EP-DT
Detector Technologies

RPC **2022**

Possible alternatives to SF_6 for Resistive Plate Chambers

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CERN

The XVI Workshop on Resistive Plate Chambers
CERN, 28th September 2022

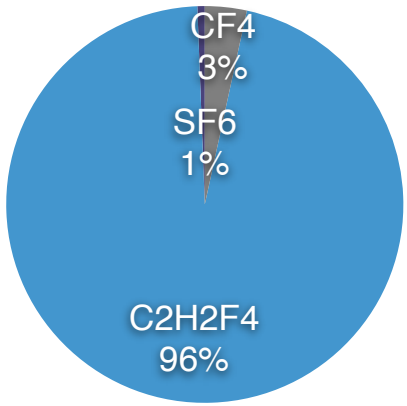
Outline

SF_6 impact on GHG emissions and possible alternatives

RPC performance with new gases as substitutes of SF_6

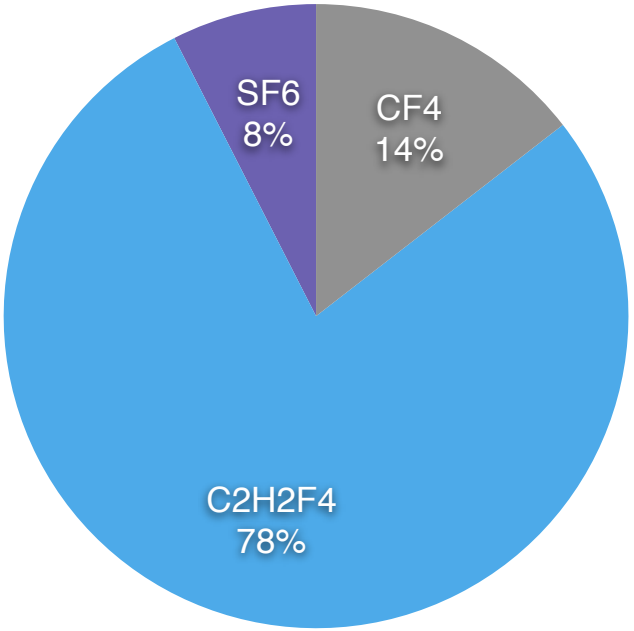
Thoughts and tests on properties of new gases

Use of SF_6 in RPC detectors at CERN



Impact of GHG in LHC Run 2 considering quantities used in **kg**

from kg to tCO2e



Impact of GHG in LHC Run 2 considering quantities used in **tCO2e**

- CF4 **GWP 7390**
- C2H2F4 **GWP 1430**
- SF6 **GWP 22800**

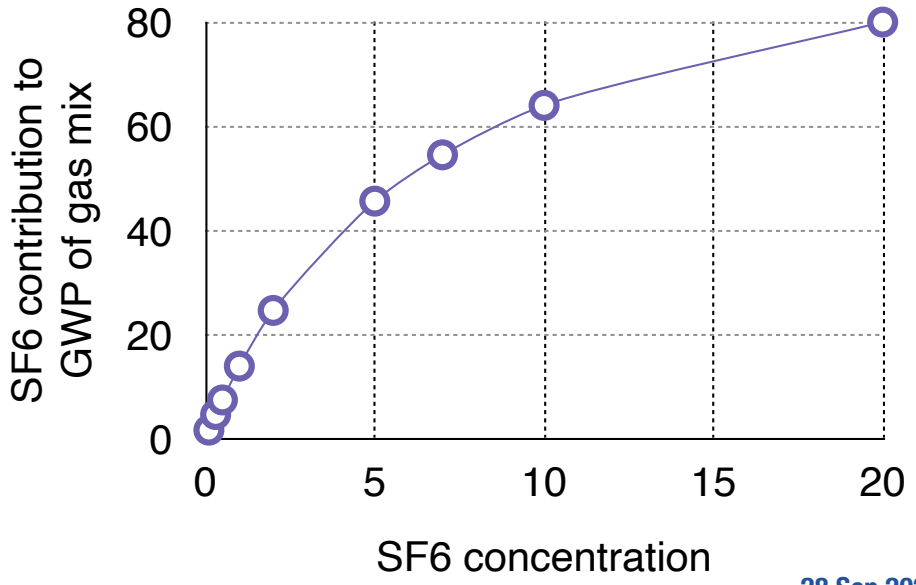
SF_6 contributes for a high fraction in the GWP of RPC gas mixture even if it is used in small concentrations

HPL RPC: ~0.3%

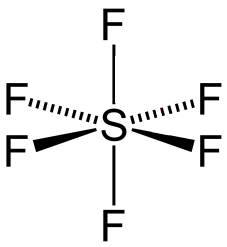
~5% of the GWP of the gas mixture

glass RPC: ~7%

~50% of the GWP of the gas mixture



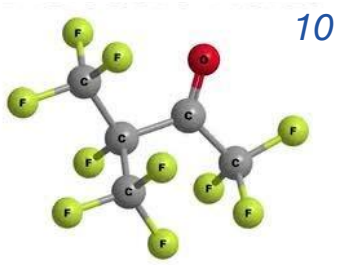
Alternatives to SF_6



SF_6

GWP 23900

- Chemical inertness: extremely stable
- Exceptionally long lived in the atmosphere
- Excellent dielectric property
  - SF_6 x 2.5 than Air
- Non-flammable and toxic
- Gaseous form
- No major reactions
  - Ok with H_2O, Cl and acids

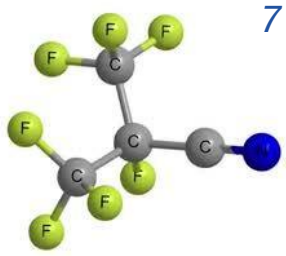


3M™ Novec™ 5110

$(CF_3C(O)CF(CF_3)_2)$

GWP <1

Atm. lifetime 15 days

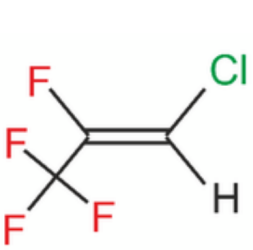


3M™ Novec™ 4710

$((CF_3)_2CFCN)$

GWP 2100

Atm. lifetime 30 years

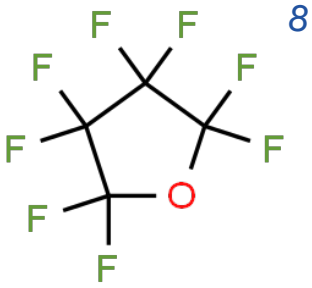


AMOLEA™ HFO-1224yd

$(CF_3\text{-}CF{=}CHCl)$

GWP <1

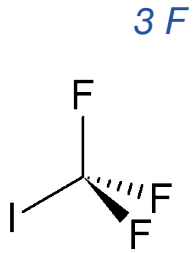
Atm. lifetime 20 days



C_4F_8O

GWP 8700

Atm. lifetime >3000 years

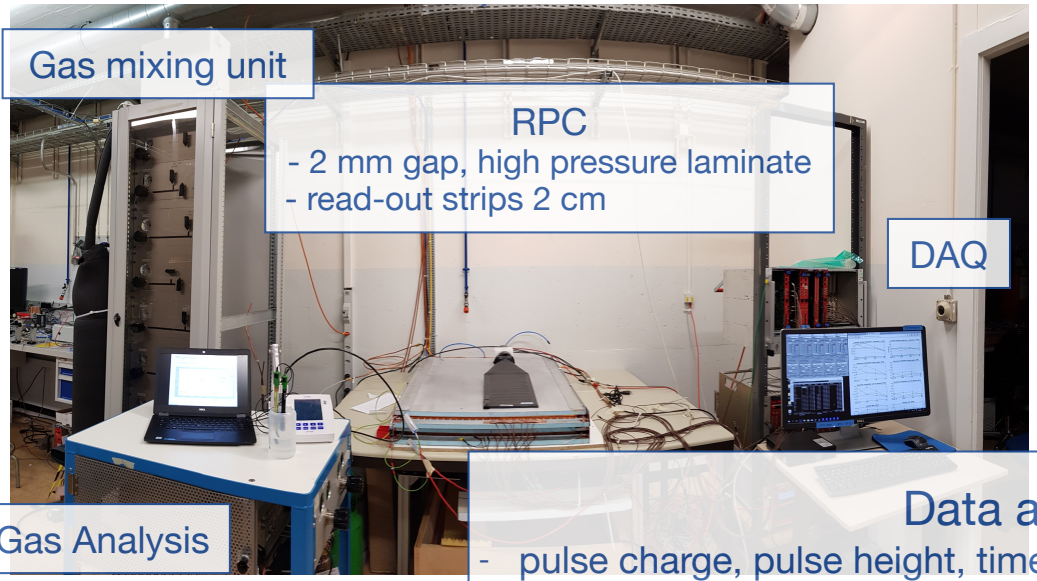


CF_3I

GWP 0.4

Atm. lifetime 6 days

Set-ups: laboratory and GIF++



Laboratory

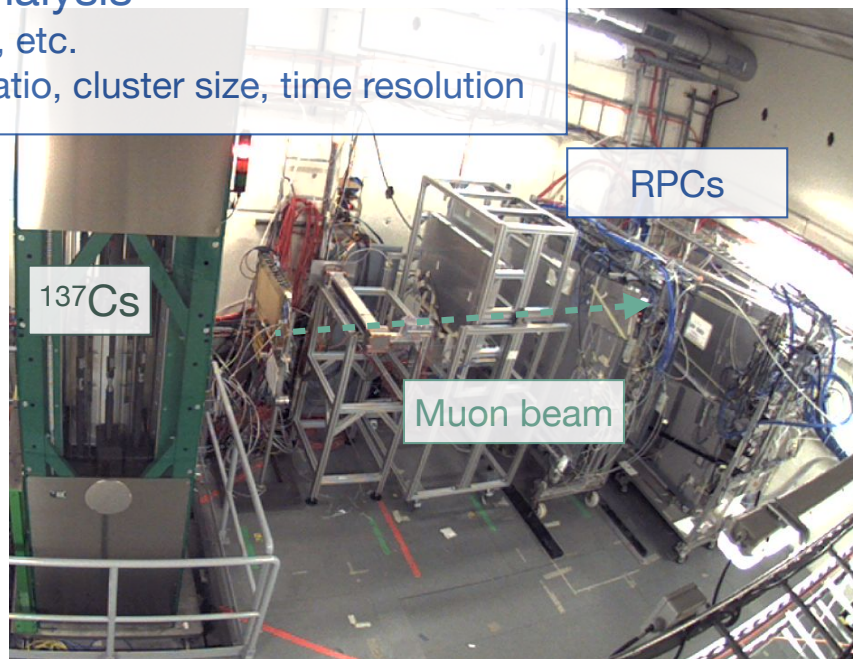
- Gas mixing unit
  - Gas mixture up to 6 components
- DAQ
  - CAEN Digitizer V1730: resolution 0.122 mV, sampling 500 MS/s
- Gas analysis
  - GC, MS and ISE

