Performance studies of RPC detectors with new environmentally friendly gas mixtures in presence of LHC-like radiation background

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Outline

Overview on the Resistive Plate Chambers ***gas mixtures*** and possible alternatives

Characterization of RPCs with new eco-friendly gas mixtures
- RPC ***performance*** with ***R134a*** alternatives
- RPC ***performance*** with ***SF6*** alternatives

RPC ***operation*** with new environmentally friendly gas mixtures at CERN Gamma Irradiation Facility (GIF++)

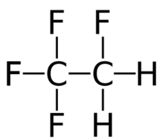
Greenhouse Gases in RPC operation

RPC gas mixture at LHC

→ Made out of **three** components

→ **High Global Warming Potential** due to presence of <u>*SF6*</u> and <u>*R134a*</u>

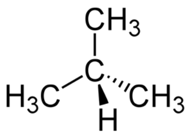
~95%



GWP 1430

+

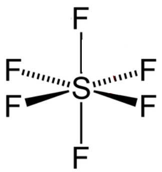
4-5%



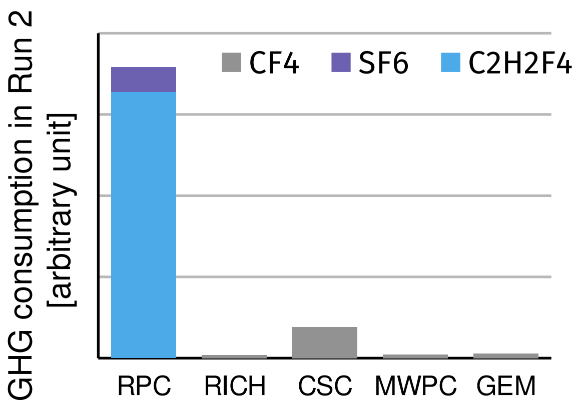
GWP 3.3

+

0.3%



GWP 22800



GHG emissions

→ The **main** contribution is from <u>***R134a***</u>

→ <u>*R134a*</u> and <u>*SF6*</u> due to ***leaks*** at ***detector level*** at ATLAS and CMS RPCs

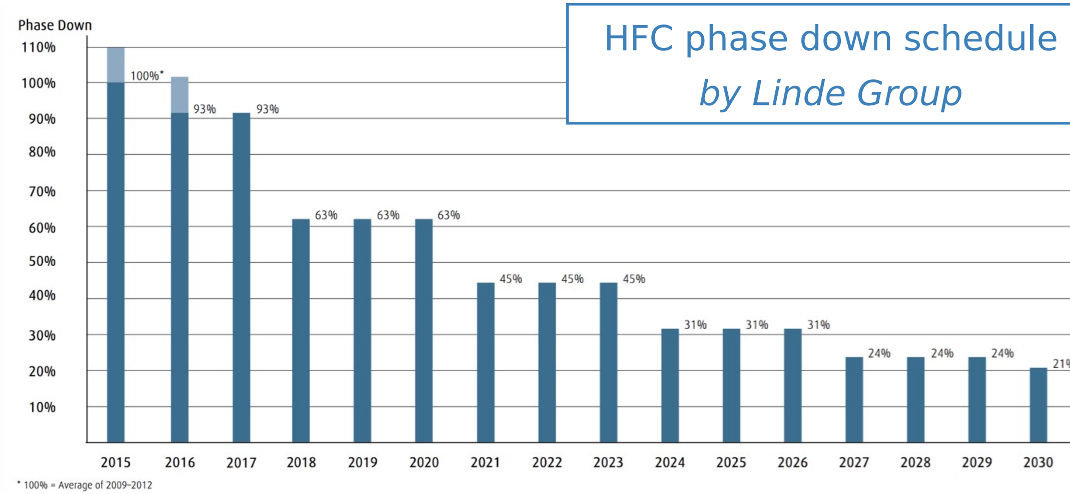
→ A campaign of ***leaks reparation*** is currently ongoing

European Union F- regulation

→ **Limit the total amount** of F- gases that can be sold → Phase down process

→ **Banning the use of F- gases** where eco friendly alternatives are present

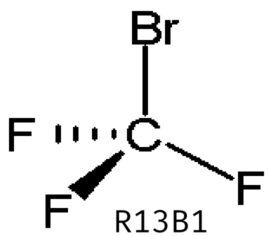
→ **Preventing emissions** by requiring proper checks and servicing of the gases and recovery of the gases



HFC phase down schedule
by Linde Group

RPC gas mixtures - R134a

First gas mixtures for RPCs were based on Ar and/or R13B1 (Halon 1301)

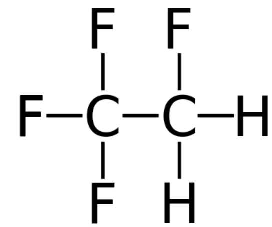


R13B1

(CBrF3)

GWP 6900 - ODP 10

R13B1 was then replaced with R134a



R134a

($C_2H_2F_4$)

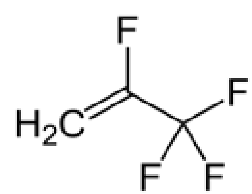
GWP 1430 - ODP 0

Refrigerant industry **started using HFO** gases as replacement of R134a

Thermodynamical *characteristics* ***are known*** *for HFOs but studies on* **ionization properties** *have* **just started**

Hydro-Fluoro-Olefin (HFO)

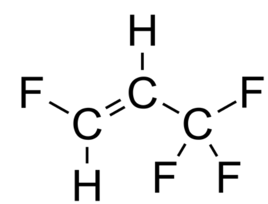
- Contains C=C bound
- Contains Fluorine
- Contains Hydrogen



HFO-1234yf (flam)

($C_3H_2F_4$)

GWP 4



HFO-1234ze

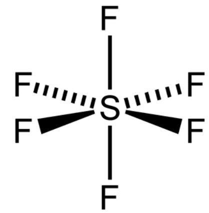
($C_3H_2F_4$)

GWP 6

Goal: find and eco-friendly gas mixture compatible with the current ATLAS and CMS RPC systems (i.e. requires no change in the HV cables, FE electronics, gas system etc.)

RPC gas mixtures - SF6

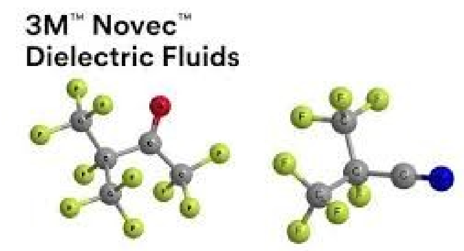
SF6 was added to reduce the streamer probability (0.3 %)



SF6

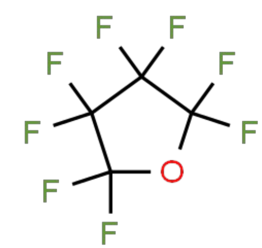
GWP ~ 23000

Gas with the ***highest*** GWP known (~23000), heavily used in power plants

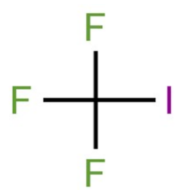


Novec 5110 **Novec 4710**

Energetic/electrical industry **started investigating** on possible alternatives as replacement of SF6



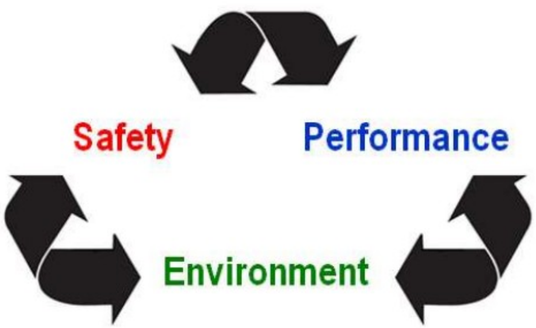
C4F8O



CF3I

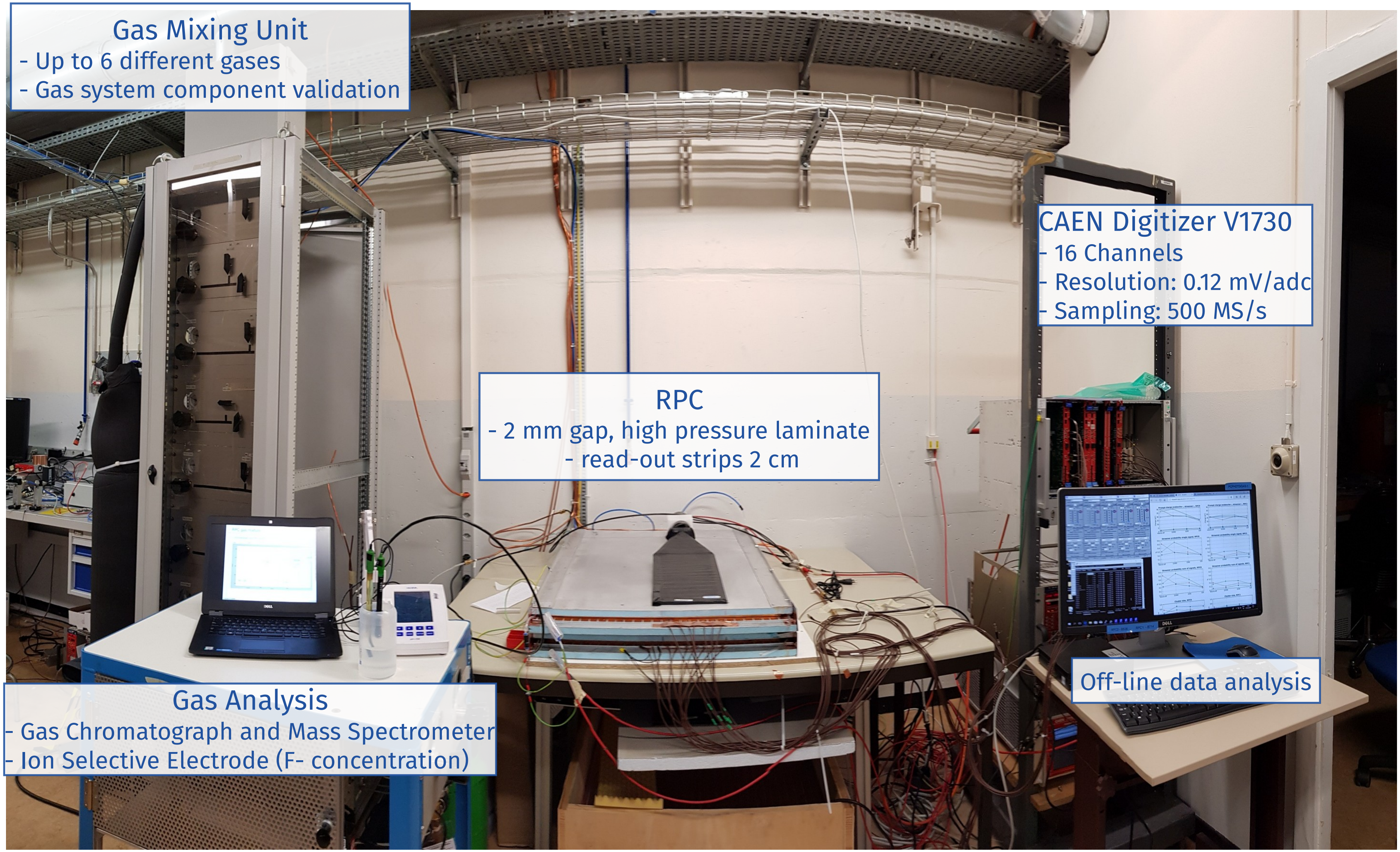
Research on ***alternatives*** still going on

