Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Replacement of the SF_6 in the RPC detector

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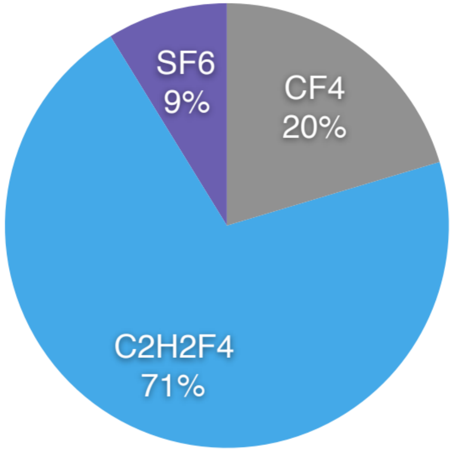
6° DRD1 Collaboration Meeting
Warsaw
6-10 October 2025

Search of an eco friendly gas mixture

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



Total GHG contribution

$C_2H_2F_4$ +i-C_4H_{10} + SF_6

GWP ~ 1430 GWP ~ 5 GWP ~ 23000

Total GWP ~ 1450

GWP(CO_2) = 1

European union regulation have imposed a progressive phase down in the production and use of the F-gases, like $C_2H_2F_4$ and SF_6 in industry

Reduction of the availability

Increase of the cost

These gases represent the biggest contribution of the CERN particle detectors greenhouse gas emission

Search for an alternative gas mixture →

- Performance comparable to those of the standard gas (efficiency, current, rate capability, time resolution…)
- Low GWP
- Longevity of the detector for collider experiments

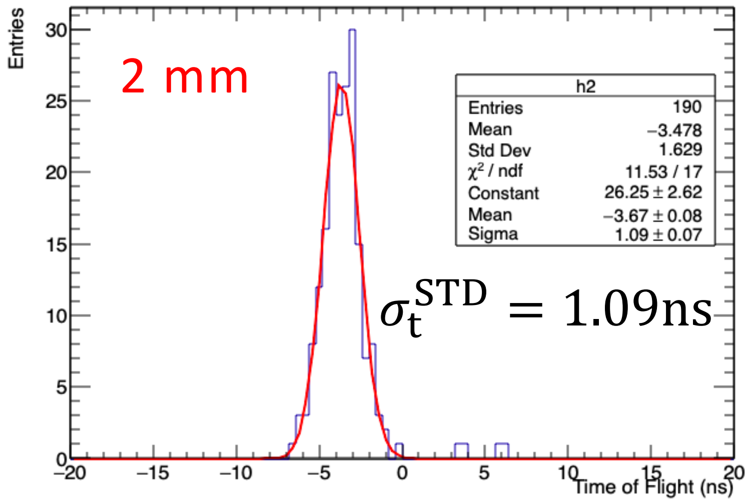
Eco-gases in ATLAS during HL-LHC

During HL-LHC there will be two types of ATLAS RPC : 2 mm (legacy) and 1 mm (upgrade) thick

1) Performance

High efficiency (>90%) for both options (more critical for 1 mm)

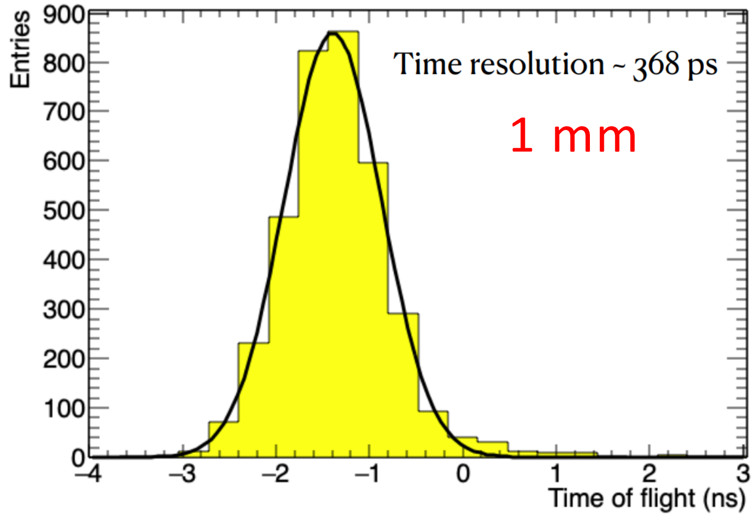
Time resolution (~ 1 ns for 2 mm gas gap and ~ 400 ps for 1 mm gas gap)



2) Rate capability :

Average rate expected during HL-LHC in ATLAS RPC : 200 $\mathrm{Hz/cm^2}$

Hottest spot during HL-LHC in ATLAS RPC : 500 $\mathrm{Hz/cm^2}$



3) Aging

Low total charge delivered within the gas →low current

Low Fluorine radicals production

Substitution of the $C_2H_2F_4$

Largest contribution to the GWP of the standard gas due to the Tetrafluoroethane (TFE) because it is the main gas component (94.7% for a total GWP ~ 1390)

1) Substitute the $C_2H_2F_4$ with an environment friendly gas mixture:

$CO_2/C_3H_2F_4$ +i-C_4H_{10} + 1% SF_6 ⟶ GWP ~ 200

1. Reduction of the GWP
2. Larger production of fluorine molecules (possible faster aging)
3. Concentration of $C_3H_2F_4$ strongly depends on the gas gap thickness

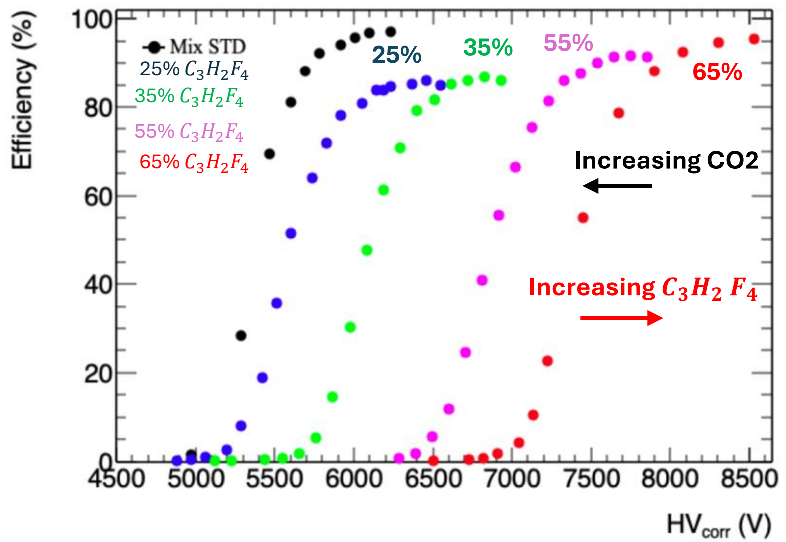
2) Reduction of the $C_2H_2F_4$ concentration introducing CO_2 (ATLAS intermediate):

