Green transition of Resistive Plate Chamber detectors for HEP applications

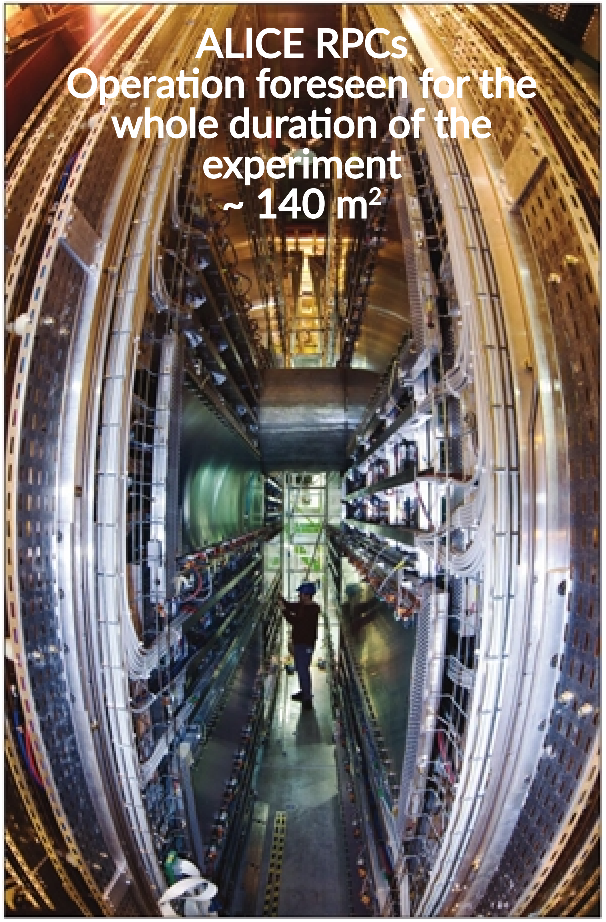
Luca Quaglia[1] on behalf of the RPC ECOgas@GIF++ collaboration

[1]INFN Torino

Overview

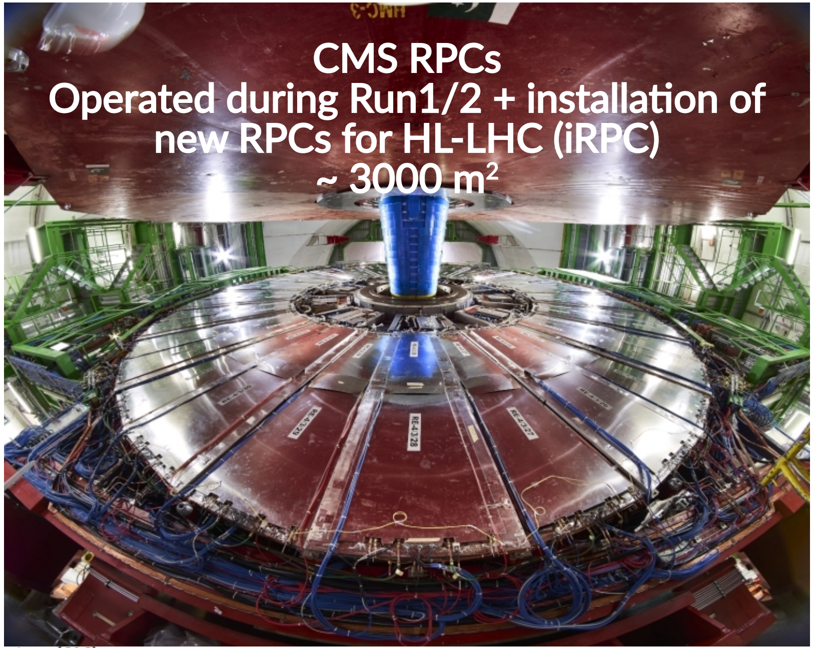
- Resistive Plate Chambers (RPCs) at the LHC
- Currently employed gas mixture and environmental issues
- RPC gas consumption @ LHC
- Two case studies
  - The ALICE MID gas re-circulation system
  - Alternative gas mixtures study: the RPC ECOgas@GIF++ collaboration
- Conclusions

RPCs at the LHC

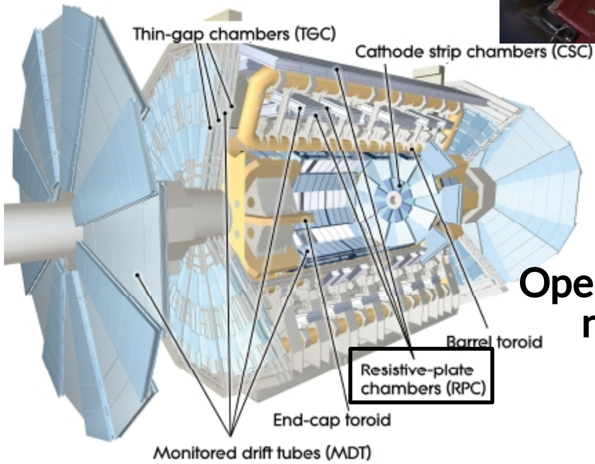


ALICE RPCs
Operation foreseen for the whole duration of the experiment
~ 140 m²

LHCb phase 2 upgrade – RPCs are a possibility



CMS RPCs
Operated during Run1/2 + installation of new RPCs for HL-LHC (iRPC)
~ 3000 m²



ATLAS RPCs
Operated during Run1/2 + installation of new RPCs for HL-LHC (BI project)
~ 4000 m²

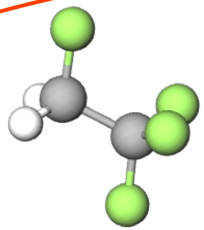
The currently employed gas mixture

- RPC working parameters depend on the gas mixture employed
- The currently-used gas mixtures at the LHC grant the following properties:

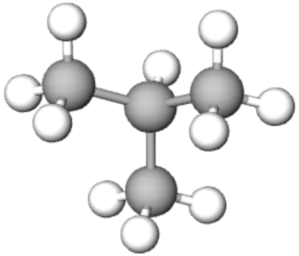
1) High density of primary ion-electron pairs

2) Relevant quenching properties
→ Ability of capturing recombination photons without further ionization

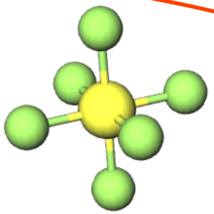
3) Enough electron affinity to capture free electrons, reducing the spatial size of the discharge



$C_2H_2F_4$ (R-134a): provides primary electrons



i-C_4H_{10} - isobutane: quenching gas

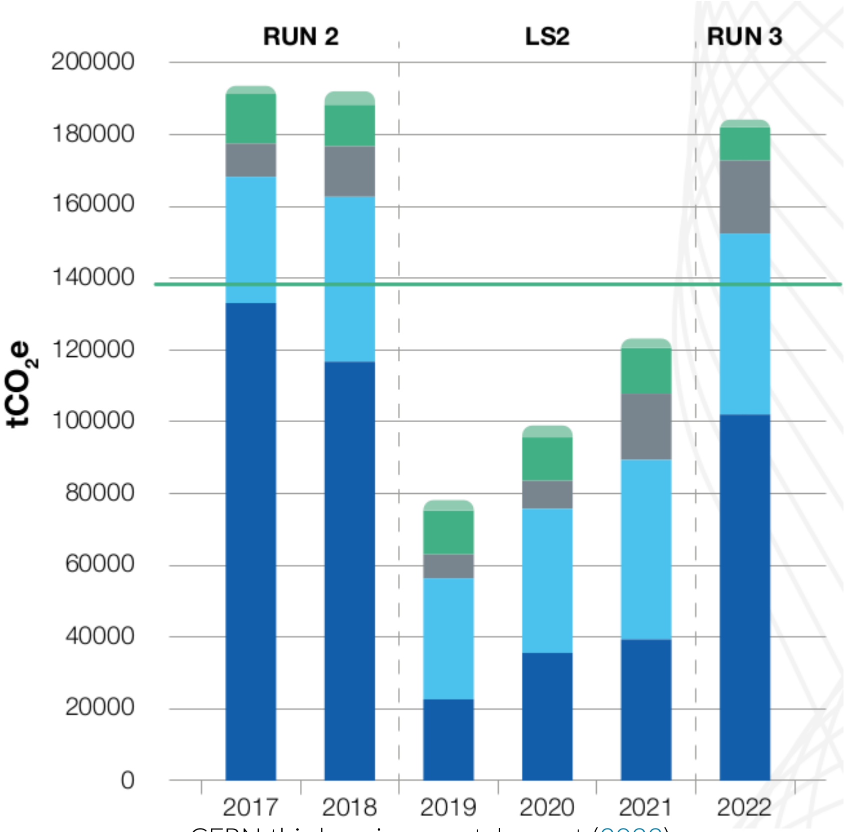


SF_6 – sulfur hexafluoride: electronegative gas

Currently employed gas mixtures consist of these gases in different proportions

Emissions @ CERN

- Scope 1 (direct) emissions of CERN from facilities and vehicles
  → Expressed in equivalent tonnes of CO_2
  → Highest fraction of emissions by particle detectors and cooling

