Performance and longevity of ATLAS RPCs with new lower GWP mixtures

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VCI 2025

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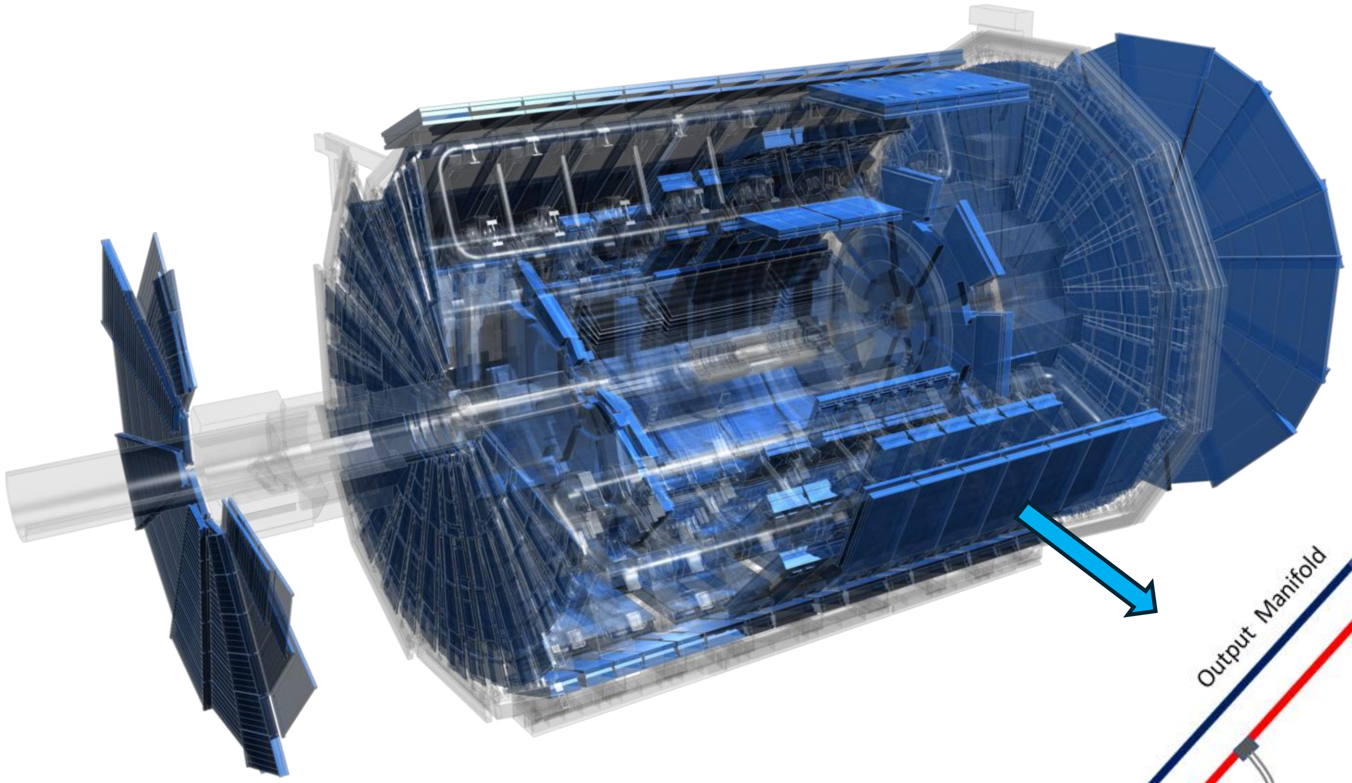
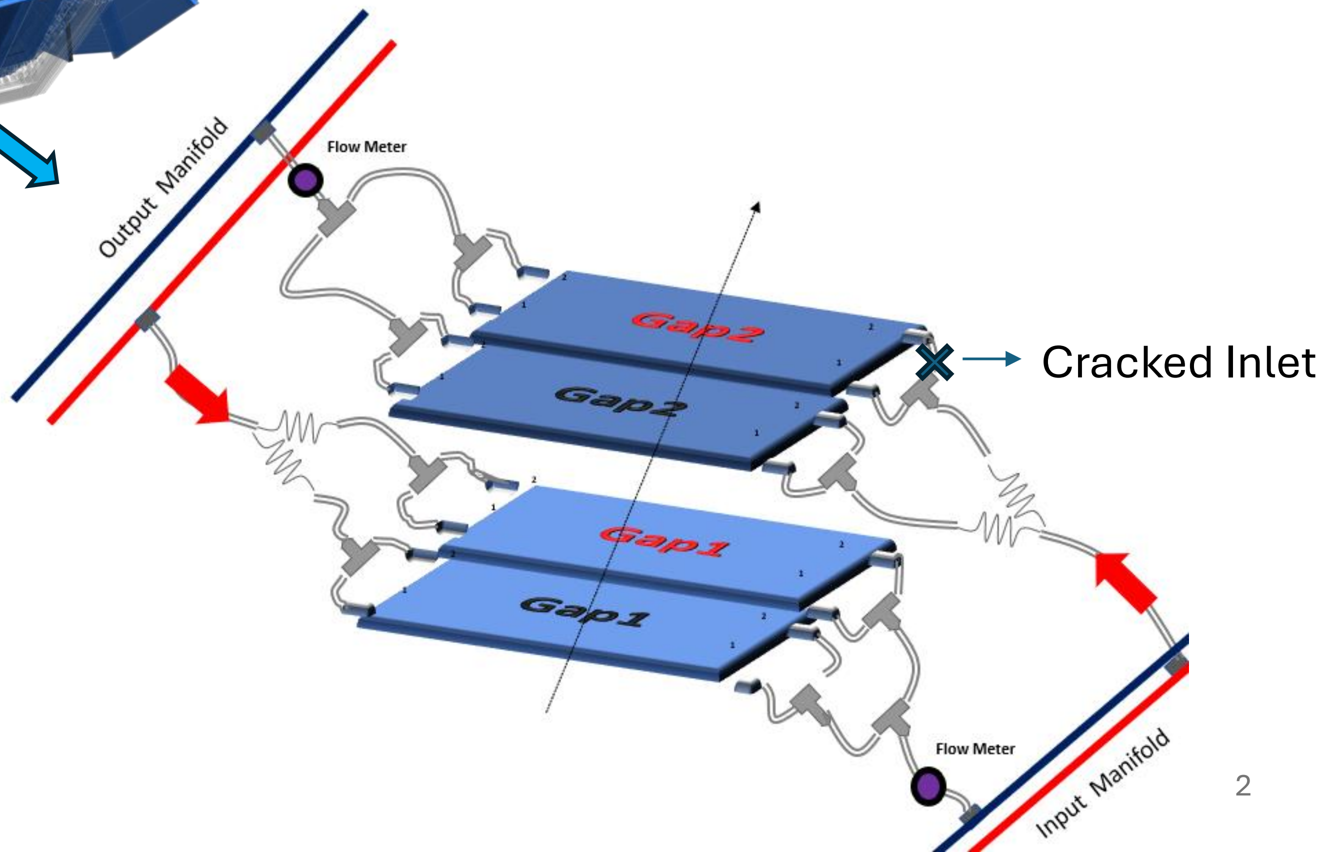
ATLAS RPC in the Cavern



The Resistive Plate Chamber (RPCs) is a gaseous detector responsible for the muon triggering in ATLAS detector barrel.



