Study of environment friendly SF_6 substitute for the Resistive Plate Chambers

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XVII International conference on Resistive Plate Chambers and Related Detectors

Santiago De Compostela

9-13 September 2024

Outline

1. Introduction to the search of alternative gas mixtures for the Resistive Plate Chambers

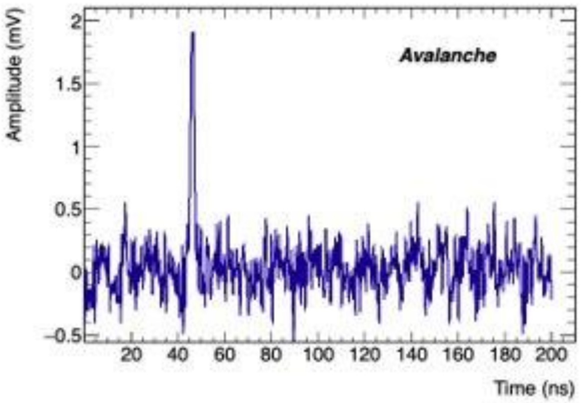
2. Replacement of the SF_6

3. Results of the tests performed under irradiation with several gas mixtures

4. Conclusions

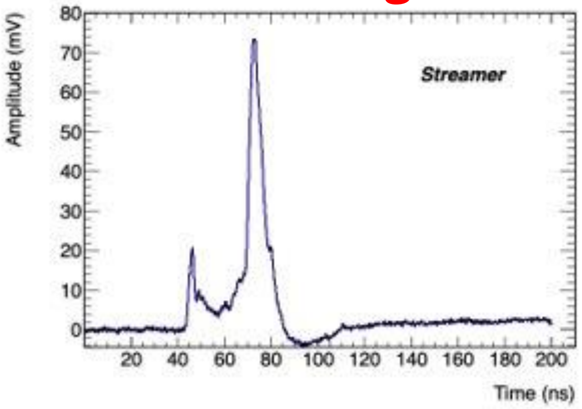
RPC in avalanche mode with the standard gas mixture

Avalanche signal



- Low current (good longevity)
- High rate capability
- RPC in high radiation environment (like ATLAS)

Streamer signal

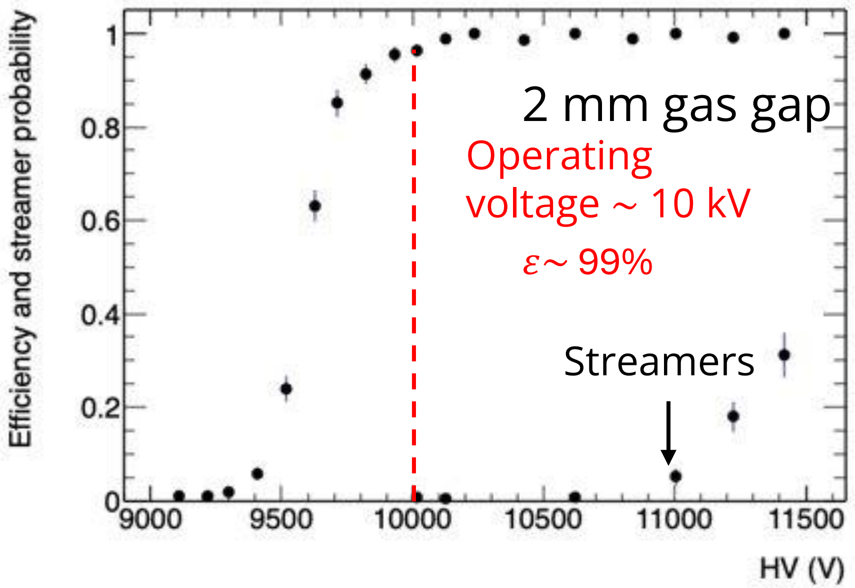


- High current
- No sophisticated FE electronics needed
- Low rate experiment

The standard gas mixture is composed of 94.7% $C_2H_2F_4$ (TFE)/5%i-C_4H_{10}/0.3%SF_6

$C_2H_2F_4$ → Primary target; i-C_4H_{10} → Quencher; SF_6 → Streamer suppressor

- High gas density ensuring high detection efficiency
- Modest working current and good rate capability
- Comfortable avalanche-streamer separation



Search of an eco friendly gas mixture

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

$C_2H_2F_4$ +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

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

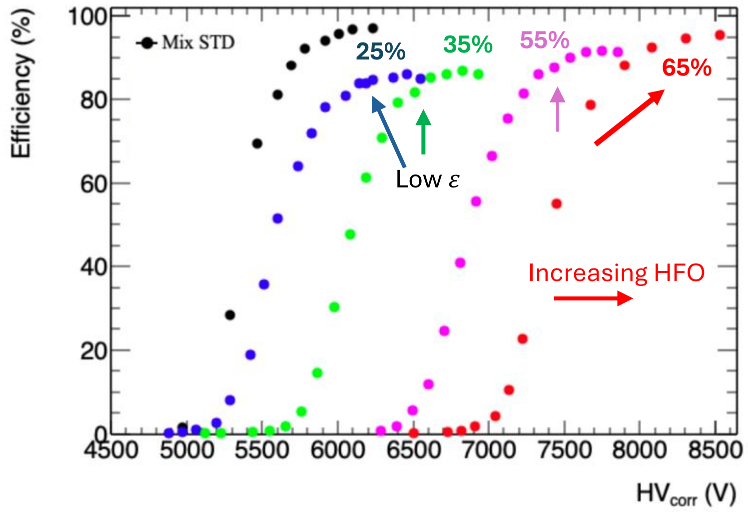
1. Reduction of the GWP
2. Concentration of $C_3H_2F_4$ strongly depends on the gas gap thickness
3. Larger production of fluorine molecules (possible faster aging)

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

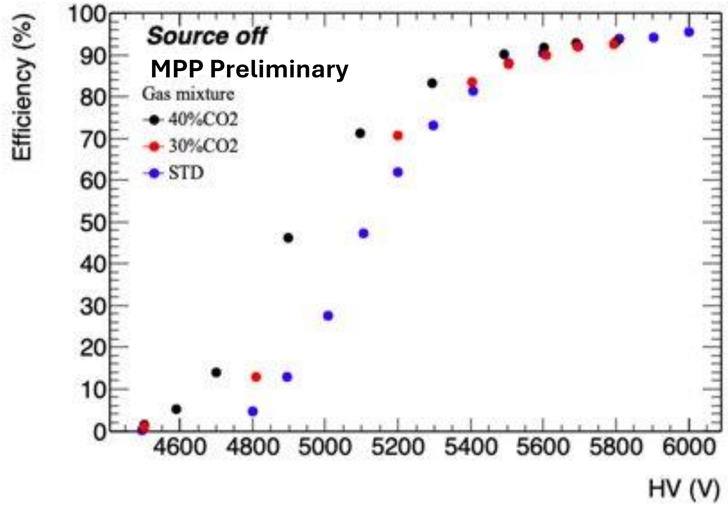
$CO_2/C_2H_2F_4$ +i-C_4H_{10} + 1% SF_6 ⟶ GWP ~ (1017-1162)

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

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)

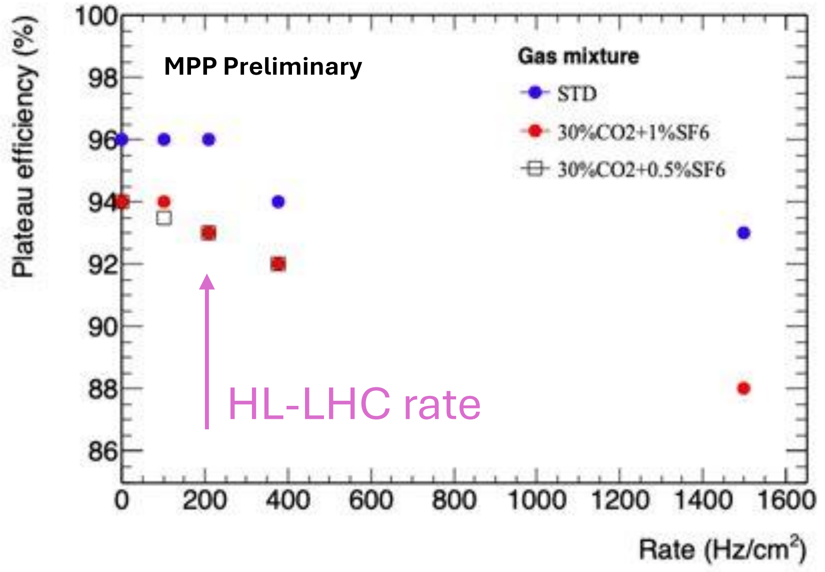
All the alternatives to the $C_2H_2F_4$ require an increase in the SF_6 concentration in order to avoid streamers→ higher GWP

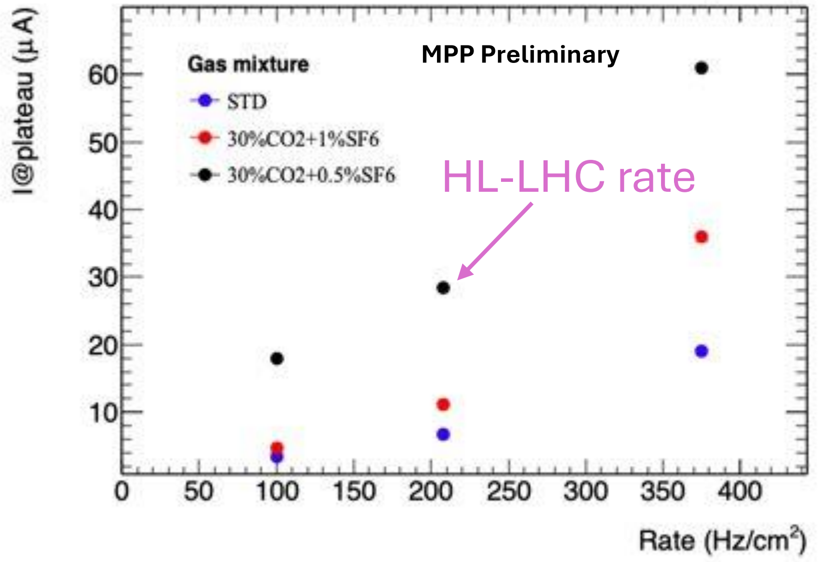
What happen if we reduce the SF_6 concentration in the ATLAS intermediate solution?

