Eco-friendly Resistive Plate Chamber detectors for future HEP applications

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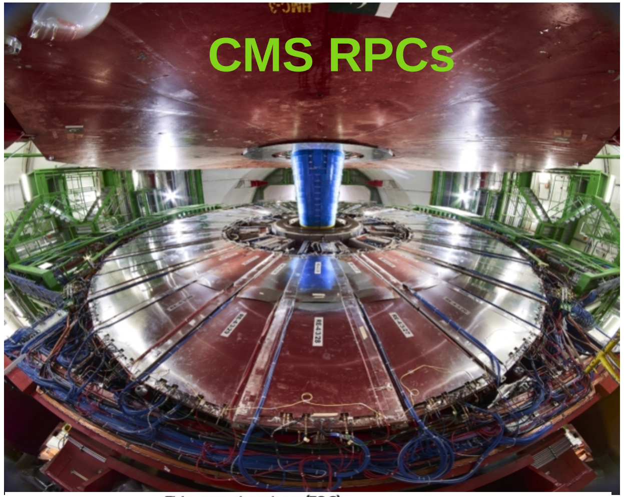
Overview

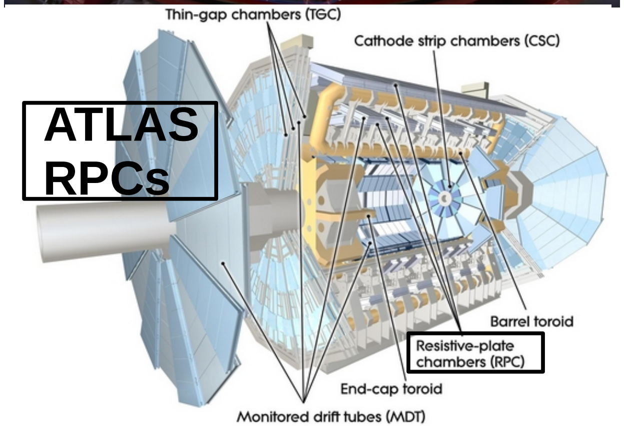
- RPCs and their gas mixture
- Need for more eco-friendly gases
- The RPC EcoGas@GIF++ collaboration
- Beam test results
- First aging studies and other activities
- Conclusion

RPCs in High Energy Physics

- Resistive Plate Chambers
  - Gaseous detectors widely employed in HEP



- For muon detection
- Relatively cheap
  → Large area coverage
- Fast response
  → Used for triggering and identification purposes



Issues with current gas mixture

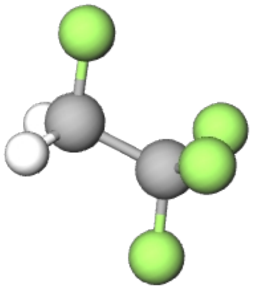
- Currently employed gas mixture in HEP (standard gas mixture in the following)

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

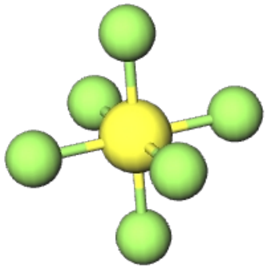
- Operated in avalanche mode

  → To grant timing 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

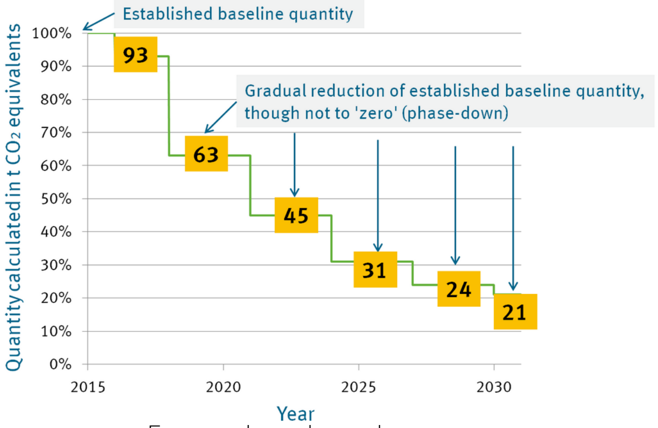
→ Is this a problem? Yes!

[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)

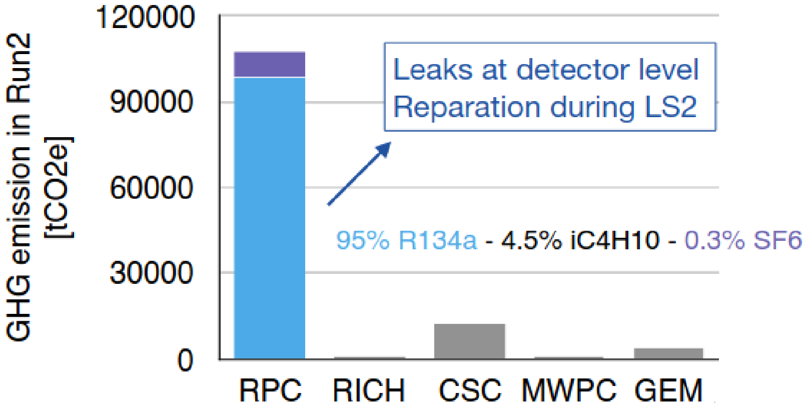
The need for an eco-friendly gas mixture

- New EU regulations have 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 phase down plan



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 studies in more controlled environments i.e. beam tests
  → Studies on long-term behavior of detectors operated with such gases i.e. aging tests

The RPC EcoGas@GIF++ collaboration

- Cross-experiment collaboration

  → It includes CMS, ALICE, ATLAS, ShiP/LHCb and the detector technology group of CERN

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

  → Experimental facility located at the CERN North Area

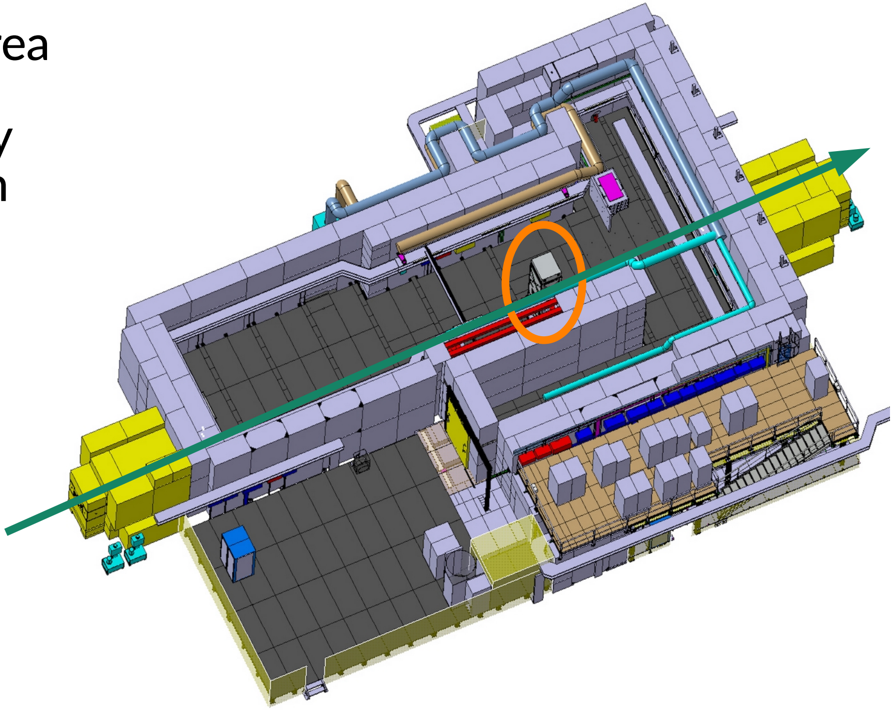
  → Provided with a 12.5 TBq ^{137}Cs source, high activity allows one to simulate long operating periods in much shorter time spans (aging studies) – irradiation can be modulated by means of attenuation filters