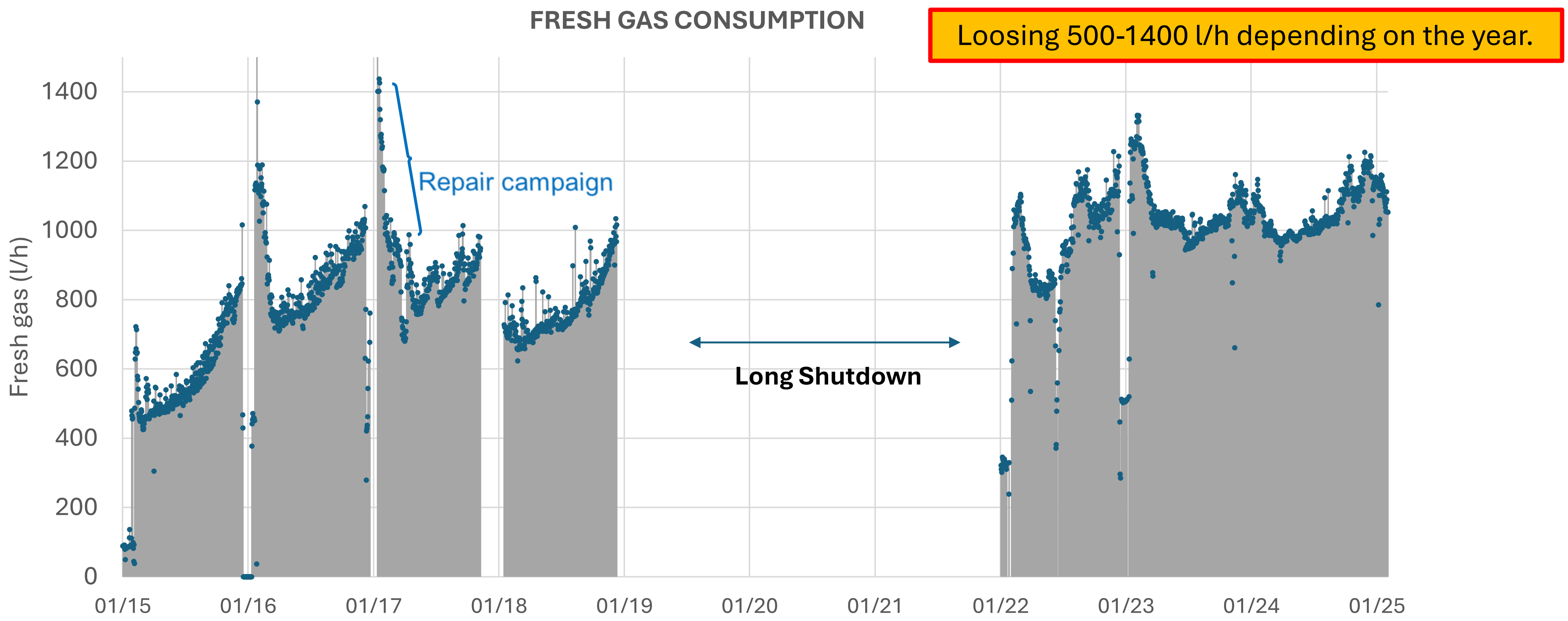
ATLAS RPCs with numbers:

- ~ 3800 RPC gas gap surround the barrel region
- The total gas volume is 15 m^3
- 128 I/O gas manifolds
- Manifolds are connected to chambers through 8000 gas inlets

The gas inlets tend to crack due to intrinsic fragility

Total Fresh Gas Consumption

Since the gas is circulated in the system, the fresh gas should be injected to the system to compensate the leaks.



Consequences:

- Lower detector functionality; Higher running cost; remarkable contribution to the CERN GWP impact.

Mitigations:

- Continuous **inlet reparation and preventive consolidation** is in place to minimize gas loss.
- Searching for the **new gas alternatives** to reduce operational costs and environmental impact.

New RPC Gases: Validation Method

Standard RPC mixture: 94.7% **R134a** - 5.0% **iC_4H_{10}** - 0.3% **SF_6**

Gas search strategy

- Replace a fraction of R134a (GWP 1430) with CO_2
- Limit as much as possible the fraction of SF_6 (GWP 22800)

Method:

Performance measurements: measuring the efficiency, current, counts vs. HV by changing the photon intensity, gas composition and FE threshold

Ageing test: monitoring through periodic performance measurements, observing in particular, ohmic current, exponential current, electrode resistivity

Validation in ATLAS: validating the performance results obtained in the laboratory with the RPC chambers in ATLAS cavern.

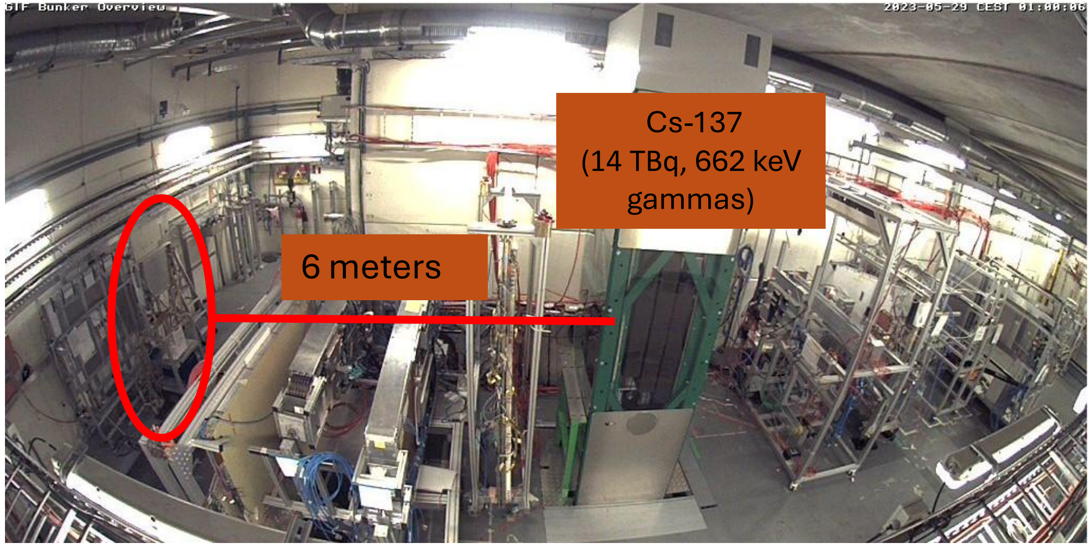
Since the beginning of Aug 2023 the ATLAS RPCs are operated with a new gas mixture:
- **current mixture**: 64% **$C_2H_2F_4$** - 30% **CO_2** - 5% **iC_4H_{10}** - 1% **SF_6**

Environmental impact is reduced by ~14%

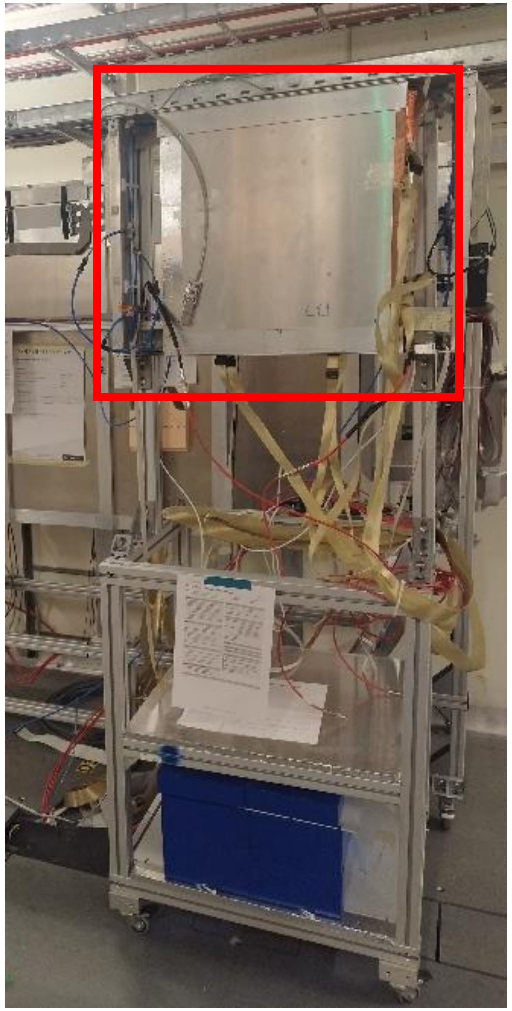
ATLAS-like RPC Prototype Test Setup

Test chamber: 50 cm x 50 cm ATLAS-like RPC doublet (same gas gap, electronics, Farady cage structure and power**)**

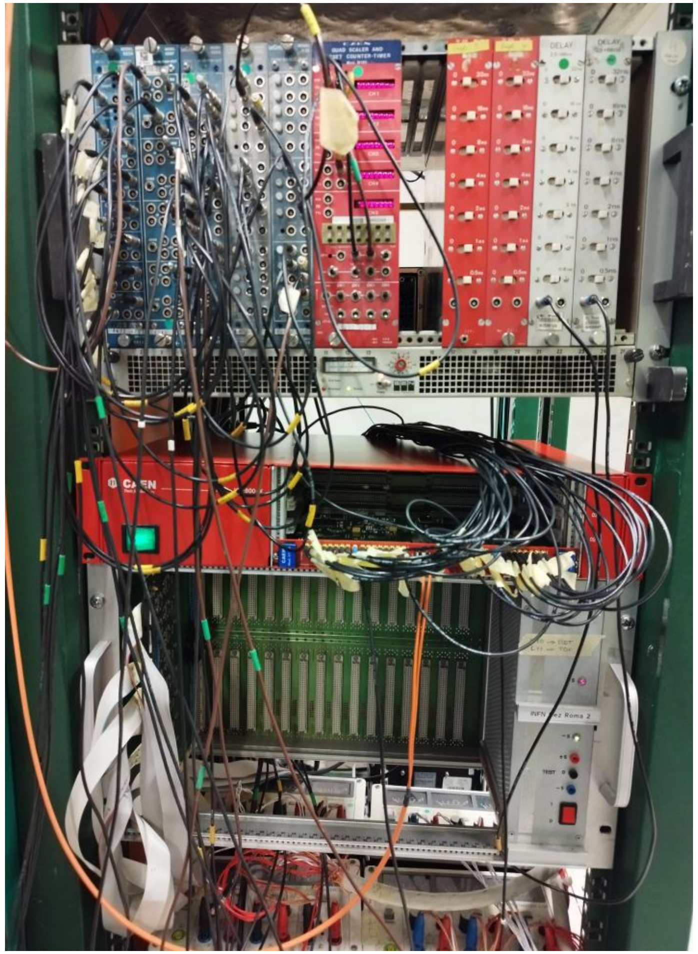
Test Area: CERN Gamma Irradiation Facility (GIF++)



