RPC performances and gas quality in a closed loop gas system for the new purifiers configuration at LHC experiments

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ABSTRACT: In the ATLAS and CMS experiments the RPC detector covers a large surface of about 4000 m$^2$ equivalent to 14 m$^3$ of gas volume for each system. RPCs are operated using a C$_2$H$_2$F$_4$ (R134a) based humidified gas mixture. A flow of the order of one volume exchange per hour is needed for the detector operation. These characteristics make the closed-loop circulation unavoidable. Nowadays the gas systems are operated with a 90–95% re-circulation factor.

Results from tests performed over the past few years have shown how the molecules in the gas mixture are broken up under the action of the high electric field and the high radiation background during LHC operation.

Several RPCs were operated at the CERN Gamma Irradiation Facility in a high radiation environment in order to observe the production of typical impurities and to find an optimal purifiers configuration for their absorption. During the test, the detector performances were monitored in terms of current stability and HPL resistivity.

KEYWORDS: Gaseous detectors; Gas systems and purification; Resistive-plate chambers

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1 Introduction

Resistive Plate Chambers (RPCs) [1] are widely employed for the muon trigger systems at the Large Hadron Collider (LHC) thanks to their fast time resolution (~ 1 ns), suitable space resolution (~ 1 cm) and low production cost (~ 100 euro/m²). Most RPC systems at LHC are operated with a non-flammable gas mixture of C₂H₂F₄·iC₄H₁₀·SF₆·H₂O, which is relatively expensive (~ 60 euro/m³). Based on economic grounds and related to the large system size (~ 4000 m²), RPCs are operated in re-circulating gas systems (90–95% closed loop circulation) [2, 3].

Several studies indicate a clear correlation between RPC performance and the quality of the gas mixture [4, 5]. The current drawn by the chambers can rapidly rise if the amount of pollutants in the mixture increases. Furthermore in the high radiation environment at LHC many different chemically reactive impurities are created in the RPC gas, mainly hydrocarbons, HF, F⁻ [6–8], Freon-type molecules and other chemical species [9–11]. They are potentially dangerous for the detector materials, the gas system and ultimately they will degrade the detector performances.

This study investigates the impurities produced in heavily irradiated RPC chambers and the properties of possible absorbers to be used at LHC in order to keep the gas purity near the level of the fresh gas quality. Several RPCs are operated at the CERN Gamma Irradiation Facility (GIF) [12] in a high radiation environment that permits to accelerate by several factors the irradiation levels expected at LHC. In this way, the production of typical impurities can be enhanced, and at the same time long-term accelerated tests of the RPC performances can be carried out. Results of these tests have revealed an optimized configuration of absorbers that is now being implemented in the closed-loop gas system of the ATLAS and CMS RPC systems.
The experimental setup consists of a set of double gap High Pressure Laminate (HPL) RPCs [13], which are irradiated at the CERN Gamma Irradiation Facility. The GIF is equipped with a $^{137}$Cs source, nowadays with an activity of about 590 GBq. Each detector has a surface of $(120 \times 205)$ cm$^2$ and a 2 mm wide gas gap. The RPCs were located in a tent where temperature and relative humidity were regulated to about 20°C and 40% respectively. The distance between the RPCs and the $^{137}$Cs source was 2 m, resulting in an average counting rate of 200 Hz/cm$^2$ over almost the whole surface, and a dose rate of 1 cGy/h (with respect to operation at nominal luminosity in the barrel region, equivalent to about $|\eta| < 1$ of the ATLAS and CMS experiments, the overall acceleration factor is about 30). In the double gap layout used for this test, the two gaps are connected in series (i.e. the output of the first gap is the input of the second and the read-out strips are in between the two gaps). Each detector is then connected to a versatile closed-loop gas system, which is a small replica of the gas systems installed in the LHC experiments, where purifiers can be studied in detail thanks to several gas analysers [10] and at the same time the chambers behaviour can be regularly monitored. This system, in addition, allows the simultaneous operation of two sets of RPCs in different gas conditions: one set is operated in open-mode (i.e. after being used in the detectors the gas is exhausted to atmosphere) and it serves to monitor chamber performances in ideal conditions; the second set is connected to the closed-loop gas circuit to test the chamber performance for a given gas quality condition.

