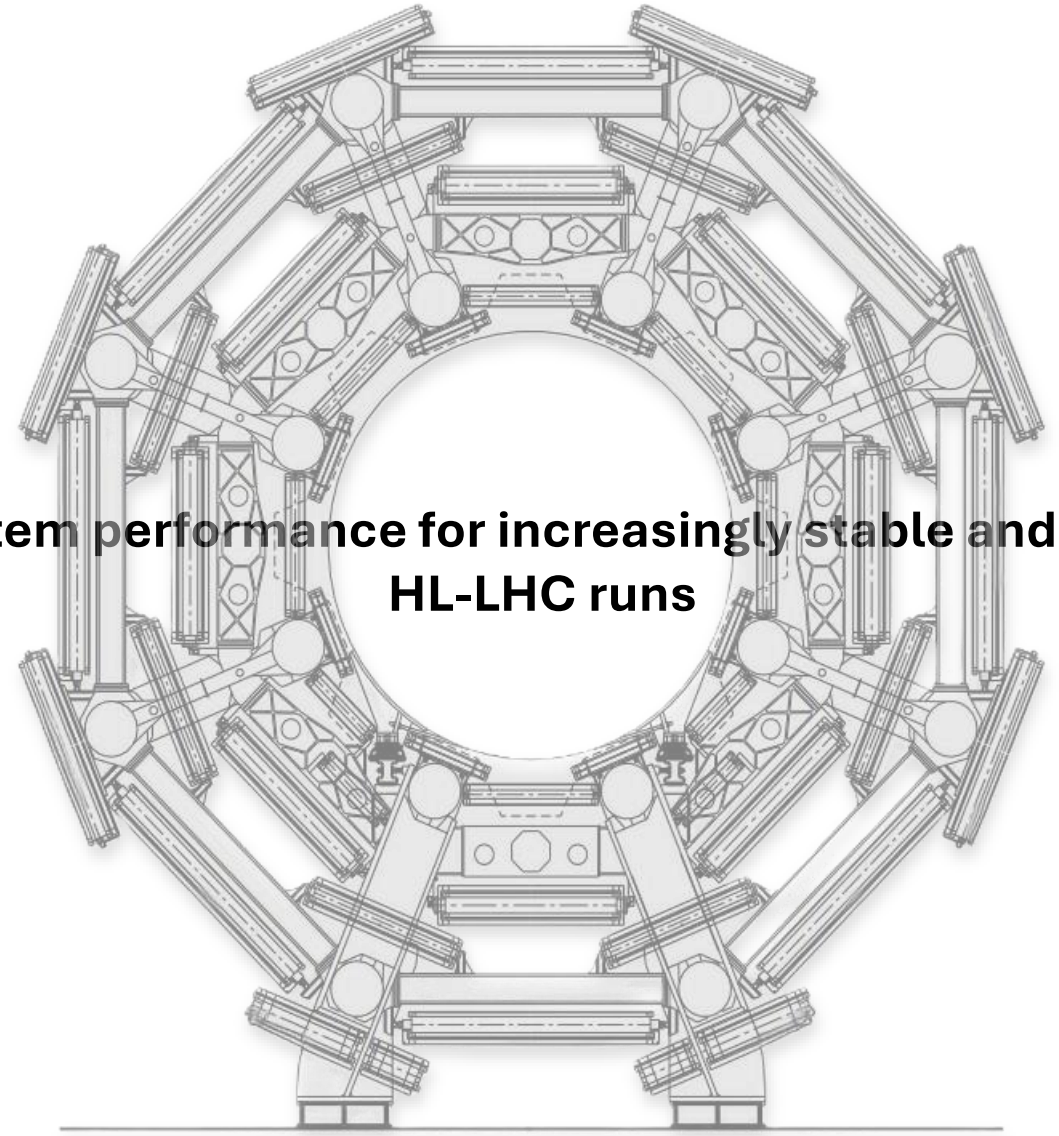


Study of ATLAS RPC system performance for increasingly stable and sustainable operation in HL-LHC runs

Sinem Simsek on behalf of the ATLAS Muon Community

RPC2026
14 – 18 September 2026

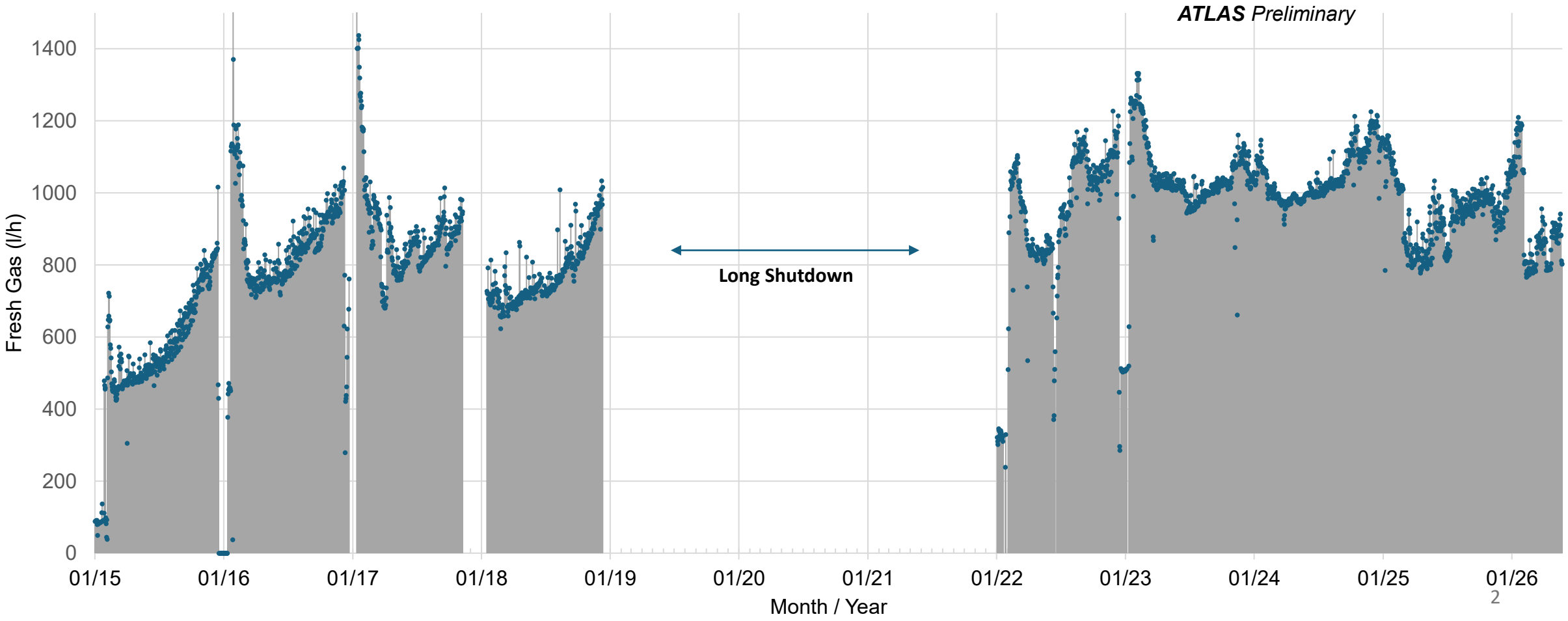
ATLAS RPC Gas Issue

Gas leaks in the ATLAS RPC system mainly originate from the intrinsic mechanical **fragility of the gas inlets**. (see P. Camarri's talk)

- Yearly expected leak rate development is **13.2%** at minimum
- Leak-driven fresh gas demand: **500–1400 L/h**

R-134a and SF_6 have **high global-warming potentials** (GWPs) and regulations/operational costs motivate replacements.