  → High energy (100 GeV/c) muon beam

  in dedicated beam time periods

  → Combination of muon beam with source

  → Study of detector rate capability



GIF++ bunker layout

Experimental setup

- 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

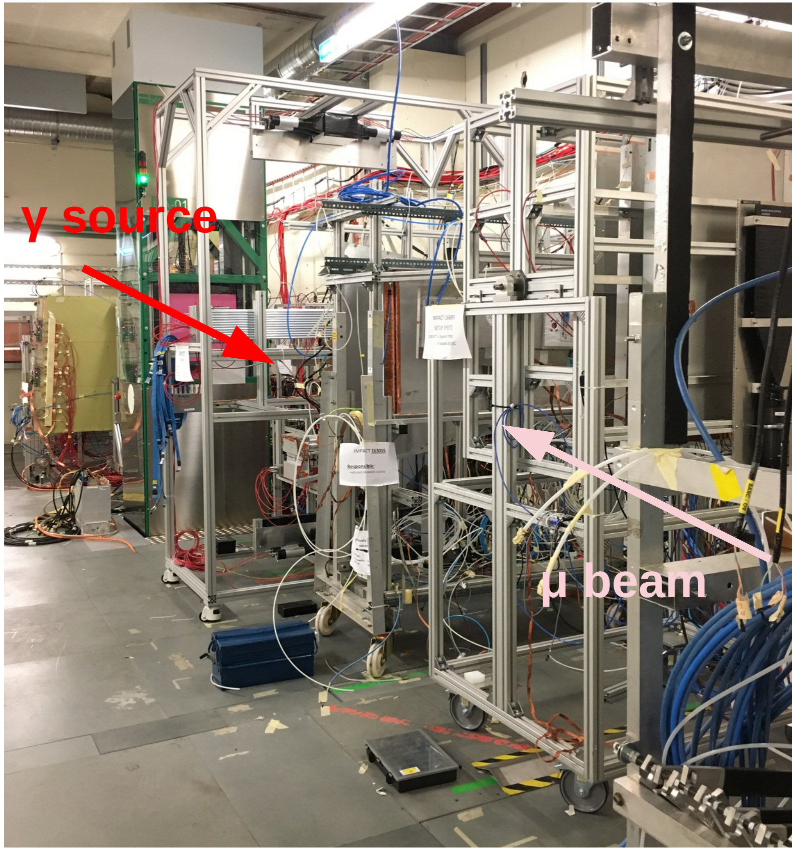
- Common gas and HV systems

- Online data monitoring tool and DCS system provided by CMS

- Two different DAQs for beam tests (TDCs and digitizer)

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
EP-DT	7000	1	2 / 2	Digitizer	7
ALICE	2500	1	2 / 2	TDC	32
ShiP/LHCb	7000	1	1.6 / 1.6	TDC	64

Summary table of all the RPCs of the collaboration

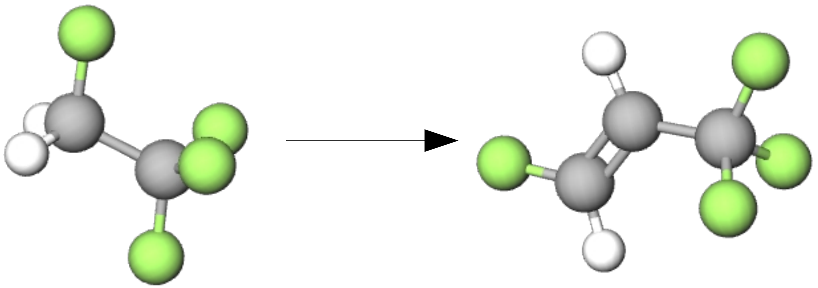


View of the setups inside the GIF++ bunker

Experimental approach

- $C_2H_2F_4$ is the main contributor to the gas mixture GWP
  → First step is to find a substitute for this gas

- Possible candidate is *tetrafluoropropene* ($C_3H_2F_4$, HFO-1234ze) → HFO in the following
  → Similar chemical structure to $C_2H_2F_4$
  → Lower GWP ~ 6



GWP ($C_2H_2F_4$) ~ 1430

GWP ($C_3H_2F_4$) ~ 6

- Replace completely $C_2H_2F_4$ with $C_3H_2F_4$?
  → Not possible because HFO has a lower Townsend coefficient
  → Working point goes to over 15 kV
- Dilute HFO with “space-holder gas” to lower the working point
  → CO_2 is a promising choice

Gas mixtures that have been tested by the collaboration

Gas mixture	$C_2H_2F_4$	HFO-1234ze	CO_2	$I\text{-}C_4H_{10}$	SF_6	GWP
STD	95.2	0	0	4.5	0.3	1430
ECO1	0	45	50	4	1	230
ECO2	0	35	60	4	1	231
ECO3	0	25	69	5	1	230

Dose measurements @ GIF++

- Different RPCs are at different distances from the source
  → Different gamma rate
  → To compare performances we carried out instant dose rate measurements with a dosimeter

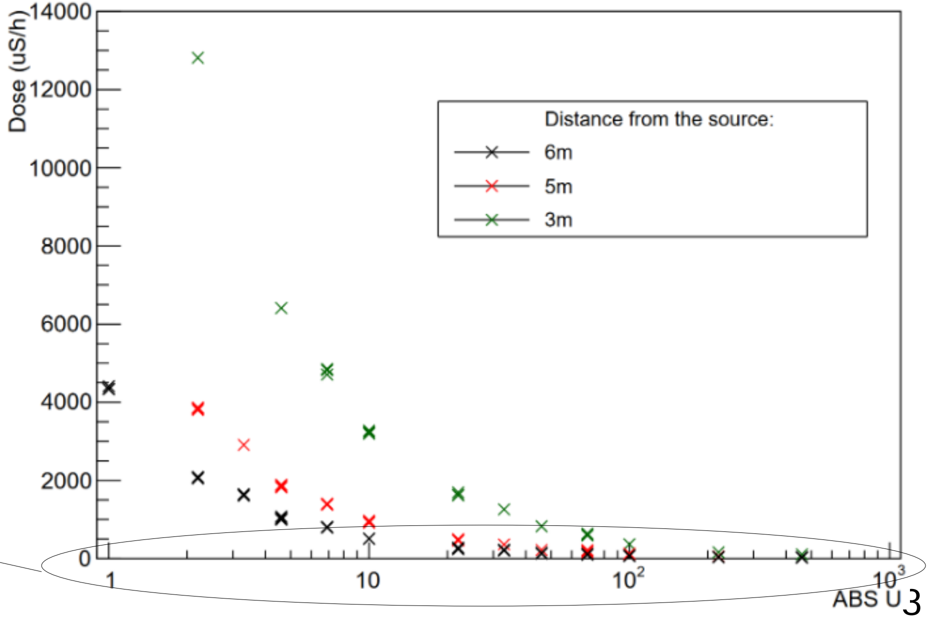
Dosimeter installed in the GIF++

- We compared the dose rate and found values of absorption factors that correspond to similar doses
  → 3 conditions