Chamber Under Test



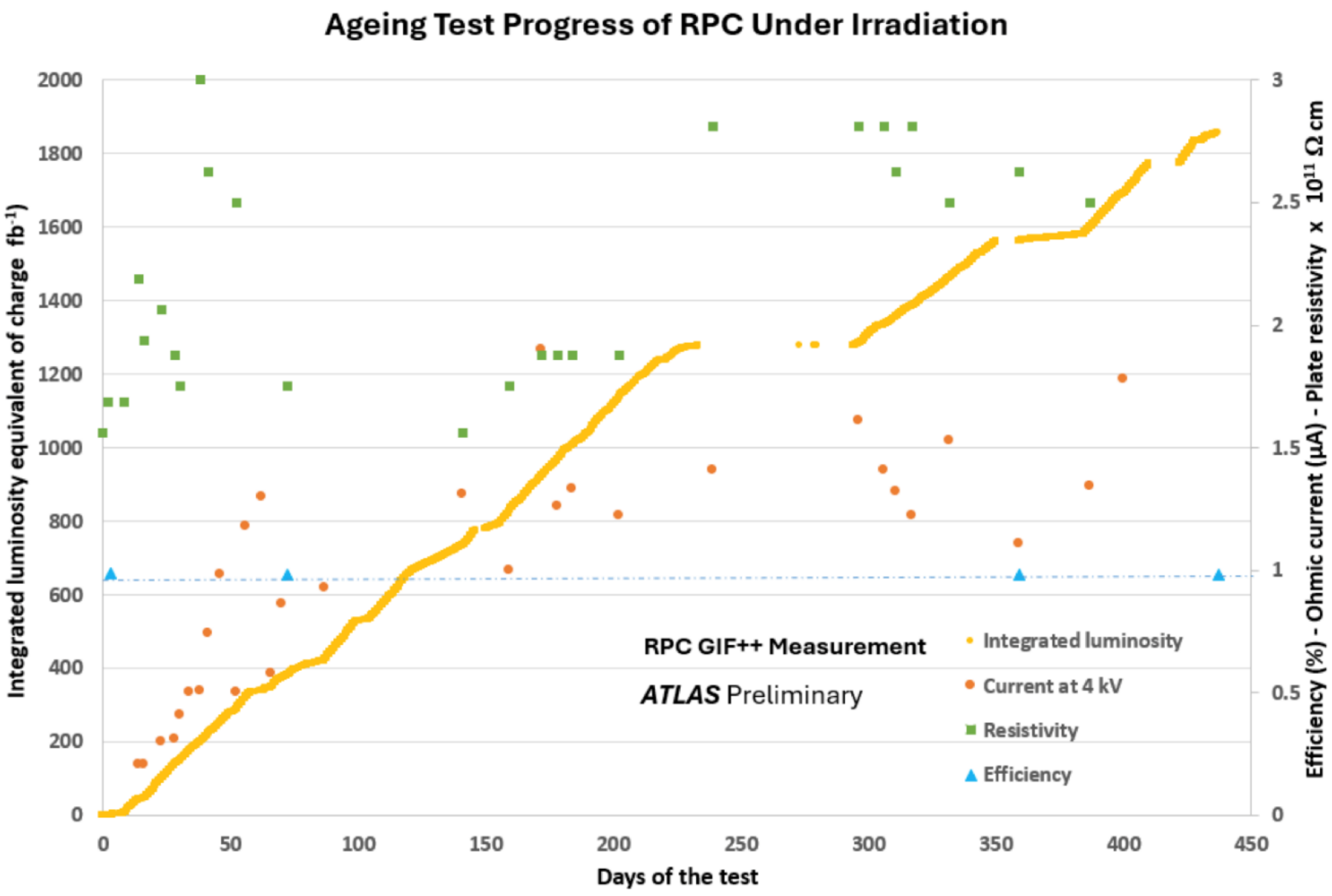
DAQ System



- Reproduce the HL-LHC background for performance test
- Perform accelerate ageing tests

In all performance measurements, one layer is used as reference the other as test, alternatively.

New RPC gas: AGEING RESULT



- First gas candidate: 30% TFE replaced with CO2 + increased SF6 to 1% for precaution

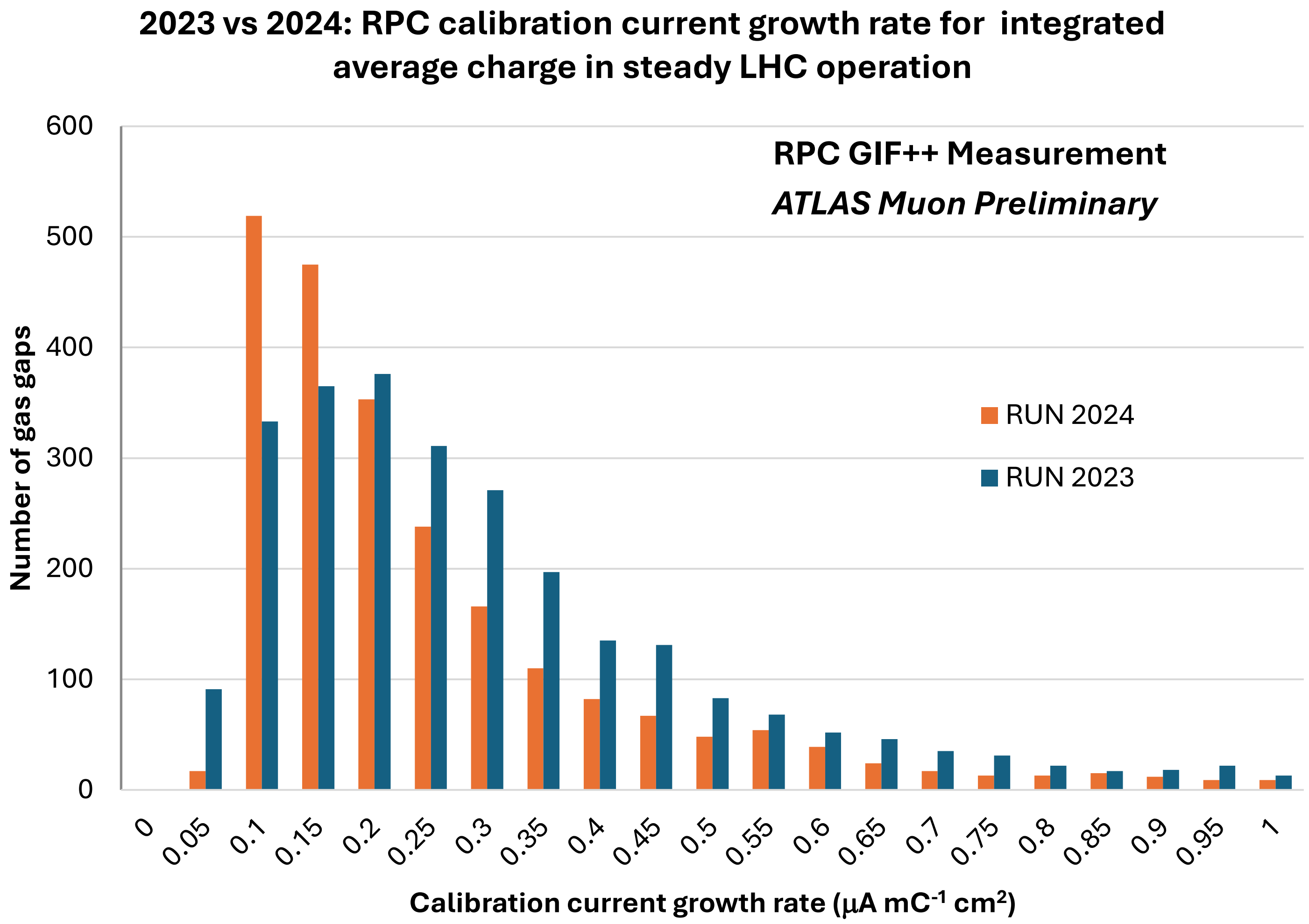
64% $C_2H_2F_4$ - 30% CO_2 - 5% iC_4H_{10} - 1% SF_6

- We accumulated in 1.5 years the equivalent of half of the HL-LHC program (2000 fb^{-1})

- Performance validation:
  - Ohmic current stabilized after initial increase
  - Electrode resistance is stable within a factor 2
  - The efficiency is unchanged

For more information see: **Mitigation of the ATLAS RPC environmental impact**, **ICHEP 2024**

Comparison of STD & New RPC Gas Mixture in ATLAS Cavern



@ ATLAS, the impact on the longevity has been evaluated by comparing the evolution of the Beam OFF working current vs. integrated charge, for 2023 and 2024, where standard mix. and new mix. have been used respectively. The study shown that in the comparable periods and integrated charge, the new mix had a remarkably lower Beam OFF increase rate → there is a lowered risk of dark current development in the gaps.

