Consolidation and extension of the CMS Resistive Plate Chamber system in view of the High-Luminosity LHC Upgrade

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Grasping an understanding of the world in which they are leaving in has always been part of human life. Beyond the metaphysical questioning of our origins and purpose, curiosity has brought mankind to question its surroundings. Following the philosophy of the ancient Greeks and Indians came the development of the sciences as the systematic experimentation aimed at testing hypothesis and reproducing results obtained by fellow natural philosophers. With the industrial revolution and the organisation of science, it became possible to go always further in the understanding of the universe and of the matter in particular. Investigation on the constituent of matter proved to require more and more powerful machines in order to break apart the bricks of the world into ever smaller pieces, study their behaviour and extract new knowledge to help the development of humanity. So far, the largest and most powerful machine that was built to study the particles composing matter and test the models thought by physicists to explain their behaviour is the Large Hadron Collider (LHC), a circular particle accelerator used to collide protons and heavy ions. After only a few years of investigations conducted thanks to the LHC, several discoveries, predicted by the existing models, have been made. In the future, in order to boost the discovery potential on the LHC and be able to test hypotheses lying beyond the already acknowledged models, the instantaneous luminosity, i.e. the rate of particle interactions, will be slightly increased into a so-called High Luminosity phase to boost its discovery potential.

As the Large Hadron Collider will see its instantaneous luminosity be increased, the detectors on the different experimental sites will have to suffer an increased background irradiation due to the byproducts of the interaction of the beams with the infrastructure. This will cause for the detectors a stress which implications need to be understood throughout the High Luminosity LHC (HL-LHC) phase of operations. In the case of the Compact Muon Solenoid (CMS) experiment, it is important to understand if the detectors that will be subjected to the higher levels of radiation will be able to sustain higher detection rates while displaying the same performance they have so far been operated at and if this level of performance of the detectors will stay stable for a period longer than ten years. More specifically, the detectors placed very close to the beam line will be the most subjected to the change of luminosity. In CMS, the endcap detectors will then be particularly affected by the stronger
background radiation. The endcap detectors compose a part of the muon system of CMS and among them, the Resistive Plate Chamber (RPC) plays a key role in providing the experiment a reliable trigger on potentially interesting data. This PhD work takes place into this very specific context of muon detector consolidation and certification for the HL-LHC period in order to provide the CMS experiment with robust new detectors and confirm that the present system will survive through the next 20 years.

CMS experiment main focus revolves around testing the Standard Model (SM) of particle physics using a multipurpose detector design to detect the interaction products of the protons and ions colliding along the LHC. Looking at the successive evolution of the theoretical models that gave birth to the SM, the need for very intense particle beams in high energy physics experiment becomes clear in that the higher the center-of-mass energy for each interaction, the greater the probe on very small cross-section processes predicted by the theory, justifying the successive increase in beam energy and intensity at LHC.

The implications for LHC experiments and in particular for the CMS detector explain the need for longevity and rate capability studies conducted on the Resistive Plate Chambers which are an important part of its Muon System as it is needed to certify the quality of operation of the trigger detectors throughout the lifetime of HL-LHC.

RPCs are gaseous detectors which physics principles are non trivial and are still being investigated. Nevertheless, key processes driving the electron multiplication in the gas volume, rate capability and ageing have been successfully identified and will define the parameters that will have to be taken into consideration while producing the detectors extending the pseudo-rapidity coverage of RPCs toward the beam line as well as the ones to be monitored during the on-going longevity and rate capability certification campaign.

On the one hand, the present RPC sub-system consists in two different RPC productions. Indeed, most of the RPC detectors were produced in view of the start of LHC activities in 2010. These detectors were built in between 2007 and 2008 to equip the barrel and the three disks of each endcaps of the CMS apparatus. But during the First Long Shutdown (LS1) of LHC in between end of 2012 and 2015, a fourth disk of endcap was added in order to reinforce the redundancy of the endcap trigger. Hence, new RPC detectors using the same technology were built in between 2012 and 2013. These two sets of detector productions only differ in the properties of the High-Pressure Laminate (HPL) used for their electrodes that could lead to a different ageing rate. This is why spare detectors of both production periods have been tested over the past years to certify their good operation through HL-LHC.

On the other hand, producing detectors to equip a highly irradiated region such as the extension of CMS RPC endcaps requires to substantially improve the ageing properties of the chosen technology by reducing the charge deposition per ionizing particle. This can be achieved both by modifying the design of the detector volume or by improving the signal to noise ratio of the Front-End Electronics (FEE) used to process the charge collected by the read-out strips making them more sensitive to weaker signals. Two FEE technologies were selected and tested in order to equip the improved RPC (iRPC) that will extend the coverage of the CMS endcaps.

Thanks to the study presented in this document, preliminary conclusions will be brought on the production of iRPCs and on the longevity of the present RPC system, providing with a better understand of the future performance of the RPC sub-system within the CMS experiment.
Throughout history, physics experiment became more and more powerful in order to investigate finer details of nature to help understanding the building blocks of matter and the fundamental interactions that bind them in the microscopic world. Nowadays, the Standard Model of particle physics is the most accurate theory designed to explain the behaviour of particles and is able to make very precise predictions that are constantly verified. Nevertheless, some hints of new physics are visible as bricks are still missing to obtain a global description of the Universe.

To highlight the limits of the SM and test the different alternative theories, evermore powerful machines are needed. It is in this context that the Large Hadron Collider has been thought and built to accelerate and collide particles at energies exceeding anything that had been done before. Higher collision energies and high pile-up imply the use of enormous detectors to measure the properties of the interaction products. The Compact Muon Solenoid is a multipurpose experiment that has been designed to study the proton-proton collisions of the LHC and give answers on various high-energy physics scenarios such as different supersymmetry (SUSY) extensions to the Standard Model or Extra Dimensions models.

This Chapter will be the occasion to go through the history of the Standard Model of Particle Physics to understand the research conducted today in High-Energy Physics (HEP) facilities. From the discovery of the atom and of its inner structure to the development of the theories governing the fundamental interactions, all the elements leading to the construction SM will be discussed. Furthermore, highlights on the Physics beyond the Standard Model (BSM) will be given to replace the document in the context of today’s research. Finally, a full description of the LHC and of the CMS detector will be provided.

2.1 The Standard Model of Particle Physics

In the early 21st century it is now widely accepted that matter is made of elementary blocks referred to as elementary particles. The physics theory that classifies and describes the best the behaviour and interaction of such elementary particles is the so-called Standard Model. The SM formalizes three of
the four fundamental interactions (electromagnetic, weak and strong interactions). Its development happened since the 1960s thanks to a strong collaboration between theoretical and experimental physicists.

2.1.1 A history of particle physics

The idea that nature is composed of elementary bricks, called atomism, is not contemporary as it was already discussed by Indian or Greek philosophers during antiquity. In Greece, atomism has been rejected by Aristotelianism as the existence of atoms would imply the existence of a void that would violate the physical principles of Aristotle philosophy. Aristotelianism has been considered as a reference in the European area until the 15th century. With the Rinascimento, antic text and history started to be more deeply studied. The re-discovery of Platon’s philosophy allowed opening the door to alternative theories and give a new approach to natural sciences where experimentation would become central. A new era of knowledge was starting. By the beginning of the 17th century, atomism was re-discovered by philosophers. The very first attempt at estimating the number of particles in a volume was provided by Magnenus in 1646 by calculating that the number of particles in a stick of incense [1]. He found a value of the order of $10^{18}$ simply by considering the time necessary to smell it everywhere in a large church after the stick was lit on. It is now known that this number only falls short only by 1 order of magnitude.

An alternative philosophy to atomism popularized by Descartes was corpuscularianism. Built on ever divisible corpuscles, contrary to atoms, its principles were mainly used by alchemists like Newton who would later develop a corpuscular theory of light. Boyle combined together ideas of both atomism or corpuscularianism leading to mechanical philosophy. The 18th century has seen the development of engineering providing philosophical thought experiments with repeatable demonstration and a new point of view to explain the composition of matter. Lavoisier greatly contributed to chemistry and atomism by publishing in 1789 a list of 33 chemical elements corresponding to what are now called atoms [3]. In the early 19th century Dalton summarized the knowledge on composition of matter [4]. In his atomic model, the atoms are ball-like constituents of the chemical elements. All atoms of a given element are identical, in size, mass, and other properties while the atoms of different elements differ. He also considered that atoms cannot be divided into smaller particles, created nor destroyed and that they combine into chemical compounds. The essence of chemical reaction was then the combination, separation or rearrangement of atoms. Soon after,
Fraunhofer invented the spectrometer and discovered the spectral lines in the sunlight spectrum, as showed in Figure 2.1 [5]. These were later linked to the absorption by chemical elements present in the solar atmosphere by Kirchhoff and Bunsen. The rise of atomic physics, chemistry and mathematical formalism unraveled the different atomic elements and ultimately, the 20th century saw the very first sub-atomic particles.

**Discovery of the inner structure of the atom**

The negatively charged *electron* was the first to be discovered in 1897 by Thomson after three decades of research on cathode rays [6]. He proved that the electrification observed in an electroscope, as reported by Perrin [7], was due to the rays themselves. Hence, they had to be composed of electrically charged particles. In 1900, Becquerel showed the *beta rays* emitted by radium had the same charge over mass ratio as was measured by Thomson for cathode rays, pointing to electrons as a constituent of atoms [8]. This discovery leads to Thomson’s plum pudding atomic model in which electrons are embed into a uniform positively charged atom [9]. In 1907, Rutherford and Royds showed that *alpha* particles were helium ions [10]. Indeed, once captured in a tube and subjected to an electric spark causing an electron avalanche, they could combine with two electrons to form a $^4$He.
This discovery was directly followed by the constraint of the atom structure in between 1908 and 1913 through the Geiger–Marsden gold foil experiments in which the deflection angle of alpha particles fired at a very thin gold foil was measured \[11, 14\]. It highlighted that atoms were mainly empty with nearly all their mass contained into a tiny positively charged nucleus. With these two observations, Rutherford could formulate the Rutherford planetary model of the atom in 1911 \[15\], shown together with the Thomson plum pudding model in Figure 2.2. The link between atomic number and number of positive and negative charges contained into the atoms would fast be understood. Hence, the different kinds of element transmutations appeared to be purely nuclear processes making clear that the electromagnetic nature of chemical transformations could not possibly change nuclei. A new branch in physics appeared to exclusively study nuclei: nuclear physics. By studying alpha emission and the product of their interaction with nitrogen gas, Rutherford reported in 1919 the very first nuclear reaction \[16\]. It leads to the discovery that the hydrogen nucleus was composed of a single positively charged particle that was later baptised proton \[17\]. This idea came from 1815 Prout’s hypothesis proposing that all atoms are composed of ”protyles” (i.e. hydrogen atoms) \[18, 19\]. By using scintillation detectors, Rutherford could highlight typical hydrogen nuclei signature and understand that the impact of alpha particles with nitrogen would knock out a hydrogen nucleus and produce an oxygen 17, as showed in Formula 2.1 and would then postulate that protons are building bricks of all elements.

\[
^{14}_\text{N} + \alpha \rightarrow ^{17}_\text{O} + \text{p}
\]

With this assumption and the discovery of isotopes together with Aston, elements with identical atomic number but different masses, Rutherford proposed that all elements’ nuclei but hydrogen are composed of both charged particles, protons, and of chargeless particles, which he called neutrons \[17, 20\]. These neutral particles helped maintaining nuclei as one, as charged protons were likely to electrostatically repulse each other. He then introduced the idea of a new force, a nuclear force. The first idea concerning neutrons was a bond state of protons and electrons as it was known that the beta decay, emitting electrons, was taking place in the nucleus. However, it was then shown that electrons being confined into the nucleus would hardly be possible due to Heisenberg’s uncertainty principle. Finally, in 1932, following the discovery of a new neutral radiation, Chadwick could discover the neutron as an uncharged particle with a mass similar to that of the proton which would solve the nucleus puzzle \[21–25\].

Development of the Quantum Electrodynamics

Historically, the development of the quantum theory revolved around the question of emission and absorption of discrete amount of energy through light. Einstein used the initial intuition of Planck about the black-body radiation to develop in 1905 a model to explain the photoelectric effect in which light was described by discrete quanta now called photons \[25, 27\]. For this model, Einstein introduced the concept of wave-particle duality as classical theory was not able to describe the phenomenon. With the new understanding of atoms and of their structure, classical theories also proved unable to explain atoms’ stability. Indeed, using classical mechanics, electrons orbiting around a nucleus should radiate an energy proportional to their angular momentum and hence, loose energy through time and the spectrum of energy emission should then be continuous. However, it was known since the 19th century and the discovery of spectral lines that the emission spectrum of material was discrete \[5\].
In 1913, quantum physics was introduced into the atomic model by Bohr to overcome the electron’s energy loss due to orbiting radiation emission [28]. Using the correspondence principle stating that for large enough numbers the quantum calculations should give the same results than the classical theory, he proposed the very first quantum model of the hydrogen atom explaining the line spectrum by introducing the principal quantum number $n$ describing the electron shell. The same year, Moseley confirmed Bohr’s model through the Moseley’s law [29]. Debye and then Sommerfeld extended it by introducing the quantization of the angular momentum [30]. The quantization the $z$-component of the angular momentum led to the second and third quantum numbers, or azimuthal and magnetic quantum number, $l$ and $m$. The second defines the orbital angular momentum of the electrons on their shells and hence, the shape of the orbital, while the third the available orbital on the subshell for each electron as shown in Figure 2.3.

Nevertheless, although the model was not only limited to spherical orbitals anymore, making the atom more realistic, the Zeeman effect couldn’t be completely explained by just using $n$, $l$ and $m$ [31-34] nor could the result of the Stern-Gerlach experiment [35]. Both experiments are shown in Figure 2.4. A solution was brought after Pauli in 1925 proposed together with his exclusion principle the idea of a new quantum degree of freedom in order to resolve the apparent problem [36, 37]. This degree of freedom was interpreted as an intrinsic angular momentum vector associated to the particle itself, not to the orbital [38], and associated to a new quantum number $s$, the spin projection quantum number explaining the lift of degeneracy to an even number of energy levels [39]. The new quantum number helped in theorizing the neutron as a neutral particle rather than a bond state of a proton and an electron confined in the nucleus itself.

The introduction of the spin happened one year after another attempt of improvement of the theory was made by De Broglie in his Ph.D. thesis [40]. The original formulation of the quantum theory only considered photons as energy quanta behaving as both waves and particles. De Broglie proposed...
that all matter are described by waves and that their momentum is proportional to the oscillation of quantized electromagnetic field oscillators. This interpretation was able to reproduce the previous version of the quantum energy levels by showing that the quantum condition involves an integer multiple of $2\pi$, as shown by Formula \ref{eq:2.2}.

\begin{equation}
    p = \hbar k \Leftrightarrow \int p\, dx = \hbar \int k\, dx = 2\pi \hbar n
\end{equation}

Although the intuition of De Broglie about the wave-particle duality of all matter was a step in the right direction, his interpretation was semiclassical and it is in 1926 that the first full quantum wave equation would be introduced by Schrödinger to describe electron-like particles, reproducing the previous semiclassical formulation without inconsistencies \cite{41}. This complex equation describes the evolution of the wave function $\Psi$ of the quantum system, defined by its position vector $\mathbf{r}$ and time $t$ as an energy conservation law, in which the Hamiltonian of the system $\hat{H}$ is explicit, by solving the Equation \ref{eq:2.3}.

\begin{equation}
    i\hbar \frac{\partial}{\partial t} |\Psi(\mathbf{r}, t)\rangle = \hat{H} |\Psi(\mathbf{r}, t)\rangle
\end{equation}
The spin was then included into Schrödinger equation by Pauli to take into account the interaction with an external magnetic field, as shown in Equation 2.4 in which the Hamiltonian operator is a $2 \times 2$ matrix operator due to the Pauli matrices $[39]$. $\mathbf{A}$ is the vector potential and $\phi$ is the scalar electric potential.

\begin{equation}
\tag{2.4}
i \hbar \frac{\partial}{\partial t} |\Psi\rangle = \left[ \frac{1}{2m} \left( \mathbf{\sigma} \cdot (\mathbf{p} - q \mathbf{A})^2 + q\phi \right) \right] |\Psi\rangle
\end{equation}

Later in 1927, Dirac went further in his paper about emission and absorption of radiation by proposing a second quantization not only of the physical process at play but also of the electromagnetic field $[42]$. His equation provided the ingredients to the first formulation of Quantum Electrodynamics (QED) and the description of photon emission by electrons dropping into a lower energy state in which the final number of particles is different than the initial one. Nevertheless, in order to properly treat electromagnetism, the incorporation of the special relativity developed by Einstein was necessary. Derived in 1928, the Dirac equation, shown as Equation 2.5, similarly to Schrödinger equation, is a single-particle equation but it incorporates special relativity in addition to quantum mechanics rules $[43]$. 

\begin{equation}
\tag{2.5}
i \hbar \gamma^\mu \partial_\mu \psi - mc\psi = 0
\end{equation}

It features the $4 \times 4$ gamma matrices $\gamma^\mu$ built using $2 \times 2$ Pauli matrices and the unitary matrix, the 4-gradient $\partial_\mu$, the rest mass $m$ of any half integer spin massive particle described by the wave function $\psi(x, t)$, also called a Dirac spinor and the speed of light $c$. In addition to perfectly reproduce the results obtained with quantum mechanics so far, it also provided negative-energy solutions that would later be interpreted as a new form of matter, antimatter $[44, 45]$. In the non-relativistic limit, the Dirac equation gives a theoretical justification to the Pauli equation that was phenomenologically constructed to account for the spin.

The successes of the QED were soon followed with theoretical problems as computations of any physical process involving photons and charged particles were shown to be only reliable at the first order of the perturbation theory $[46]$. At higher order of the theory, divergent contributions were appearing giving nonsensical results. Only two effects were contributing to these infinities.

- The self-energy of the electron (or positron), the energy that the particle has due to its own interaction with its environment.
- The vacuum polarization, virtual electron–positron pairs produced by a background electromagnetic field in the vacuum which is not an "empty" space. These virtual pairs affect the charge and current distributions generated by the original electromagnetic field.

Solving this apparent problem was done by carefully defining the concepts of each observable, for example mass or charge, as these quantities are understood within the context of a non-interacting field equation. From the experimental point of view, they are abstractions as what is measured is "renormalized observables" shifted from their "bare" value by the interaction taking place in the measuring process. The infinities needed to be connected to corrections of mass and charge as those are fixed to finite values by experiment. This was the intuition of Bethe in 1947 who successfully computed the effect of such renormalization in the non-relativistic case $[47]$. Full covariant formulations of QED including renormalization were achieved by 1949 by Tomonaga, Schwinger, Feynman,
and Dyson [48]. With the resolution of infinities, QED had mostly reached its final form, being still today the most accurate physical theory, and would serve as a model to build all other quantum field theories.

**Development of the quark model and Quantum Chromodynamics**

To explain the nuclear force that holds nucleons (protons and neutrons) together, Yukawa proposed in 1934 the existence of a force carrier called *meson* due to its predicted mass in the range in between the electron and nucleon masses [49]. Discovered in 1936 by Anderson and Neddermeyer [50, 51], and confirmed using bubble chambers in 1937 by Street and Stevenson [52], a first meson candidate was observed in the decay products of cosmic rays. Assuming it had the same electric charge as electrons and protons, this particle was observed to have a curvature due to magnetic field that was sharper than protons but smoother than electrons resulting in a mass in between the two. But its properties were not compatible with Yukawa’s theory, which was emphasized by the discovery of a new candidate in 1947, again in cosmic ray products using photographic emulsions [53–55]. The detections of the *μ*-meson and of the *π*-meson in emulsions are showed in Figure 2.5.

This new candidate, although it had a similar mass than the already believed *meson*, would rather decay into it. For distinction, the first candidate would then be renamed "*mu meson*" when the second would be the "*pi meson*". The *mu meson* was behaving like a heavy electron and didn’t participate in the strong interaction whereas the pion was believed to be the carrier of the nuclear interaction. This led to classify the *μ* in a new category of particles that shared similar properties called *leptons* under the name of *muon* together with the electron. The *pi meson* was finally found to be a triplet of particles: a positively charged, a negatively charged, and a neutral particle. The neutral *pi meson* has been more difficult to identify as it wouldn’t leave tracks on emulsions nor on bubble chambers and needed to be studied via its decay products. It was ultimately identified in University of California’s cyclotron in 1950 through the observation of its decay into 2 photons [56].