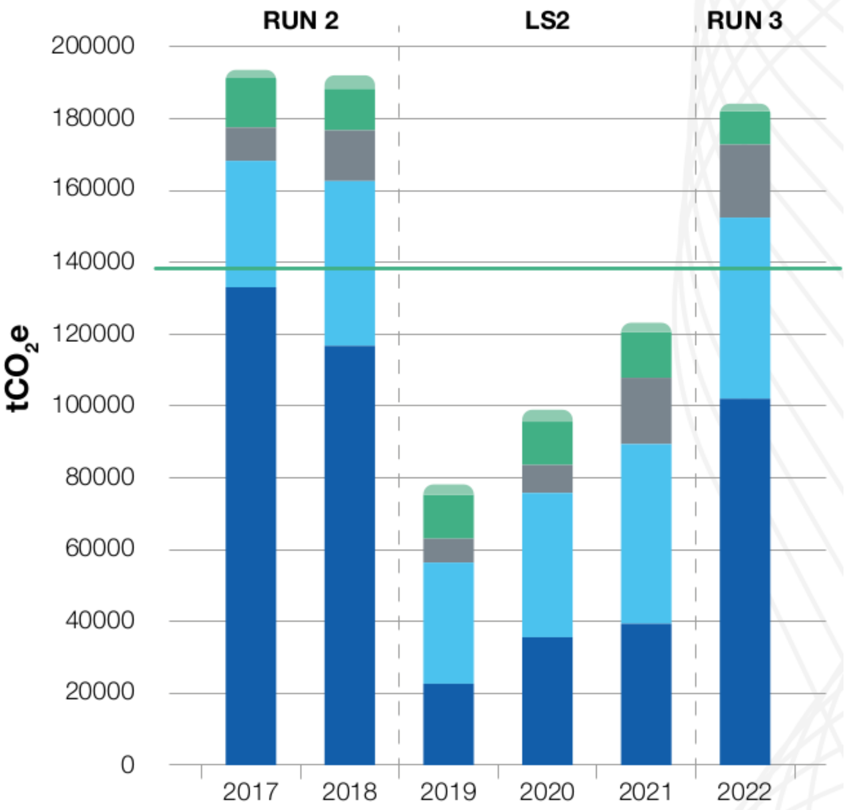


CERN third environmental report (2023)

By the end of LHC RUN3 (2025)
→ -28% of 2018

Emissions @ CERN

- Scope 1 (direct) emissions of CERN from facilities and vehicles
  → Expressed in equivalent tonnes of CO_2
  → Highest fraction of emissions by particle detectors and cooling



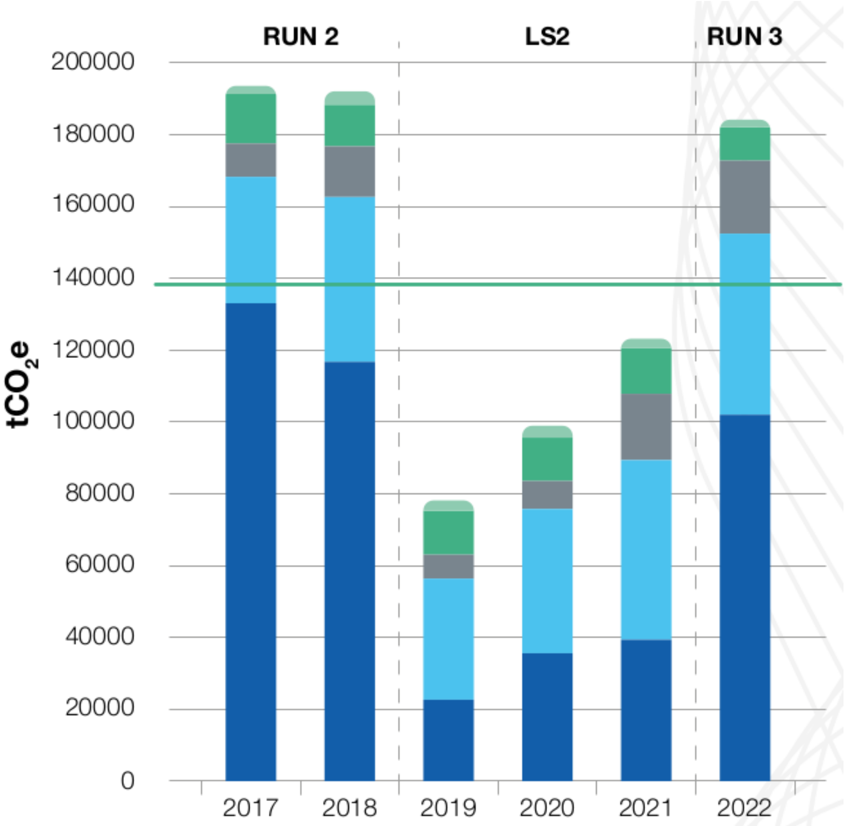
CERN third environmental report (2023)

GROUP	GASES	tCO_2e 2021	tCO_2e 2022
Perfluorocarbons (PFCs)	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	55 921	68 989
Hydrochlorofluorocarbons (HFCs)	HFC-23 (CHF_3) HFC-32 (CH_2F_2) HFC-134a ($C_2H_2F_4$) HFC-404a HFC-407c HFC-410a HFC-507	36 557	86 211
Other F-gases	SF_6, NF_3	16 838	18 355
Hydrofluoroolefins (HFO)/HFCs	R-449 R1234ze NOVEC 649	86	199
	CO_2	13 771	10 419
Total Scope 1		123 174	184 173

Equivalent CO_2 tonnes per gas in 2021 and 2022

Emissions @ CERN

- Scope 1 (direct) emissions of CERN from facilities and vehicles
  → Expressed in equivalent tonnes of CO_2
  → Highest fraction of emissions by particle detectors and cooling



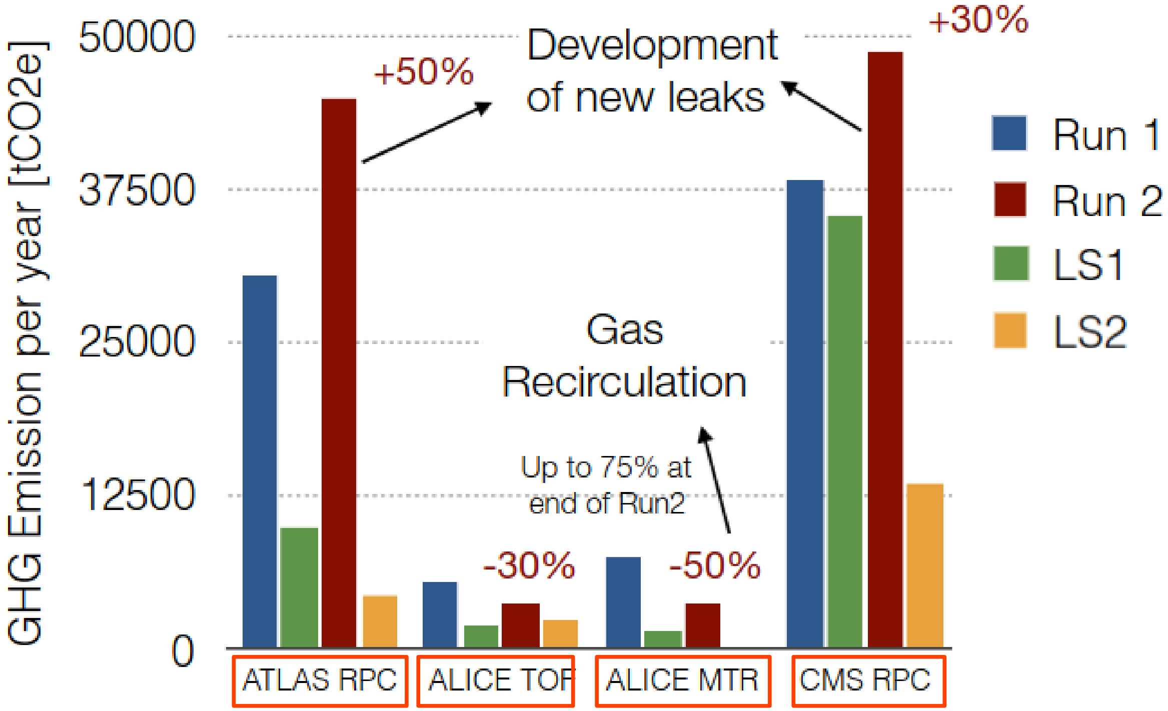
CERN third environmental report (2023)