Need to take into account key considerations:
- → Dielectric/Ionization ***performance***
- → ***Safety*** risks
- → environmental ***sustainability***



Goal: find and eco-friendly gas mixture compatible with the current ATLAS and CMS RPC systems (i.e. requires no change in the HV cables, FE electronics, gas system etc.)

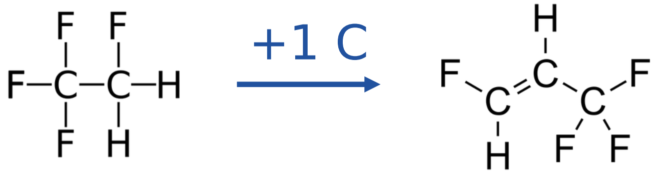
Experimental setup for cosmic muons



Characterization of alternative gas mixtures

Initially, R134a was completely replaced by HFO

- Results indicate **higher working voltage** (>12kV) → Related to C=C bound
- **Avalanche signals smaller compared** to Standard Gas Mixture

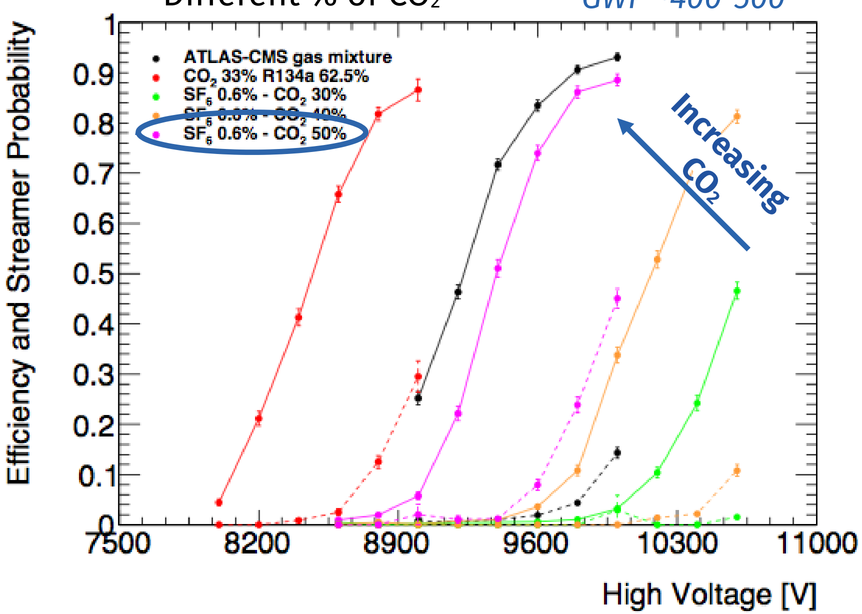


An addition of a gas to lower the working point is required

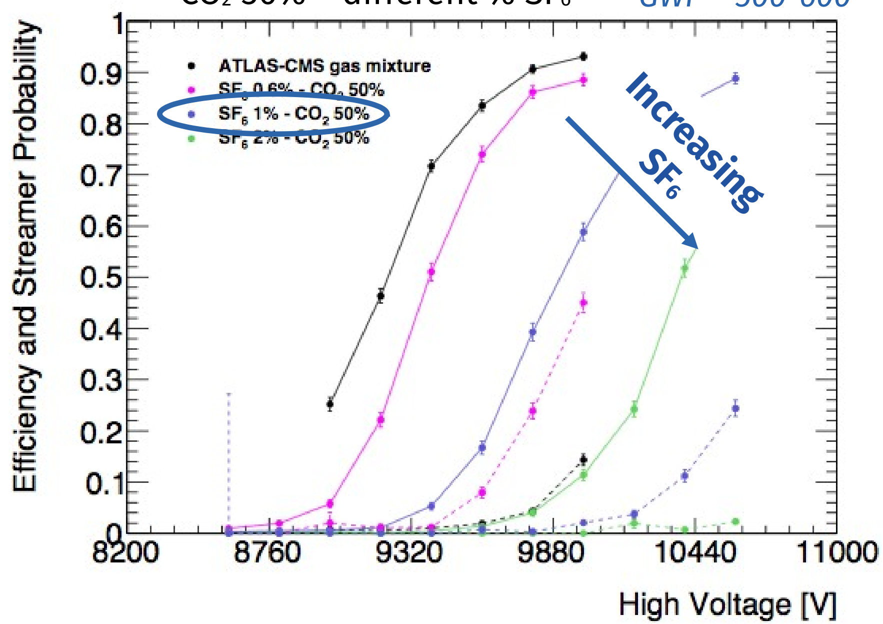
- Use of ***CO_2*** as an inert gas: +10 % CO_2 → - 800V

The streamer probability increases → CO_2 different quenching properties w.r.t. to iC_4H_{10}
Need to keep a ***small amount of R134a*** and increase ***SF_6*** concentration

Different % of CO_2 *GWP ~400-500*



CO_2 50% + different % SF_6 *GWP ~ 500-600*



Selected HFO based gas mixtures

Over 50 different gas mixtures tested

Tested 3, 4 and **5 components** gas mixtures

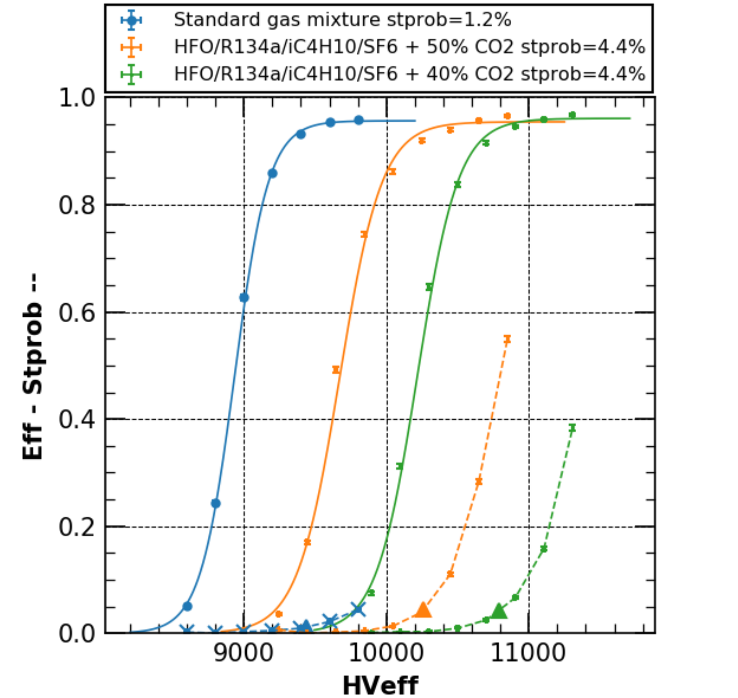
HFO based gas mixture

Performed best together with ***CO_2*** and ***R134a***

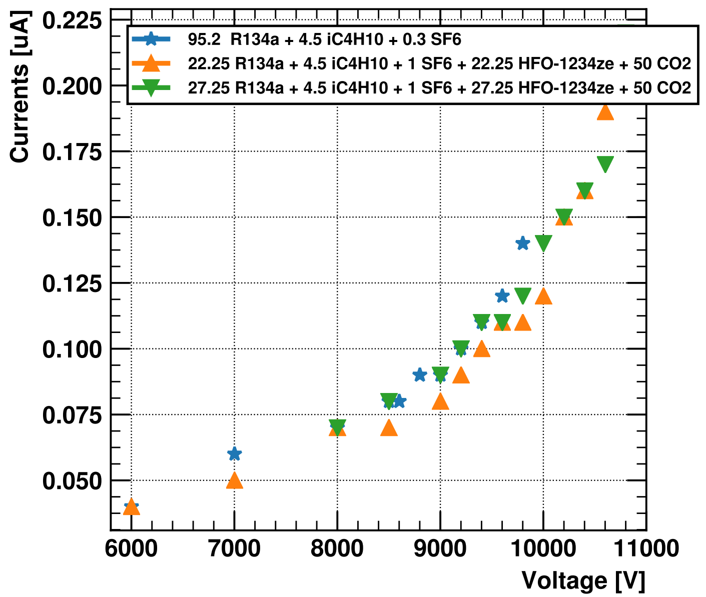
HFO + CO_2 + R134a + 4.5% iC_4H_{10} + 1% SF_6

Fine tuning of HFO gas mixtures

Two candidates that can compete with the standard gas mixture



Gas mixture	Working point [V]	St. Prob. [%]	Pulse charge av [pC]	Pulse charge st [pC]	Cluster size [#/2cm]	Time resolution [ns]
Standard	9440	1.2	0.8	10.1	2	1.9
HFO/R134a/ iC4H10/SF6 + 50% CO2	10260	4.4	1.1	14.7	2.3	2
HFO/R134a/ iC4H10/SF6 + 40% CO2	10790	4.4	1.1	11.8	2.2	1.8