Further improvement of the GWP performance

Scope:

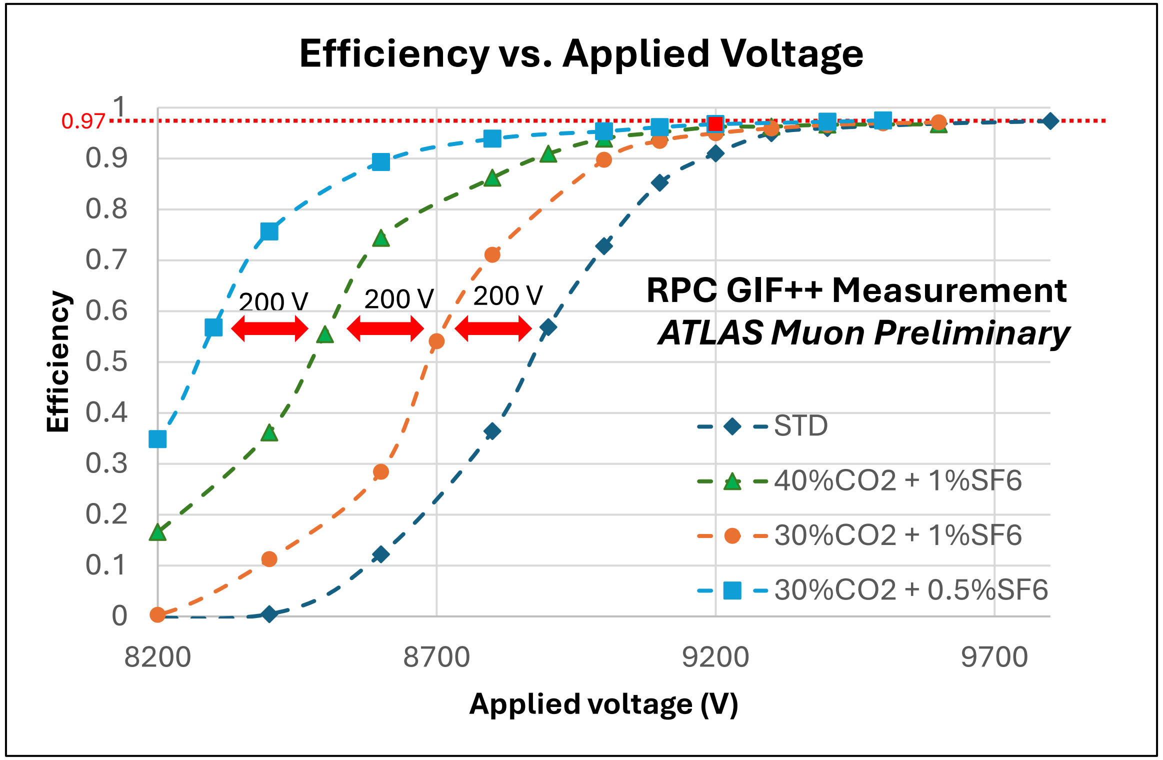
- The validation of 3 new mixture candidates, with a lower GWP with respect to the presently used one:

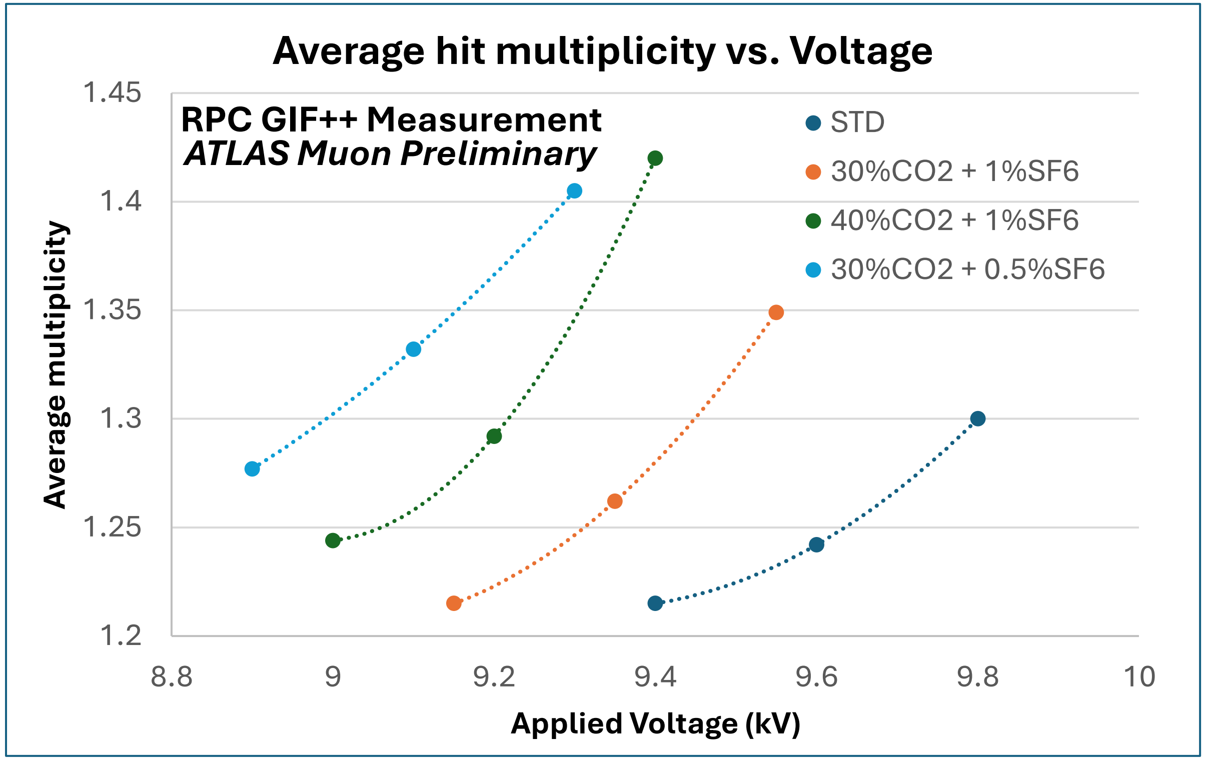
1. 40% of CO_2 with 1% of SF_6 → further lowering the TFE by 10% (**GWP ~ 1002**)
2. **30% CO_2 with 0.5% of SF_6 → halving the impact of SF_6 (GWP ~ 1037)**
3. 30% or 40% CO_2 with 1% or 2% of Chlorotrifluoropropene (a low GWP substitute of SF_6) (**GWP ~793**)[*]

- The validation of 1. and 2. above started with 2 mm ATLAS RPC prototype at GIF++ .
- Longevity tests requires several months to be completed. We expect to start the 2025 run with the 2nd mixture and aim to identify the best mixture candidate to reduce the GWP already during Run3.
- In the next slides the candidate gases are evaluated on the base of their performance.

*G. Proto, "Study of environment friendly **SF6** substitute for the Resistive Plate Chambers", RPC2024

