Strategies for reducing the use of greenhouse gases from particle detectors operation at the CERN LHC experiments

Beatrice Mandelli\textsuperscript{1}, M. Corbetta\textsuperscript{2}, R. Guida\textsuperscript{1}, G. Rigoletti\textsuperscript{2}

\textsuperscript{1}CERN
\textsuperscript{2}Université de Lyon
CERN commitment to reduce GHG emissions

Greenhouse gas emissions at CERN arise from the operation of the Laboratory’s research facilities. With climate change a growing concern, the Organization is committed to reducing its direct greenhouse gas emissions.

- 192,000 tCO₂eq in 2018
- 92% of emissions related to large LHC experiments
- Most emissions from particle detection

GHGs for particle detection at LHC: Run 2

**GHGs are used in CERN experiments mainly due to their properties necessary for good detector operation**

Leaks in detectors (ATLAS and CMS)

Permeation to Air (CMS)

Upgrade to gas recirculation (LHCb)

Leaks are concentrated in the gas inlets, polycarbonate gas connectors and Polyethylene pipes

Big leak search campaign on-going in LS2: fundamental to have access to chambers for repairing

All gas systems already recirculate gas!
EU HFC phase-down policy

**European Union “F-gas regulation”:**

- **Limiting the total amount** of the most important F-gases that can be sold in the EU from 2015 onwards and phasing them down in steps to one-fifth of 2014 sales in 2030.
- **Banning the use** of F-gases in many new types of equipment where less harmful alternatives are widely available.
- **Preventing emissions** of F-gases from existing equipment by requiring checks, proper servicing and recovery of the gases at the end of the equipment’s life.

**Average purchase prices of the most commonly used HFC refrigerants**

- Increase due to EU HFC phase-down/reduced availability
- Decrease due to industrial conversion to new low GWP gases

*Prices could increase in EU and availability in the future is not known. Reduction of the use of F-gases is fundamental for future particle detector applications*
CERN strategies for GHG reduction

CERN Strategies to reduce GHG emissions in particle detection

Optimization of current technologies
- Gas Recirculation
  - Particular attention to operation
  - Improved control and monitoring

Gas Recuperation
- Pressure swing
- Membrane separation
- Cryogenic/cold separation

Alternative Gases
- To $\text{C}_2\text{H}_2\text{F}_4$
- To $\text{SF}_6$
- To $\text{CF}_4$

Gas Disposal
- GHG destruction
  - Discarded

Short-term
Long-term
CERN strategies for GHG reduction

CERN Strategies to reduce GHG emissions

Optimization of current technologies

- Gas Recirculation
  - Pressure swing
  - Membrane separation
  - Cryogenic/cold separation

- Particular attention to operation

- Improved control and monitoring

Gas Disposal
- GHG destruction
  - To $\text{C}_2\text{H}_2\text{F}_4$
  - To $\text{SF}_6$
  - To $\text{CF}_4$
Gas recirculation

**Thanks to gas recirculation GHG emission already reduced by > 90% wrt to open mode systems!!!**

**Advantages**
- Reduction of gas consumption

**Disadvantages**
- Complexity in operation
  - Pressure and flow fluctuations, etc.
- Creation of impurities
  - Especially when F-gases present
  - Accumulation in the gas mixture, concentration depends on luminosity and recirculation fraction
  - They could affect long-term detector operation
- Gas purifying techniques
  - Needed to absorb impurities

Example of studies performed for ALICE MTR in LHC Run 2

More info for F- production in gaseous detectors in poster: [https://indico.cern.ch/event/981823/contributions/4295490/](https://indico.cern.ch/event/981823/contributions/4295490/)
**Minimization of flow/pressure fluctuations**

**Goal: to minimize the hydrostatic pressure on the detectors**
- The RPC gas mixture has a high hydrostatic pressure: ~0.3 mbar/m
- The gas distribution racks are located in the cavern on different levels
  - The addition of new distribution racks will allow a better pressure equalisation between the chambers

**Goal: to minimize any chamber pressure/flow fluctuations from some 0.1 to ~ 0.1 mbar**
- New automated regulation valves on the return of each distribution rack to minimize any pressure changes
  - To decrease the risk of developing new leaks at the detector level
- Installation of reference volumes
  - To have a good reference for the regulation of the detectors pressure
CERN Strategies to reduce GHG emissions