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

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

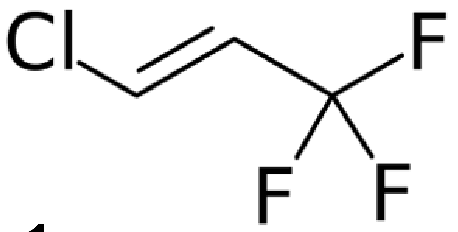
✗ Large increase of the currents due to transition (high-charge) events and/or streamers





Solution : Replacement of the SF_6

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



Case 1

$CO_2/C_3H_2F_4$ +i-C_4H_{10} + 1% SF_6 ⇨ $CO_2/C_3H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$

→ Main advantage : Totally environment friendly gas mixture

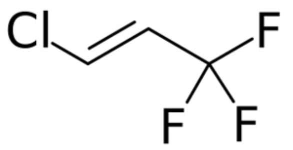
Case 2 (main topic of this presentation)

$CO_2/C_2H_2F_4$ +i-C_4H_{10} + 1% SF_6 ⇨ $CO_2/C_2H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$

→ Main advantage : Maximize the reduction of the GWP with NO impact on the detector performance

Substitution of the SF_6 : Case 1

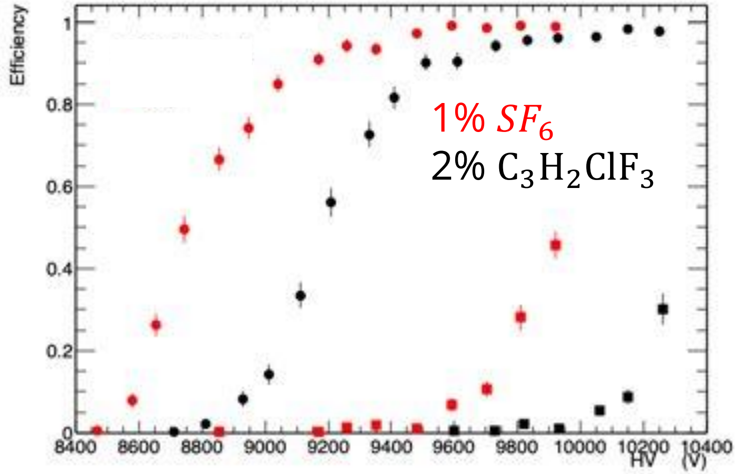
Possibility to replace the highest GWP molecule, the SF_6, with an environment friendly gas: the Chlorotrifluoropropene ($C_3H_2ClF_3$)



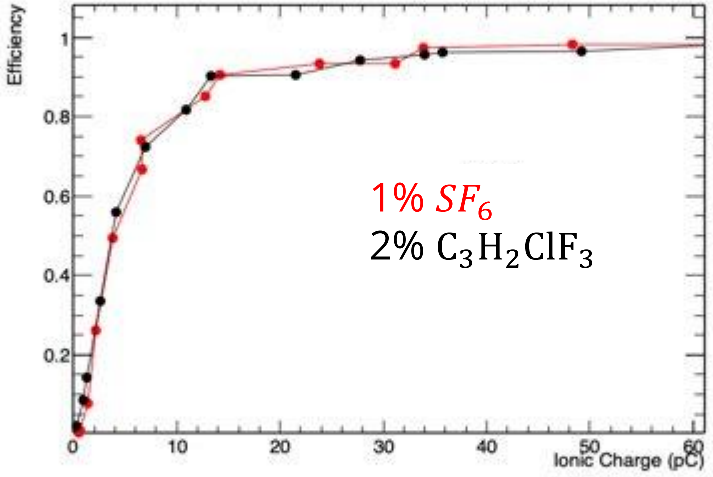
$CO_2/C_3H_2F_4$ + i-C_4H_{10} + $C_3H_2ClF_3$ ⟶ GWP ~ 10 (100 times less than the standard gas!!)

Possibility to operate the RPC with a totally environment-friendly gas mixture for the first time (G. Proto *et al* 2022 *JINST* **17** P05005)

Efficiency vs high-voltage



Efficiency vs total charge delivered



- Same avalanche-streamer separation(~ 400 V)
- Same current at the same efficiency

Substitution of the SF_6 : Case 2

1.Premature presence 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 $C_3H_2ClF_3$ from the other gases

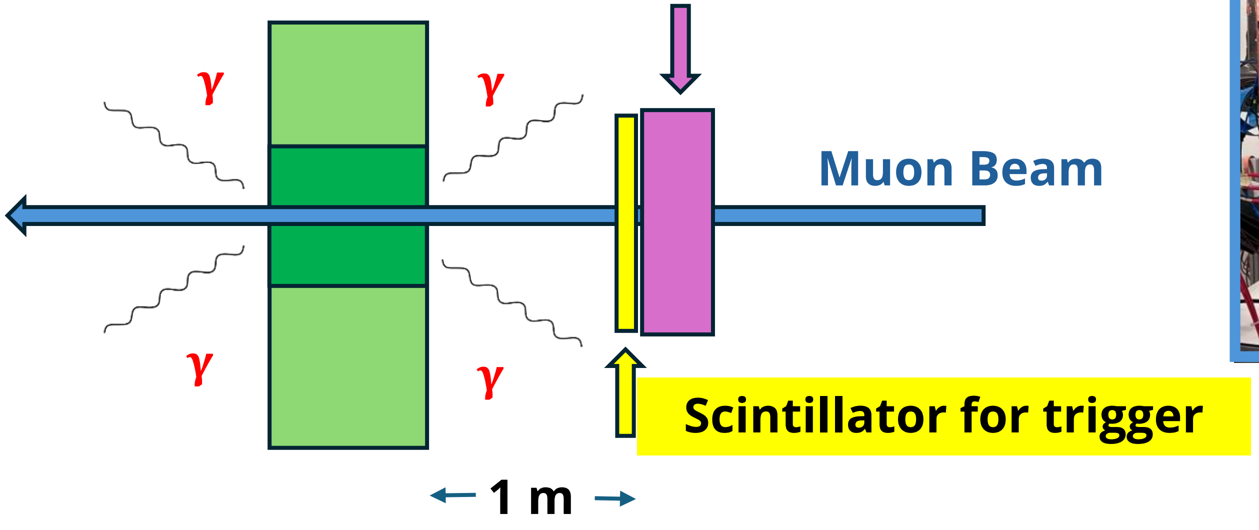
$C_2H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ → The behaviour of $C_2H_2F_4$ and i- C_4H_{10} is well known → Any of the effect cited above due to $C_3H_2ClF_3$

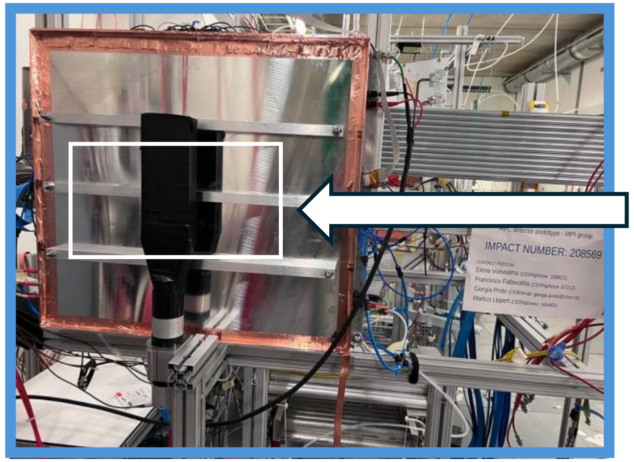
2. Application to case 2

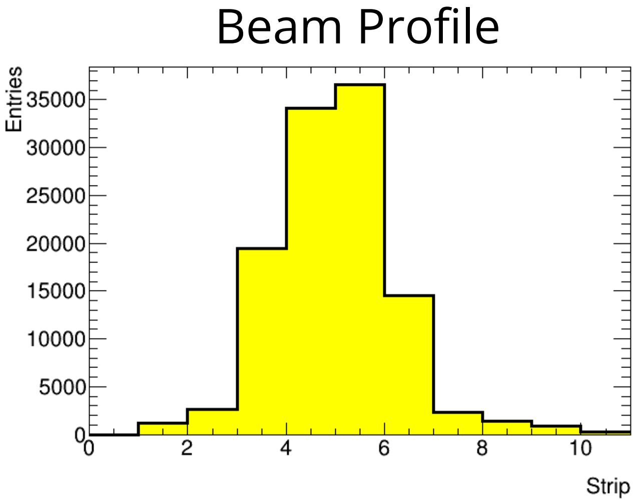
$CO_2/C_2H_2F_4$ +i-C_4H_{10} + $C_3H_2ClF_3$ →