$CO_2/C_2H_2F_4$ +i-C_4H_{10} + 1% SF_6 ⟶ GWP ~ (1017-1162)

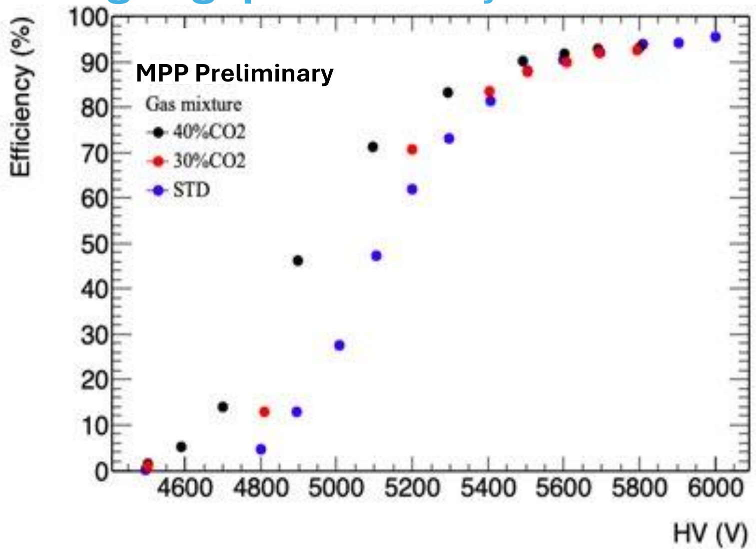
1. No large impact expected on detector longevity in terms of fluorine production
2. Small reduction of the GWP

Both cases → higher current wrt standard gas (1.5-1.7 times higher)

1 mm gas gap : efficiency vs HV vs %$C_3H_2F_4$



1 mm gas gap : efficiency vs HV vs %CO2



The impact of SF_6

The SF_6 is the molecule with the largest GWP in the standard gas (22900)

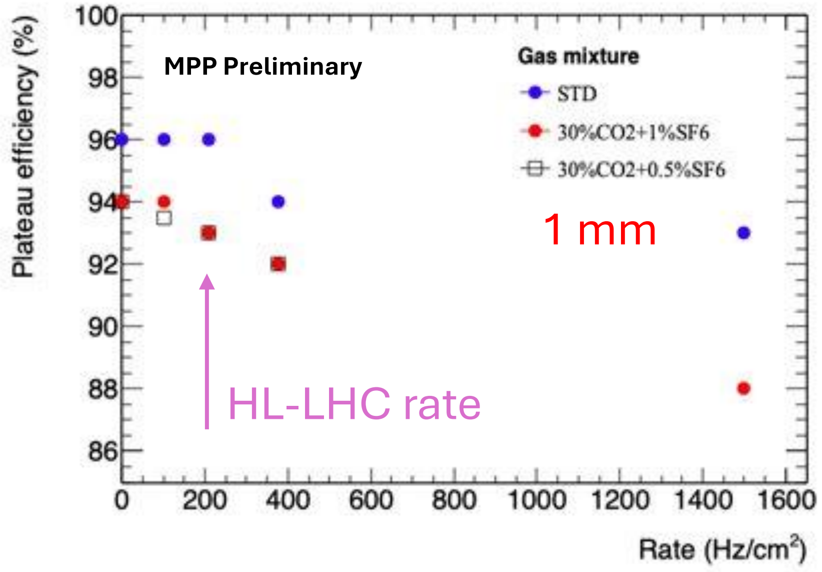
All the alternatives to the $C_2H_2F_4$ require an increase in the SF_6 concentration in order to avoid streamers→ higher GWP

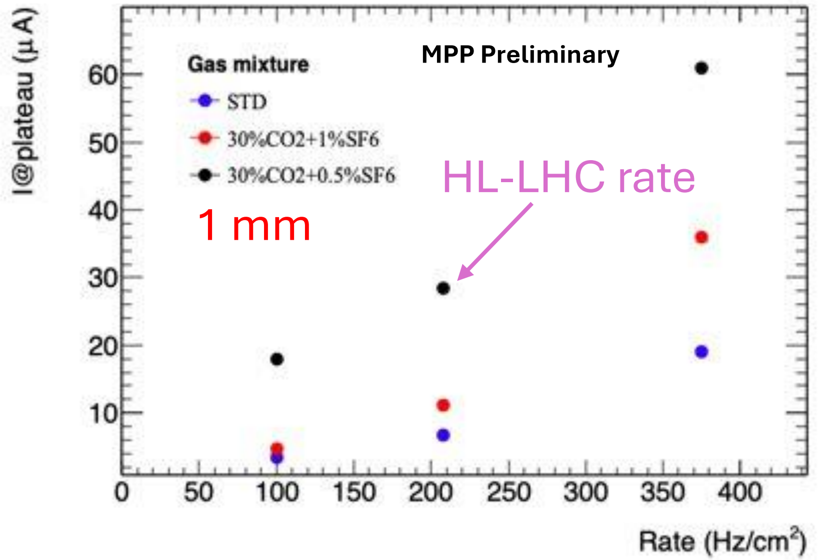
What happen if we reduce the SF_6 concentration in the ATLAS intermediate solution(currently used in ATLAS)?

$$CO_2/C_2H_2F_4 + \text{i-}C_4H_{10} + 0.5\%\ SF_6$$

✓ Reduction of the GWP (**1041** vs **1164**)

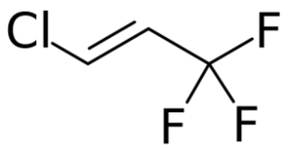
✘ Large increase of the currents in 1 mm gap due to transition (high-charge) events and/or streamers





Substitution of the SF_6

Possibility to replace the highest GWP molecule, the SF_6, with an environment friendly gas: the Chlorotrifluoropropene ($C_3H_2ClF_3$, **GWP ~ 1**)