Data analysis

- pulse charge, pulse height, time, etc.
- efficiency, avalanche/streamer ratio, cluster size, time resolution

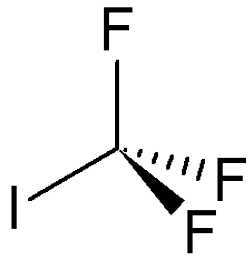
Gamma Irradiation Facility (GIF++)

- Gamma source
  - ^{137}Cs of 12 TBq —> 662 keV gamma
  - Lead filters to allow attenuation factors (ABS) between 1 and 46000
- Muon Beam
  - 100 GeV and 10^4 muons/spill (10 x 10 cm^2)
- Detectors tested up to to ~ kHz/cm^2
- Very similar DAQ, gas system and gas analysis of laboratory



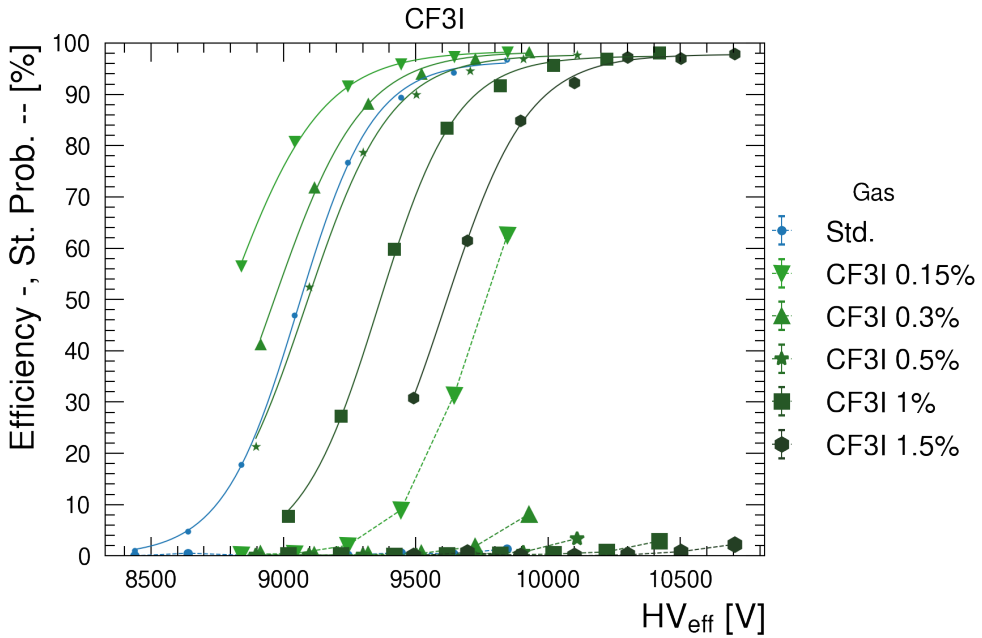
SF_6 alternatives were tested in different concentrations as substitute of SF_6 in RPC standard gas mixture

CF_3I



PRO

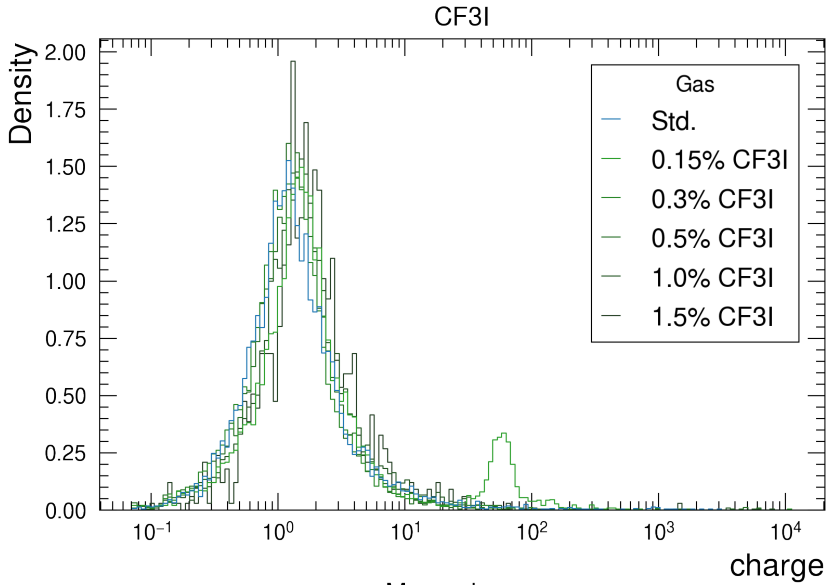
- Very low GWP: 0.4
- Application in industry

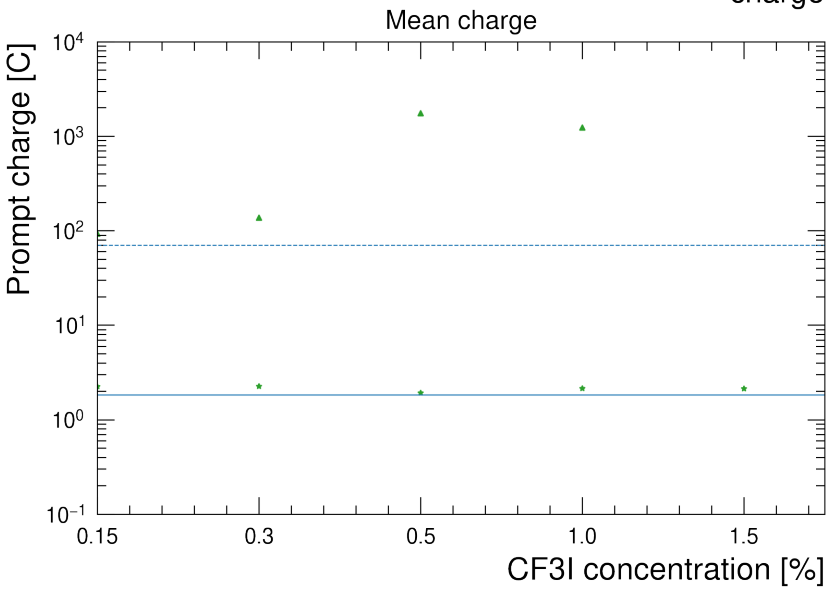


- Low concentration (0.3-0.5%) enough for good streamer suppression
- Working point similar to std gas mixture with 0.3-0.5% of CF_3I
- Avalanche charge similar to std gas mixture
  - Streamer charge much affected by error due to low statistics