- GWP of Standard mixture: ~**1426**



Two Complementary Strategies for Reducing RPC Gas Emissions

RPC Gas Emissions ∝ Fresh-gas Consumption × Mixture GWP

1 LEAK MITIGATION AND CONSOLIDATION

Leak-prone gas inlet → Standard repairs + Preventive resin injection → Lower fresh-gas injection

2 GAS-MIXTURE OPTIMISATION

High-GWP components: R134a and SF_6 → CO_2 substitution + SF_6 reduction and replacement studies → Lower mixture GWP

Lower CO_2-equivalent emissions while preserving detector performance and long-term reliability

Consolidation of RPC Gas Inlets by Resin Injection

ATLAS RPC gas system:

- 3714 gas gaps
- 15 m^3 total gas volume
- 9120 gas inlets located in 4560 service boxes

Two applications:

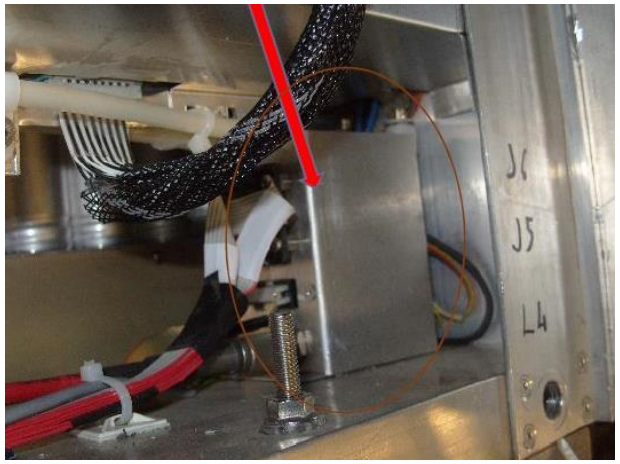
Standard technique: Repair of lines with largest leaks by gluing or replacing cracked gas inlets

Resin injection: consolidation of a slightly leaking connection / treatment before a leak develops

How does it work?

- Two liquid PUR components (A+B) are mixed and injected into service boxes located at RPC corners.
- The mixture expands within seconds, encapsulating the gas inlets and outlets.
- After hardening (~1-12 hours), a gas-tight seal is created.





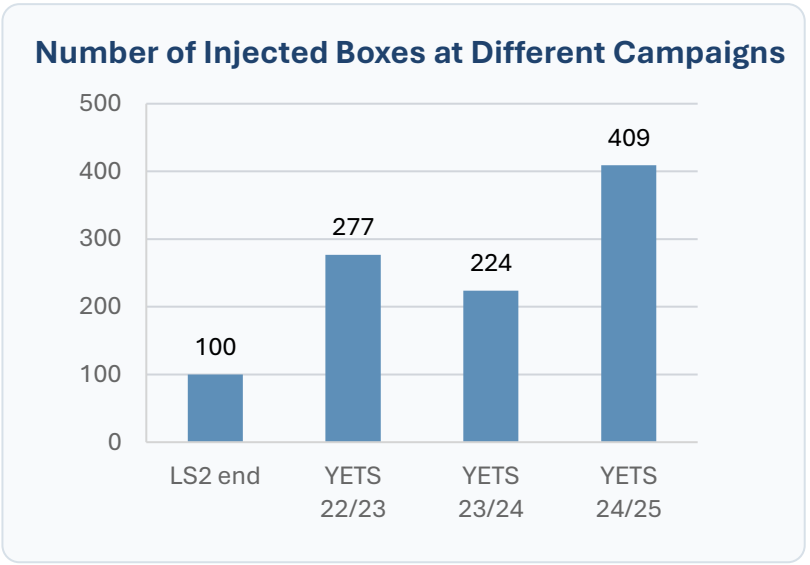


Resin Injection: Performance at Scale

1,010 service boxes injected
application count

297 layers in performance analysis
follow-up sample

Boxes are the injection units; layers are the analysis units. Counts are not directly interchangeable because the campaign total includes partial coverage



94%
currently leak-free
279/297 analysed layers

Observed remaining cases
10/297 (≈3%)
Correctable operational failures
8/297 (≈3%)
Cause not yet identified

INTRINSIC FAILURE RATE OF THE METHOD
Number of successfully repaired inlets that developed a new leak after the repair

0/109
reappearing leaks
out of the successfully repaired layers tested so far

At the ≥13.2% baseline rate, ≈103 of 297 layers would be expected to develop leaks over three YETS
Only 8 unresolved cases remain

≈9×
reduction in annual rate
≥13.2% → 1.51%

0/109 is the observed intrinsic-failure count; one-sided 95% CL upper limit ≈2.7%.

Stepwise Gas-Mixture Optimisation for Existing ATLAS RPCs

Replace a fraction of **R134a** (GWP: 1,430) with CO_2 (GWP: 1)
Reduce the **SF_6** (GWP: 24,300) fraction as much as possible by replacing it with **R1224yd** (C_3HClF_4 , GWP: ~1) or **R1233zd** ($C_3H_2ClF_3$, GWP: ~4)

OPERATED
2023–2025
64% R134a · 30% CO_2 · 5% i-C_4H_{10} · 1% SF_6
GWP ≈ 1159
−19%

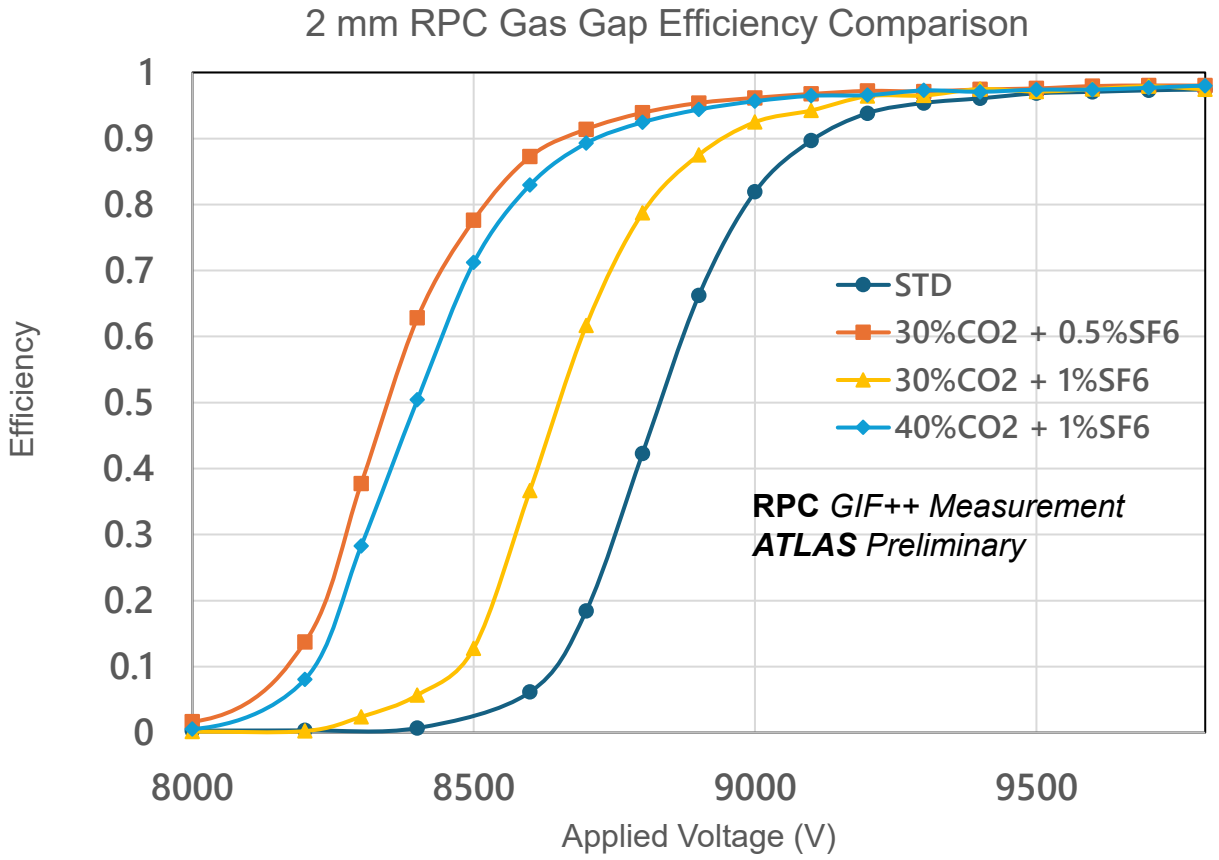
CURRENT MIXTURE
Since 2025
64.5% R134a · 30% CO_2 · 5% i-C_4H_{10} · 0.5% SF_6
GWP ≈ 1044
−27%