GROUP	GASES	tCO_2e 2021	tCO_2e 2022
Perfluorocarbons (PFCs)	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	55 921	68 989
Hydrochlorofluorocarbons (HFCs)	HFC-23 (CHF_3) HFC-32 (CH_2F_2) HFC-134a ($C_2H_2F_4$) HFC-404a HFC-407c HFC-410a HFC-507	36 557	86 211
Other F-gases	SF_6, NF_3	16 838	18 355
Hydrofluoroolefins (HFO)/HFCs	R-449 R1234ze NOVEC 649	86	199
	CO_2	13 771	10 419
Total Scope 1		123 174	184 173

Equivalent CO_2 tonnes per gas in 2021 and 2022

Mainly due to RPC detectors

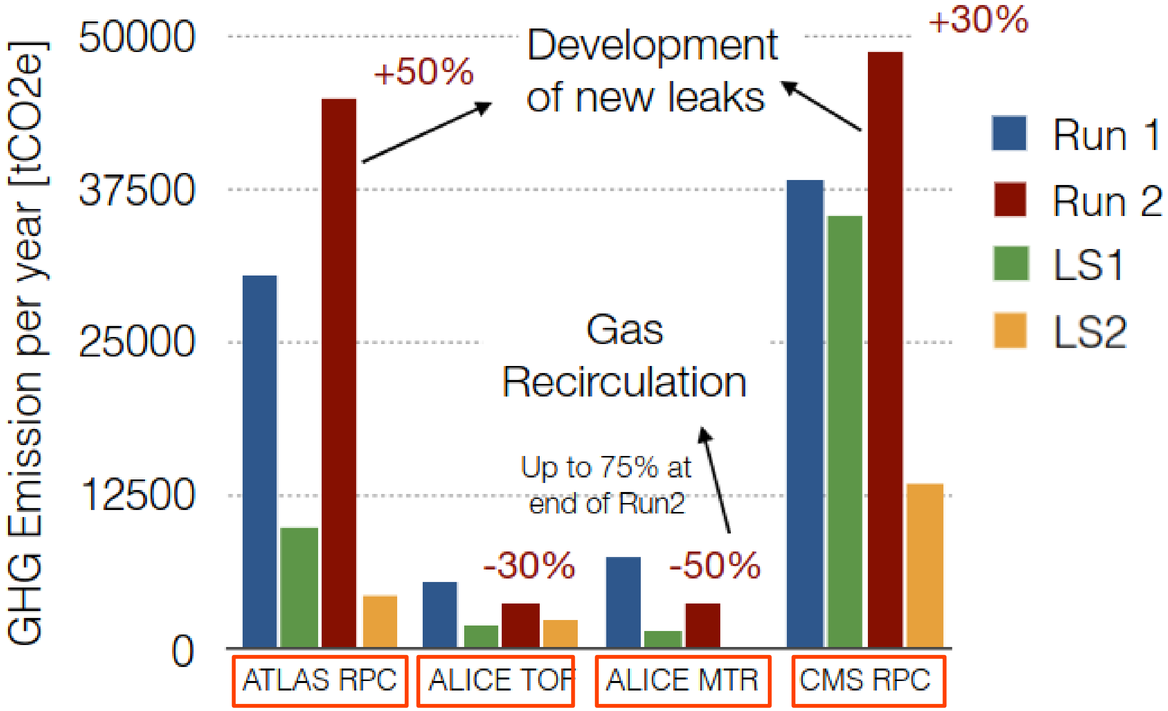
RPC gas emission @ LHC



GHG emission per year by all the LHC systems, original figure shown by Beatrice Mandelli at the ECFA Detector R&D Roadmap symposium

- Gas consumption due to RPCs @ LHC only
- RPC detectors represent the main consumers of GHG gases at CERN

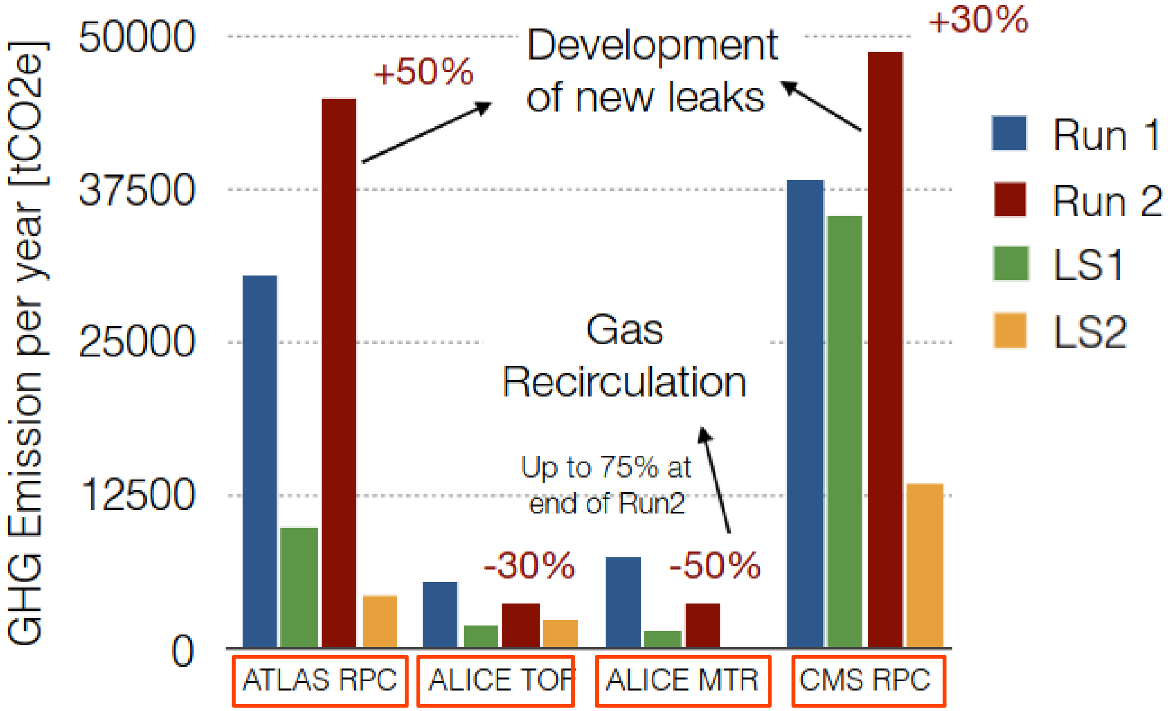
RPC gas emission @ LHC



GHG emission per year by all the LHC systems, original figure shown by Beatrice Mandelli at the ECFA Detector R&D Roadmap symposium

- Gas consumption due to RPCs @ LHC only
- RPC detectors represent the main consumers of GHG gases at CERN
- Emission increase from Run 1 and Run 2 in the ATLAS/CMS RPC systems are due to new leaks at the detector level

RPC gas emission @ LHC



GHG emission per year by all the LHC systems, original figure shown by Beatrice Mandelli at the ECFA Detector R&D Roadmap symposium

- Gas consumption due to RPCs @ LHC only
- RPC detectors represent the main consumers of GHG gases at CERN
- Emission increase from Run 1 and Run 2 in the ATLAS/CMS RPC systems are due to new leaks at the detector level
- Intensive leak repair campaign carried out during LS2 reduced the amount of leaks (here and here)
- First Run 3 consumption data still to be produced

The need for a new RPC gas mixture

- All currently employed RPC gas mixtures contain different fractions of R134a (> 90%) and SF_6 (< 1%)
  → **Fluorinated greenhouse gases** (F-gases)

- New EU regulations to reduce the impact of F-gases

  → Phase down of the production and consumption of F-gases
  → Ban of the gases if a more eco-friendly alternative is available
  → Reduction of emissions from existing equipment