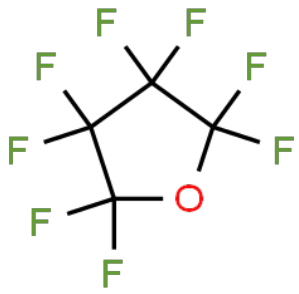
CONS

- Toxic (inhalation), low human genotoxic risk
- May react with H_2O





C_4F_8O

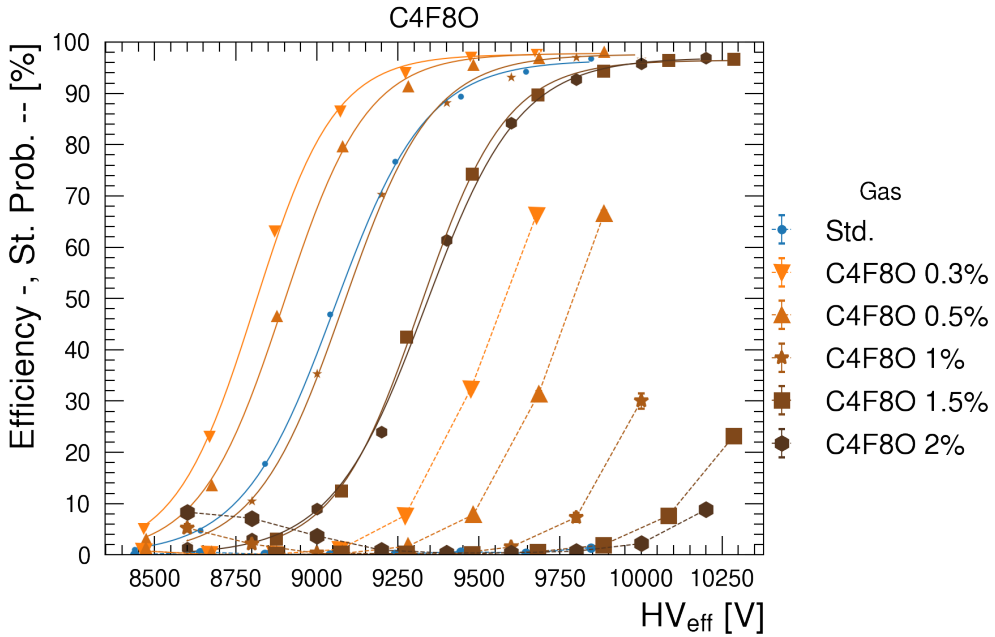


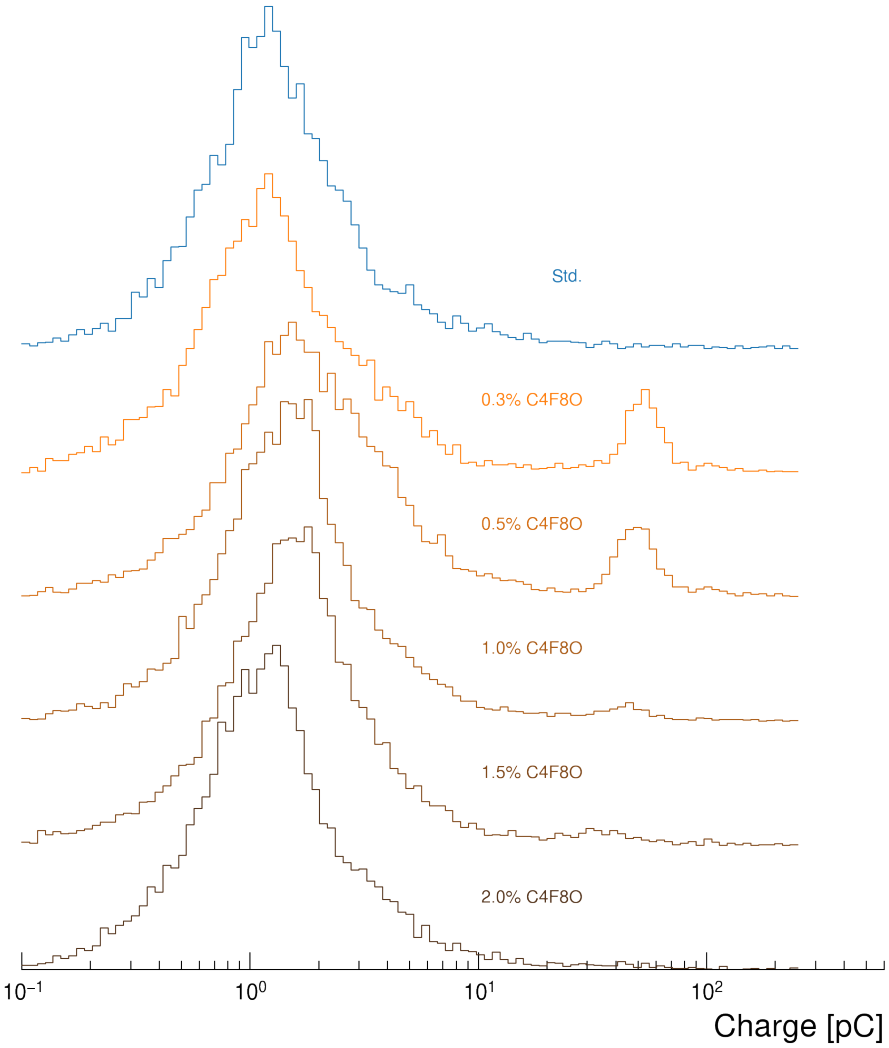
PRO

- Good quantity of F atoms
- Easy to use in gas form

CONS

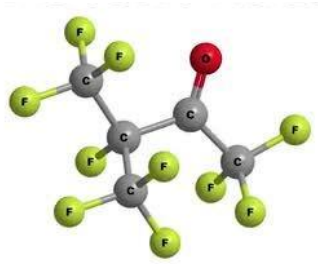
- High GWP: 8000
- When used as alternative to SF_6, a large fraction is needed





- 1.5% needed for good performance
  - GWP contribution therefore similar to SF_6 in std gas mixture
- At 1.5%-2% similar streamer probability of SF_6
- Higher working point for concentration >1%
- Avalanche charge a bit higher than std gas mixture
  - Streamer charge similar

Novec 5110

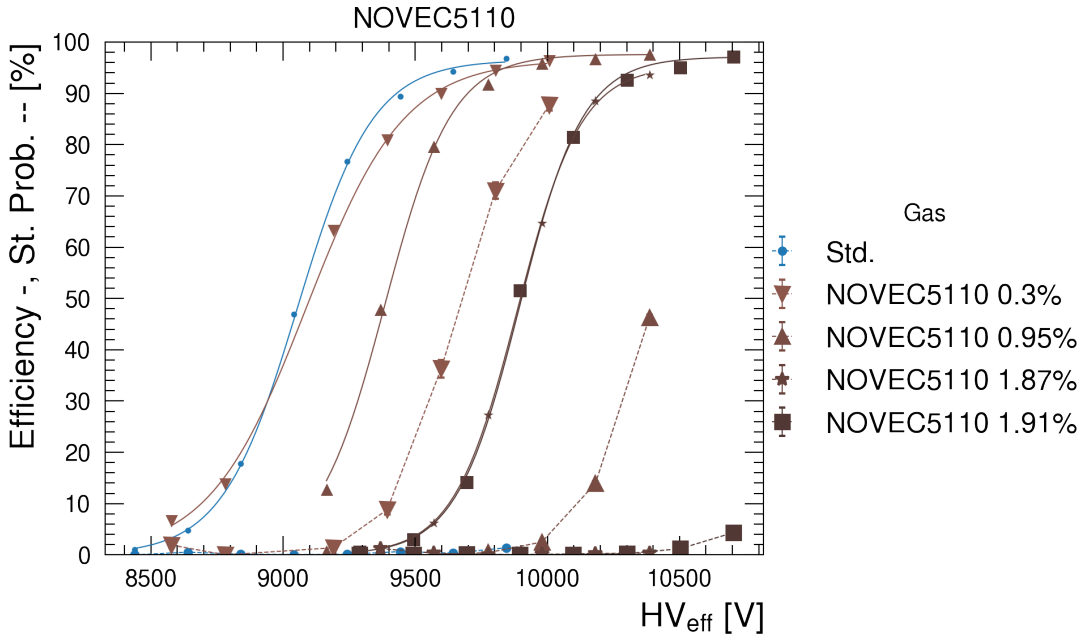


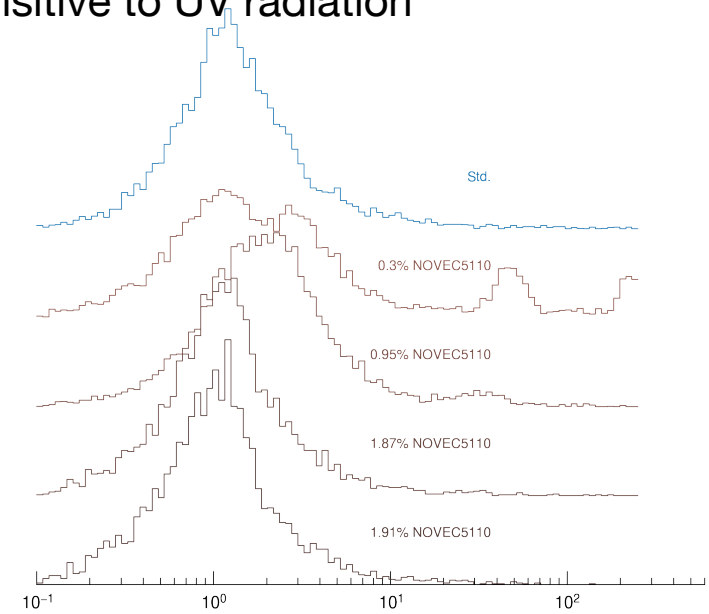
PRO

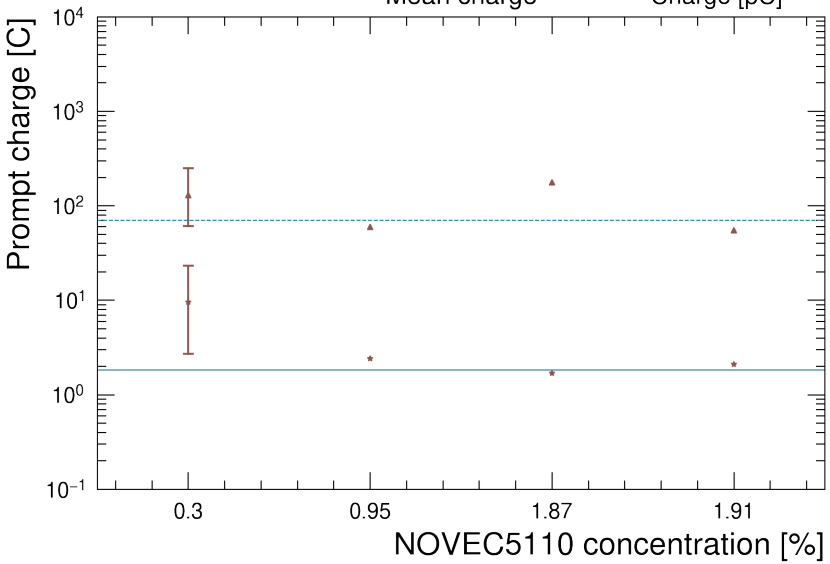
- Very low GWP: <1
- Application in industry
- High dielectric strength

CONS

- High boiling point: 27 C
- Sensitive to UV radiation

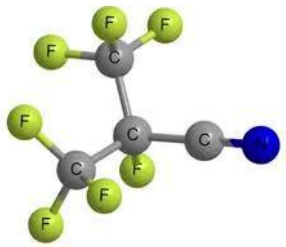






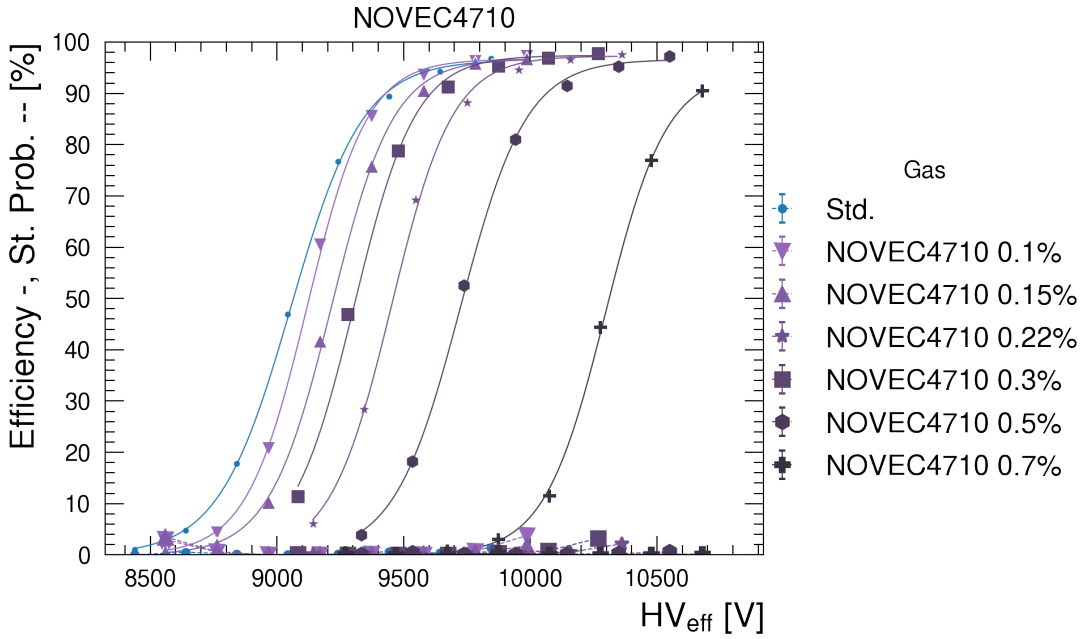
- High concentration (~2%) of NOVEC 5110 needed to obtain good streamer suppression
  - Suspect that NOVEC 5110 breaks inside the RPC
- Higher working point for concentrations > 0.3%
- Avalanche and streamer charge similar of std gas mixture from 0.9%
  - At 0.3% very large avalanche signals