- 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++)





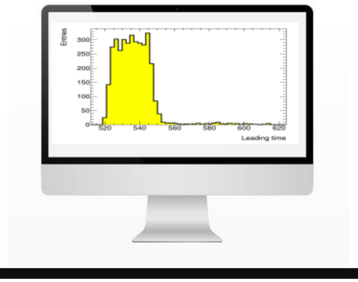


Three 1 mm gas gap RPCs
1.4 mm electrode thickness
Amplified signal with Cardarelli FE electronics (transimpedence amplifier)

Discriminator (4 mV thr)

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

Laptop for DAQ and offline analysis



Measurement strategy

Gas mixtures studied:

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% $C_3H_2ClF_3$

→ Directly compared with the standard gas mixture
Used to select the mixture that will undergo the aging

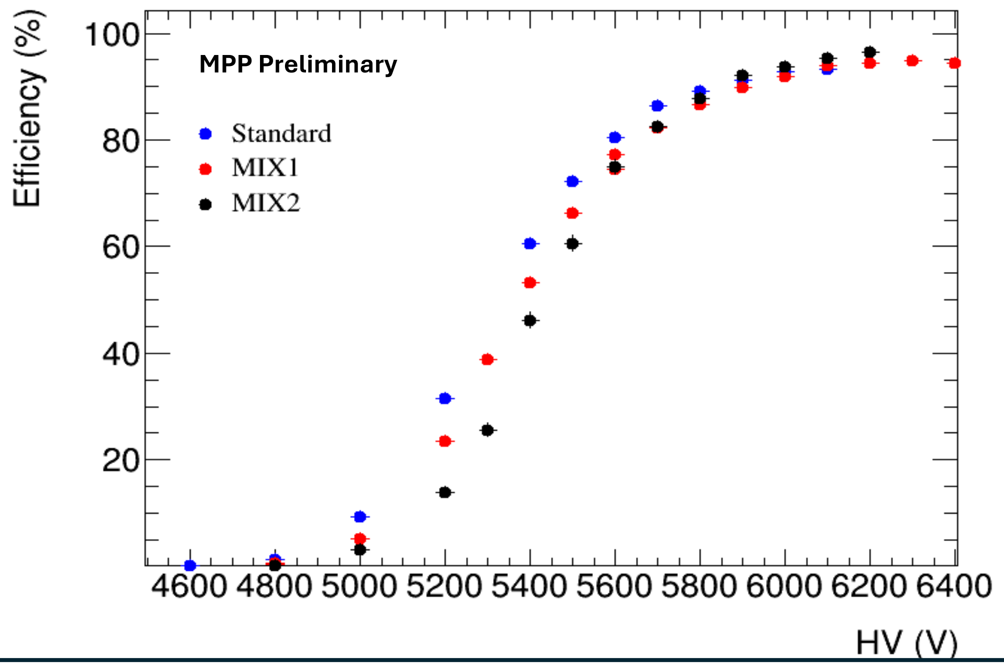
3. MIX3 : 63.3% $C_2H_2F_4$/30% CO_2/4.7%i-C_4H_{10}/2% $C_3H_2ClF_3$
4. MIX4 : 53.3% $C_2H_2F_4$/40% CO_2/4.7%i-C_4H_{10}/2% $C_3H_2ClF_3$

→ Optimization of the mixture with reduced TFE concentration

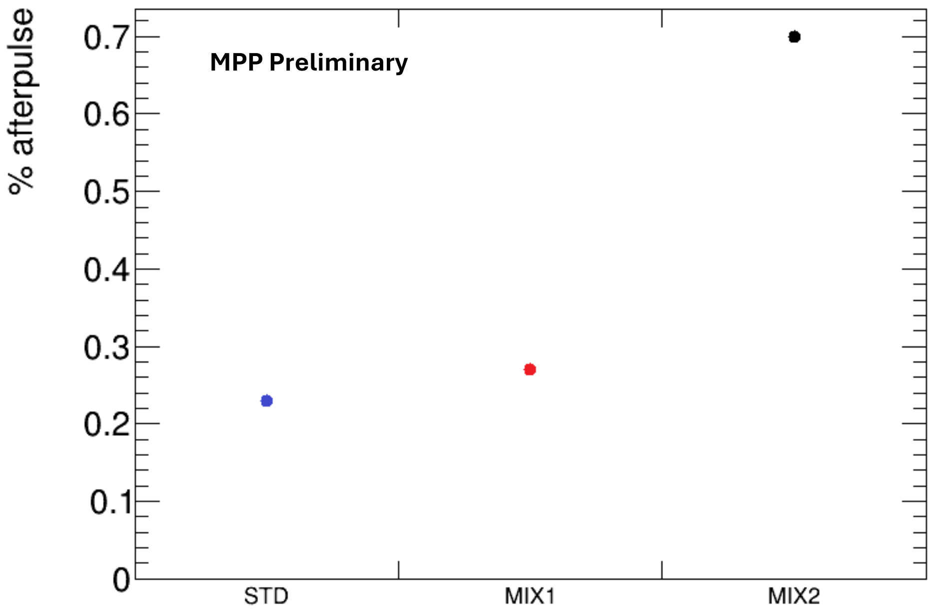
Topic of this presentation : Study of the performance of these gas mixtures in presence of ATLAS HL-LHC background

Results STD vs MIX1 vs MIX2 : Study of the efficiency

Efficiency vs HV with NO irradiation



% 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% $C_3H_2ClF_3$

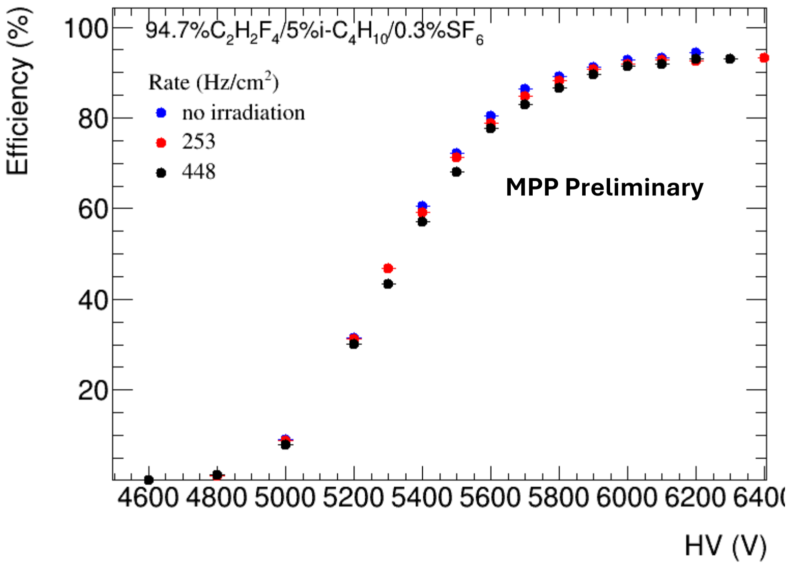
1. Same efficiency around 95%
2. Working point shifted by 100 V (0.6% $C_3H_2ClF_3$) and 200 V (1% $C_3H_2ClF_3$) wrt the standard gas

After pulse = number of multiple hits on the same strip

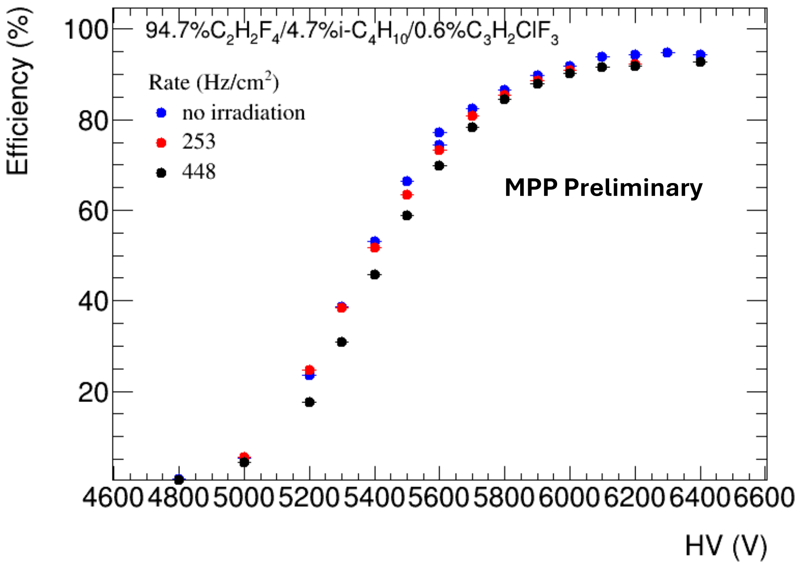
1. Number of after pulses of MIX1 consistent with the standard gas (at the same efficiency)
2. Slightly increase of after pulse using MIX2 (still at low level)

