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Eco-friendly gas mixtures for future RPC detectors

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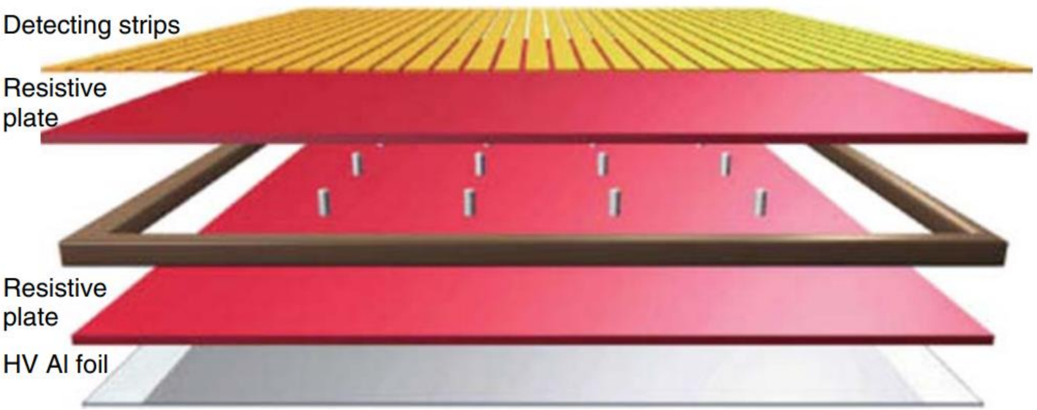
Resistive Plate Chambers

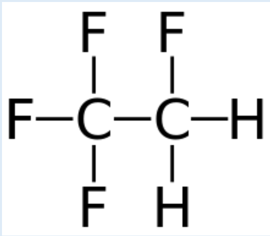


RPCs widely used in HEP experiments:

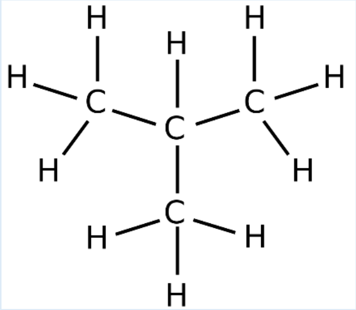
- low cost per unit area;
- high time resolution;
- good space resolution;
- high efficiency;
- ease of construction and robustness.

Standard gas mixture in avalanche mode of operation

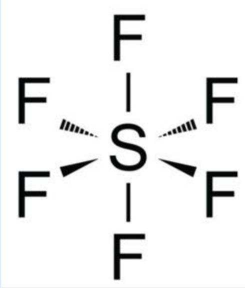
- High density of primary ion-electron pairs: high RPC efficiency
- Good quenching properties and electronegativity: reduced streamer probability



R134a (>90%)



iC_4H_{10}



SF_6

Limitation of GHG emissions

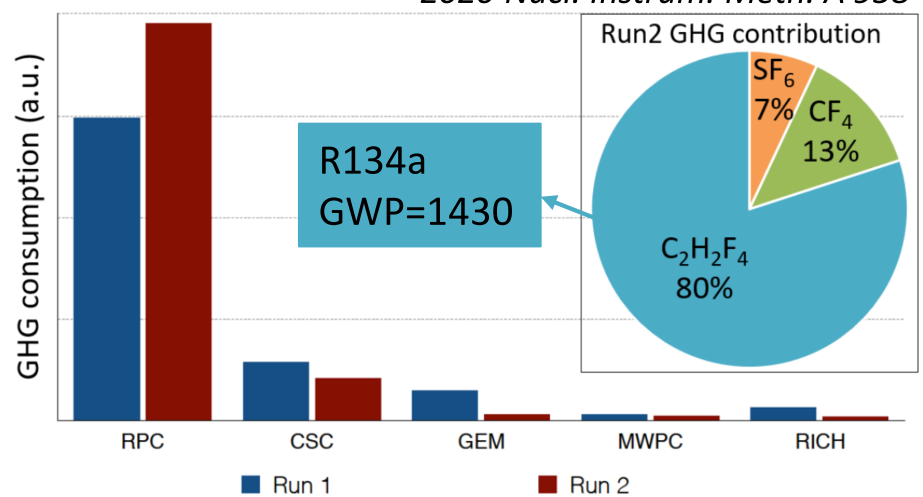
- Fluorinated greenhouse gases (GHGs) with high **Global Warming Potential (GWP)** have been limited in EU [EU regulation 517/2014].

quantifies the contribution of a gas to the greenhouse effect, normalized to the effect of CO_2

- CERN is committed to reducing its direct greenhouse gas emissions [CERN Env. Report].

Intense research activity on alternative eco-friendly gas mixtures for RPCs.

2020 Nucl. Instrum. Meth. A 958



The **RPC ECOGAS@GIF++ Collaboration** is a joint effort between RPC communities from different experiments [ALICE, ATLAS, CERN Gas team, CMS, LHCb/SHiP]

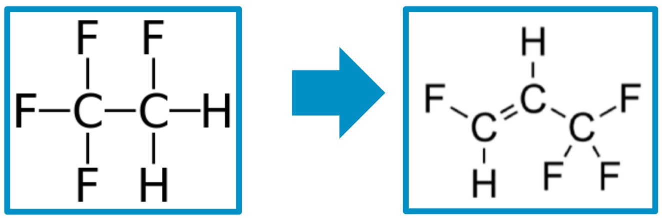
goal: study of new eco-friendly gas mixtures for RPCs

1) New gas mixtures studied independently in laboratories from different institutes. → *2) Tests of eco-gas mixtures at different LHC-like background conditions at CERN GIF++.*

Towards new eco-gas mixtures

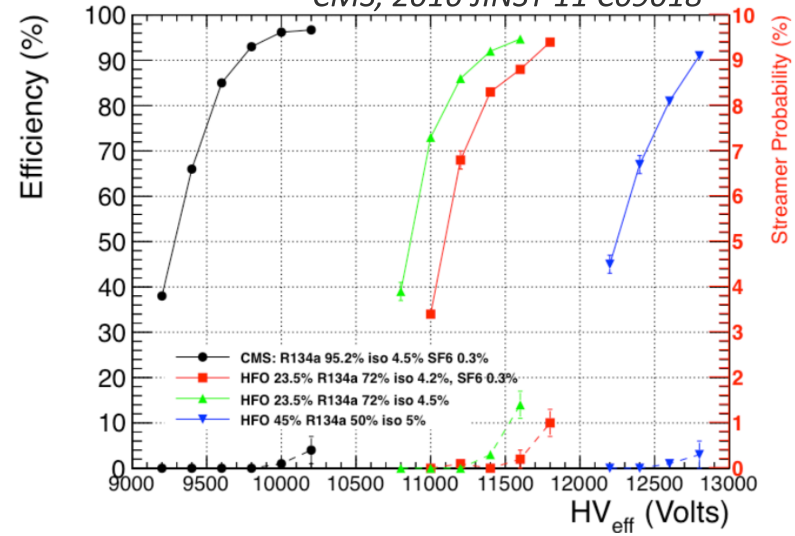
- New mixture requirements: low GWP, low toxicity, not flammable and detector performance comparable with standard gas mixture.
- R134a is being replaced in industrial applications with HydroFluoro-Olefins (HFOs).

R134a, GWP=1430 **HFO-1234ze, GWP=6**

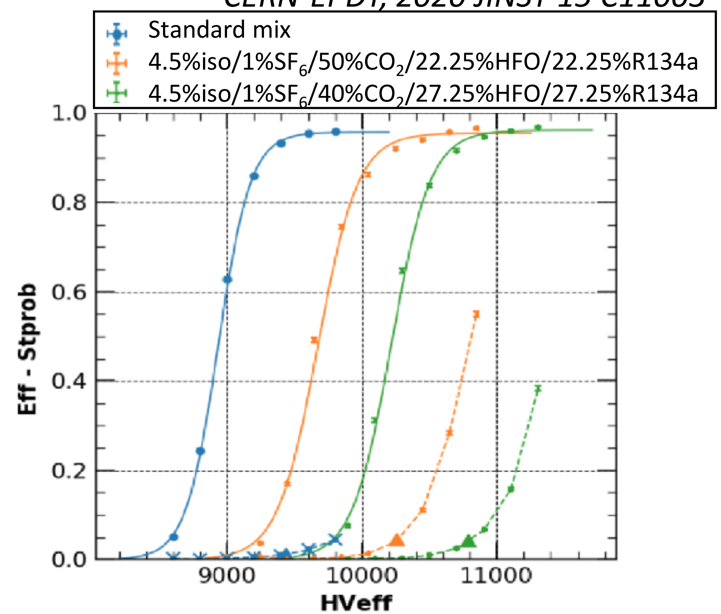


- Replacing increasing R134a % with HFO, the RPC working point increases correspondingly: the direct replacement of R134a with HFO moves the operating voltage for standard RPCs with 2 mm gaps to values > 13 kV.
- The addition of CO_2 helps in decreasing the WP.