Novec 4710



PRO

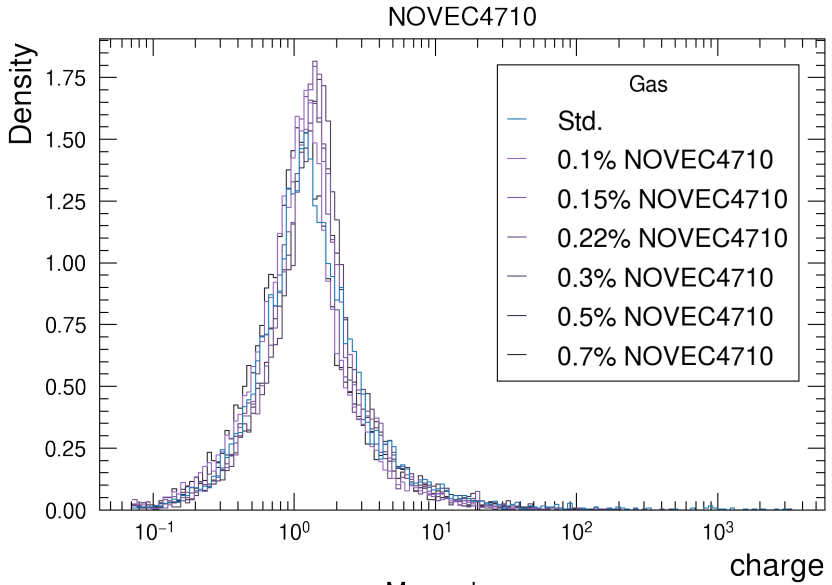
- Good vapour pressure
- Application in industry
- High dielectric strength

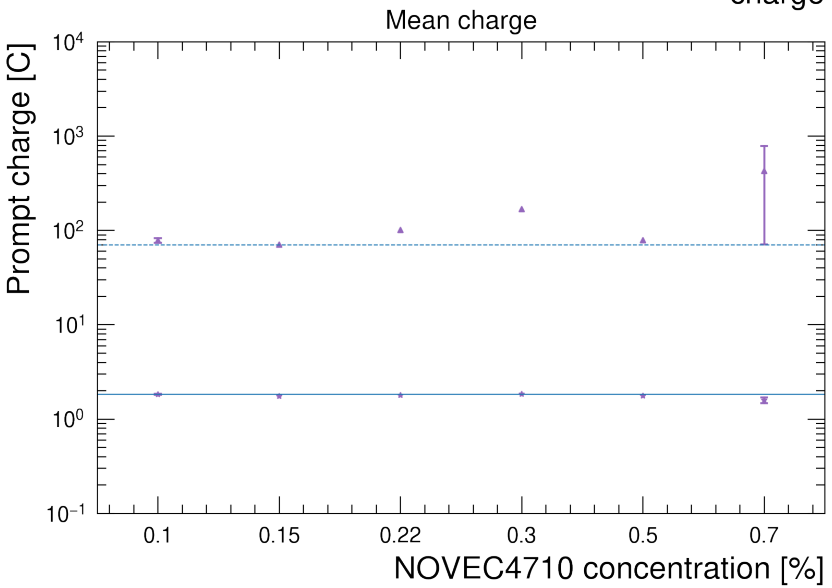


- Streamer probability always lower than std gas mixture
  - 0.1% of NOVEC 4710 already enough!
- Avalanche charge and cluster size lower than std gas mixture
- Higher working point for concentrations > 0.1%