Also discovered in 1947 but in cloud chamber photographs, the *K meson* has also been an impor-
tant step towards the establishment of the Standard Model \[57\]. A triplet of particles, two charged and a neutral, with a mass roughly half that of a proton, were reported. These particles were baptised $K$ meson in contrast to the "light" $pi$ and $mu$ "L-mesons". The particularity of the $K$ is their very slow decays with a typical lifetime of the order of $10^{-10}\text{s}$ much longer than the $10^{-23}\text{s}$ of $pi$-proton reactions. The concept of strangeness, a new quantum number was then introduced thanks to an idea of Pais as an attempt to explain this phenomenon as strange particles appeared as the pair production of a strange and anti-strange particle \[58\].

With the development of synchrotrons, the particle zoo grew to several dozens during the 1950s as higher energies were reachable through acceleration. In 1961, a first classification system, called Eightfold Way, was proposed by Gell-Mann \[59\]. It found its roots in the Gell-Mann–Nishijima formula, which relates the electric charge $Q$, the third component of the isospin $I_3$, the baryon number $B$ and the strangeness $S$, as showed in Formula \[2.6\] \[\text{60–62}\].

\[Q = I_3 + \frac{1}{2}(B + S)\]

The isospin is a quantum number introduced in 1932 to explain symmetries of the newly discovered neutron using representation theory of SU(2) \[63\]. The baryon number, was introduced by Nishijima as a quantum number for baryons, i.e. particles of the same family as nucleons \[60\]. The mesons were classified in an octet and baryons of spin $\pm \frac{1}{2}$ and $\pm \frac{3}{2}$ were respectively classified into an octet and a decuplet, as shown in Figure 2.6. To complete the baryon decuplet, Gell-Mann predicted the existence of baryon $\Omega^-$ which would later be discovered in 1964 \[64\].

Gell-Mann, and independently Zweig, then proposed a full theoretical model in which hadrons (strongly interacting particles, i.e. mesons and baryons) were not elementary particles anymore \[65–67\]. They were rather composed of three flavors of particles called quarks and their anti-particles. The three flavors were called up, down and strange. Up and down were used to explain the nucleons and non-strange mesons, while strange came into the composition of hadrons showing strangeness. Up and down flavors were discovered in 1968 thanks to the deep inelastic scattering experiments conducted at the Stanford Linear Accelerator Center (SLAC) \[68\] \[69\], and strange could only be indirectly validated even though it provided a robust explanation to kaon ($K$) and pion ($\pi$).
However, in the decade following the Gell-Mann-Zweig quark model proposition, several improvements to the model were brought. First by Glashow and Bjorken the same year that predicted the existence of a fourth quark flavor, the charm, that would equalize the then known number of quarks and leptons [70, 71]. Finally in 1973 by Kobayashi and Maskawa that increased the number of quarks to six to explain the experimental observation of CP violation [72, 73]. These two quarks were referred to as top and bottom for the first time in 1975 [74]. It’s only after these additions to the quark model that finally the charm was discovered in 1974 at both SLAC and Brookhaven National Laboratory (BNL) [75, 76]. A meson in which the charm is bonded with an anti-charm, called $J/\psi$ and presented in Figure 2.7, helped convince the physics community of the validity of the model. The bottom was discovered soon after in 1977 in Fermilab [77] and indicated the existence of the top that resisted to discovery until Fermilab’s experiments CDF and D∅ in 1995 due its very large mass and the energy needed to produce it [78, 79].

![Figure 2.7: Discovery of the $J/\psi$ by both (a) SPEAR (SLAC [75]) and (b) AGS (BNL [76]). In Figure (a) the cross section versus energy is showed for (a) multi hadron final states, (b) $e^+e^-$ final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$ and $K^+K^-$ final states.](image-url)
As remarked by Struminsky, due to mesons such as $\Omega^- \text{ or } \Delta^{++}$, the first SU(3) model already should have possessed an additional quantum number \cite{80}. Indeed, these mesons are composed of three identical quarks, respectively three strange and up quarks, with parallel spins, which should be forbidden by the exclusion principle. Independently, Greenberg, and Han and Nambu proposed an additional SU(3) degree of freedom for the quarks \cite{81,82}. It was later referred to as color gauge, that could interact through gluons, the gauge boson octet corresponding to this degree of freedom. The color field is presented in Figure 2.8a. Nevertheless, as observing free quarks to prove their existence proved to be impossible, two visions of the quarks were argued. On one side, Gell-Mann proposed to see quarks as mathematical construct instead of real particles, as they are always confined, implying that quantum field theory would not describe entirely the strong interaction. He promoted the S-matrix approach to treat the strong interaction. Opposed to this vision, Feynman on the contrary argued that quarks are real particles, that he would call partons, that should be described as all other particles by a distribution of position and momentum \cite{83}. The implications of quarks as point-like particles were verified at SLAC and helped abandon the S-matrix to the benefit of QFT \cite{84}. The concept of color was then added to the quark model in 1973 by Fritzsch and Leutwyler together with Gell-Mann to propose a description of the strong interaction through the theory of Quantum Chromodynamics (QCD) \cite{85}. The discovery the same year of asymptotic freedom within the QCD by Gross, Politzer, and Wilczek, allowed for very precise predictions thanks to perturbation theory \cite{86,87}. The evolution of the gauge constant of QCD with respect to the energy as described by asymptotic freedom is showed in Figure 2.8b.

Figure 2.8: (a) the color field of QCD only allows for "white" baryons, particles composed of quarks, to exist. Examples are given for mesons, composed of a quark and its anti-quark, and hadrons, composed of three differently colored quarks or anti-quarks. Other exotic baryons have been predicted and observed, such as tetraquarks and pentaquarks. Image by Maschen. (b) a crossed analysis performed thanks to the data collected by various experiments at different energies have showed that the coupling constant evolves as predicted by the mechanism of asymptotic freedom \cite{88}.
The Weak interaction, spontaneous symmetry breaking, the Higgs mechanism and the Electroweak unification

The weak interaction is the process that causes radioactive decays. Thanks to the neutron discovery [24], Fermi could explain in 1934 beta radiations through the beta decay process in which the neutron decays into a proton by emitting an electron [89]. Though the missing energy observed during this process triggered a huge debate about the apparent non-conservation of energy, momentum and spin of the process, Fermi, as Pauli before him [90], proposed that the missing energy was due to a neutral not yet discovered particle that was then baptised neutrino. The impossibility to detect such a particle left some members of the scientific community sceptical, but hints of energy conservation and of the existence of the neutrino were provided by measuring the energy spectrum of electrons emitted through beta decay, as there was a strict limit on their energy, as showed in Figure 2.9.

Figure 2.9: Energy spectrum of beta particles emitted by a source of $^{210}$Bi. Image by HPaul.

It’s only 30 years later in 1953 that it was discovered by the team of Cowan and Reines using the principle of inverse beta decay described through Formula 2.7 [91].

\[
\nu + p \rightarrow n + e^+ 
\]

The experiment consisted in placing water tanks sandwiched in between liquid scintillators near a nuclear reactor with an estimated neutrino flux of $5 \times 10^{13}$ cm$^{-2}$ s$^{-1}$. However, in order to explain the absence of some reactions in the experiment of Cowan and Reines and constraint the beta decay theory of Fermi and extend it to the case of the muon, Konopinski and Mahmoud proposed in 1953 that the muon decay would eject a particle similar to the neutrino [92]. They predicted the existence of a muon neutrino that would be different to the one involved in the beta decay, related to the electron. With this, the idea of lepton number arised. The muon neutrino was successfully detected in 1962 by Lederman, Schwartz, and Steinberger [93].

The theory could not be valid though as the probability of interaction, called cross-section, would have been increasing without limitation with the square of the energy. Fermi had proposed a two vector current coupling but Lee and Yang noted that an axial current could appear and would violate parity [94]. Gamov and Teller had already tried to account for such parity violation by describing Fermi’s interaction through allowed (parity-violating) and superallowed (parity-conserving) decays [95]. The Wu experiment in 1956 confirmed the parity violation [96], as showed by Figure 2.10.

But the success of QED as a quantum field theory sparked the development of similar theory to describe the weak interaction.

As previously discussed, the great success of QED was built on an underlying symmetry, interpreted as a gauge invariance so that the effect of the force is the same in all space-time coordinates, and of the possibility to renormalize it in order to resolve infinities. In 1967, Weinberg found a way to unite both the electromagnetic and weak interaction into a gauge theory involving four gauge bosons, three of which are massive and carry out the weak interaction and the last is a massless bo-
son carrying the electromagnetic interaction [97]. Among the three massive bosons, two are charged and one is neutral, similarly to the previously theorized pi meson vector of the Yukawa model [49] and all have a mass much greater than nucleons and thus a very short life time implying a finite very short range, contrary to the contact interaction originally proposed by Fermi.

![Diagram](image1)

Figure 2.10: As explained through (a), the Wu experiment consisted in measuring the preferred direction of emission of beta rays of a Co bulletin source placed in a stable magnetic field aligned, in one case, and anti-aligned, in the other case, with the nuclear spin (image by nagualdesign). The result in (b) showed a violation of parity [96].

Breakthroughs in other fields of physics contributed in giving theoretical support and interpretation to the unified electroweak theory. The stepping stone was the use of spontaneous symmetry breaking that was inspired to Nambu at the beginning of the 1960s [98, 99] following the development of the Bardeen–Cooper–Schrieffer (BCS) superconductivity mechanism in 1957 [100]. Cooper had shown that BCS pairs, pairs of electrons bound together at low temperature, can have lower energy than the Fermi Energy and are responsible for superconductivity. This led to the discovery of Goldstone-Nambu bosons [101, 102] as a result of the spontaneous breaking of the chiral symmetry in a theory describing nucleons and mesons developed by Nambu and Jona-Lasinio in 1961, and now understood as a low-energy approximation of QCD. Similarly to the mechanism of energy gap appearance in superconductivity, the nucleon mass is suggested to be the result of a self-energy of a fermion field and is studied through a four-fermion interaction in which, as a consequence of the symmetry, bound states of nucleon-antinucleon pairs appear and can be regarded as virtual pions. Though the symmetry is maintained in the equations, the ground state is not preserved. Goldstone showed that the bound states correspond to spinless bosons with zero mass [102].

Although the model in itself didn’t revolutionize particle physics, spontaneous symmetry breaking was generalized to quantum field theories. As all fundamental interactions are described using
gauge theories based on underlying symmetries, processes such as the chiral symmetry breaking were introduced soon after the publication of Nambu and Jona-Lasinio. In 1962, Anderson, discussed the implications of spontaneous symmetry breaking in particles physics [103]. He did so by following the idea of Schwinger who suggested that zero-mass vector bosons were not necessarily required to describe the conservation of baryons, contrary to the bosons emerging from chiral symmetry breaking [104]. A model was finally independently built in 1964 by Brout and Englert [105], Higgs [106], and Guralnik, Hagen, and Kibble [107], who discovered that combining an additional field into a gauge theory in order to break the symmetry, the resulting gauge bosons acquire a nonzero mass. Moreover, Higgs stated that this implied the existence of at least one new massive, i.e. self-interacting, scalar boson corresponding to this additional field, that is now known as Higgs boson. The Higgs mechanism today specifically refers to the process through which the gauge bosons of the weak interaction acquire mass. In 1967, Weinberg could point to the Higgs mechanism to integrate a Higgs field into a new version of the electroweak theory in which the spontaneous symmetry breaking mechanism of the Higgs field would explicitly explain the masses of the weak interaction gauge bosons and the zero-mass of photons [97].

2.1.2 Construction and validation of the Standard Model

The Standard Model of particle physics was built in the middle of the 1970s after the experimental confirmation of the existence of quarks [108]. It is based on the assembly of the models previously introduced and describing the fundamental interactions and their gauge bosons, except for gravitation, as well as the way elementary "matter" particles interact with the fields associated with these force carriers. In this sense, the development of QED and the unification of the electroweak interaction, of the Yukawa interaction and of QCD, and of the Higg mechanism made it possible to explain most of the contemporary physics.

In the SM, "matter" particles, are described by twelve fermion fields of spin $\frac{1}{2}$ obeying the Fermi-Dirac statistics, i.e. subjected to the Pauli exclusion principle. To each fermion is associated its corresponding anti-particle. The fermions are classified according to the way they interact and thus according to the charges they carry. Six of them are classified as quarks ($u$, $d$, $c$, $s$, $t$, and $b$) and are subjected to all interactions and the six others as leptons ($e^-$, $\mu^-$, $\tau^-$, $\nu_e$, $\nu_\mu$, and $\nu_\tau$). Leptons are not subjected to the strong interaction and among them, the three neutrinos only interact weakly as they are neutral particles, which explains why they are so difficult to detect. The gauge boson fields are the gluons $g$ for the strong interaction, the photon $\gamma$ for the electromagnetic interaction and the weak bosons $W^+$, $W^-$, and $Z^0$ for the weak interaction. Finally, the Higgs field $H^0$ is responsible, through the spontaneous symmetry breaking, of the mixing of the massless electroweak boson fields $W_1$, $W_2$, $W_3$, and $B$ leading to the observable states $\gamma$, $W^+$, $W^-$, and $Z^0$ that can gain mass while interacting with the Higgs field. This picture of the SM is summarized through Figure 2.11, where the antifermions are not shown.

When the model was first finalized, the existence of the weak gauge bosons, of the charm, of the third quark generation composed of top and bottom quarks to explain the observed CP violation was not proven but the predictions were measured with good precision in the years following [75–79]. The weak bosons $W$ and $Z$ were discovered during the next decade in 1983 [109,112]. The very last predicted elementary particle of the model that was not observed yet proved to be very difficult to observe. The Higgs boson needed the start of the LHC to finally be observed in 2012 [113,114]. A few years more of tests were necessary to measure its properties to confirm the observation of a scalar boson compatible with the predicted Higgs boson $H^0$ [115].
Investigating the TeV scale

In High-Energy Physics, the number of experimental events depends on the total interaction cross-section of the colliding particles and of the instantaneous luminosity \([116]\). The luminosity is a quantity providing an information on the interaction rate normalised to the interaction cross-section. The relationship between number of events \(N\), cross-section and instantaneous luminosity \(\mathcal{L}\) is given in Formula (2.8)

\[
\mathcal{L} = \frac{1}{\sigma} \frac{dN}{dt} \quad \Leftrightarrow \quad N = \sigma \int \mathcal{L} \, dt = \sigma \mathcal{L}_{\text{int}}
\]

The integral of the luminosity over time is referred to as the integrated luminosity \(\mathcal{L}_{\text{int}}\). In fact, the instantaneous luminosity can be deduced from the beam parameters. New colliders now use bunched beams. The instantaneous luminosity then depends on the bunch crossing frequency \(f_{BX}\), on the number of particles contained in each bunch \(n\), and on the RMS transverse beam sizes in the...
horizontal, $\sigma_x^*$, and vertical directions, $\sigma_y^*$, at the level of the interaction point. The beam sizes can be assumed to be identical, leading to the relation of Formula 2.9.

$$\mathcal{L} = \int_B \frac{n^2}{\sigma^*}$$

This expression doesn’t depend on time anymore and leads to a simple estimation of the integrated luminosity and hence, knowing the cross-section of each available physics channel, to the expected number of events in each channel. The total interaction cross section is the sum of all the different output channels allowed by the interaction process. In the case of highly relativistic protons, the proton-proton (pp) total cross-section increases with the center-of-mass energy of interactions, as can be seen from Figure 2.12.

Enhancing rare processes that allow to finely test the Standard Model is then achieved through an increase in both energy and luminosity. At the energy range that were scanned thanks to high-energy colliders, the SM has so far been a well tested theory. Nevertheless, several hints of physics going beyond its scope have been observed.

**Dark matter and gravity:** The discrepancy of velocity dispersion of stars in galaxies with respect to the visible mass they contain is known since the end of the 19th century where Kelvin proposed that this problem could be solved if a great majority of the stars would be dark bodies, idea strongly criticized by Poincaré [119]. Throughout the 20th century, physicists like Kapteyn [120] or Zwicky [121, 122], showed the first hints of a dark matter by studying star velocities and galactic clusters, followed by robust measurements of galaxy rotation curves by Babcock which suggested that the mass-to-luminosity ratio was different from what would be expected from watching the visible light [123]. Later in the 1970s, Rubin and Ford from direct light observations [124] and Rogstad and Shostak from radio measurements [125] showed that the radial velocity of visible objects in galaxies was increasing with increasing distance to the center of gravity.
the galaxy. An example of galaxy rotation curve is provided in Figure 2.13. Finally, observation of lensing effect by galaxy clusters, temperature distribution of hot gas in galaxies and clusters, and the anisotropies in the Cosmic Microwave Background (CMB), showed in Figure 2.13, kept pointing to dark matter [126]. From all the data accumulated, the visible matter would only account to no more than 5% of the total content on the visible universe [127]. Alternative theories have tried to investigate modified versions of the General Relativity as this theory is only well tested at the scale of the solar system but is not sufficiently tested on wider ranges or even theories in which gravitation is not a fundamental force but rather an emergent one [128, 129]. But so far, such theories have difficulties to reproduce all the experimental observations as easily as through dark matter.

A possible theory to offer dark matter candidates would be supersymmetry (SUSY) which proposes a relationship in between bosons and fermions in the frame of the Minimal Supersymmetric Standard Model (MSSM). In this model, each elementary particle, through a spontaneous space-time symmetry breaking mechanism would have a super partner from the other family of particles, pairing bosons and fermions together. The model was first introduced as a way to solve the Hierarchy Problem [131]. The discrepancy between the strength of the weak force and gravity translates into a light Higgs boson compared to the Planck Mass. In the SM, the Higgs mass is left to be a measured parameter rather than a calculated one even though the model requires a mass in between 100 and 1000 GeV/c² to stay unitary. Nevertheless, quantum corrections to the Higgs mass coming from its interactions with virtual particles should make the scalar boson much heavier than what measured [132]. Through the MSSM, the stability of fermion masses would provide stability to the Higgs boson mass via the introduction of a fermionic super partner.

On top of providing a solution to the Hierarchy Problem, the model comes with heavy dark matter candidates in the TeV scale [133]. Indeed, in the case R-parity is not violated, the lightest supersymmetric particle (LSP) cannot decay and could then explain the dark matter. The LSP in the model is neutral and can only interact through the weak and gravitational interactions. Typical candidates are the neutralino, the sneutrino or the gravitino.

Finally, gravity is not explained through the SM, and huge difficulties are encountered when trying to include it. The strength of gravitational interaction is expected to be negligible at the scale of elementary particles, nevertheless, adding gravitation in the perspective of developing a “theory of everything” leads to divergent integrals that could not be fixed through renormalization. Extensions to the MSSM, and in particular minimal SUper GRAvity (mSUGRA), include general relativity as mediator of the symmetry breaking. mSUGRA gives access to the hidden sector in which the MSSM only interacts gravitationally and suppresses the infinities arising from attempts to include gravity into the SM thanks to possible renormalization [134].

Signatures for the MSSM would come from the super partners of quarks and gluons that can...
decay into an LSP that could then be identified as missing energy as it escapes the detectors undetected. But even in the case MSSM predictions are not to be seen, the other models treating dark matter also propose Weakly Interacting Massive Particles (WIMPs) that could be observed in similar ways than LSPs [135]. Moreover alternative models exist to provide solutions to the Hierarchy Problem. The most investigated models are extra dimensions such as Arkani-Hamed Dimopoulos Dvali [136][137], Kaluza–Klein [138][139] or Randall-Sundrum models [140][141] that usually also include gravitation. Finally, alternative models also exist for the production of dark matter candidates. Models with a hidden valley that would unravel the existence of a new group of light particles through the extension of the SM with a new confining gauge group [142].

![Figure 2.14](image_url) Cosmic Microwave Background as measured by the space observatory Planck which mean temperature is \( T_\gamma = (2.7255 \pm 0.0006) \text{K} \) with anisotropies of the order of a few \( \mu \text{K} \). Image by ESA and the Planck Collaboration.

**Baryon asymmetry:** Another intriguing fact is that the universe is dominated by matter. However, the SM predicted that matter and antimatter should have been created in equal amounts. For an interaction to produce matter and antimatter at different rates within the SM, three necessary conditions were highlighted by Sakharov [143]. First of all, there must be a violation of the baryon number \( B \). Then, there must be a C-symmetry and CP-symmetry violation. The C-symmetry violation must happen to make sure that the processes creating more baryons than antibaryons are not compensated by processes creating more anti-baryons and similarly, the CP-symmetry violation makes sure that there are not equal numbers of left-handed baryons and right-handed anti-baryons produced. Finally, the interactions must happen out of thermal equilibrium to make sure that CPT-symmetry does not balance the processes increasing the baryon number with processes doing otherwise [144]. An out-of-equilibrium interaction implies a new instable heavy particle.