- Source OFF
  → No irradiation

- 500 µS/h
  → ABS **10**/**69**

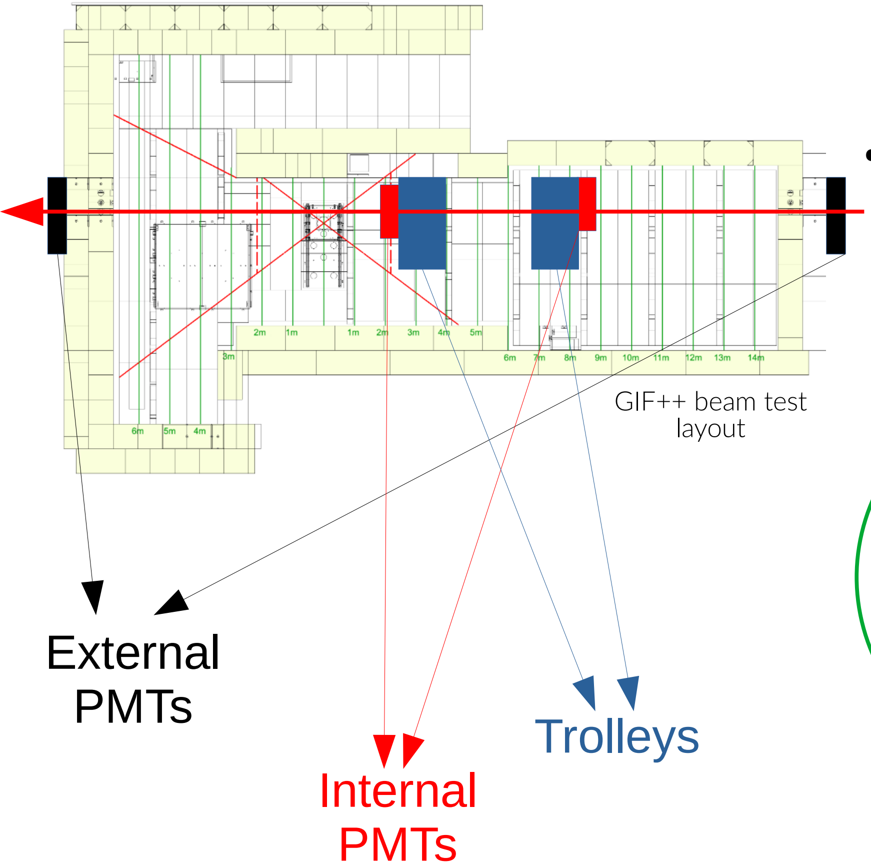
- 2000 µS/h
  → ABS **2.2**/**22**



“Absorption factors”, “ABS” = pure number to quantify background attenuation

Beam test setup

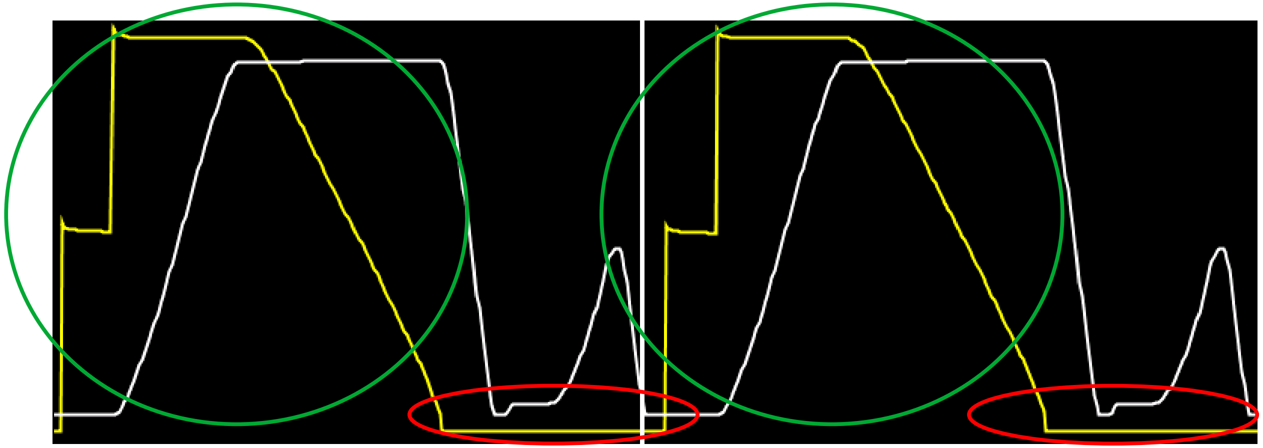
- Trigger provided by coincidence of 4 scintillators (2 inside the bunker and 2 outside)
- Readout of signals from the detector using TDCs and digitizers



GIF++ beam test layout

- **TDCs** → dual readout
  1) **During μ spill** → PMT trigger → efficiency measurement
  2) **Outside spill** → random trigger → rate measurement

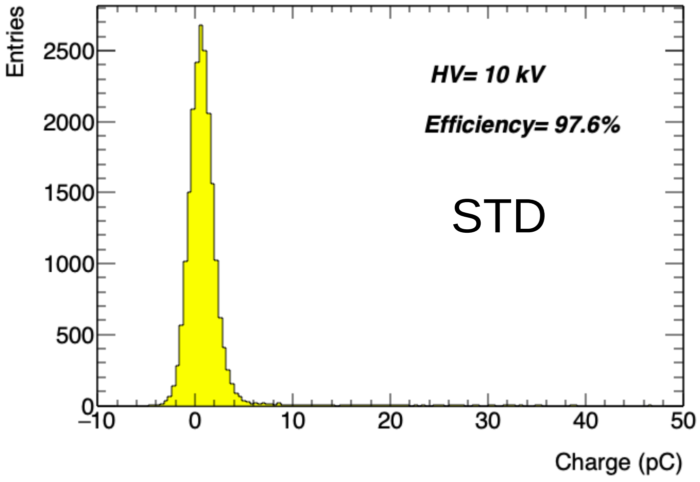
- **Digitizer**
  1) Same trigger for efficiency measurements
  2) Long acquisition window (1.2 μs) and peak count for rate