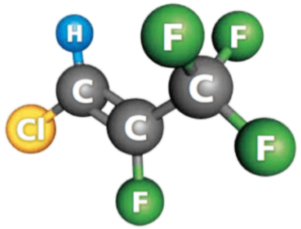
CONS

- GWP of 2200
- It may react with H_2O





HFO-1224yd

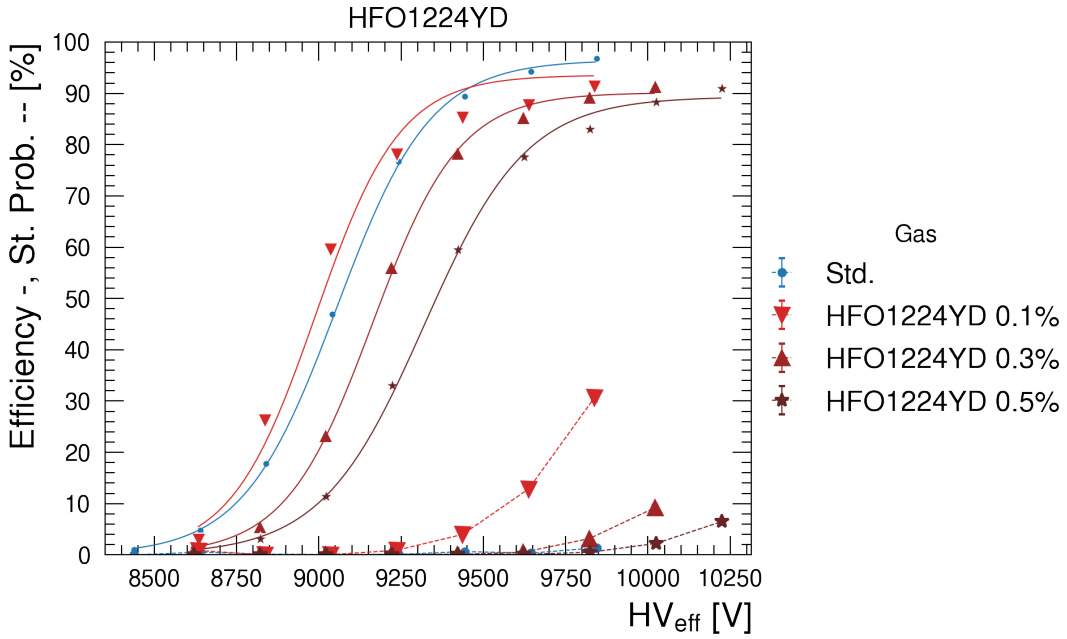


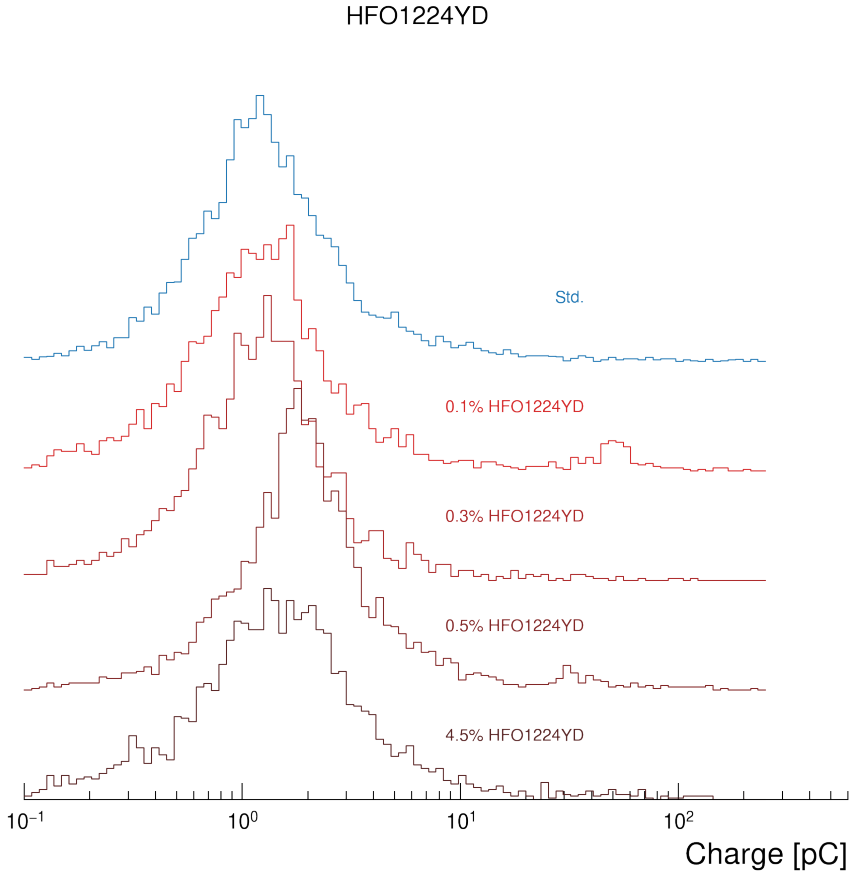
PRO

- Very low GWP: 1
- Application in industry

CONS

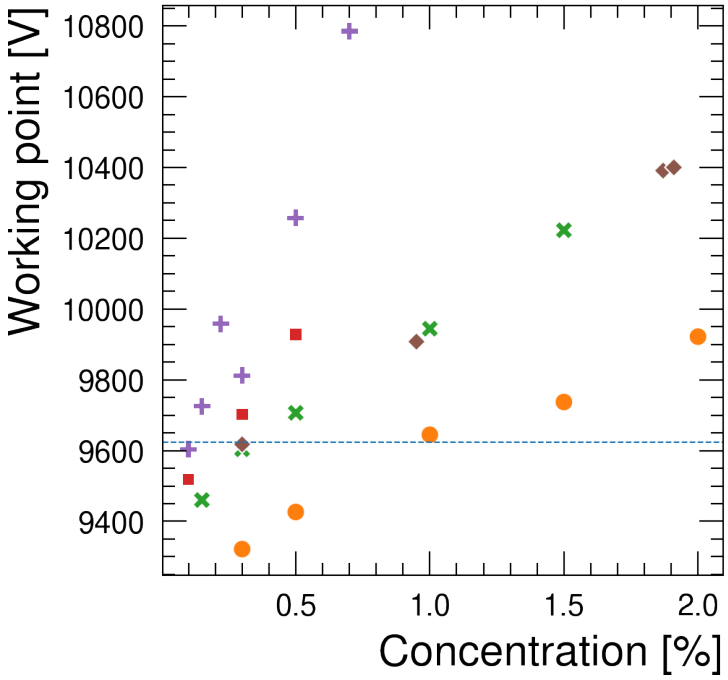
- Presence of Cl

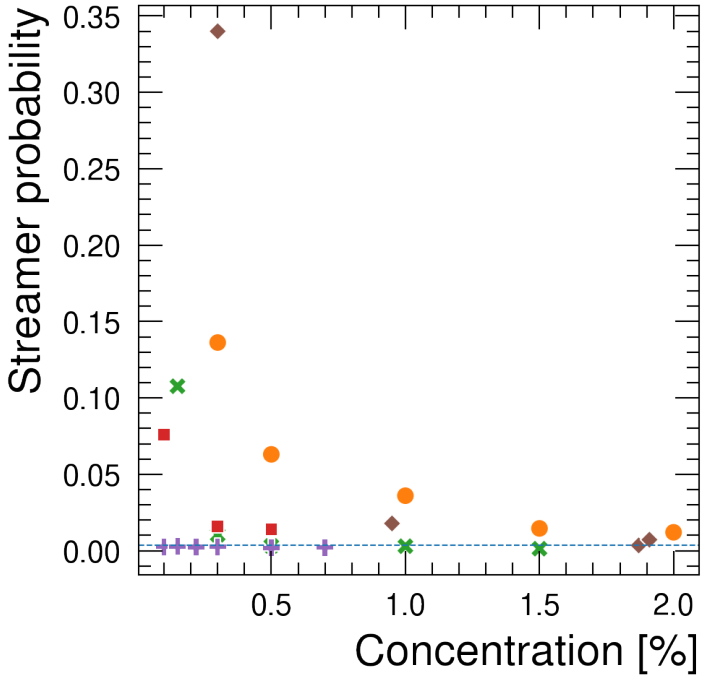


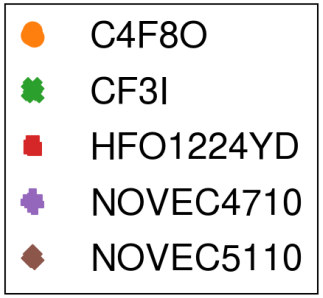


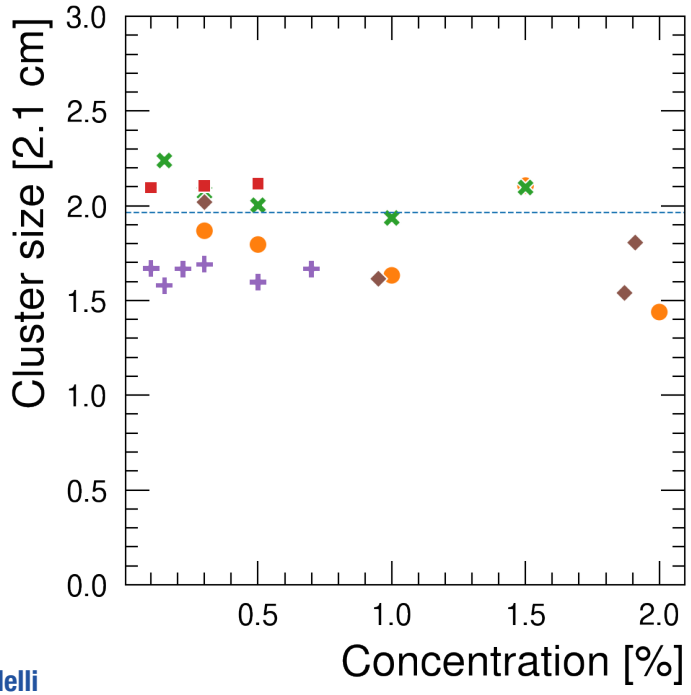
- Lower efficiency than std gas mixture
  - Under investigation
- Streamer probability acceptable from 0.5%
- Avalanche charge a bit higher than std gas mixture
- Higher working point for concentrations > 0.3%

Comparison of all tested gases



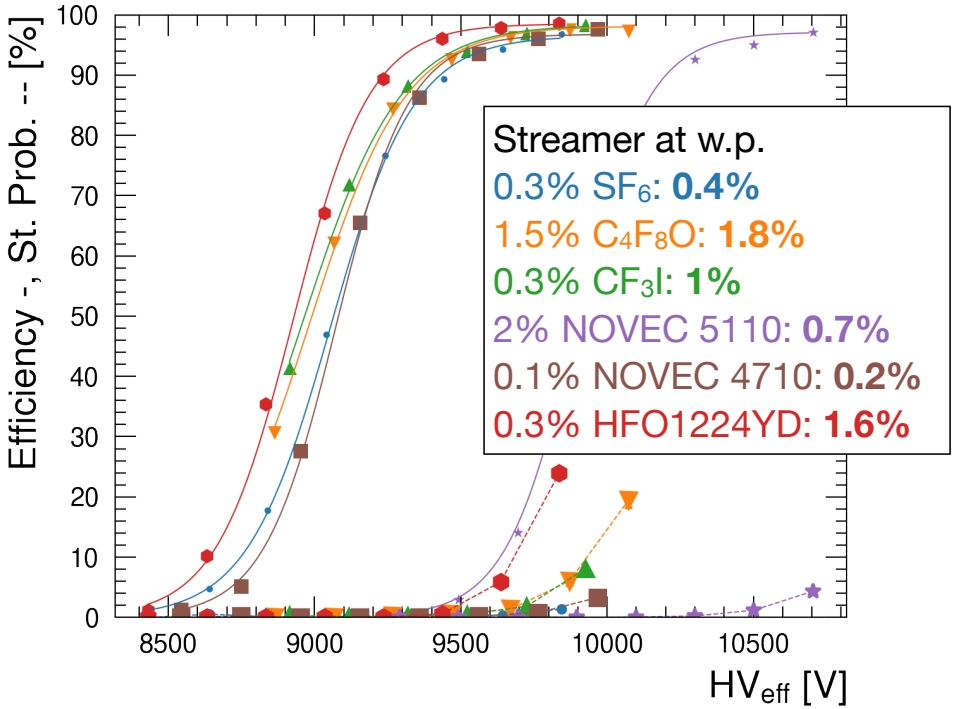






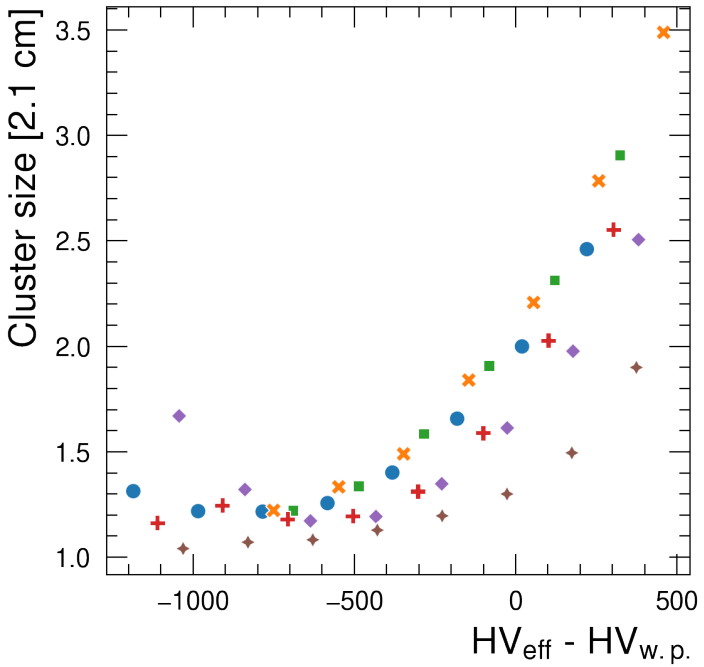
- Working point
  - Increasing with different slopes depending on gas
- Streamer probability
  - Decreasing with increase of concentration except for NOVE4710 where it is stable
- Charge
  - Avalanche charge very similar for all gases tested at all concentrations
- Cluster size
  - Lower for NOVECs and C_4F_8O
- Time resolution
  - Very similar for all gases tested at all concentrations

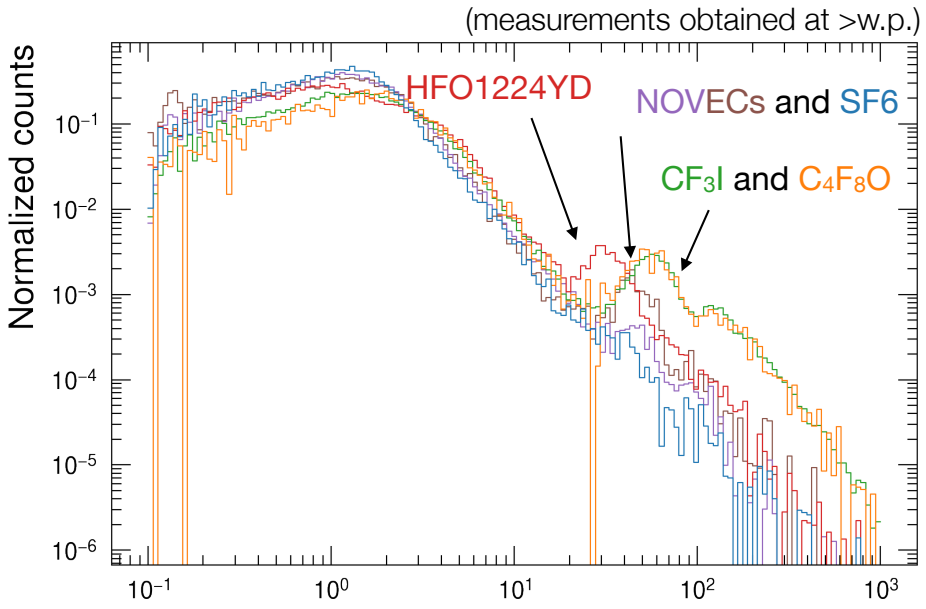
Comparison between best concentration



For each SF_6 alternative the best concentration has been selected

- Very small concentration of NOVEC 4710, Amolea and CF_3I are enough to obtain satisfactory performance
  - But CF_3I now discarded
- Working point very similar to std gas mixture except for NOVEC 5110
- Best streamer probabilities obtained with NOVEC gases
  - Excellent dielectric strength
- NOVEC gases also improve the cluster size
- Three different streamer population depending on the gas