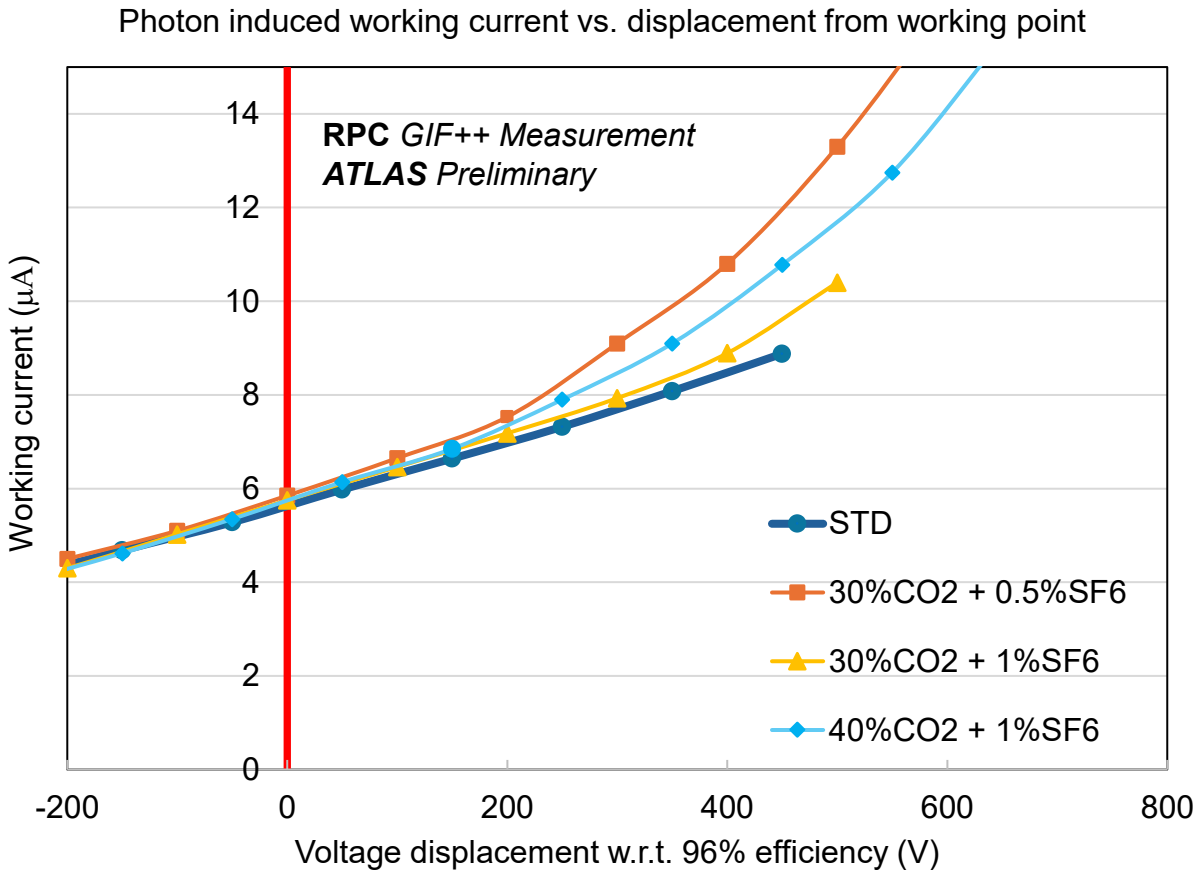
RUN-4 CANDIDATE
Under validation
63% R134a · 30% CO_2 · 5% i-C_4H_{10} · 2% R1233zd
GWP ≈ 901
−37%

LONG-TERM R&D TARGET
Future challenge
52% R134a · 40% CO_2 · 5% i-C_4H_{10} · 3% R1233zd
GWP ≈ 744
−48%

ATLAS RPC gas search strategy: balancing detector performance and environmental compliance while controlling ageing effects

Efficiency & Streamer Comparison





All mixtures reach the same efficiency plateau (~ 97%), with working voltages shifted by 200–500 V depending on the CO_2 and SF_6 content.

- Increasing CO_2 shifts the working voltage to lower values.
- Increasing SF_6 shifts the working voltage to higher values.

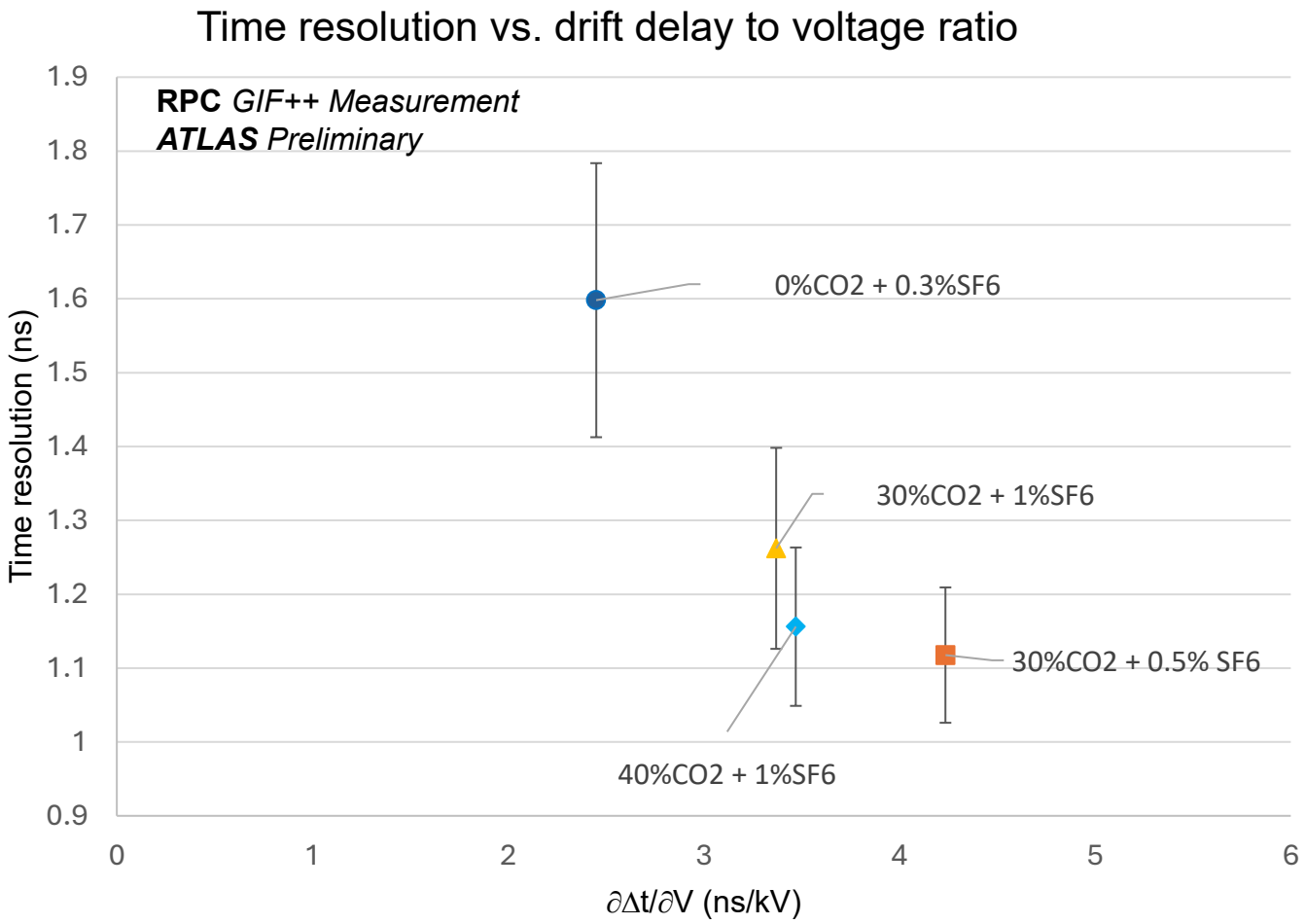
Same efficiency, different operating voltage.

Saturated Avalanche Model: deviation from linearity → streamer

The selected eco-gas mixtures preserve a streamer margin comparable to the standard gas, (200V–400V) while higher CO_2 and lower SF_6 increase non-linear currents.

ATLAS RPC working voltage (~9.0 kV) remains below the streamer region.