Increase in cost and reduction in availability

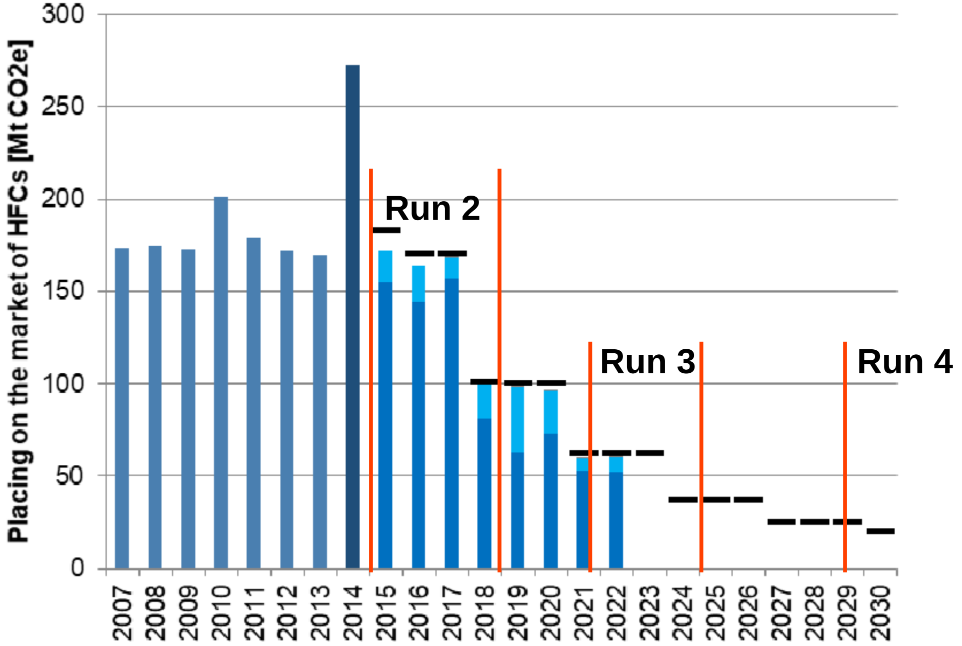
The need for a new RPC gas mixture

- All currently employed RPC gas mixtures contain different fractions of R134a (> 90%) and SF_6 (< 1%)
  → **Fluorinated greenhouse gases** (F-gases)

- New EU regulations to reduce the impact of F-gases

  → Phase down of the production and consumption of F-gases
  → Ban of the gases if a more eco-friendly alternative is available
  → Reduction of emissions from existing equipment

Increase in cost and reduction in availability



F-gases placing on the market (POM) plan obtained from ETC CM Report 2023/04

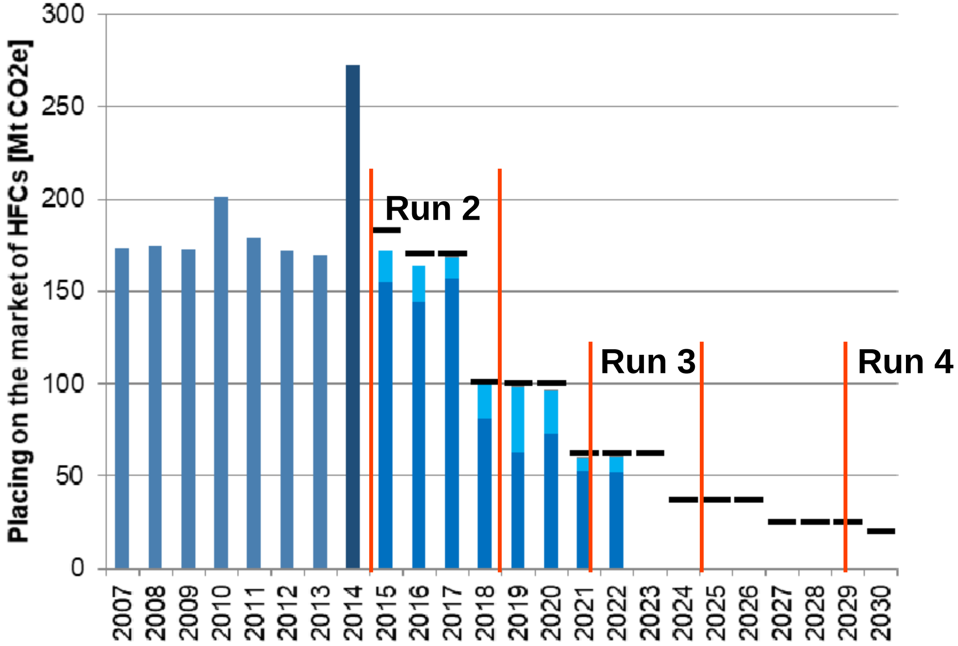
The need for a new RPC gas mixture

- All currently employed RPC gas mixtures contain different fractions of R134a (> 90%) and SF_6 (< 1%)
  → **Fluorinated greenhouse gases** (F-gases)

- New EU regulations to reduce the impact of F-gases

  → Phase down of the production and consumption of F-gases
  → Ban of the gases if a more eco-friendly alternative is available
  → Reduction of emissions from existing equipment

Increase in cost and reduction in availability



F-gases placing on the market (POM) plan obtained from ETC CM Report 2023/04

- Different ways to tackle the issue at CERN, two examples presented in this talk:
  1) Gas mixture re-circulation
  2) Search for alternative gas mixture

- For detailed description of other ways see Beatrice Mandelli's talk here

ALICE RPC re-circulation system

- Interesting example provided by the ALICE Resistive Plate Chambers (RPCs) muon trigger (MTR)/identifier (MID) re-circulation system

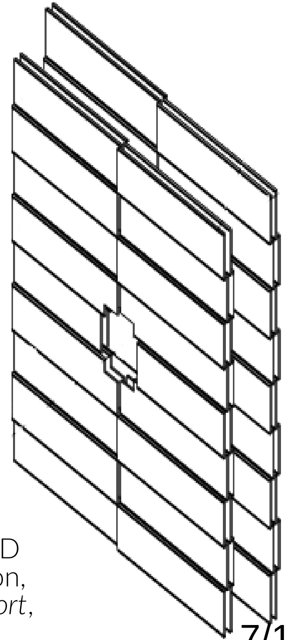
- 72 RPCs arranged in 4 detection planes, active area of ~35 m^2 each used to provide muon triggering (up to Run 2) and identification (from Run 3)

- Gas mixture composed by:
  89.7% $C_2H_2F_4$ (GWP ~ 1430) – **10% i-C_4H_{10}** (GWP ~ 3) - **0.3% SF_6** (GWP ~22800) → Total **GWP ~ 1440**

- Total gas volume of ~0.3 m^3 and gas flow of 0.5 vol/h

- During Run 1 the gas system was operated in open loop mode (no re-circulation)

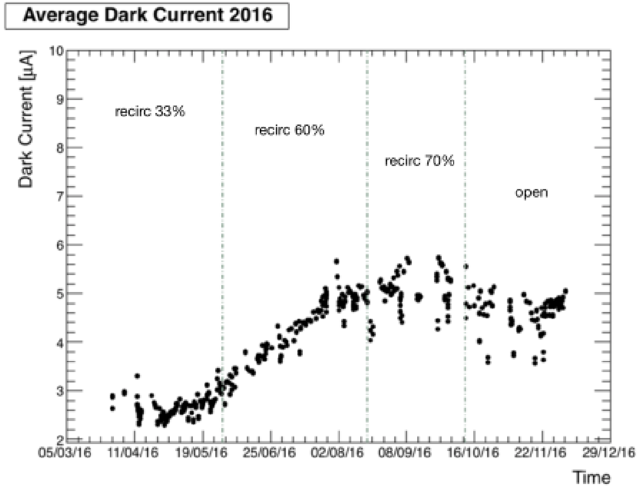
- Creation of pollutants in the gas when the RPCs are operated
  → Gas re-circulation requires the use of purifying materials
  → Dedicated feasibility study in 2016 and 2017