- Optimization of current technologies
  - Gas Recirculation
    - Pressure swing
    - Membrane separation
    - Cryogenic/cold separation
  - Particular attention to operation
  - Improved control and monitoring

- Alternative Gases
  - To C$_2$H$_2$F$_4$
  - To SF$_6$
  - To CF$_4$

- Gas Disposal
  - GHG destruction
Gas Recuperation systems at LHC experiments

- Sometimes it is not possible to recirculate 100% of the gas mixture and a fraction cannot be re-used and therefore it would have been sent to atmosphere
  - Detector permeability, detector requirements (max recirculation fraction tested), impurities, etc.
  - To keep lower $N_2$ concentration
- This fraction of gas mixture is sent to a recuperation plant where the most valuable component is extracted, stored and re-used
  - Often challenging to extract a single component
  - The quality of recuperated gas is fundamental

Many LHC gas systems with gas recuperation

Advantages:
- further reduction of gas consumption

Disadvantages:
- higher level of complexity
- dedicated R&D
- gas mixture monitoring
Gas recuperation: CMS CSC CF$_4$

CSC Gas System
- Detector volume ~90 m$^3$
- Gas mixture: 50% CO$_2$, 40% Ar, 10% CF$_4$
- Gas recirculation: 90%
  - No possible to increase due to detector permeability to Air
  - ~600 l/h at exhaust -> 60 l/h of CF$_4$

CSC Recuperation System
- Recuperation of CF$_4$ with warm separation
  - 3 phases needed
  - Current recuperation efficiency ~65%
    - Several parameters affect recuperation efficiency
  - CF$_4$ quality satisfactory
    - Recuperated CF$_4$ quality to monitor
  - CSC detectors operated with recuperated CF$_4$ during Run 2
    - No change in the CSC performance observed

GHG reduction from Run1 to Run2 up to 45%
Gas Recuperation: \( \text{C}_2\text{H}_2\text{F}_4 \) for RPC detectors

New \( \text{C}_2\text{H}_2\text{F}_4 \) recuperation prototype under study/test since 2019

**Phase 1**
- Removal of \( \text{N}_2/\text{SF}_6 \) by simple distillation
- Gas mixture in buffer 1 cools down at -35 °C
- \( \text{N}_2/\text{SF}_6 \) in vapour phase

**Phase 2**
- Detachment of R134a from iC\(_4\)H\(_{10}\)
  - Liquid heats up and vapour is made of azeotrope
  - Vapours go back in buffer 1
  - Liquid R134a go in buffer 2

**Phase 3**
- Compression of R134a
- Vapour is compressed in liquid storage

Recuperation efficiency ~80%

Recuperated R134a is liquified again to separate from previous phase
- Gas mixture in buffer 1 cools down at -35 °C
- \( \text{N}_2/\text{SF}_6 \) in vapour phase

Remaining vapours (-35 °C): \( \text{N}_2, \text{SF}_6, \text{iC}_4\text{H}_{10} \) and R134a losses
- To GC for analysis

\( \text{C}_2\text{H}_2\text{F}_4 \) recuperation prototype under study/test since 2019

25 May 2021
CERN strategies for GHG reduction

CERN Strategies to reduce GHG emissions in particle detection

- Optimization of current technologies
  - Gas Recirculation
    - Particular attention to operation
    - Improved control and monitoring
  - Improved control and monitoring

- Gas Recuperation
  - Pressure swing
  - Membrane separation
  - Cryogenic/cold separation

- Alternative Gases
  - To C$_2$H$_2$F$_4$
  - To SF$_6$
  - To CF$_4$

- Gas Disposal
  - GHG destruction
Possible alternatives to $\text{C}_2\text{H}_2\text{F}_4$ and $\text{SF}_6$

New eco-friendly liquids/gases have been developed for industry as refrigerants and HV insulating medium… not straightforward for RPC operation

R134a  
$\text{(C}_2\text{H}_2\text{F}_4)$  
GWP 1430

HFO-1234yf  
$\text{(C}_3\text{H}_2\text{F}_4)$  
GWP 4

HFO-1234ze  
$\text{(C}_3\text{H}_2\text{F}_4)$  
GWP 6

$\text{SF}_6$  
GWP 23900

$\text{3M}^{\text{TM}}$ Novec$^{\text{TM}}$ 5110  
$\text{GWP} <1$

$\text{3M}^{\text{TM}}$ Novec$^{\text{TM}}$ 4710  
$\text{GWP} 2100$

+ others

The goal is to find an eco-friendly gas mixture that is compatible with the current ATLAS and CMS RPC systems (i.e. no change in HV cables, FEB electronics, gas system, etc.)
HFO-based gas mixtures