CMS, 2016 JINST 11 C09018

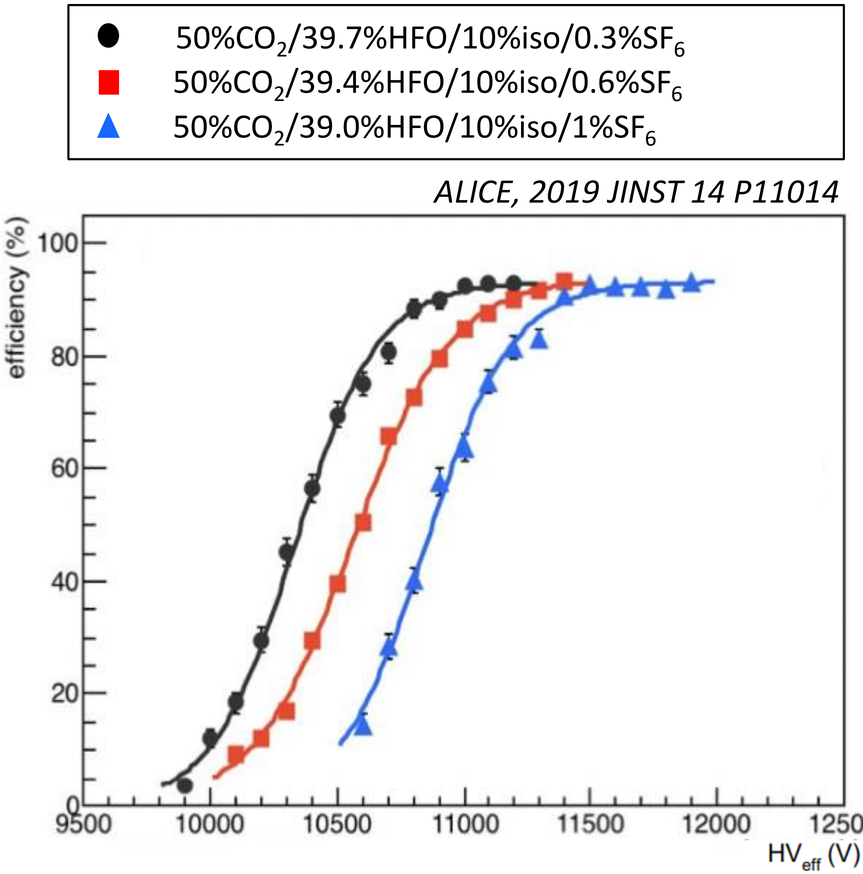


CERN-EPDT, 2020 JINST 15 C11003

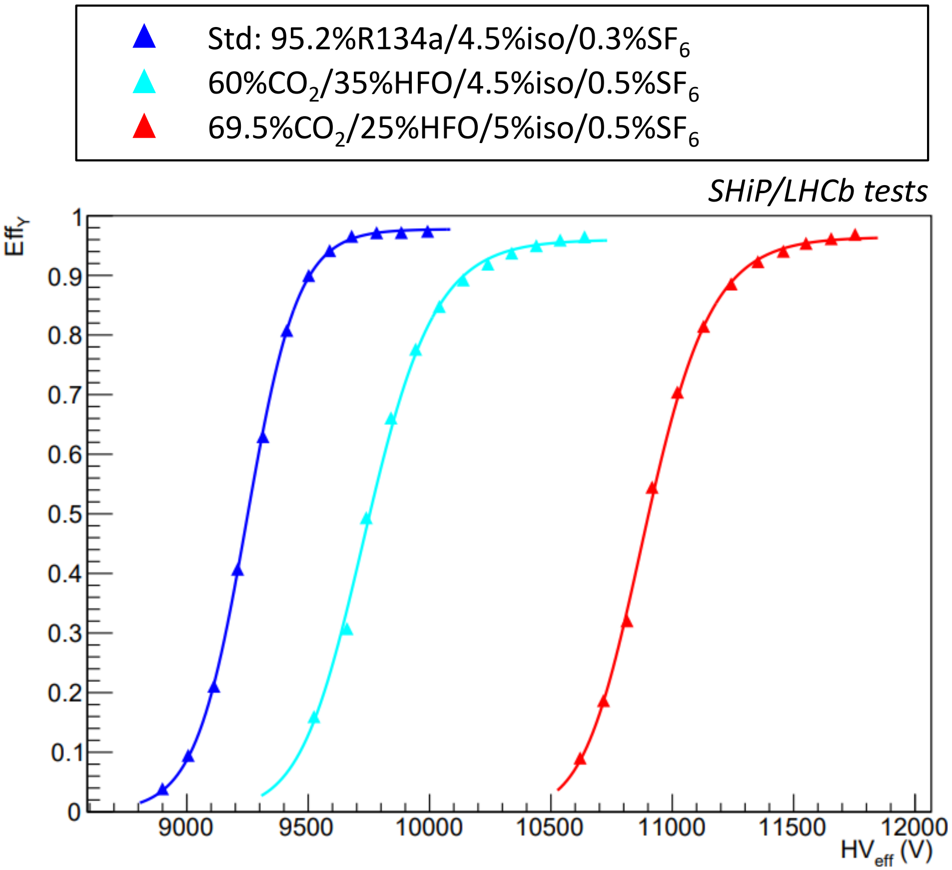


New eco-gas mixtures

Mixtures without R134a



ALICE, 2019 JINST 14 P11014

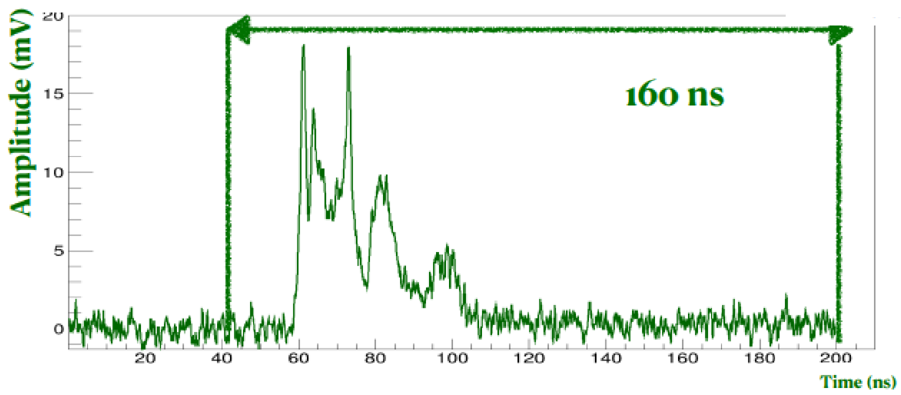


SHiP/LHCb tests

Several mixtures with CO_2/HFO/iso/SF_6 have been tested by all groups, showing efficiency above 95% and WPs below 12 kV for 2mm gaps.

New eco-gas mixtures

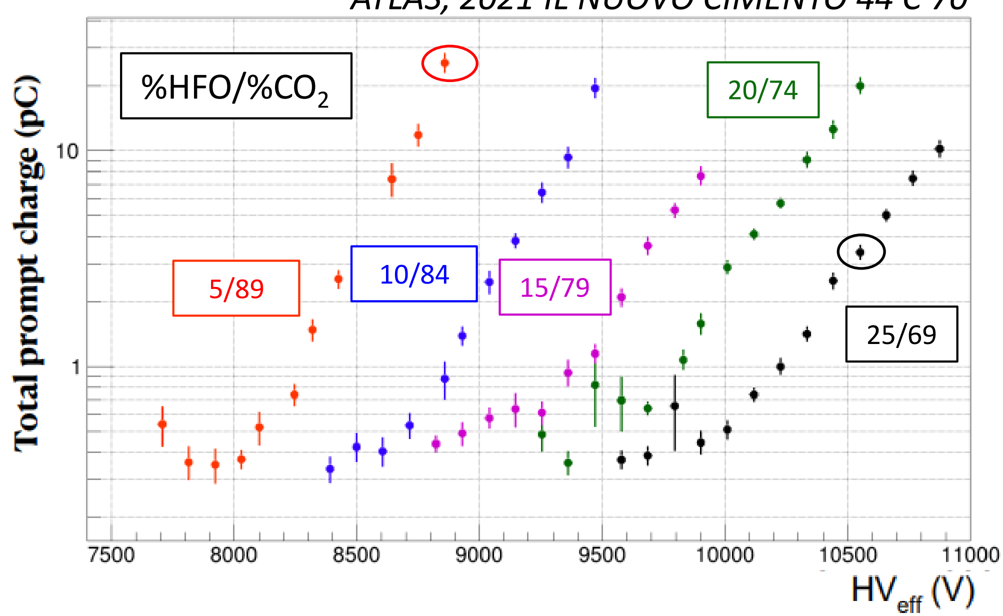
Mixtures without R134a



Total prompt charge: integrated charge in a given time window (around 160 ns)