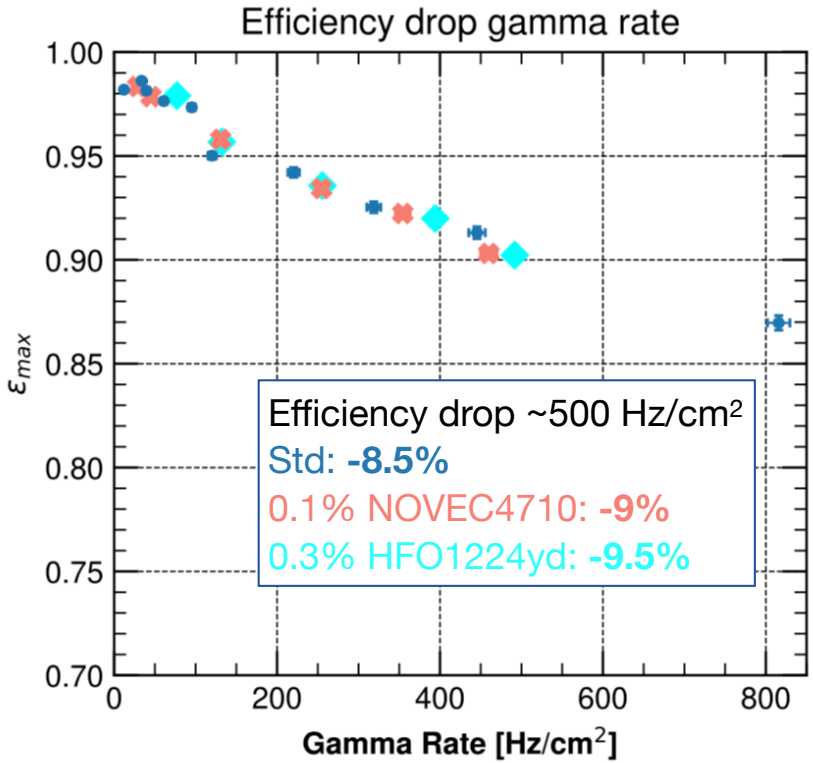


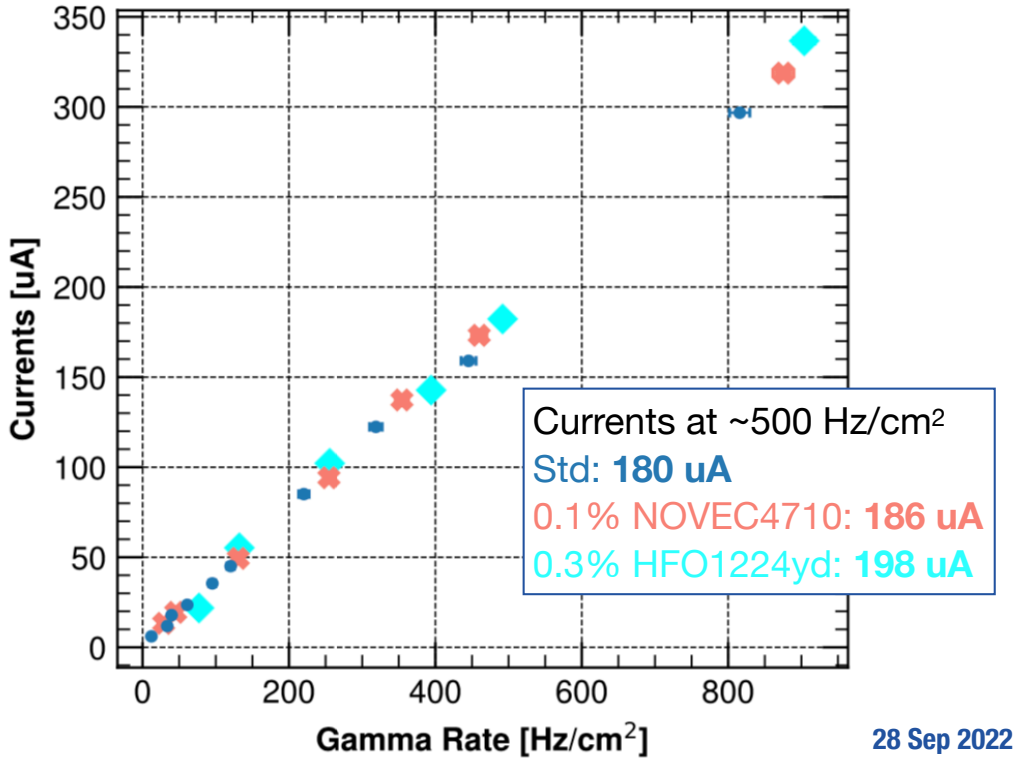


Testbeam with best candidates at GIF++

RPC tested at high gamma background rate and muon beam

- Selection of 0.1% NOVEC4710 and 0.3% AMOLEA HFO1224yd for testing at GIF++
  - Best compromise between streamer probability, working point and avalanche and streamer charge
  - NOVEC5110 to further test
- Small increase of currents and efficiency drop at high gamma rates
  - A bit worse for HFO1224yd
- Best option seems NOVEC4710 but undergoing studies since it reacts with H_2O
- HFO1224yd is also very promising
  - Streamer probability still a bit higher





Not only detector performances….

Two factors identify the greenhouse gases and their effects on climate: the radiative efficiency and lifetime in the atmosphere

↓

The lower are the GWP and the lifetime, the easier is the creation of sub-products

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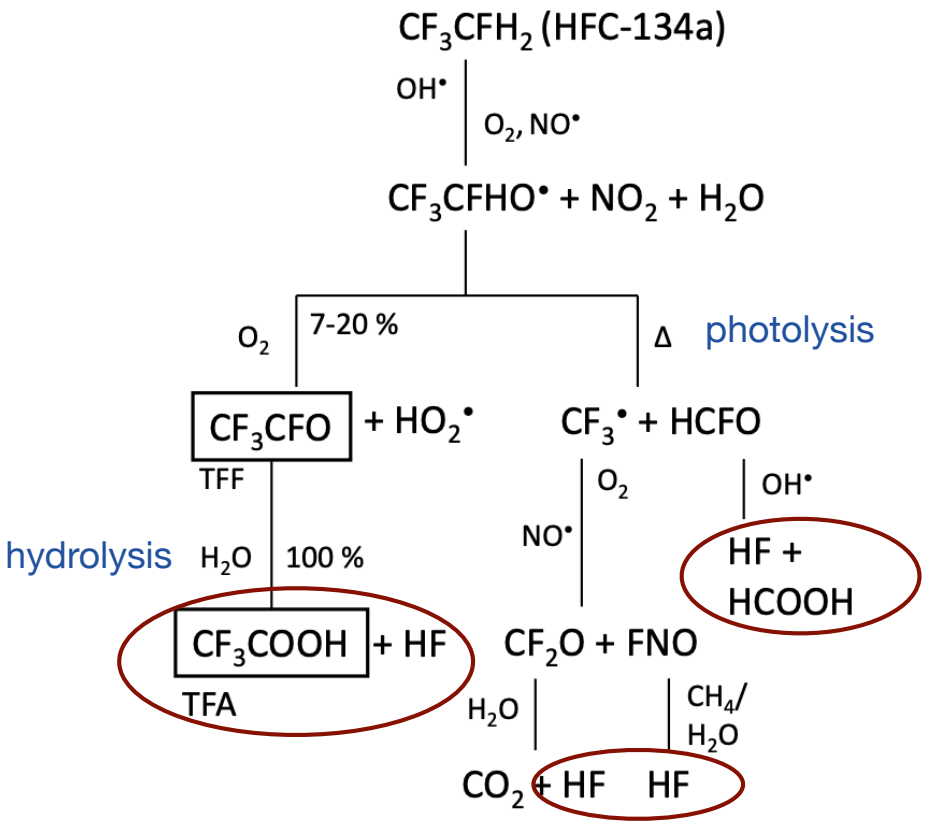
Do these sub-products have an impact on detector lifetime?

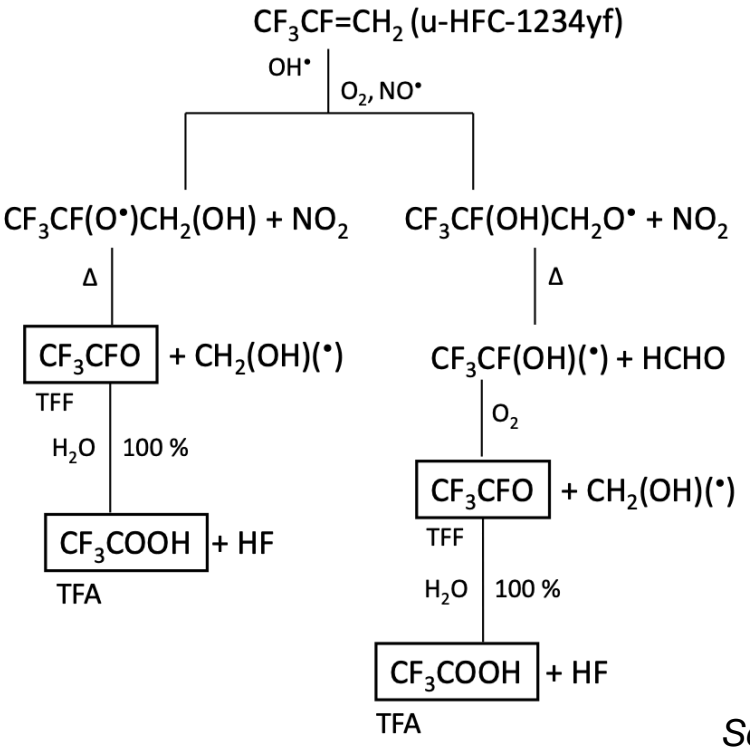
Three factors determine the atmospheric lifetime

