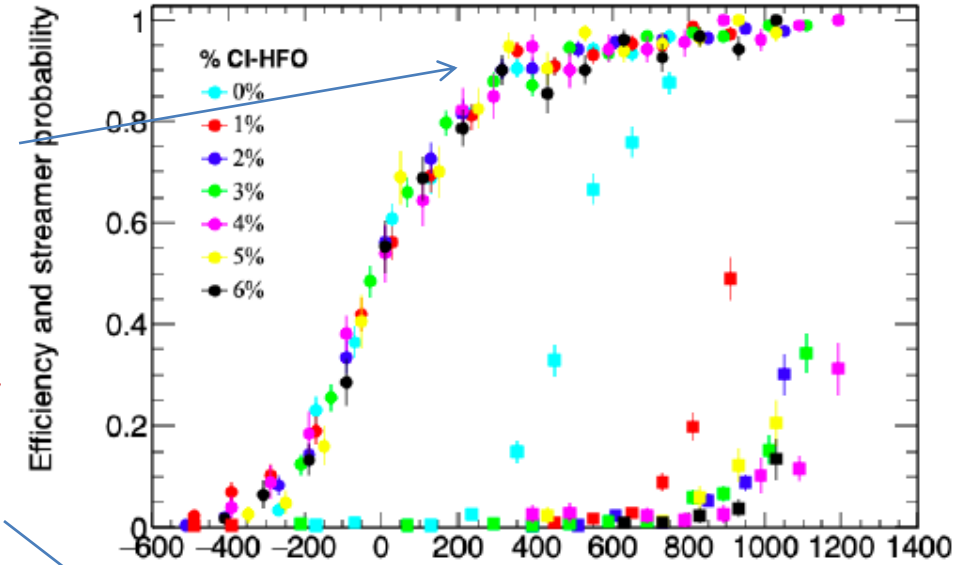
- CO_2 / $C_3H_2F_4$ **(F-HFO)** + i-C_4H_{10} + $C_3H_2ClF_3$ **(Cl-HFO)** → **GWP ~ 10**

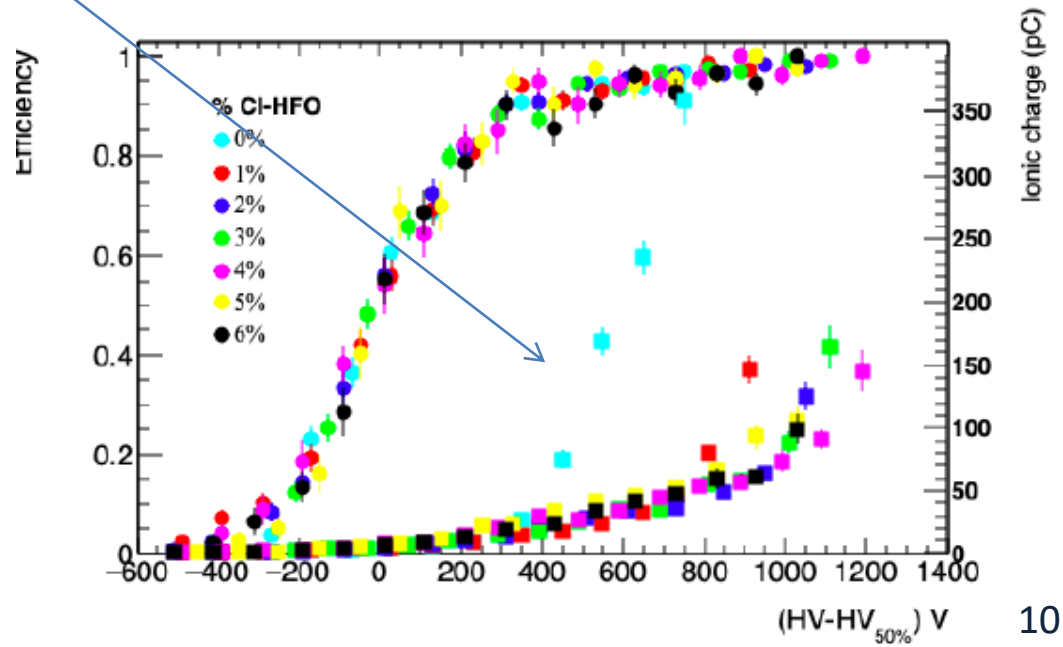
On a new environment-friendly gas mixture for Resistive Plate Chambers
G. Proto[1,2], B. Liberti[2], R. Santonico[1,2], et al. 2022 *JINST* **17** P05005

In terms of reduction of GWP, the replacement of TFE is just **part of the problem**; in the new eco-friendly gas mixture, the residual GWP is **almost ALL due to the presence of SF6.**