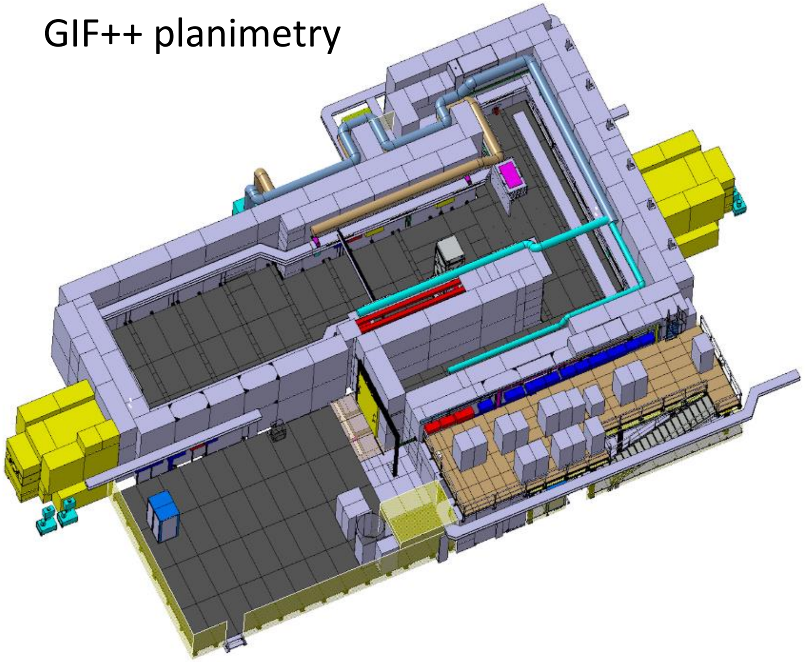
- Measurements of total prompt charge for a 2mm gap readout by a single strip with mixtures having 5%/1% of iso/SF_6;
- The event charge content is higher for mixtures with smaller HFO/CO_2 fraction: at the same eff (~97%) Q is >10 pC for 5%/89% of HFO/CO_2 and is a few pC for 25%/69% of HFO/CO_2.

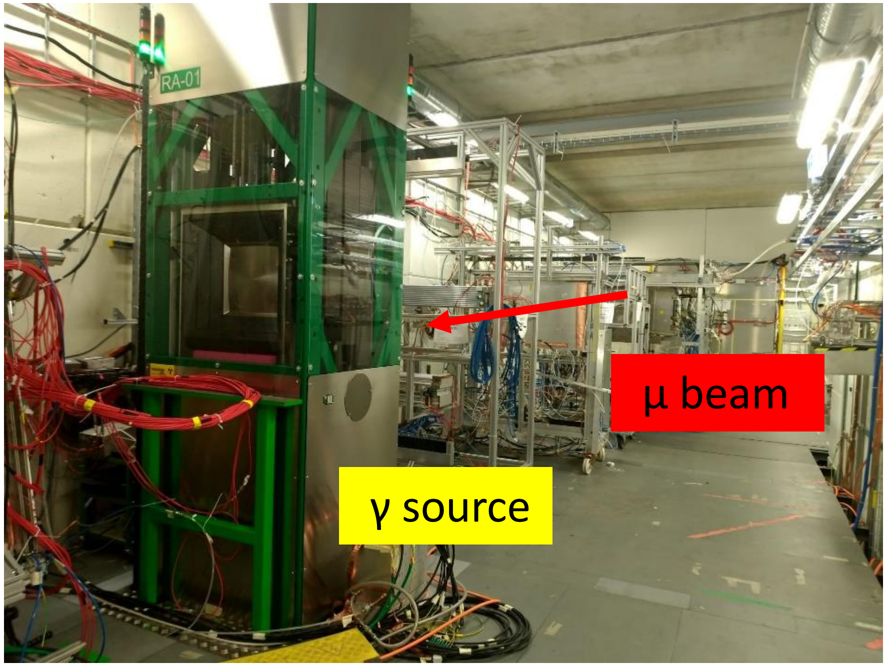
ATLAS, 2021 IL NUOVO CIMENTO 44 C 70



Gamma Irradiation Facility (GIF++)

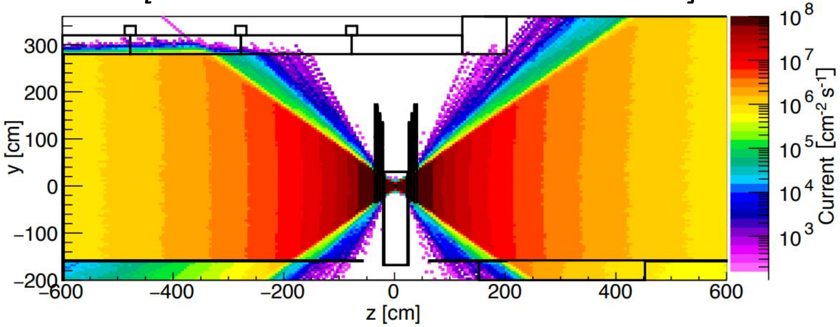
GIF++ planimetry





Photon current at x=0.65 m with ABS=1

[2017 Nucl. Inst. Meth A 866 91-103]

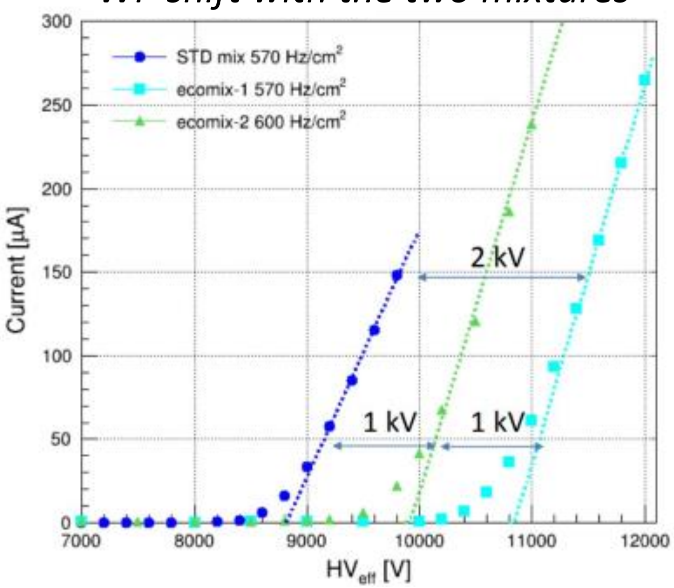


- ^{137}Cs source producing γ (primary photons at ~660 keV) with activity ~13 TBq + adjustable filters (24 possible attenuation factors, ABS);
- High-energy muon beam (100 GeV/c) from the secondary CERN SPS H4 beam line.

First results at GIF++

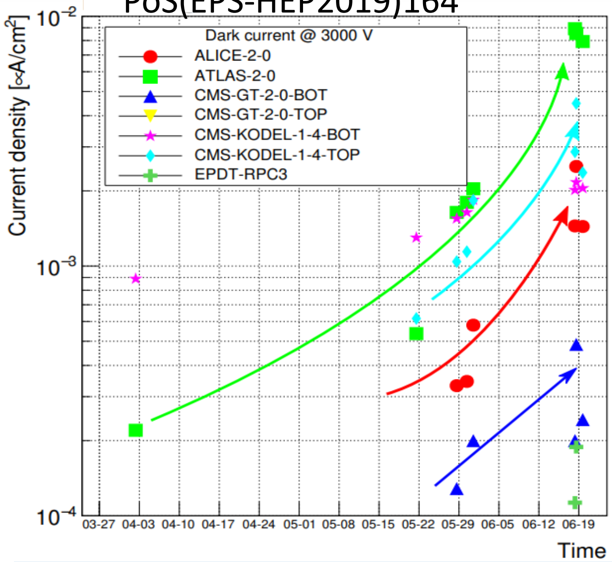
Chamber name	Gap width (mm)	Type
CMS-GT-2-0	2	double gap
CMS-KODEL-1-4	1.4	double gap
ATLAS-2-0	2	single gap
ALICE-2-0	2	single gap
EPDT-RPC3	2	single gap

WP shift with the two mixtures



Eco1: 50%CO_2/45%HFO/4%iso/1%SF_6 (GWP~230)