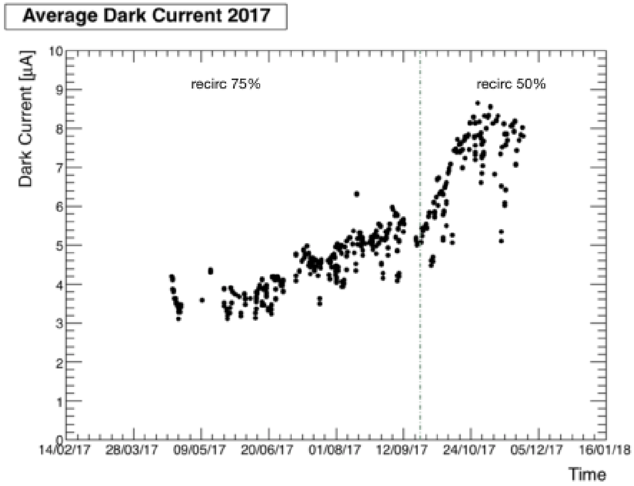


Schematic view of the MID RPCs – ALICE collaboration, *ALICE Technical Design Report*, (2008)

ALICE RPC re-circulation system

- Study of RPCs dark current (current with no beam, possibly linked to impurities in the gas) for different re-circulation fraction
- A small amount of fresh gas still has to be injected
- Total flow = fresh gas + re-circulated gas
- Re-circulation fraction = re-circulated gas/total flow



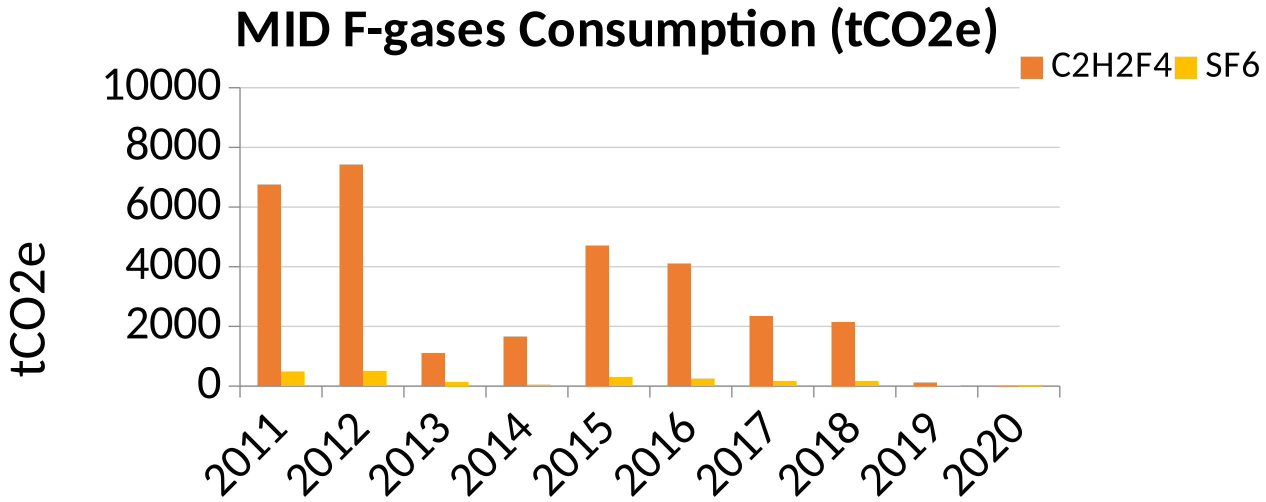


- Dark currents increase when RF from 33 % to 60 % then stable
- In 2017 a change in RF did not show improvement in the dark current
- Currently the re-circulation fraction is ~ 87%

Average dark current for different re-circulation fractions, B. Mandelli, RPC workshop 2018, Puerto Vallarta

ALICE RPC re-circulation system

- The introduction of re-circulation system lead to a great decrease in gas consumption, from LHC Run 2 onward

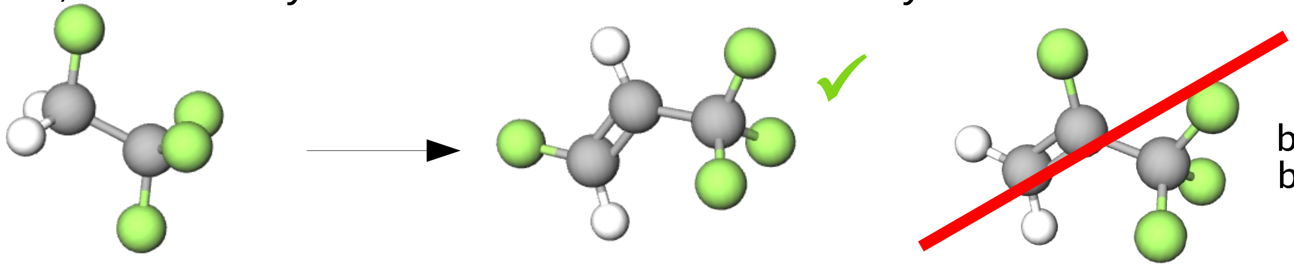


MID RPCs GHG consumption in equivalent tonnes of CO_2 – data provided by Beatrice Mandelli

- From Run 3
  → ALICE RPCs operated at lower voltage thanks to new front-end electronics
  → Less impurities produced and possibility to increase the re-circulation fraction even more
  → Under study

Search for alternative gas mixture

- First efforts of LHC RPC groups focused on R134a replacement
- **Industrial use:** from **R134a** to **hydro-fluoro-olefine** (HFO) family of gases
  → Similar chemical structure as R134a but lower Global Warming Potential
  → Among all HFOs, HFO-1234yf and HFO-1234ze are currently used



Not usable at LHC because reported to be mildly flammable

GWP ($C_2H_2F_4$) ~ 1430 GWP (HFO-1234ze) ~ 6 GWP (HFO-1234yf) ~ 4

- 1:1 replacement of R134a with HFO not possible
  → Lower effective first Townsend coefficient
  → Working voltage of the detectors moves to over 15 kV
- HFO has to be diluted with other gases
  → Studies with cosmic muons by different LHC RPC groups [1-4]
  → CO_2 found to be the most promising candidate for dilution
  → **In-depth studies on RPCs long-term behavior with eco-friendly alternatives needed**

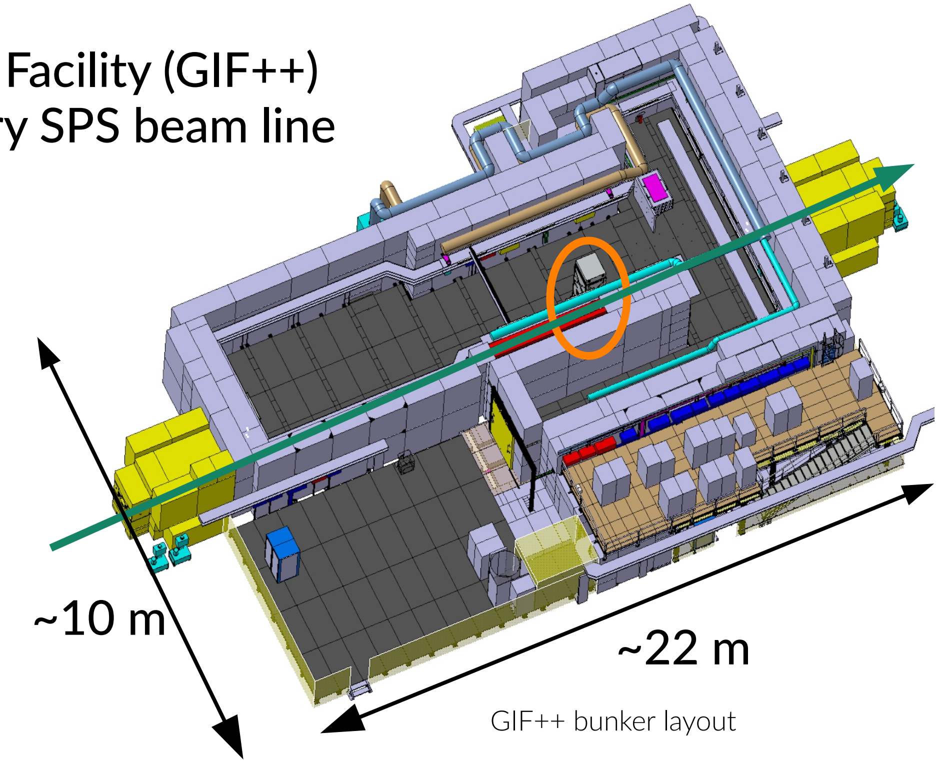
The RPC ECOGas@GIF++ collaboration

- Cross-experiment collaboration to join forces and perform aging/beam test studies with eco-friendly gas mixtures for RPCs
  → Includes CMS, ALICE, ATLAS, SHiP/LHCb and the detector technology group of CERN