Tests with SF6 replaced with Cl-HFO for ATLAS

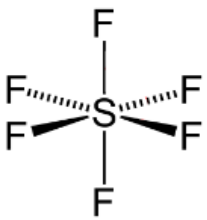
In general, **very promising results**.
-Efficiency always higher than 93%
-WP increases at a rate of 400V/1% of CL-HFO
-Avalanche/streamer separation ("useful" plateau) **larger than 400V**





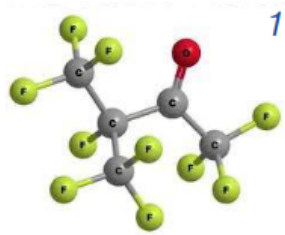
From: B. Liberti, "Recent results on environmental-friendly gas mixtures for ATLAS RPC", 66th INFN Eloisatron workshop: New gas mixtures for RPC and MRPC detectors

Other possible replacements for SF_6



SF_6

GWP 23900

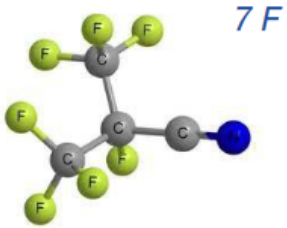


3M™ Novec™ 5110

($CF_3C(O)CF(CF_3)_2$)

GWP <1

Atm. lifetime 15 days

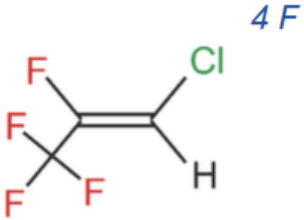


3M™ Novec™ 4710

($(CF_3)_2CFCN$)

GWP 2100

Atm. lifetime 30 years

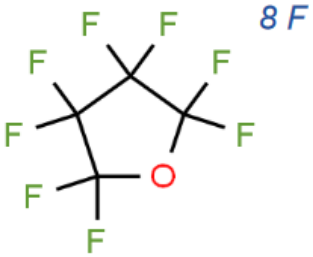


AMOLEA™ HFO-1224yd

(CF_3-CF=CHCl)

GWP <1

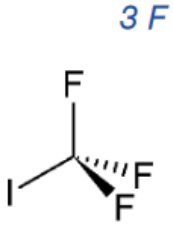
Atm. lifetime 20 days



C_4F_8O

GWP 8700

Atm. lifetime >3000 years



CF_3I

GWP 0.4

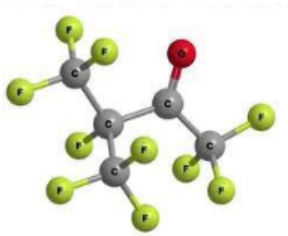
Atm. lifetime 6 days

- Chemical inertness: extremely stable
- Exceptionally long lived in the atmosphere
- Excellent dielectric property
  - SF_6 x 2.5 than Air
- Non-flammable and toxic
- Gaseous form
- No major reactions
  - Ok with H_2O, Cl and acids

Test performed by CERN EP-DT

See B. Mandelli, **Possible alternatives to SF6 for Resistive Plate Chambers** RPC2022