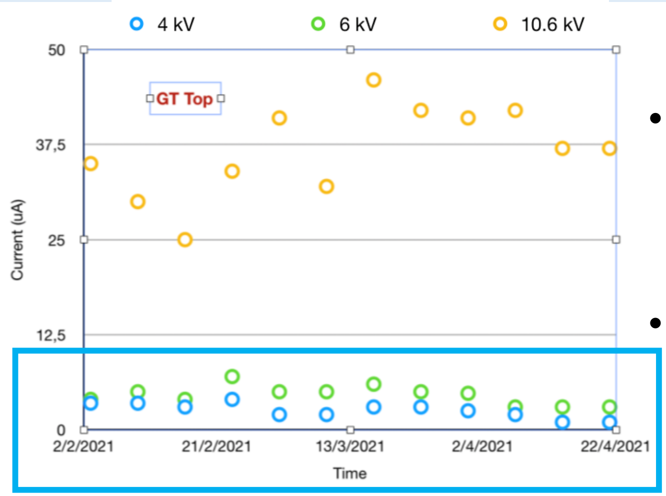
PoS(EPS-HEP2019)164



Issues observed after a few months of irradiation campaign:

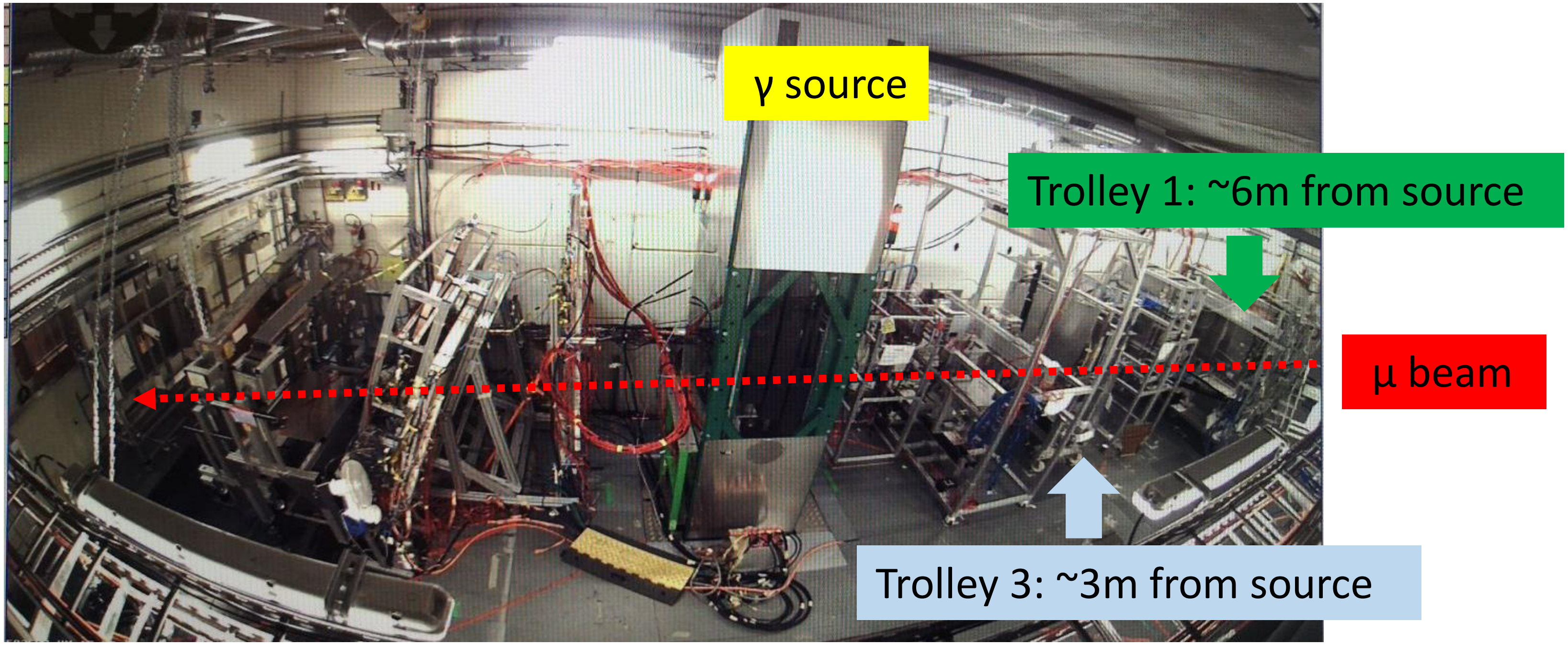
- High WP shift w.r.t. std case;
- Significant increase of the Ohmic currents.

Eco2: 60%CO_2/35%HFO/4%iso/1%SF_6 (GWP~230)



- More stable trend of ohmic currents: no clear sign of aging effects;
- Lower WP shift.

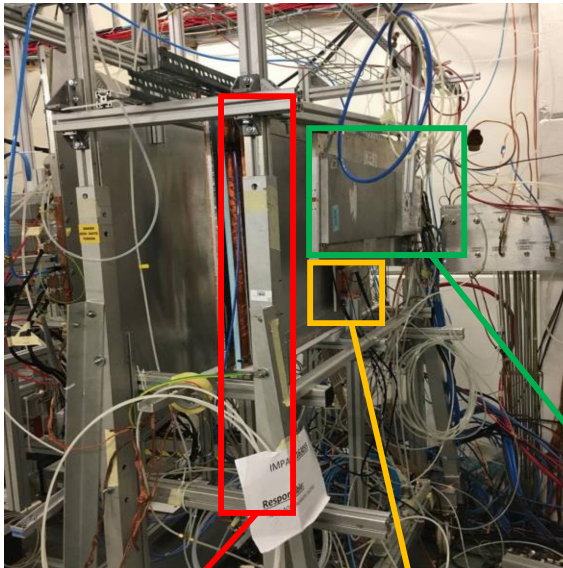
2021 beam tests at GIF++



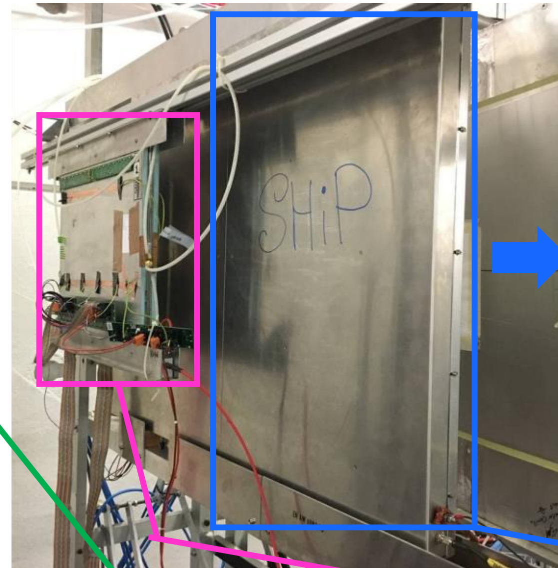
- Five chambers tested (ALICE, ATLAS, CMS RE1_1, EPDT, LHCb/SHiP) readout instrumented;
- Beam trigger during μ spill provided by the coincidence of two 10x40 cm^2 scintillators with the GIF++ scintillators (10x10 cm^2 effective area);
- Gamma rate evaluation (autotrigger mode) during interspill;
- Three mixture tested with several ABS:
  Std: 95.2% R134a/4.5% iso/0.3% SF_6 (GWP~1430)
  Eco2: 60%CO_2/35%HFO/4%iso/1%SF_6 (GWP~230)
  Eco3: 69%CO_2/25%HFO/5%iso/1%SF_6 (GWP~230)

2021 beam tests at GIF++

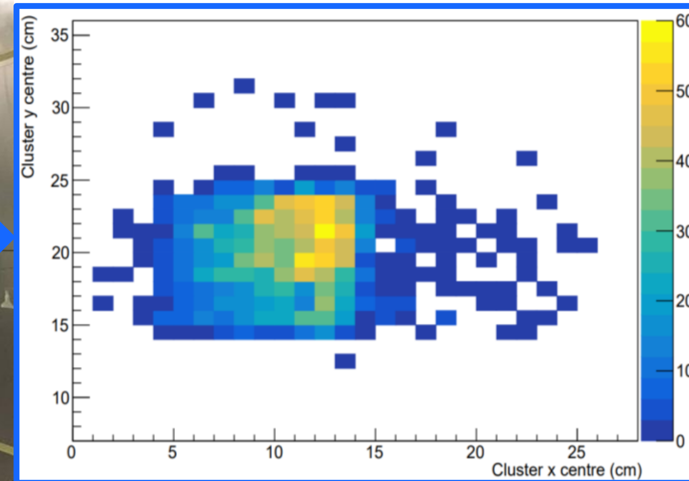
Trolley 3 (~3m from source)



Trolley 1 (~6m from source)



SHiP/LHCb chamber



EPDT RPC:

- 70 x 100 cm^2
- 2 mm single gap
- 2 mm Bakelite electrodes
- 1D readout, 7 strips, 2.1 cm pitch
- Digitizer

ATLAS RPC:

- 10 x 55 cm^2
- 2 mm single gap
- 1.8 mm Bakelite electrodes
- 1D readout, 1 strip
- Digitizer

CMS RE1_1 RPC:

- Trapezoidal (height 10 cm and bases 51 cm and 33 cm)
- 2 mm double gap
- 2 mm Bakelite electrodes
- 1D readout, 128 strips, 1 cm pitch
- TDC

ALICE RPC:

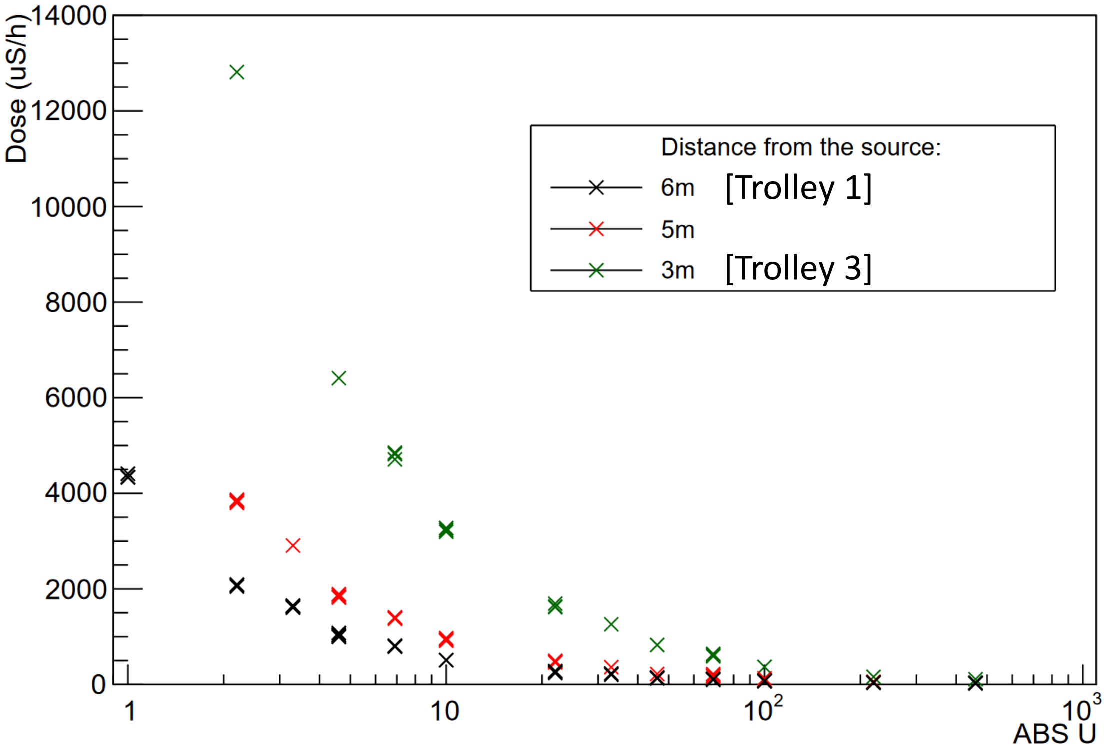
- 50 x 50 cm^2
- 2 mm single gap
- 2 mm Bakelite electrodes
- 2D readout, 16+16 strips, 3 cm pitch
- TDC

SHiP RPC:

- 70 x 100 cm^2
- 1.6 mm single gap
- 1.6 mm Bakelite electrodes
- 2D readout, 32+32 strips, 1cm pitch
- TDC

Dose/rate measurements

In order to compare data from different chambers (located at different distances from source) in similar conditions, dose measurements were performed.

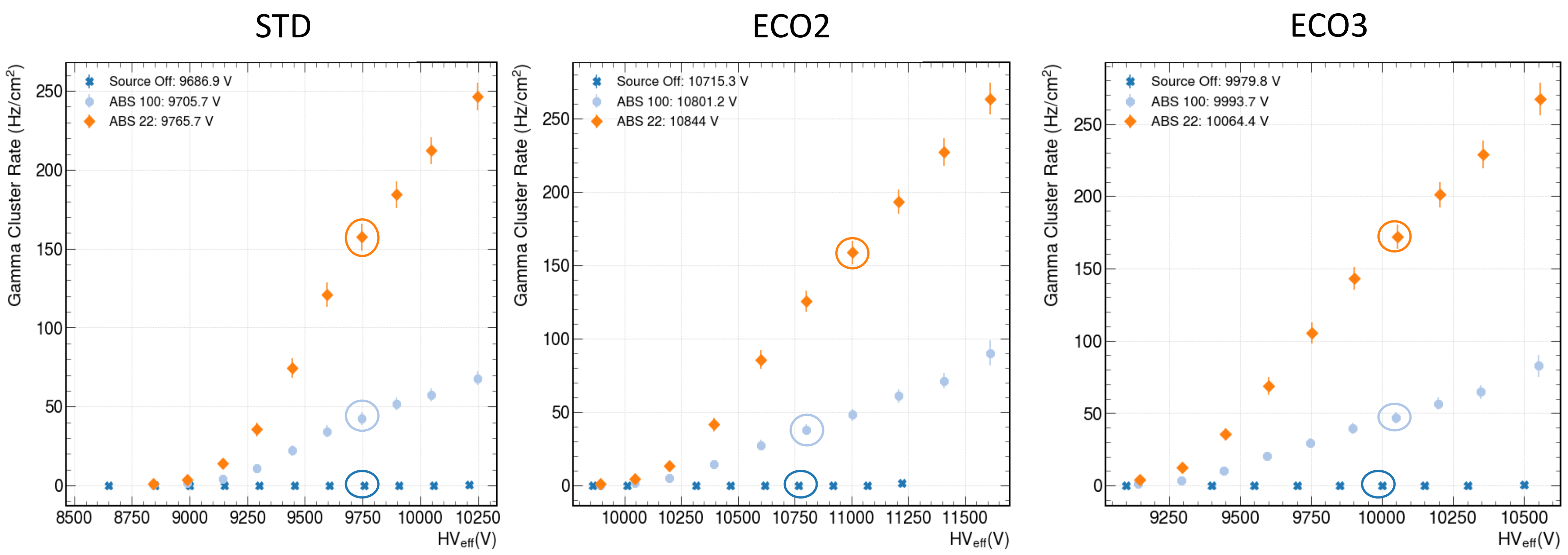


Results are reported in three different conditions:

- source OFF (no irradiation)
- Dose ~500 uS/h (ABS 10 for Trolley 1 and ABS 69-100 for Trolley 3)
- Dose ~2000 uS/h (ABS 2.2 for Trolley 1 and ABS 22 for Trolley 3)

Gamma cluster rate

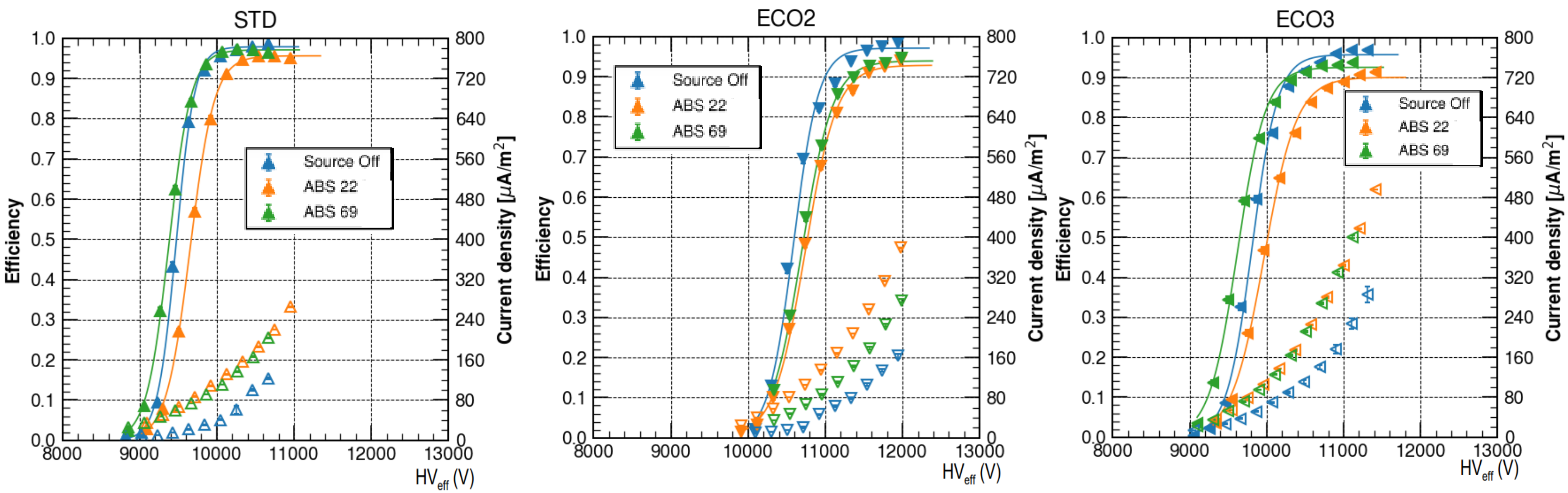
CMS RE1_1 – 2 mm double gap, trolley 3 (~3m from source)



- Gamma rates measured with the three mixtures are comparable at the WP for the same ABS
- The increase with HV is more pronounced at higher irradiation conditions

Efficiency and currents

EPDT – 2mm gap



WP= HVeff at 95% of the plateau efficiency ε_{max}.