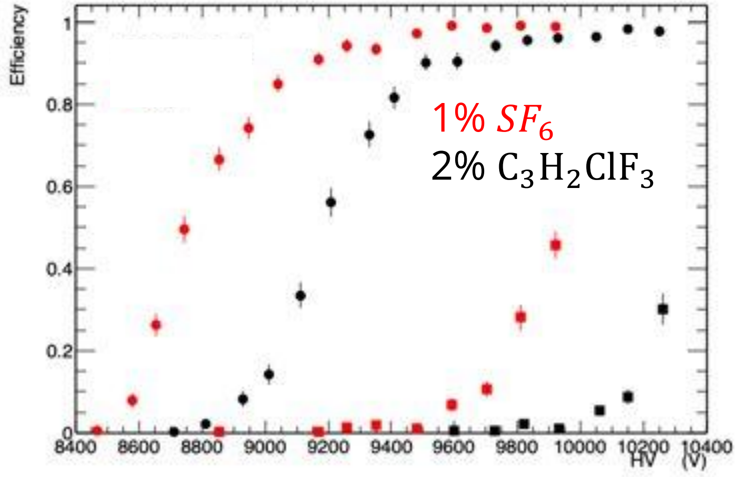


$CO_2/C_3H_2F_4$ + i-C_4H_{10} + $C_3H_2ClF_3$ $\longrightarrow$ GWP ~ 10 (100 times less than the standard gas!!)

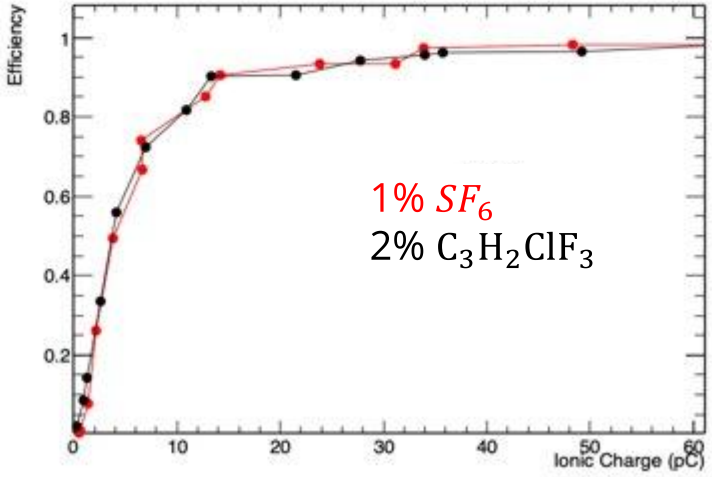
Possibility to operate the RPC with a <u>totally</u> environment-friendly gas mixture (see here)

Main results (2 mm gas gap)

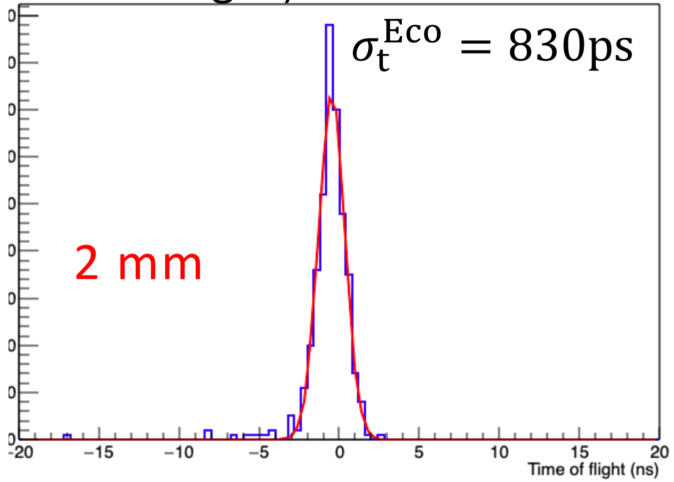
Same avalanche-streamer separation



Same current @ same efficiency



Good time resolution (24%better wrt standard gas)



Certification of $C_3H_2ClF_3$ for short-term applications

1.Early appearance of streamers/transition events → high current and low rate capability

2. High current under irradiation → aging and low rate capability

3. Long term effects → Study of the behaviour of the gas after integrating the corresponding HL-LHC charge

1. Decouple the contribution of the $\mathrm{C_3H_2ClF_3}$ from the other gases

$C_2H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ → The behaviour of $C_2H_2F_4$ and i- C_4H_{10} is well known → Any of the effect cited above due to $C_3H_2ClF_3$

2. Application to ATLAS intermediate gas mixture

$CO_2/C_2H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ →

- Opportunity to start to replace the SF_6
- Possibility to reduce the $C_2H_2F_4$ by increasing the $C_3H_2ClF_3$ with an improvement of the GWP

Set-up at the Gamma Irradiation Facility (GIF++)