HFO cannot directly replace \( \text{C}_2\text{H}_2\text{F}_4 \)
- Higher applied voltage necessary (>12kV)
  - One C more with a double bond

Addition of He or \( \text{CO}_2 \) to lower the HV working point

- Helium helps in reducing the HV working point
  - +10% He \( \rightarrow \) 1 kV
  - in first approximation it doesn’t take part in the avalanche processes
- \( \text{CO}_2 \) helps in reducing the HV working point
  - + 10% \( \text{CO}_2 \) \( \rightarrow \) 0.8 kV
  - \( \text{CO}_2 \) is used as quencher gas in gaseous detectors but it has different quenching properties wrt \( \text{iC}_4\text{H}_{10} \) (different absorption coefficient)
- With both He and \( \text{CO}_2 \) in HFO-based gas mixture: higher streamer probability
  - Also higher charges
  - Necessary to increase \( \text{SF}_6 \) concentration
  - Keep a small fraction of \( \text{C}_2\text{H}_2\text{F}_4 \) helps in reducing the signal charge

\[ \text{GWP} \approx 400-500 \]
Long-term studies with HFO gas mixtures

Performance studies of several eco-friendly gas mixtures for RPCs operated at different background conditions

- GIF++: 12.2 TBq $^{137}$Cs + H4 SPS beam line
- Long-term studies (aging-test)
  - Fundamental for the validation of new eco-friendly gas mixtures. Accumulation of high integrated charge
- Studies on detector performance
  - In presence of LHC and HL-LHC like background radiation
- Studies on creation of impurities
  - HFO breaks easier than C$_2$H$_2$F$_4$ during detector operation

![Graph showing performance studies]

- Standard gas mixture
- HFO + 40% CO$_2$
- HFO + 50% CO$_2$

- ~ 40 kHz/cm$^2$
- +600 V
- +1400 V
- x2
- x4 F$^-$ production
Possible SF₆ replacements

SF₆ has a very high GWP and it contributes for ~5% in the GWP of RPC gas mixture

3M™ Novec™ Dielectric fluids

- Very good alternative to SF₆ for arc quenching and insulation applications
  - Developed few years ago
  - Dielectric breakdown strength approximately 1.4-2 times that of SF₆
  - Especially used in HV industrial plants

- Novec 4710 (GWP 2100)
  - Very good performance but...
  - It may react with water

- Novec 5110 (GWP <1)
  - Very low GWP but..
  - RPC performance not optimal
  - Sensitive to UV radiation

Other alternatives

- Looks for other gases not used only for HV plants
  - Other electronegative gases could work

- CF₃I (GWP 0.4)
  - Good performance but...
    - Toxic, mutagenic, ODP 0.008

- C₄F₈O (GWP ~8000)
  - Good performance at 1.5%
  - 1.5% C₄F₈O GWP equivalent to 0.5% SF₆
Conclusions

*With climate change a growing concern, CERN is committed to reducing its direct greenhouse gas emissions*

**Optimization of current technologies**
- Gas recirculation systems are the best way to reduce GHG consumption
- Nowadays upgrades of gas systems beyond original design

**Gas recuperation plants**
- Used when not possible to recirculate 100% of the gas
- Very complex and different technologies depending on the GHG to recuperate

**Alternative gases**
- A lot of work especially in RPC community to search for alternatives to $\text{C}_2\text{H}_2\text{F}_4$
- Not an easy task to find new eco-friendly gas mixture for current detectors

**GHG Disposal**
- Very last alternative: only if previous strategies will not work
Back-up slides
Why it is so difficult to find alternatives

Several key factors to take into account

- **Environment** —> GWP
  - Related to IR absorbance over time
- **Performance** —> Atmospheric lifetime
  - Water solubility —> Rain out
  - OH reactivity —> Oxidation
  - UV absorbance —> Photolysis
- **Safety**
  - Non toxic
  - Non flammable (depending on detector/experiment)

C₂H₂F₄ and SF₆ have good performance also because of their stability in atmosphere

Example for Novec gases

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

Abatement plants are employed when GHGs are polluted and therefore are not reusable

In case all studies on recuperation will not bring to efficient recuperation plants, industrial system able to destroy GHGs avoiding their emission into the atmosphere have been considered.