Fit: $\varepsilon = \frac{\varepsilon_{max}}{1+e^{-\gamma(HV-HV_{50\%})}}$

- WP shift at source OFF within 1200 V *[Δ($WP_{eco2\text{-}std}$)~1200 V and Δ($WP_{eco3\text{-}std}$) ~450 V]*
- Maximum efficiency comparable at source OFF;

  Efficiency degradation at ~ 2000 µS/h higher for eco3 *[~2% for std, ~4% for eco2 and ~6% for eco3]*
- Current density with eco-gas mixtures higher at WP w.r.t. std. Rapid increase on eff. plateau.

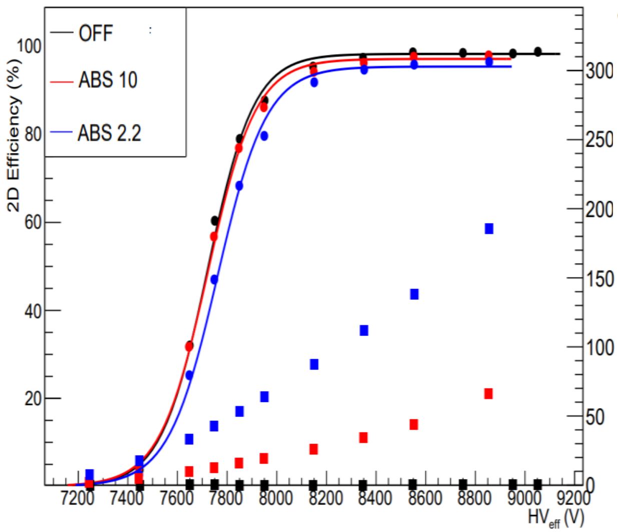
  [At WP and source OFF: I_{std}~25 µA/m², I_{eco2}~2I_{std} and I_{eco3}~3I_{std}

  At ~ 2000 µS/h: I'_{std}~140 µA/m², I'_{eco2}~1.5I'_{std} and I'_{eco3}~1.8I'_{std}.]

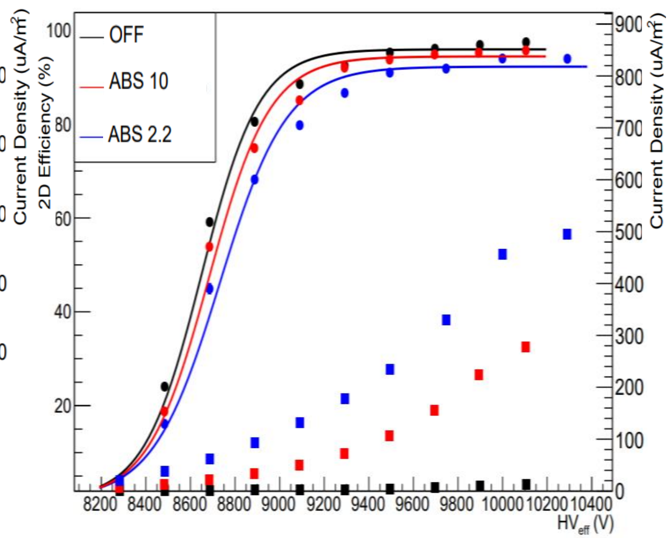
Efficiency and currents

LHCb/SHiP – 1.6 mm gap

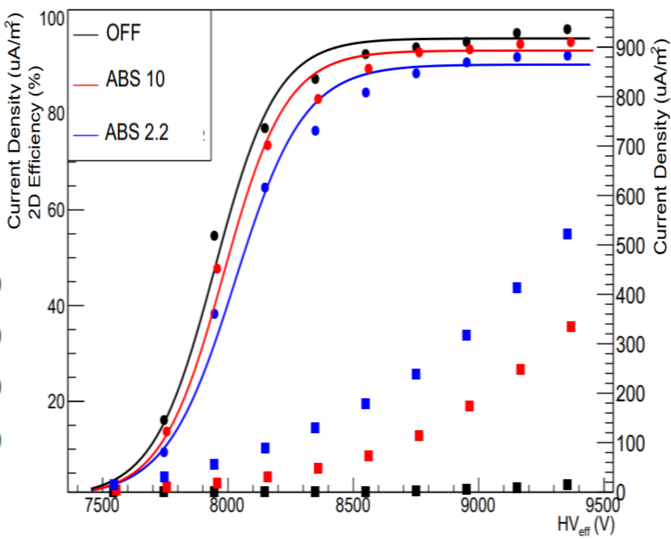
STD



ECO2



ECO3



- WP shift at source OFF within 1 kV *[Δ($WP_{eco2-std}$)~1000 V and Δ($WP_{eco3-std}$) ~300 V]*
- Maximum efficiency comparable at source OFF;

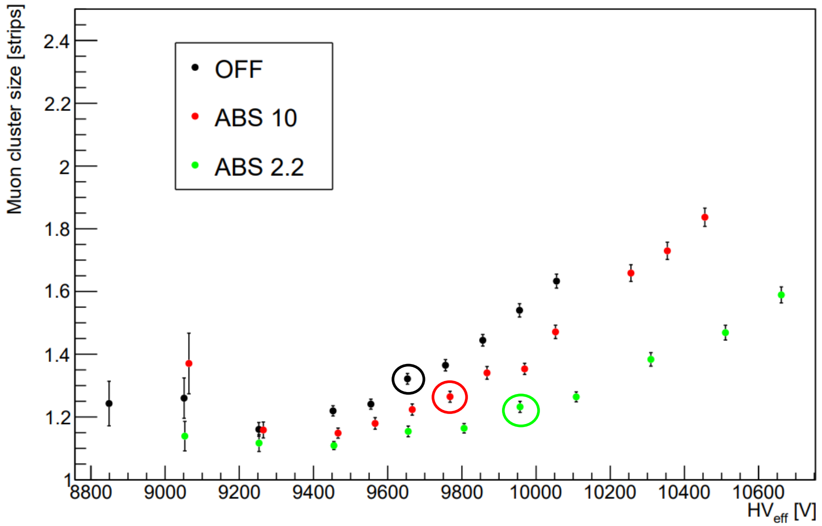
  Efficiency degradation at ~ 2000 μS/h higher for eco3 *[~3% for std, ~4% for eco2 and ~6% for eco3]*
- Negligible current density at source OFF. Current density with eco-gas mixtures higher at WP w.r.t. std at higher irradiation conditions. Rapid increase on eff. plateau.

  [At~ 2000 μS/h: I'_{std}~70 μA/m^2 , I'_{eco2}~2I'_{std} and I'_{eco3}~2I'_{std}]