RPC Intrinsic Time Resolution



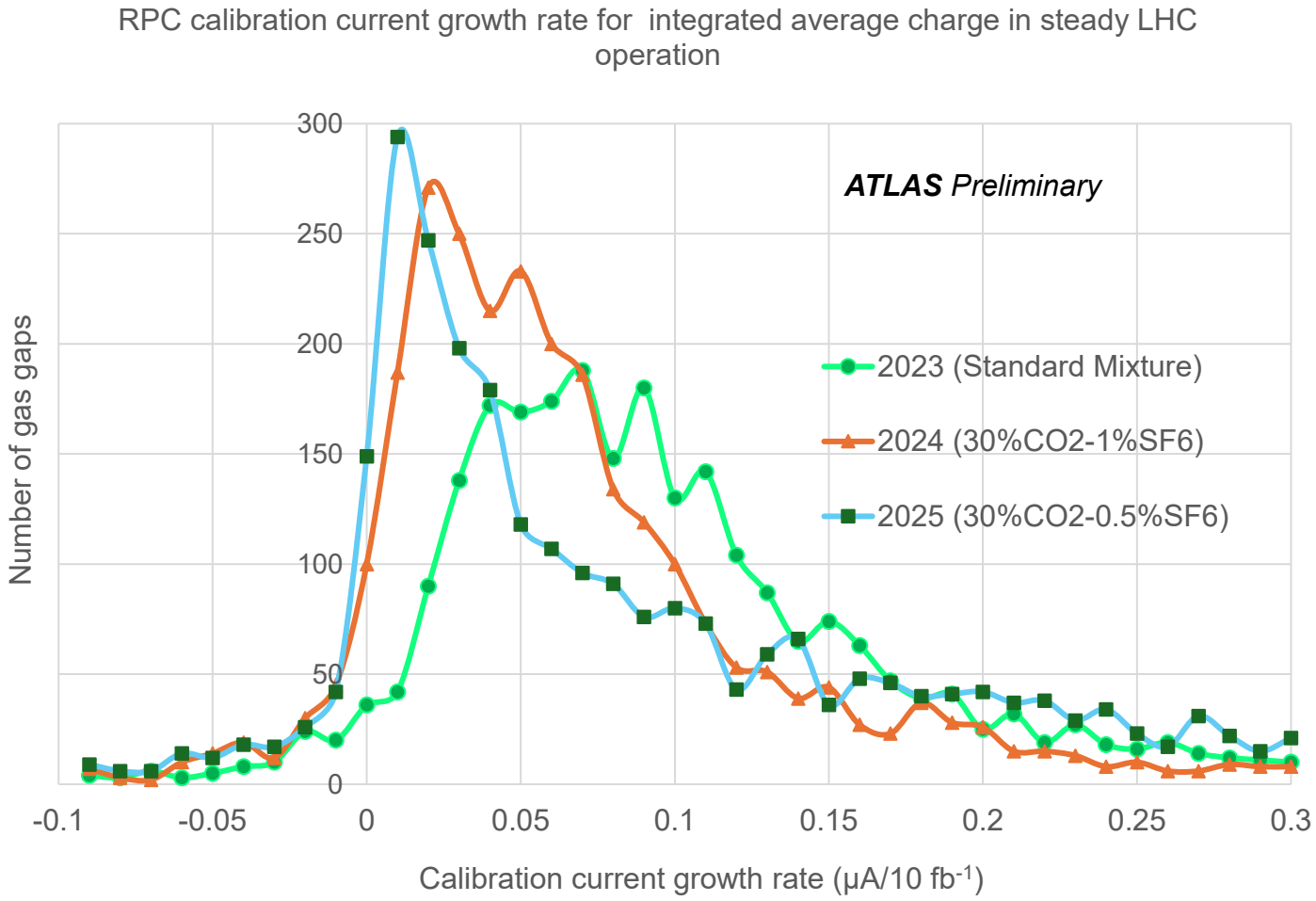
The derivative of drift delay with respect to voltage ($\partial\Delta t/\partial V$) indicates how faster an avalanche is growing with respect to given increments of electric field.

- Strong correlation with avalanche growth rate ($\partial\Delta t/\partial V$)
- **By increasing CO2 and lowering SF6, the RPC intrinsic time resolution is improved by up to ~ 30%.**

Comparison of STD & New RPC Gas Mixtures in ATLAS Cavern

Calibration current (I_{calib}): Current measured at the operating voltage without beam-induced background.
For a stable detector, it should remain constant with accumulated charge; therefore;