Efficiency and Multiplicity vs. HV





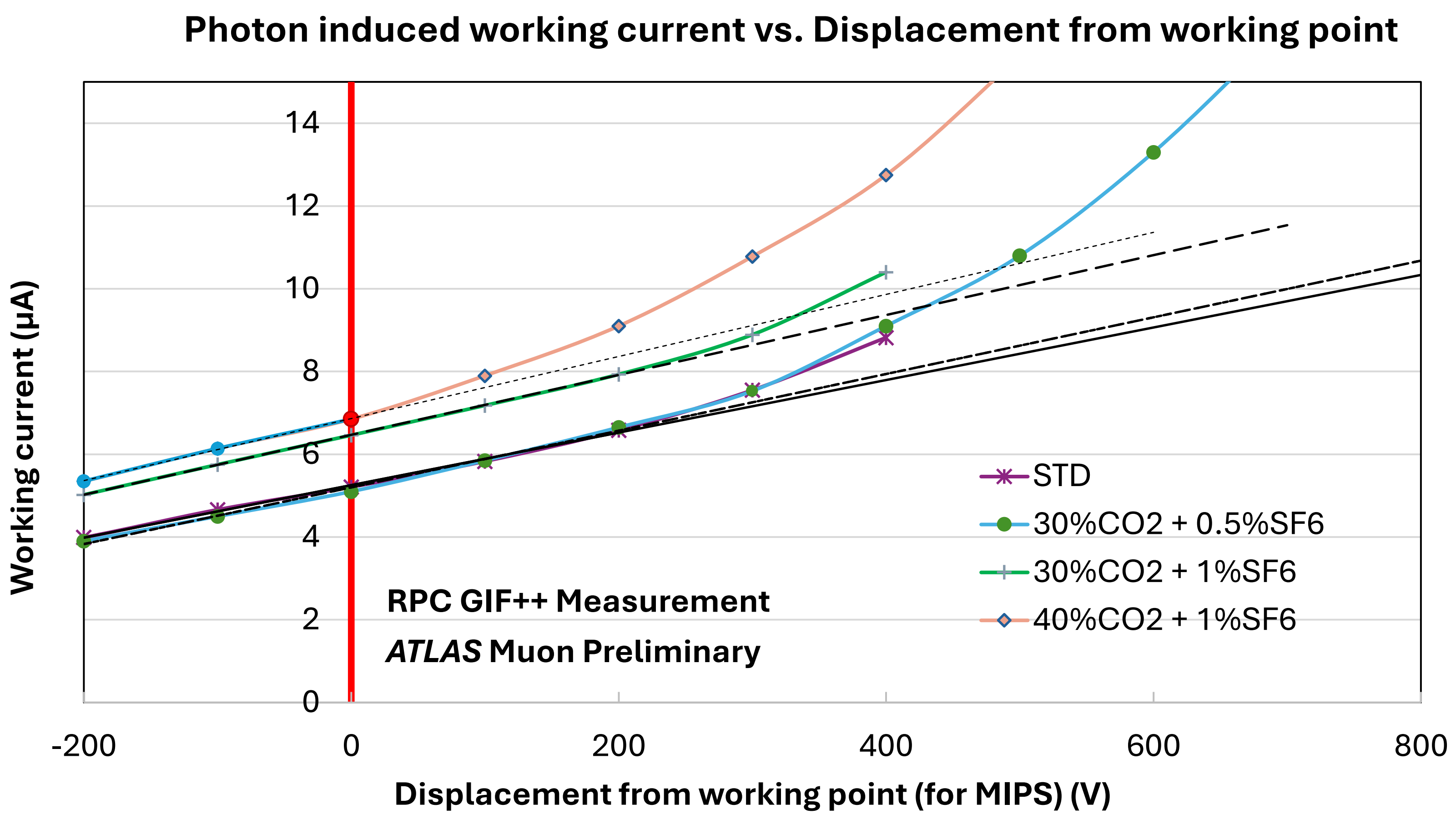
- The maximum efficiency is not significantly dependent on the gas, while the W.P. is lowered by higher concentration of CO_2 and enhanced by higher concentrations of SF6.
- The combination of CO_2 and SF6 concentrations in the various mixtures equally shifts the plateau by about 200V.

→ The maximum efficiency is reaching up to **97%** for all mixtures.

- Multiplicity value at W.P. is enhanced by higher concentrations of CO_2 and lower SF6.

→ The multiplicity increase rate with HV is faster with higher concentration of CO_2, and it seems depending less on the SF6 concentration. The mixture with 0.5% of SF6 has a slightly higher multiplicity but growing slower with the HV with respect to the mixture with 40% of CO_2.

Separation of the streamer appearence



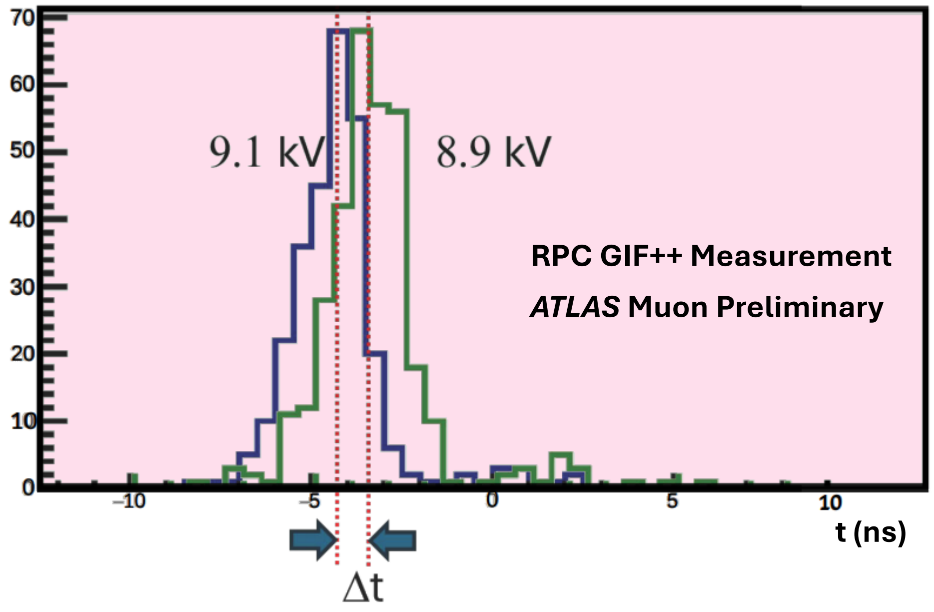
Gas mixture	Displacement
STD	200
30%CO2 + 0.5%SF6	200
30%CO2 + 1%SF6	200
40%CO2 + 1%SF6	0

- The expected current growth law is linear in the saturation region: the deviation from linearity → the appearance of streamers.
- For each mixture, the distance in voltage between W.P. and the start of the deviation is reported in the table.
- The rate of deviation is similar for the mixtures except for 40% CO_2.

The mixtures with higher SF_6 have also higher total current due to the production of negative SF_6 ions by electron attachment.

Timing features of the mixtures

ToF measurement for 30% CO_2 + 0.5% SF_6



The ToF is defined as the leading time difference for signals generated by the same muon in the two RPCs.

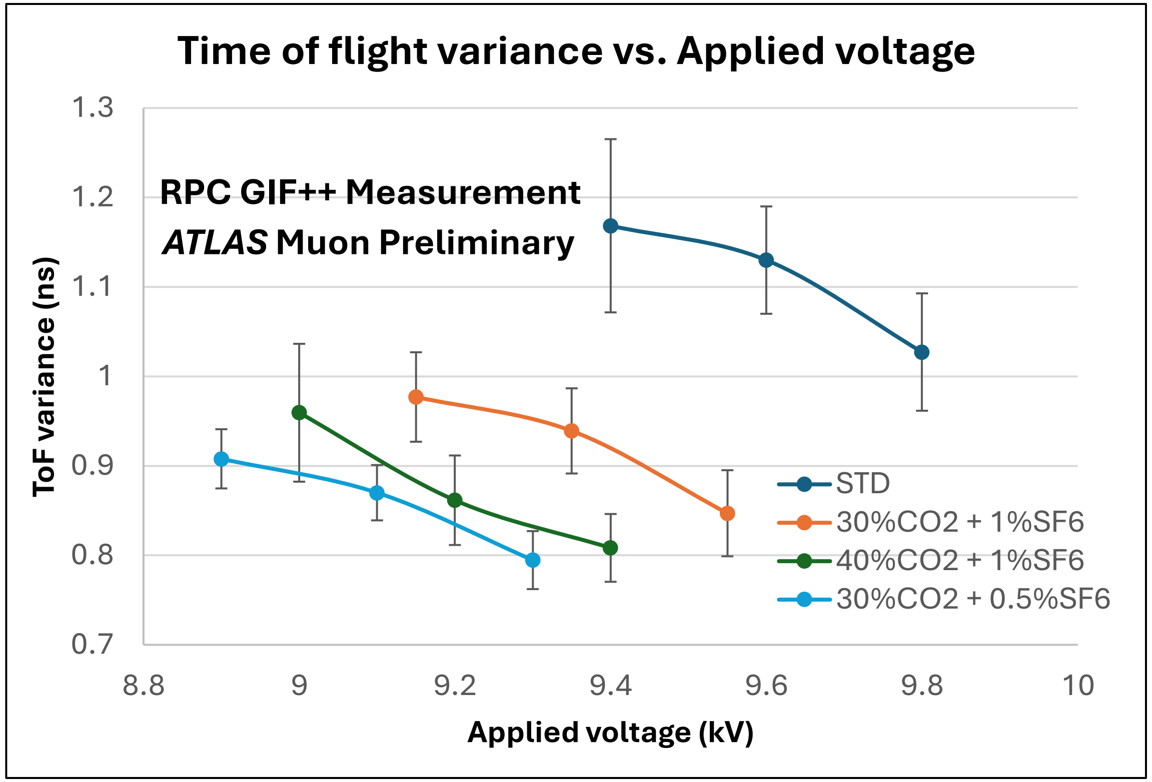
Time of flight distribution comparison: In each distribution, the reference chamber of the doublet is kept at a fixed W.P., while the voltage applied to the test chamber changes.