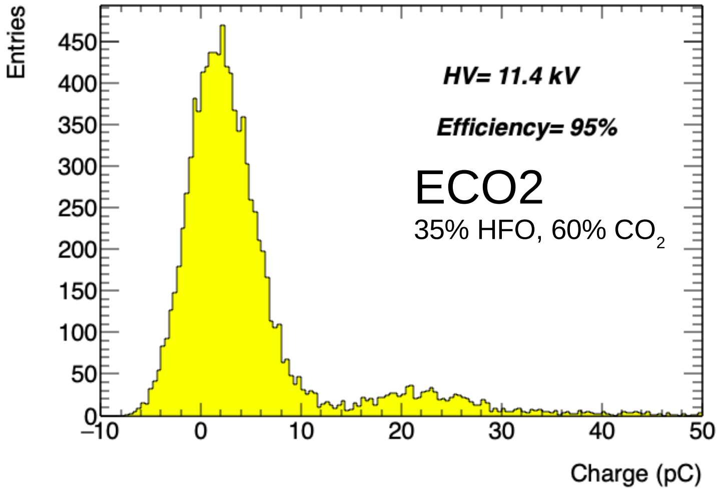
SPS spill cycle

ATLAS - 2 mm

Charge development

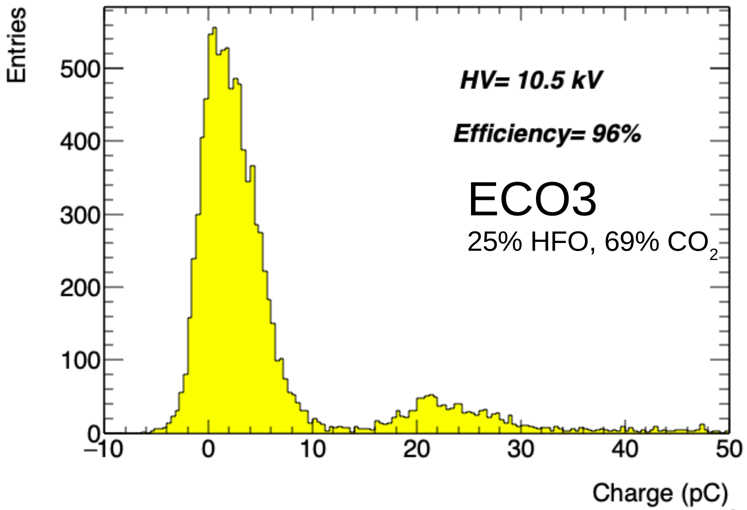


- Measurements of signal charge, picked up by a single strip and readout with a digitizer
- Data shown is without irradiation and at same efficiency values for the three different gas mixtures
- Single and well defined peak with STD gas mixture
- Appearance of a secondary peak with ECO2 and ECO3 due to the presence of secondary avalanches (“transition signals”)

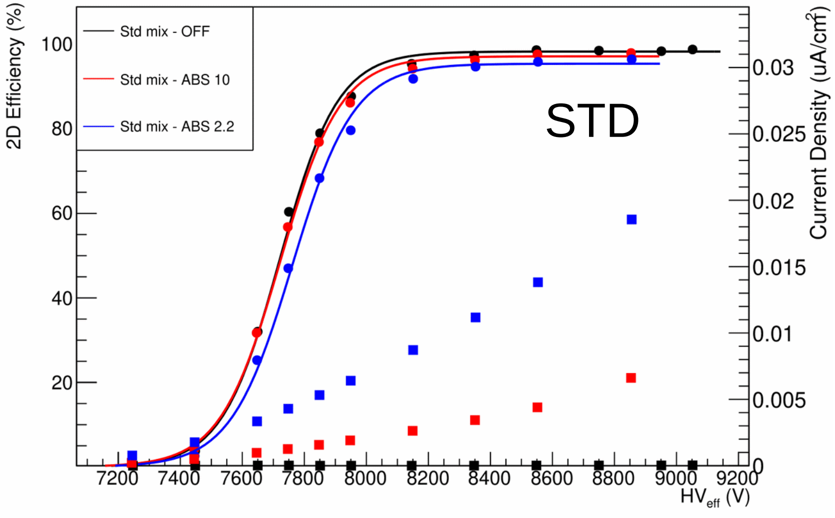


- Increase of mean signal charge
  → Possible acceleration of aging process that has to be closely monitored

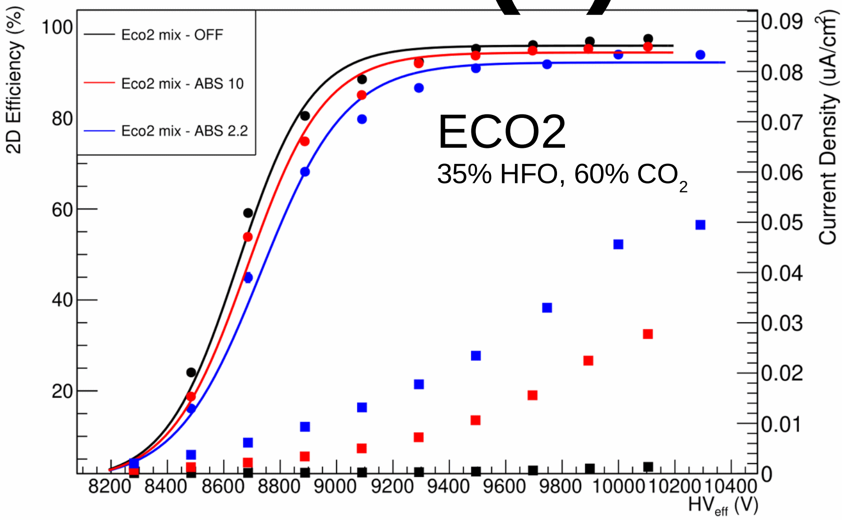
  → Reduction of rate capability

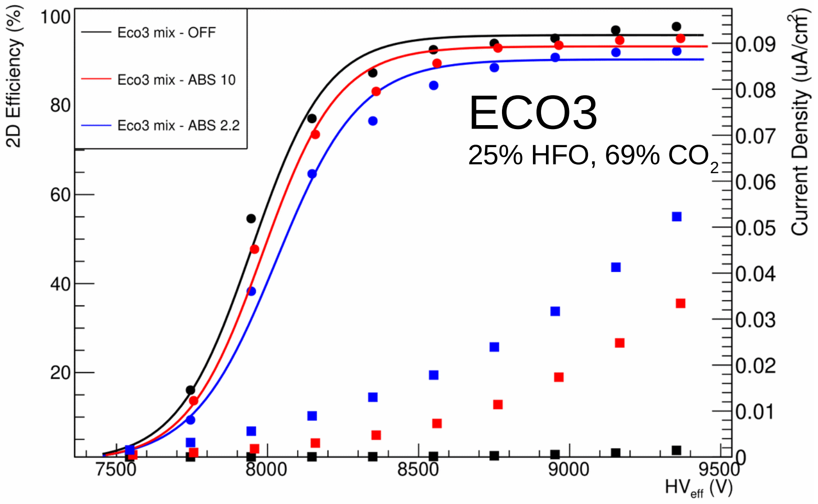


Efficiency and currents (1)