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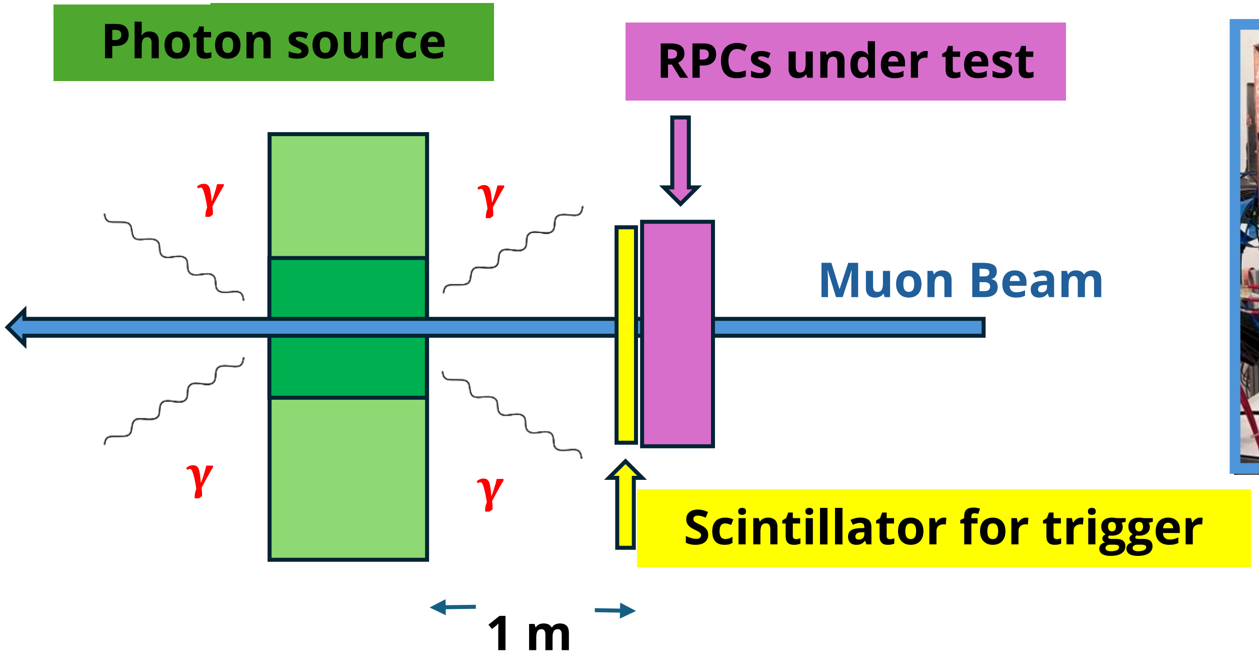
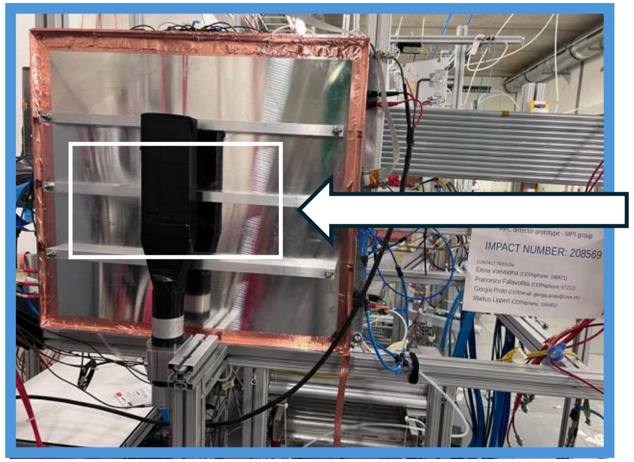
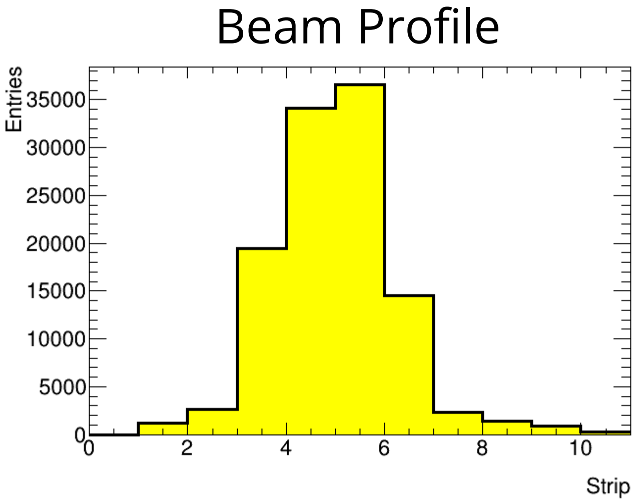




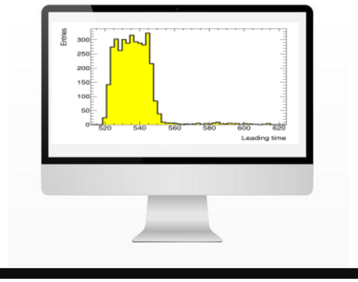


Three 1 mm gas gap RPCs
1.4 mm electrode thickness
Amplified signal with Cardarelli FE electronics (transimpedence amplifier)

Discriminator
(4 mV thr)

TDC CAEN
100 ps (LSB)-
400 ps effective resolution

Laptop for DAQ and offline analysis



Results (I)

Mixtures

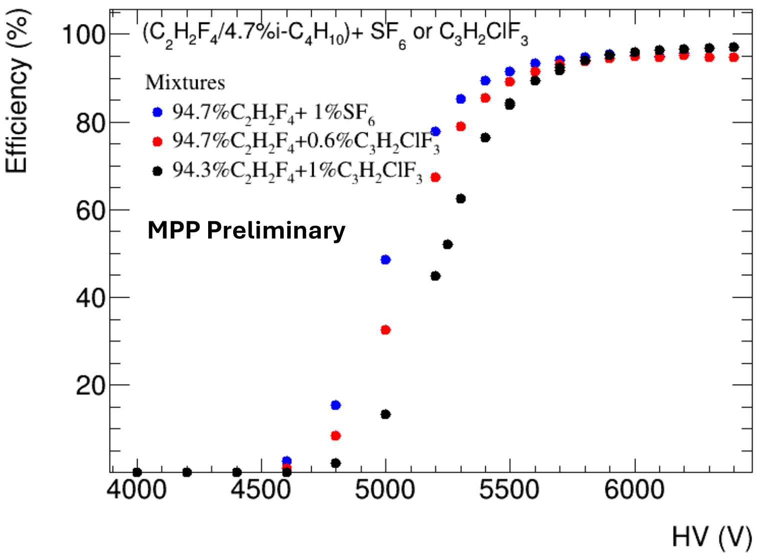
$94.7\% C_2H_2F_4$ $+ 4.7\%$i-C_4H_{10} $+$ $\boxed{0.6\% C_3H_2ClF_3}$

$94.3\% C_2H_2F_4$ $+ 4.7\%$i-C_4H_{10} $+$ $\boxed{1\% C_3H_2ClF_3}$

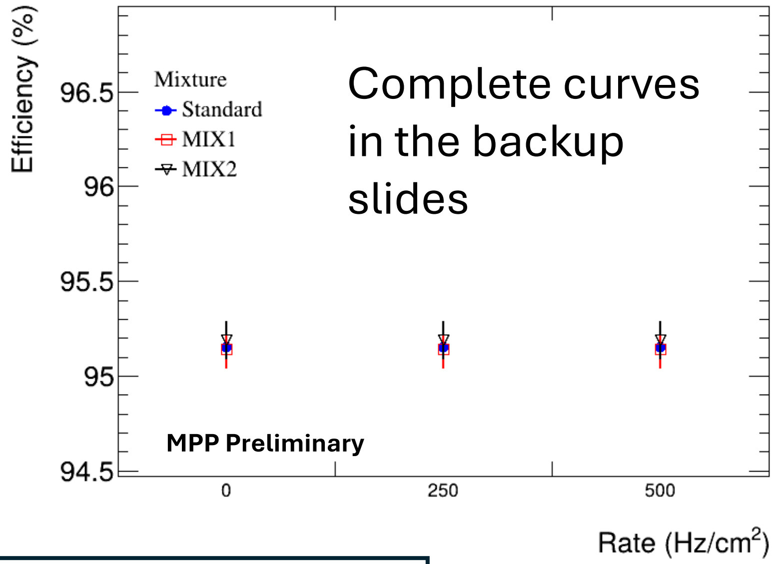
Efficiency and currents in presence of γ-irradiation in comparison with the standard gas