2.1 Gas analysis

The gas quality is a fundamental parameter for the RPC performances. Thus, several gas analysers have been selected and are continuously used to characterize in detail the gas quality at different sampling points at the GIF and at the LHC gas systems. Furthermore a network of several sensors (temperature, relative humidity and pressure) monitors the environmental conditions and the gas mixture concentration.

Several studies have been conducted in previous tests concerning the fluoride ions, which are largely produced inside the gas volume during RPC operation and are very reactive impurities. These studies proved that the fluoride ions present in the gas mixture are harmful to RPCs. A systematic study has been conducted using a double channel Ione Selective Electrode (ISE) station allowing the simultaneous measurement of fluoride ions concentration in different detectors or different gas sampling points. In addition to the important amount of fluoride ions measured at the exhaust of irradiated RPCs, many other molecules are produced as a result of the breaking of the main gas mixture components by means of ionization, UV photons, charge multiplication and the subsequent recombination/re-arrangement of fragments. In order to identify unknown pollutants, an Agilent 3000 microGas Chromatograph (microGC) coupled to an Agilent 5975 Mass Spectrom-

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1The pseudorapidity $\eta$ is a commonly used coordinate describing the angle of a particle relative to the beam axis. It is defined as

$$\eta = -\log \left[ \tan \left( \frac{\theta}{2} \right) \right]$$

where $\theta$ is the angle between the particle momentum and the beam axis.

2Purifier refers to the module used in the gas system. Usually a purifier contains two cartridges in which the absorber materials are hosted.
Figure 1. Average integrated charge seen by the irradiated RPCs from the beginning of the test. Four different time periods corresponding to the test of different purifier configurations are visible. For each test period, the purifiers’ configurations are also visible.

3 Long-term validation of the purifiers configuration in a closed-loop gas system

Based on the detailed understanding and systematic characterization of several absorbers [5], three different configurations of purifiers have been tested at the GIF set-up during the years 2009–2011. Figure 1 shows the average integrated charge by irradiated RPCs versus time; the total accumulated charge is equivalent to about 10 years of operation in the LHC systems. The test time is subdivided into four intervals:

1. ‘Set-up validation’ corresponds to the irradiation of RPCs operated in an open mode gas system. It serves to optimize and validate the GIF set-up, the RPC chambers and to characterize in detail and individually different absorbers exposed to exhausted gas from the heavily irradiated RPCs.

2. The period ‘Current configuration at LHC experiments’ is a long-term, systematic test of the combination of absorbers currently in use in the LHC RPC systems; therefore it aims at revealing the possible limitations of the current RPC closed-loop gas systems for the future higher luminosity runs.
3. The third period is a test of the so-called ‘first optimized configuration’, using a new combination of absorbers.

4. The last period corresponds to the so-called ‘second optimized configuration’, which simplifies the previous absorbers’ combination while it improves the overall performance of the gas system.

3.1 Optimization of the filters configurations

As a result of the detailed and systematic characterization of each individual absorber, it has been found that there is a combination that would filter more efficiently some of the gas pollutants typically present in the irradiated RPC mixture, in addition to H$_2$O and O$_2$. The so-called ‘first optimized configuration’ consists of four different absorbers (figure 1). In comparison to the current LHC configuration:

- The MS 3 Å has been replaced by 4 Å, which permits to reduce the conditioning time and it absorbs more efficiently water and RPC-related impurities.
- The catalyst CuZn R12 has been removed, as it does not filter any of the radiation-induced impurities. The remaining metallic catalysts double their volume (by using two individual cartridges instead of one) and so their cleaning capacity, especially for O$_2$.

In this configuration one disadvantage remains: the low water and Freon-like impurities absorption capacity due to the presence of only one cartridge of MS.

In order to correct this limitation, the second optimized configuration consists of three physical purifiers, two of which have an important abundance of MS 4 Å (figure 1). The advantages with respect to the other two configurations are:

- The water absorption capacity is increased by a factor 2, and the increased amount of MS also guarantees an effective filtering of RPC-pollutants.
- The metallic catalyst Ni-Al$_2$O$_3$ is abandoned because it has shown that under some conditions can pollute the gas mixture [10]. Cu R11 remains as the unique O$_2$ filter.