SHiP - 1.6 mm



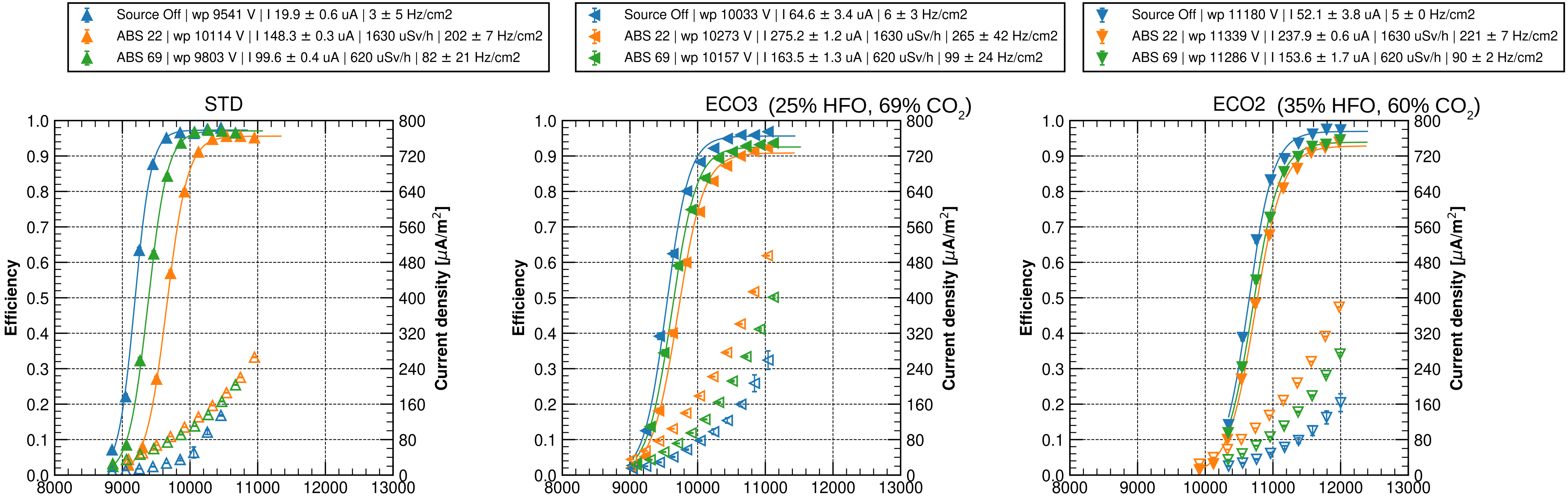


- Data discrimination and digitization using FEERIC front-end cards, developed for ALICE (see Livia Terlizzi's talk on 26th September)
- 2D readout with two planes of perpendicular strips

  → RPC is efficient if at least one hit in both detection planes
- WP shift wrt STD (source OFF) ~ 1000 V (ECO2) and ~ 300 V (ECO3)
- Maximum efficiency comparable w/o irradiation
- Efficiency degradation at 2000 μS/h (ABS 2.2) ~ 3% for STD, 4% for ECO2 and 6% for ECO3
- Currents absorbed under irradiation with ECO2 and ECO3 are almost doubled wrt STD

EPDT - 2 mm

Efficiency and currents (2)

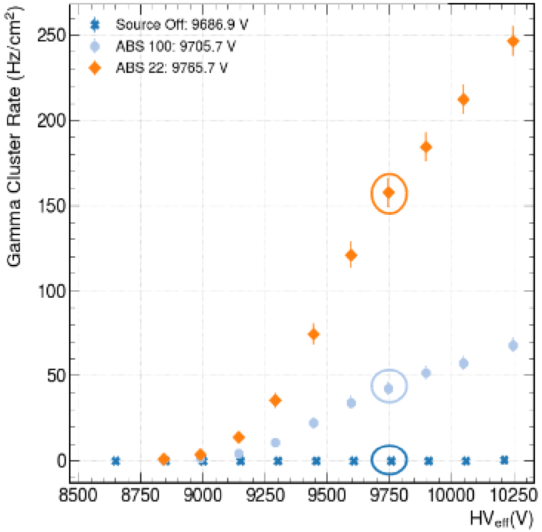


- 1D readout with digitizer
- WP shift wrt STD (source OFF) ~ 1200 V (ECO2) and ~ 450 V (ECO3)
- Maximum efficiency comparable w/o irradiation
- Efficiency degradation at 2000 μS/h (ABS 2.2) ~ 2% for STD, 4% for ECO2 and 6% for ECO3
- Currents at source off are doubled wrt STD with ECO2 and tripled with ECO3
- Currents with irradiation is 1.5 times greater with ECO2 and 1.8 times with ECO3

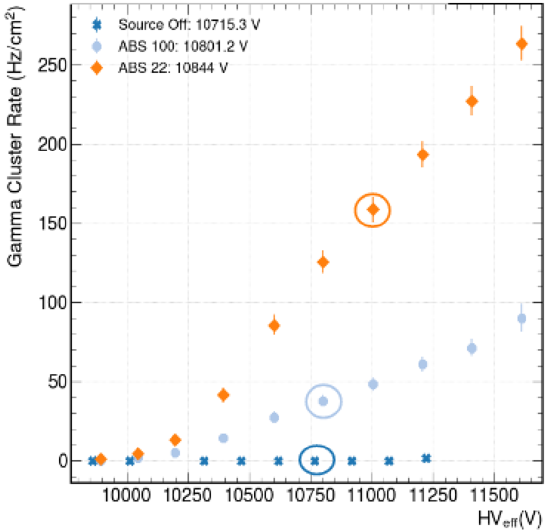
CMS - 2 mm

Measured gamma rate

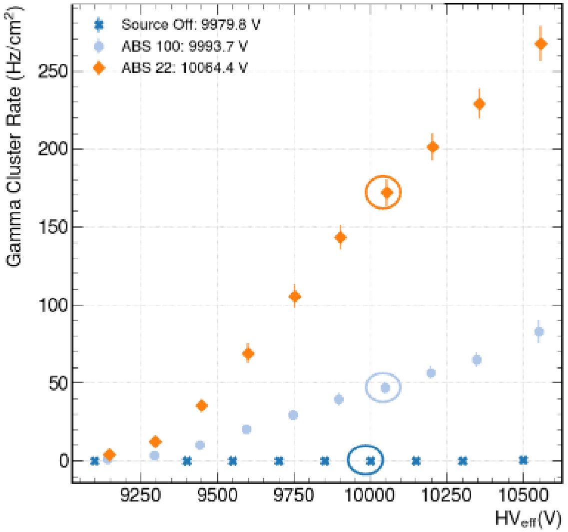
STD



ECO2 (35% HFO, 60% CO_2)



ECO3 (25% HFO, 69% CO_2)



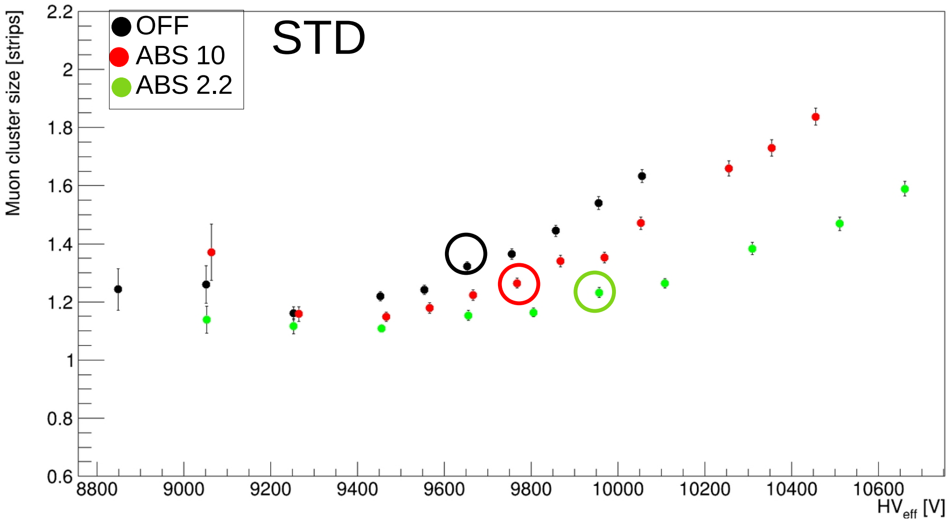
- Cluster rate = strip rate in interspill period divided by the gamma cluster size
  → Measurement of the background radiation due to the presence of the source