Study of the efficiency

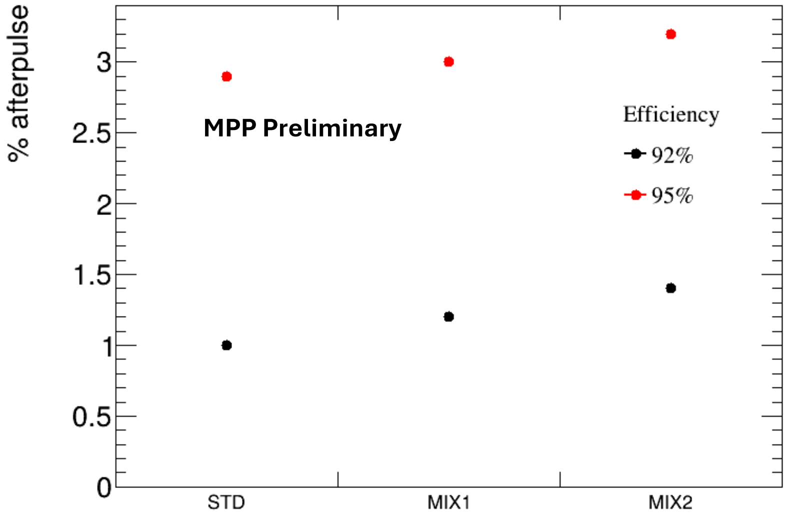
Efficiency vs HV:NO irradiation



Plateau vs γ-rate



% after pulse vs mixture @ WP



1. MIX1 : 94.7%$C_2H_2F_4$/4.7%i-C_4H_{10}/**0.6%** $C_3H_2ClF_3$

2. MIX2 :94.3%$C_2H_2F_4$/4.7%i-C_4H_{10}/**1%** $C_3H_2ClF_3$

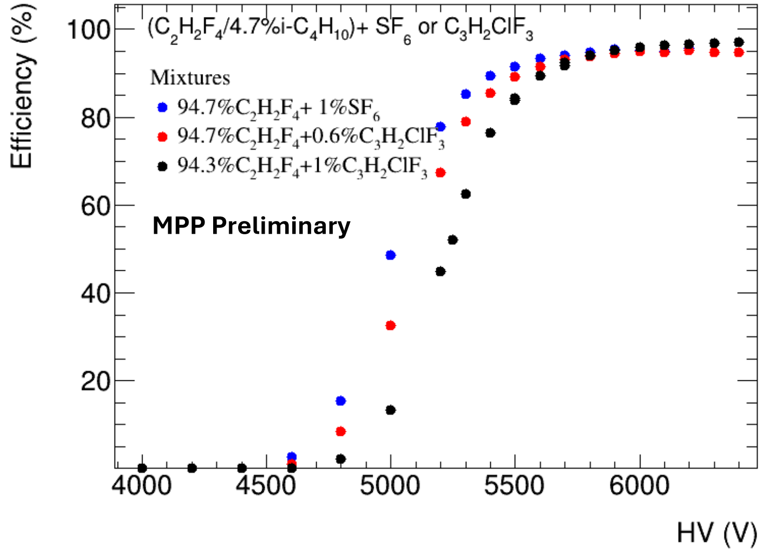
1. Same efficiency around 95%
2. Working point shifted by 100 V (0.6% $C_3H_2ClF_3$) and 200 V (1% $C_3H_2ClF_3$) wrt the standard gas
3. No efficiency loss under irradiation→Same rate capability up to 448 Hz /cm^2

After pulse = number of multiple hits on the same strip

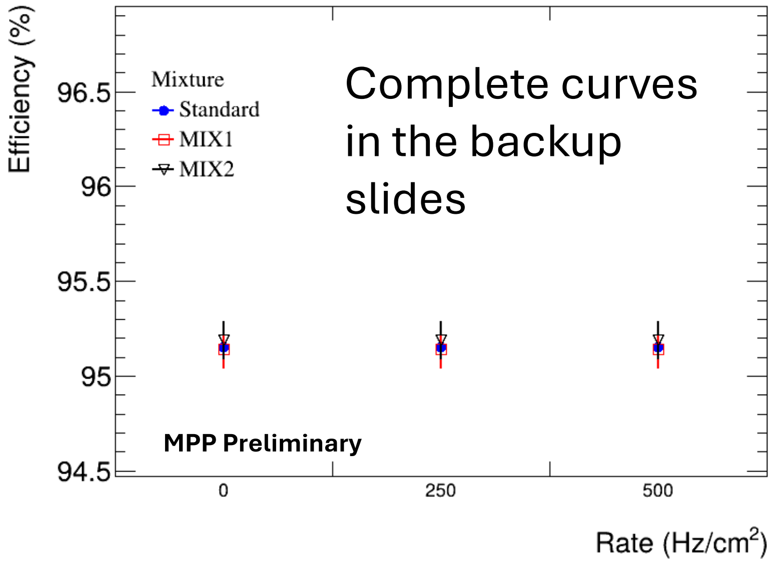
1. Number of after pulses of MIX1 (0.6% $C_3H_2ClF_3$) and MIX2 (1% $C_3H_2ClF_3$) consistent with the standard gas (at the same efficiency)