- Studies carried out at the CERN Gamma Irradiation Facility (GIF++)
  → Experimental facility located on the H4 secondary SPS beam line

- **12.5 TBq ^{137}Cs source**, high activity allows one to simulate long operating periods in much shorter time spans (**<u>aging studies</u>**) – irradiation can be modulated by means of attenuation filters (absorption factors)

- **High energy** (~150 GeV/c) **muon beam** in dedicated **beam time periods**

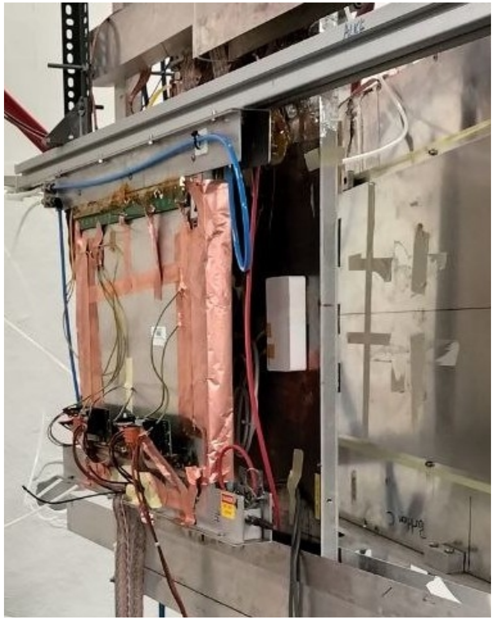


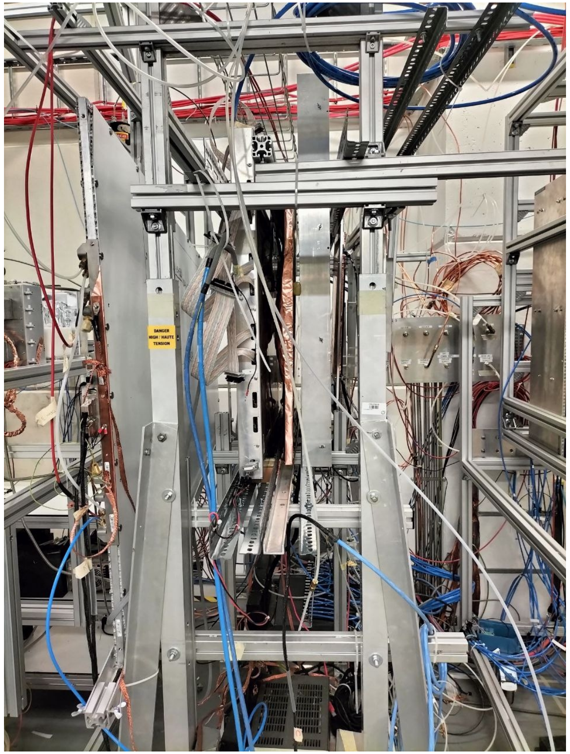
GIF++ bunker layout

Experimental setup

- Two mechanical frames installed inside the GIF++ bunker
  → At 3 and 6 m from the source
  → Different requirements of collaboration members
- Gas/HV/DAQ outside the GIF++ bunker

View of the setups inside the GIF++ bunker

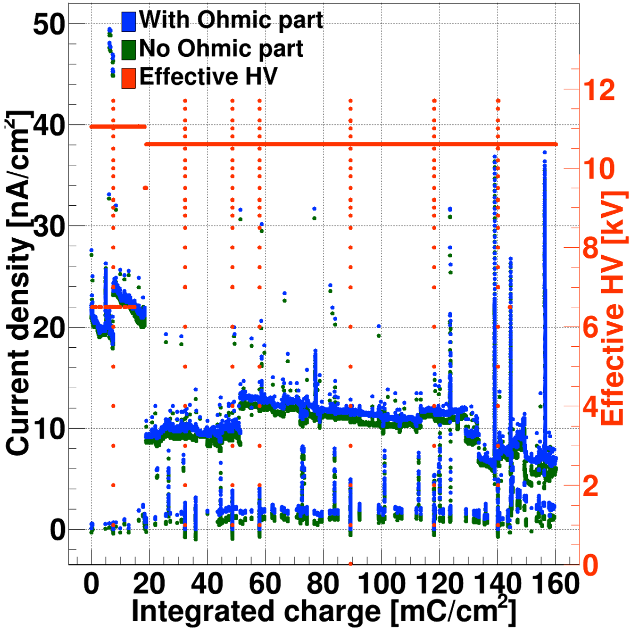

Details of the detectors at 6 m from the source


Details of the support at 3 m from the source

Activities of the collaboration

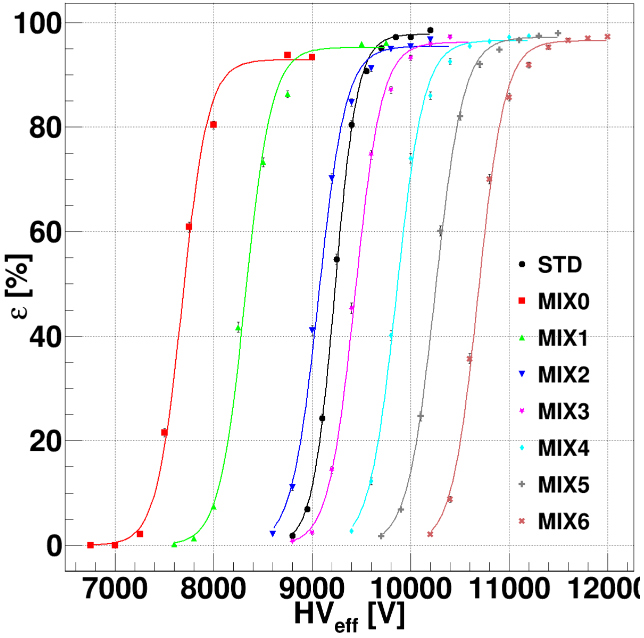
- **Multi-front approach to exploit both the GIF++ radioactive source and the μ beam**
  → For more details on the work you can check this paper and this pre-print, main activities summarized here
  → Efforts ongoing from late 2019

Aging studies

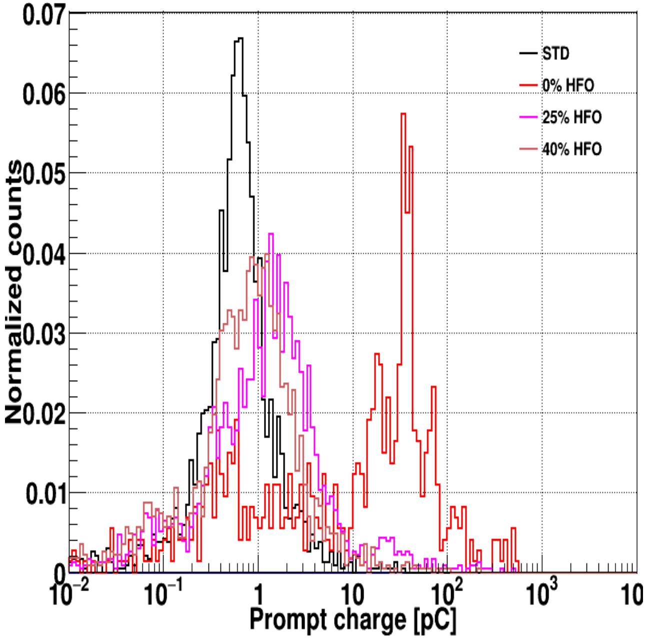


Stability of the absorbed current vs integrated charge for the ECO2 gas mixture (60% CO_2 35% HFO, 4% i-C_4H_{10} and 1% SF_6) period corresponds to roughly one year exposure to the gamma source