The favoured model to explain this imbalance is the *baryogenesis* that requires electroweak symmetry breaking to be first order phase transition to fall within the scope of SM [145][146]. This means that the symmetry breaking process must involve the absorption or release of a fixed latent heat. Through the baryogenesis, the phase transition breaks P-symmetry spontaneously and allows for CP-symmetry violation. In turn, the CP violation makes the amplitude of interactions involving quarks different than the ones involving anti-quarks leading to the greater creation rate of baryons with respect to anti-baryons. The key to this baryon net creation would be found into the *sphaleron*. 
A sphaleron is a particle-like saddle point of the energy functional that appears at the top of the transition barrier and that could be created if a sufficiently large amount of energy is brought as the tunneling effect through the barrier is largely suppressed for electroweak interactions. The existence of the sphaleron would allow violation of the conservation of $B$ but also of the leptonic number $L$ while conserving $B - L$. The detection at $p - p$-colliders of such a transition is foreseen to be made through processes with high-multiplicity final states such as $u + u \rightarrow e^+ \mu^+ \tau^+ \bar{b} \bar{c} \bar{s} \bar{d} + X$ [147]. To be probed, the sphaleron transition requires an energy $E_{sph} \approx 9$ TeV. Nevertheless, if such transition cannot be observed, other BSM models such as the WIMP baryogenesis could be then observed thanks to the detection of displaced vertices, featuring the decay of a WIMP leading to violation of $B$ [148].

Another possibility to explain the apparent asymmetry would be the existence of an electric dipole moment (EDM) in any fundamental particle that would permit matter and antimatter particles to decay at different rates [149]. Indeed, the presence of an EDM violates in itself both $P$ and $T$ symmetries. Experiments are able to probe for the EDM of various fundamental particles such as the electron [149], the charm and strange quarks [150] or even a heavy neutrino EDM [151].

**Neutrino mass and sterile neutrino scenario:** The SM considers neutrinos to be massless. But it was showed in the late 1960s by the Homestake experiment that the flux of solar neutrinos (i.e. $\nu_e$) measured didn’t match the predicted values [152]. The mechanism of neutrino oscillations as a solution to the discrepancy was proposed by Pontecorvo [153] and confirmed in the early 2000s by the Sudbury Neutrino Observatory [154]. This oscillation implies that neutrinos that can be observed are a superposition of massive neutrino states. The research on neutrino oscillation is already quite advanced with experiments looking at atmospheric, reactor or beam neutrinos in order to determine the elements of the mixing matrix (Pontecorvo–Maki–Nakagawa–Sakata matrix [155]) similar to the Cabibbo–Kobayashi–Maskawa (CKM) matrix describing the mixing of quarks [73]. Nevertheless, no answer to the origin of neutrino mass is yet provided.

Explaining the light non-zero mass of the neutrinos $\nu_l$ ($l = e, \mu, \tau$) of the order of the eV can be done through the Seesaw mechanism [156, 157]. This model features heavy Majorana counterparts $N_l$ ($l = e, \mu, \tau$) to the $\nu_l$. The masses of the light and heavy neutrinos are linked through a $2 \times 2$ mass matrix $A$ with eigenvalues $\lambda_{\pm}$ expressed as in Equation 2.10.

$$A = \begin{pmatrix} 0 & M \\ M & B \end{pmatrix}$$

$$\lambda_{\pm} = \frac{B \pm \sqrt{B^2 + 4M^2}}{2}$$

The Majorana mass term $B$ is assumed to be comparable to the Grand Unified Theory scale ($10^{16}$ GeV) while the Dirac mass term $M$ is of the order of electroweak scale (246 GeV). In these conditions, the eigenvalue $\lambda_+$ is almost $B$ while $\lambda_-$ is close to the ratio $M^2 / B$ compatible with very light neutrinos with masses of the order of 1 eV. Studying the left-right symmetric model seeking for the parity violation in weak interactions leads to the incorporation of three additional gauge bosons $W_R$ and $Z'$ as a result of the spontaneous symmetry breaking. The processes that are predicted by the model and can be probed at colliders are processes such as $pp \rightarrow W_R \rightarrow l + N_l + X$ and $pp \rightarrow Z' \rightarrow N_l + N_l + X$ where the heavy neutrinos decay as $N_l \rightarrow l + j_1 + j_2 + j_3$ being jets [158]. Other versions of the Seesaw mechanism exist to account for the neutrino mass that can also be explained thanks to supersymmetric models [159].
2.2 The Large Hadron Collider & the Compact Muon Solenoid

Throughout its history, CERN has played a leading role in high-energy physics. Large regional facilities such as CERN were planned after the second world war in an attempt to increase international scientific collaboration and to allow scientists to share the forever increasing costs of experimental facilities. Indeed, it is necessary to use always more powerful tools to improve the fine understanding of our Universe. The construction of the first CERN accelerators at the end of the 50s, the Synchrocyclotron (SC) and the Proton Synchrotron (PS), was directly followed by the first observation of antinuclei in 1965 [160]. The very first proton-proton collider showing hints of protons not being elementary particles was the Intersecting Storage Rings (ISR). From this experience, the Super Proton Synchrotron (SPS) was built in the 70s to investigate the structure of protons, the preference for matter over antimatter, the state of matter in the early universe or exotic particles, and led to the discovery in 1983 of the W and Z bosons [109–112]. These newly discovered particles and the electroweak interaction were then studied in detail by the Large Electron-Positron (LEP) collider that proved that there only are three generations of elementary particles in 1989 [161]. The LEP was then dismantled in 2000 to allow for the LHC to be constructed in the existing tunnel.

2.2.1 LHC, the most powerful particle accelerator

![CERN accelerator complex](image-url)

The different aspects of physics beyond the Standard Model of particle physics and the Standard Model itself can be tested through the use of very energetic and intense hadron and ion colliders. Powerful hadron colliders are suited for searching for strongly interacting particles. The LHC at
CERN is a perfect tool to seek answers to these open questions and the experiments build along its beam lines already started investigating further into the SM and BSM physics.

The LHC has always been considered as an option for the future of CERN. At the moment of the construction of the LEP beneath the border between France and Switzerland, the tunnel was built in order to accommodate what would be a Large Hadron Collider with a dipole field of 10 T and a beam energy in between 8 and 9 TeV [162]. In 1985, the creation of a ‘Working Group on the Scientific and Technological Future of CERN’ took place to investigate such a collider [163]. The decision was finally taken almost ten years later, in 1994, to construct the LHC in the LEP tunnel [164] and the approval of the 4 main experiments that would take place at the four interaction points came in 1997 [165] and 1998 [166].

- ALICE [167] has been designed for the purpose of studying the confinement of quarks through exploration of the quark-gluon plasma that is believed to have been a state of matter that existed in the very first moment of the universe.

- ATLAS [168] and CMS [169] are general purpose experiments that have been designed with the goal of continuing the exploration of the Standard Model and the investigation of new physics.

- LHCb [170] has been designed to investigate the preference of matter over antimatter in the universe through CP violation.

These large-scale experiments, as well as the full CERN accelerator complex, are displayed in Figure 2.15. The LHC is a 27 km long hadron collider and the most powerful accelerator used for particle physics since 2008 [171]. The LHC is designed to collide protons at a center-of-mass energy of 14 TeV and luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, as well as Pb ions at a center-of-mass energy of 2.8 TeV/A with a peak luminosity of $10^{27}$ cm$^{-2}$s$^{-1}$. The collider is the last of a long series of accelerating devices. Indeed, before being accelerated by the LHC, the particles need to...
pass through different acceleration stages. All these acceleration stages are visible on Figure 2.15 and pictures of the accelerators are shown in Figure 2.16.

The story of accelerated protons at CERN starts with a bottle of hydrogen gas injected into the source chamber of the linear particle accelerator LINAC 2 in which a strong electric field strips the electrons off the hydrogen molecules only to keep their nuclei, the protons. The cylindrical conductors then accelerate the protons to an energy of 50 MeV. When exiting the LINAC 2, the protons are divided into four bunches and injected into the four superimposed synchrotron rings of the Booster where they are then accelerated to reach an energy of 1.4 GeV before being injected into the PS. The four proton bunches are hence sent as one to the PS where their energy eventually reaches 26 GeV. The PS not only accelerates protons. It also accelerates heavy ions from the Low Energy Ion Ring (LEIR). Lead is first injected into the dedicated linear collider LINAC 3, that accelerates the ions. Electrons are stripped off the lead ions all along the acceleration process and eventually, only bare nuclei are injected in the LEIR whose goal is to transform the long ion pulses received into short dense bunches for LHC. Ions injected and stored in the PS were accelerated by the LEIR from 4.2 MeV to 72 MeV. Directly following the PS, is finally the last acceleration stage before the LHC, the 7 km long SPS. The SPS accelerates the protons to 450 GeV and inject them in both LHC accelerator rings that will increase their energy up to 7 TeV. When the LHC runs with heavy lead ions for ALICE and LHCb, ions are injected and accelerated to reach the energy of 2.8 TeV/A.

The LHC beams are not continuous but are rather organised in bunches of particles. When in pp-collision mode, the beams are composed of 2808 bunches of $1.15 \times 10^{11}$ protons separated by 25 ns. When in Pb-collision mode, the 592 Pb bunches are on the contrary composed of $2.2 \times 10^8$ ions separated by 100 ns. The two parallel proton beams of the LHC are contained in a single twin-bore magnet due to the space restriction in the LEP tunnel. Indeed, building two completely separate accelerator rings next to each other was impossible. The dipoles of the 1232 twin-bore magnets are shown in Figure 2.17 alongside the magnetic field generated along the dipole section to accelerate the particles. The dipoles generate a nominal field of 8.33 T, needed to give protons and lead nucleons their nominal energy. Some 392 quadrupoles, presented in Figure 2.18, are also used to focus to the beams, as well as other multipoles to correct smaller imperfections.
2.2.2 Timeline of operation

LHC accelerated its first proton in September 2008 but the first collisions only started one year later in November 2009. At this moment the LHC machine officially became the world’s most powerful particle accelerator and entered its Physics Run 1 that lasted until February 2013. During Run 1 of the LHC program, the center-of-mass energy was only half of the nominal LHC energy. Nevertheless, the energy and luminosity displayed during Run 1 were enough for both CMS and ATLAS to discover the Higgs boson [113, 114] as showed in Figure 2.19 and for LHCb to discover pentaquarks [172] and confirm the existence of tetraquarks [173]. During this period, ALICE also reported a successful observation of the quark-gluon plasma aimed at studying the early universe [174], ATLAS reported the observation of a new particle before the discovery of the Higgs [175] and a first test of super-symmetric models was performed [176].

Run 1 was brought to an end with the start of the First Long Shutdown, an almost two years technical stop aimed at increasing the energy of the center-of-mass collisions to $\sqrt{s} = 13$ TeV.
as well as the instantaneous luminosity. This maintenance stop was also effectively used by the experiments which upgraded part of their detection systems. Run 2 then started in 2015 and lasted until end of 2018 where the activities ended with a last heavy ion run. During the operation, the instantaneous was successfully brought to a value of $1.7 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ exceeding the design value. Run 2 has been the occasion to acquire more data to study the properties of the Higgs boson with more precision. The boson discovered in the first physics run seems to be consistent with the SM Higgs boson [115].

![Luminosity Timeline](image)

**Figure 2.20:** Detailed timeline projection of LHC and HL-LHC operation until 2039 showing the evolution of the instantaneous and integrated luminosity as designed (a) and in the ultimate case where the instantaneous luminosity is increased to $7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ thanks to a new increase of instantaneous luminosity during Run 5 (b) [177–179].

From the end of 2018 to early 2021 the Second Long Shutdown will take place. This second maintenance stop will be the occasion to boost once again the beam energy to finally reach the design energy of LHC, 14 TeV. On the side of the maintenance work, preliminary work for the High Luminosity LHC will be performed. The preparations will consist of detector, on the side of the
experiments, and beam machine upgrades, on the side of LHC. In 2021, the physics program will be resumed with an instantaneous luminosity fixed at $2 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. During these 3 years of run, the LHC will deliver as much integrated luminosity as what what brought during the almost 7 years of both Run 1 and 2 of data taking. Phase-1 will end with an overall $300 \text{fb}^{-1}$ delivered. The timeline so far described is summarized through the evolution of the instantaneous luminosity and of the corresponding integrated luminosity provided in Figure 2.20.

After the Third Long Shutdown (2024-2026) that will close the activities of Run 3, the accelerator will enter the HL-LHC configuration [177], increasing the instantaneous luminosity to an unprecedented level of $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ for pp-collisions ($4.5 \times 10^{27} \text{cm}^{-2} \text{s}^{-1}$ for Pb-collisions), boosting the discovery potential of the LHC. The HL-LHC phase should last at least another 10 years depending on the breakthrough this machine would lead to. Already a new accelerating device, the FCC, as been proposed and is being investigated to prepare the future of high-energy physics after the LHC.

### 2.2.3 High Luminosity LHC

After approximately fifteen years of operation, the LHC will undergo a new series of upgrades during the LS3 in order to boost its discovery potential as previously discussed. The period after LS3 is what is referred to as HL-LHC or Phase-2. The goal is to aim for a luminosity 5 to 7 times stronger than the nominal one trying to reach even 10 times this value if possible [177, 178]. Increasing the luminosity means that the beam size at the collision points needs to be reduced to boost the number of collisions per bunch crossing. For this purpose, new focusing and bending magnets and collimators will be installed at the collision points as well as newly developed "crab cavities" that will tilt the particle bunches just prior to the collisions by giving them transverse momentum and thus increasing their meeting area. In addition, the full proton injection line will be upgraded.

On the experiments side, the pile-up (PU) will be increased up to 150 to 200 interactions per bunch crossing in ATLAS and CMS, making necessary a strong upgrade of the trigger system and of the inner trackers and of the calorimeters. Both ATLAS and CMS will also need to upgrade the muon trigger at the level of their endcaps mainly focusing on the coverage near the beam line in order to increase the detection acceptance and event selection. Moreover, the increased luminosity will also lead to an increased background rate and a faster ageing of the detectors.

The end of 2018 marked the beginning of LS2 and the start of Phase-2 upgrade activities. From the HL-LHC period onwards, i.e. past LS3, the performance degradation due to integrated radiation as well as the average number of inelastic collisions per bunch crossing will rise substantially. This has become a major challenge for all of the LHC experiments, like CMS, that were forced to address an upgrade program for Phase-2 [179]. Dealing with the data from the muon detectors will force to upgrade the detectors and electronics towards the most recent technologies.

### 2.2.4 The Compact Muon Solenoid experiment

Among the four main LHC experiments is the Compact Muon Solenoid used as a multipurpose tool to investigate the SM and the physics beyond its scope. The CMS apparatus in itself is the heaviest detector ever built starring a 15 m diameter and a 29 m length for a total weight of 14 kT. A thick 4 T solenoid magnet located at the beam interaction point hosts trackers and calorimeters. Extending in all directions around the magnet, heavy iron return yokes are installed to extend the magnetic field and support a muon system. The apparatus consists of a barrel, referring to the magnet
and the detectors contained in it and the part of the muon system built directly in the cylinder around the magnet, and of two endcaps in the forward and backward region of the detector that closes the apparatus and complete the detection coverage along the beam line. A front view on the barrel is provided in Figure 2.21 while a detailed view of the apparatus is given in Figure 2.22.

In order to efficiently detect all long living particles and measure their properties with good precision, the CMS detector uses an onion like layout around of the interaction point in order to maximize the covered solid angle. As detailed in Figure 2.23, in the innermost region of the detector, closest to the interaction point, the silicon tracker records the trajectory of charged particles. Around it, the electromagnetic calorimeter (ECAL) stops and measures the energy deposition of electrons and photons. In the next layer, the hadron calorimeter (HCAL), hadrons are stopped and their energy measured. These layers are contained inside of the magnet of CMS, the superconducting solenoid. Outside of the magnet are the muon chambers embedded into iron return yokes used to control the magnetic field and gives muons, the only particles traveling completely through the whole detector, a double bending helping in reconstructing their energy and trajectory. Note that photons and neutral hadrons are differentiated from electrons and charged hadrons in the calorimeters by the fact that they don’t interact with the silicon tracker and are not influenced by the magnetic field, as can be seen in Figure 2.23.

Figure 2.21: Picture of the CMS barrel. The red outer layer is the muon system hosted into the red iron return yokes. The calorimeters are the blue cylinder inside in magnet solenoid and the tracker is the inner yellow cylinder built around the beam pipe. Image by CERN.

Figure 2.22: View of the CMS apparatus and of its different components. Image by CERN.
2.2.4.1 The silicon tracker

The silicon tracker visible in Figure 2.24 is divided into two different sub-systems: the pixel detector at the very core and the microstrip detector around it. This system is composed of 75 million individual read-out channels with up to 6000 channels per squared centimeter for the pixels making it the world’s biggest silicon detector. This density allows for measurements of the particle tracks with a precision of the order of $10 \mu m$. This is necessary to reconstruct all the different interaction vertices with precision and have a precise measure of the curvature of the charged particles traveling through the magnetic field to estimate their charge and momentum.

2.2.4.2 The calorimeters

The ECAL directly surrounding the tracker is composed of crystals of lead tungstate, $PbWO_4$, a very dense but optically transparent material used to stop high-energy electrons and photons. These crystal blocks basically are extremely dense scintillators which scintillate in fast, short light bursts proportionally to the energy deposition. The light is contained at 80% in the corresponding 25 ns
lasting bunch crossing. Each crystal is isolated from the other by the carbon fiber matrix they are embedded in.

![Figure 2.25: (a) The electromagnetic calorimeter. (b) The lead tungstate crystals composing the ECAL. Images by CERN.](image1)

The ECAL is composed of a barrel containing more than 60,000 crystals and of closing endcaps containing another 15,000 crystals. In front of the ECAL endcap is installed a preshower detector made out of two layers of lead and silicon strip detectors to increase the spatial resolution close to the beam line for pion-photon and single-double photon discrimination purposes. Figure 2.25 shows the calorimeter inside of the magnet and the crystals.

![Figure 2.26: The CMS hadron calorimeter barrel. Image by CERN.](image2)

The next layer is the HCAL. The role of these forward calorimeters, made using steel and quartz fibers, is to precisely measure the momentum very energetic hadrons. Several layers of brass or steel are interleaved with plastic scintillators readout by photodiodes using wavelength-shifting fibers. The HCAL is also composed of a barrel, shown in Figure 2.26 and of endcaps. It also features forward calorimeters on both sides of CMS in the region very close to the beam line at high pseudorapidity (3.0 < |η| < 5.0).

### 2.2.4.3 The muon system

Finally, in the outer region of the apparatus, a muon system is used to trigger on potentially interesting event by identifying muons. Three different subsystems compose the muon system as shown in Figure 2.27 in which a quadrant of the CMS detector focuses on muon system. Drift Tubes (DTs) are found in the barrel region covering the low pseudorapidity region where particles transverse momentum is lower and Cathode Strip Chambers (CSCs) are found in the endcap region covering higher pseudorapidity region closer to beam line where particles have a stronger momentum. The redundancy of the system is insured by Resistive Plate Chambers (RPCs) in both the barrel and endcap. Nevertheless, the region closest to the beam line (|η| > 1.8) was not equipped with RPCs. This
lack of redundancy in the high pseudo rapidity region will be solved during LS2, the following Year End Technical Stop (YETS) in 2021 and 2022, and LS3 where the necessary services, detectors and Link System, that collects the data and synchronizes them, will be installed.

2.2.5 Description of the muon system

Figure 2.27: A quadrant of the muon system, showing DTs (yellow), RPCs (blue), and CSCs (green) [180].
The barrel region is divided into five wheels made out of four rings of detectors with iron return yokes between them. The endcaps are made out of four disks, each divided into pseudorapidity stations, two for CSCs (except for the first disk where three stations are equipped) and three for RPCs. Only two RPCs stations are equipped at present. The wheels and disks are shown in Figure 2.28. So far, each subsystem was dedicated to a particular task. DTs, in the barrel, and CSCs, in the endcaps, are used mainly for their spatial resolution. Indeed, DTs’ resolution is of the order of 100 \( \mu m \) along both the \( (r - \phi) \) and \( (r - z) \) components while the resolution of CSCs is similar but varies in a range from 50 \( \mu m \) to 140 \( \mu m \) depending on the distance to the beamline. On the other hand, RPCs are used as redundant detection system in the whole muon system. They display a very good intrinsic time resolution of 1.5 ns although the electronics only provide bunch crossing information with a time resolution of 25 ns.