Study of the efficiency

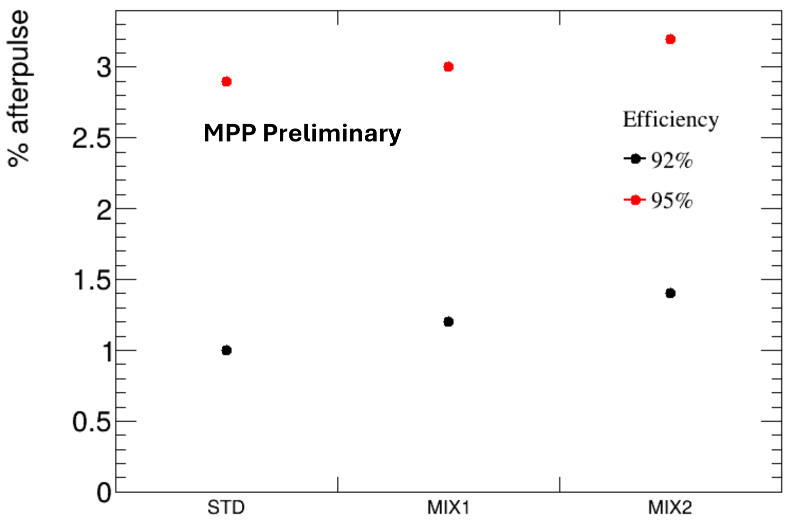
Efficiency vs HV:NO irradiation



Plateau vs γ-rate



% after pulse vs mixture @ WP

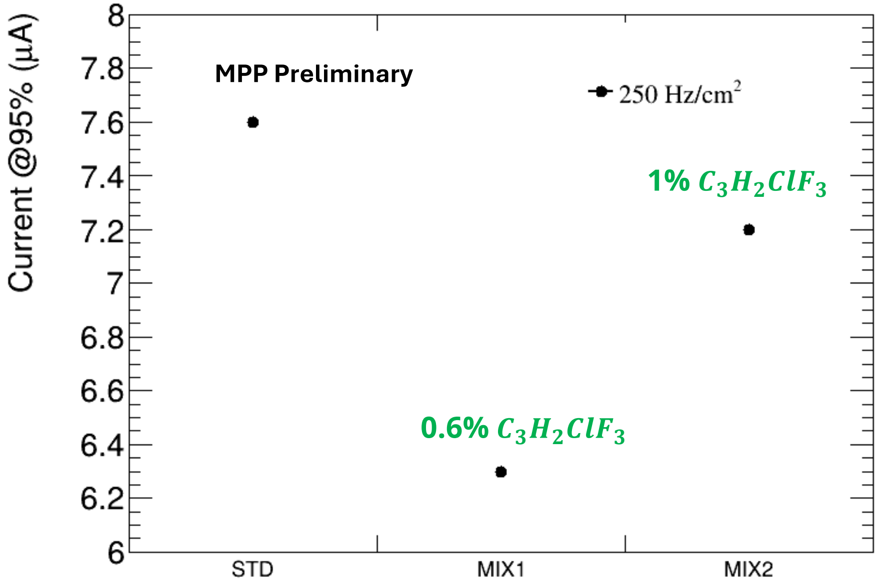


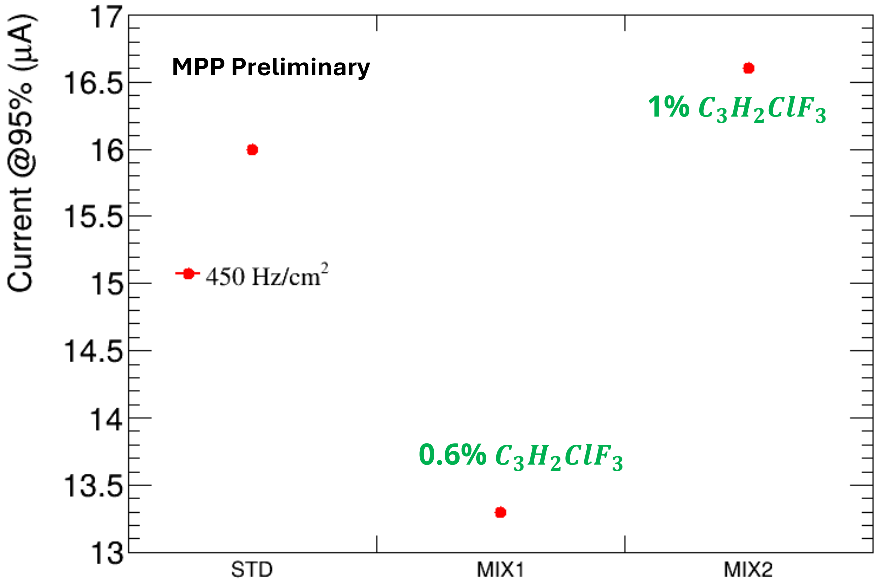
The $C_3H_2ClF_3$ shows the same behaviour of the SF_6 with no impact on the rate capability

More info [here]

Results : Comparison at 95% efficiency

Currents at 95% efficiency at different irradiation : no irradiation, 235 Hz/cm^2 and 448 Hz/cm^2





The currents at the WP are at the same order of magnitude up to 448 Hz/cm^2 (slightly better in MIX1)

The $\mathrm{C_3H_2ClF_3}$ shows the same behaviour of the SF_6 with no impact in the detector performance

Results (II)

Mixtures :
(**30%** CO_2/4.7% i-C_4H_{10}) +

$64.3\%C_2H_2F_4 + 1\%C_3H_2ClF_3$
$63.3\%C_2H_2F_4 + 2\%C_3H_2ClF_3$
$62.3\%C_2H_2F_4 + 3\%C_3H_2ClF_3$
$61.3\%C_2H_2F_4 + 4\%C_3H_2ClF_3$

Mixtures :
(**40%** CO_2/4.7% i-C_4H_{10}) +

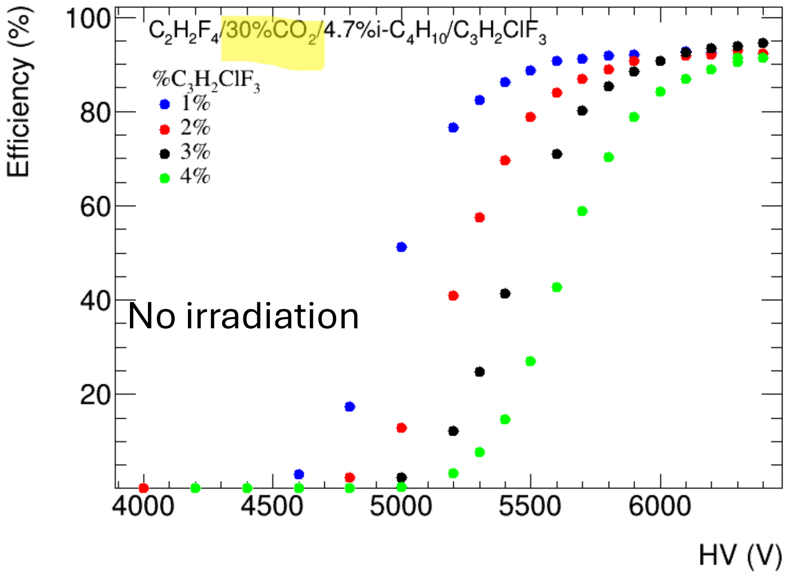
$53.3\%C_2H_2F_4 + 2\%C_3H_2ClF_3$
$52.3\%C_2H_2F_4 + 3\%C_3H_2ClF_3$
$51.3\%C_2H_2F_4 + 4\%C_3H_2ClF_3$