NOVEC5110

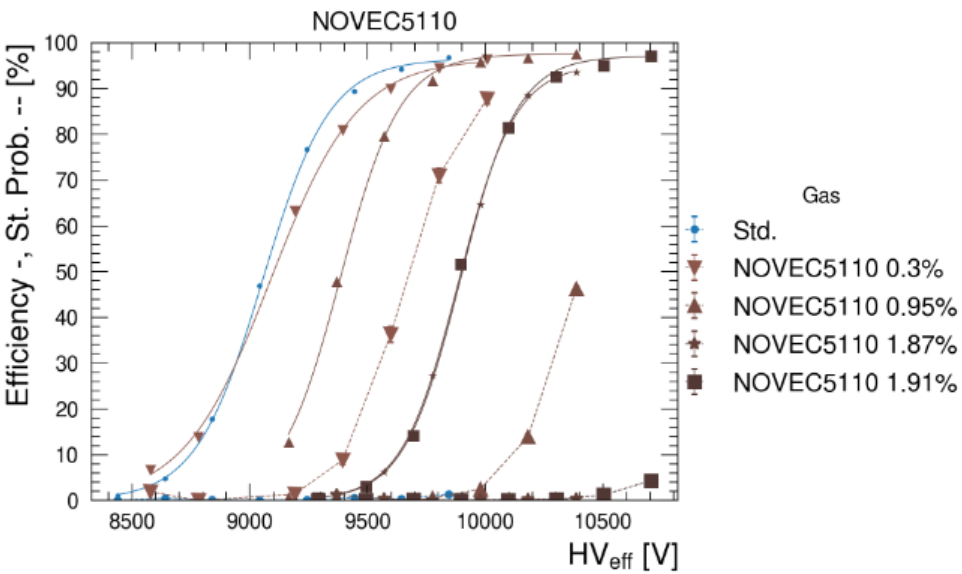


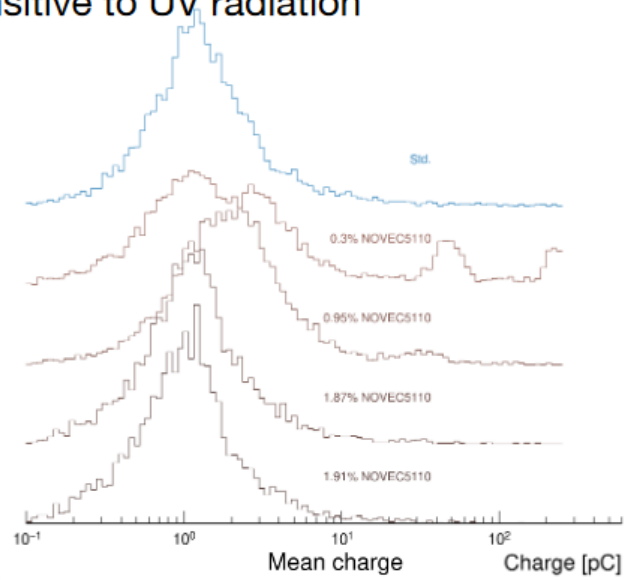
PRO

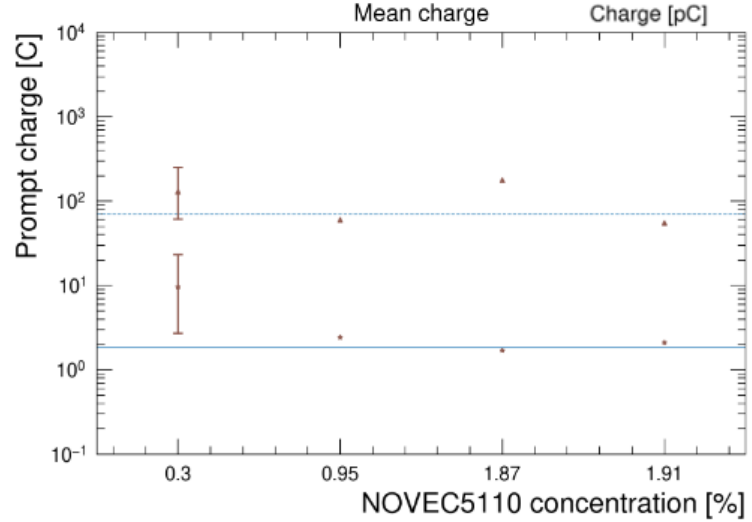
- Very low GWP: <1
- Application in industry
- High dielectric strength

CONS

- High boiling point: 27 C
- Sensitive to UV radiation

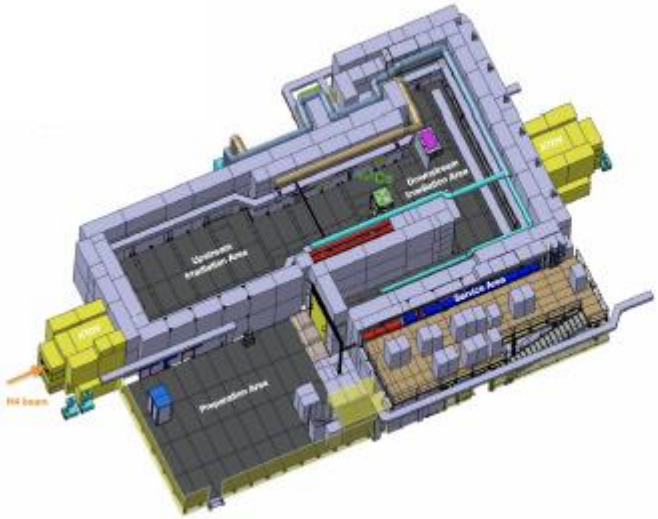


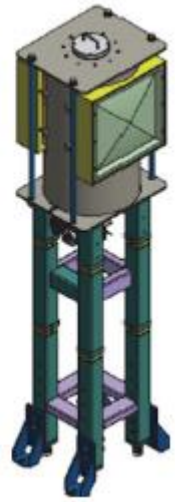




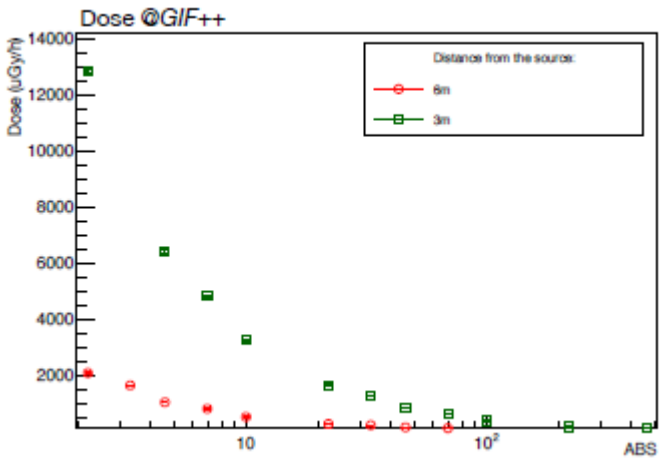
- High concentration (~2%) of NOVEC 5110 needed to obtain good streamer suppression
  - Suspect that NOVEC 5110 breaks inside the RPC
- Higher working point for concentrations > 0.3%
- Avalanche and streamer charge similar of std gas mixture from 0.9%
  - At 0.3% very large avalanche signals