SF6 alternatives - C_4F_8O

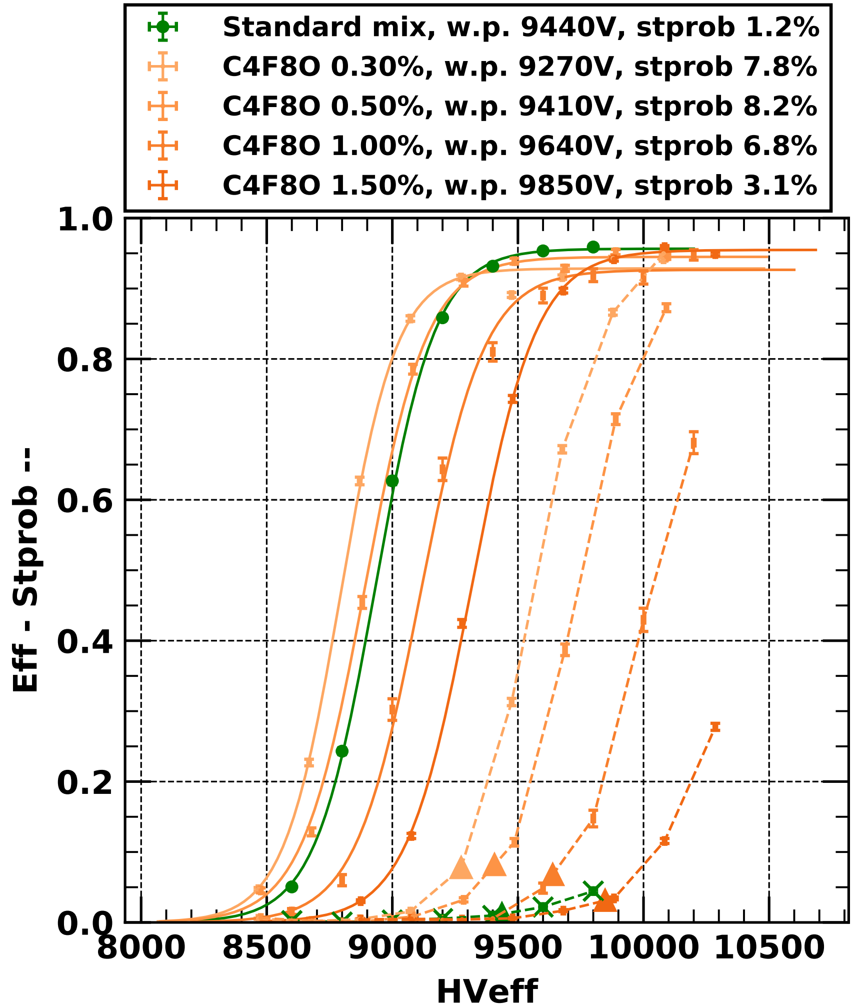
Pros:

→ Good performance and stability
→ Easy enough to be used in gas form (sufficient vapour pressure)

Cons:

→ Not really eco-friendly (GWP ~ 8000)
→ Required percentage to match SF6 is not eco-friendly anymore

Gas mixture	Working point [V]	St. Prob. [%]	Pulse charge av [pC]	Pulse charge st [pC]	Cluster size [#/2cm]	Time resolution [ns]
standard	9440	1.2	0.8	10.1	2	1.9
R134a/iC4H10 4.5/C4F8O 0.3	9270	7.8	1.4	23.9	2	3.2
R134a/iC4H10 4.5/C4F8O 0.5	9410	8.2	1.3	18.1	2.1	3.1
R134a/iC4H10 4.5/C4F8O 1.0	9640	6.8	1.4	16.7	1.6	3.1
R134a/iC4H10 4.5/C4F8O 1.5	9850	3.1	0.9	19.5	2.5	1.7



SF6 alternatives - CF_3I

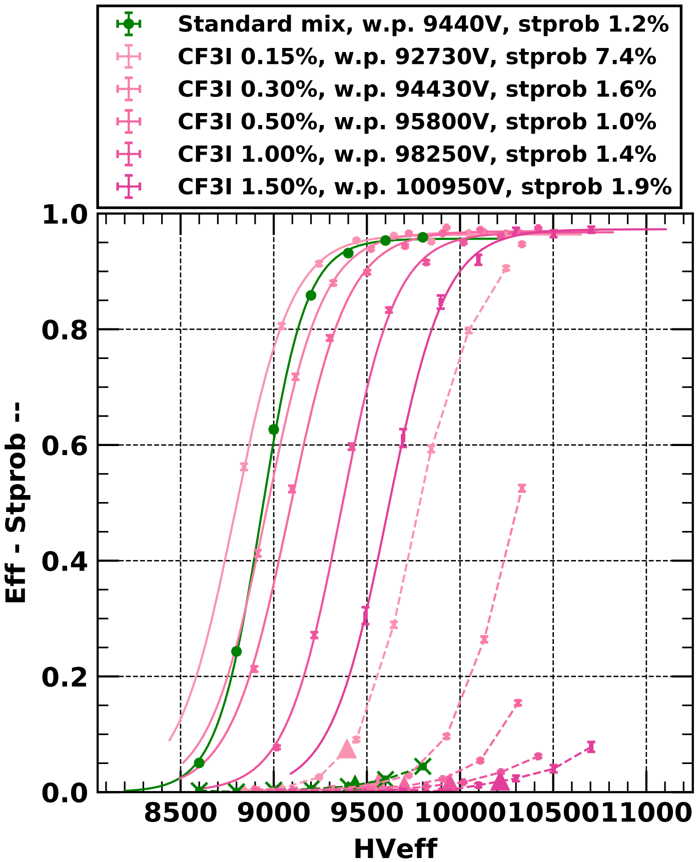
Pros:

- → Very low GWP (0.4)
- → Very good performance for SF6
- → Good vapour pressure

Cons:

- → Toxic, mutagenic
- → ODP very low (0.008) but not 0
- → May react with water

Gas mixture	Working point [V]	St. Prob. [%]	Pulse charge av [pC]	Pulse charge st [pC]	Cluster size [#/2cm]	Time resolution [ns]
standard	9440	1.2	0.8	10.1	2	1.9
R134a/iC4H10 4.5/CF3I 0.1	9390	7.4	1.2	30.5	2.4	1.7
R134a/iC4H10 4.5/CF3I 0.3	9560	1.6	0.8	25.9	2.4	1.7
R134a/iC4H10 4.5/CF3I 0.5	9700	1	0.8	25.8	2.4	1.8
R134a/iC4H10 4.5/CF3I 1.0	9940	1.4	0.8	16.5	2.3	1.8
R134a/iC4H10 4.5/CF3I 1.5	10220	1.9	0.8	7.6	2.6	1.8



SF6 alternatives - Novec 4710 $(CF_3)_2CFC{\equiv}N$

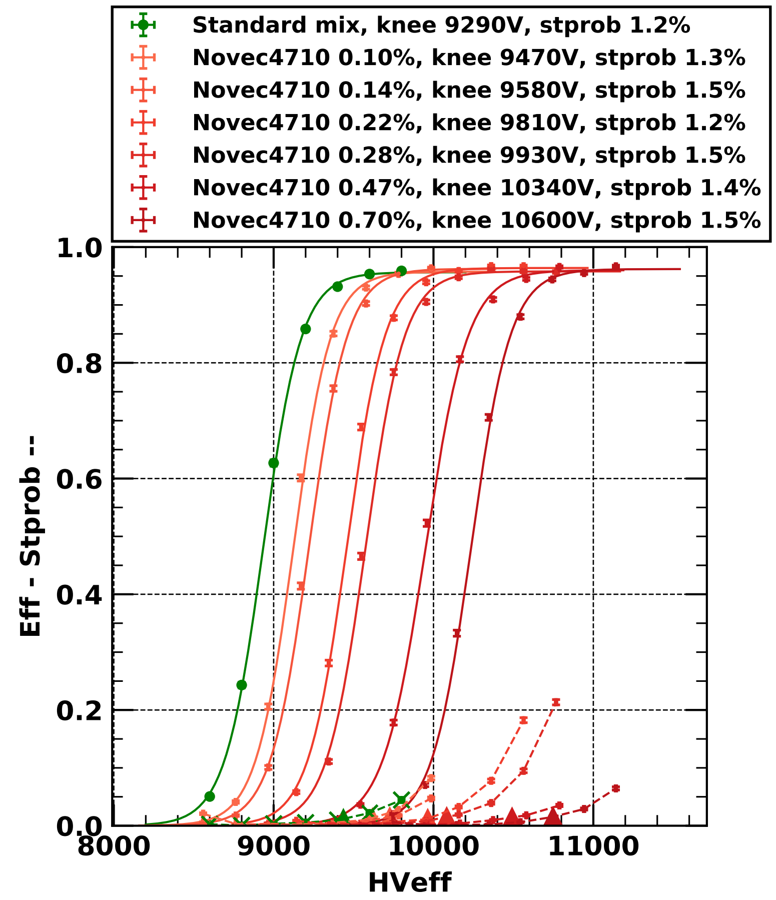
Pros:

→ Very good performance in small concentrations, high dielectric strength
→ Good vapour pressure

Cons:

→ GWP not 0 (~ 2200)
→ May react with water

Gas mixture	Working point [V]	St. Prob. [%]	Pulse charge av [pC]	Pulse charge st [pC]	Cluster size [#/2cm]	Time resolution [ns]
standard	9440	1.2	0.8	10.1	2	1.9
R134a/iC4H10 4.5/4710 0.1	9620	1.3	0.9	8.5	2	1.9
R134a/iC4H10 4.5/4710 0.15	9730	1.5	0.9	9.7	1.9	1.8
R134a/iC4H10 4.5/4710 0.2	9960	1.2	0.9	8.8	2	1.9
R134a/iC4H10 4.5/4710 0.3	10080	1.5	0.9	14	2	1.9
R134a/iC4H10 4.5/4710 0.5	10490	1.4	0.9	9.7	1.8	1.9
R134a/iC4H10 4.5/4710 0.7	10750	1.5	0.8	10.8	2.1	1.9



