

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

Beatrice Mandelli, Mara Corbetta, Roberto Guida, Gianluca Rigoletti

CERN, Espl. des Particules 1, Meyrin, Switzerland

E-mail: beatrice.mandelli@cern.ch

Abstract. A wide range of gas mixtures is used for the operation of the gaseous detectors at the CERN LHC experiments. Some gases, as $C_2H_2F_4$, CF_4 , C_4F_{10} and SF_6 , are greenhouse gases (GHG) with high global warming potential and therefore subject to a phase down policy.

The reduction of GHG emissions is of paramount importance for CERN, which has identified four different strategies. The first strategy is based on the optimization of the gas mixture recirculation plants already in use. The second approach is the recuperation of used gas mixtures followed by separation of the GHG for its re-use. Several R&D are ongoing to evaluate this possibility and prepare the design of final systems. A third approach is making use of industrially available solutions for disposal of GHGs. Finally, the search of new eco-friendly gases is object of many R&D programs by the detector communities.

The four strategies will be compared by considering investment required, return benefit and technological readiness.

1. Introduction

At CERN greenhouse gases (GHGs) emissions arise from the operation of the Laboratory's research facility. Most of the emissions are related to the activities of the LHC experiments and are due to the use of fluorinated gases in particle detection [1]. Given the concerns on climate changing, CERN is committed in reducing as much as possible the GHG emissions.

GHGs are employed in LHC experiment for particle detection because of their specific properties necessary for good detector operation. In particular $C_2H_2F_4$ and SF_6 are used for the Resistive Plate Chambers (RPCs) while CF_4 is used by Cathode Strip Chambers (CSCs), Multi Wire Proportional Chambers (MWPCs), Gas Electron Multipliers (GEMs) and Cherenkov Detector (RICH). All four LHC experiments make use of these gases in different quantities, depending on detector volume, replenishing rate or presence of leaks. The majority of the emissions are coming from the ATLAS and CMS experiments where RPCs are employed as muon trigger. The high consumption is mainly due to the present of leaks at the detector level concentrated in the gas inlets, polycarbonate gas connectors and polyethylene pipes. A big leak repairing campaign is on-going during LHC Long Shutdown 2 (LS2) since in this period is possible to get access to these leaks while, unfortunately, during data taking and short technical stops there could not be access.



In addition to the willing of CERN to reduce its GHG emissions, it is also to be considered that the European Union set a F-gas regulation [2] starting from January 2015 with the aim of reducing the usage of F-gases. It is therefore foreseeable that F-gases availability would be uncertain in Europe for the future and their price could raise possibly making gas detectors operation very costly. The reduction of GHGs usage and the search of new environmentally friendly gas mixtures for particle detection is therefore advisable since these detectors will be operated for the next decades in the LHC experiments.

2. CERN strategies to reduce GHG emissions from particle detection

Reducing the use of GHGs is a worldwide objective to which CERN wants to contribute. In this context and with the idea of preparing the very long-term operation, the CERN EP-DT Gas Systems Team, the CERN Environmental Protection Steering board (CEPS) and the LHC experiments elaborated a strategy based on several action lines [3], which will be described below.

2.1. Optimization of current technologies

The first identified research line focuses the attention on the optimization of current technologies. Indeed with the use of GHGs and expensive gases as well as in presence of large detector volumes, the gas system are operated under gas recirculation allowing already a reduction of gas consumption of more than 90% with respect to open mode gas systems. These recirculation gas systems are complex to operate and require dedicated personnel. In particular possible pressure and flow fluctuations in the system as well as creation of impurities when F-gases are used have to be addressed.

During LS2, dedicated studies have been performed to upgrade the ATLAS and CMS RPC gas systems in order to minimize any possible pressure and flow fluctuations and to reduce the risk of developing new leaks. This required redesigning the gas distribution systems. For the ATLAS RPC gas system new distribution modules were located in the cavern on different levels of the experiment in order to minimise the hydrostatic pressure of the detectors (0.3 mbar/m). Furthermore the new distribution modules have been equipped with new regulation valves at the detectors input and output to have a better pressure regulation. For the CMS RPC gas system several studies have been performed for the installation of new automated regulation valves on the return of each distribution module (total of 28 distribution modules) to minimise any pressure changes at the level of less than 0.1 mbar. These valves will be installed during LS2 and they will have custom made seats allowing to better regulate each distribution module both in Endcap and Barrel regions where flow and pressure can be completely different. One last upgrade for both RPC gas systems consists in the installation of stainless steel reference volumes that simulate detector volume and are located at the same height as the real detectors. These volumes will allow to have a reliable pressure measurement (not always possible with real detector in presence of leaks) and they can be used as reference for pressure regulation of real detectors.

2.2. Gas Recuperation Systems

In some cases, it is not possible to recirculate 100% of the gas mixture due to detector permeability to Air, detector requirements (for example detector operation validated to a well defined recirculation fraction), presence of impurities, etc. In these cases, a fraction of gas mixture is replenished with fresh one and it is exhausted to the atmosphere. Instead of sending to atmosphere, this fraction of gas mixture can be sent to a recuperation plant where the most valuable component is extracted, stored and then re-used in the gas system. Recuperation of a single gas component from a gas mixture is often challenging both in term of recuperation efficiency and quality of recuperated gas.