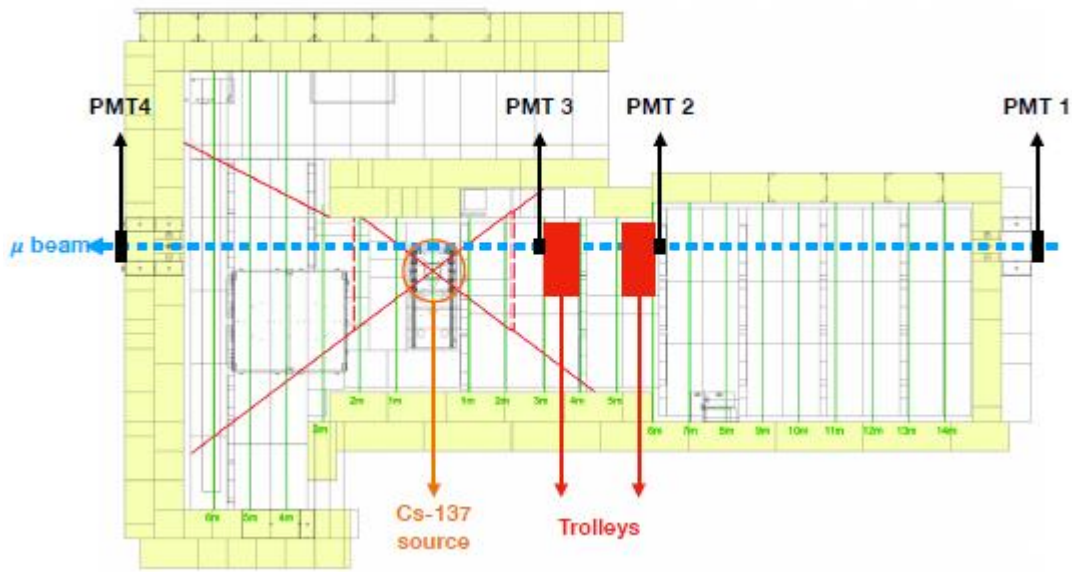
Tests at high rate: the Gamma Irradiation Facility





- H4 beam line in EHN1, CERN NA
- **Cs-137 gamma source** up to 12 TBq
- **Muon beam** 10-450 GeV/c
- Gamma flux modulated independently using a system of six attenuation filters (ABS)