SF6 alternatives - Novec 5110 - $(CF_3)_2CFC(O)CF_3$

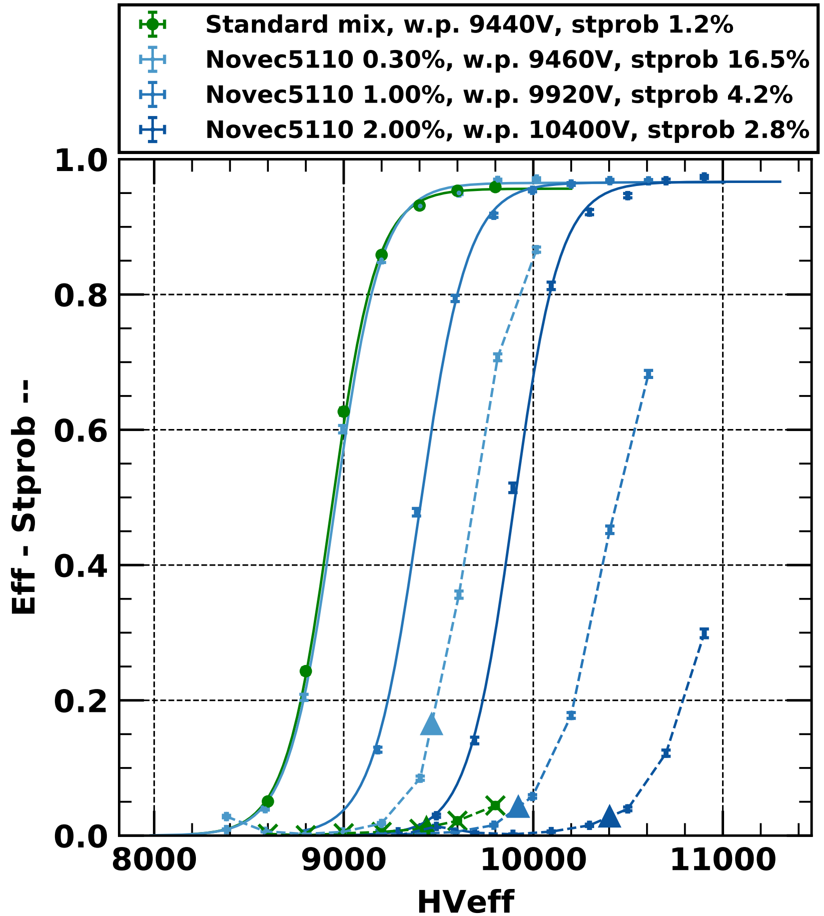
Pros:

→ Very low GWP (<1)
→ Theoretically high dielectric strength

Cons:

→ Difficult to be treated as a gas (high boiling point ~ 27 °C)
→ May solubilize in water
→ Sensitive to UV radiation

Gas mixture	Working point [V]	St. Prob. [%]	Pulse charge av [pC]	Pulse charge st [pC]	Cluster size [#/2cm]	Time resolution [ns]
standard	9440	1.2	0.8	10.1	2	1.9
R134a/iC4H10 4.5/5110 0.3	9460	16.5	1.9	20.8	2.2	16.9
R134a/iC4H10 4.5/5110 1.0	9920	4.2	1.2	12.8	1.9	1.9
R134a/iC4H10 4.5/5110 2.0	10400	2.8	1	10.5	2.3	2



Why it is difficult to find eco-friendly alternatives

GWP is related to:

- IR absorbance
- Residence time in the atmosphere

Three factors determine the atmospheric lifetime

Water solubility → Rain out
Reactivity with OH → Oxidation
UV absorbance → Photolysis

*Atmospheric lifetime is a **sum** of these effects!*

*SF6 and R134a performance are difficultly matched also because of their **stability in atmosphere***

Novec gases atmospheric properties

Novec 5110 gas $(CF_3)_2CF\overset{O}{\overset{\|}{C}}CF_3$

Rain Out	→	Water Solubility very low water solubility (1 ppmw)
Oxidation	→	Reactivity with •OH unreactive w/ •OH radicals
Photolysis	→	UV Absorbance strong absorbance in near UV (wavelengths ≥ 300 nm)

Novec 4710 gas $(CF_3)_2CFC{\equiv}N$

Rain Out	→	Water Solubility very low water solubility (272 ppbw)
Oxidation	→	Reactivity with •OH reactive w/ •OH radicals
Photolysis	→	UV Absorbance transparent in near UV

John G. Owens, 3M, *Greenhouse Gas Emission Reductions from Electric Power Equipment through Use of Sustainable Alternatives to SF6*

CERN Gamma Irradiation Facility (GIF++)

*Goal: study **RPC performance** with **muon beam**, **gamma background** and **HFO** based gas mixtures*

GIF++ facility

- Located along SPS line, north area
- Built to emulate the background conditions of LHC

→ Gamma Source

^{137}Cs of 14 TBq → 662 KeV gamma peak background

→ Muon Beam

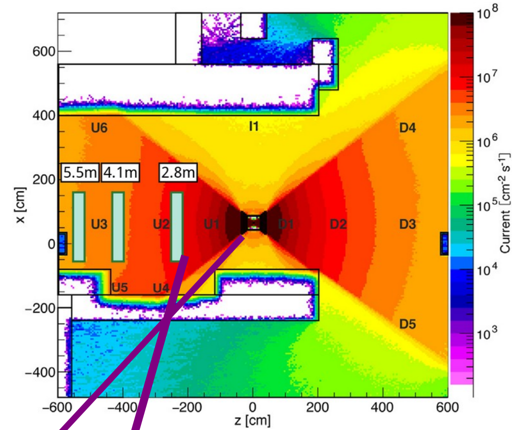
100 GeV, 10^4 muons/spill, 10x10 cm^2 area

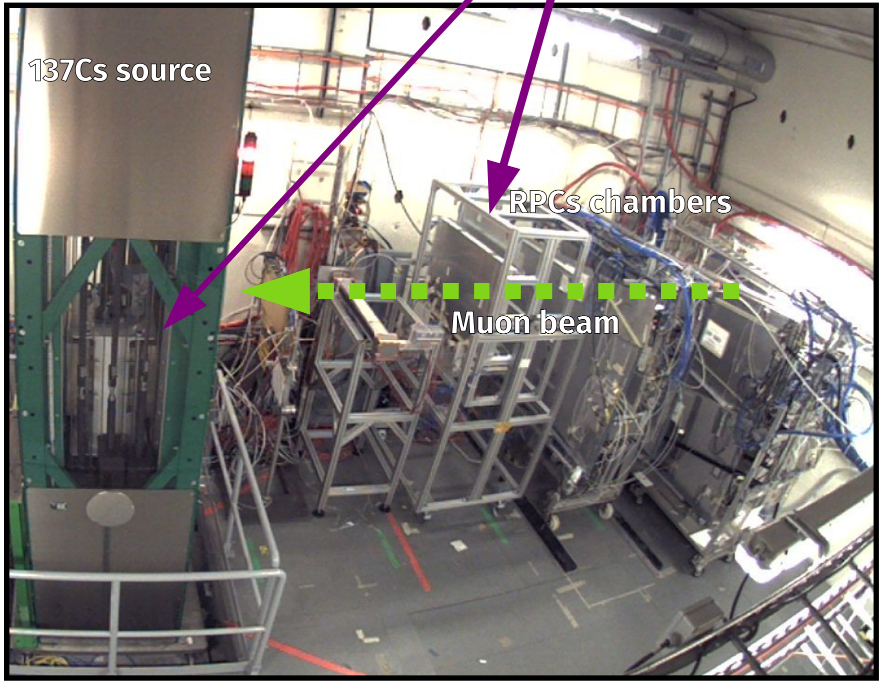
Test beam 2018

Setup DAQ and DCS

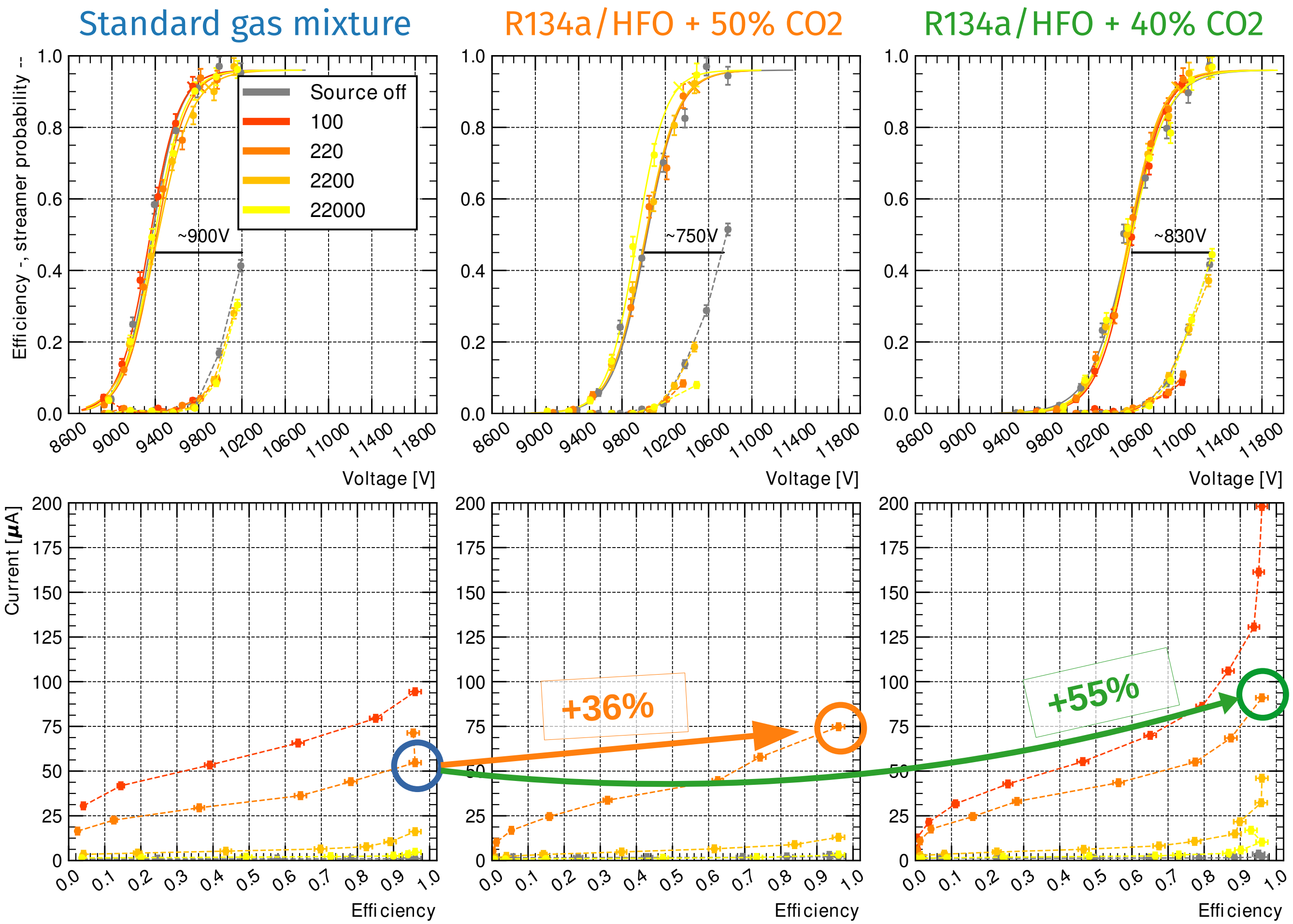
- Raw waveform acquisition via v1730 digitizer
- HV control via dcs
- Online monitoring of gas parameters via influxdb + grafana
- EOS storage of data
- Offline analysis python + pandas + numpy on SWAN