→The distribution width represents the combined time fluctuations

→The mean value represents the time of flight including all instumental delays

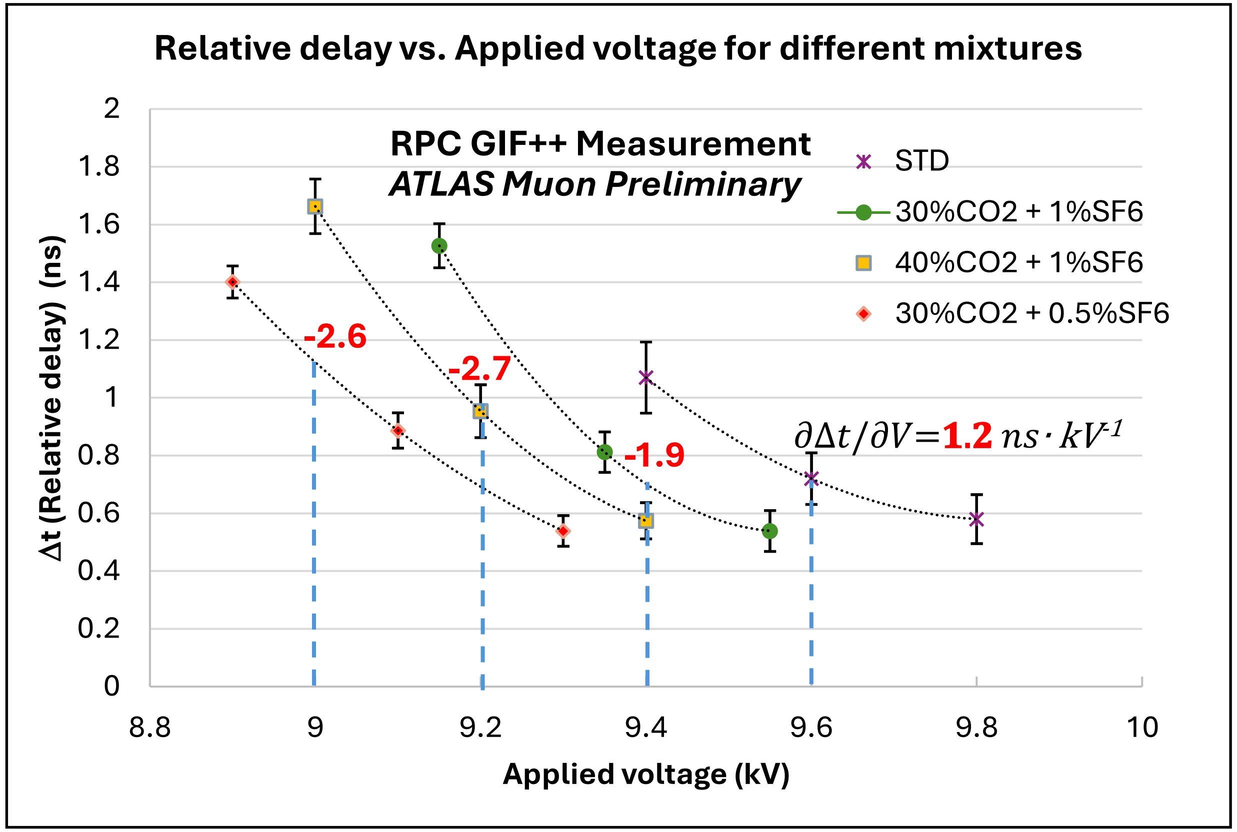
Mean is delayed when a lower voltage is applied to the test chamber

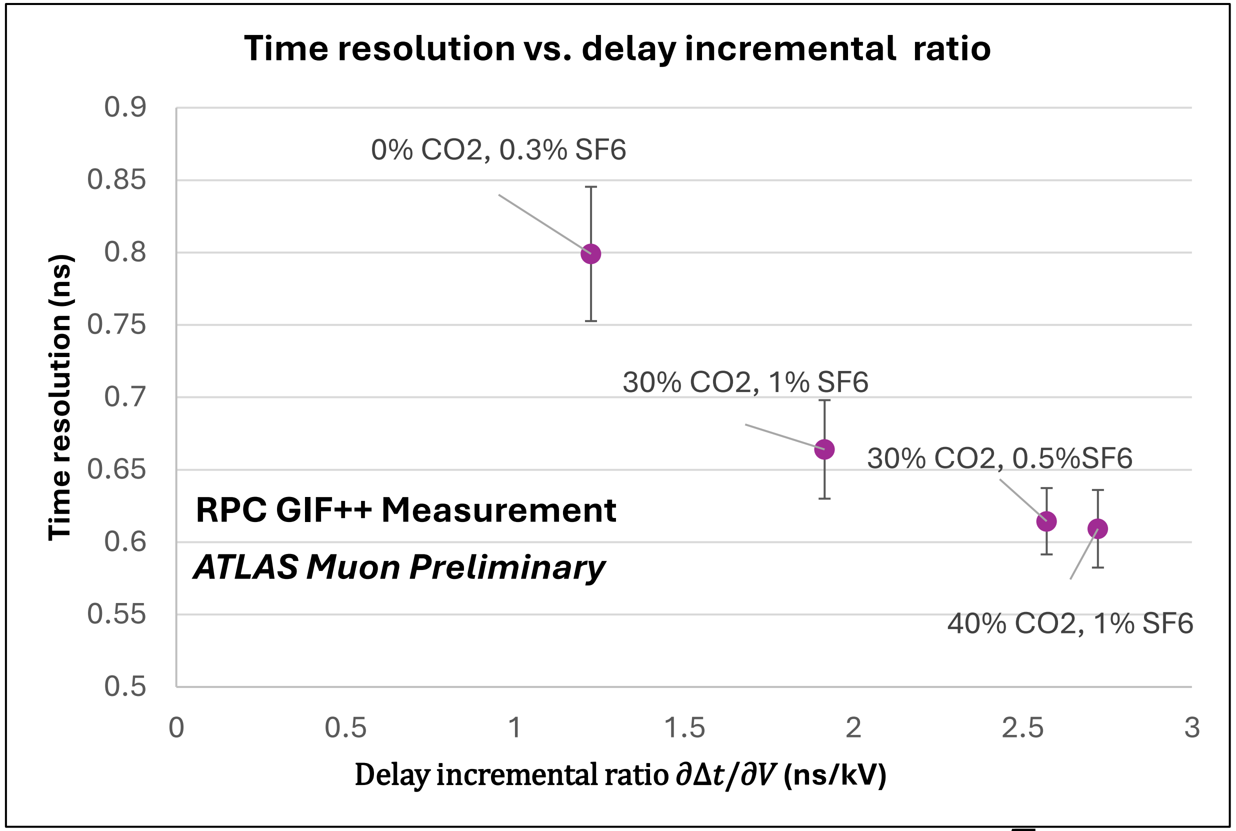
This example is given for illustration, showing that to a given ΔV *corresponds a given* Δt.



- The ToF variance decreases with applied voltage for each gas mixture
- Increasing fraction of CO_2 corresponds to lower width
- Different fractions of SF_6 (for fixed amounts of CO_2) produces small effects with respect to the uncertainties.

Time of flight and time resolution vs. HV





- We study how the delay depends on HV for various gases
- The incremental ratio of the delay in ns/kV is obtained from the first derivative of a quadratic interpolation calculated for each gas at own equivalent W.P.

→The results show that signal delays vary more quickly with respect to HV changes, for CO_2 -containing mixtures.

- The time resolution is obtained for each mixture by $ToF/\sqrt{2}$ for identical chambers operated at each mixture equivalent W.P.
- The plot demonstrates that time resolution is correlated to the delay incremental ratio with respect to HV
- higher CO_2 concentration corresponds to higher derivative, the opposite to what happens for higher SF6 concentrations.
- We will measure the relation between delay incremental rate and drift velocity

CONCLUSIONS

- The ATLAS RPC system plays a critical role in muon detection, and its performance must be maintained while addressing challenges related to gas leaks, environmental impact, and long-term stability.

- Our first gas mixture candidate has been fully validated in ATLAS, showing the performance better than the STD gas mixture.

- A further reduction of GWP is possible and in this presentation 2 promising mixtures have been evaluated in terms of performance with respect to STD and newly validated gas mixture. It worths to notice that the timing performance of 2 mm RPCs are improved beyond the known state of the art, reaching 600 ps.