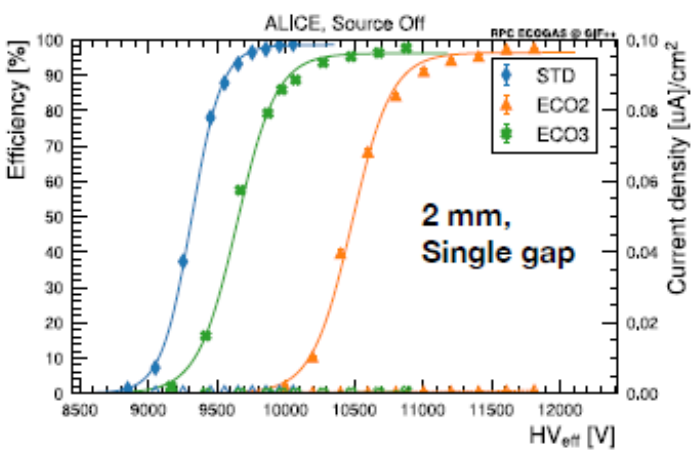


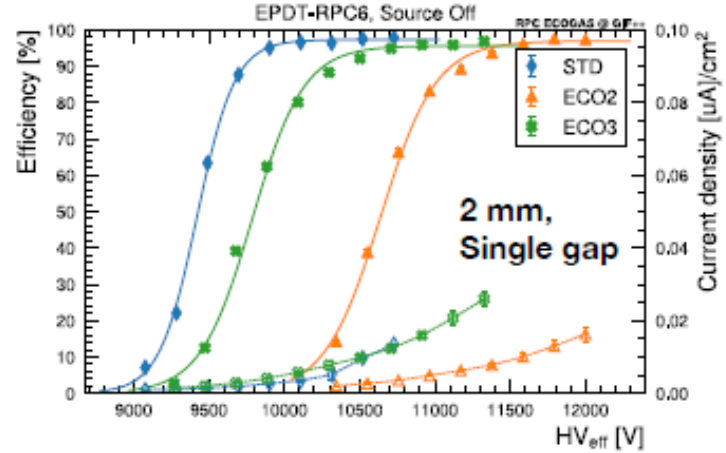
Detector Set-up at GIF++

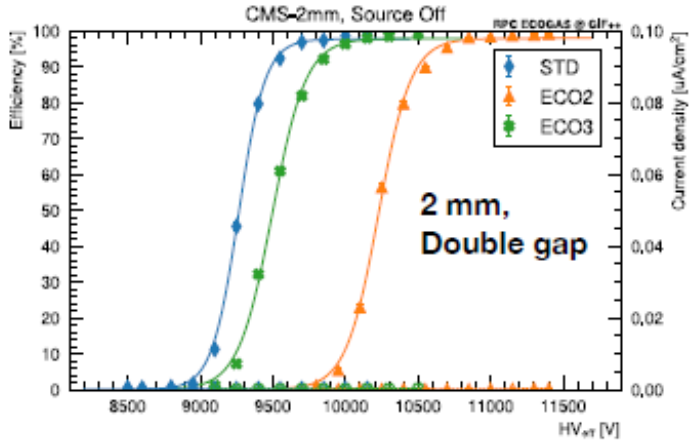
	RPC characteristics	Readout
ALICE	50x50 cm^2 2 mm single gap 2 mm bakelite electrodes	2D readout (16+16 strips) 3 cm pitch TDC
ATLAS	10x55 cm^2 2 mm single gap 1.8 mm bakelite electrodes	1D readout (1 strip) 3 cm pitch Digitizer
CMS BARI-1p0	70x100 cm^2 1.0 mm single gap 1.43 mm bakelite electrodes	1D readout (32 strip) 0.5 cm pitch TDC
CMS	Trapezoidal (height 10 cm, bases 51cm and 33 cm) 2 mm double gap 2 mm bakelite electrodes	1D readout (128 strip) 1 cm pitch TDC
CERN EP-DT	50x50 cm^2 2 mm single gap 2 mm bakelite electrodes	1D readout (7 strips) 2.1 cm pitch Digitizer
LHCb-SHiP	70x100 cm^2 1.6 mm single gap 1.6 mm bakelite electrodes	2D readout (32+32 strips) 1 cm pitch TDC

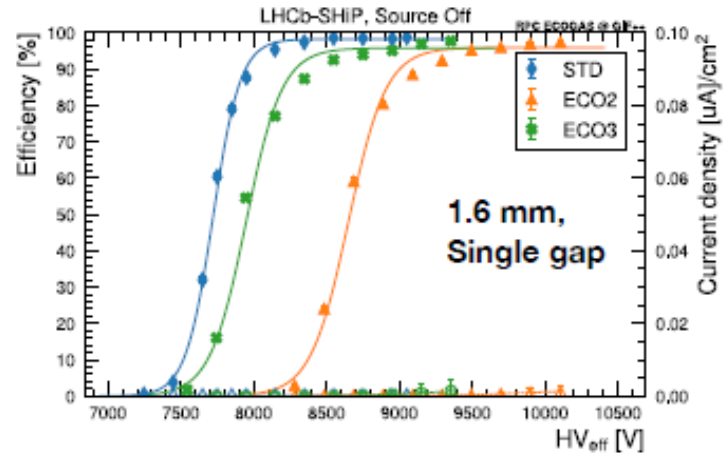
The RPC EcoGas@GIF++ is a collaboration **transversal to ALICE, ATLAS, CERN EP-DT, CMS**, and LHCb willing to put togethere expertise and resources in order to test different detectors and electronics, in the same conditions and 2-3 potential candidates of eco-friendly gas mixtures.

Performance without irradiation (no source)