3.2 RPC gas quality using optimized filter configurations

In order to characterize in detail the impurities produced in heavily irradiated RPCs, and the filtering capacity of several absorbers, systematic analysis of the composition of the RPC gas mixture by means of the microGC/MSD were carried out daily. Figure 2 shows a zoom of chromatograms from the gas supply (clean) and the gas returning from the irradiated chambers. In the latter, a multitude of minor peaks have been identified with the MSD and reveal that pollutants are mainly Freon-types and hydrocarbons molecules, with typical concentrations of the order of hundreds of ppm.

Six sampling points are available in the gas system:

- Point 1 (FreshMix): fresh mixture delivered by the gas mixer;
- Point 2 (OMReturn): the gas mixture from the chambers exhaust in the open-mode gas circuit;
Figure 2. Zoomed area of the PPU chromatogram of the clean gas supply and the returned mixture of irradiated RPC detectors, where pollutants show up [10].

- Point 3 (CLReturn): the gas mixture from the chambers exhaust in the closed-loop gas circuit;
- Points 4–5–6 (after P1–P2–P3): the gas mixture after the first, second and third purifiers respectively.

In these six points the correct proportion of the gas mixture and the impurities concentration downstream the detectors are calculated and monitored.

3.2.1 Monitoring of the gas mixture humidity and radiation-induced impurities

A crucial parameter for the stable operation of RPC detectors is the gas mixture relative humidity. In order to control the relative humidity in the closed-loop, which should be about 40%, the water in the return mixture from irradiated chambers is completely removed by means of MS absorbers. Then, the right amount of water is freshly injected in the chambers’ supply line.

The H$_2$O concentration in the filtered gas (after purifiers 1, 2 and 3) was monitored all along the test period using dedicated moisture analysers (i.e. chilled mirror) and mass-spectrometer. In figure 3 it can be noticed that in the ‘current LHC configuration’ and in the ‘first optimized configuration’ there is about the same amount of water after the purifiers, between 100 and 300 ppm. The highest levels are reached when the MS absorbers are saturated, and slowly decrease to the hundred-ppm level after MS are regenerated.\(^3\) In the ‘second optimized configuration’ when purifier 1 is saturated (CLAFTERP1 in figure 3) the gas remains dry because the MS 4 Å in purifier 2

\(^3\)MS absorbers were always regenerated by heating up the material at 220°C and, simultaneously, making the vacuum (about 100 mbara) in the cartridge hosting the absorber.
still absorbs water. In this configuration, the water concentration inside the gap is easily kept under control for longer periods (about a factor 2 with respect to ‘current LHC and the first optimized configurations’).

Another quality of the second optimized configuration concerns the radiation-induced impurities in the gas. Impurities have been constantly monitored during the long test in order to check their presence and concentrations (in general from 100 ppm to 1000 ppm). In the final configuration of absorbers the impurities are present with a lower concentration and some even disappear. The monitor of impurities along time is also useful to understand when the absorbers need to be regenerated: the sudden increase of the pollutants concentration is correlated with the saturation of the absorbers.

### 3.2.2 The effect of different fresh gas injection flows

In the LHC RPC gas systems about 5–10% of fresh mixture is injected in the circulation loop. At the GIF, a systematic study has been done in order to understand how the impurities concentration changes with a different fraction of fresh mixture injected in the presence of the three purifiers. The attention for this test should be focused on the ‘second optimized configuration’ test time which can be sub-divided in three periods with different percentages of fresh mixture: 3% (period A), < 1% (period B) and 6% (period C). It has to be considered that at the GIF the dose rate acceleration factor is about 30, so the time period for each test should to be multiplied by this factor to possibly obtain a realistic, equivalent operation time in LHC conditions.

Figure 4 shows the concentration of one detected impurities in the RPC irradiated gas. The pollution concentration is lower for the second optimized configuration with respect to the other periods (where the percentage of fresh mixture injected was always about 7%). The impurity concentration gets steadily higher with decreasing fresh gas amount addition. In period C, when
Figure 4. Concentration of $C_2H_3F_2$ vs. time during the GIF test. The zoomed region represents the concentration during the test period for the second optimized configuration.

6% fresh gas is injected in the closed-loop, the impurity concentration remains at the same level of its concentration in chambers operated in open mode, which means that the impurity is completely absorbed by the purifiers in the closed-loop. Therefore the injection of the proper amount of fresh gas inside the chamber in closed-loop helps in avoiding an exponential increase of the impurities and it is necessary to safely operate RPC systems.