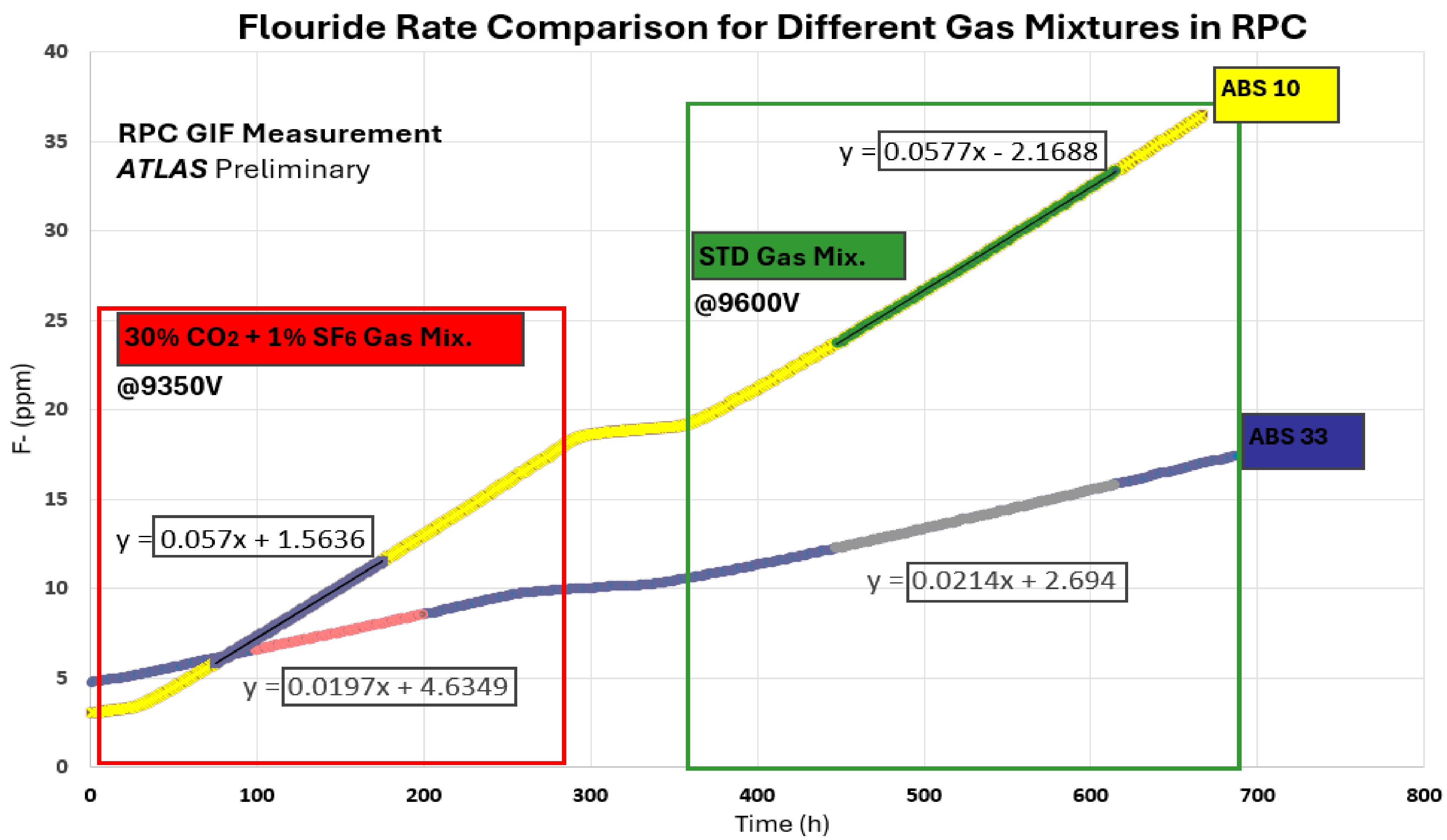
- Next step will be validating the new mixtures in ageing tests and trials in the ATLAS detector to establish the best possible mixture for the LHC Run-4.

- Our study has demonstrated that the mixture with halved SF_6 and 30% CO_2 seems more stable and can reduce the GWP 25% wrt. STD gas mixture, for this reason our next ageing study will be on this mixture.

THANK YOU!

BACKUP SLIDES

Flouride Measurement



Impact of a given gas mixture on the **ageing** which depends on the amount of F^- ions produced per unit of working current, which depends on

- amplification required in the gas to produce signals above threshold
- chemical properties of the used gas components.

Method: Using an Ion Selective Electrode (ISE) station, measuring the F production rate from the gas output of the gap

To eliminate the systematic and environmental effects

Starting with 30% CO_2 gas mixture for 2.5h

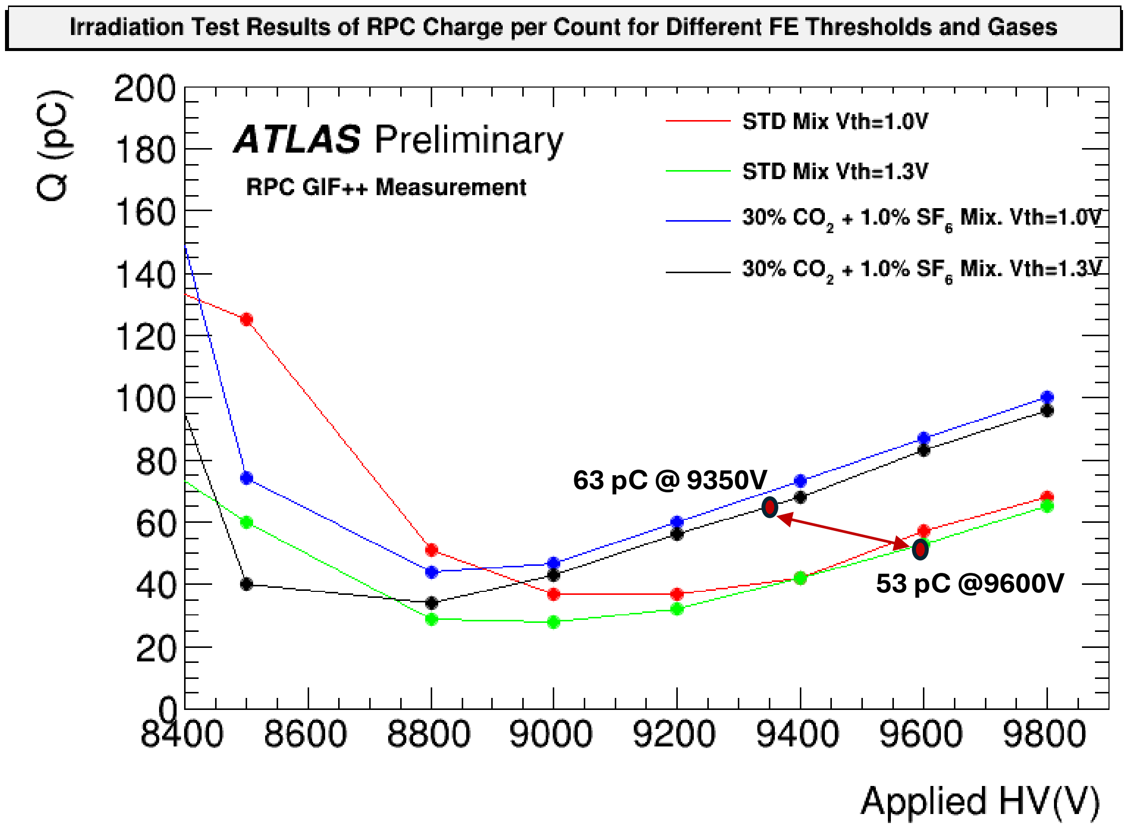
Switching the gas and waiting for the gas change for 1h

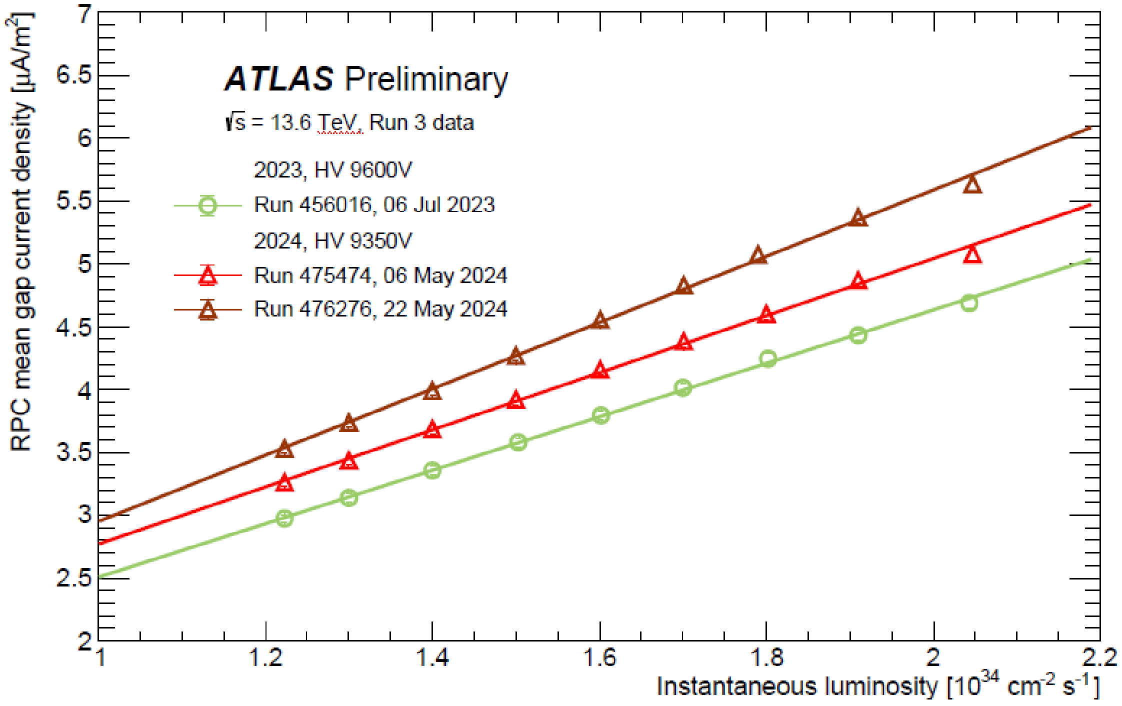
Continuing with Standard Gas Mixture for 2.5h

Comparison STD vs 30% CO_2 mixtures:

For the same efficiency we have the similar amount (or slightly less) of fluoride production!