Beam tests



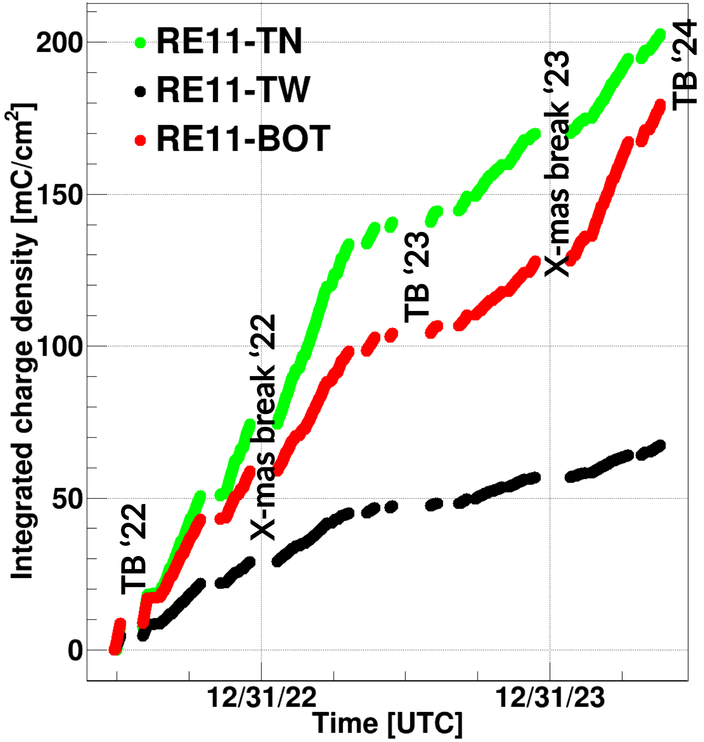
RPC response to the muon beam: efficiency vs high voltage for different ratios of CO_2/HFO. MIX0 contains 0% HFO while MIX6 contains 40%
Data taken without gamma background

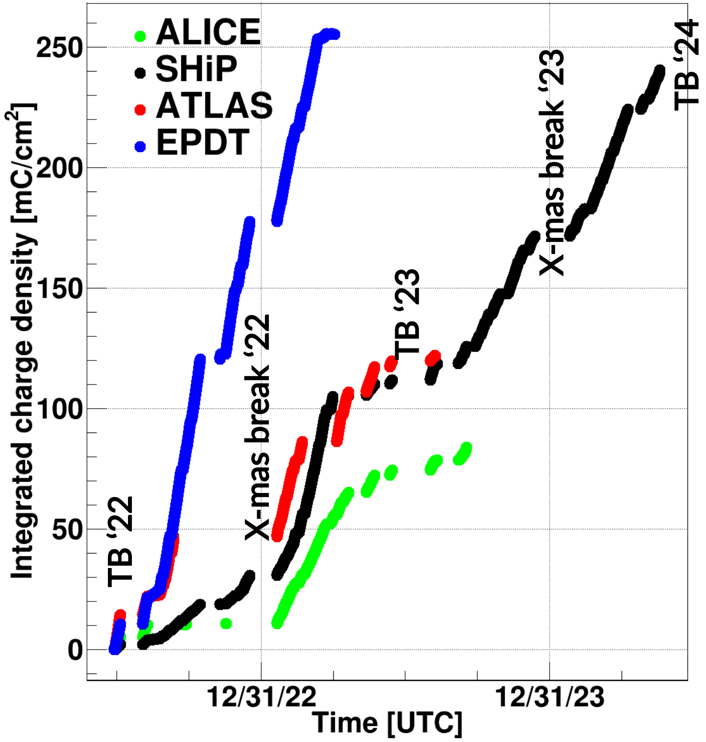


Prompt charge distribution for mixtures with different HFO concentrations. Increasing HFO concentration decreases the contamination from high charge content signals

Integrated charge progression

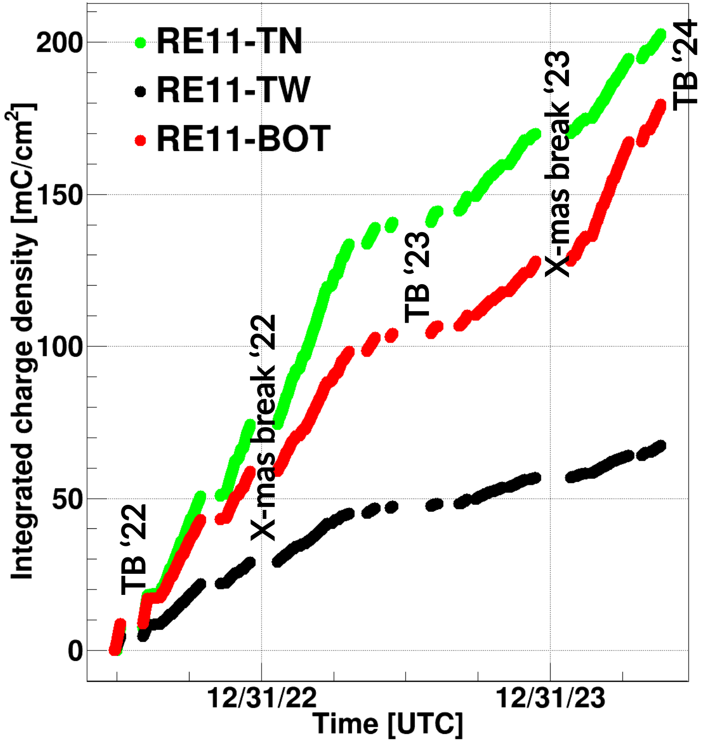
- μ beam test studies pinpointed one promising HFO mixture (35/60 HFO/CO_2)
- Long-term stability study ongoing since July 2022
  → reach HL-LHC integrated charge values

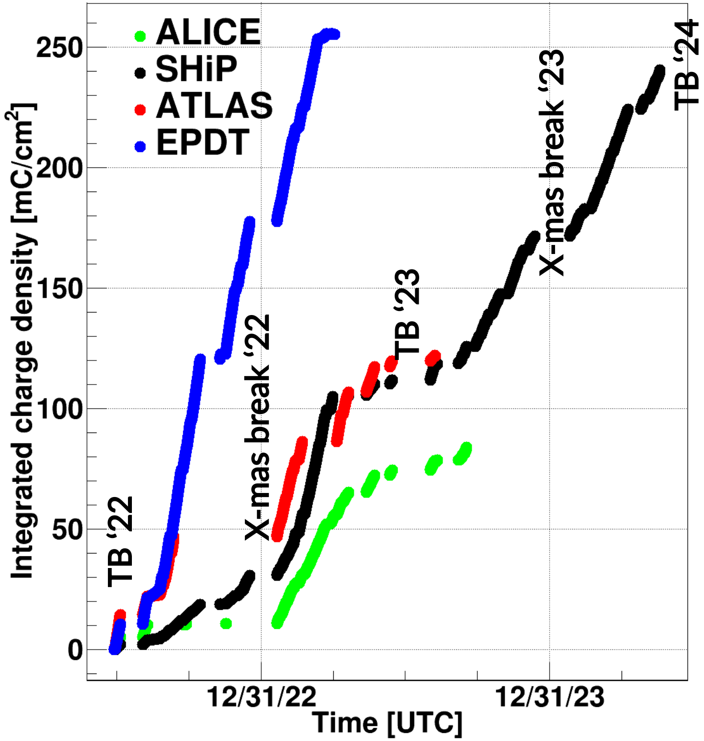




Integrated charge progression

- μ beam test studies pinpointed one promising HFO mixture (35/60 HFO/CO_2)
- Long-term stability study ongoing since July 2022
→ reach HL-LHC integrated charge values





HL-LHC projected Q_{int} 10-10^3 mC/cm² depending on the experiment

- Monitoring of RPC performance with the μ beam (**TB**) throughout the long-term irradiation study
→ Quite stable behavior of the RPCs observed

Conclusions

- RPC detectors are one of the main consumer of F-gases at CERN
  → Mainly due to unfixable leaks at the detector level
  → Intense leak repair campaign during LS2 reduced gas consumption
  → First Run 3 data still to be published

- EU phase down on F-gases consumption and placing on the market
  → Effort to reduce CERN consumption

- Implementation of gas re-circulation systems lowers consumption
  → Example of the ALICE muon RPCs from Run 1 to Run 2

- Search for alternative gas mixtures as most desirable long-term solution
  → RPC ECOgas@GIF++ collaboration studying $C_2H_2F_4$-free gas mixture
  → $C_2H_2F_4$ → HFO+CO_2 mixtures
  → RPC performance characterization with muon beam and long-term stability studies still ongoing

References

[1] A. Bianchi et al., *Characterization of tetrafluoropropene-based gas mixtures for the Resistive Plate Chambers of the ALICE muon spectrometer*, 2019, JINST 14 P11014, https://doi.org/10.1088/1748-0221/14/11/P11014

[2] B. Liberti et al., *Further gas mixtures with low environment impact*, 2016, JINST 11 C09012, https://doi.org/10.1088/1748-0221/11/09/C09012