A test with the closed-loop system operated without purifiers, but just adding 6% fresh gas in the loop, was also performed. After about 6 days of operation, equivalent to few months at LHC, the impurities concentration increased and some new impurities appeared (figure 5). Furthermore the water concentration inside the gap could not be kept under control. This means that the purifiers are really needed.

4 Long-term performances of RPC irradiated at the GIF

During the many months of exposure to the high-intensity gamma source, the RPC detectors accumulate an integrated charge of 50 mC/cm$^2$ equivalent to about 10 years of operation in the CMS RPC barrel region. This achievement is very useful to understand the RPC performances and their behavior over the next LHC running periods. The performance of the detectors has been monitored in terms of HPL bulk resistivity and current stability over time.

4.1 HPL bulk resistivity

The HPL bulk resistivity has a great impact on the RPC performances, especially at very high particle rate where an important voltage drop can occur if the resistivity of the HPL electrodes is too high. At the GIF, the RPC resistivity is regularly measured in order to check its stability during all the operation time.

Figure 6 shows the HPL bulk resistivity measured for each irradiated gap at different time periods. The x-axis shows the gap number: i.e. gaps $-1$ to 4 are operated in open mode, while
Figure 5. Gas chromatograph obtained with the PPU column. In the test without purifiers (blue line) the impurities increase and even some new signals appear.

Figure 6. HPL electrode bulk resistivity (normalized at 20°C) for all the detectors measured at different time periods. An average increase of about a factor 3–5 is visible in all gaps, with the exception of gaps 5 to 8.

gaps 5 to 10 in closed-loop. For almost all gaps there is a visible increase of a factor 3–5. However, gaps 5 to 8 do not show any significant change with respect to the original values.

Any correlation with the gas system operation (i.e. open mode or closed-loop) and the mixture relative humidity (i.e. constant to 40% for all gaps) at this stage can be excluded.
4.2 Gas gain long term stability

The RPC current (in all its aspects) is a fundamental parameter to be monitored because its stability indicates that the RPC detector is working properly. Any variation represents a change in the detector gas gain.

The gas gain depends on the condition of the gas, which can be altered by temperature and pressure variations. A possible correction can be applied leaving the High Voltage (HV) fixed, letting the current free to follow the environmental variations and applying later a correction that takes into account all possible mechanisms related to environmental fluctuations [14].

Figure 7 shows the current drawn by an irradiated RPC before and after the environmental correction is applied, resulting in a RPC that behaves remarkably stable during the test period of the second optimized configuration.

5 Conclusions

A detailed analysis of the exhausted gas from heavily irradiated RPC chambers has been performed and the behavior of several detectors operated at the GIF with a gas recirculation system has been monitored for 3 years, which correspond to about 10 years of operation in the LHC systems.

It has been found that some impurities are created inside the RPC detectors during the avalanche and streamer process, and accumulate inside the re-circulated gas mixture. Impurities have been identified as other gases of the Freon family, hydrocarbons (C1 to C3) and fluoride ions. In order to avoid the accumulation of impurities inside the RPC chambers a systematic and detailed study on purifier materials has been conducted. Three different absorber configurations have been tested at the GIF and an optimized configuration for the LHC gas systems has been found in perfect agreement with the requirements of the large RPC gas systems at the LHC experiments. It consists of three purifiers: the first filled with Molecular Sieve 5 Å–4 Å (10%–90% ratio), the second with...
Molecular Sieve 4 Å only and the third with a metallic catalyst Cu-R11. The primary improvements are the complete control of the gas humidity, the total absorption of O\textsubscript{2}, the removal of most gas pollutants and an increase of the purifier cycle duration by a factor 2.5 with respect to the current LHC configuration, which can easily handle an increase of a factor > 1.5 in flow if needed during LHC high luminosity runs.

A set of 12 double gap RPCs operated in conditions equivalent to those used at LHC, but heavily irradiated (amplification factor about 30 with respect to LHC nominal), and using a gas system with the optimized set of cleaning agents, shows a very stable behaviour, both in terms of currents and HPL resistivity. The performances of these heavily irradiated RPCs seem to be unaffected at long-term by the achieved low concentration of impurities: after correction for changes due to environmental conditions (current fluctuations induced by pressure and temperature variations), the currents drawn by the RPCs connected to the optimized closed-loop gas system have been very stable over the entire test period.

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