### 2.2.5.1 The Drift Tubes

The 250 CMS DTs, found in the barrel covering the pseudorapidity region \( 0 < |\eta| < 1.2 \) and whose structure is shown in Figure 2.29, are composed of three superlayers of DT cells. Two of these superlayers are dedicated to measuring the \( \phi \) coordinate of the muons and while the last one measures the \( \eta \) (or \( z \)) coordinate. Each superlayer consists on four layers of 60 to 70 DT cells arranged in quincunx to allow for a precise reconstruction of the muon path through the DT layers. Each DT cell is a rectangular aluminium gas volume with a central anode wire. Cathode strips are placed on the narrow surface of the cells and electrode strips are placed on the wide surface to help shaping the electric field to ensure a consistent drift velocity of electrons in the drift volume. These detectors are operated using a 85/15 mixture of Ar and CO\(_2\). Outside the gas volume of each DT chamber is attached a Minicrate electronics (MiC) that hosts both read-out and trigger electronics.

![Figure 2.29: Cross section of a DT module showing the two superlayers measuring the \( \phi \) coordinate, perpendicular to the cross section plane, and the superlayer measuring the \( \eta \) coordinate, placed in between the two others with a honeycomb plate and parallel to the cross section plane. The DT detector is sandwiched in between 2 RPCs whose readout strips are perpendicular to the cross section plane, measuring the \( \phi \) coordinate.](image)

(a) A DT cell is shown together with its electric field. The path of a muon through a superlayer is shown [181].
2.2.5.2 The Cathode Strip Chambers

![Diagram of cathode strips and anode wire layout](image1)

**Figure 2.30:** (a) Cathode strips and anode wire layout of a CSC panel. (b) Avalanche development and charge collection by anode wires and induction on cathode strips inside of a CSC panel [182].

![Diagram of muon track reconstruction](image2)

**Figure 2.31:** Muon track reconstruction through the six panels of a CMS CSC using the information of anode wire groups and cathode strip charge distribution combined with comparator bits to decide on which half strip the muon is more likely to have passed [183].

The 540 CMS CSCs are found in the endcaps covering the pseudorapidity region $0.9 < |\eta| < 2.5$ and described through Figures 2.30 and 2.31. Each module is composed of six panels of CSC, each panel consisting in a wide gas volume of 9.5 mm (7 mm in the case of ME1/1 station) containing anode wires and whose surfaces are cathodes. The top cathode is a wide copper plane of the size of the gas volume. The bottom cathode is divided into thin trapezoidal copper strips radially arranged to measure the azimuthal coordinate $\phi$ with a pitch ranging from 8 to 16 mm. The 0.50 $\mu$m anode wires are placed perpendicularly to the strips to measure radial coordinate $r$ and are grouped by ten to fifteen with a wire to wire distance of 3.2 mm. In the specific case of ME1/1 placed against the HCAL endcap, the 0.30 $\mu$m anode wires have a wire to wire distance of 2.5 mm and are not disposed perpendicularly to the strips but slightly tilted by an angle of 29 deg to compensate for the
lorentz force due to the very strong local magnetic field of 4 T. These detectors are operated with a 40/50/10 mixture of Ar, CO₂ and CF₄. Combining the information of the multiple CSC panels, the detectors achieve a very precise measurement of the muon track. The read-out of the cathode strip signals is performed by cathode front-end boards (CFEBs) mounted on the detectors. The boards are used to collect and digitize the charge of the signals and transfer it to off-chamber electronics called Data acquisition mother boards (DMBs). In parallel, the data from the CFEBs together with the data from the anode wires, after treatment by on-chamber electronics called Anode local charged track boards (ALCTs), is used to build a fast trigger information which is sent other off-chamber electronics called Trigger mother boards (TMBs).

2.2.5.3 The Resistive Plate Chambers

Despite their excellent spatial resolution, the wire chambers (DTs and CSCs) are limited in terms of time resolution by the fact that the charge needs to drift towards the anode wire and be collected before having the confirmation that a particle was detected as the drift volume is not used to develop avalanches. Indeed, the stronger electric field close to the anode wire triggers the avalanche and the gain of the detector. Due to the drift, the time resolution is thus limited at best to approximately 2 to 3 ns. In addition, even though the intrinsic time resolution of the tracking chambers is rather good compared to the 25 ns in between successive collisions, the processing time of the trigger system doesn’t allow for very fast triggering as it provides a time precision of only 12.5 ns. Thus, detectors fully dedicated to timing measurement have been installed as a redundant system. These detectors are RPCs, also gaseous detectors but that use current induction instead of charge collection allowing for a time resolution of the order of 1 ns only. Theoretically, depending on the design used, RPCs could reach a time resolution of the order of 10 ps but in the context of LHC where bunch crossing happen every 25 ns, a time resolution of 1 ns is sufficient to accurately assign the right bunch crossing to each detected muon.

The 1056 RPCs equip the CMS muon system both in the barrel and endcap regions and cover the pseudorapidity region 0 < |\( \eta \) | < 1.6. They are composed of two layers of RPC gaps as described in Figure 2.32. Each gap consists in two resistive electrodes made out of 2 mm thick Bakelite enclosing a 2 mm thick gas volume containing a 95.2/4.5/0.3 mixture of \( C_2H_2F_4 \), \( i-C_4H_{10} \) and \( SF_6 \). Due to this geometry, the electric field inside of a gap is homogeneous and linear at every point in the gas translating into a uniform development of avalanches in the gas volume as soon as a passing muon ionises the gas. The two gaps sandwich a readout copper strip plane. A negative voltage is applied on the outer electrodes, used as cathodes, and the inner electrodes, the anodes, are simply connected to the ground as well as the readout panel that picks up the current induced by the accumulated charge of the growing avalanches in one or both of the gas gaps. This OR system allows for a lower gain (i.e. a lower electric field) on both gaps to reach the maximal efficiency of such a detector.

Figure 2.32: Double-gap layout of CMS RPCs [184]. Muons passing through the gas volumes will create electron-ions pairs by ionising the gas. This ionisation will immediately translate into a developing avalanche.
In the barrel, each layer of RPCs is made out of twelve sectors for a full $2\pi$ coverage. A wheel consists in four detector stations corresponding to a same radius $R$ around the beam line as can be seen in Figure 2.33. Both the two first stations are equipped with two RPC layers, one on each side of a DT module. On the other stations, further away to the beam line, a single layer of two RPCs placed side by side is installed along each DT chamber with some exceptions for the fourth station. The barrel RPCs are labeled "RB$n \pm w\"$, where $n$ is the station number increasing with $R$ and $\pm w$ is the wheel number ($w = 0$ corresponds to the central wheel). On each layer, the RPCs are distinguished thanks to extra "in" and "out" (stations 1 and 2) or "- and +" (stations 3 and 4).

In the endcap, the detectors are mounted on the disks on three rings, two of which are equipped with RPCs, that can also be referred to as stations. A view of an RPC endcap disk can be seen in Figure 2.34. Contrary to the barrel stations, the endcap stations correspond to detectors mounted at a similar $z$ value. Indeed, in this case the detectors are orthogonal to the beam line. Each ring covers a different $R$ range and is composed of 36 trapezoidal detectors. The endcap RPCs are labeled "RE$\pm n/r\"$, where $n$ is the station number, i.e. the endcap disk, and $r$ is the ring number increasing with $R$.

Finally, the RPC read-out is segmented along the $z$-coordinate in the barrel and along the $R$-coordinate in the endcap. This segmentation aims at dividing the read-out into several pseudo-rapidity ranges for particle assignment. At the level of a single chamber, the pseudo-rapidity segmentation is referred to as partition. At the level of the full system, the read-out segments corresponding to the same pseudo-rapidity range are called rolls. In the barrel, the read-out is divided along $z$ into two partitions except for some RB2 detectors that have three partitions. In the endcap, all the current detectors feature three partitions along $R$.

![Figure 2.33: View of the positions of DT and RPC detectors in barrel Wheel W+2 Image by CMS.](image-url)
Figure 2.34: View of the positions of RPC detectors in endcap Disk +2 [185]. The first ring corresponding to RE+2/1 is not equipped with RPC detectors.
Physics of Resistive Plate Chambers

The Resistive Plate Chamber (RPC) has been developed in 1981 by Santonico and Cardarelli [186], under the name of Resistive Plate Counter, as an alternative to the local-discharge spark counters proposed in 1978 by Pestov and Fedotovich [187],[188]. Working with spark chambers implied using high-pressure gas and high mechanical precision which the RPC simplified by formerly using a gas mixture of argon and butane at atmospheric pressure and a constant and uniform electric field generated in between two parallel electrode plates. Moreover, a significant increase in rate capability was introduced by the use of electrode plate material with high bulk resistivity, preventing the discharge from growing throughout the whole gas gap. Indeed, the effect of using resistive electrodes is that the constant electric field is locally canceled out by the development of the discharge, limiting its growth.

Through its development history, different operating modes [189–191], gas mixtures [186, 191–196] and new detector designs [197–199] have been discovered, leading to further improvement of the rate capability of such a detector. The low construction costs and easily achievable large detection areas offered by RPCs, as well as the wide range of possible designs, made them a natural choice as muon chambers and/or trigger detectors in multipurpose experiments such as CMS [181] or ATLAS [200], time-of-flight detectors in ALICE [201], calorimeters with CALICE [202] or even detectors for volcanic muography with ToMuVol [203].

In this chapter, the general operating principles of RPCs will be introduced leading to a deeper description of the parameters having an influence on the rate capability and the time resolution of such detectors. Even though the principle behind the operation of RPCs might seem straightforward, attempts at proposing a model of the signal formation inside of the gas volume have so far failed at fully explaining what can be observed from the data. A detailed summary of the understanding of RPC physics will be provided. Finally, more practical information will be given on the influence of the environment on the operation of a real detector. The changing conditions might alter the collected data and needs to be addressed in order to limit the systematics on the final results.
3.1 Principle

RPCs are proportional counters composed of two parallel resistive plate electrodes in between which a constant electric field is set. The space in between the electrodes, referred to as gap, is filled with a gas that is used to generate primary ionization into the gas volume. The free charge carriers (electrons and cations) created by the ionization of the gas molecules are then accelerated towards the electrodes by the electric field, as shown in Figure 3.1 [204]. Since RPCs are passive detectors, a current on copper pick-up strips or pads placed outside of the gas volume is induced by the charge accumulation during the growth of the avalanche resulting from the acceleration of the charge carriers. As a consequence, the time resolution of the detector is substantially increased compared to detectors using charge collection at the level of the electrode as the output signal is generated by the movement of the electrons in the electric field. The advantage of a constant electric field, over multi-wire proportional chambers, is that the electrons are being fully accelerated from the moment charge carriers are freed. They feel the full strength of the electric field that doesn’t depend on the distance to the readout.

![Figure 3.1](image.png)

Figure 3.1: Different phases of the avalanche development in the RPC gas volume subjected to a constant electric field $E_0$ [204]. a) An avalanche is initiated by the primary ionisation caused by the passage of a charged particle through the gas volume. b) Due to its growing size, the avalanche starts to locally influence the electric field. c) The electrons, lighter than the cations reach the anode first. d) The ions reach the cathode. While the charges have not recombined, the electric field in the small region around the avalanche stays affected and locally blinds the detector.

After an avalanche developed in the gas, a time long compared to the development of a discharge is needed to recombine the charge carriers in the electrode material due to its resistivity. This property has the advantage of affecting the local electric field only, and avoiding sparks in the detector but, on the other hand, the rate capability is intrinsically limited by the time constant $\tau_{RPC}$ of the detector. Using a quasi-static approximation of Maxwell’s equations for weakly conducting media, it can be shown that the time constant $\tau_{RPC}$ related to the charge recombination at the interface in
between the electrode and the gas volume is given by Equation \(3.1\) \[205\].

\[
\tau_{RPC} = \frac{\epsilon_{electrode} + \epsilon_{gas}}{\sigma_{electrode} + \sigma_{gas}}
\]

A gas can be assimilated to vacuum, leading to \(\epsilon_{gas} = \epsilon_0\) and \(\sigma_{gas} = 0\), and the electrodes permittivity and conductivity can be written as \(\epsilon_{electrode} = \epsilon_r \epsilon_0\) and \(\sigma_{electrode} = 1/\rho_{electrode}\), showing the strong dependence of the time constant on the electrodes resistivity in Formula \(3.2\).

\[
\tau_{RPC} = (\epsilon_r + 1)\epsilon_0 \times \rho_{electrode}
\]

The resistivity targeted to build RPCs ranges from \(10^9\) to \(10^{12}\ \Omega \cdot \text{cm}\). Very few materials with a low enough resistivity exist in nature. The most common RPC electrode materials are displayed in Table \(3.1\). When the doped glass and ceramics can offer short time constants of the order of 1 ms, the developing cost of such materials is quite high due to the very low demand. Thus, High-Pressure Laminate (HPL) is often the choice for high-rate experiments using very large RPC detection areas. To be effectively used, the surface of HPL electrodes requires a linseed oil treatment which allows for a lower intrinsic noise rate and dark current of the detectors by improving the smoothness of the electrodes surface \[206\]. Other experiments working at cosmic muon fluxes can safely operate with ordinary float glass.

<table>
<thead>
<tr>
<th>Material</th>
<th>(\rho_{electrode} (\Omega \cdot \text{cm}))</th>
<th>(\epsilon_r)</th>
<th>(\tau_{RPC} (\text{ms}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Float glass</td>
<td>(10^{12})</td>
<td>~7</td>
<td>~700</td>
</tr>
<tr>
<td>High-Pressure Laminate</td>
<td>(10^{10}) to (10^{12})</td>
<td>~6</td>
<td>~6 to 600</td>
</tr>
<tr>
<td>Doped glass (LR S)</td>
<td>(10^9) to (10^{11})</td>
<td>~10</td>
<td>~1 to 100</td>
</tr>
<tr>
<td>Doped ceramics (SiN/SiC)</td>
<td>(10^9)</td>
<td>~8.5</td>
<td>~1</td>
</tr>
<tr>
<td>Doped ceramics (Ferrite)</td>
<td>(10^8) to (10^{12})</td>
<td>~20</td>
<td>~0.2 to 2000</td>
</tr>
</tbody>
</table>

Table 3.1: Properties of the most used electrode materials for RPCs.

### 3.2 Rate capability and time resolution of Resistive Plate Chambers

The electrode material plays a key role in the maximum intrinsic rate capability of RPCs. R&D is continuously being done to develop at always cheaper costs material with lower resistivity. Nevertheless, the amount of charge released, i.e. the size of the discharge, if reduced leads to a smaller blind area in the detector, increasing the rate capability of the detector. On the other hand, the drift velocity of electrons in the gas volume being quite stable with the applied electric field, the design of a detector and the associated read-out and pulse-processing electronics will be a major component of the time resolution of RPCs. Moreover, the sensitivity of the electronics will also help increasing the rate capability. An improved sensitivity will allow for a lower gain to operate the detector. This will result in a more spatially contained signal development.

#### 3.2.1 Operation modes

Being a gaseous detector using an accelerating electric field to amplify the signal of primary charge carriers, the RPC can be operated in different modes depending on the electric field intensity. Each
mode offers different performances for such a detector, and it will be shown that the operating mode corresponding to the lowest electric field possible is best suited for high-rate detectors working in collider experiments.

RPCs were developed early 1980s. At that time they were used in an operating mode now referred to as **streamer mode**. Streamers are large discharges that develop in between the two electrodes far enough to locally discharge the electrodes. If the electric field inside of the gas volume is strong enough, a large and dense cloud of positive ions will develop near the anode and extend toward the cathode. Indeed, the electrons traveling faster will be collected leaving the gas region near the anode filled with positively charged ions. The field is then strong enough so that electrons are pulled out of the cathode leading to a streamer discharge. Electrodes, though they are a unique volume of resistive material, can be assimilated to capacitors. At the moment an electric field is applied between their outer surfaces, the charge carriers inside of the volume will start moving leading to a situation where there is no potential difference across the electrodes and a higher density of negative charges, i.e., electrons, on the inner surface of the cathode. Finally, when a streamer discharge occurs, these electrons are partially released in the gas volume contributing to increase the discharge strength until the formation of a conductive plasma, the streamer. This can be understood through Figure 3.2 [189].

Streamer signals are very convenient in terms of read-out as no further amplification is required with output pulses amplitudes of the order of a few tens to few hundreds of mV as can be seen on Figure 3.3 [189].

In contrast to the above, when the electric field is lowered, the electronic gain is reduced until the electrons get close enough to the anode and the positive ion cloud remains much smaller. The electric field doesn’t reach the point where a field emission of electrons on the cathode is possible. The resulting signal is weaker, of the order of a few mV as shown on Figure 3.3 and requires amplification. This is the **avalanche mode** of RPC operation. This mode offers a higher rate capability by providing smaller discharges that don’t affect the electrodes charge and are more locally contained in the gas volume as was demonstrated by Crotty with Figure 3.4 [189]. The de-
Detector only stays locally blind the time the charge carriers are recombined and there is no need for electrode recharge which is a long process affecting a large portion of the detector. Another advantage of avalanche signals over streamers is the better time consistency. Figure 3.3 shows very clearly that avalanche signals have a very small time jitter. Using such a mode is a natural choice for experiments in which the detectors are required to have a high detection rate.

![Figure 3.3: Typical oscilloscope pulses in streamer mode (a) and avalanche mode (b) [189].](image)

In the case of streamer mode, the very small avalanche signal is visible.

![Figure 3.4: Rate capability comparison for the streamer and avalanche mode of operation [189]. An order of magnitude in rate capability for a maximal efficiency drop of 10% is gained by using the avalanche mode over the streamer mode.](image)
3.2.2 Standard gas mixture for RPCs operated in collider experiments

The first RPC working in streamer mode was operated with a 50/50 mixture of argon and butane [186], a standard mixture used at that time in multi-wire proportional chambers. This mixture takes profit of the good effective Townsend coefficient of argon to maximize the number of primary charge carriers freed in the gas by ionizing particles and of the quenching properties of butane. The Townsend coefficient of a gas tells about the multiplication and attachment of primary ionization electrons and will be discussed in Section 3.3.3.

Before the discovery of the avalanche mode of RPC operation, the rate capability of RPCs operated in streamer mode was a concern. A possible performance improvement of the detectors could be achieved through the increase of fast charge ratio in the signal development, decreasing the charge induced per avalanche. As it can be seen through Figure 3.5, this effect was studied by adding fractions of Freon-based quenchers, such as $\text{CF}_3\text{Br}$, into the typical Ar/C$_4$H$_{10}$ gas mixture and showed that a lower induced charge could lead to an improvement of the rate capability [192]. This consideration led to the discovery of the avalanche mode which confirmed that the smaller the induced charge, the better the rate capability of the RPCs [189].

From this moment onward, more and more studies were conducted in order to find a gas mixture that would allow for the best suppression of streamers for the benefit of low charge avalanches. Most R&D groups working with narrow gaps started using Freon-based gas mixtures while users of wide gap RPCs kept using Ar/CO$_2$ based mixtures. The differences between narrow and wide gaps will be later discussed in Section 3.2.3. With $\text{CF}_3\text{Br}$ having a high Global Warming Potential (GWP), C$_2$H$_2$F$_4$ was preferred over it as it was considered a more suitable ecofriendly gas in the middle of the 90s. An advantage of this new Freon component is that it features a high primary ionization and a low operating voltage, as reported by Cardarelli et al. [191]. Thus, the new gas mixtures used were mainly composed of C$_2$H$_2$F$_4$ alone with lower content of i-C$_4$H$_{10}$ in order to reduce the flammability of the mixtures for safety reasons. Performance and models about such mixtures

![Figure 3.5: Comparison of the charge distribution of signals induced by cosmic muons in an RPC operated with a gas mixture of argon, butane and bromotrifluoromethane ($\text{CF}_3\text{Br}$). The Ar/C$_4$H$_{10}$ is kept constant at 60/40 in volume while the total amount of $\text{CF}_3\text{Br}$ in the mixture is varied: 0% (a), 4% (b) and 8% (c) [192].](image-url)
were discussed in papers of Abbrescia et al. [193, 194] and showed a better suitability of such a gas mixture with respect to Argon-based ones for operations with high radiation backgrounds requiring high-rate capable detectors, as can be seen from Figures 3.6 and 3.7. Indeed, although the operating voltage of a Freon-based mixture is higher than that of an Argon-based mixture, the efficiency under irradiation is more stable, the voltage range with negligible streamer probability is much wider, and the fast charge ratio available is much greater, providing with more stable operation of the detector.