Results : Study of the efficiency under irradiation

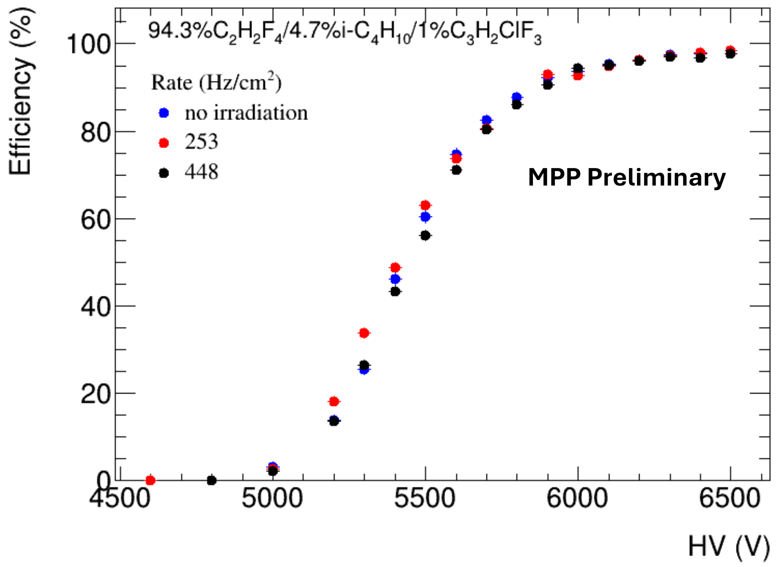
Standard gas



MIX1



MIX2



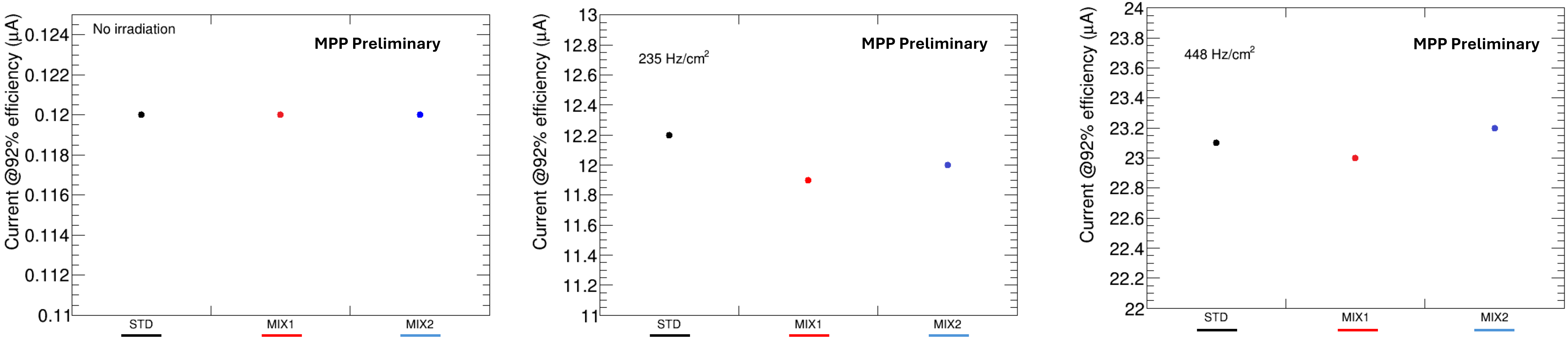
Maximum rate in ATLAS RPC during HL-LHC ~ 500 Hz/cm^2

All the curves show the same plateau efficiency at different irradiation

NO efficiency loss up to 448 Hz /cm^2

Results : Comparison at 92% efficiency

Currents at 92% efficiency at different irradiation : no irradiation, 235 $\mathrm{Hz/cm^2}$ and 448 $\mathrm{Hz/cm^2}$

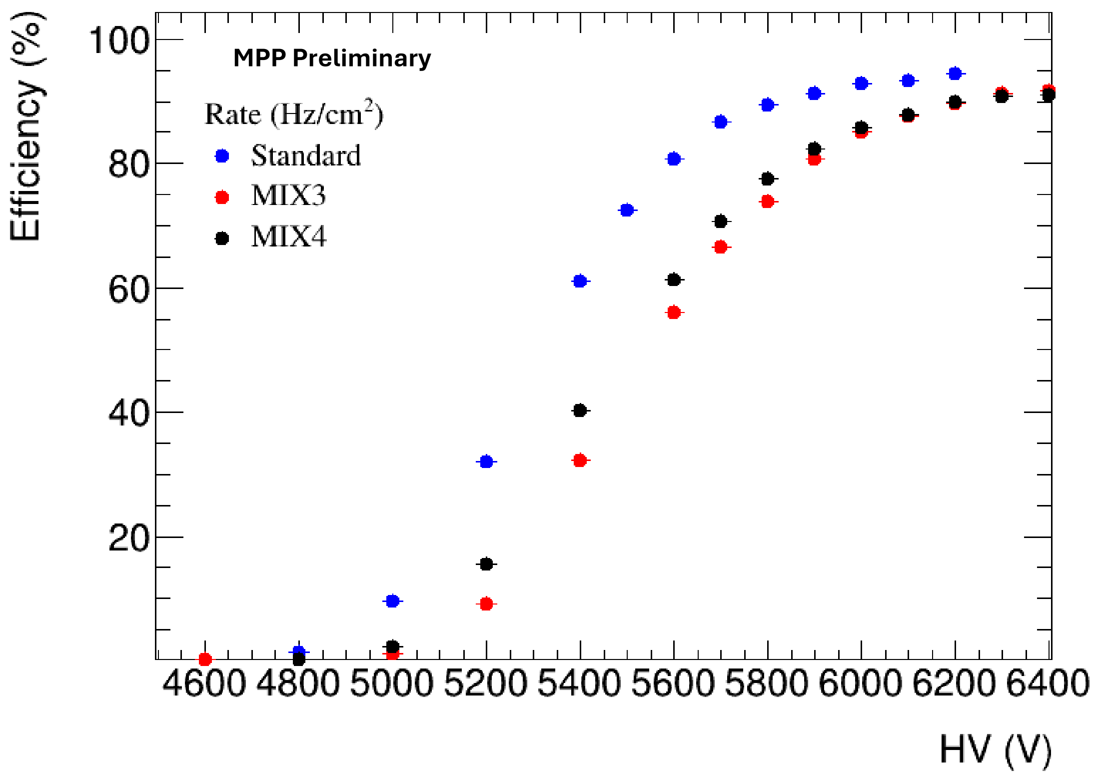


The currents at the WP are at the same order of magnitude within 1% up to 448 $\mathrm{Hz/cm^2}$

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

Results STD vs MIX3 vs MIX4 : Study of the efficiency

Efficiency vs HV with NO irradiation



1. MIX3 : 63.3%$C_2H_2F_4$/30%CO_2/4.7%i-C_4H_{10}/2% $C_3H_2ClF_3$

2. MIX4 : 53.3%$C_2H_2F_4$/40%CO_2/4.7%i-C_4H_{10}/2% $C_3H_2ClF_3$

The working point is shifted by ~ 200 V (MIX4) and ~ 300 V (MIX3) wrt the standard gas

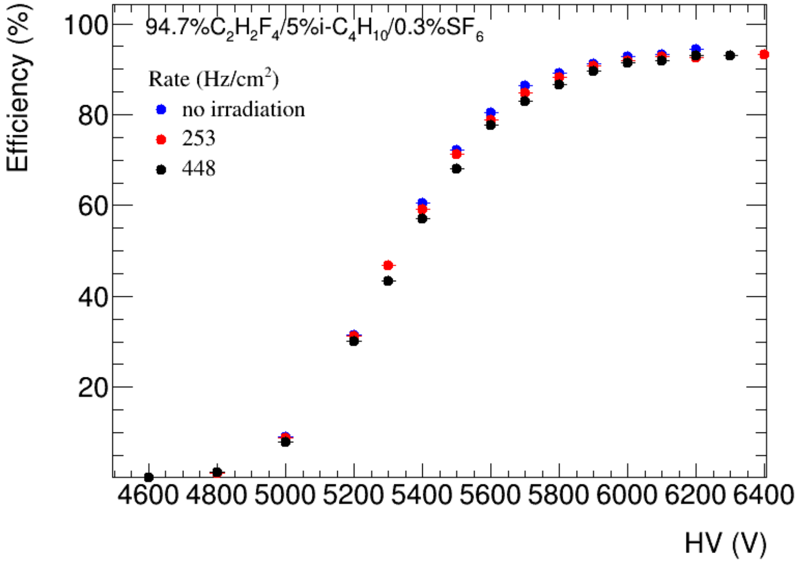
The plateau efficiency of the standard gas, 95%, is 3% higher wrt the mixtures containing CO_2 → less active target