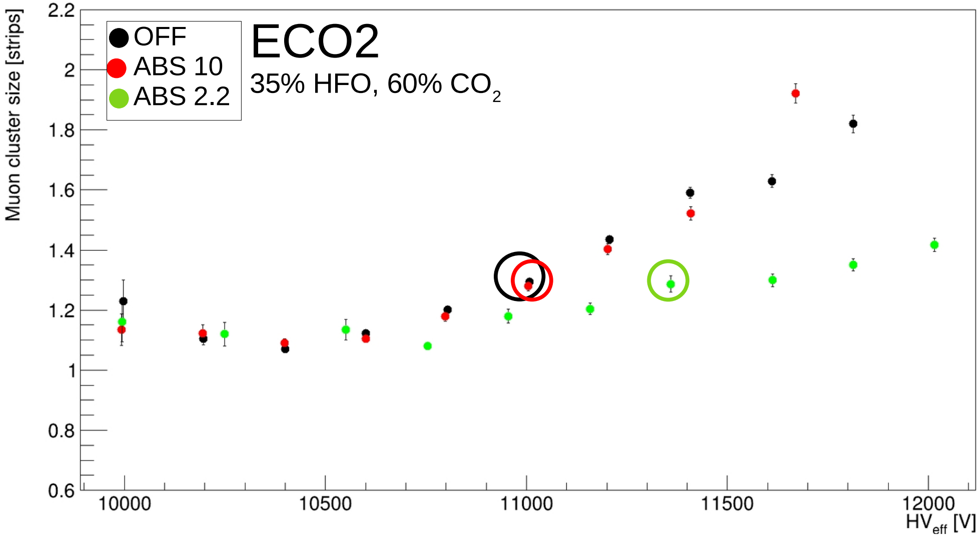
- Values are different for the different detectors since they are at different distances from the source
  → Rate measurement with dosimeter to compare results from different chambers

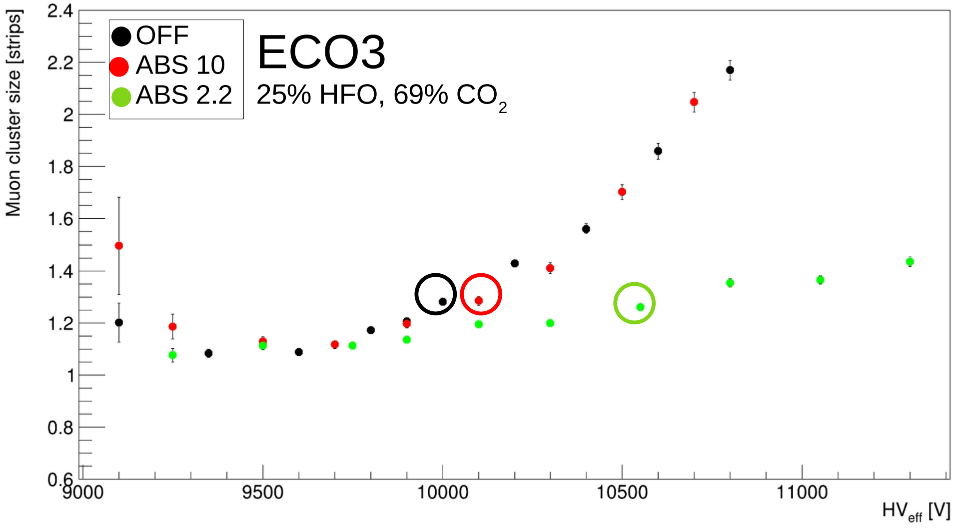
- ~ 0 Hz/cm^2 at source OFF, ~ 40 Hz/cm^2 for ABS 100 and ~ 160 Hz/cm^2 at ABS 22

- Values are comparable for the 3 gas mixtures tested

Cluster size





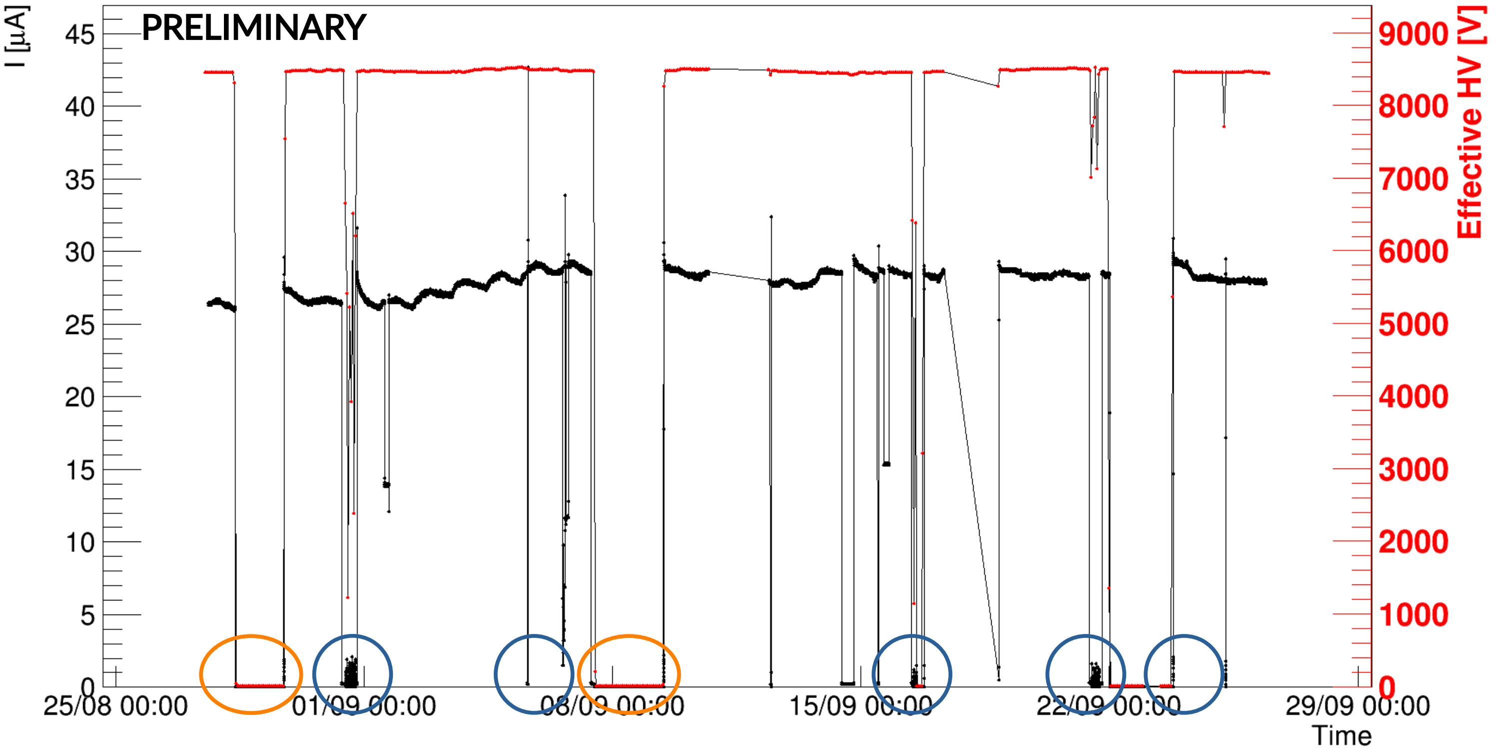


- Data obtained using the FEERIC front-end cards
- Mean muon cluster size for the three tested gas mixtures for the three different irradiation conditions
- Values in the circles correspond to the working point
- Comparable for the three mixtures and for the three irradiation conditions
- Average cluster size values slightly decreases with increasing irradiation