Quite heavy infrastructure required:
- CH₄/city gas + O₂ supply + N₂ supply
- Waste water treatment
- PFC/HFC are converted in CO₂ + HF acid dissolved in water
- disposal of remaining waste/mud
- To have the gas at the exhaust (600-1000 l/h)

Joint CMS and EP-DT gas team is studying the feasibility

Found also companies available to take PFC/HFC based mixture for disposal: but extremely expensive
The gas systems are complex apparatus that extend over several hundred meters and have to ensure an extremely high reliability in terms of stability and quality of the gas mixture delivered to the detectors.

At LHC Experiments we have 30 gas systems for a total of ~300 modules interconnected with ~90 km of pipes and controlled/monitored with PLCs and > 1000 sensors.

**Reliability**
- LHC experiments are operational 24/24 7/7
- Gas systems must be available all time

**Automation**
- Large and complex infrastructure
- Resources for operation
- Repeatability of conditions

**Stability**
- Detector performance are strictly related with stable conditions (mixture composition, pressures, flows, ...)
Optimization of distribution systems: ATLAS RPC

Goal: to minimize the hydrostatic pressure on the detectors
- The RPC gas mixture has a high hydrostatic pressure: \(~0.3\) mbar/m
- The gas distribution racks are located in the cavern on different levels
- The addition of 4 new distribution racks will allow a better pressure equalisation between the chambers (total 9 racks)

Goal: to minimize any chamber pressure/flow fluctuation from some 0.1 to \(~0.1\) mbar

Addition of regulation valves: to better regulate and smooth the input pressure going to the flow distribution
Reference chamber: to have a good reference for the regulation of the detectors pressure
Gas impedance: to smooth pressure and flow fluctuations at the output of distribution system, i.e. pressure and flow seen by the detectors
Optimization of distribution systems: CMS RPC

**Goal: to try to minimise as much as possible any fluctuation of pressure and flow at the detector level**

- New automated regulation valves on the return of each distribution rack to minimize any pressure changes
- To decrease the risk of developing new leaks at the detector level
- 30 distribution racks for Barrel and Endcap divided into top and bottom
  - Different valve seats depending on pressure, flow, etc.
- Installation of 30 reference volumes
  - To have a good reference for the regulation of the detectors pressure
Gas recuperation: LHCb RICH2 CF$_4$

RICH2 Gas System
- Detector volume ~100 m$^3$
- Gas mixture: 92% CF$_4$, 8% CO$_2$
- Gas recirculation: ~100%
  - Small quantity lost in leaks or for gas system operation

RICH2 Recuperation System
- Two recuperation modes (warm separation)
  - During long shutdown: emptying detector
  - During Run: recuperation of small quantities otherwise lost in gas modules
- New system implemented in LS2
  - Upgrades on-going

Performance
- Recuperation efficiency ~60%
- About 30 m$^3$ of CF$_4$ recuperated in LS2
- CF$_4$ quality satisfactory
- CF$_4$ recuperated will be re-used for Run 3 operation

GHG reduction from Run1 to Run2 up to 60%
Gas Recuperation: azeotrope $\text{C}_2\text{H}_2\text{F}_4/\text{iC}_4\text{H}_{10}$

ATLAS and CMS RPC Gas Systems
- Detector volume ~15 m$^3$
- Gas mixture: ~95% $\text{C}_2\text{H}_2\text{F}_4$, ~5% $\text{iC}_4\text{H}_{10}$, 0.3% $\text{SF}_6$
- Gas recirculation: ~90%
  - maximum recirculation validated for RPC detectors
  - Fundamental to repair detector leaks
  - To have the gas at the exhaust (600-1000 l/h)

RPC Recuperation System
- Not convenient to recuperate the gas mixture
- Cold separation for R134a
  - Thermodynamic phase transitions
  - R134a and $\text{iC}_4\text{H}_{10}$ form an azeotrope
    - A mixture of liquids whose proportions cannot be altered or changed by simple distillation
    - Intramolecular force of same-species is much higher than the reciprocal attraction
    - Separation by quasi-static increase of temperature

\[ \text{Slow heating of the liquified azeotrope allows to enrich the liquid of R134a and the vapour of iC}_4\text{H}_{10}, \text{ obtaining the separation} \]