ABS	Gamma Rate [kHz/cm²]
100	55.3
220	41.2
2200	3.75
22000	0.774





Test beam 2018 - Muon efficiency vs. currents



Streamer probability at ABS 220 (counting rate ~ 250 Hz/cm²)

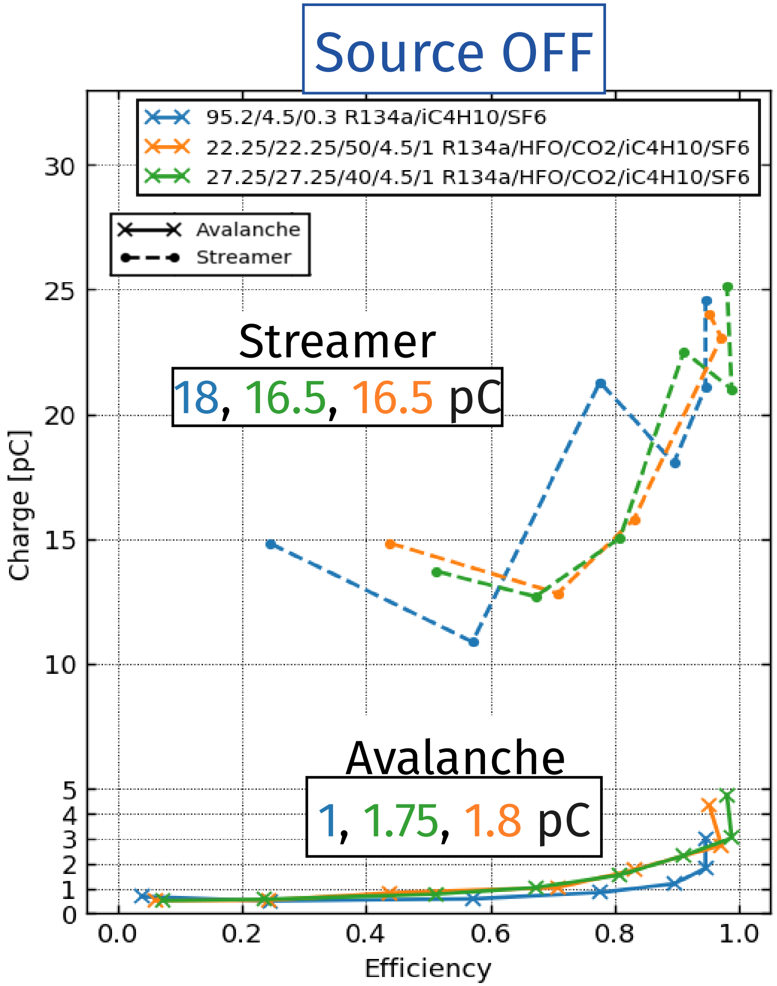
Gas mixture	At HV knee	At efficiency (+150 V)
Standard gas mixture	3%	13%
HFO + 40% CO_2	8%	25%
HFO + 50% CO_2	15%	23%

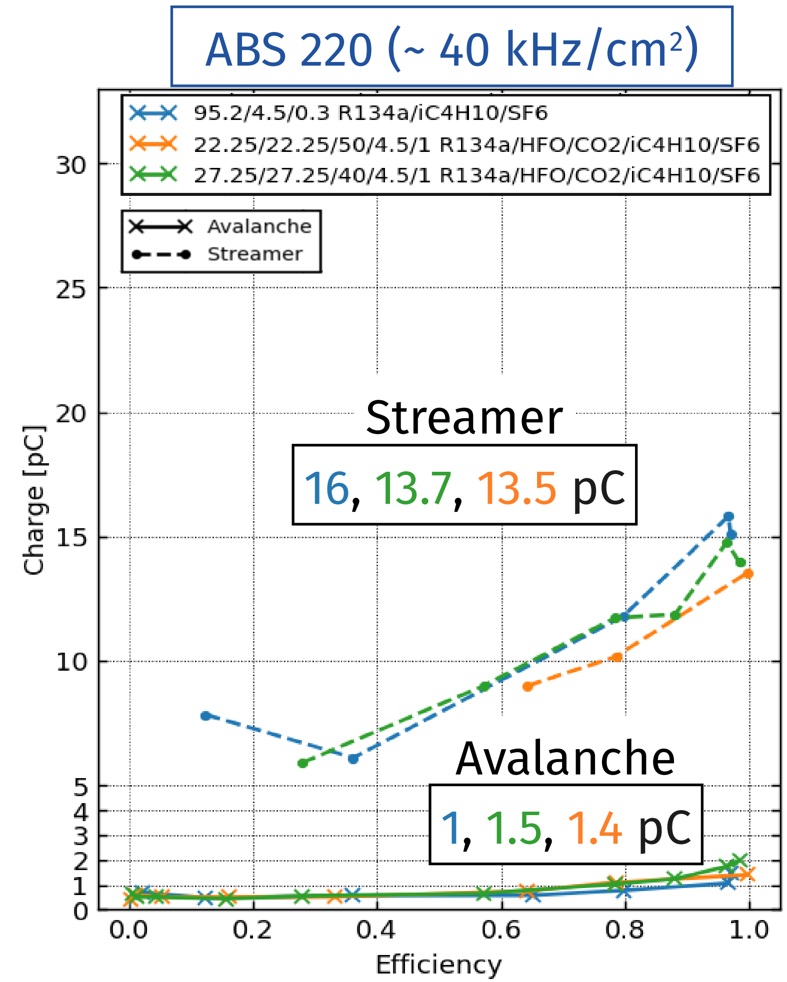
+10%

Streamer probability is 10% higher at working point

- →Efficiency curves are plotted against **effective voltage** seen by **gas gap** ($HV_{eff} = HV_{app} - RI$)
- →Data is fitted with a **sigmoid** → Information about **maximum efficiency** and **knee**
- →**Currents raise** of ~20% with a change of 10% of CO_2
- →**Δ(eff – str.)** increases when CO_2 decrease

Test beam 2018 - Pulse charge





→ The mean avalanche charge is higher for the eco-friendly gas mixtures

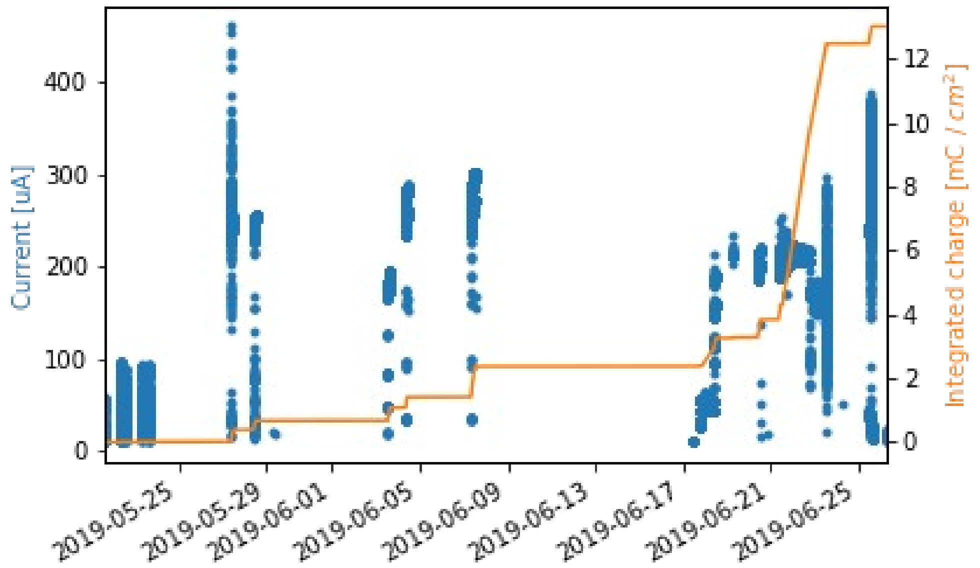
→ The mean streamer charge is slightly lower for the eco-friendly gas mixtures