Figure 3.6: Comparison of the efficiency and streamer probability, defined as the fraction of events with an induced charge 10 times larger than that of the average avalanche, with and without irradiation by a 24 GBq $^{137}$Cs source of an RPC successively operated with a 90/10 mixture $C_2H_2F_2/i-C_4H_{10}$ (a) and a 70/5/10/15 mixture of $Ar/i-C_4H_{10}/CO_2/C_2H_2F_4$ (b) [193].

Figure 3.7: Comparison of the fast charge ratio with and without irradiation by a 24 GBq $^{137}$Cs source of an RPC successively operated with a 90/10 mixture $C_2H_2F_2/i-C_4H_{10}$ (a) and a 70/5/10/15 mixture of $Ar/i-C_4H_{10}/CO_2/C_2H_2F_4$ (b). The results are provided for both single-gap and double-gap operation [193].
Figure 3.8: Efficiency (circles and stars with 30 mV and 100 mV thresholds respectively) and streamer probability (opened circles) as function of the operating voltage of a 2 mm single-gap HPL RPC flushed with a gas mixture containing (a) 5%, (b) 2%, (c) 1% and (d) no SF$_6$ [195].

It was later found that the streamers could be further suppressed by adding an electronegative compound into the gas mixture. The benefits of adding SF$_6$ in order to push the transitions from avalanche to streamers towards high voltages has been discussed in 1998 [195, 196]. Eventually, the high-rate RPC destined to be used in accelerator-based experiments would unanimously start using this compound into their gas mixtures. Being able to control the creation of streamers allows for slower ageing of the detector and lower power consumption as the currents going through the electrodes following the induced charges are smaller. Research is being conducted into new more ecofriendly gas mixture using gases with a much lower Global Warming Potential. Nonetheless, the typical gas mixture with which RPCs are operated is generally composed of the following 3 gas compounds:

- **Tetrafluoroethane** ($C_2F_4H_2$), also referred to as Freon or R134a, is the principal compound of the RPC gas mixtures, with a typical fraction above 90%. It is used for its high effective Townsend coefficient and the large average fast charge that allows to operate the detector with a high threshold compared to Argon, for example, that has a similar effective Townsend coefficient but suffers from a lower fast charge. To operate with similar conditions, argon would require a higher electric field leading to a higher fraction of streamers, thus limiting the rate capability of the detector [193, 194].

- **Isobutane** ($i-C_4H_{10}$), only present in a few percent in the gas mixtures, is used for its UV quenching properties [207] helping to prevent streamers due to UV photon emission during the avalanche growth.

- **Sulfur hexafluoride** ($SF_6$), is used in very little quantities for its high electronegativity. Any excess of electrons is absorbed by the compound, and streamers are suppressed [195, 196]. Nevertheless, a fraction of $SF_6$ higher than 1% will not bring any extra benefit in terms of streamer cancelation power but will lead to higher operating voltage [195], as can be understood from Figure 3.8.

Nevertheless, the European Commission adopted a new “F-gas regulation” in 2014 [208] with the goal to strongly control and reduce the use of fluorinated gases with high GWP. As potential replacement for tetrafluoroethane was proposed the trifluoriodomethane ($CF_3I$), a molecule...
with similar properties than \(CF_3Br\) which was replaced by the tetrafluoroethane, and the 1,3,3,3-tetrafluoropropene (\(C_3H_2F_3\) or HFO-1234ze), a molecule with similar properties than the actual tetrafluoroethane and proposed as a replacement in refrigerating and air conditioning systems \[299\]. These two gases have stronger quenching properties than \(C_2H_2F_4\) which means a much stronger electric field needs to be applied on the parallel electrodes of the RPCs in order to reach full efficiency. But the power supply system of most experiments involving RPCs would not be adapted to such high voltages. But a reduction of the working voltage can be achieved by mixing the potential replacements together with \(CO_2\) \[179, 210\]. Introducing carbon dioxide into the mixture while keeping similar levels of isobutane and \(SF_6\) increases the streamer probability and the best candidate identified for a compromise in between low enough working voltage and acceptable levels of streamers corresponds to a mixture containing 50% of \(HFO\), 4.5% of \(iC_4H_{10}\), 0.3% of \(SF_6\) and 45.2% of \(CO_2\) but is not yet considered satisfactory. On the other hand, no good replacement for \(SF_6\) has yet been identified. With its very high Global Warming Potential (23900), even small fractions of this gas in the mixture substantially increase the danger for the environment. Although finding a replacement for this gas is less critical than for the tetrafluoroethane composing more than 90% of usual RPC standard mixtures, the problem will need to be addressed.

### 3.2.3 Detector designs and performance

Different RPC designs have been used, each of them presenting its own advantages. Historically, the first type of RPC that was developed is what is now referred to as narrow gap RPC \[186, 211\].

After the avalanche mode was discovered \[189\], it has been shown that increasing the width of the gas gap leads to higher rate capability, due to lower charge deposition per avalanche, and lower power dissipation \[211\], as is shown in Figures 3.9 and 3.10. With the distance in between the electrode being larger, a weaker electric field can be applied, and a lower gain is used as a longer gas volume will contribute to the signal induction on the read-out circuit. Nevertheless, by increasing the gas gap width, the time resolution of the detector decreases. This is a natural result if the increase of active gas volume in the detector is taken into account. Indeed, for a given detection threshold on the induced charge per signal, only the small fraction of gas closest to the cathode will provide enough gain to have a detectable signal. In the case of a wider gas volume, the active region is then larger and a larger time jitter is introduced with the variation of starting position of the avalanche, as discussed in \[197\] and shown in Figure 3.11.

To improve both the time resolution and the rate capability, different methods were used starting from the middle of the 90s, trying to take advantage of both narrow and wide gap RPCs into a single design. Double-gap RPCs combine two narrow gaps into a single detector to increase the effective sensitive volume. Multigap RPCs in which the large volume a wide gap RPC is divided into thinner
sub-gaps by adding intermediate electrodes in between the cathode and anode, were developed to improve the time resolution by mimicking narrow gap RPCs.

![Graphs showing distributions of induced charge on 2 mm and 8 mm RPCs](image)

Figure 3.10: Distributions of the induced charge of fast signals on 2 mm\(^*(a)*\) and 8 mm\(^*(b)*\) RPCs exposed to a radiation rate of 100 Hz/cm\(^2\). Average induced charge of fast signals as a function of the high voltage applied on 2 mm and 8 mm RPCs\(^*(c)*\). In the case of the 2 mm RPC, a saturation of the pre-amplifier was observed. The average of the distribution is underestimated, and the median is shown together with the average to account for this bias\(^*\)\(^[277]\).
Figure 3.11: Time distributions of the leading, trailing, and average of both leading and trailing edges for 2 mm (top row) and 8 mm (bottom row) RPCs exposed to a 100 Hz/cm² radiation rate. The data were collected with RPCs operated at the voltage corresponding to the knee of the efficiency distribution, defined as the point where 95% of the maximum efficiency is obtained [277].

3.2.3.1 Double-gap RPC

Figure 3.12: Possible double-gap RPC layouts [181]: a) “standard” 1D double-gap RPC, as used in the CMS experiment, where the anodes are facing each other and a 1D read-out plane is sandwiched in between them, b) double read-out double-gap RPC as used in ATLAS experiment, where the cathodes are facing each other and 2 read-out planes are used on the outer surfaces. This last layout can offer the possibility to use a 2D reconstruction by using orthogonal read-out planes.

Made out of two narrow RPC detectors stacked on top of each other as shown in Figure 3.12, this detector layout, popularized by the CMS [181] and ATLAS [200] LHC experiments, can be used as an OR system in which each individual chamber participates in the output signal and increases the overall sensitive volume of the detector apparatus. Keeping the copper strip read-out system at ground potential, CMS and ATLAS, with different goals in mind, have chosen different designs as
CMS RPCs possess a 1D read-out while ATLAS RPCs offer a 2D read-out. The difference comes from either placing the read-out in between the gaps with the anodes facing each other, or both RPC gaps in between two layers of read-out panels, one along the X-axis and one along the Y-axis with the cathodes facing each other.

![Comparison of performance of CMS double and single-gap RPCs using cosmic muons](image)

**Figure 3.13:** Comparison of performance of CMS double and single-gap RPCs using cosmic muons [212]. (a) Comparison of efficiency curves. (b) Voltage distribution at 95% of maximum efficiency. (c) Distribution of the voltage difference between the point at 90% and 10% efficiency $\Delta_{90\%}$.

The gain of such a detector is reduced by a factor 2 with respect to single-gap RPCs with an efficiency plateau reached at lower voltage, as visible on Figure 3.13 due to the two gas gaps contributing to the signal formation and offering a dynamic range, the voltage range between the reaching of the efficiency plateau and the start of streamers, closer to that of a wide gap RPC. A double-gap is then fully efficient while the individual RPC gaps composing it are only 70 to 80% efficient. Naturally, by operating the double-gap at a lower voltage, the rate capability increases as the induced charge per gap is decreased with respect to a single-gap detector also leading to a reduction of the streamer probability and a better extraction of the fast charge of the total signal as was shown already in Figure 3.7.
3.2.3.2 Multigap RPC (MRPC)

MRPCs have a design in which floating sub electrode plates are placed into a wide gap RPC to divide the gas volume and create a sum of narrow gaps [197] [198]. Similarly to the double-gap RPC for which the gain could be reduced by increasing the dynamic range, the multigap reduces the gain while keeping a total dynamic range similar to that of a wide gap RPC by reducing the size of each individual sub-gap composing the detector. The dynamic range, associated to the sensitive volume, and the comparison of each detector layout to the wide gap RPC is shown in Figure 3.14.

By operating the detector with thinner gaps, its time resolution is improved. Similarly to the time resolution presented in Figure 3.11 for the wide gap RPC of 8 mm, a complementary study was conducted on multi-gap RPCs using two 4 mm and four 2 mm subgaps. As shown in Figure 3.15, an improvement of the time resolution with the reduced gap width and increased number of gaps, keeping the same total sensitive volume [198].

After the problem of streamers was solved by adding $SF_6$ into the gas mixture, the size of the MRPCs decreased as the research groups started applying the concept to the narrow gap RPCs leading to the now widely used micro-gap MRPCs. The time resolution of such a detector can reach of few tens of ps, with gas gaps of the order of a few hundred µm as shown in Figure 3.16 representing a single cell of ALICE Time-of-flight (ToF) system consisting of double MRPCs, as studied in the early 2000s [213].

The MRPC is mainly used as ToF detector [213–217] due to its excellent timing properties that allows performing particle identification as explained by Williams in [218]. The principle of particle identification using ToF consists in the measurement of the velocity of a particle. Indeed, particles are defined by their mass (which is the parameter of interest here, assuming e.g. that their electric charge being measured using the bending angle of the particles traveling through a magnetic field) and this mass can be calculated by measuring the velocity $\beta$ and momentum $p$ of the particle:

\[
\beta = \frac{p}{\sqrt{p^2 + m^2}}
\]
Figure 3.15: Time distributions of the leading, trailing, and average of both leading and trailing edges for multigap RPCs consisting in two 4 mm \([a]\) and four 2 mm \([b]\) exposed to a 100 Hz/cm\(^2\) radiation rate. The data were collected with RPCs operated at the voltage corresponding to the knee of the efficiency distribution, defined as the point where 95% of the maximum efficiency is obtained \([198]\).

Figure 3.16: Presentation of a study for an ALICE MRPC cell prototype using 250 \(\mu\)m gas gaps, 620 \(\mu\)m outer glass electrodes, and 550 \(\mu\)m inner floating electrodes \(\text{[a]}\) and of its time resolution performance as a function of the applied high voltage for different radiation levels corresponding to different filter settings of the 740 GBq \(^{137}\)Cs source at the former CERN GIF facility \(\text{[b]}\) \([213]\).
Intuitively, it is trivial to understand that two different particles having the same momentum will have a different velocity due to the mass difference and thus a different flight time $T_1$ and $T_2$ through the detector and this is used to separate and identify particles. The better the time resolution of the ToF system used, the stronger the separation will be:

\[ T = \frac{L}{v} = \frac{L}{c \cdot \beta} \]

\[ \Delta T = T_1 - T_2 = \frac{L}{c} \left( \sqrt{1 + \frac{m_1^2}{p^2}} - \sqrt{1 + \frac{m_2^2}{p^2}} \right) \]

\[ \approx (m_1^2 - m_2^2) \frac{L}{2cp^2} \]

Taking into account the distortion effect on the electric field inside of an MRPC built using micro gaps due to the exposition to irradiation, distortion that can be understood by monitoring the current drawn by the detector which should stay constant at a constant electric field, another benefit of using such small gas gaps is the strong reduction of the average avalanche volume and thus of the blind spot on MRPCs leading to an improved rate capability. Multigaps can sustain backgrounds of several kHz/cm² as demonstrated in Figure 3.17.

3.2.3.3 Charge distribution and performance limitations

A direct consequence of the different RPC layouts is a variation of intrinsic time resolution of the RPC depending on the gap size, and of its rate capability when the deposited charge per event is spread over a larger number of amplification volumes. This allows reducing of the overall gain of the detectors which is compensated by a pre-amplification of the signals at the level of the electronics. In this sense, an advantage is given to multi-gap RPCs with their sub-millimeter gas volumes providing very consistent signals.

From the charge spectrum point of view, each layout has its own advantages. While the double-gap has the highest ratio between the total charge it induces on the read-out and the charge that effectively drifts through its volume, as seen in Figure 3.18, the multigap has a charge spectrum with a maximum significantly above zero, as visible in Figure 3.19. A high induced-over-drifting charge ratio means that the double-gap can be safely operated at a high threshold or that at a similar threshold it can be operated with a twice smaller drifting...
charge, leading to a higher rate capability if operated with sensitive enough electronics. On the other hand, the strong detachment of the charge spectrum from the origin in the MRPC case allows reaching a higher efficiency with increasing threshold as most of the signals have a higher charge content due to the convolution of several single-gap spectra. The range of stable efficiency increases with the number of gaps, as presented in Figure 3.20.

![Figure 3.19: Charge spectra have been simulated for single-gap, double-gap and multigap layouts [220]. It appears that while single-gaps show a decreasing spectrum, double and multigap layouts exhibit a spectrum whose maximum is significantly above zero. The shift of maximum value in the spectrum increases along with the number of gaps.](image1)

![Figure 3.20: The maximal efficiency theoretical is simulated for single-gap, double-gap and multigap layouts [220] at a constant gap thickness of 2 mm and using an effective Townsend coefficient of $9 \text{ mm}^{-1}$.](image2)
3.3 Signal formation

The many aspects of the physics of Resistive Plate Chambers still are far from fully understood and many attempts are made to describe these detectors using phenomenological models \[204, 221, 222\]. These theoretical works have led to a better understanding of the key principles that account for RPCs signal formation. As previously discussed, the typical mixture of such a detector is to a large extent composed by a gas with some quenching properties and a low ionization potential to easily produce electrons, with the addition of UV quencher and electronegative compounds. The electronic avalanche formation will be triggered by a charged particle passing through the gas, typically a muon in the case of most applications involving RPCs. The production of electrons in the gas of a detector is related to the energy lost by the incoming particle traveling through a material medium. The example of the mass stopping power of copper on muons is given in Figure 3.21 on which the different energy loss mechanisms at different energy ranges are visible. Once primary ionization electrons have been freed in the gas volume, the electric field applied in between the electrodes of the RPC will make the charges move and there will be a competition in the gas in between the Townsend and attachment coefficient which describe the evolution of the number of electrons in an avalanche. While drifting through the gas, the electrons are also subjected to diffusion that will affect the evolution of the avalanches. Finally, when the avalanche is big enough, the accumulation of negative (electrons) and positive (ions) charges in the gas volume will start affecting the local electric field. This effect is known as the space charge effect.

![Mass stopping power as a function of $\beta\gamma = p/Mc$ for positive muons in copper \[116\]. The total stopping power is indicated with a solid line and local components with dashed lines. The vertical bands are used to indicate boundaries between different approximations used at different energy range.](image-url)
### 3.3.1 Energy loss at intermediate energies

A particle traveling through a medium will interact with its components, losing energy. When a muon travels through the gas of a gaseous detector, at the energy range usually observed, typically of the order of a few GeV for cosmic muons \[116\] to a few hundreds of GeV in accelerators such as the LHC, it interacts with the molecules of the gas leading to dissipation of the transferred energy in the form of inelastic scattering or ionization. The photons and electron-ion pairs resulting from these interactions can trigger avalanches in the gas which will contribute to feed the avalanche growth thanks to the strong electric field applied in between the two electrodes of an RPC.

At higher energies, the energy loss through photon radiation can’t be neglected anymore as can be seen in Figure 3.21.

The mass stopping power of moderately relativistic \((0.1 \lesssim \beta \gamma \lesssim 1000)\) heavy particles \((M \gg m_e)\) traveling through a medium via excitation and ionization processes was studied by Bethe in 1930 \[225\] and is well described by the so called the Bethe Formula given in Equation 3.5.

\[
\left(\frac{-dE}{dx}\right) = K z^2 \frac{Z}{A} \beta^2 \left( \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \delta(\beta \gamma) \right)
\]

The different parameters used in this equation are

- \(E\) - incident particle energy \(\gamma M c^2\) MeV
- \(x\) - mass per unit area g cm\(^{-2}\)
- \(N_A\) - Avogadro’s number \(6.022 \times 10^{23}\) mol\(^{-1}\)
- \(c\) - speed of light in vacuum \(299792458\) m s\(^{-1}\)
- \(\mu_0\) - permeability of free space \(4\pi \times 10^{-7}\) N A\(^{-2}\)
- \(\varepsilon_0\) - permittivity of free space \(\varepsilon_0 = 1/\mu_0 c^2\)
- \(\alpha\) - fine structure constant \(\alpha = e^2/4\pi\varepsilon_0 \varepsilon c\) \(1/137.035999139(31)\)
- \(r_e\) - classical electron radius \(r_e = e^2/4\pi\varepsilon_0 m_e c^2\)
- \(e\) - elementary charge of the electron \(-1.6021766208(98) \times 10^{-19}\) C
- \(m_e c^2\) - electron mass \(0.5109989461(31)\) MeV
- \(K\) - constant defined as \(K = 4\pi N_A r_e^2 m_e c^2\) \(0.307075\) MeV mol\(^{-1}\) cm\(^{-2}\)
- \(z\) - charge number of incident particle
- \(Z\) - atomic number of absorbing medium
- \(A\) - atomic mass of absorbing medium g mol\(^{-1}\)
- \(\beta\) - velocity of particle \(\beta = v/c\)
- \(\gamma\) - Lorentz factor \(\gamma = (1 - \beta^2)^{-1/2}\)
- \(W_{max}\) - maximum energy transfer through a single collision MeV
- \(I\) - mean excitation energy of absorbing medium eV
- \(\delta(\beta \gamma)\) - density effect correction to ionization energy loss
In this equation, the maximum energy transfer $W_{\text{max}}$ is defined as function of the incident particle mass $M$ expressed in MeV/$c^2$:

$$W_{\text{max}} = \frac{2m_e^2c^2\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

and the mean excitation energy $I$ depends on the absorber. Its determination is non-trivial, but recommendations are given by the International Commission on Radiation Units & Measurements (ICRU) based on experimental measurements and interpolations as shown in Figure 3.22.

For the case of copper, the mean stopping power is visible in Figure 3.21. The mean stopping power corresponding only to the Bethe range for other materials is given in Figure 3.23 and shows that $\langle -dE/dx \rangle$ is similar for each material with a slow decrease with $Z$.

The factor affecting the equation the most is $\beta$. Indeed, the dependence on $M$ is introduced at higher energies in the logarithm via the max transfer energy per single collision. In most practical cases, only the dependence on $\beta$ is considered as most of the relativistic particles are closed to the lowest mean energy loss rate and are referred to as minimum ionizing particles (mip’s). The almost logarithmic relation between the mean energy loss rate for minimum ionizing particles and $Z$ is shown in Figure 3.24.

Finally, the term $\delta(\beta\gamma)/2$ in Equation 3.5 corresponds to the density effect correction introduced to account for the polarization of a real media that limits the spatial extension of the electric field of relativistic particles. As the energy of a particle increases, the associated electric field will flatten and extend. Due to this effect, the distant collision contribution to Equation 3.5 will increase as $\ln(\beta\gamma)$ but the polarization of the media truncates this rise.
At high energies, the correction is given by Equation [3.7]

\[ \frac{\delta}{2} \rightarrow \ln(h\omega_p/I) + \ln(\beta\gamma) - 1/2 \]

where \( h\omega_p \) represents the plasma energy that depends on the electron density of the media and the electron mass and can be calculated as \( \sqrt{\rho(Z/A)} \times 28.816 \text{ eV} \). The introduction of this correction term reduces the increase of the mean stopping power at higher energies as can be seen in Figure 3.21. Moreover, due to lower electron density, the effect is less visible for gases than for liquids and solids as can be seen in Figure 3.23.