Aging campaign (1)

- Aging campaign started with ECO2 (60% HFO, 35% CO_2) gas mixture, better performance shown in beam test
  → Detectors are exposed to gamma irradiation with high voltage applied at fixed value
  → Measure of current stability in time under irradiation
  → Weekly voltage scans to monitor the stability of the current without irradiation (dark current)

- Fixed ABS set to 2.2 (2000 μS/h)
- Due to higher currents wrt STD gas mixture
  → RPCs operated at 50% efficiency (8.7 kV for RPC shown in plot) for initial stability studies
- Pressure and temperature correction applied every 10 minutes to ensure fixed effective HV
- Weekly HV scans
- Periods in which the irradiation is stopped/change of HFO bottle
- Results from roughly 1 month irradiation are promising

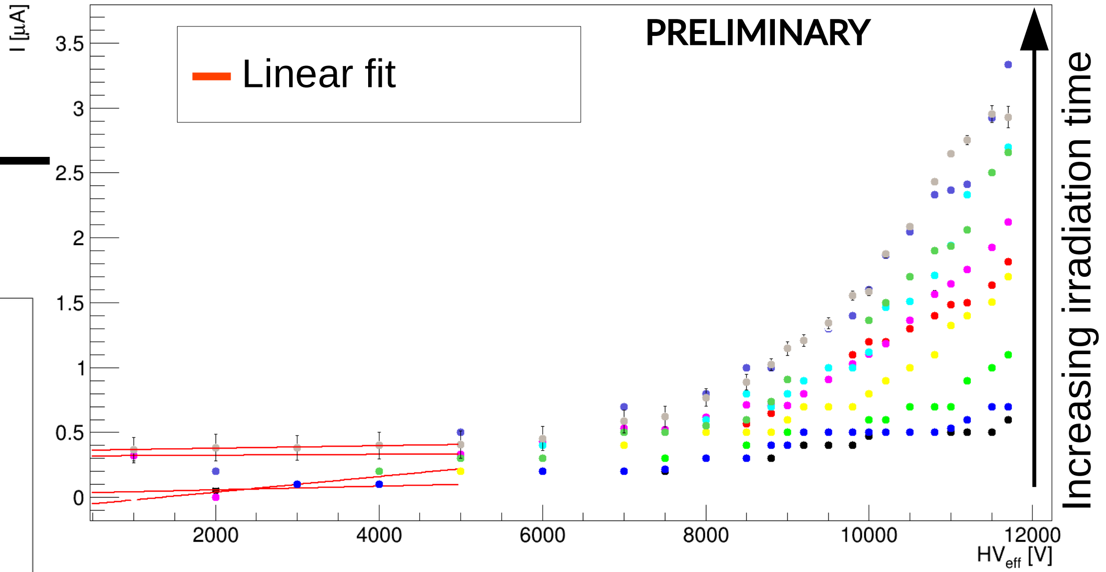


Irradiation campaign ongoing now
→ Still preliminary results

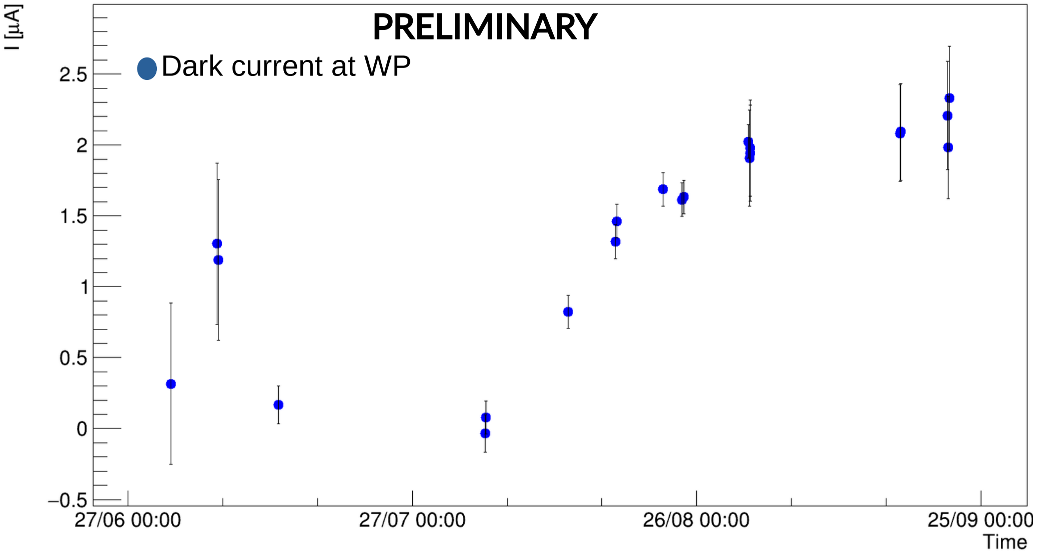
CMS - 2 mm

Aging campaign (2)

- Studies on the stability of the dark current (absorbed when RPC is ON but not exposed to irradiation)
  → Monitoring of the current in the physics region (multiplication region) and the Ohmic one (no multiplication)
  → Ohmic part of the current obtained from linear fit to I(HV) curve from 0 to 5000 V (for 2 mm gaps) and 0 to 4000V (for 1.6 mm gaps)



- Value of current taken at WP (11050 V for this detector) plotted as a function of time
- Ohmic component is subtracted



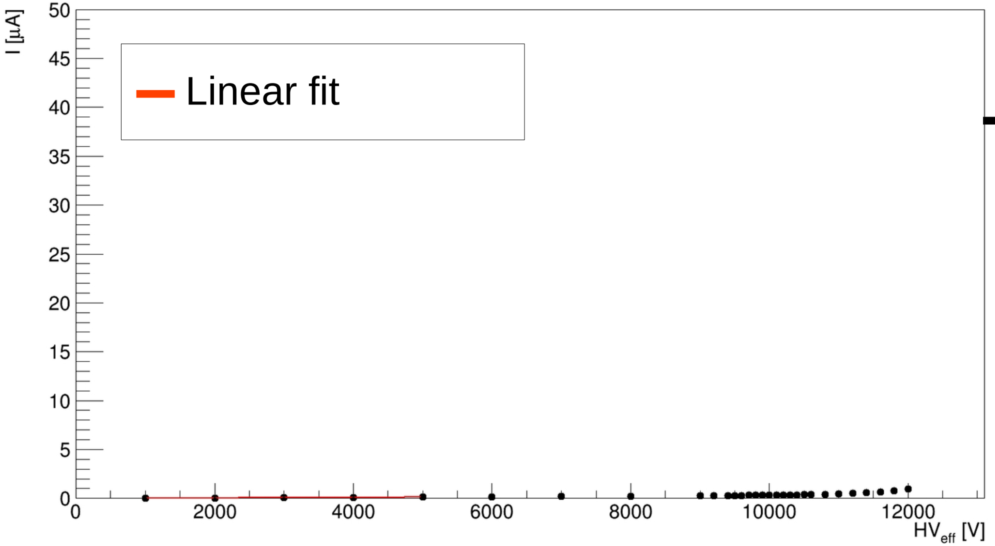
- I(HV) curves taken w/o irradiation (roughly once per week)
- Irradiation between the curves