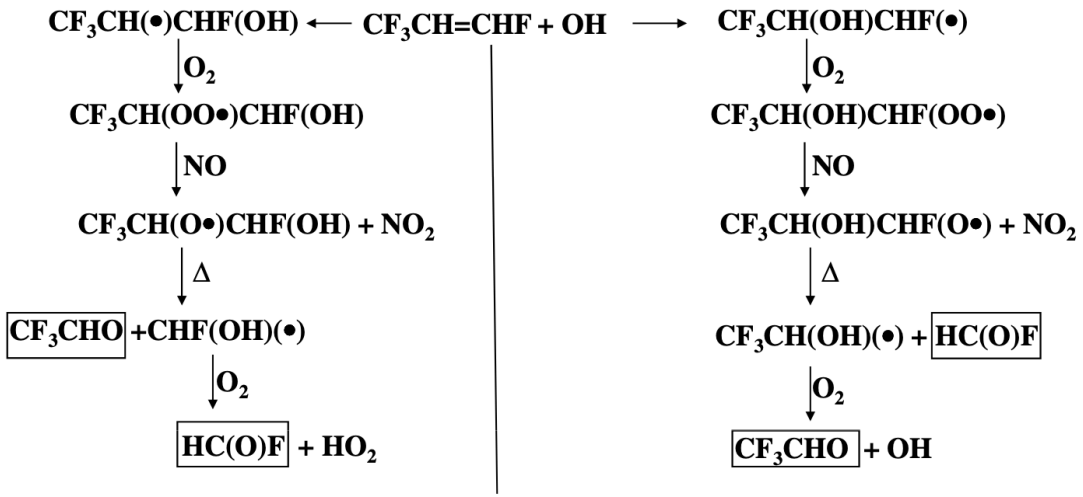
Rain out	→	Water solubility
Oxidation	→	Reactivity with OH
Photolysis	→	UV absorbance



HFO degradation

Atmospheric lifetime of HFO1234yf is 11 days
Atmospheric lifetime of HFO1234ze is 18 days ⟷ **Atmospheric lifetime of R134a is 500 years**





See poster "Measurements of fluoride production in RPC" by G. Rigoletti

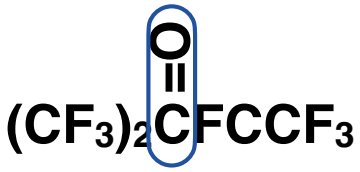
Hydrofluoric Acid (HF)

- It has already been measured that HFO produces much more HF than R134a in RPC detectors

Trifluoroacetic acid (TFA)

- HFO1234ze is estimated to break down into TFA at less than 10%, whereas R-1234yf will break down into TFA at 100% (R134a at 21%)
- TFA highly soluble: no formation of insoluble salts
- Phytotoxic

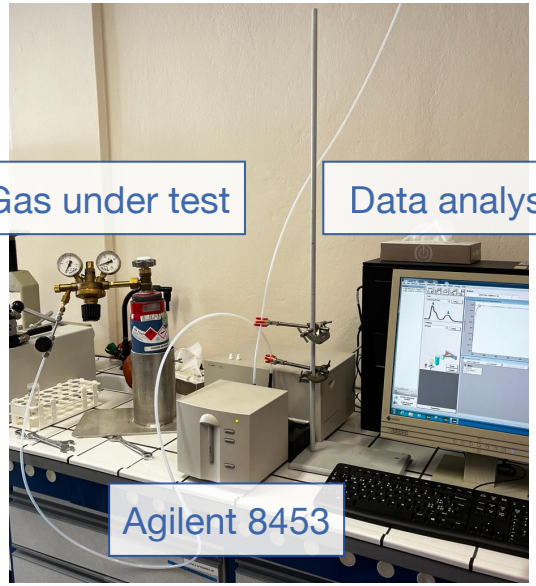
NOVEC 5110



Rain out → water solubility (1ppmw)

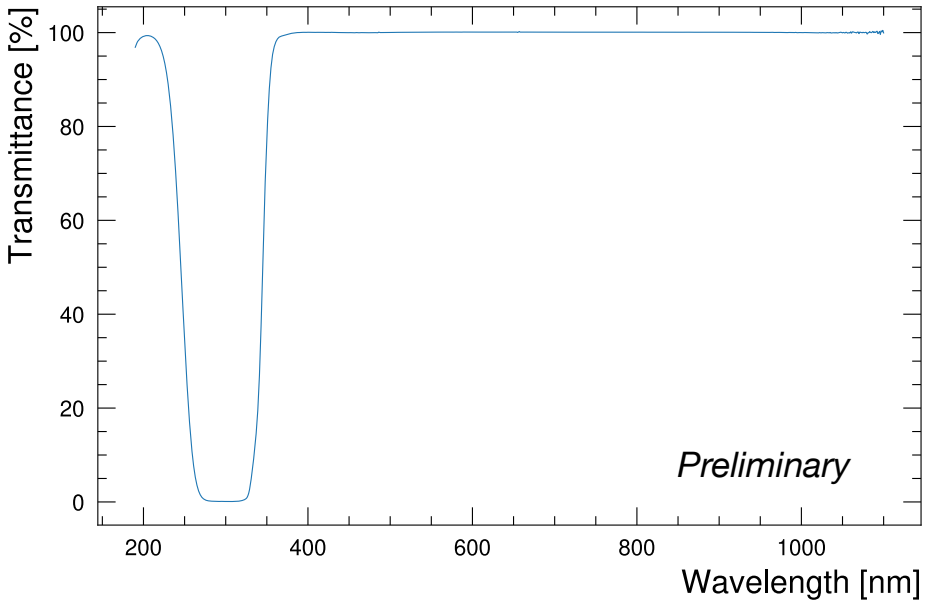
Oxidation → unreactive with OH

Photolysis → strong absorbance in near UV (wavelength > 300 nm)



Thanks to B. Teissandier for helping in the measurements and providing the instrument

- Several gases tested: NOVEC 5110, NOVEC 4710, iC_4H_{10}, HFO, N_2, CO_2
- Agilent 8453 UV-visible Spectroscopy system
  - Wavelength range: 190-1100 nm
- First measurements in agreement with 3M company
- Works on-going to go to lower wavelengths
  - No commercially available instruments (custom made from companies >500 kCHF)



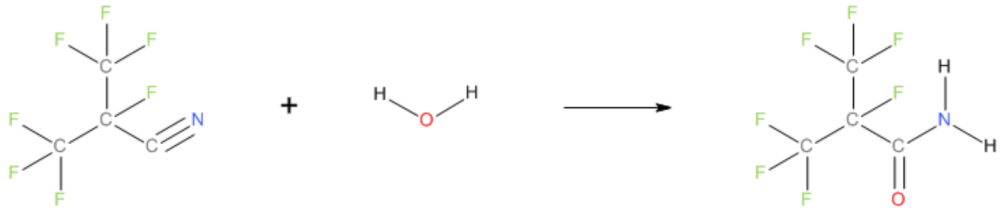
NOVEC 4710

$(CF_3)_2CFC{\equiv}N$

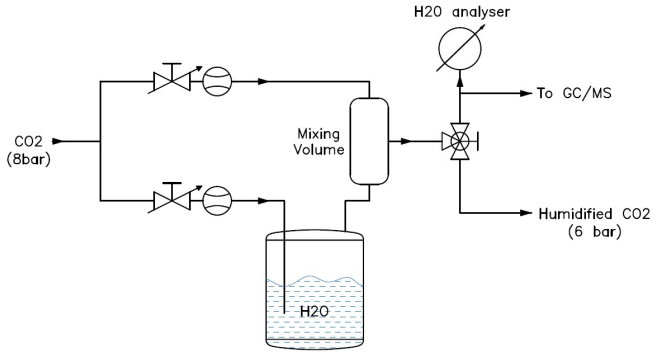
Rain out → **Water solubility (272 ppbw)**

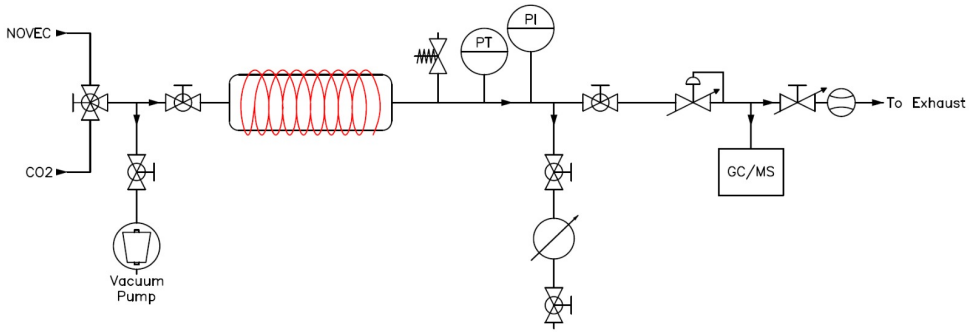
Oxidation → reactivity with OH radicals

Photolysis → transparent in near UV



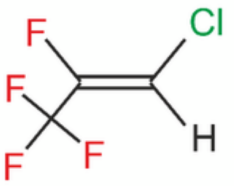
Set-up for studies of NOVEC 4710 water solubility





- Bakelite RPCs use 40% relative humidity
  - Already a concern for the creation of HF
- 3M recommend to use NOVEC gases in a dry environment
- Production of an amide from NOVEC 4710 + H_2O
  - Sub-products in the order of ppb
  - Solid at room T with a melting point of 49°C
  - The amide has appreciable vapor pressure at 60°C, it remains in gas phase at low concentrations
- Tests on-going in laboratory
  - Try to reproduce 3M tests
  - Analysis at the output of an RPC