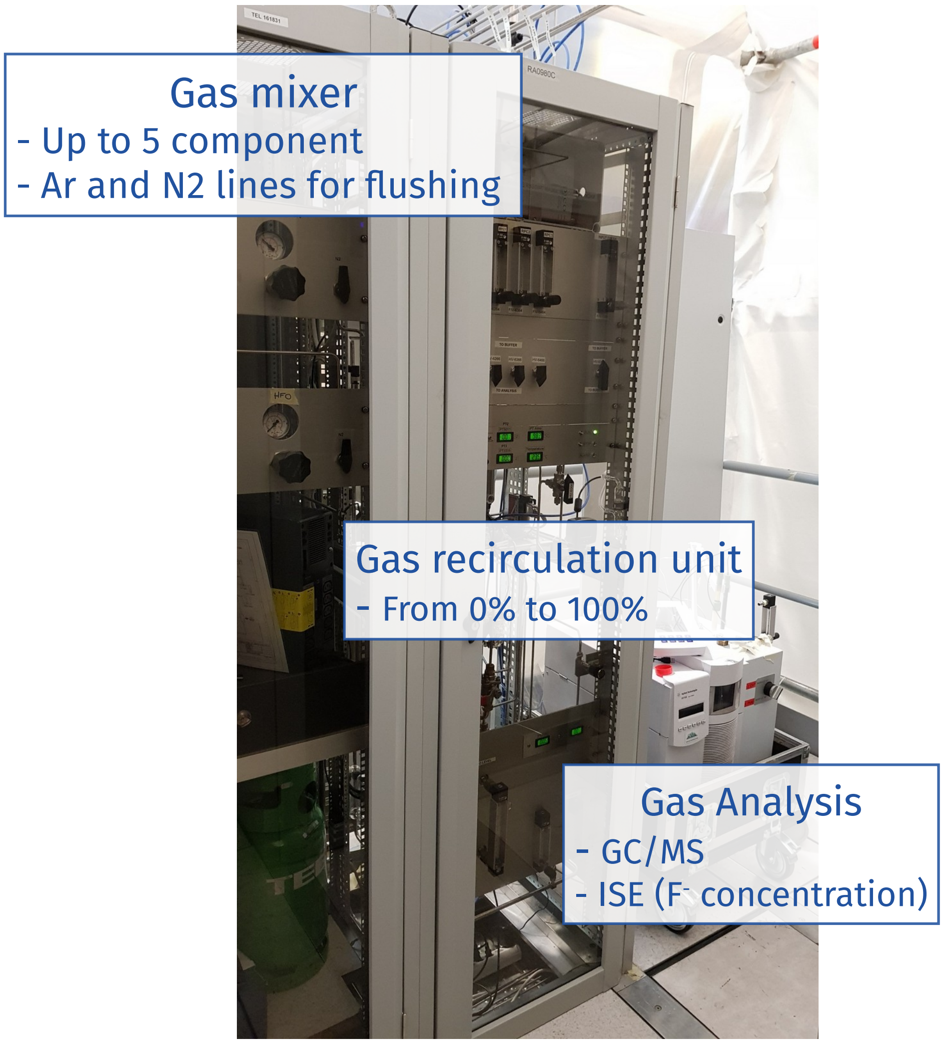
Gas recirculation system

RPC operation must be validated under LHC like conditions → **High background rate** → ***Gas recirculation***

RPCs operated under gas recirculation with eco-friendly gas mixtures
Validation with selected HFO based gas mixture

Cosmics validated
Stable performance, low current
Gamma irradiation validation ongoing
Stable currents, change in detector resistivity observed
Monitoring of currents and integrated charge





Creation of impurities under irradiation

Impurities created from R134a and HFO

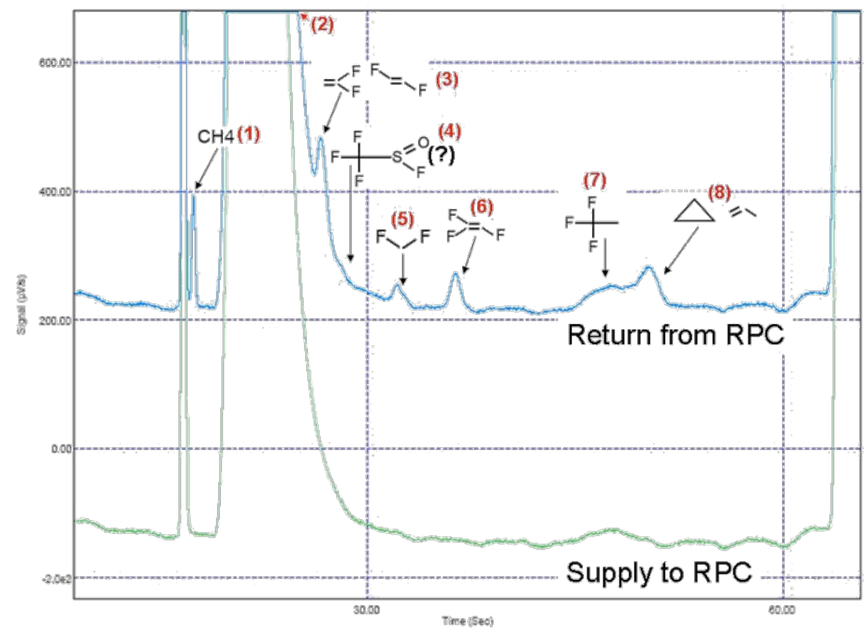
- Under the effect of high background radiation and electric fields Freons molecules break into fluorine radicals
- F- radicals are very reactive, especially with water → HF formation, may be aggressive for electrode surface
- Sub-products in the order of the ppm
- Accumulation in case of closed loop system

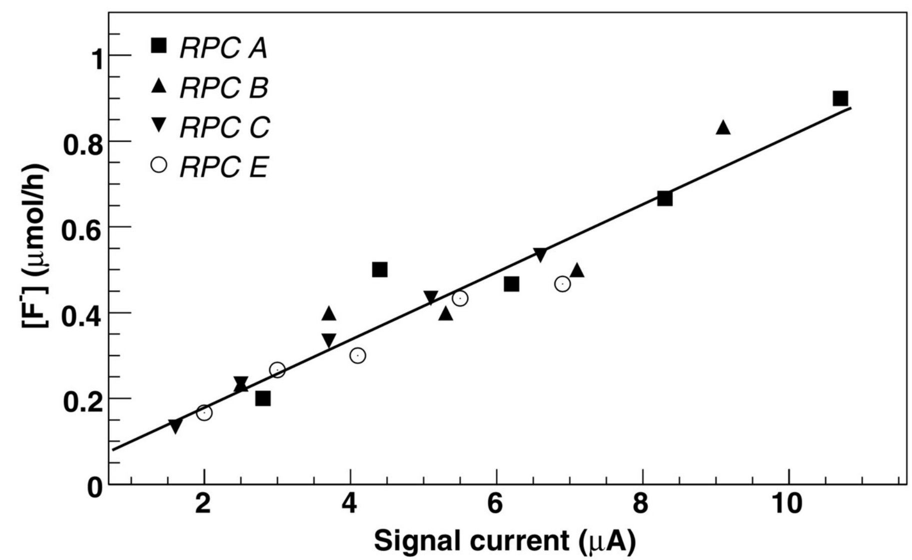
Creation of impurities observed also in RPCs at LHC experiments during Run 2

- Safety limit is still being understood

HFO gases have shorter atmospheric lifetime than R134a

- They could break more easily
- F- production depends on the current of the detector and the prompt charge size





Creation of impurities under irradiation

Radiation measurements with HFO based gas mixture

Test performed by irradiating 2 RPCs at different background rates and at different voltages
- Open mode, fixed flow and correction for environmental conditions

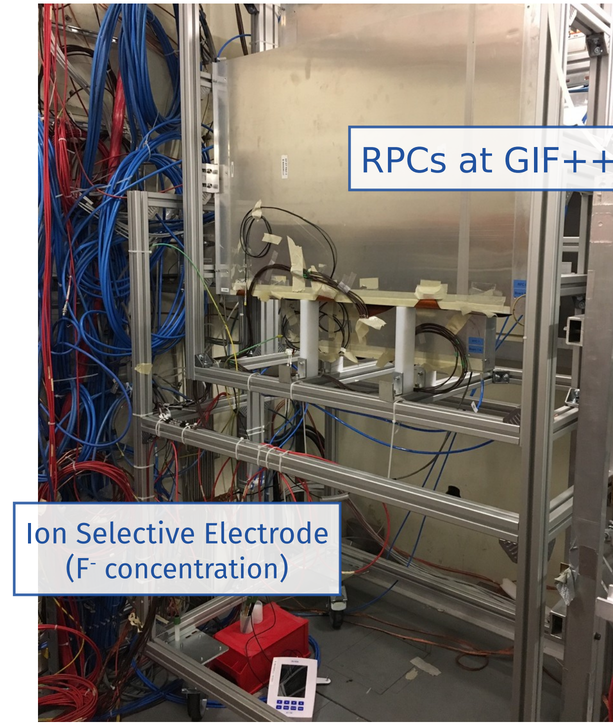
Gas mixture tested:
- Standard Gas mixture and selected eco-friendly
- Comparison between the production of impurities

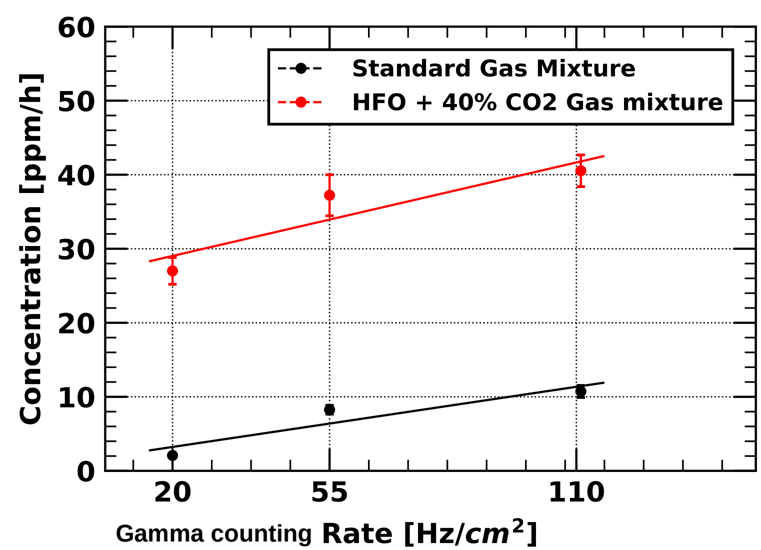
Impurities measured with different instruments
- Gas Chromatographer / Mass spectrometer
- Ion Selective Electrodes (ISE) for F- measurements

At detector efficiency
- The production depends on the background rate
- The F- production of the selected eco-friendly gas mixture is ~4 times higher than the standard gas mixture

Assuming contribution from SF6 neglectable

HFO is breaking ~10 times more easily than R134a





Conclusions

R&D goal: find an eco-friendly gas mixture compatible with the current ATLAS and CMS RPC systems