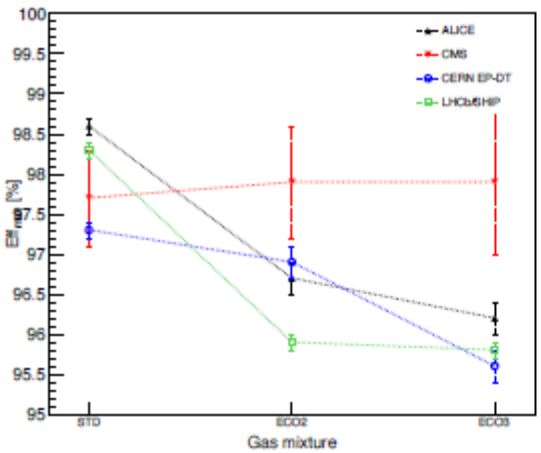


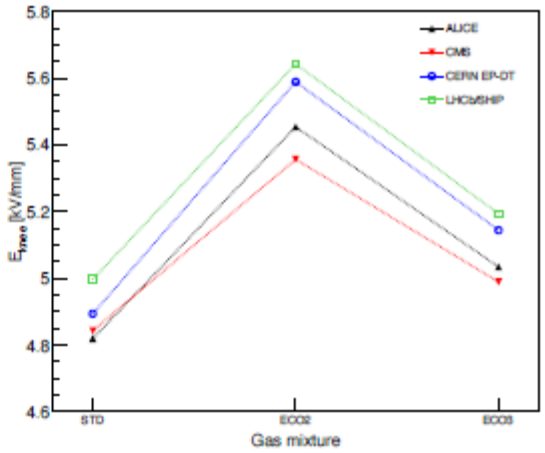


Gas mixtures tested:

	R134a (%)	HFO-1234ze (%)	CO_2 (%)	i-C_4H_{10} (%)	SF_6 (%)	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		

Performance without irradiation





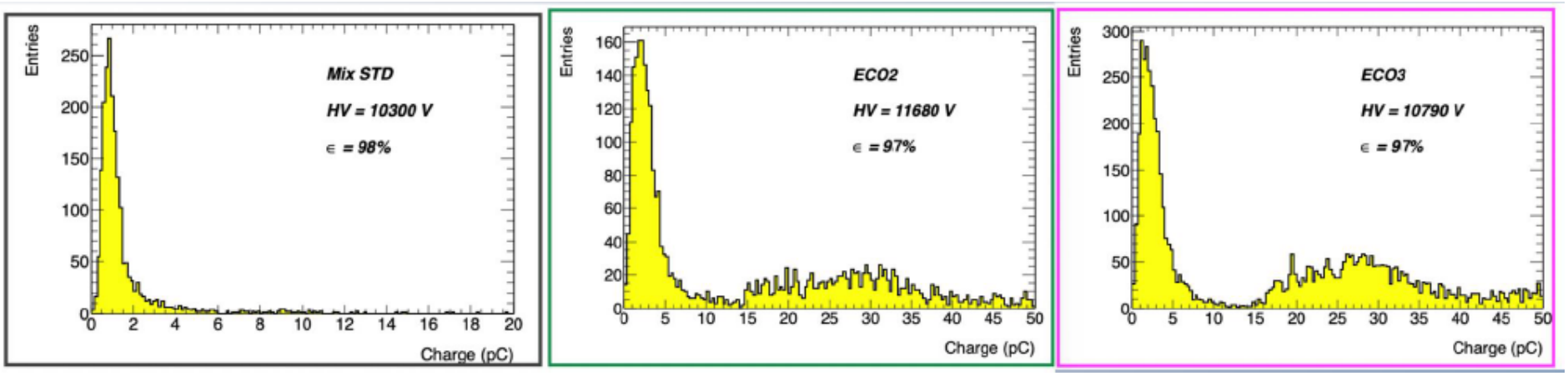
Efficiency curves fitted with sigmoid functions:

$$Eff(H_{Veff}) = \frac{Eff_{max}}{1 + e^{-\lambda*(H_{Veff} - HV50)}}$$

Effmax well above 95% decreases for ECO2 and ECO3 (lighter target due to CO2)
Double gap CMS is less sensitive