Comparison of STD & New RPC Gas Mixture





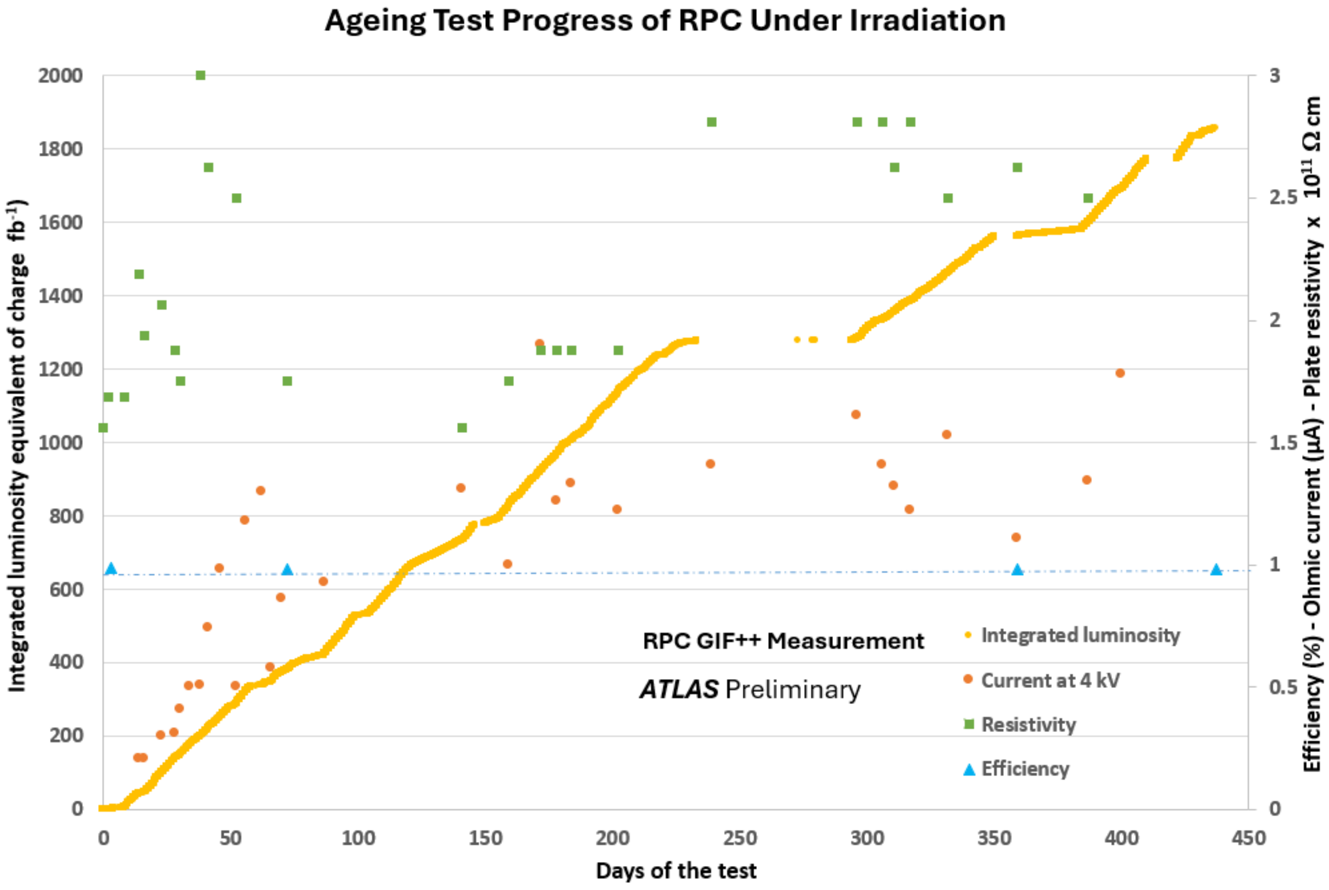
For 30% CO_2, the charge per count is ~**19%** higher wrt. STD gas mixture

- As will be shown later, the increase of current is related to the increas of SF6 fraction

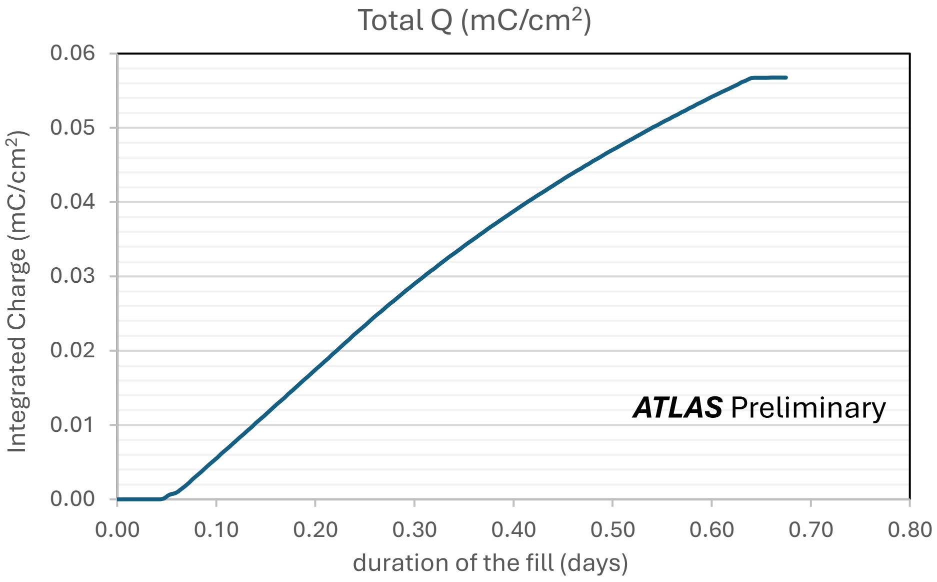
- This current increase has been confirmed in ATLAS as the ratio between gas gap current and Instantaneous Lumi (which is proportional to charge/count) is increased by ~**17%** **[*]**
- **However this current increase is not sıgnificant for the detector ageing but as shown in the next slide**

[*] "Performance of ATLAS RPC detectors and L1 Muon Barrel Trigger with a new CO2 based gas mixture" , ICHEP 2024.

Ageing STUDY with 30% CO_2 + 1% SF6



High background ref. chamber
(BML6A13.CO.Ly0 in ATLAS cavern)



Calibration Q vs. Lumi

fill lumi	0.821 fb^{-1}
int. charge	0.05677 mC/cm^2
conversion factor	0.069145 $mC/cm^2 \cdot fb$

- Target → Full HL-LHC program corresponds to ~ 3000 fb^{-1}
- We are in more than half of the target corresponding to ~1900 fb^{-1}
- Ohmic current is very good! It increased slightly due probably the accelerated ageing at the beginning
- Electrode resistance started very high and is not changing much
- Efficiency is not changing after 1.5 years!

30% CO_2 add to the standard mixture case

Legacy RPCs features:

- 2 mm gaseous target → about 7 primary clusters
- Approximately 10% more current (with respect to std.) per count at the standard FE threshold

Performance:

- Ageing properties comparable to 2002-2004 ageing test, HL-LHC rate for 2/3 of 10 ATLAS years (100 Hz/cm^2)
- Absolute efficiency > 98% thanks to at least 7 primary clusters in the gas

Upgrade RPCs features:

- 1 mm gaseous target → about 4-5 primary clusters
- Average 3 pC per count at the standard FE threshold

Performance:

- Ageing properties extrapolated from 2002-2004 ageing test, assessing compatibility of RPCs to work at about 10 x HL-LHC rate for 10 ATLAS years
- Absolute efficiency > 97.5% due to at least 3.5 primary clusters in the gas