The mean energy loss per collision can be difficult to measure for data samples with low statistics but is not always representative of the energy loss distribution for a given incident particle energy. Hence, it is easier to access the most probable energy loss which is a lower value than the average loss due to the distribution of the energy transfer. This value is well described by a highly skewed Landau distribution for detectors with "moderate" thickness \( x \), expressed in \( \text{g mol}^{-1} \). But for gas volumes, a Landau distribution greatly underestimates the width \( w \) of the distribution and only succeeds to provide with a correct value for the most probable energy loss, as shown in Figure 3.25.

Thus, the energy loss distribution is better represented by its most probable energy loss \( \Delta p \) and its full-width-at-half-maximum (FWHM) \( w \). As showed by Figure 3.26, the distribution is affected by the thickness of the gas volume with the most probable energy loss normalized to the thickness increasing and the width decreasing for increasing thickness, converging towards the Landau distribution, whereas the mean energy loss is unchanged. Corrections to include the electron binding energy and the atomic shell structure are brought to the original Landau equation in order to account better for the number of collisions leading to an increased width of the energy loss distribution [226]. The corrected energy loss distribution is usually referred to as straggling function.

In the case of gas mixtures, composed of several elements, using Bragg additivity it can be understood that the mean energy loss of the mixture is the sum of the mean energy losses in each layer of individual element \( j \) of weight fraction in the mixture \( w_j \) [116].

\[ \langle \frac{dE}{dx} \rangle = \sum w_j \langle \frac{dE}{dx} \rangle_j \]
3.3.2 Primary ionization

Using the Bethe formula to compute the mean energy transfer of charged particles when traveling through a gas volume may give some feeling on the physics that affect the particle but doesn’t provide detailed enough information about the individual ionizations along its tracks at a microscopic level. In order to simulate efficiently an RPC and hence understand the processes governing avalanche creation and growth, knowledge on the ionization process is necessary.

To convert the energy loss rate into a number of primary ionizations, the Photo-Absorption Ionization (PAI) model \cite{227} was developed in 1980. It is based on the cross section of photoionization of gas atoms and the dielectric constant of the medium through which the charged particles are going. Indeed, the interaction of charged particles with the gas molecules, being of electromagnetic nature, is mediated by photons and, hence, the cross section for photoionization is important to understand. This approach is nevertheless semi-classical as it relies on classical electrodynamics. It only gives access to the energy transfer to the gas atoms, and no information on the energy dissipation and secondary emissions is available. The energy transferred to the medium is not all used for ionization.
For an energy deposition $\Delta$, the number of electron-ion pairs produced is:

\[
\Delta = n_e W
\]  

$W$ corresponds to the average energy per pair production that depends on the medium and is greater than the ionization potential leading to the conclusion that part of the transferred energy is dissipated through other processes \cite{222, 230}. In order to understand the energy dissipation and the secondary emissions, the fine structure of each atom is taken into account. Through the PAI model, the incident charged particle is assumed to interact with the full atom rather than with a single electron. With the incoming particle interacting with a single electron, the atom is left in an excited state once the photo-electron has been emitted with an energy corresponding to the transferred energy minus the binding energy of the electron shell. The resulting vacancies in the electronic shell will be filled through emission of photons or Auger electrons and can contribute to further ionization or excitation in the gas volume. Fluorescence photons are usually not considered as they only constitute a very small fraction of secondary emissions \cite{231}.

Assuming that the transferred energy is absorbed in its totality by a single electronic shell, the PAI model was extended to the new Photo-Absorption Ionisation with Relaxation (PAIR) model \cite{231} to include relaxations. In this model, the cross section corresponding to the whole atom is re-expressed using a sum of partial cross sections corresponding to the different electronic shells. When one or more electrons are knocked out of the atom, the vacancies are filled by electrons of the shell above with relaxation by Auger electron emission. These processes happen in cascade from the inner shell to the outer one until all the vacancies are filled and the energy has been released. This model is included in the program HEED developed at CERN \cite{232} and gets called by Garfield \cite{233}, a program developed for the simulation of gaseous detectors. The results for the cross section for a few noble gases are given in Figure 3.27. It can be seen that for each shell, the cross section exhibits an absorption peak. More complex patterns are seen with larger atoms such as Xenon on Figure 3.27d. For gas mixtures, like the typical RPC mixtures, the cross section is shown in Figure 3.28. Both mixtures being mainly composed of $C_2H_2F_6$, the variations in between the two cross section profiles are very subtle and depend on the concentration of the other compounds.

Once the interaction cross section is known, it is possible to determine the distribution of energy loss and the number of produced electrons, as shown in Figure 3.29 for Helium, Argon, which is used in gaseous detectors, and for a typical RPC mixture \cite{222}. The distributions are computed using HEED and show typical straggling function profiles with some complex structures that can be related to interaction of the incoming particle with the different electron shells. Helium does not have a large photoabsorption cross-section according to Figure 3.27a and a muon will not likely lose
a lot of energy and create a lot of electrons. In a more complex atom like Argon, the cross-section is larger and will lead to a larger energy loss of muons and more produced electron. Finally, a complex gas mixture used in RPCs will offer an even larger cross-section, a wider energy loss distribution and will be able to produce more electrons. The same information is confirmed by looking at the evolution of the mean number of electron clusters produced along a muon track as a function of the lorentz factor associated to muons shown in Figure 3.30. The size of these clusters is studied through Figure 3.30b which shows that in most of the cases (≈80%) the clusters are only composed of a single electron which is consistent with minimum ionizing particles.

Figure 3.29: Distributions of number of electrons (left) and energy loss (right) for a 5 GeV/c muon passing through 1.2 mm of Helium (a), Argon (b) or a typical RPC gas mixture (c) [222].
3.3.3 Development and propagation of avalanches

From the clusters released in the gas volume by the charged particles, free electrons will start drifting due to the electric field applied between the electrodes of the RPC. Gaining velocity and energy, these electrons in their turn will be able to ionize the gas. This process being repeated by all the produced electrons will trigger an avalanche to develop.

The growth of the avalanche can be intuitively understood as a competition between two effects. Due to their increasing energy, electrons have a probability to trigger new ionizations by interacting with gas molecules. On the other hand, before the minimal amount of energy is reached, the electrons can get attached to a gas molecule instead. These two effects can be described using a simple model in which the multiplication and attachment processes are given by the Townsend coefficient $\alpha$ and the attachment coefficient $\eta$, assuming that the history of previous interactions in the gas does not influence new interactions. This model simply takes into account probabilities to have at the gas depth $z$, for a given number $n$ of free electrons in the gas, $n + 1$ or $n - 1$ electrons at the depth $z + dz$ (respectively $n\alpha dz$ and $n\eta dz$).
The mean number of electrons $\bar{n}$ and cations $\bar{p}$ can be written for single compound gases as

$$
\frac{d\bar{n}}{dz} = (\alpha - \eta)\bar{n}, \quad \frac{d\bar{p}}{dz} = \alpha\bar{n}
$$

which, assuming the initial conditions $\bar{n}(0) = 1$ and $\bar{p}(0) = 0$, leads to the mean number of electrons and cations at a depth $z$

$$
\bar{n}(z) = e^{(\alpha - \eta)z} \\
\bar{p}(z) = \frac{\alpha}{\alpha - \eta} \left(e^{(\alpha - \eta)z} - 1\right)
$$

The Townsend and attachment coefficient as a function of the applied electric field are given in Figure 3.31 for a standard RPC gas mixture using Magboltz [235]. Nevertheless, there is more to the avalanche growth than simply these two factors. Throughout the 20th century, models have been developed to better understand the physics of discharges in gas. In 1937, Furry developed a model to describe electromagnetic cascades [234] that would be used for electron avalanches in gas during the 1950s. Furry realized that the use of a Poisson law to describe the distribution of shower sizes could not be accurate as he understood that the events occurring in the development of a cascade are not independent from each other, as a Poisson law would suggest. Indeed, part of the particles produce others and this process depends on both their original energy and energy lost. Compared to a Poissonian distribution, experimental results showed an excess of small showers and an underestimate of very large ones. To solve this problem, Furry proposed a distribution of sizes according to the likelihood described in Equation 3.12, in which $\bar{n} = e^{\alpha z}$. The Furry distribution is compared with a Poisson law in Figure 3.32.

$$
P(n, \bar{n}) = \bar{n}^{-1}(1 - \bar{n}^{-1})^{n-1}
$$

In this model, no extra energy is brought to the electrons in the showers, contrary to the case of a gaseous detector such as an RPC where an electric field accelerates them. Using the Furry model, Genz studied the fluctuations in electron avalanches in gaseous detectors [236]. Collisions leading to ionizations leave electrons with an energy much smaller than the ionization energy $eU_i$, where $U_i$ is the ionization potential of a gas molecule. Hence, the electrons need to travel a distance $s = U_i/E$ along the electric field $E$ to acquire a high enough energy to trigger a new ionization. For the probability of a new ionization to be independent from the path followed by the electrons since the previous ionization, the mean free path $1/\alpha$ of electrons in the gas has to be large compared to $s$ and thus $E/\alpha \gg U_i$. The Townsend coefficient is related to the gas pressure $p$. Keeping $E/\alpha$ large compared to $U_i$ implies that the value of $E/p$ needs to stay lower than 100 V/cm/torr. In the case of proportional counters such as RPCs, avalanches are large compared to the showers Furry has studied in his original paper. For very large avalanche sizes, Equation 3.12 can be written as an exponential, as shown in Equation 3.13.

$$
P(n, \bar{n}) = \bar{n}^{-1}e^{-n/\bar{n}}
$$
This exponential behaviour is illustrated in Figure 3.33. In practice, to fully understand the avalanche growth, taking into account the path followed by the electrons from one ionization to another is necessary. In the same paper, Genz then discusses models using Polya distributions to estimate the charge multiplication by looking at the size of the avalanche itself. Indeed, the number of charge carriers in the avalanche might become important enough to have an effect on the multiplication process. To account for this, it was proposed to use a varying Townsend coefficient such as described by Equation 3.14 depending on the depth $x$ in the gas volume in which $\theta$ is an empirical parameter leading to the probability distribution of Equation 3.15. In the limit where $\theta$ goes to 0, the formula describes again the Furry model. But the data deviates from this model as well at large $n$ values. Moreover, the introduction of an empirical parameter makes the model hard to interpret physically.

\begin{align}
\alpha(n, x) &= \alpha(x) \left(1 + \frac{\theta}{n}\right), \quad n > 0 \\
\theta \bar{n}(x) &= \frac{1 + \theta}{\bar{n}(x)} \frac{n(1 + \theta)}{\bar{n}(x)}^{-\theta} e^{-\frac{\theta}{\bar{n}(x)}}
\end{align}

In order to have a model that describes reality better, the introduction of the attachment into the model is an important step. Despite its limitations, the Furry model had the advantage to well describe avalanches occurring when the attachment could be ignored. An extension of this model was provided by Riegler, Lippmann and Veenhof [229] who showed that it was important to consider both the Townsend coefficient describing the multiplication and the attachment coefficient, and not only the effective multiplication coefficient $\bar{\alpha} = \alpha - \eta$. The probability to see an avalanche started by a single electron grow to a size $n$ after having traveled a distance $z$ through the gas is given by Equation 3.16.

\begin{align}
P(n, z) &= P(n-1, z) (n-1) \alpha dz \left(1 - (n-1) \eta dz\right) \\
&\quad + P(n, z) \left(1 - n \alpha dz\right) (1 - n\eta dz) \\
&\quad + P(n, z) n \alpha dz \ n\eta dz \\
&\quad + P(n + 1, z) \left(1 -(n +1) \alpha dz\right) (n+1) \eta dz
\end{align}
The first term of this probability describes that from a state with \( n - 1 \) electrons, only 1 multiplies while the others don’t get attached. Both the second and third terms describes the probability that from a state with already \( n \) electrons the total number of electrons stay the same. With the second term, no electron gets attached nor multiplies while with the third term, 1 electron gets multiplied and 1 gets attached to compensate. Finally, the fourth term describes the probability to fall from a state with \( n + 1 \) to a state with \( n \) electrons due to the attachment of a single electron. At the first order, the evaluation of the previous expression leads to Equation \( 3.17 \) whose general solution is given in Equation \( 3.18 \). The variables \( \bar{n}(z) \), defined as in Equation \( 3.11 \) and \( k = \eta/\alpha \) making explicit the fact that the distribution does not depend on the effective Townsend coefficient only are introduced in the equation.

\[
\frac{dP(n, z)}{dz} = -P(n, z)n(\alpha + \eta) + P(n - 1, z)(n - 1)\alpha + P(n + 1, z)(n + 1)\eta
\]

\[
P(n, z) = \begin{cases} 
\bar{n}(z)^{-1} n(\alpha + \eta), & n = 0 \\
\bar{n}(z)^{-1} \left( \frac{1 - k}{\bar{n}(z) - k} \right)^2 \left( \frac{n(\alpha + \eta)}{\bar{n}(z) - k} \right)^{n - 1}, & n > 0 
\end{cases}
\]

The example given in Figure 3.34 shows the importance of each individual process in the growth of avalanches and the fluctuation of their size. The values of \( \alpha \) and \( \eta \) will influence the probability distribution, as can be seen from Figure 3.34a. Then, Figure 3.34b shows that the fluctuation really takes place within the very first interactions. Indeed, when the avalanche contains a large enough number of charge carriers (a few hundred), its size increases like \( e^{z(\alpha - \eta)} \).

\[\text{Figure 3.34:} \ \text{[a]} \ \text{Comparison of avalanche size distributions for different values of Townsend and attachment coefficients. The effective Townsend coefficient is the same for both distributions.} \ \text{[b]} \ \text{Fluctuation in avalanche sizes for avalanches started by a single electron with } \alpha = 13 \text{ mm}^{-1} \ \text{and } \eta = 3.5 \text{ mm}^{-1}. \]
3.3.4 Drift and diffusion of the electron cloud

During the growth of avalanches, an electron cloud drifting along the electric field through the gas will undergo thermal diffusion due to random collisions with the gas molecules. This phenomenon can be studied using the Maxwell-Boltzmann distribution whose mean is defined by the thermal energy of the cloud \( \langle E \rangle = \frac{3}{2} kT \) with an extra component coming from the constant drift motion. The drift of electrons along the field lines is usually observed on a macroscopic scale through which the speed can be assimilated to a constant \( v_D \) which corresponds to the mean drift speed over a large number of collisions in the gas.

At the microscopic scale, the electrons are drifting over a distance \( \delta z \) while acquiring the corresponding kinetic energy \( T = e_0 |E| \delta z \) until they are slowed down by a collision in which they lose part of their energy. This process is repeated as long as electrons are free carriers. Starting at time \( t = 0 \) from a point-like electron cloud at a position \( -\vec{r}_0 \), the Gaussian density distribution at a time \( t \) will be described by Equation 3.19 in which the width of the isotropic distribution is \( \sigma = 2 \bar{D} t \), with \( D \) being a diffusion coefficient expressed in \( m^2/s \) [204].

\[
\varphi(r, t) = \frac{1}{\sqrt{2\pi\sigma(t)}} \exp \left( -\frac{(r - r_0)^2}{2\sigma^2(t)} \right)
\]

Now, if the constant drifting motion is added, the distribution is anisotropic and can be divided onto transversal (Equation 3.20) and longitudinal (Equation 3.21) terms, \( \varphi(r, z, t) = \varphi_T(r, t) \varphi_L(z, t) \), with a cylindrical symmetry around the field axis [204]. The dependence on \( t \) and \( \sigma_{T,L}(t) \) can be absorbed into the diffusion coefficients by using the relations \( v_D = l/t \) and \( \sigma_{T,L}^2(t) = 2D_{T,L} l/v_D \) and introducing new diffusion coefficients \( D_{T,L} = \sqrt{2D_{T,L}/v_D} \) in order to explicitly show the dependence of the Gaussian width in drifted distance \( l \).

\[
\varphi_T(r, t) = \frac{1}{D_T l} \exp \left( -\frac{(r - r_0)^2}{2D_T^2 l} \right)
\]
These coefficients, as well as the drift velocity of the electrons, can be calculated thanks to Magboltz as shown in Figure 3.35. The influence of the diffusion on the distribution of charge carriers throughout the gas volume is depicted in Figure 3.36. From very localised electron clusters in the gas in Figure 3.36a a Gaussian diffusion is then visible in Figure 3.36b. Due to the interactions with gas molecules during the drift, diffusions can occur in the forward and backward direction. Electrons diffused backward will effectively drift over a longer distance and multiply more than electrons diffused forward that will see a shorter drift length. As an effect, the avalanche develops over a longer time and extends over a larger gas volume than in the case the electron cloud is considered as point like and without diffusion. Moreover, as a side effect to the longer growth of the avalanche due to backward longitudinal diffusion, the total production of electrons is increased.

\[
\varphi_L(z, t) = \frac{1}{\sqrt{2\pi l D_L}} \exp \left( -\frac{(z - z_0)^2}{2D_L^2 l} \right)
\]

Figure 3.36: Comparison of the free charge carriers in the gas after a time \( t = 7.90 \) ns in the case where no diffusion is taken into account to simulate the avalanche (a) and in the case where the diffusion is implemented (b) [222].

### 3.3.5 Space charge effect & streamers

In addition to the basic processes that influence the development of avalanches in a gaseous detector, it is important to consider also the influence of the charge carriers present in the avalanche on the electric field seen by the avalanche. Indeed, each charged particle induces an electric field and it is only natural that the increasing density of electrons and ions in the detector volume will affect the electric field. Thus, parameters such as the Townsend and attachment coefficients, drift velocity or diffusion coefficients will find themselves to be modified along the gas gap length due to this effect referred to as space charge effect. Figure 3.37 is a more detailed version of Figure 3.1b in which three electric field regions are distinguished [204]. When compared to the linear electric field of strength \( E_0 \) that is developed in between the detector’s electrodes, the accumulation of negative charges (electrons) on the front of the avalanche will reinforce the effective electric field in between the anode and the avalanche front. Deeper in the gas volume, the positive charges (cations) slowly drift towards the cathode and can induce together with the avalanche front opposite electric field...
loops. Finally, due to the density of positive charges, the electric field seen in between the ions tails and the cathode charged with negative charges is on average stronger than $E_0$ and compensate for the locally reversed field $E_2$. By considering that $10^6$ charges were contained in a sphere of radius $r_d = 0.1 \text{ mm}$ Lippmann roughly estimated that the space charge effect could change the electric field by 3\% and the Townsend and attachment coefficient up to 14\% [204, 222].

To account for the space charge effect, the electric potential and field of free charges are solved and applied to each charge in the avalanche [204, 222]. The computation of these equations for each individual charge carrier to dynamically know the space charge field at every stage of an avalanche development is a difficult task and would require far too much computation time. A solution is to pre-compute an interpolation table keeping an adequately large number of values of the space charge field for each position in space. The values stored in the interpolation table then become very close to the analytic solution and allow for a much faster simulation.

The study of the space charge effect through simulation shows that it can lead to a saturation of the avalanche growth due to the deformation of the electric field, as shown through Figure 3.38. Additionally, a more precise understanding of the space charge effect is given through Figure 3.39 which looks at the distribution of charges and the distortion of the electric field at different steps of the evolution of an avalanche in a RPC. At the moment a 5 GeV muon ionizes the gas, electron-ion pairs are created in the gas in different clusters (Figure 3.39a). Later, the first clusters have reached the anode while the clusters that where created closest to the cathode are now big enough to start influencing the electric field in the gap (Figure 3.39b). When a cluster is big enough, the electric field
in front of it locally increases a lot and contributes to a stronger but very localised multiplication. At the same moment, the positive ions right behind the cluster avalanche front decrease the electric field, saturating the electron multiplication on the tail of the electron cloud (Figure 3.39). Finally, when all the electrons have reached the anode and are recombining, the electric field still is very deformed by the distribution of both positive and negative ions in the gas volume closest to the anode (Figure 3.39).