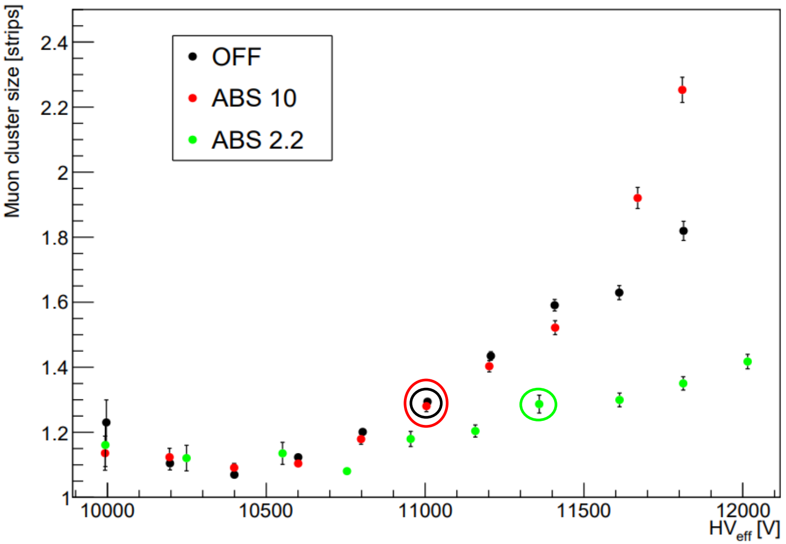
Cluster size

ALICE – 2 mm gap, strip pitch ~3 cm

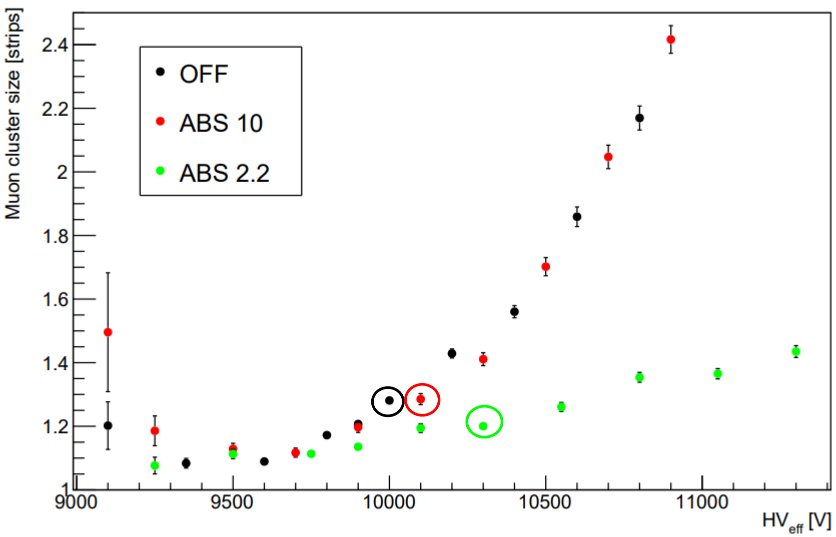
STD



ECO2



ECO3

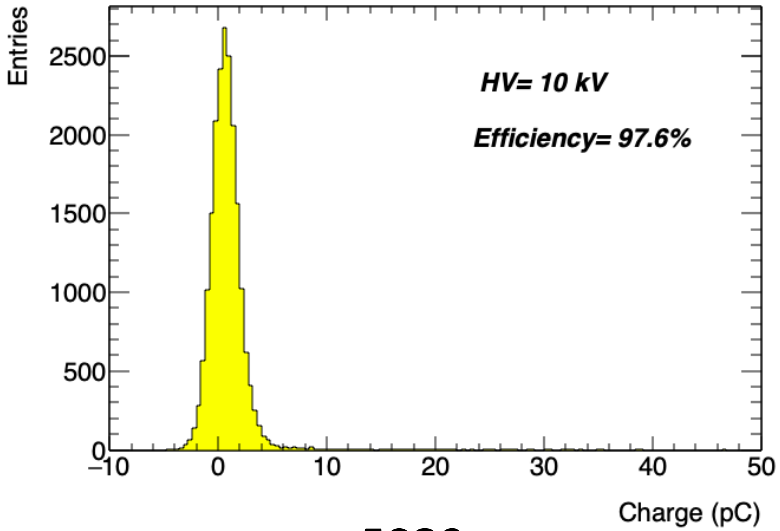


The average cluster size at WP is comparable for the three mixtures at the same irradiation conditions.

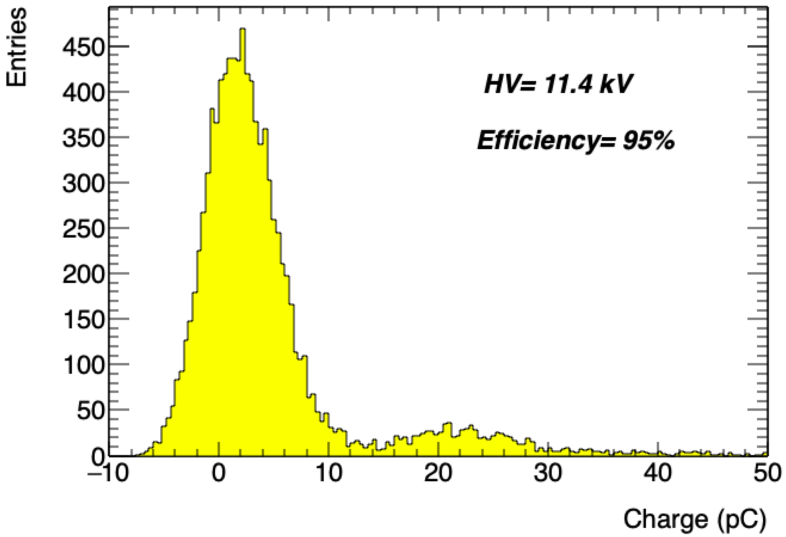
Charge

ATLAS – 2 mm gap, 1 readout strip

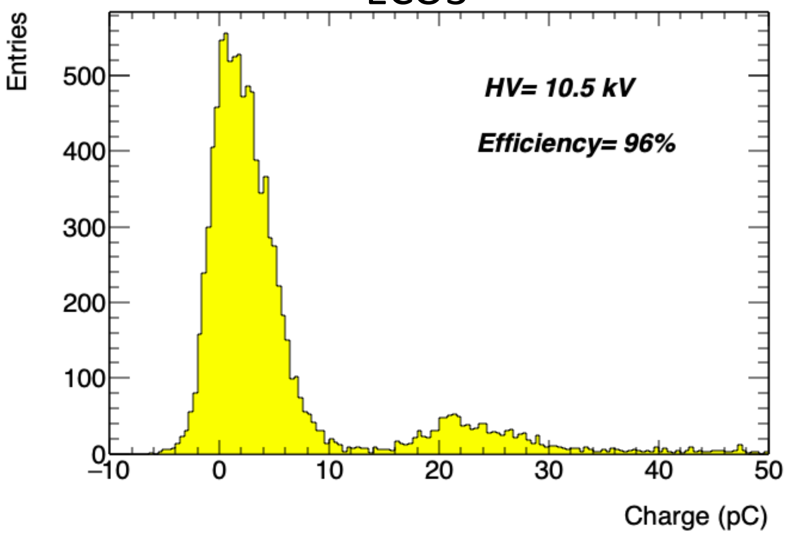
STD



ECO2



ECO3



- Total prompt charge measured at source OFF on the efficiency plateau;
- Second peak at ~20 pC with eco mixtures due to «extra-charge» events (multiple avalanche signals);
- The majority of these events have charge within 30 pC.

Summary

Eco-mixtures (GWP ~ 230) performance w.r.t. standard mixture (GWP ~ 1430)

Mix	$\Delta(WP_{eco-std})$	Eff_max at source OFF	Eff degradation	Curr. Density	Av. Cs	Gamma cl. Rate at the same ABS	Charge content of events
Eco2	~ 12% WP_{std}	compatible	~ 4%	~1.5-2I_{std}	compatible	compatible	small fraction of extra-charge events
Eco3	~ 4% WP_{std}	compatible	~ 6%	~1.8-2I_{std}	compatible	compatible	small fraction of extra-charge events

- Promising results. However, higher operating currents w.r.t. std case measured.
- Higher currents → higher probability of pollutant production.
- RPC aging processes with the new mixtures to be carefully studied.

Conclusion

- The RPC ECOGAS@GIF++ Collaboration is a joint effort between RPC communities from ATLAS, ALICE, CERN Gas team, CMS, LHCb/SHiP with the aim of searching for new eco-friendly gas mixtures for RPCs.

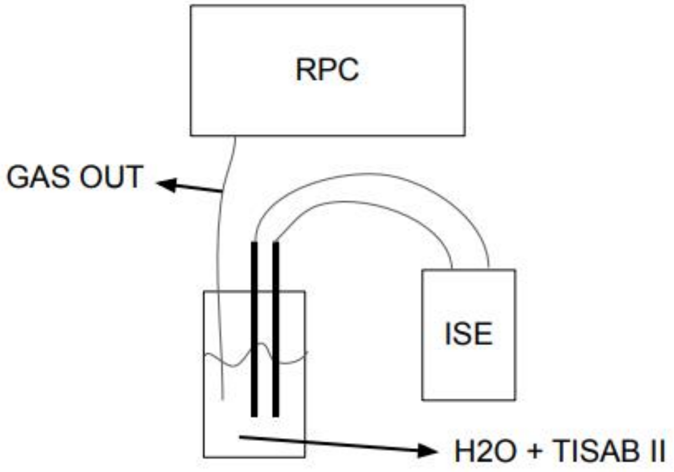
- Laboratory tests with cosmic rays have been performed by each group in order to replace R134a, the standard gas mixture main component. Current results are focused on HFO-1234ze/CO_2 based mixtures.

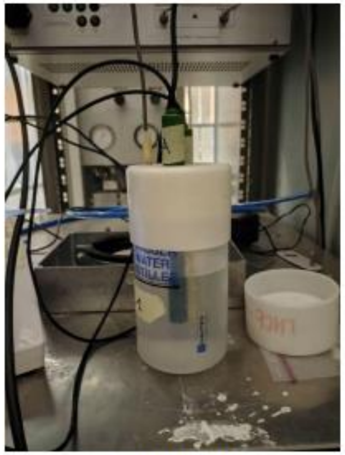
- Several campains at GIF++ show promising RPC performance with mixture having 60% CO_2/35% HFO and 69% CO_2/25% HFO. Aging effects are under investigation.

Thank you!