Irradiation campaign ongoing now
→ Still preliminary results

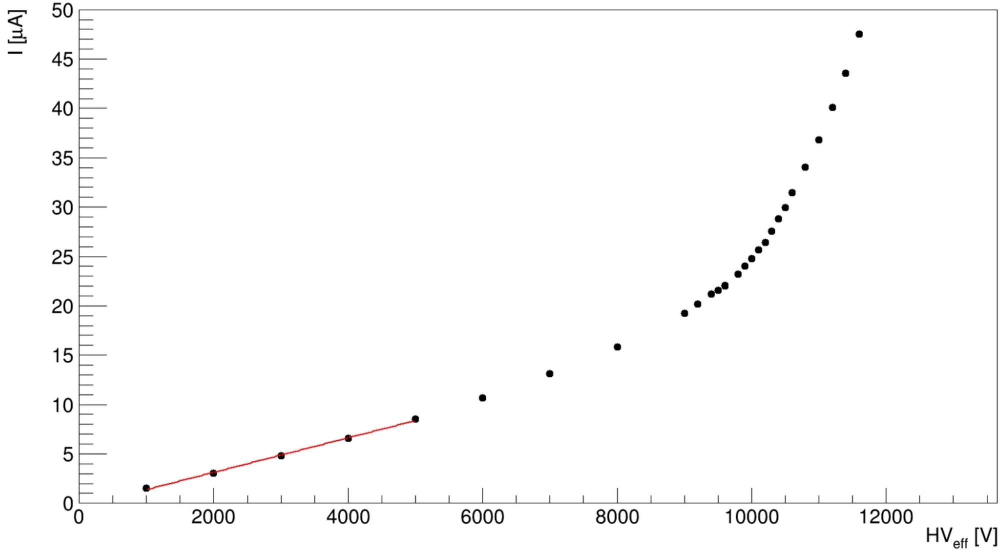
ALICE - 2 mm

Aging campaign (3)

- First irradiation campaign was carried out with ECO1 (45% HFO, 50% CO_2)
  → Preliminary tests of the data taking procedure
  → After the integration of ~ 20 mC/cm^2 an important increase in the absorbed current and dark current (physics and Ohmic component) appeared



- Two HV scans without irradiation
- Irradiation between two scans
- Integrated charge between the two scans ~ 20 mC/cm^2



- Increase in both Ohmic and physics component
- **Observed in all detectors**

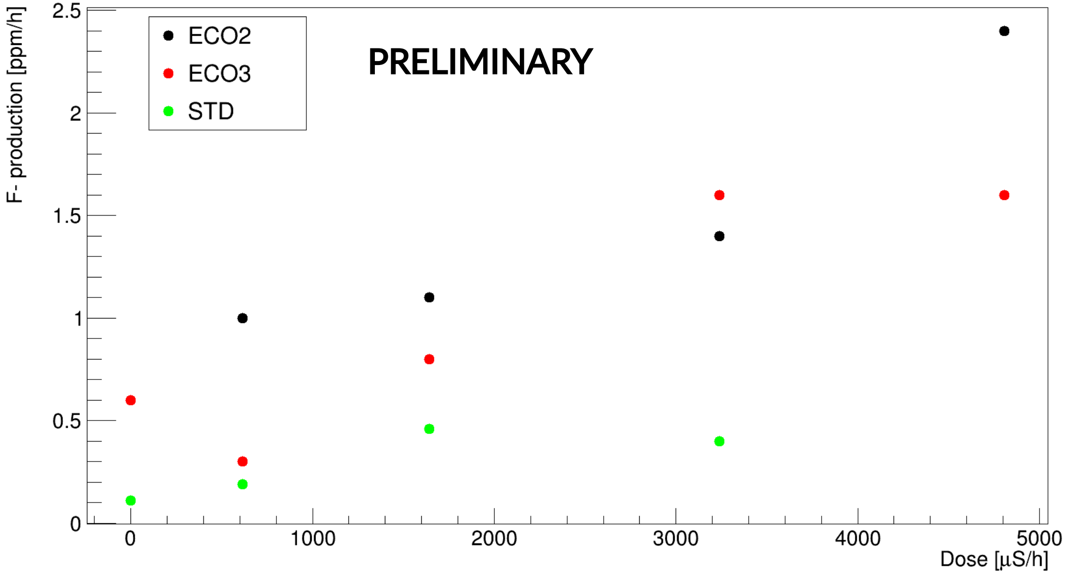
- Due to such an increase we decided to not continue the studies with this mixture and moved to ECO2

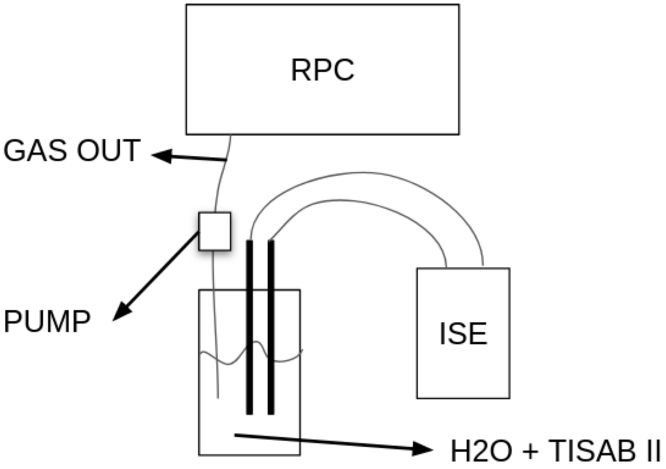
Other activities – ISE measurements

- Gas radiolysis under irradiation leads to the formation of fragments that can combine with water and create hydrofluoric acid (HF)
  → This can attack the bakelite and lead to accelerated aging effects

- F^- ions production can be measured using an **I**on **S**elective **E**lectrode (ISE) station

- RPC is exposed to different gamma rates and F^- concentration of output gas is measured (in ppm) and production (in ppm/h) is estimated





Setup for ISE measurement

- Production at fixed ABS for the gas mixtures tested

- Hints to a higher production for eco-friendly gases, no clear trend clearly visible
  → **More in depth studies foreseen for the near future**

Conclusions

- RPC standard gas mixture contains F-gases, with very high GWP
  → New EU regulations are imposing a phase out in the use and marketing of such gases
  → RPCs are the main contributor to CERN F-gases emission
  → Need to find more eco-friendly gas mixtures for current and future experiments

- RPC EcoGas@GIF++ collaboration born to perform in-depth studies on more eco-friendly gas mixtures for RPC detectors
  → Studies under gamma irradiation for aging purposes
  → Beam test studies to better characterize the operation of RPCs with new gas mixtures

- Studies on two gas mixtures where $C_2H_2F_4$ is replaced by a combination of $C_3H_2F_4$ and CO_2 to lower the working point. Two mixtures have been tested, ECO2 (60% CO_2/35% HFO) and ECO3 (69% CO_2/25% HFO)
  → Promising results in terms of efficiency and cluster size
  → Absorbed current higher wrt standard gas mixture
    → Aging studies are ongoing to study the long-term effects on the detectors
    → Systematic ISE campaign to monitor F^- production

Thank you for your attention!