I_{calib} growth rate ≈ 0 → **no current increase with accumulated charge**

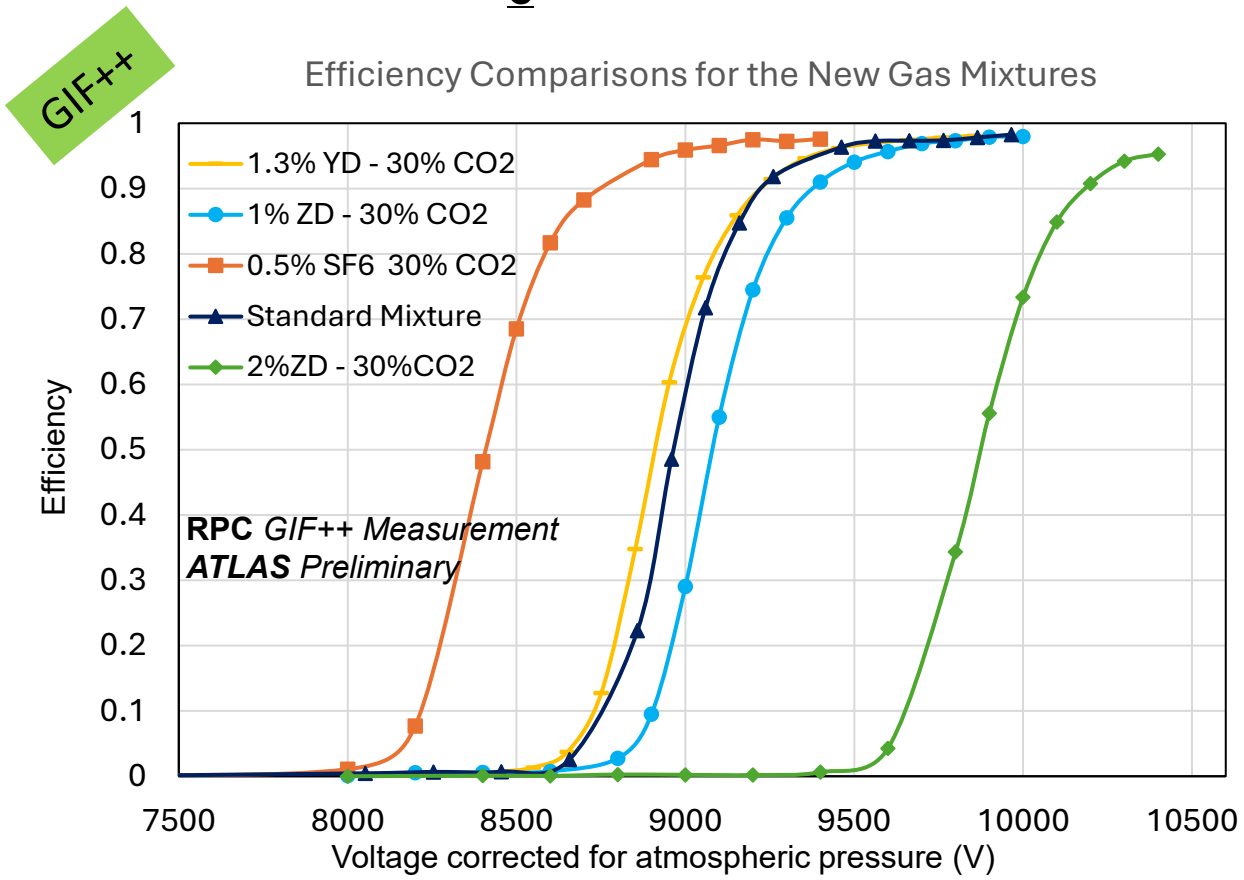


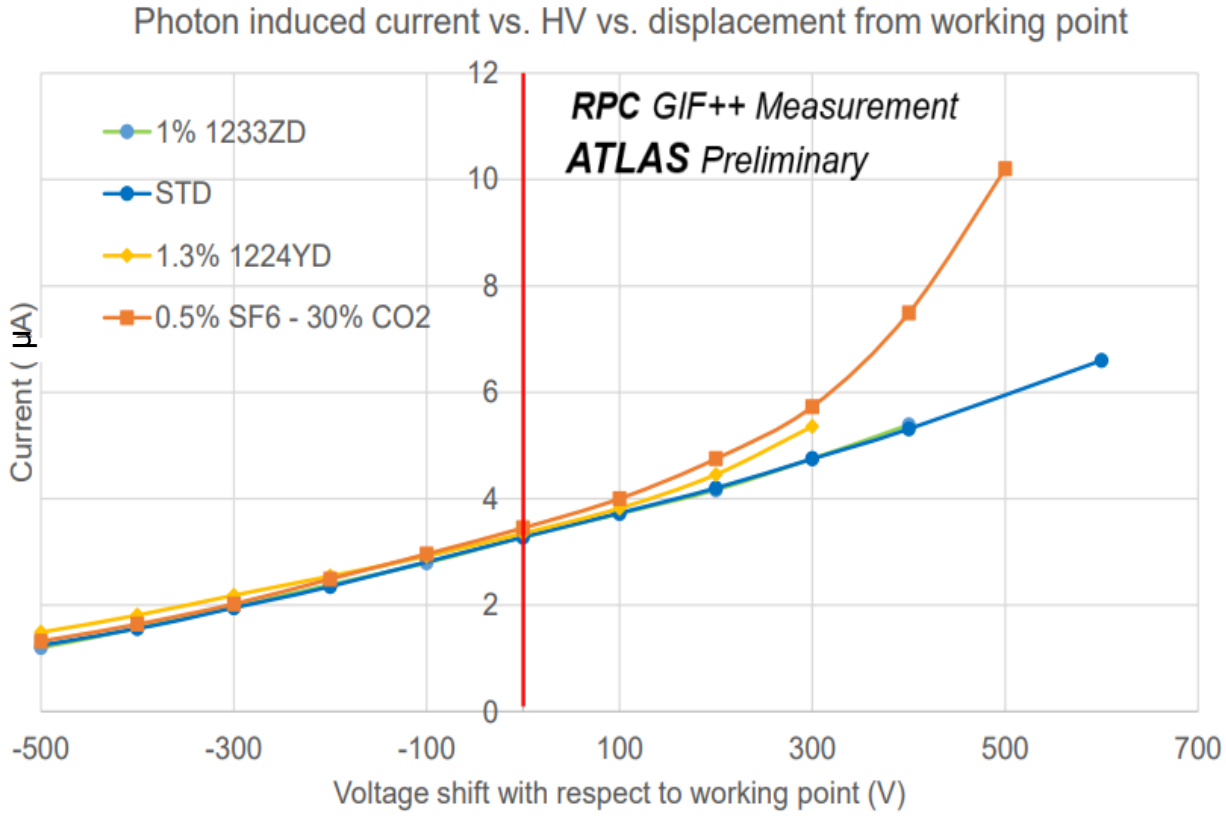
Results:

- The mixtures with reduced fluorinated-gas content show distributions more concentrated around zero
  → **smaller increase in the rate of I_{calib}.**
- Halving the SF_6 fraction further reduces I_{calib}, due to **lower dark-current contribution.**

The luminosity delivery rate in the selected periods:
0.31 fb^{-1}/week in 2023
0.54 fb^{-1}/week in 2024/2025