⇩

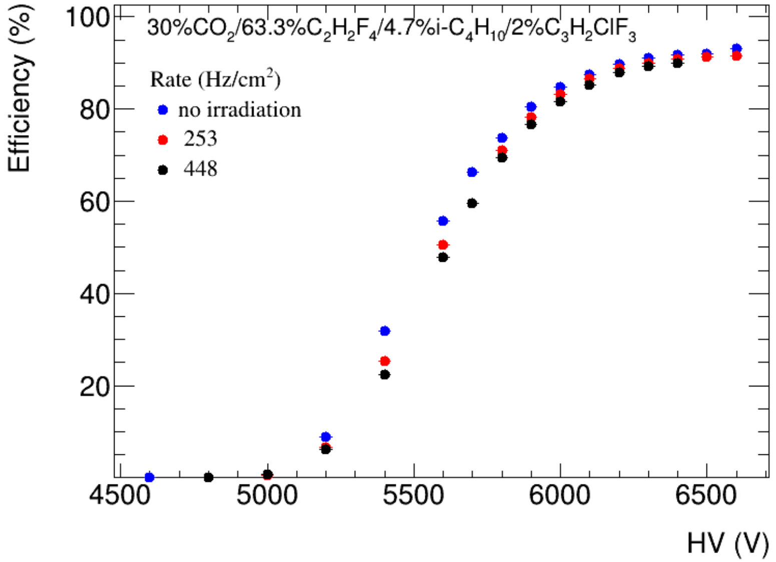
This result is consistent with the one obtained with $C_2H_2F_4/CO_2$/%i-C_4H_{10}/SF_6 gas mixtures (Nucl.Instrum.Meth.A 1066 (2024) 169580)

Results : Study of the efficiency under irradiation

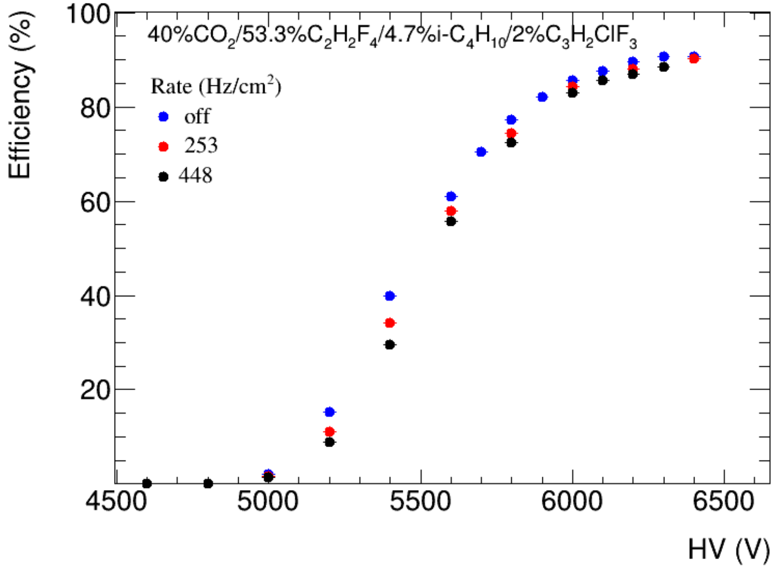
Standard gas



MIX3



MIX4



The efficiency plateau drop under irradiation is:

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

The currents at WPs are : I(30%CO_2) = 1.5•I(STD), I(40%CO_2) = 1.7•I(STD),

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

The $C_3H_2ClF_3$ has the same performance as the SF_6 → It can efficiently substitute the SF_6

Conclusions

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

In this presentation a good alternative to the SF_6, the $C_3H_2ClF_3$, has been studied, testing the following gas mixtures:

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% $C_3H_2ClF_3$
3. MIX3 : 63.3%$C_2H_2F_4$/30%CO_2/4.7%i-C_4H_{10}/2% $C_3H_2ClF_3$
4. MIX4 : 53.3%$C_2H_2F_4$/40%CO_2/4.7%i-C_4H_{10}/2% $C_3H_2ClF_3$

The results show that the $C_3H_2ClF_3$ can replace the SF_6 without any degradation of the RPC overall performance.

This is a groundbreaking achievement with significant implications for future developments