Aging studies: HF impurities

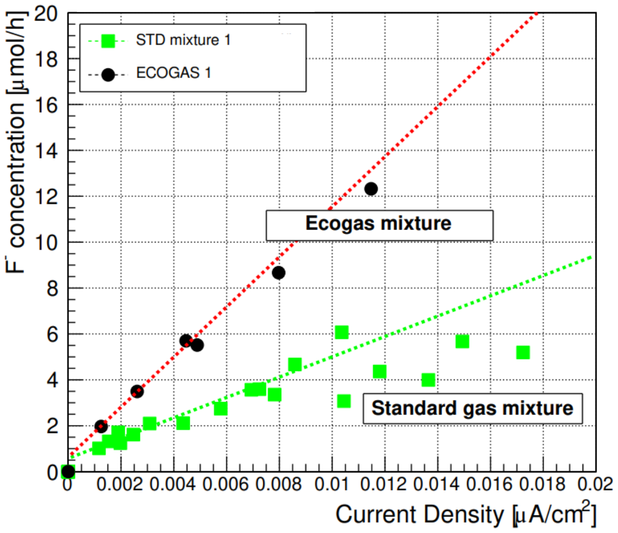
- Aging effects with eco1 observed also with dedicated measurements of HF impurities.
- F^- produced from the R134a and HFO molecules, expecially in high irradiation conditions and high electric fields. It combines with H_2O, producing HF acid → **aging effects**;
- Measurement of the HF production is performed with Ion Selective Electrodes (ISE);
- The HF production rate is ~2 times higher for eco1 mixture w.r.t. std case;
- Measurements with eco2 and eco3 ongoing.





water + TISAB II

Meas. with CMS GT chamber, 2mm gap

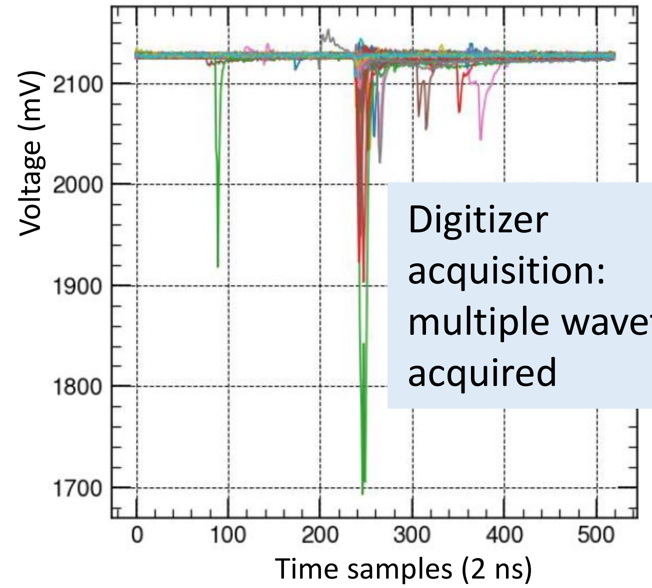


2021 beam tests at GIF++

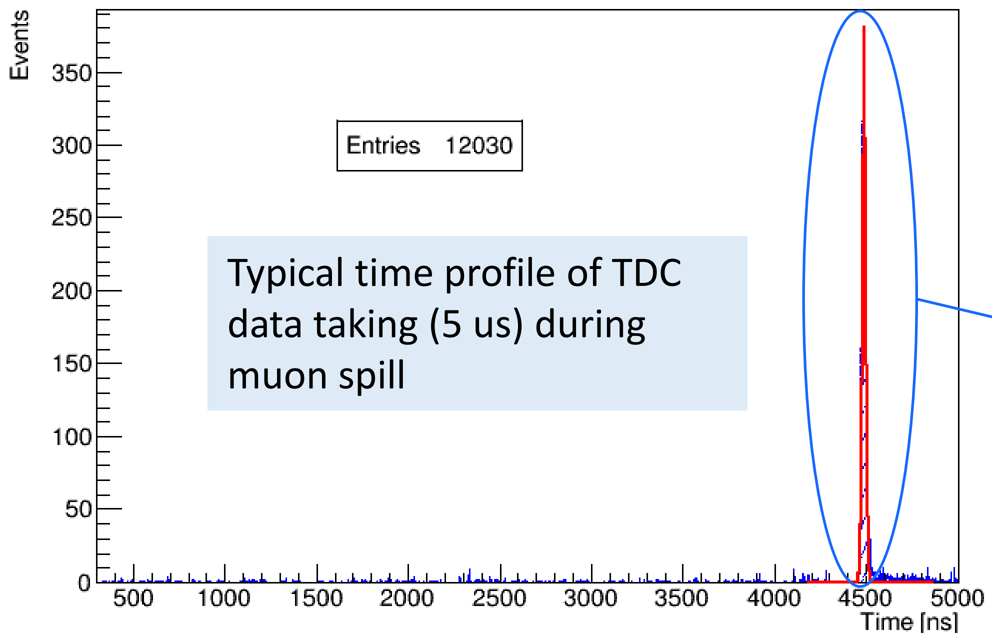
Two readout systems used:

- TDC, dual readout:
  acquisition triggered by muons +
  random triggers during interspill; → Gamma rate evaluation

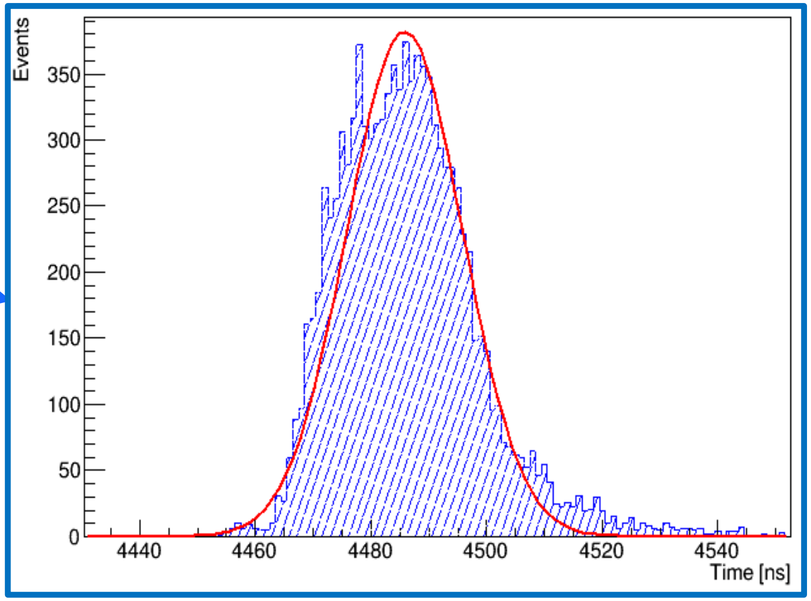
- Digitizer, direct waveform acquisition:
  acquisition triggered by muons +
  autotrigger acquisition (1.2 ms).



Digitizer acquisition: multiple waveforms acquired

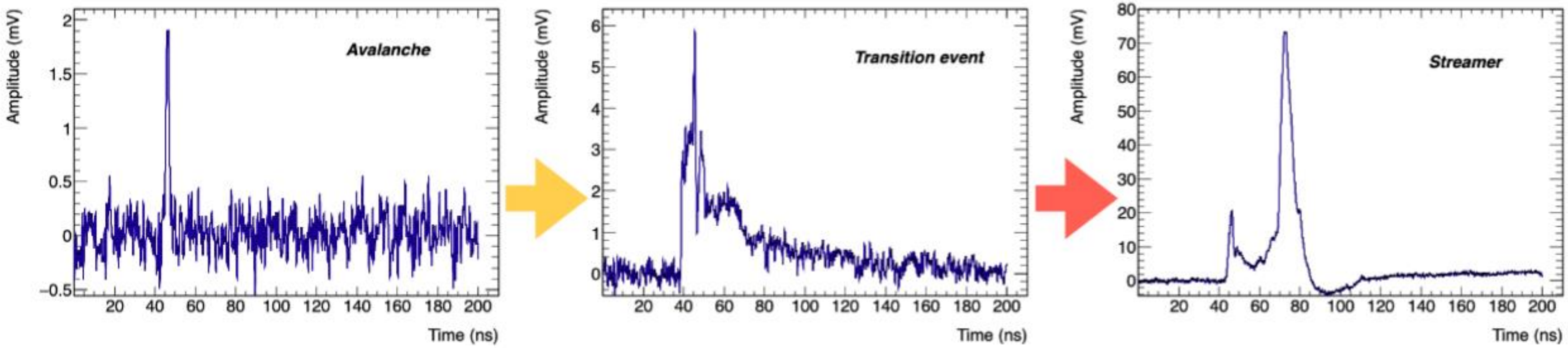


Typical time profile of TDC data taking (5 us) during muon spill



Event classification

Roma Tor Vergata group, contribution to VCI2022



Avalanche: very short signal

Extra-charge events: multiple avalanche signal and/or large tail following the avalanche precursor

Streamer events: avalanche signal precursor followed by a signal lasting tens of ns