R1233zd as an SF_6 replacement

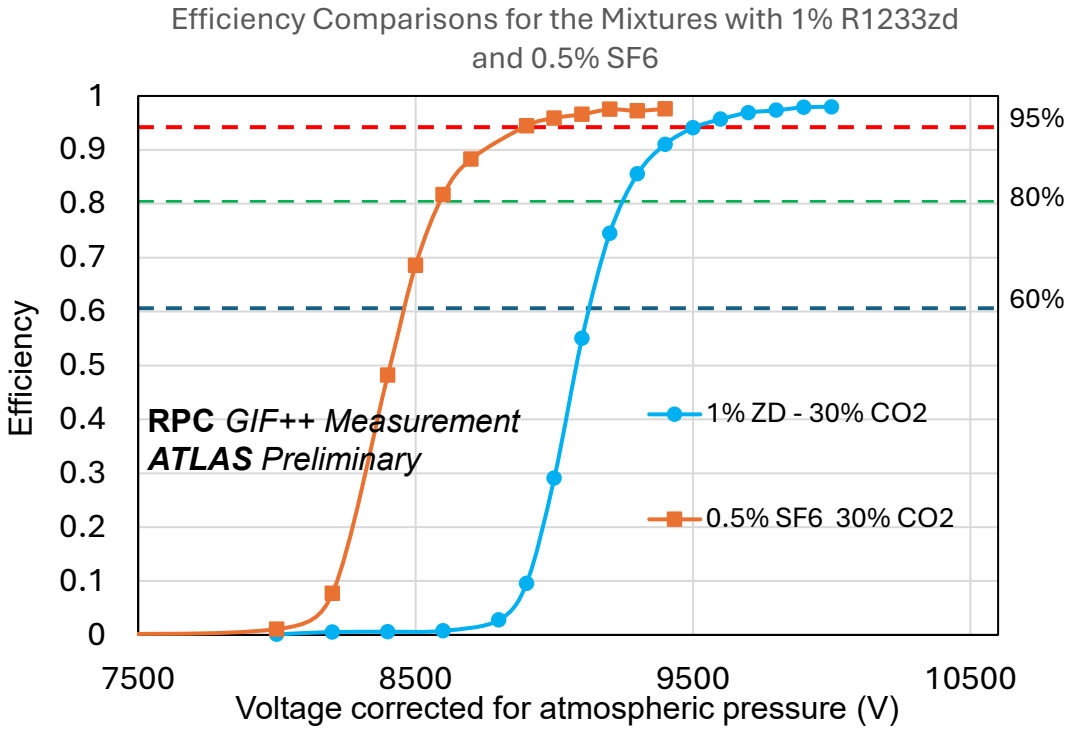


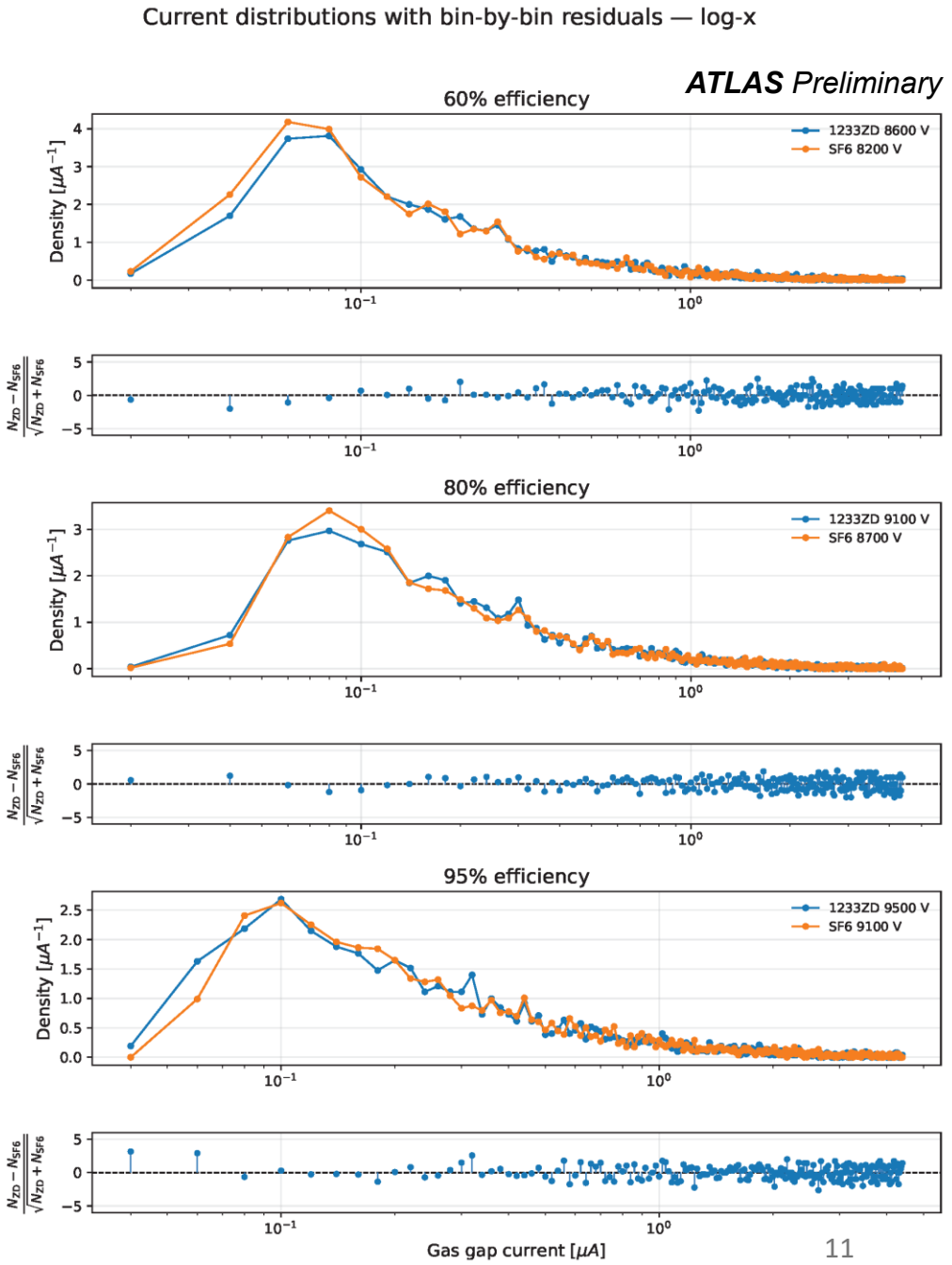


- SF_6 replacement with R1224yd and R1233zd results in similar maximum efficiencies (~97%) but shifted working voltages, with the 0.5% SF_6 mixture reaching the efficiency plateau at the lowest voltage and the 2% R1233zd mixture requiring the highest operating voltage.

- The results remain comparable up to 250 V above the voltage for 96% efficiency.
- The mixture using 1233zd demonstrates a charge-per-count behavior similar to that of the standard (STD) mixture.
- **Its lower fluorine content may reduce ageing-related stress, although dedicated long-term validation is still required.**

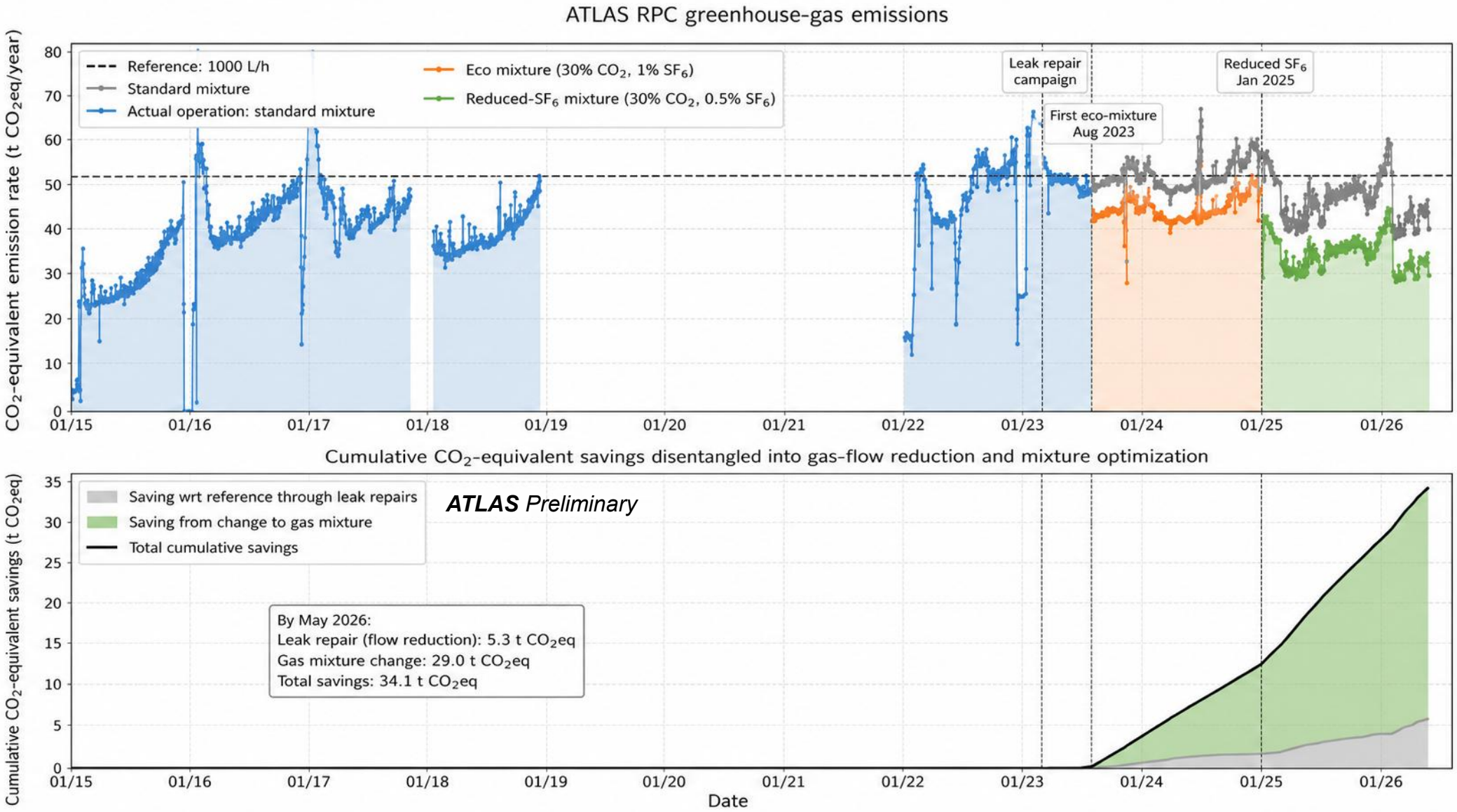
R1233zd vs SF_6: Current Behaviour in ATLAS





- **Similar current behaviour** is observed with R1233zd and SF_6 in gas gaps exhibiting spontaneous currents, regardless of the individual gas-gap quality.
- The strength of this study is not in the irradiation, but in the **large number of gas gaps and the wide range of spontaneous-current** behaviours available for comparison.
- Testing these mixtures during LS3 would provide a unique opportunity to evaluate their effects directly in the ATLAS detector.

CONCLUSIONS: Environmental Impact = Gas Consumption × Mixture GWP



Beyond the environmental benefit (**−35 t CO_2eq/year**), the new gas mixture also reduces R134a consumption by **~34.5 t/year**, corresponding to an estimated annual saving **of ~0.35 MCHF** for ATLAS.

CONCLUSIONS

- The resin-injection performance analysis covered **297 layers**. After treatment and recovery, **279 layers (94%) were leak-free**, and none of the **109 successfully repaired leaking layers** developed a new leak.

- The current **30% CO_2 / 0.5% SF_6 mixture** reduces GWP by approximately **27%** while maintaining efficiency, timing performance and stable detector operation.

- Replacing **SF_6** with **R1233zd** could increase the GWP reduction to approximately **37%**. The ageing campaign for this mixture has recently started.

- The Run-4 strategy combines **inlet consolidation, gas-mixture optimisation and long-term validation**.

Special thanks to the CERN Gas Group for their support with gas-mixture implementation in ATLAS, and to the GIF++ coordinators and CMS RPC team for enabling the experimental studies at GIF++.