Final step: certification of its long-term aging performance

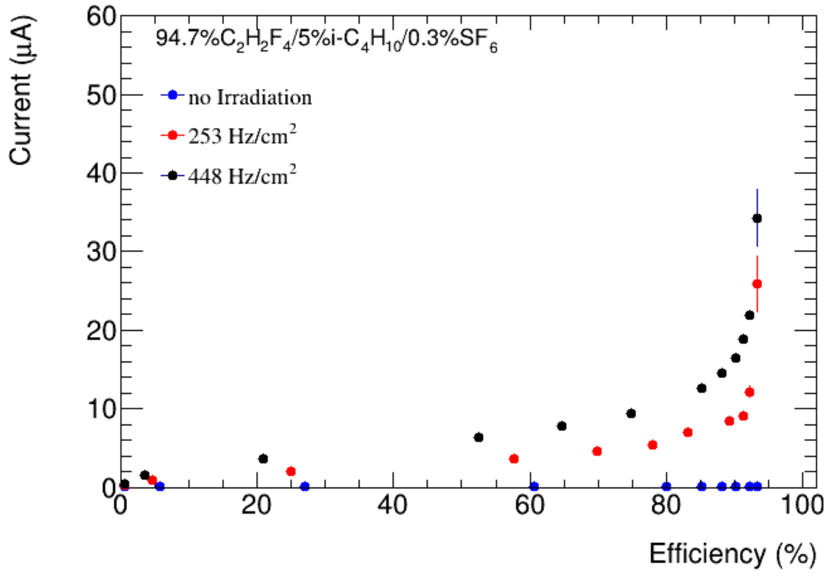
THANK YOU!!!
Questions are welcome

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

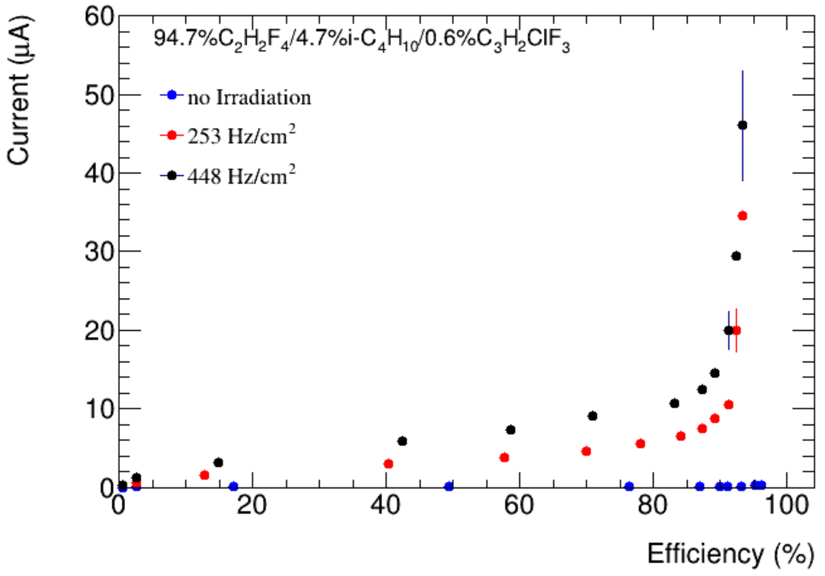
Backup

Results : Currents under irradiation

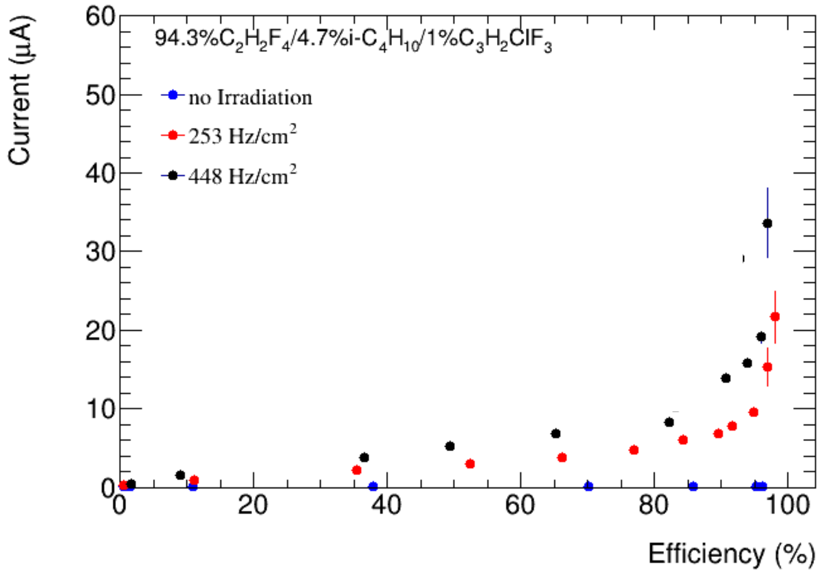
Standard gas



MIX1

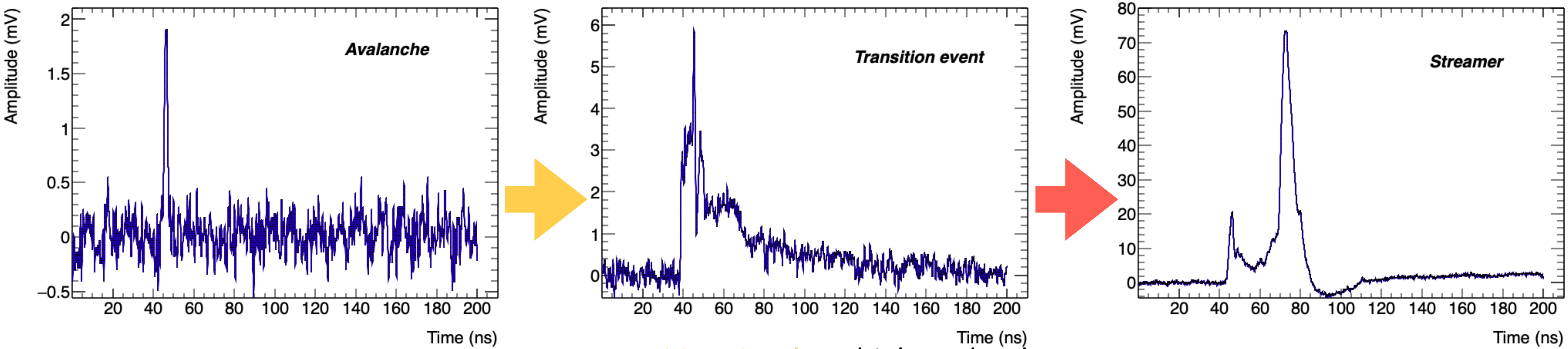


MIX2



Here I have to modify the slides → current with lower threshold

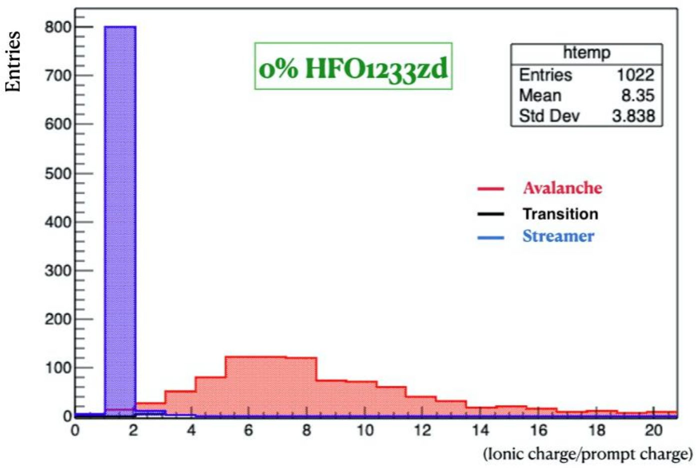
Operating the RPC with $C_3H_2F_4/CO_2$-based gas mixtures: the transition events

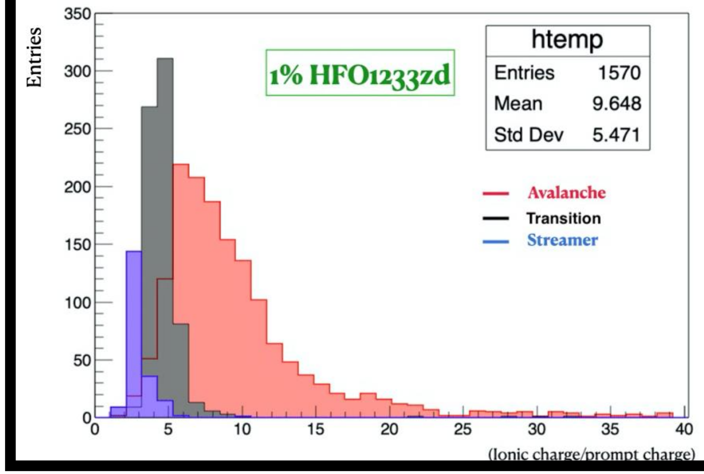


- Avalanche : very short single signal (4-5 ns), low amplitude (~ mV) and low charge content (~ 1 pC)
- Transition signal: multiple avalanche signal and/or a large tail following the precursor
- Streamer: avalanche signal precursor followed by a wide signal (~100 mV) lasting tens of ns and with a high charge content (~ 100 pC).

Interpretation: streamers precursor, representing those events in which the delayed avalanches don't merge together to form the streamer but they ionize the gas: the CO_2 produces many photons which produce secondary electrons that ionize the gas but are not able to trigger the streamer because they are restrained by the HFO.

Operating the RPC with $C_3H_2F_4/CO_2$-based gas mixtures: the transition events





Following the pure exponential avalanche model:

Avalanche (Q/q) ~ 8-12

Transition (Q/q) ~ 5

Streamer (Q/q) ~ 1.5

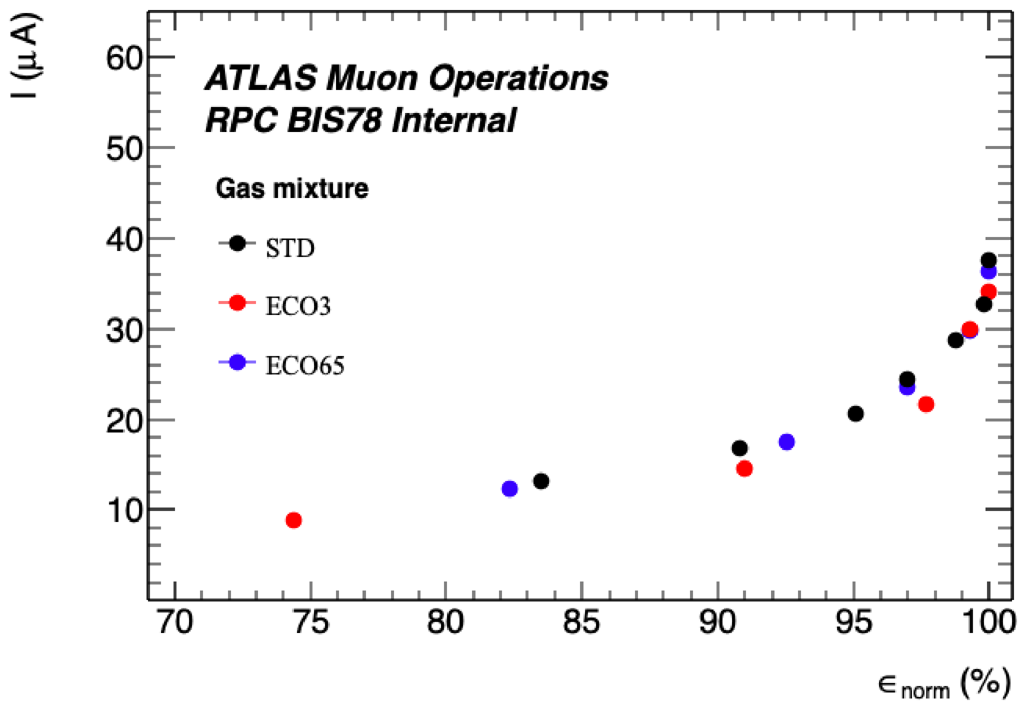
Avalanche, transition events and streamers belong to different categories of signals

Signals classification

Signal type	Prompt charge (pC)	Time over threshold (ns)	Exceeding charge (*)
Avalanche	≤ 5	< 12	-
Transition	$5 < q < 30$	> 12	> 0.21
Streamer	≥ 30	≥ 30	-

(*) Exceeding charge = integrated charge over the tail of the signal, excluding the avalanche contribution

Current study



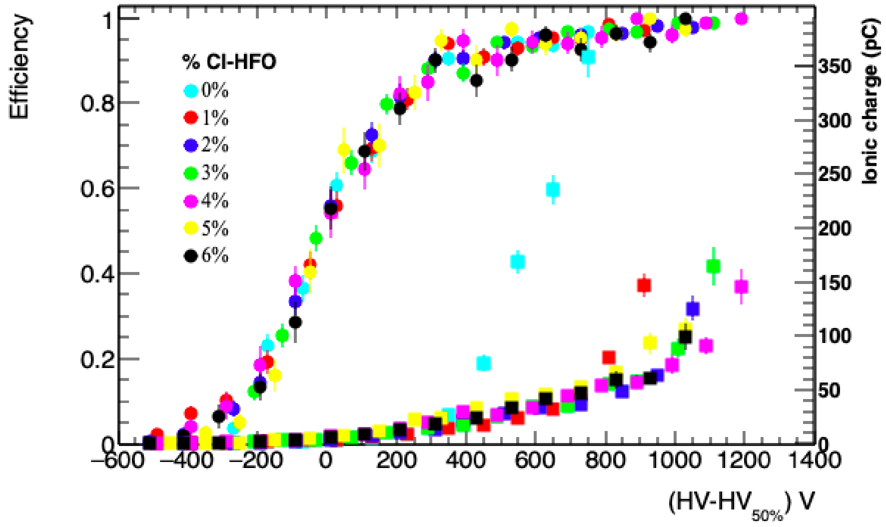
- ϵ_{norm} = efficiency to MIPs normalized to the plateau asymptotic efficiency value
- I = photon current

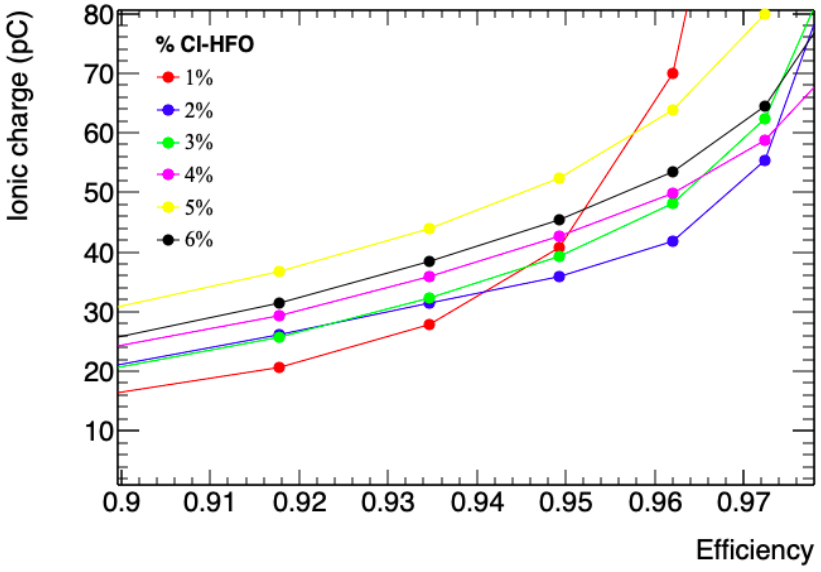
Conclusion

The photon contribution to the detector current is independent from the gas mixture at the same normalized efficiency.