At CERN several gas recuperation systems are employed for GHGs and expensive gases, as the ones for CMS-CSC (CF_4), ATLAS-TGC (nC_5H_{12}), ALICE TRD (Xenon), ATLAS TRT (Xenon), LHCb-RICH1 (C_4F_{10}) and LHCb-RICH2 (CF_4). For most recuperation plants, the mixture returning from the detector is cooled down until the liquefaction point of gas to be extracted is reached. Then the liquid is recuperated and stored. The recuperation efficiency is usually 95% or higher.

A different method was developed for the CF_4 recuperation [4] due to the very low CF_4 boiling point. In this case the recuperation is performed through warm separation in three different phases, making use of gas separation membranes and selective adsorption during pressure swing cycles in different molecular sieves. Currently the recuperation efficiency is $\sim 65\%$ and the quality of recuperated CF_4 very satisfactory. Furthermore the recuperated CF_4 has been used with success for CSC detectors during Run 2 without observing any change in the CSC performance.

R&D studies are now ongoing for the design of a $\text{C}_2\text{H}_2\text{F}_4$ (R134a) recuperation plant for the RPC detectors, which gas mixture is made of 95% $\text{C}_2\text{H}_2\text{F}_4$, 4.5% iC_4H_{10} and 0.3% SF_6 with 40% relative humidity. Figure 1 shows a sketch of the prototype under studies today. The separation process can be divided into three phases:

Phase1: removal of N_2 and SF_6 by simple distillation by cooling down the gas mixture at -35°C .

The N_2 and SF_6 stay in their vapour phase and they are exhausted.

Phase2: separation of R134a from iC_4H_{10} . The liquified gas mixture heats up and the vapour is made of azeotrope. The vapours go back in previous buffer while the liquid R134a goes in next buffer at $\sim 5^\circ\text{C}$ where it becomes vapour.

Phase3: compression of vapour $\text{C}_2\text{H}_2\text{F}_4$ in liquid storage.

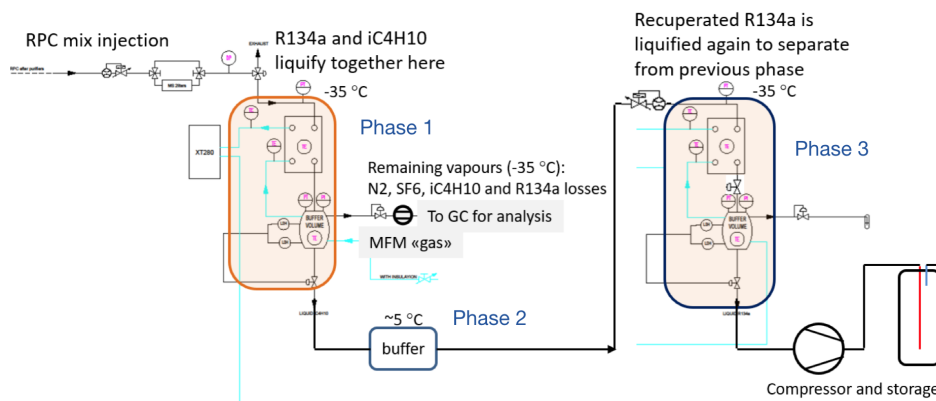


Figure 1. Schematic view of the working principle of the first R134a recuperation prototype system.

The difficulty in this process is due to the fact that R134a and iC_4H_{10} form an azeotrope, i.e. a mixture of liquids whose proportions cannot be altered or changed by simple distillation because intramolecular force of same-species is much higher than the reciprocal attraction. The solution found is to slowly heat the liquified azeotrope allowing to enrich the liquid of R134a and the vapour of iC_4H_{10} , obtaining then the separation. Nowadays the efficiency of the R134a recuperation plant is around 80% with a very good quality of R134a. The plant has been tested up to 400l/h at the input. The R&D continues with tests at higher flow, design and validation of the compression and storage module and, finally, possible re-use of the recuperated gas. A second version of the prototype will be built in 2022.

2.3. Search for alternative eco-friendly gas mixtures for gaseous detector

A third research line is based on the long-term replacement of currently used GHGs for the operation of gaseous detectors. An intense R&D activity is already ongoing since many years in the detector community for finding a green replacement in particular for R134a, SF₆ and CF₄ [5]-[7].

The alternatives to GHGs are nowadays dictated by the industrial market, which is evolving to meet the challenges presented by the EU regulations. Concerning the C₂H₂F₄, the industrial replacement are the HydroFluoroOlefins (HFOs) with a very low global warming potential (less than 6). With respect to R134a, HFOs contain one carbon more and a double-bond. In the recent years, research has also focused in alternatives to SF₆, which is mainly used as insulator for high-voltage plants. The 3M Company has developed two new sustainable alternatives to SF₆ with a high dielectric strength and low GWP: 3M Novec 5110 (CF₃C(O)CF(CF₃)₂) and 3M Novec 4710 ((CF₃)₂CFCN).