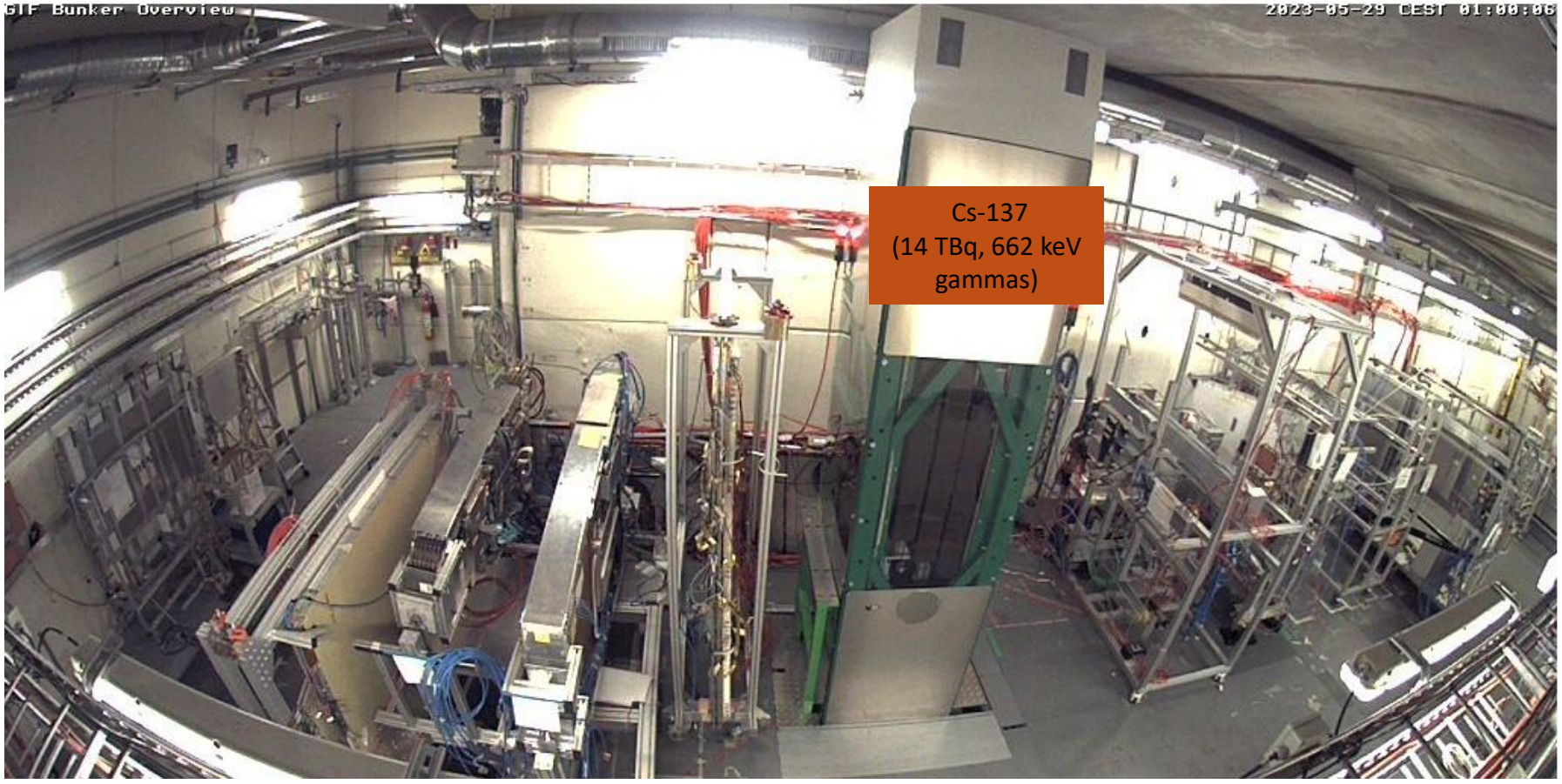
THANK YOU

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

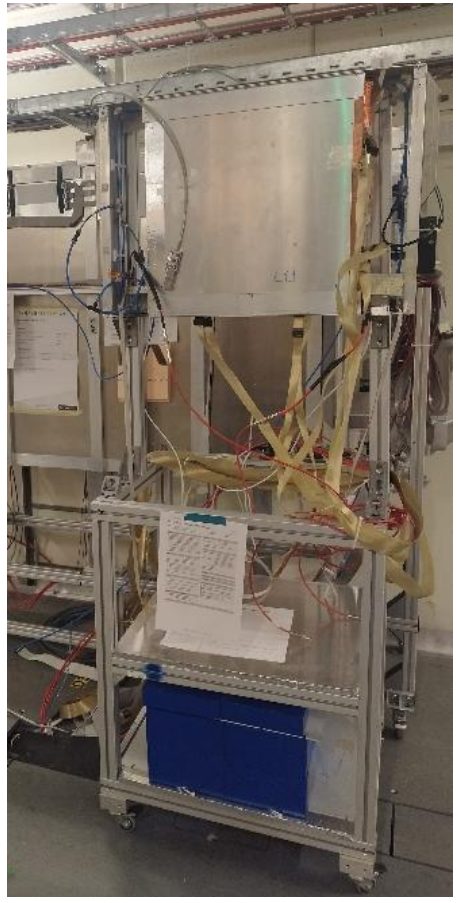
50 cm x 50 cm ATLAS-like RPC prototype (2 mm gas gaps, same Front-End technology, same Faraday cage) was installed at GIF ++.

Performance measurements are done during each available muon beam period
Ageing test: A significant fraction of the expected HL-LHC integrated workload has been accumulated

to validate the gas mixtures operated in ATLAS in 2023, 2024 and 2025.



ATLAS RPC Setup



Performance Analysis on Leak Development

The otherwise yearly expected leak rate development is 13.2% at minimum.

Let “x” represent yearly leak development probability with foam; then:

YETS	# of layers injected	Representation of # of leaks developed
22/23	81	81x
23/24	74	74x + (81-81x)x
24/25	142	142x + [155 - (74x + (81-81x)x)]x
Total	**297**	(81)x^3 + (-81-74-81)x^2 + (81+74+81+142+155)x = **81x^3 - 236x^2 + 533x**

81x^3 - 236x^2 + 533x (leaks developed)	x turns out to be	Reduction power wrt 13.2%
8 unrepairable *(classified as gray area in this review)*	**1.51 %**	**8.7**
12 **8** unrepairable + 4 repairable by standard technique (*classified as operational failure in this review*)	2.27 %	5.8
18 **8** unrepairable + 4 repairable by standard technique + 6 repairable by 2nd injection (*classified as operational failure in this review*)	3.43 %	3.8

Calculation

1 Expected leaks in 2022/23

There were 81 injected layers:

$$N_{22/23} = 81x$$

2. Expected leaks in 2023/24

There were 74 newly injected layers, giving:

$$74x$$

Of the previous 81 layers, the expected number that did not develop a leak in the first year is:

$$81 - 81x = 81(1 - x)$$

These layers remain exposed to the probability x during the following year:

$$N_{23/24} = 74x + (81 - 81x)x$$

3. Expected leaks in 2024/25

There were 142 newly injected layers:

$$142x$$

The total number injected in the previous two years was:

$$81 + 74 = 155$$

The expected number of these layers still without a leak is:

$$155 - [74x + (81 - 81x)x]$$

Therefore:

$$N_{24/25} = 142x + [155 - (74x + (81 - 81x)x)]x$$

4. Total expected number of leaks

Adding the expected leaks over the three years gives:

$$N_{\text{total}} = 81x^3 - 236x^2 + 533x$$

Eight layers were classified as unrepairable, so:

$$81x^3 - 236x^2 + 533x = 8$$

Solving this equation numerically gives:

$$x \approx 0.0151$$

Interpretation of Performance Analysis in Leak Development

Scenario	Oct 25 (n=155)	Apr 26 (n=297)	Improvement factor	Trend
Foam technique failure (unrepairable only)	1.70 %	1.51 %	7.8 → 8.7	***improved***
Foam + standard repair (operational failures fixed)	2.60 %	2.27 %	5.3 → 5.8	***improved***
Foam + standard + 2nd injection (all addressable leaks fixed)	5.60 %	3.43 %	2.4 → 3.8	***improved***
Sample size	155 layers	297 layers	+92 %	***more robust***

Key takeaways

- **Sample size nearly doubled** (155 → 297 layers, including YETS 24/25), strengthening the statistical reliability of the result.
- **Foam-technique failure rate dropped** from 1.70 % to **1.51 %**, corresponding to an improvement factor of **8.7** over the 13.2 % baseline (vs. 7.8 in Oct 25).
- **Operational failures (4)** are recoverable with the standard technique, and **6 additional layers** are recoverable with a 2nd injection — these are not technique failures, but addressable cases.
- **Counterfactual:** without the foam technique, the natural 13.2 % yearly leak rate would have produced **≈ 103 leaking layers (35 % of 297)** after three YETS — instead, only 8 remain unrepairable.
- **Conclusion:** the larger dataset confirms and strengthens the Oct 25 result. The foam technique reduces the yearly leak development rate by approximately an order of magnitude.

Summary of Injection Performance

Out of 297 fully analysed injections

SUCCESS RATE

94%

Successful injections

The vast majority of injections produced gas-tight, durable repairs across all measured campaigns.

RECOVERABLE

3%

Recoverable failures

Identified failure cases that can be resolved through additional repair techniques developed in the R&D programme.