Electric field @ knee higher for ECO2 and ECO3

ATLAS RPC charge distributions

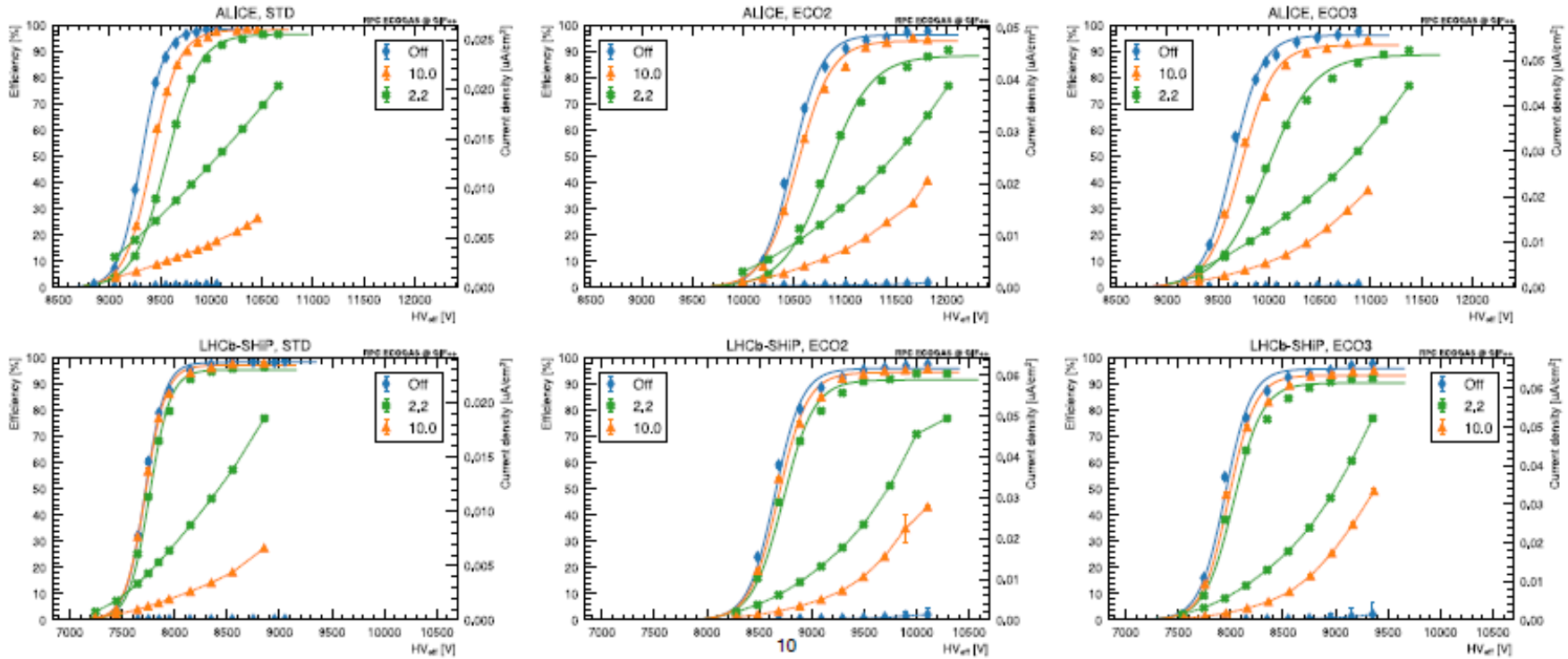


Larger streamer contamination for ECO2 and ECO3

Performance with irradiation

ALICE

LHCb-SHiP



Efficiency and current density

Data taken at different ABS:

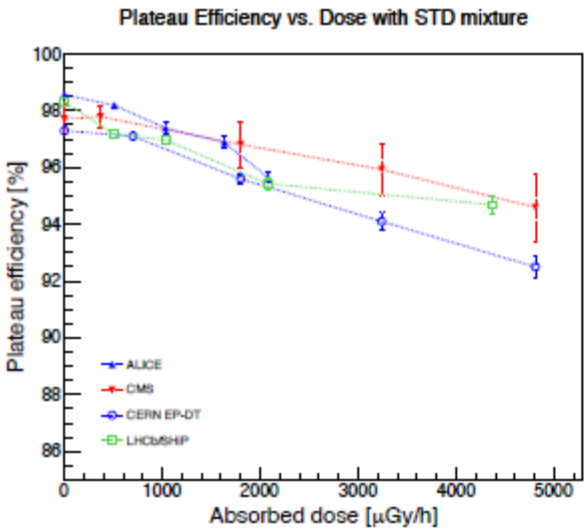
- ALICE-LHCb/Ship (6 m far from source)
  - OFF
  - ABS 10 (510 uSievert/hour; 70* Hz/cm² @knee)
  - ABS 2.2 (2070 uSievert/hour; 280* Hz/cm² @knee)

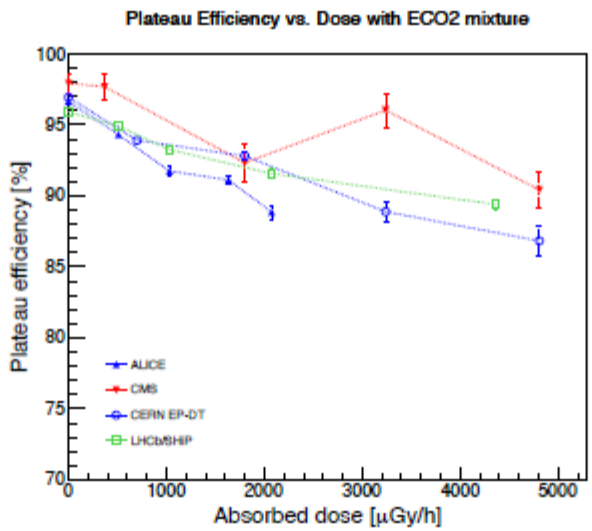
Data taken at different ABS:

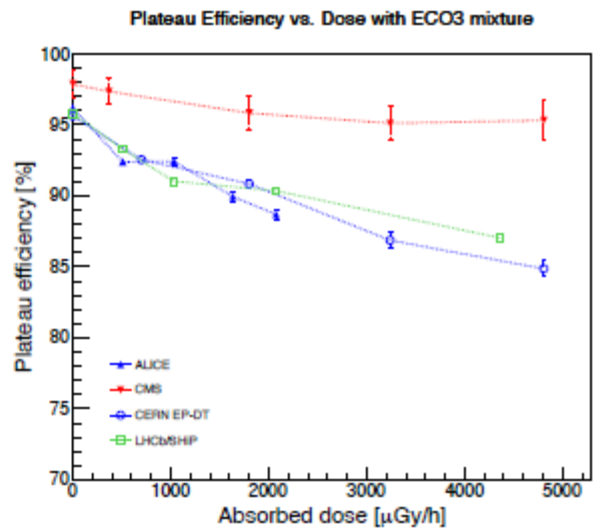
- CMS-EPDT (3m far from source)
  - OFF
  - ABS 69 (700 uSievert/hour; 80* Hz/cm² @knee)
  - ABS 22 (1800 uSievert/hour; 200* Hz/cm² @knee)

Performance with irradiation

Efficiency summary for each gas mixture



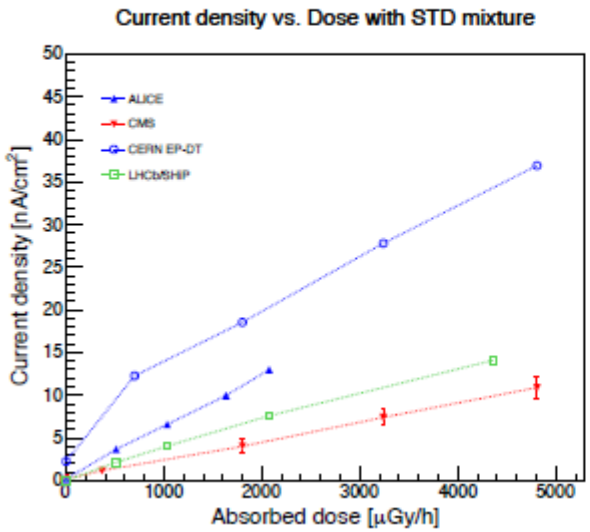


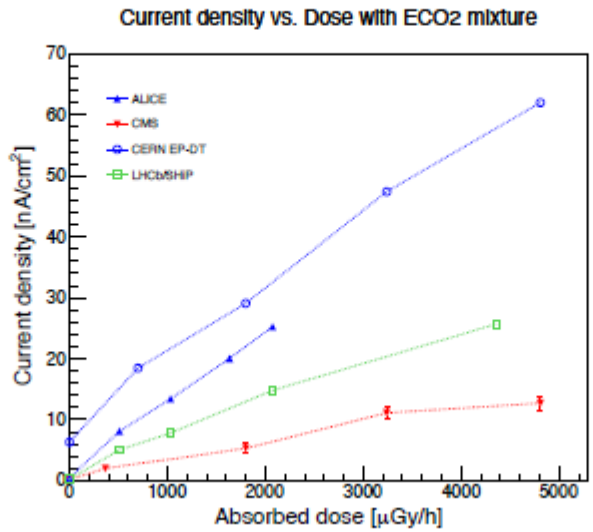


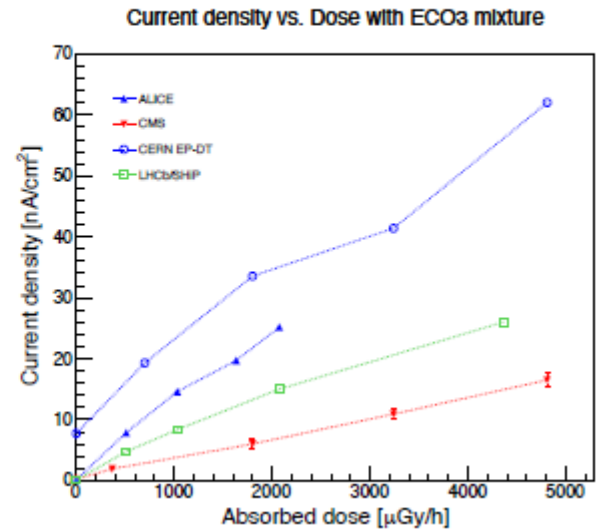
Larger efficiency drop when using ECO2 and ECO3 mixtures

Performance with irradiation

Current density summary for each gas mixture







Slightly higher currents for at higher doses when using ECO2 and ECO3

Aging issues?

Conclusions

- In general –within some limitations- the idea of replacing TFE with HFO (+CO2 to reduce the operating voltage) seems to work.
  - **ECO2 and ECO3 might be good candidate gas mixtures**
- Of course, more severe tests are to be performed, in particular for what concerns aging effects, are due → stay tuned!
- First, encouraging results, on effectively replacing SF6
  - It's responsible for most of GWP of ECO2 and ECO3

- The RPC community is on the eve of its **ecological transition (?)**