ECOGAS might guarantees same aging and same rate capability as the standard gas mixture working with 1 fC threshold → still to be demonstrated

RPC operating with CO_2/F-HFO/ i-C_4H_{10}/Cl-HFO : Ionic charge





- The ionic charge of the mixture without Cl-HFO reaches very high values (~ 75 pC) at low efficiency
- The mixture with 5% and 6% Cl-HFO have an ionic charge more than 30 pC at the first plateau value
- The mixture with 1% Cl-HFO shows the lowest ionic charge for $\epsilon < 94\%$
- The mixture with 2% Cl-HFO shows the lowest ionic charge for $\epsilon > 94\%$

Conclusion

Optimal choice : 2% Cl-HFO due to the lower ionic charge

ECOGAS for the ATLAS Phase-2 upgrade: primary clusters

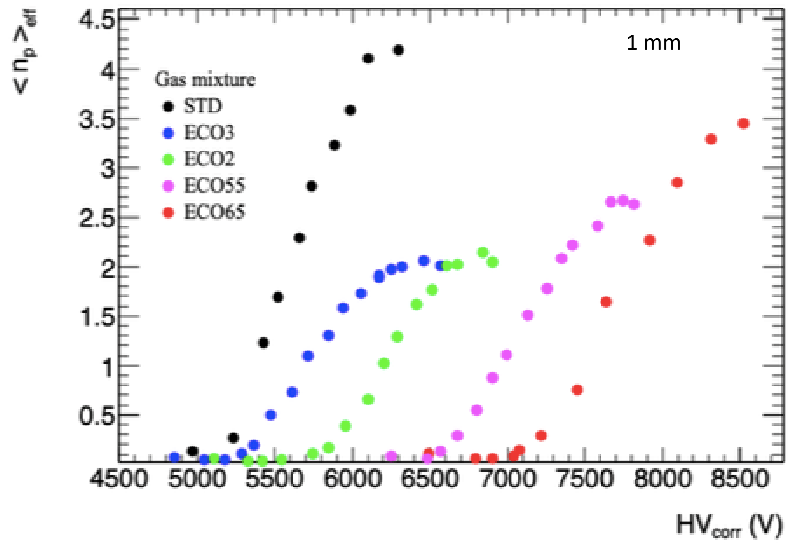
Not all primary clusters have the same probability to give a detectable signal: those generated near the anode give a small number of electrons, which will not go above the discriminator threshold.

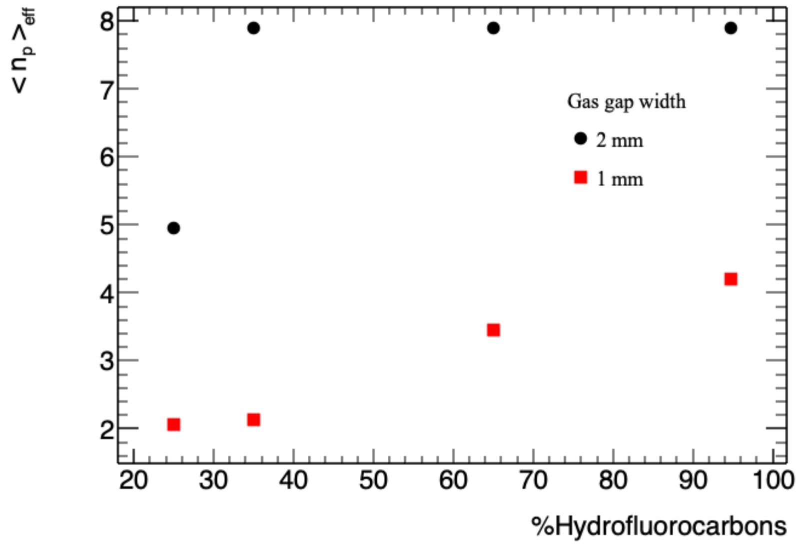
Interpretation of the detector inefficiency as the probability to have zero effective primary ionization:

$$1 - \epsilon_{intr} = P(0) = e^{-<n_p>_{effective}}$$

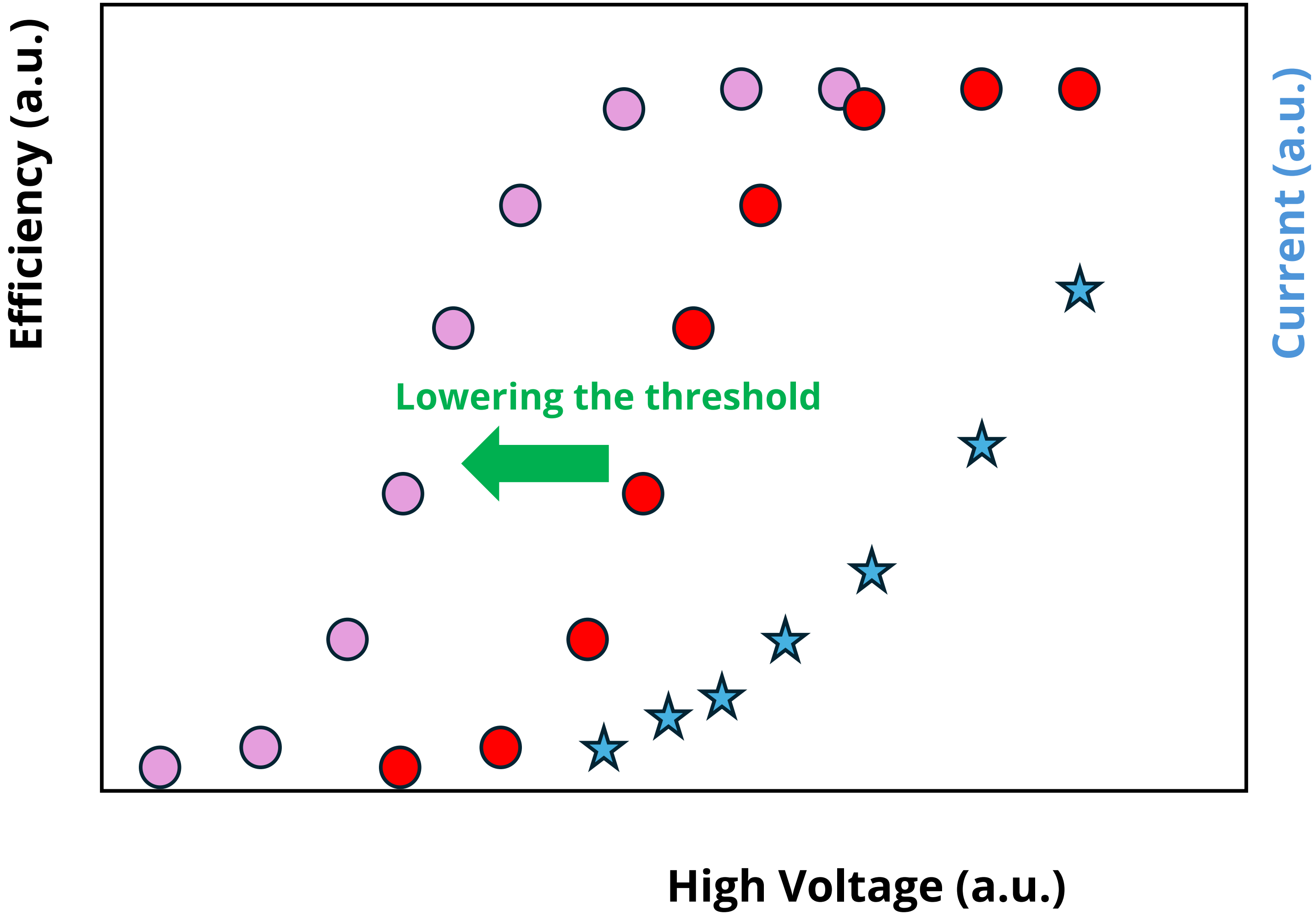
$$< n_p >= ln(\frac{1}{1 - \epsilon_{intr}})$$