[3] R. Guida et al., *Performance studies of RPC detectors with new environmentally friendly gas mixtures in presence of LHC-like radiation background*, Nuclear Inst. and Methods in Physics Research, A 958 (2020) 162073, https://doi.org/10.1016/j.nima.2019.04.027

[4] R . Albanese et al., *RPC-based Muon Identification System for the neutrino detector of the SHiP experiment*, 2023, JINST 18 P02022, https://doi.org/10.1088/1748-0221/18/02/P02022

[5] Young, C. J. et al., *Atmospheric Perfluorinated Acid Precursors: Chemistry, Occurrence, and Impacts*, Rev. Environ. Contam. T., 208, 1–109, (2010) https://pubmed.ncbi.nlm.nih.gov/20811862/

[6] George, C. at al., *Kinetics of mass transfer of carbonyl fluoride, trifluoroacetyl fluoride, and trifluoroacetyl chloride at the air/water interface*, J. Phys. Chem., 98, 10857–10862, https://doi.org/10.1021/j100093a029, (1994), https://pubs.acs.org/doi/10.1021/j100093a029

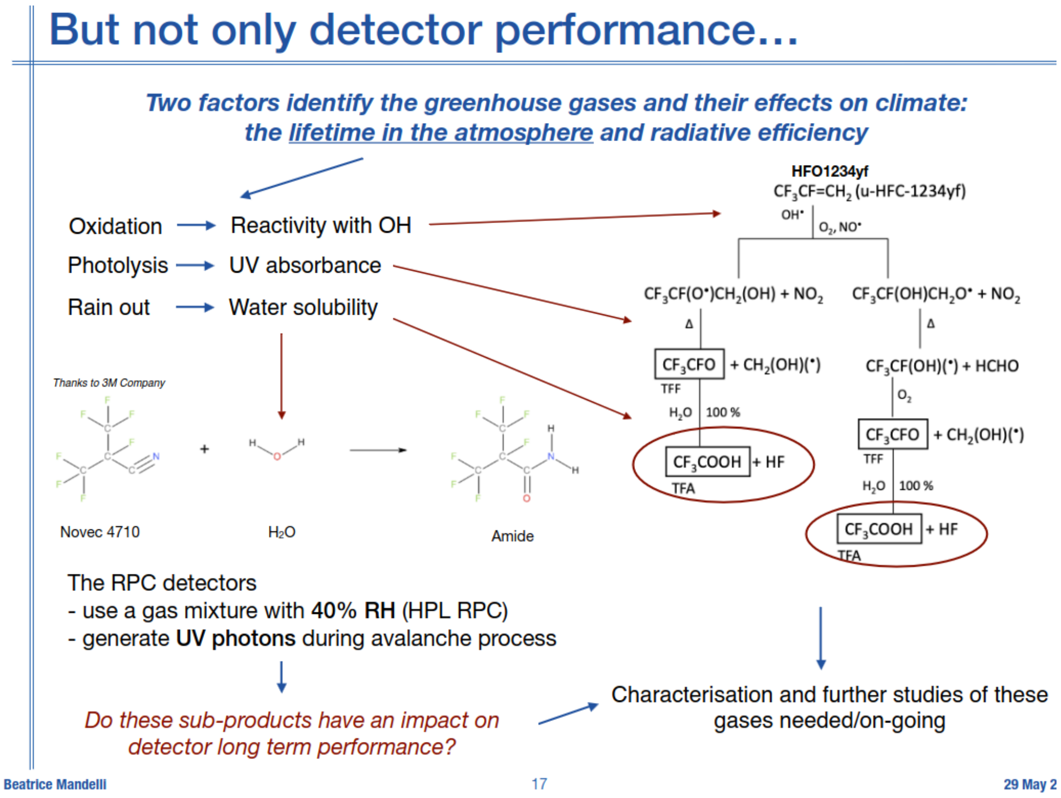
[7] L. M. David et al., *Trifluoroacetic acid deposition from emissions of HFO-1234yf in India, China, and the Middle East* Atmos. Chem. Phys., 21, 14833–14849, 2021, https://doi.org/10.5194/acp-21-14833-2021

Thank you for your attention!

Backup

On the HFO ecology - 1

B. Mandelli
https://indico.cern.ch/event/1263322/



- HFO dissociation in atmosphere might leas to the creation of TFA (toxic chemical for humans)
- Deposition on land following rain fall and consequent exposure to humans
- Studies on the matter (such as those reported in [1-3]) are not yet conclusive
- Research work on this direction is ongoing and we are studying these gases since for now they are not deemed as pollutants

On the HFO ecology - 2

B. Mandelli
https://indico.cern.ch/event/1263322/

- PFAs: Per- and polyfluoroalkalyl substances:

  - Group of synthetic substances consisting of carbon chain + fluorine

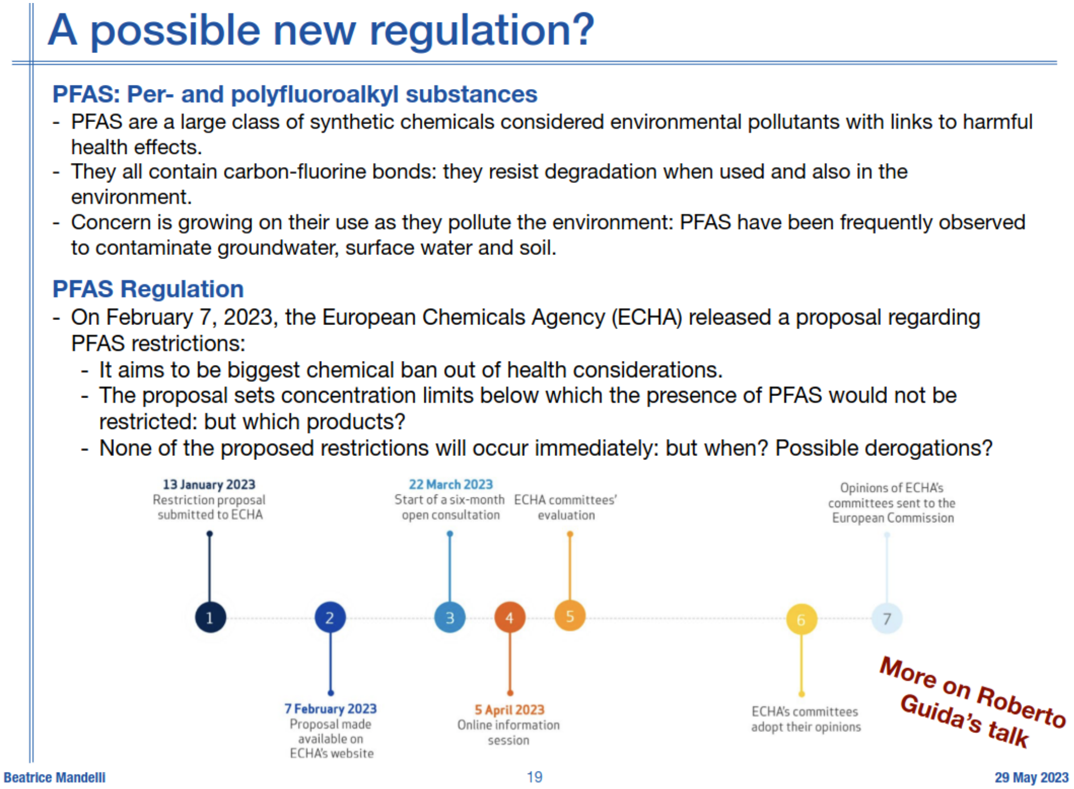
  - Widely used in the industry and can leak into water/air/soil

  - Prolonged exposure harmful for humans

  - More than 15k PFAs identified

- Possible new regulations to ban PFAs

  - Not yet clear if HFO will be included + not clear if the ban will be immediate or if derogations are foreseen



A possible new regulation?

PFAS: Per- and polyfluoroalkyl substances
- PFAS are a large class of synthetic chemicals considered environmental pollutants with links to harmful health effects.
- They all contain carbon-fluorine bonds: they resist degradation when used and also in the environment.
- Concern is growing on their use as they pollute the environment: PFAS have been frequently observed to contaminate groundwater, surface water and soil.

PFAS Regulation
- On February 7, 2023, the European Chemicals Agency (ECHA) released a proposal regarding PFAS restrictions:
  - It aims to be biggest chemical ban out of health considerations.
  - The proposal sets concentration limits below which the presence of PFAS would not be restricted: but which products?
  - None of the proposed restrictions will occur immediately: but when? Possible derogations?

Beatrice Mandelli 19 29 May 2023