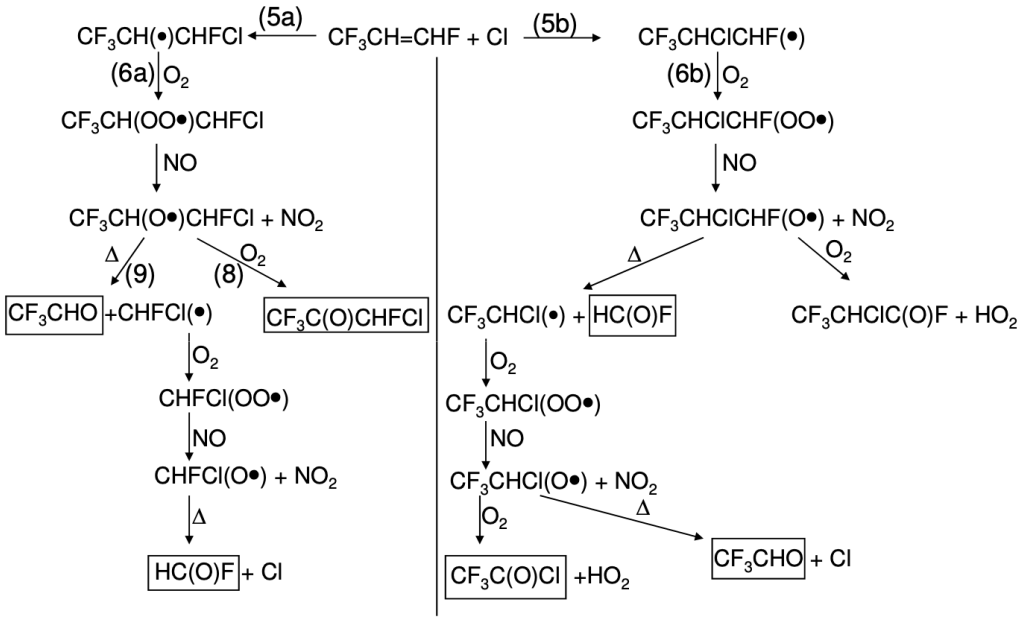
HFO-1224yd



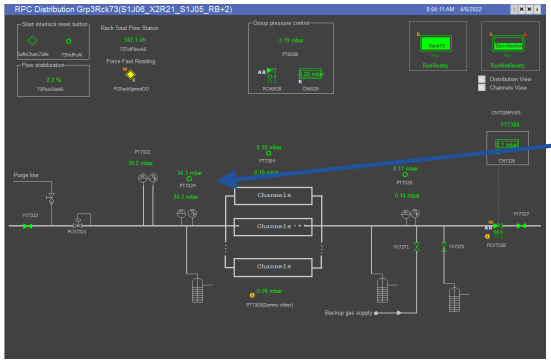
Degradation products: $CF_3C(O)OH$, CO_2, HF, HCl

TFA yield from atmospheric degradation very low

Reactions of HFO with Cl

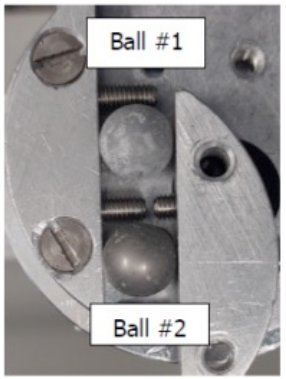


The Cl case of CMS RPC system



Increase of input pressure

presence of white dust at detector input!



	Float balls	
Element	Ball #1	Ball #2
C	5.3	6.1
O	4.6	7.9
F	0.0	0.0
Na	0.0	0.1
Al	0.0	0.0
Si	0.7	1.8
Cl	53.0	28.1
Cr	0.0	8.6
Fe	36.5	47.2
Ni	0.0	0.3

Conclusions

Search for alternatives to SF_6

- It has a very high GWP and even if used in small quantities it accounts for a large fraction of the gas mixture GWP
- Not yet a problem as in industry SF6 is largely employed for HV insulating plants but new alternatives start to be used

Detector performance

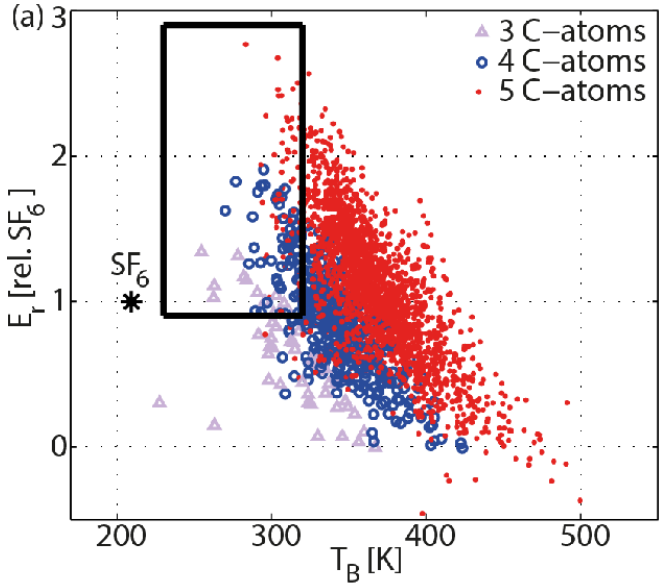
- Several alternatives were tested in concentrations from 0.1% to 2% in the standard RPC gas mixture
- Very promising candidates with excellent streamer suppression
- Test performed in laboratory and at GIF++

Properties of new gases

- The new low-GWP gases can easily breaks in well-defined conditions (UV radiation, presence of OH, presence of humidity)
- Studies on-going to characterise these gases
- Detailed studies needed to understand possible effects on RPC long-term operation

Back-up slides

Alternatives to SF_6: search in HV industry



	Dielectric Strength	GWP	Lifetime (year)	T_b (◦C)
SF_6	1	23900	3200	-63.8
N_2	0.36	0	-	-198
CO_2	0.3	1	300-1000	-78
CF_4	0.4	6300	50000	-128
CF_3I	1.2	0.4	6 days	-21.8
C_4F_8O	1.2	8000	>3000	-
C_4F_7N (Novec 4710)	2	1490	30	-4.7
$C_5F_{10}O$ (Novec 5110)	1.5 - 2	1	15 days	27
C_3F_4HCl (HFO1224yd)	-	0.88	20 days	15

group	$\langle E_r \rangle$ [rel. SF_6]	$\langle T_B \rangle$ [K]	$\langle z \rangle$	n
C_3-Ketones	0.39	319	2.00	17
C_3-Aldehydes	0.56	320	1.89	18
C_3-Acyl Fluorides	0.98	293	3.15	13
C_4-Ketones	0.69	352	2.58	138
C_4-Aldehydes	0.77	345	2.39	117
C_4-Acyl Fluorides	1.14	326	3.36	110
C_5-Ketones	0.94	375	3.30	923
C_5-Aldehydes	1.00	370	2.91	685
C_5-Acyl Fluorides	1.35	356	3.85	590
SF_6	1	209 [18]	6	1

Nr	SMILES	E_r	T_B	T_B^L
	C_3–compounds			
(1)	FC(=O)C(C(F)(F)F)(F)F	1.34	255	280
(2)	O=C(C(F)(F)F)C(F)(F)F	1.03	262	280
(3)	FC(C(C(=O)F)(F)F)F	1.11	263	288
(4)	FC(=O)CC(F)(F)F	1.31	278	302
	C_4–compounds			
(5)	FC(=O)C(C(C(F)(F)F)F)(F)F	1.63	270	317
(6)	FC(C(C(F)(F)F)(C(=O)F)F)F	1.82	277	
(7)	FCC(C(F)(F)F)(C(=O)F)F	1.91	295	
	C_5–compounds			
(8)	FC(=O)C(C(F)(F)F)(C(F)(F)F)C(F)(F)F	2.77	283	303
(9)	O=C(C(C(F)(F)F)(C(F)(F)F)F)C(F)(F)F	1.93	293	310
(10)	FC(C(C(C(F)(F)F)(F)F)(C(=O)F)F)F	2.28	296	
(11)	O=C(C(C(C(F)(F)F)(F)F)(F)F)C(F)(F)F	2.01	302	322
(12)	FC(=O)C(C(C(F)(F)F)C(F)(F)F)(F)F	2.67	304	

M. Rabie, C. Franck, predicting the electric strenght of proposed sf6 replacement gases by means of density functional theory

By-products under Arcing Conditions

SF_6

Data provided by 3M Company

Compound	CAS no.	Molecular formula
Bispentafluorosulfur oxide	42310-84-9	S_2OF_{10}
Carbon tetrafluoride	75-73-0	CF_4
Carbonyl fluoride	353-50-4	COF_2
Fluorine	7782-41-4	F_2
Hydrogen fluoride	7664-39-3	HF
Hydrogen sulfide	7783-06-4	H_2S
Nitrogen trifluoride	7783-54-2	NF_3
Oxygen difluoride	7783-41-7	F_2O
Silicon tetrafluoride	7783-61-1	SiF_4
Sulfur dioxide	7446-09-5	SO_2
Sulfur fluoramide fluorine	81625-84-5	$(SF_5)_2NF$
Sulfur fluoride fluorosulfate	81439-35-2	$S_2O_3F_6$
Sulfur fluoride peroxide	12395-41-4	$S_2O_2F_{10}$
Sulfur pentafluoride	5714-22-7	S_2F_{10}
Sulfur tetrafluoride	7783-60-0	SF_4
Sulfur tetrafluoride oxide	13709-54-1	SOF_4
Sulfuryl fluoride	2699-79-8	SO_2F_2
Thionyl fluoride	7783-42-8	SOF_2
Trifluoromethyl sulfur pentafluoride	373-80-8	SF_5CF_3

3M NOVEC 4710

Compound	Concentration (ppm)
CO_2	935018
$(CF_3)_2CFCN$ (Novec 4710)	40600
CO	24000
CF_2=CFCN	130
CNCN	65
C_2F_5CN	60
CF_3CN	58
$(CH_3)_2SiF_2$	52
COF_2	14
$(CF_3)_2CHCN$	1.9
$(CF_3)_2C=CF_2$	1.3

Calculated LC_{50} value for arced-gas mixture = 39000 ppmv

3M NOVEC 5110

Compound	Concentration (ppm)
CO_2	61000
CO	6200
HF	690
CF_4	100
$(CF_3)_2CFC(O)CF_3$ (Novec 5110)	39
C_3F_8	19
C_3F_7H	<15
C_3F_6	14
C_2F_6	<10
C_4F_8O	5
C_4F_{10}	2

Calculated LC_{50} value for arced-gas mixture = 122000 ppmv