Eco friendly gas mixture for RPCs
- HFO not suitable for direct substitution to R134a in currents 2mm gap RPCs
- HFO requires an inert gas to work at lower working points (<12 kV)

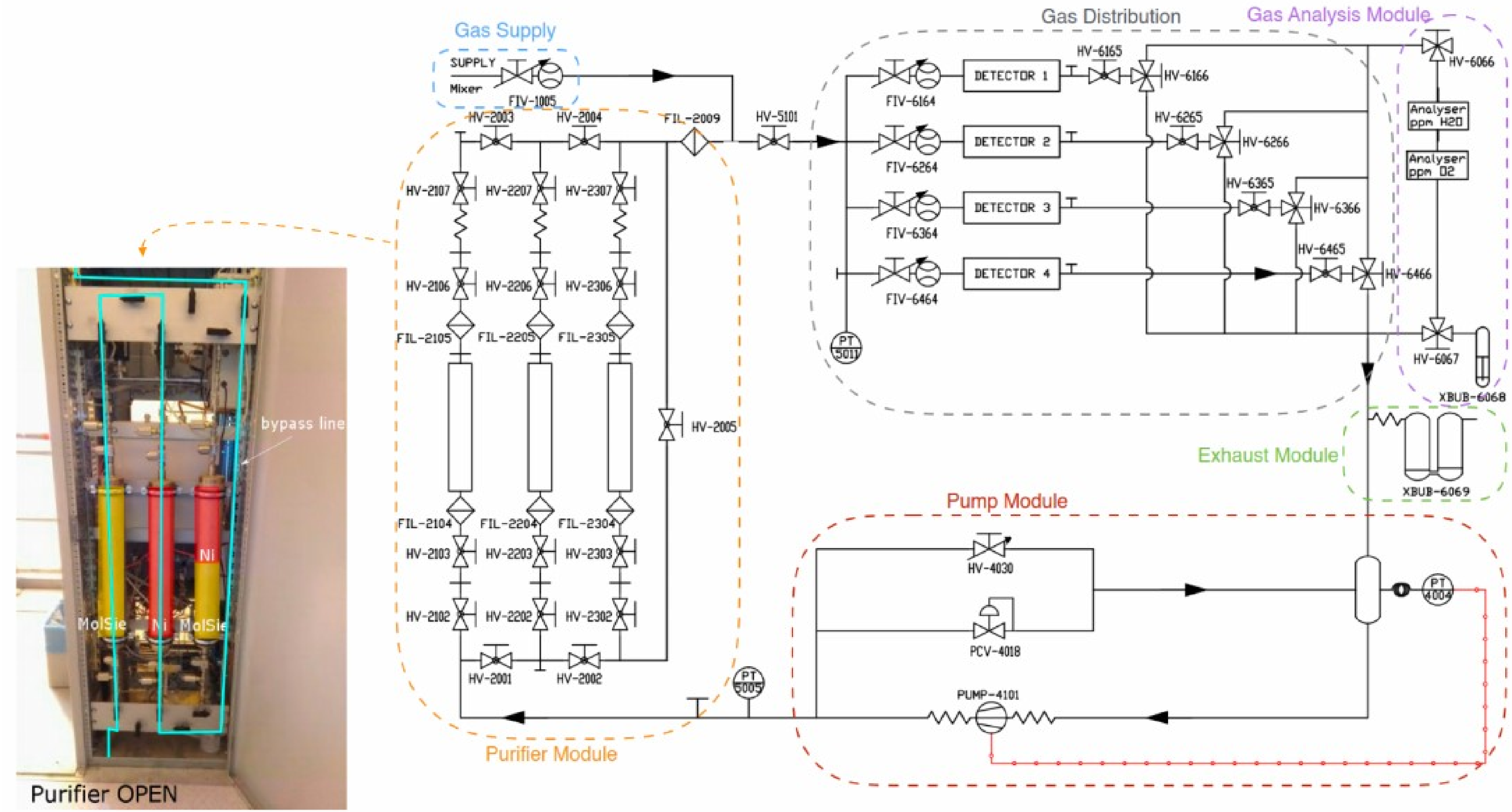
Characterization of RPCs with eco-friendly gas mixtures
- More than 50 different gas mixture tested
- HFO + CO_2 shows similar properties to the standard gas mixture

SF6 alternatives studies are on going
- Difficult to find eco-friendly gas with matching performance or safety
- Some promising gas mixtures show similar performance

RPCs operation with eco-friendly gas mixtures under background irradiation
- RPC tested up to HL-LHC expected rate (~300 Hz/cm^2 counting rate)
- Streamer probability and currents are slightly higher for HFO based gas mixtures
- Long term performance studies of eco-friendly mixture are currenly going on
- HFO seems to break more easily to R134a: studies ongoing on the causes and possible solutions

Thank you

Recirculation system

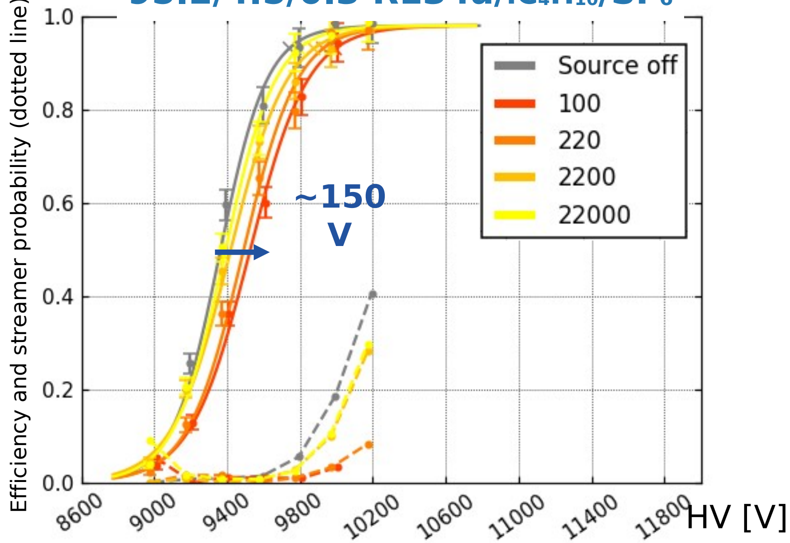


Other tested mixtures

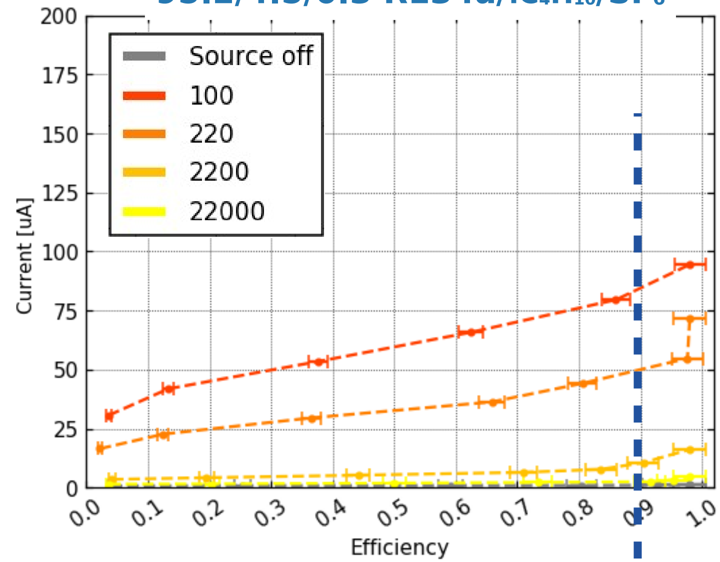
	Chem struc	GWPmix	HV (V)	Streamer (%)	Pulse charge (pC)	ΔV Eff-Stream (V)	Clu Size (strip)
R32-iC_4H_{10} -SF_6 0.6	c	1030	7500	14	0.5 / 6.5	600	1.5
R134a-iC_4H_{10}-SF_6 0.3	**c-c**	**1490**	**9600**	**1.5**	**0.5 / 6**	**1000**	**1.5**
R152a-iC_4H_{10}-SF_6 0.6	c-c	430	10000	10	1 / 8.5	760	1.6
R245fa-iC_4H_{10}-SF_6 0.6-He 50	c-c-c	1260	6600	20	1 / 7	610	2
HFO-iC_4H_{10}-SF_6 0.3-Ar 42.5	c=c-c	130	8900	70	2 / 15	160	4
HFO-iC_4H_{10}-SF_6 0.6-He 50	c=c-c	370	9000	20	1.5 / 8	700	4
HFO-R134 37.45-iC_4H_{10}-SF_6 0.6-He 20	**c=c-c**	**890**	**10500**	**1.8**	**0.5 / 6**	**970**	**1.6**
HFO-R134a 50-iC_4H_{10}-He 20	c=c-c	430	10800	50	1.5 / 8	400	2.5
HFO-R134a 22.5 -iC_4H_{10}-CO_2 50- SF_6 1	**c=c-c**	**560**	**10500**	**5**	**1.5 / 7.5**	**950**	**1.5**