UNDER INVESTIGATION

3%

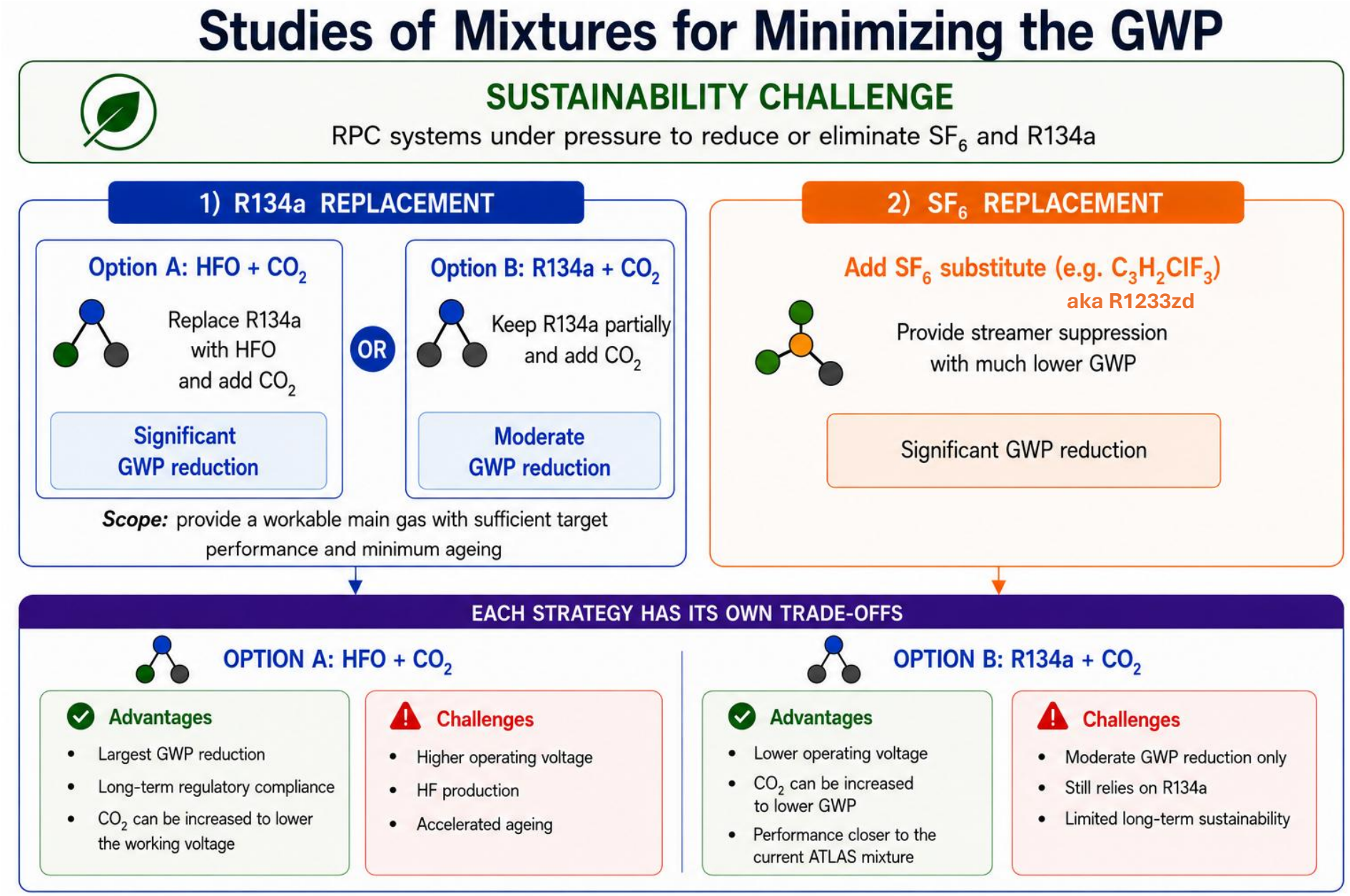
Open cases

Cases where the underlying cause is not yet identified — diagnostics ongoing.

LOOKING AHEAD

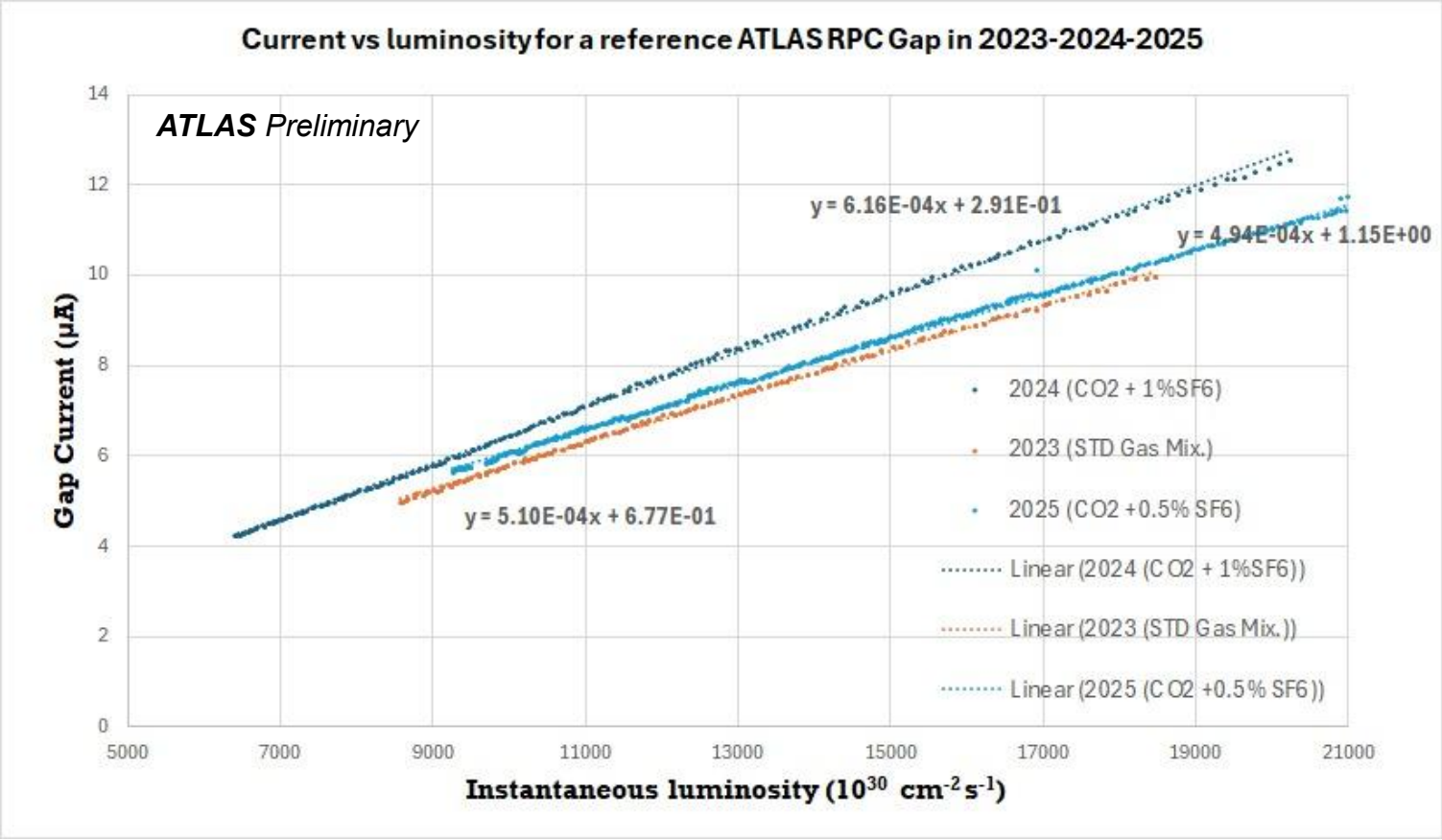
The technique has been improved to overcome the observed failure modes — full details follow in the R&D Studies presentation.

There is no universal solution. The optimal strategy depends on the detector technology and on the desired balance between environmental benefit and detector performance.



ATLAS RPC IN CAVERN:
COMPARISON OF THE CURRENT AFTER THE GAS MIXTURE CHANGE

This analysis considering the most radiation-exposed chambers in ATLAS, BML6A.09.CO as a reference chamber.



The plot confirms that the current vs. HV measured at GIF for the various gases shows that the mixture with 1% SF_6 has a current approximately 17% higher than the STD mix, while the one with 0.5% SF_6 shows a very similar current to the STD mix.