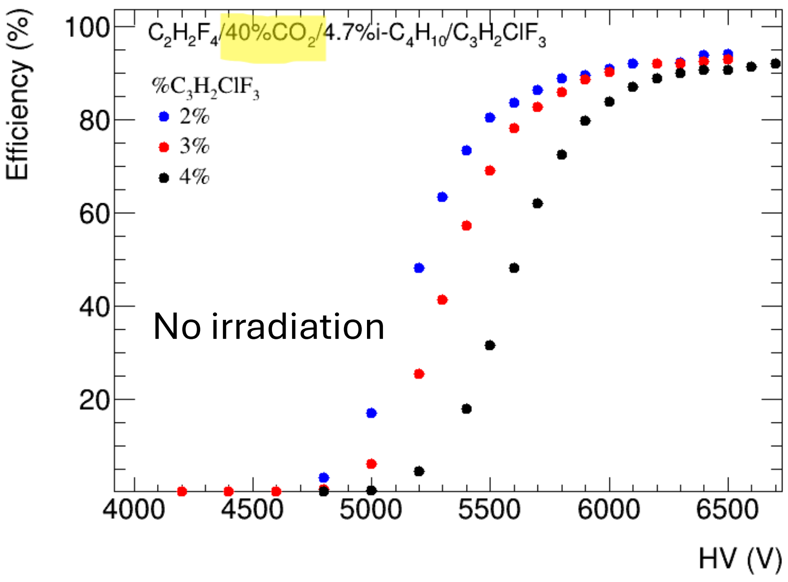
Efficiency and currents in presence of γ-irradiation in comparison with:

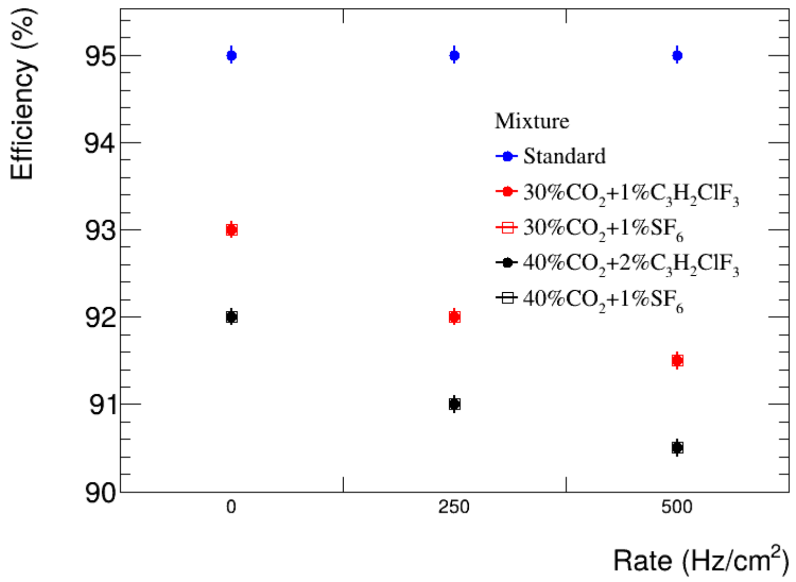
- standard gas
- $\mathrm{C_2H_2F_4/CO_2/i\text{-}C_4H_{10}}/\underline{\mathbf{1\%}\boldsymbol{SF_6}}$
- $\mathrm{C_2H_2F_4/CO_2/i\text{-}C_4H_{10}}/\underline{\mathbf{0.5\%}\boldsymbol{SF_6}}$

Direct comparison with SF_6

$C_2H_2\ F_2$ / CO_2 / i-$C_4\ H_{10}$/ $C_3\ H_2\ ClF_3$: Efficiency







plateau efficiency of the standard gas ~3% higher wrt the mixtures containing CO_2

Efficiency drop under irradiation:

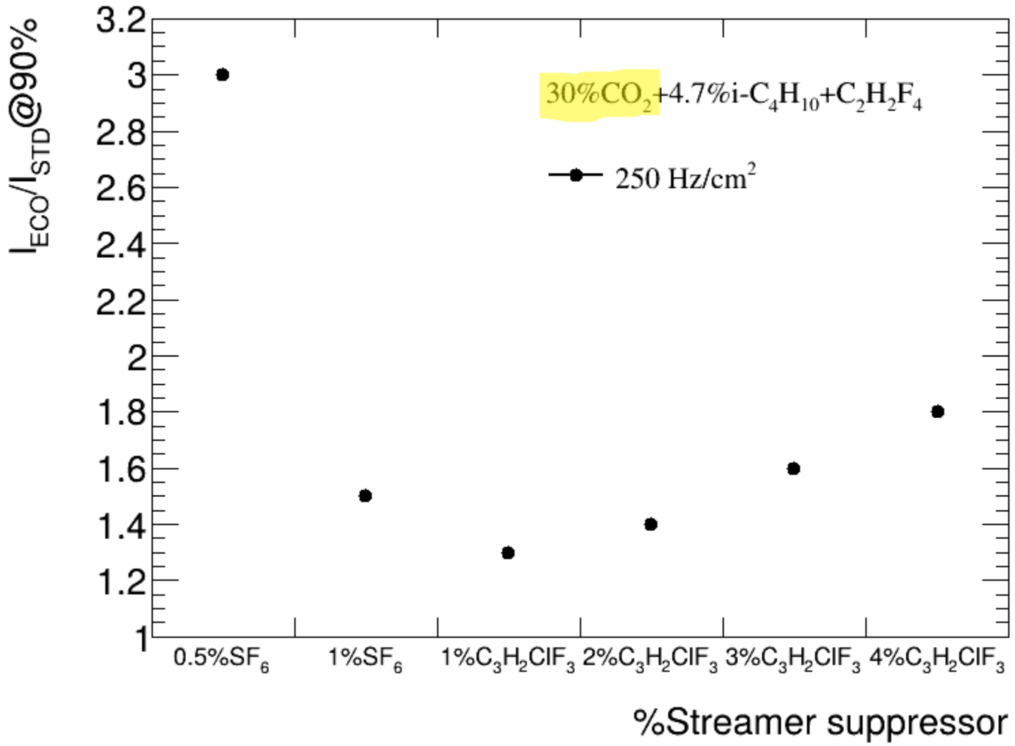
1) 253 Hz/ cm^2 : 0% for the standard gas, 1% for the other mixtures