The 1 mm gas gap needs double the F-HFO concentration wrt the 2 mm gas gap to exploit all the clusters available for the multiplication and detection. In the saturation plateau, the effective clusters in the 1 mm gas gap are half those available in the 2 mm gas gap





Decreasing the threshold



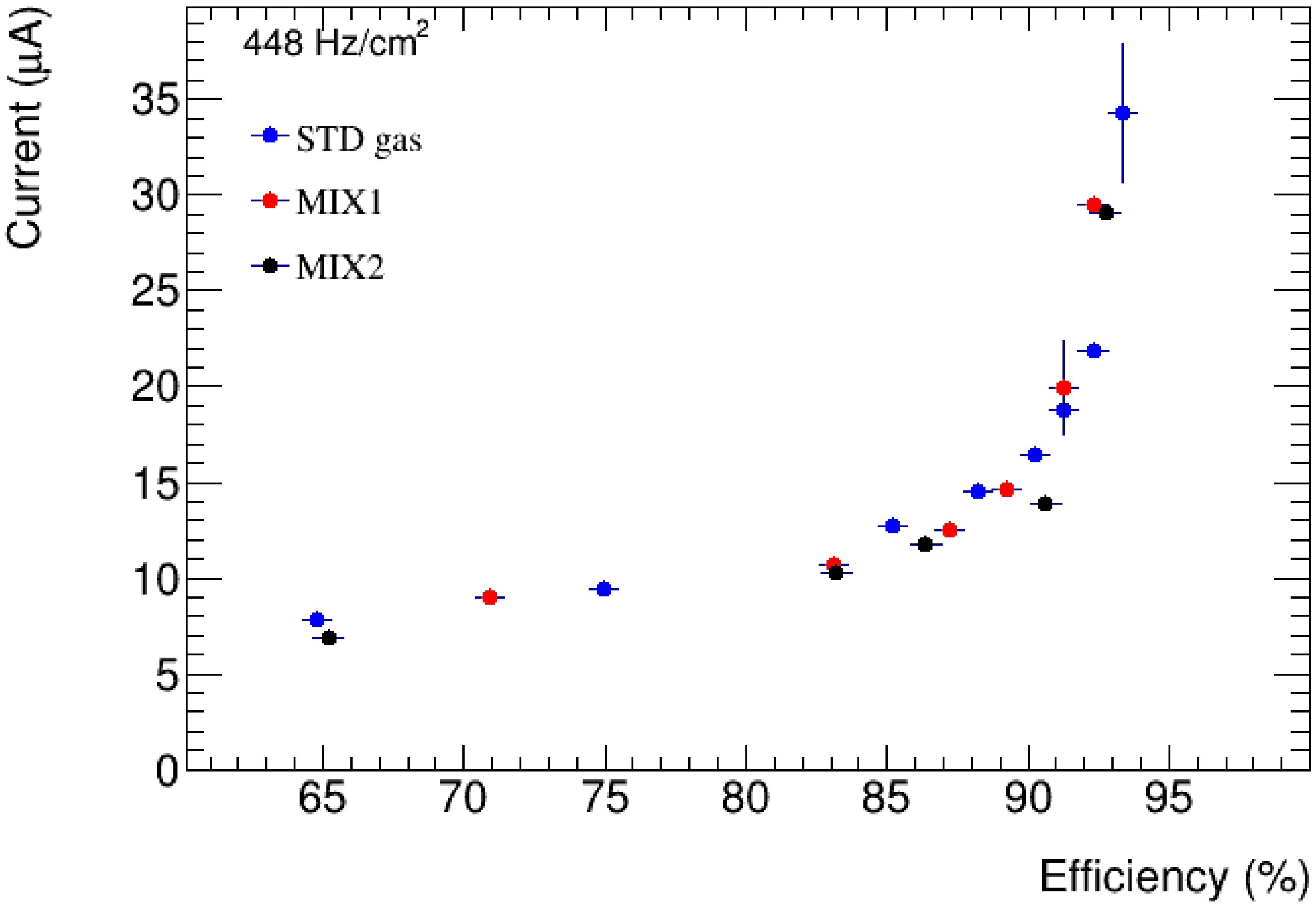
If the RPC is operated with a certain threshold **Thr1**, its characteristic efficiency curve (●) and current (★) will be obtained

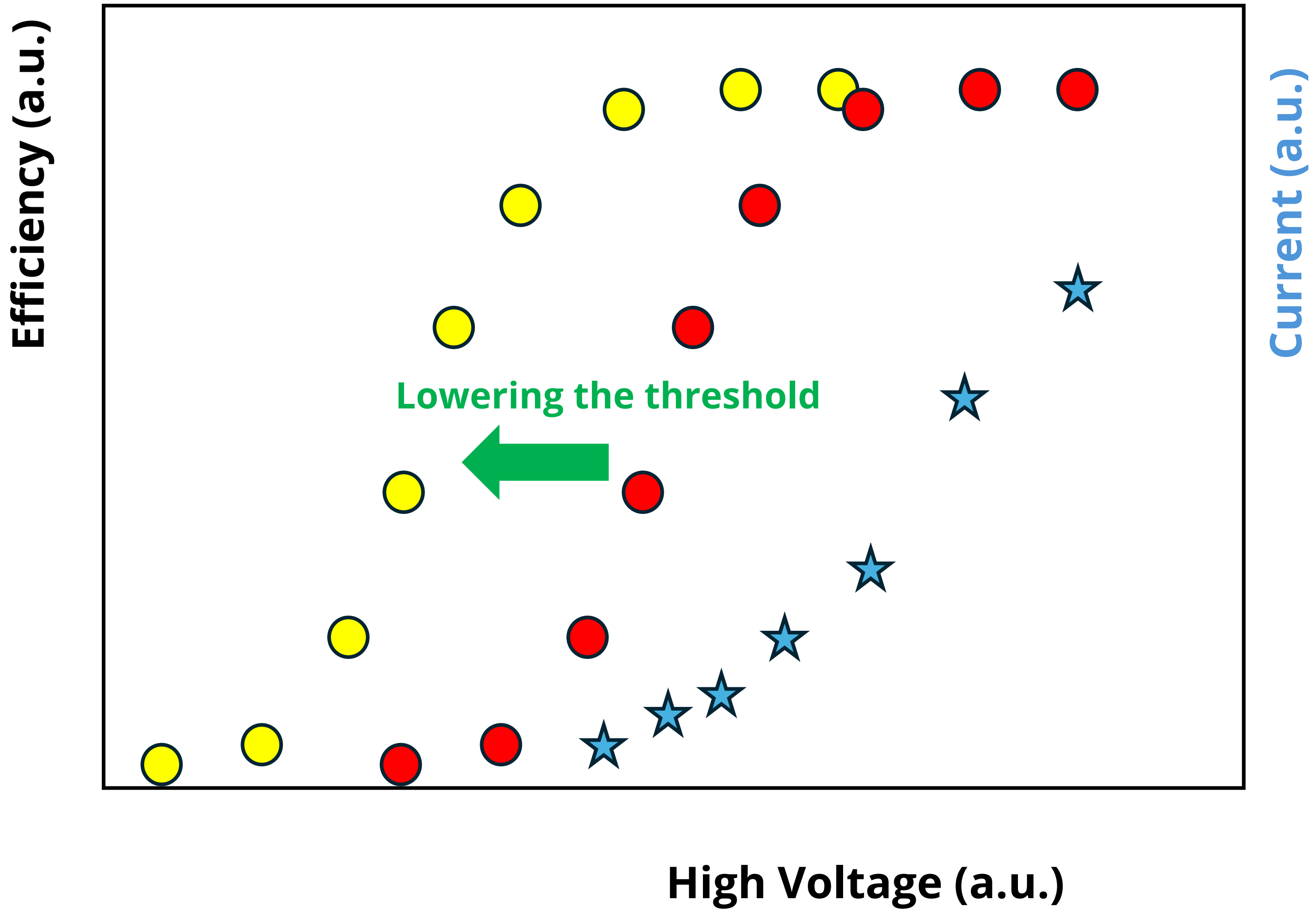
Moving the threshold from **Thr1** to a lower one **Thr2**, the efficiency curve will move to lower voltages, without loosing its shape (●)

The curve of the trend of the current will **NOT** move accordingly

Possibility to work at the same efficiency with lower current

Effect of decreasing the threshold

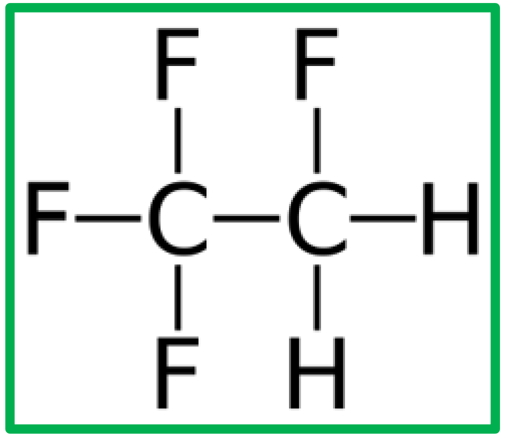



Efficiency (a.u.)
Current (a.u.)
Lowering the threshold
High Voltage (a.u.)

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)

Tetrafluoroethane ($C_2H_2F_4$) molecule



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 (faster aging)

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

Tetrafluoropropene ($C_3H_2F_4$) molecule