More details on muon efficiency

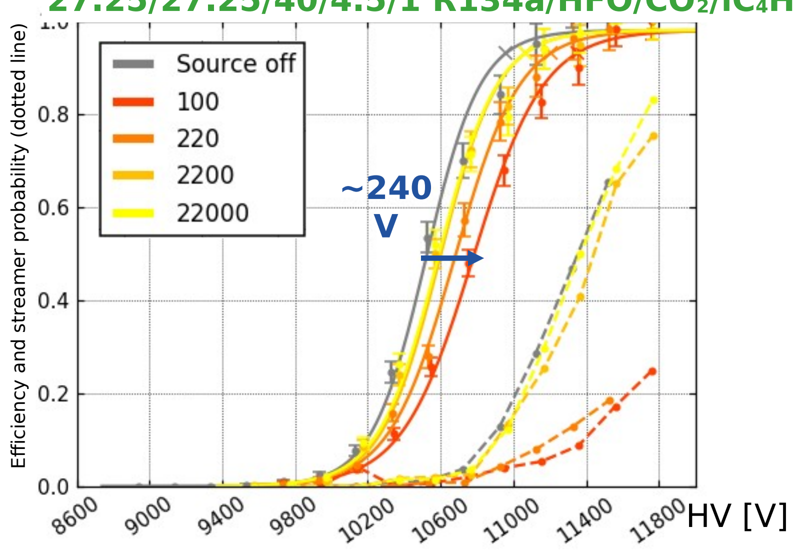
95.2/4.5/0.3 R134a/iC_4H_{10}/SF_6



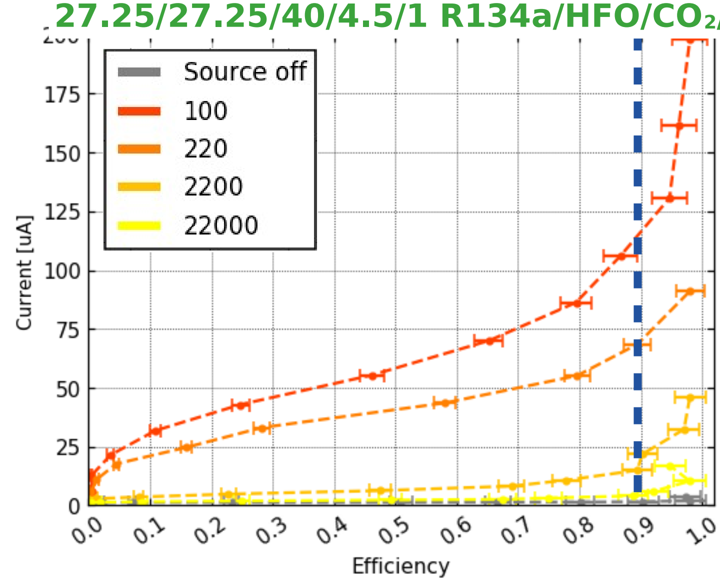
95.2/4.5/0.3 R134a/iC_4H_{10}/SF_6



27.25/27.25/40/4.5/1 R134a/HFO/CO_2/iC_4H_{10}/SF_6

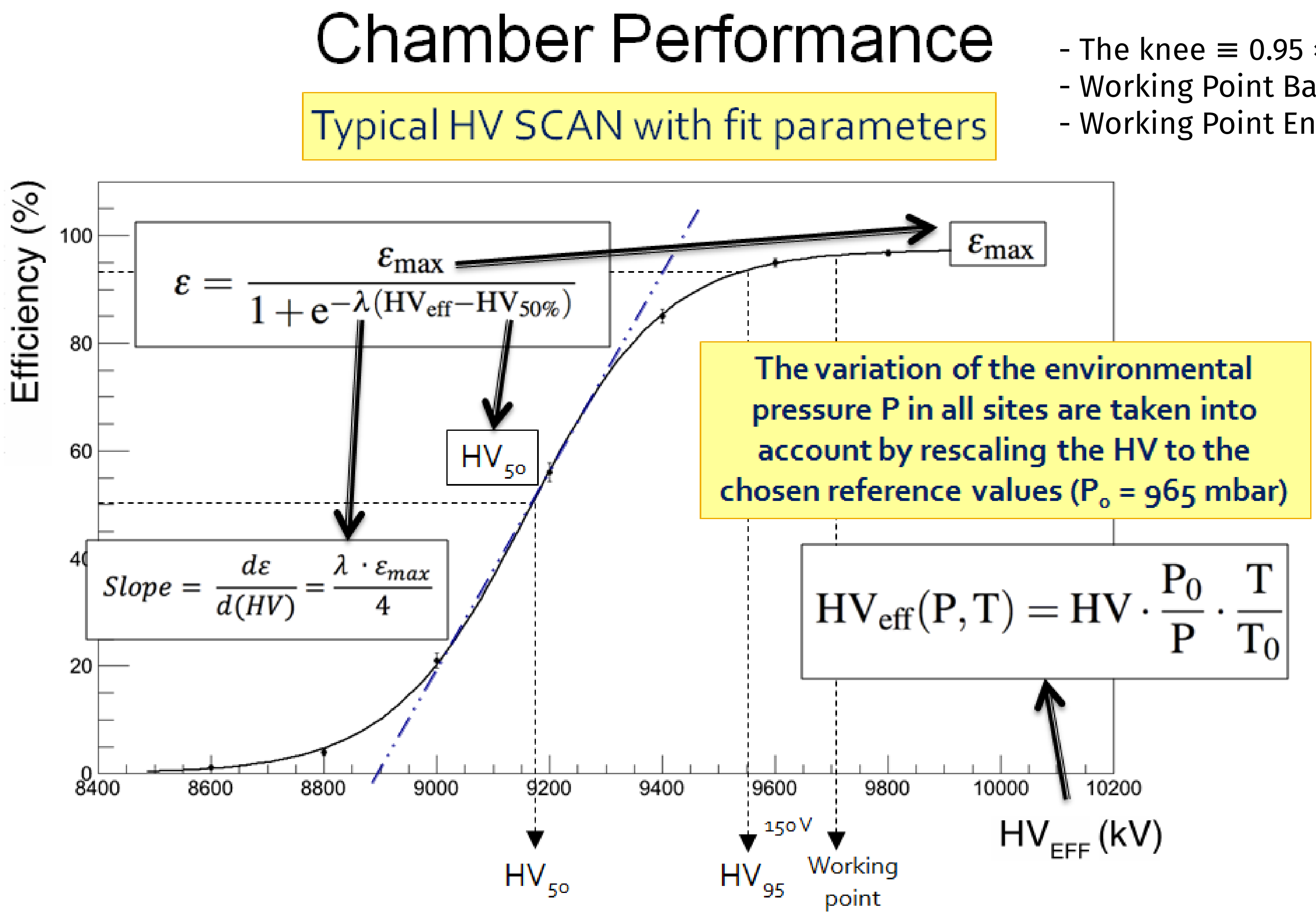


27.25/27.25/40/4.5/1 R134a/HFO/CO_2/iC_4H_{10}/SF_6



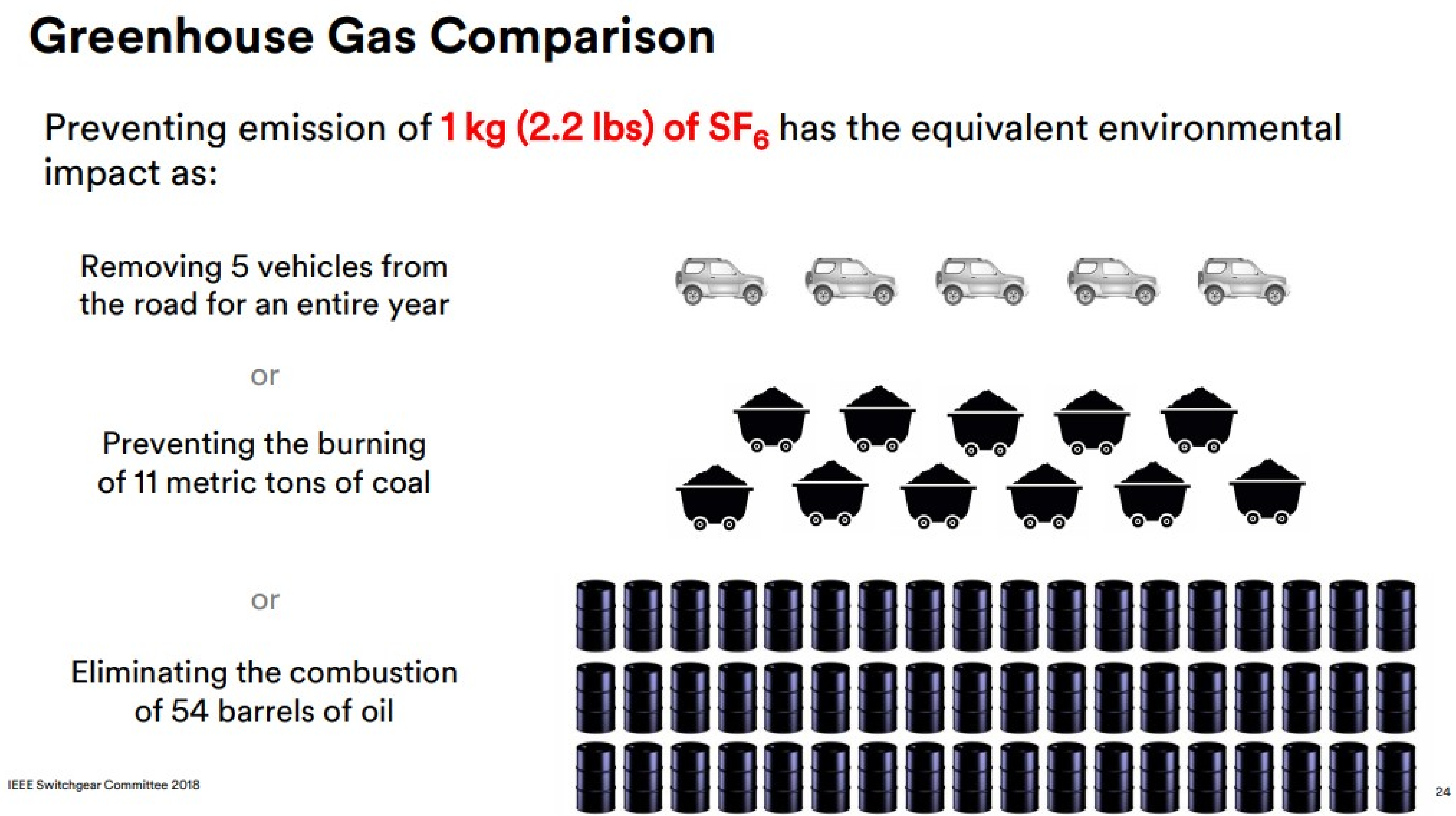
Software analysis

- The knee ≡ 0.95 × Eff max
- Working Point Barrel ≡ knee +100V
- Working Point Endcap ≡ knee +150V



https://twiki.cern.ch/twiki/bin/view/Main/EndcapReshufflingRpc

SF6 equivalent emissions



John G. Owens, 3M, *Greenhouse Gas Emission Reductions from Electric Power Equipment through Use of Sustainable Alternatives to SF6*

More details on muon efficiency

Mixture	F- rate production	Contribution to the mixture
95.2% R134a	10ppm/h	R134a = 10.5ppm/h
HFO + 40%CO2	40ppm/	HFO = 136ppm/h