The electric field following the development of an avalanche can stay perturbed for a long time with respect to the avalanche development due to the slow drift of the much heavier ions. This can result in powerful secondary avalanches triggered by the fluctuation of the electric field together with the emission of UV-photons. This is a slow phenomenon compared to the development of avalanches. Experimentally, it is observed that the stronger the electric field applied over the gap, the sooner after the primary avalanche, referred to as precursor signal in this context, and the stronger the secondary avalanche will be. This could be due to the amount of UV-photons emitted by the growing precursor. These photons will be able to trigger new avalanches in a radius of a few mm around the precursor by knocking electrons from the cathode by photoelectric effect. The strong distortions of the electric field due to a large avalanche will be more likely to emit UV-photons as the electric field at the front of the precursor avalanche will be large, providing the electrons with a larger energy. Eventually, the new avalanches can grow to form streamers.

![Figure 3.39: Distributions of charge carriers within the gas volume of a 1.2 mm thick RPC and the corresponding deformation of the electric field at different time steps with an applied electric field of 55.5 kV/cm](image-url)
3.4 Signal induction and detection in the CMS RPC Read-out

Accordingly to the Shockley-Ramo theorem, the movement of charge carriers, and in particular, the movement of a dense electron cloud toward the anode induces a current signal on one or more of the readout electrodes (strips or pads) \[237\] \[238\]. The ions, on the other hand, induce only a very small current as their movement is much slower than which of the electrons. The current induced by \(n_{cl}\) clusters of \(N_j(t)\) charge carriers drifting at velocities \(\vec{v}_{Dj}(t) = \frac{\vec{x}_j(t)}{\Delta t}\) at a time \(t\) is given by Formula 3.22 in which \(e_0\) is the unit charge and \(E_w\) is the weighting field.

\[
i(t) = \sum_{j=1}^{n_{cl}} E_{wj}(\vec{x}_j(t)) \cdot \vec{v}_{Dj}(t) e_0 N_j(t)
\]

The weighting field, depicted in Figure 3.40 corresponds to the electric field that would be observed in the gas gap if a readout electrode is placed at a potential of 1 V while keeping all the other electrodes grounded. Then the induced charge in the readout can be simply obtained by integrating Formula 3.22 over the duration \(T\) of the signal, as given by Formula 3.23.

\[
Q(t) = \int_0^T \sum_{j=1}^{n_{cl}} E_{wj}(\vec{x}_j(t)) \cdot \vec{v}_{Dj}(t) e_0 N_j(t)
\]

The signal induced in the readout of RPCs operated in avalanche mode is then sent into Front-End Electronics in which they will be pre-amplified and discriminated. The discrimination and digitization of signals in CMS FEE are described through Figure 3.41. On a first stage, analog signals are amplified, following the curve given on Figure 3.42 and then sent to a Constant Fraction Discriminator (CFD). At the end of the chain, 100 ns long pulses are sent to the LVDS output. The digital signals are both used as trigger for CMS and to evaluate the performance of the detectors. The performance will depend on the applied HV, i.e. on the electric field inside of the gas volume, but also on the threshold applied on the CFDs. Indeed, in order to reduce the probability to measure noise, the threshold is set to a level where the noise is strongly suppressed while the signals are not too affected. Typically, CMS FEEs are set to a threshold of 215 mV after pre-amplification, corresponding to an input charge of about 140 fC.

![Figure 3.40: Representation of the weighting field in the volume of an RPC and the resulting induced current in the strip placed at 1 V and its neighbour connected to the ground. The induced current corresponds to the sum over all the produced clusters, as can be understood from Formula 3.22.](image)

![Figure 3.41: Schematics of CMS RPC FEE logic.](image)
The efficiency of a detector can be measured using a reference detector used as trigger as the ratio between the number of events recorded in coincidence in the detector and the reference and the total number of trigger events, $\epsilon = n_{\text{events}} / n_{\text{triggers}}$. An example of an efficiency measurement as a function of the effective voltage $HV_{\text{eff}}$ is given in Figure 3.43. The data can be fitted with a sigmoidal function described as in Equation 3.24, where $\epsilon_{\text{max}}$ is the maximal efficiency of the detector, $\lambda$ is proportional to the slope at half maximum and $HV_{50}$ is the value of the voltage when the efficiency reaches half of the maximum.

$$
\epsilon(HV_{\text{eff}}) = \frac{\epsilon_{\text{max}}}{1 + e^{-\lambda(HV_{\text{eff}}-HV_{50})}}
$$

CMS RPC also define two points on this sigmoid that called knee and working point. $HV_{knee}$ is defined as the voltage at 95% of the maximum efficiency, and $HV_{WP}$ is defined as in Formula 3.25.

$$
HV_{WP} = HV_{knee} + \begin{cases} 
100\,\text{V} & \text{barrel} \\
150\,\text{V} & \text{endcap before LS1} \\
120\,\text{V} & \text{endcap after LS1}
\end{cases}
$$

3.5 Effect of atmospherical conditions

The voltage applied on a detector may vary due to a change in environmental conditions. Indeed, the variation of temperature and/or pressure will have effect on the gas density and the electrode resistivity. This can be compensated by changing the electric field accordingly. The influence of variation in temperature and pressure are depicted respectively in Figure 3.44 and Figure 3.45. A standard procedure to correct for temperature and pressure variations is to keep the factor $HV \cdot T/P$ constant using Formula 3.26 with reference values for $T_0$ and $P_0$. For example, CMS uses $T_0 = 293.15\,\text{K}$ and $P_0 = 965\,\text{hPa}$.
It was actually found that such a simple procedure overcorrects the applied voltage in case the variations of temperature or pressure become significant \cite{243,246}. CMS, considering that the temperature variations in the detector cavern were very small, decided only to improve the pressure correction, giving rise to Formula (3.27) \cite{243} while on the other hand, ATLAS decided to have a more robust correction for both parameters and uses Formula (3.28) instead \cite{246}. The coefficients $\alpha$, in the case of CMS, and $\alpha, \beta$, in the case of ATLAS, are extracted from a fit to data obtained during the operation of the detectors.

\begin{align*}
(3.26) \quad & HV_{\text{app}} = HV_{\text{eff}} \frac{P_0}{P} \frac{T}{T_0} \\
(3.27) \quad & HV_{\text{app}} = HV_{\text{eff}} \left(1 - \alpha + \frac{P_0}{P}\right) \frac{T}{T_0} \\
& \alpha = 0.8 \\
(3.28) \quad & HV_{\text{eff}} = HV_{\text{app}} \left(1 + \alpha \frac{\Delta T}{T_0}\right) \left(1 - \beta \frac{\Delta P}{P_0}\right) \\
& \alpha = 0.5, \beta = 0.71
\end{align*}
Figure 3.45: Effect of the pressure variation on the rate (a) and the efficiency (b) of an RPC [242].
In Chapter 2 the timeline of the LHC has been described and the upcoming High Luminosity LHC was introduced. LS3 has now started and the first HL-LHC related upgrade of CMS will take place. In order to understand the context in which the work of this thesis was performed as well as its motivations, it is necessary to give more insight into the reasons behind the increased instantaneous luminosity of LHC. In a first section of the chapter, these motivations will be discussed.

The muon system of CMS will then be presented in greater details than what was done in Chapter 2 in order to have a better understanding of the need for upgrades of its different sub-systems in the perspective of HL-LHC. Most of the detectors will require new electronics to adapt to the new data flow and be integrated into a more robust trigger. Moreover, the redundancy of the muon system in the endcaps will need to be improved. This will be achieved by the addition of new detectors.

Finally, some insight will be given on ecofriendly gas studies for the specific case of Resistive Plate Chambers. These studies don’t fall into the scope of the HL-LHC upgrades but the necessity of operating the detectors with gas mixtures that are more respectful of the environment is real. The European union is starting to press the scientific community for solutions and the research institutes are investing time into finding replacements to the gases used while maintaining similar working performances.

4.1 Motivations for HL-LHC and the upgrade of CMS

As detailed in Section 2.2.2, the first data taking period, during which the LHC was only operated at a center-of-mass energy of 7 TeV, took place until the start of LS1. It has been sufficient to claim the discovery of a new 125 GeV/c² particle compatible with the Higgs boson by both CMS and ATLAS in July 2012 and hence achieve a major milestone in the history of science towards the understanding of the fundamental nature of the universe. Nevertheless, the LHC machine holds the potential to go further and help unravel the remaining mysteries the High-Energy Physics (HEP) community is facing.
Figure 4.1: The measured transit time of an HSCP in CMS is compared to the transit time of a particle traveling at near the speed of light \[179\].

Over its full lifetime, the HL-LHC is expected to deliver an outstanding integrated luminosity of \(3000 \text{ fb}^{-1}\), nearly an order of magnitude higher than what will be delivered by LHC until LS3 starts, as shown in Figure 2.20. In the case of Higgs studies, this will lead to measuring the couplings of the boson to a precision of 2 to 5%. Thanks to the estimated 15 millions of Higgs bosons created every year, a more precise measurement of potential deviations from the theoretical predictions is expected. The properties of the boson will hence be tested and compared to the SM Higgs neutral boson. SUSY and heavy gauge boson studies would also see their mass range limits pushed away by at least 1 TeV and could lead to a new breakthrough. Many of the Standard Model extensions discussed in Section 2.1.3 yield Heavy Stable Charged Particles (HSCPs), i.e. heavy long-lived particles. These particles would be produced at the LHC with a high momentum but a velocity significantly lower than the speed of light (\(\beta < 0.9\)) \[247, 251\] and/or a charge that differs from the elementary charge (\(|Q| = e\), \(|Q| < e\) or \(|Q| > e\)) \[250, 255\]. Depending on the model considered, HSCPs could be lepton-like heavy particles or on the contrary R-hadron, i.e. particles composed of a supersymmetric particle and at least one quark \[250\].
Due to lifetimes of the order of a few ns, HSCPs would travel for long enough distances to cross through entire typical collider detectors while appearing almost stable. Because of their low velocity, they can be reconstructed and assigned to bunch crossings different to the ones they effectively have been produced, as shown in Figure 4.1 if reconstructed at all. Indeed, the trigger algorithms in use at CMS were not designed for such slow particles, and they assume most particles of interest will have a velocity close to the speed of light \(^{251, 257}\).

As HSCPs are long-lived particles, their identification would be possible thanks to the muon system. The main background will consist of wrongly measured muons which should have a lower transverse momentum, a near to speed-of-light velocity and a low ionisation energy loss. An example of passage of HSCPs through a slice of the CMS detector is showed in Figure 4.2. The tracks associated to the HSCPs would then have to be reconstructed in both the silicon detectors, for precise \(dE/dx\) measurement, and the muon system detectors. In this case, the muon system will be used to perform
Time-of-flight (ToF) measurements to discriminate between near speed-of-light particles and slower ones. The full reconstruction will then look for useful signatures such as the large transverse momentum of the candidates, or their large ionisation energy loss alongside the low velocity accurately measured thanks to the muon system as depicted in Figure 4.3. The ToF measurement to identify beyond the Standard Model particles will mostly rely on the time information provided by the Drift Tubes, in the barrel region of the detector, and Cathode Strip Chambers, in the endcaps. From CMS point of view, it will then become necessary to increase the acceptance and redundancy of the endcaps toward higher pseudo-rapidity as the pseudo-rapidity region $1.6 < |\eta| < 2.5$ is only covered by CSCs.

A natural consequence of the higher instantaneous luminosity will be the increase of collisions per bunch crossing. It is estimated that the pile-up will rise from the approximate average of 40 collisions per bunch crossing in 2017 and 2018, presented in Figure 4.4, to 140 to 200 depending on the scenario considered [258]. The trigger rate will then be affected in the same way putting a lot of stress on the trigger algorithms. Upgrading the electronics of some of the detectors and working on the data flow within the experiment would help going through HL-LHC with keeping similar performance than during Phase-1. On the other hand, the impact of the increased background will become problematic in many ways and will force for upgrades or many sub-systems of CMS. The main effects will be a large increase of the irradiation of the detectors, mainly close to the beam line. Both the detectors already installed and the new detectors that will extend the coverage of the muon system toward higher pseudo-rapidity need to be certified for the irradiation levels they will be subjected to until the end of HL-LHC. Simulations of the expected distribution of absorbed dose in the CMS detector under HL-LHC conditions show, in Figure 4.5, that detectors placed close to the beam line will have to withstand high irradiation, the radiation dose being of the order of a few tens of Gy.

Improving this situation will come with the increase of hit numbers recorded along the particle track to reduce the ambiguity on muon versus background detection. Moreover, the measurement of small production cross-section and/or decay branching ratio processes, such as the Higgs boson coupling to charge leptons, and in particular to muons, or the $B_s \to \mu^+\mu^-$ decay, is of major interest. Such considerations give more weight to the upgrade of the forward regions to maximize the physics acceptance to the largest possible solid angle.

To ensure proper trigger performance within the present coverage, the muon system will be completed with new chambers, and the electronics of the present system will need to be upgraded. A first step into this direction will be taken by installing new gaseous

![Figure 4.4: Distribution of the average number of interactions per crossing (pileup) for pp-collisions in 2011 (red), 2012 (blue), 2015 (purple), 2016 (orange), 2017 (light blue), and 2018 (navy blue). The overall mean values and the minimum bias cross sections are also shown [259].](image)
The Muon Phase-2 Upgrade

4-5

detectors in each endcap layer and extend the coverage up to $|\eta| = 2.8$. Nevertheless, the region beyond $|\eta| > 2.8$ and extending to $|\eta| = 5.0$ only is covered by the forward HCAL detectors and lack redundant muon detector coverage. Extensions of the tracker in the context of HL-LHC will increase its coverage up to $|\eta| = 4.0$ but the identification of muons and measurement of their energy with reasonable precision only using the tracker is nearly impossible. Thus, this increased tracker coverage range needs to be put in parallel with a matching muon detector and will open doors to multi-lepton final states in which leptons are likely to have a low transverse momentum and to be found near the beam line.

Finally, as the muon system is composed only of gaseous detectors, strong environmental concerns have risen over the last years as the European directives will restrict the use of fluorine based gas mixtures. Both the CSC and RPC subsystems, using $CF_4$, $C_2H_2F_4$, or $SF_6$, will need to adapt their working gas in order to strongly reduce the greenhouse potential of the mixtures released into the atmosphere due to gas leaks.

4.2 Necessity for improved electronics

Drift Tubes and Cathode Strip Chambers are important components used to identify and measure muons, especially thanks to their spatial resolution of the order of 100 $\mu$m. Nevertheless, the luminosity and irradiation during HL-LHC will cause serious event loss and ageing on the electronics of these subsystems that will comprise the triggering and data transferring needs of CMS. Thus, electronics upgrade is foreseen to address these expected problems. While only the RPCs’ electronic system is able to operate under Phase-2 requirements [260], DTs and CSCs will need to improve their trigger acceptance rate and latency to ensure that the Level-1 trigger threshold can stay at the same level [261]. The Level-1 trigger consists of custom hardware processors receiving data from the calorimeters and the muon system. In return, they generate a trigger signal within 3 $\mu$s, with a maximum rate of 100 kHz. In the perspective of HL-LHC, each subsystem needs...
to achieve a minimum rate of 500 kHz with a latency not greater than 12.5 µs. DTs and CSCs will also need to improve their Data Acquisition (DAQ) transfer rate to reach a minimum near 1 Tbit/s. The foreseen upgrades are expected to exceed the requirements.

The first version of Minicrate electronics (MiC1) used by DTs don’t allow for high enough trigger rate. In addition to this problem, it was shown that these electronics contain components that are not radiation hard enough to sustain HL-LHC conditions and hence, a too large number of channels may fail due to radiations as showed in Figure 4.6. The MiC1 will be replaced on each detector by an improved version referred to as MiC2 while Front-End Electronics (FEE) and High Voltage (HV) modules will not need any replacement. On the other hand, CSCs showed that their electronics would be able to live through the 10 years of Phase-2, but the limited buffer depth might cause memory overflows and read-out inefficiencies with a fraction of event loss ranging from 5 to more than 10% at an instantaneous luminosity similar to which of HL-LHC depending on the expected background. The replacement of CSCs’ CFEBs by digital ones, DCFEBs, with a deeper buffer would permit to make event loss negligible and satisfy HL-LHC requirements as can be seen in Figure 4.7. All these new DT and CSC electronics will be connected to the trigger electronics via optical links to ensure a faster communication [179].

The upgrade on the side of Resistive Plate Chambers will not be done at the level of the electronics but rather that of the Link System located in the service cavern of CMS. RPC Link System connects the front-end electronics data of RPCs into CMS trigger processors. The main motivation for such an upgrade is that the electronic boards composing the link system are built using obsolete and/or weak components that can easily suffer from the electromagnetic noise. These components may become the source of failing channels throughout Phase-2. Moreover, these link boards were originally designed only to match RPC digitized signals with the corresponding bunch crossing. Due to this feature, the time resolution of the full RPC chain is hence limited to 25 ns and does not make use of the full time resolution of the detectors. The time resolution foreseen after the upgrade can be seen through Figure 4.8. The time resolution, usually defined as the standard deviation of the distribution, is of the order of 1 ns.
Figure 4.9: (a) Time delay with respect to a particle traveling at the speed of light measured at consecutive RPC stations for particles originating at different bunch crossings and traveling at different velocities [179]. (b) In blue is showed the standard Level-1 muon trigger efficiency as a function of $\beta$ and in blue is showed the RPC-HSCP trigger efficiency after upgrade of the RPC Link System [179].

The exploitation of the full time resolution would make the synchronization of the RPC system easier and allow to have a finer offline out-of-time background removal within the 25 ns between consecutive bunch crossings. Moreover, this would greatly improve the trigger and reconstruction on HSCPs. Using the TOF information in between consecutive RPC stations, the minimal particle velocity that could be probed will drop from approximately 0.6 to 0.25 times the speed of light as showed in Figure 4.9. Upgrading RPC link system will require the installation of 1376 new link boards and 216 control boards. The new boards will make use of the recent progress made with fast FPGAs and will be a great improvement to the ASICs formerly used as they will be able to process signals from several detectors in parallel.

### 4.3 New detectors and increased acceptance

In the present muon system, the redundancy is assured by RPCs used for their robust bunch crossing assignments. The extension of the muon system towards higher pseudo-rapidity in an effort to complete the redundancy and to contribute to the precision of muon momentum measurements will require muon chambers with a spatial resolution less or comparable to the multiple scattering muons are subjected to while traveling through the detector volume [181].
Figure 4.10: A quadrant of the muon system, showing DTs (yellow), RPCs (blue), and CSCs (green). The locations of new forward muon detectors for Phase-2 are contained within the dashed box and indicated in red for GEM stations (ME0, GE1/1, and GE2/1) and dark blue for improved RPC (iRPC) stations (RE3/1 and RE4/1).
Figure 4.10 shows a similar quadrant of CMS than the one presented in Figure 2.27 with the addition of Gas Electron Multiplier (GEM) (ME0, GE1/1 and GE2/1) and improved RPC (iRPC) (RE3/1 and RE4/1) in the pseudo-rapidity region $1.6 < |\eta| < 2.4$. The completion of the redundancy was already scheduled in the original CMS Technical Proposal [262] but never addressed. The coming Phase-2I is then the occasion to equip the region with the newest GEM and RPC technology. In order to match CMS requirements, a spatial resolution of $O(\text{few } \text{mm})$ will be necessary for the proposed new RPC stations while the GEMs will need a resolution better than 1 mm, as showed by the simulation in Figure 4.11. Indeed, most of the plausible physics will be covered only considering muons with $p_T<100 \text{ GeV}$.

4.3.1 Gas electron multipliers

In the region closer to the interaction point where the spatial resolution is requested for the new detectors to be better than 1 mm (at least for ME0 and GE1/1 according to Figure 4.11) and where the background rate will be the highest for muon detectors, the choice has been made to use triple GEMs, micro pattern gaseous detectors, instead of the originally planned RPCs. The GE1/1 project has been the first to be approved and demonstrators have been installed in CMS already during LS1. The rest of the detectors will be installed during LS2 while the GE2/1 and ME0 projects are still under development. ME0, GE1/1 and GE2/1 will be installed respectively close to the HCAL endcap, on the first endcap disk as can be seen from Figure 4.10. Gas Electron Multipliers are gaseous detectors [263] whose gas volume is confined between two planar electrodes, the anode serving as read-out panel. The gas volume is divided in two or more regions by a single or multiple GEM foils as showed in Figure 4.12.