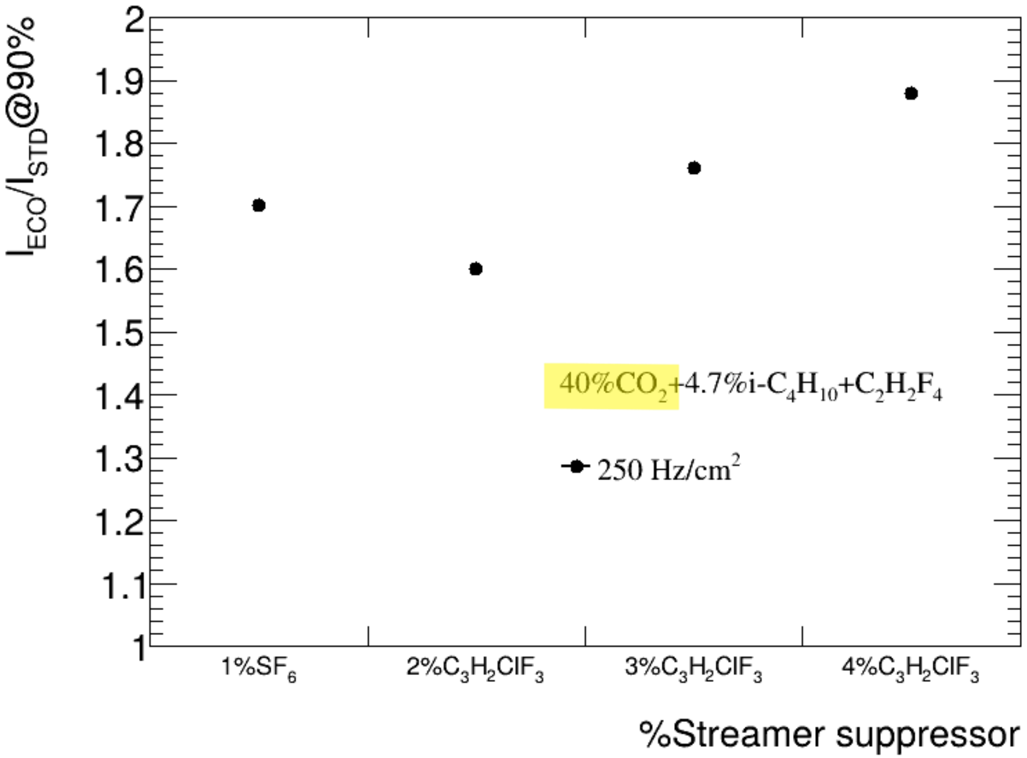
2) 448 Hz/ cm^2 : 0% for the standard gas, 2% for the other mixtures

Same results with $C_2H_2F_4/CO_2$/i-C_4H_{10}/$\underline{SF_6}$ gas mixtures (*Nucl.Instrum.Meth.A* 1066 (2024) 169580)

The $C_3H_2ClF_3$ shows the same behaviour of the SF_6 with no impact in the efficiency

SF_6 vs $C_3H_2ClF_3$: Currents



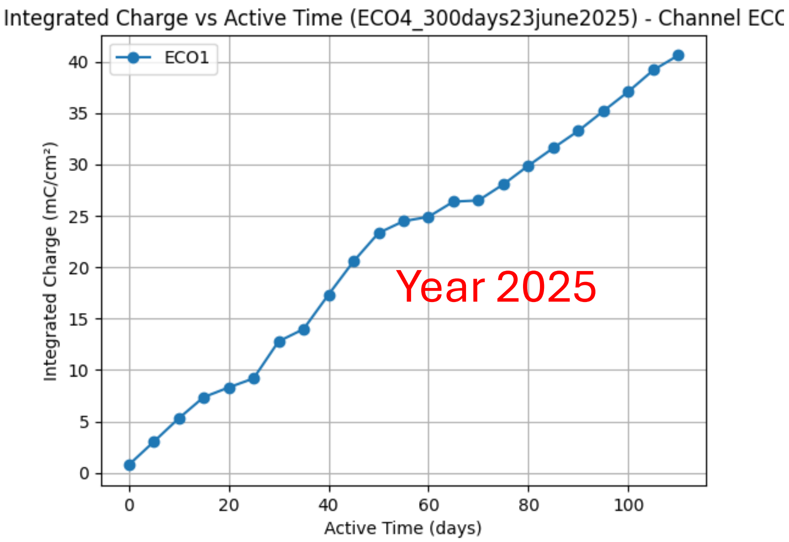


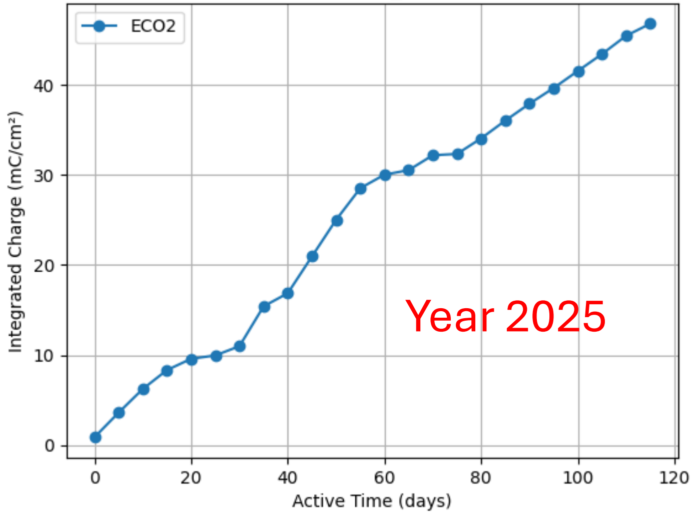
The currents are at the same order of magnitude and significantly lower wrt the 0.5% SF_6 case

The $C_3H_2ClF_3$ shows the same behaviour of the SF_6 with no impact in the current

Aging status and plan

2 prototypes in aging with the gas mixture : **94.7%$C_2H_2F_4$/4.7%i-C_4H_{10}/0.6% $C_3H_2ClF_3$**





The detectors are at 90% efficiency and the current over time is monitored under γ-irradiation

Integrated charge during **2024** (20 effective days) ~ 8.5 $\mathrm{mC/cm^2}$ (ECO1) and 9.5 $\mathrm{mC/cm^2}$ (ECO2)

Integrated charge (2024+2025) in ~100 effective days ~ 60 $\mathrm{mC/cm^2}$

Target ~ 178 $\mathrm{mC/cm^2}$ (Safety Factor 3, Duty Cycle 33%)

No increase in the current over time observed

Currents stable in both prototypes → plan to accelerate aging and finish at the end of 2025

THANK YOU

Questions are welcome