Finding a suitable replacement for the RPC systems at the LHC experiments is particularly challenging because most of the infrastructure (i.e. high-voltage systems, cables, front-end electronics) as well as the detectors themselves cannot be easily replaced. Therefore, the R&D is focused on identifying a new mixture able to reproduce the same RPC performance observed with the current R134a-based mixture. Encouraging results have been obtained with gas mixture made up of 5 components, containing HFO, R134a, iC₄H₁₀, SF₆ and He or CO₂, which are necessary to reduce the high voltage working point (which is higher due to the presence of HFO in the mixture). With these mixtures the GWP is reduced of a factor 2-3. Promising results have also been obtained by substituting the SF₆ with the 3M Novec family gases in the standard gas mixture. Especially only 0.1% of Novec 4710 is enough to reach the same streamer probability of the standard gas mixture. Nevertheless studies are on-going to understand possible chemical reaction of this gas in presence of water.

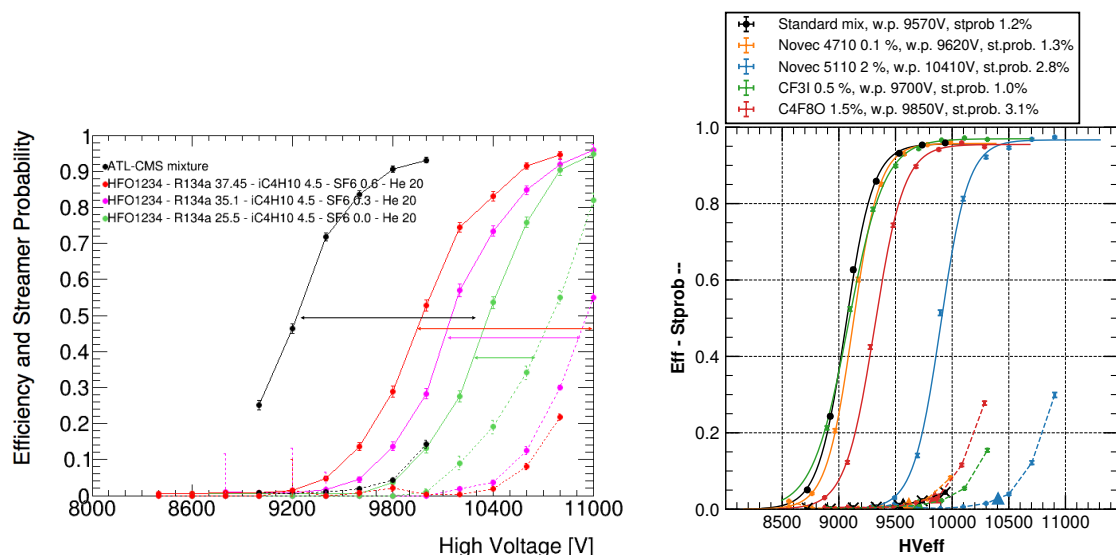


Figure 2. Efficiency (continuous line) and streamer probability (dotted lines) as a function of the HV for gas mixtures containing HFO and He (left) and for gas mixtures where the SF₆ is replaced with possible alternative gases (right).

The performance of RPC with eco-friendly gas mixtures has also been studied in LHC-like conditions, i.e. in presence of high background radiation and under gas recirculation. The test-beam measurements confirmed the laboratory tests: the HV shift of HFO-based gas mixtures

is the same in presence of high background radiation and the streamer probability is higher for HFO gas mixtures with respect to standard gas mixture. In parallel, systematic studies were performed at GIF++ to understand if the HFO goes under breaking processes under the effects of radiation and electric field. It has been demonstrated that F^- production is higher in the HFO based gas mixtures [9]. Further studies are necessary to understand the effect of these impurities on long-term detector operation.

2.4. GHGs disposal

For cases where it is not possible to recuperate or re-use the gases, systems for the disposal of GHGs have been developed by industry. They are adopted when GHGs used in industrial process are polluted to a level where recuperation for re-use is not possible. Nevertheless, GHG abatement systems are only solving part of the problem, i.e. the gas emissions. Problems like gas availability and price for detector operation are not addressed by abatement systems and they might become the challenge in the coming years due to the GHGs phase-down policy in many states. For this reason, the option of GHGs disposal is nowadays put on a side at CERN and researches are focused on the other strategies.

3. Conclusions

Several strategies are being implemented at CERN to reduce as much as possible GHG emissions from LHC experiments. These strategies have to be considered complementary to achieve the maximum possible reduction. Gas recirculation systems are the first way to reduce GHG consumption and they should be compulsory in all big experiments. Nowadays several works are on-going to further improve these system beyond original design. When it is not possible to recirculate 100% of the gas mixture, gas recuperation plants have to be considered. They are very complex and different separation technologies are necessary depending on the GHG to recuperate. On a long-term strategy, the use of alternative eco-friendly gas mixtures is advisable. The challenge in using new eco-gases is coming from the fact that they behave in a different way with respect to R134a and therefore current detectors and front-end electronics are not optimized for their use.

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