![Figure 4.10: Schematics of a GEM [SAULI2016]. On top is the cathode and on the bottom, the anode on which a 2D read-out is installed. Finally, the GEM foil separates the gas volume into the drift region, in between the cathode and the foil, and the induction region, in between the foil and the anode. A negative voltage is applied on the cathode. The anode is connected to the ground.](image)

![Figure 4.11: RMS of the multiple scattering displacement as a function of muon $p_T$ for the proposed forward muon stations [250]. All of the electromagnetic processes such as bremsstrahlung and magnetic field effect are included in the simulation.](image)

![Figure 4.12: Schematics of a GEM [SAULI2016].](image)
These foils are very thin, of the order of a few tens of µm, and are pierced with holes as can be seen in Figure 4.13. Both surfaces of the GEM foils are clad with copper in order to apply a strong electric field in between each side that will generate very strong potentials in the holes. The gas region contained in between the cathode and the GEM foil is called the drift region as the electric field is not strong enough to cause avalanches and thus start an amplification. The primary electrons drift toward the foil and are accelerated and amplified by the very high potential within the holes, as showed in Figure 4.13. Then the electrons reach the second drift region where they will induce a signal on the read-out located on the anode. By restraining the amplification process at the level of the holes, the electrons can stay confined in a very little space and thus induce a very localized current, providing the GEMs with a very good spatial resolution. The process can be repeated several times in a row, in order to achieve a stronger amplification. The GEMs that will be used in CMS are triple-GEM detectors operated with a 70/30 gas mixture of Ar/CO₂. They contain three GEM foils and hence three electron amplifications, as can be seen in Figure 4.14.

The GEM foils used in CMS are 50 µm foils clad with 5 µm of copper on each side. The foils are pierced with double-canonical holes which inner and outer diameters are respectively 50 and 70 µm which are placed 140 µm from each other in a hexagonal pattern, as showed in Figure 4.13. These detectors have a time resolution better than 10 ns and reach very good spatial resolutions of less than 200 µrad as indeed the position of the hits is not measured along the strips but following the azimuthal angle granularity of the radially organized trapezoidal strips.

The GEM Upgrade project started with GE1/1 [264]. GE1/1 detectors will already be installed during LS2. GE2/1 and ME0, on the other hand, will profit of the R&D knowledge and skills developed for GE1/1 while the requirements...
for each subsystem are different as they are not placed at the same distance from the interaction point. In this very forward region, a different position with respect to the center of the detector can dramatically change the conditions in which the detectors will have to be operated. In terms of rate capability, GE2/1, which is the furthest, is required to withstand $2.1 \text{kHz/cm}^2$ while GE1/1 needs to be better than $10 \text{kHz/cm}^2$ and ME0, better than $150 \text{kHz/cm}^2$. In terms of ageing with respect to charge deposition, ME0 needs to be certified to $840 \text{mC/cm}^2$, GE1/1 to $200 \text{mC/cm}^2$ and GE2/1 only to $9 \text{mC/cm}^2$. All 3 detectors need to have a time resolution better than $10 \text{ns}$ and an angular resolution better than $500 \mu \text{rad}$.

On each GE1/1 ring, 36 super chambers, consisting of two single GEM layers and spanning $10^\circ$, will be installed covering the pseudo-rapidity region $1.6 < |\eta| < 2.2$ together with ME1/1 CSCs. The reach of the muon system will be improved thanks to the GE2/1 that will overlap with the GE1/1 and cover a region from $|\eta| > 1.6$ to $|\eta| < 2.4$ and complete the redundancy of ME2/1. The super chambers, built with two triple-GEM layers each consisting of four single GEM modules due to the rather large surface of the GE2/1 chambers, that will be installed on the first ring of the second endcap will span $20^\circ$ each. Hence, a total of 72 chambers will be assembled to equip the muon system. Finally, the ME0 installed near the HCAL endcap will cover the region $2.0 < |\eta| < 2.8$. This subsystem will consist in super modules of six layers of triple-GEM detectors covering an azimuthal angle of $20^\circ$ leading to the construction of 216 single detectors.

Adding the GEMs into the forward region of the muon system will allow to strongly enhance the Level-1 trigger performance as shown in Figure 4.15. In the region $1.6 < |\eta| < 2.4$, the trigger efficiency of the current system would lie between 80 and 90% under HL-LHC conditions. The installation of GEMs would bring the efficiency to a consistent 92 to 94% on the entire region. At the same time, the trigger rate is expected to fluctuate from 3 to $10 \text{kHz}$ with the current system alone. The addition of detectors to complete the redundancy would allow keeping the rate mostly under 2 kHz. Moreover, benefiting from the good spatial and angular resolution of the GEMs, the precision into the muon measurement will also be improved by an order of magnitude thanks to the addition of GEMs as can be seen from the simulation presented in Figure 4.16.

![Figure 4.15: Simulated (a) efficiency and (b) rate of the standalone Level-1 muon trigger using tracks reconstructed in CSCs and all GEM stations compared with Phase-1 values in the case where only CSCs are used or CSCs+GE1/1. The zones of inefficiency of the CSC subsystem are compensated by the addition of GEMs during Phase-2 and the trigger rates is kept from increasing due to the high luminosity \cite{179}.](image-url)
Figure 4.16: (a) Simulated resolution of the muon direction measurement \( \Delta \phi \) with Phase-2 conditions. In the second endcap station, the resolution is compared in the case of CSCs (ME2/1) alone and CSCs+GEMs (GE2/1+ME2/1) while a similar resolution measurement is given in the case of the first station (GE1/1+ME1/1) \[179\]. The addition of GEM detectors on stations 1 and 2 (ME0 is considered to contribute to station 1) as redundant system to CSCs allows improving the muon momentum improvement through a more accurate measurement of the local bending angles \( \phi_1 \) and \( \phi_2 \) \[179\].

**4.3.2 Improved forward resistive plate chambers**

Figure 4.17: Simulation of the impact of RPC hit inclusion onto the local trigger primitive efficiency in station 3 (a) and station 4 (b) \[179\]. The contribution of iRPC starts above \(|\eta| > 1.8\).

Figure 4.10 shows that the iRPCs that will equip the third and fourth endcap disks in position RE3/1 and RE4/1 will finally be the partners of the CSCs in position ME3/1 and ME4/1. They will complete Phase-1 plans by bringing the needed upgrades in the perspective of Phase-2 as the older chambers are not suitable to equip the forward region of CMS due to HL-LHC rates and charge deposition. By completing the redundancy, more hits along the muon track will be available and the lever arm will be improved. The benefits from extending the redundancy of the muon system with iRPCs to
the forward most region is shown in Figure 4.17 in which the trigger efficiency is presented with and without RPCs. It is possible to see that the efficiency of the CMS muon trigger with the complete redundancy is consistently improved to a level above 95% in the region $|\eta| > 1.8$ as the iRPCs help filling the holes in the CSC system.

The detectors that will be installed in the coming years will have similarities with the already existing RPC system. 18 of the new chambers, each spanning $20^\circ$ in $\phi$ around the beam axis with 96 radially oriented trapezoidal read-out strips, will cover each muon endcap disk leading to the production of 72 iRPCs. The main difference with the old RPC detectors will be found at the level of the read-out panels. Indeed, the new chambers will not feature read-out strips segmented in $\eta$ but rather will favor a read-out on both strip ends to determine the position of the hits along the chamber. By using fast front-end electronics a radial spatial resolution of the order of 2 cm could be achieved to contribute to the better reconstruction of muons in the forward region where the bending due to the magnetic field is low. This technical choice is motivated by the fact that, in the case a $\eta$ segmentation were to be used, at least five pseudo-rapidity partitions would have been necessary to reach the minimal radial spatial resolution ($\approx 20$ cm). Having only one strip along the chamber read-out from both ends reduces by 60% the total number of channels and the necessary cabling, and allows for a better spatial resolution. The strip pitch will range from 6.0 mm (5.9 mm) on the high pseudo-rapidity end to 12.3 mm (10.9 mm) on the low one on position RE3/1 (RE4/1). The spatial resolution in the direction perpendicular to the strips should reach approximately 3 mm, better than the minimal needed resolution (Figure 4.11). Finally, the overall time resolution of the new installation will be equally 1 ns, as for the present due to the same link system being used even though the detector itself can achieve a time resolution of less than 100 ps, necessary for a spatial reconstruction of the hits with a resolution of 2 cm or less along the strip length.

![Figure 4.18: Expected hit rate due to neutrons, photons, electrons and positrons at HL-HLC instantaneous luminosity of $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ in RE3/1 and RE4/1 chambers [265, 266]. The sensitivities of iRPCs used in the simulation for each particle are reported and differ from one endcap disk to another as the energies of the considered particles varies with the increasing distance from the interaction point.](image)

Having only a single strip instead of pseudo-rapidity segmentation will increase the probability of double hits in the same channel. The probability was estimated to be low enough as it shouldn’t exceed 0.7%. This estimation was made assuming an average hit rate per unit area of 600 Hz/cm$^2$.
in the iRPCs (see Figure 4.18), a cluster size (average number of strips fired per muon) of 2, a strip active area of $158.4 \times 0.87 \text{ cm}^2$ and a safety factor 3. The corresponding rate per strip is estimated to be $380 \text{ kHz}$ leading to an average time interval in between two consecutive hits of $2600 \text{ ns}$. This is compared to the minimal time interval of $16 \text{ ns}$ necessary to avoid ambiguities. Indeed, a maximum of $10 \text{ ns}$ is spent by the signal traveling through the strip to reach the electronics to which can be added $1 \text{ ns}$ of dead time and 2 Time-to-Digital Converter (TDC) clock cycles of $2.5 \text{ ns}$ to convert the signal arrival time into a digital value in the FEEs. The probability of having ambiguous double hits in a strip is then the ratio between the minimal time interval in between two consecutive hits and the average time interval estimated from the rate the detectors would be subjected to.

The instantaneous luminosity at HL-LHC being very high, the rates at the position of the new chambers needed to be simulated in order to understand the necessary requirements for these detectors. The simulated results for different background components (neutrons, photons, electrons and positrons) are shown in Figure 4.18 assuming known sensitivities to these particles. It is shown that on average over the iRPC areas the rates would be of the order of $600 \text{ Hz/cm}^2$ ($600 \text{ Hz/cm}^2$ seen in RE3/1 and $480 \text{ Hz/cm}^2$ in RE4/1) [265, 266]. Thus, taking into account a safety factor of about 3, it was decided that improved RPCs should at least be certified for rates reaching $2 \text{ kHz/cm}^2$ which will be achieved thanks to several improvements on the design and on the electronics. The detectors design will be based on the existing RPCs as they will also feature double RPC gaps. Similarly to the existing RPC system, the electrode material will be HPL although the thickness of the electrodes and of the gas gap will be reduced to $1.4 \text{ mm}$ as a thinner gas gap leads to a decrease of deposited charge per avalanche as showed in Figure 4.19. The charge deposition in the case of a $1.4 \text{ mm}$ thick gas gap is reduced by a factor greater than 5 when compared to a $2 \text{ mm}$ gas gap at a similar electric field. The smaller the gas gap, the more the detector becomes sensitive to gap non-uniformities across the electrode planes, making a gap of $1.4 \text{ mm}$ a good compromise in between these two competing factors.

![Figure 4.19: Measured average charge per avalanche as a function of the effective electric field for different gas gap thickness in double-gap RPCs using HPL electrodes [179].](image)

A lower charge deposition inside of the detector volume means a slower ageing and a longer lifetime for detectors subjected to high irradiation. But, in order to take advantage of the lower detector gain, more sensitive electronics are required such that part of the gain that was formerly achieved in the gas volume can be moved to the electronics. Achieving this with the technology developed more than ten years ago for the present system is not possible as the signal over noise ratio of such electronics doesn’t allow to detect charges as low as $10 \text{ fC}$. Moreover, the new front-end electronics will need to be radiation hard to survive more than ten years of HL-LHC conditions. The new technology that has been chosen is based on the PETIROC ASIC manufactured by OMEGA and is a 64-channel ASIC [179, 267, 268]. The properties of these electronics will be discussed in Chapter 6.
4.4 Impact on Level-1 Trigger and physics performance

The upgrades of the different subsystems will have a subsequent impact on the Level-1 Trigger. Indeed, although its main scheme will not be affected, the efficiency of the trigger in identifying muons and provide the DAQ with good and fast trigger that can cope with HL-LHC instantaneous luminosity is a major improvement. In addition to the upgrade of the muon system in terms of trigger accept rate and latency, the Level-1 Trigger will get extra information by including the Tracker Trigger into its Muon Track Finder logic and combine the L1 Muon Trigger with Tracker and Calorimeter Triggers to generate a Global L1 Trigger, as shown in Figure 4.20. Using the track candidates of both the muon system and the tracker in spatial coincidence will allow for a much better momentum resolution thanks to better identified muons and, hence, better measured transverse impulsion as described in reference [179].

In terms of muon trigger, three regions are considered due to their different track finding logic: the Barrel Muon Track Finder (BMTF), the Endcap Muon Track Finder (EMTF) for both the barrel and endcap regions, and finally the Overlap Muon Track Finder (OMTF) which concerns the pseudorapidity region in which there is a common coverage by both the barrel and endcap muon systems. This region can be seen in Figure 4.10 for $0.9 < |\eta| < 1.2$ and requires a specific more complex logic to provide an efficient reconstruction of muons due to the different orientation of the detectors and of the more complex magnetic field of this region. The development of a track finder specific to the overlap region was achieved during the Phase-1 upgrade of the L1-Trigger [269].

The upgraded RPC link system, allowing to take profit of the full 1 ns resolution of the detectors, will help reducing the neutron induced background, slightly improve the bunch crossing assignment, and help increasing the trigger efficiency in every sector. The upgrade of DT electronics is also to take into account as the trigger primitive generator will be renewed through the use of TDCs that will send the digitized signals directly to common DT/RPC back-end electronics instead of having an on-detector trigger logic as it will be the case until the end of Phase-1. The combination of RPC hits together with DT primitives will bring extra improvement in the bunch crossing assignment in the barrel and overlap regions and improve the efficiency of the trigger between the wheels were the quality of DT primitives is the poorest.

The current EMTF already uses more sophisticated algorithms by combining together RPC hits and CSC primitives. The GEMs, in stations 1 and 2, and the iRPCs, in stations 3 and 4, will be added into the EMTF algorithm. Both these contributions will help increase the efficiency of the L1 trigger in the endcap region in one hand, as showed by Figure 4.21 and help lowering the L1 trigger rate in the other hand, especially in the most forward region. Similarly to the RPC/CSC algorithms, data from both CSCs and GEMs are combined into the Optical TMBs (OTMBs) to build on each station, GEM/CSC primitives matching space and time information from both subsystems. The efficiency improvement and rate reduction close to the beam line will be naturally enhanced by the addition of more hits along the muon tracks, as can be seen from Figure 4.22 that focuses especially in the
most challenging pseudo-rapidity region. Indeed, the contribution from the GEMs to the lever arm of each track thanks to their high angular resolution will be a great asset in achieving such results, as can be seen in Figure 4.23. The rate will be partly reduced in the forward region thanks to the better spatial resolution of iRPCs, with respect to the current RPC system. The ambiguity brought by multiple local charged tracks in CSCs will be reduced, as explained through Figure 4.24. Indeed, as the rates will increase, the probability to record more than a single local charged track will greatly increase. This is due to the fact that the trigger algorithm uses information from three consecutive bunch crossings to find muon tracks. It is estimated that with iRPCs operated at 95% efficiency the resolution of ambiguous events would be of the order of 99.7%.

![Figure 4.21: Efficiency of the L1 trigger in the endcap region after Phase-2 upgrade in the case CSC/GEM/RPC hits are requested in at least two stations out of four (a) and in all four stations (b) [179].](image)

![Figure 4.22: Comparison of L1 trigger performances for prompt muons with and without the addition of GEMs in the region $2.1 < |\eta| < 2.4$ at Phase-2 conditions [179]. GEMs would allow a reduction of the trigger accept rate by an order of magnitude (a) while increasing the trigger efficiency (b).](image)
Figure 4.23: The angular resolution on reconstructed muon tracks in the GEM overlap region $2.0 < |\eta| < 2.15$ is compared for Phase-2 conditions in the case CSC are alone (a) and in the case the GEMs’ data, including ME0, is combined to which of CSCs (b) [179].

Figure 4.24: Resolution of the LCT ambiguous events thanks to the combination of CSC and iRPC readout data. Using CSCs only, two pairs of hits are possible [179].

4.5 Ecofriendly gas studies

In the last steps of R&D, the gas mixture of CMS RPCs was foreseen to be a 96.2/3.5/0.3 composition of $C_2H_2F_4$/$C_4H_{10}/SF_6$ [212] but finally it was slightly changed into a 95.2/4.5/0.3 mixture of the same gases [240]. A summary of the operation performance of the RPCs since the start of LHC and of CMS data taking is given in Figure 4.25 [270]. The performance of the detectors is regularly monitored and the operating voltages updated in order to obtain a very stable performance through time. Nevertheless, the detectors will face new challenges during Phase-II during which they will exposed to more extreme radiation conditions. Description of the longevity tests with extreme
irradiation and the conclusions regarding the operation of the present RPC system will be given in Chapter 5.

Figure 4.25: Evolution of the efficiency, working voltage, and voltage at 50% of maximum efficiency for CMS Barrel (a) and Endcap (b) RPCs obtained through yearly voltage scans since 2011. The working voltage of each RPC is updated after each voltage scan to ensure optimal operation [270].

It was already discussed that in the future, it is likely that the use of freon gases could be banned. Using $CF_4$, $C_2H_2F_4$ and $SF_6$, both CSC and RPC subsystems will need to address this problem by finding new gas mixture for the operation of their detectors. Finding a replacement for these gas components that were used for very specific reasons is a great challenge. Indeed, CSCs use $CF_4$ in order to enhance the longevity of the detectors, increase the drift velocity of electrons and quench photons with a non-flammable gas mixture. RPCs use a mixture mainly composed of $C_2H_2F_4$, or $R134a$, that features a high effective Townsend coefficient and the great average fast charge allowing for operations with a high threshold. The mixture also contains a small fraction of $SF_6$ that is used for its electronegative properties that prevents the development of delta-rays in the gas volume that might trigger multiple ionization and avalanches. It only represents 0.3% of CMS standard mixture but more than 5% of its overall GWP.

<table>
<thead>
<tr>
<th></th>
<th>CSC</th>
<th>RPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse gases used</td>
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<td>$C_2H_2F_4$ and $SF_6$</td>
</tr>
<tr>
<td>Greenhouse gases fraction in the gas mixture</td>
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<td>95.2% and 0.3%</td>
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<tr>
<td>Global Warming Potential (relative to $CO_2$)</td>
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<td>1300 and 23900</td>
</tr>
<tr>
<td>Gas mixture re-circulation</td>
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<td>Yes, 85%</td>
</tr>
<tr>
<td>Gas mixture replenishing rate (l/hr)</td>
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<td>1100</td>
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<tr>
<td>F-gas recuperation</td>
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<td>No</td>
</tr>
<tr>
<td>F-gas venting rate (l/hr)</td>
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<td>1047 and 3.3</td>
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<tr>
<td>$CO_2$-equivalent rate (m$^3$/h)</td>
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<td>1440</td>
</tr>
<tr>
<td>Relative impact (entire muon system = 100%)</td>
<td>16%</td>
<td>84%</td>
</tr>
</tbody>
</table>

Table 4.1: Details of the greenhouse fluorinated gases used in CMS and of their GWP [179].

All these gases have a very high GWP, as reported in Table 4.1 and only few options are left. The subsystems need to work on strongly decreasing the loss of these gases due to leaks in the gas system
or need to completely change their gas mixture for more ecofriendly ones. Reducing the amount of F-gas released in the atmosphere due to leaks on the current gas system will require installation of a F-gas recuperation system on RPCs side and an upgrade of CSCs existing one in addition to the repair of existing leaks. With such measures, it is expected that the total rate of greenhouses gas vented in the atmosphere would represent only 1.6% of the current levels [179]. In the most critical case the F-gas were to be banned, it would be necessary to have replacement mixtures to operate CMS. CSC is presently investigating replacement for CF₄ such as CF₃I, C₃F₂, IF₆, C₃F₃ or CHF₃. RPCs, in collaboration with the ATLAS RPC group which uses the same gas mixture, have identified CF₃I (GWP ≤ 1) and C₃H₂F₁ (GWP ~ 6), referred to as HFO-1234ze, as potential candidates with mixtures containing CO₂. CO₂ is already widely used by various RPC experiments in mixtures with argon. More R&D needs to be conducted for both subsystems before concluding on the best alternative. Finding no good alternative to the present mixtures will require very efficient abatement system in CMS to burn and convert the greenhouse gases into less harmful ones. This way, the air pollution would be strongly reduced.

Figure 4.26: Efficiency (a) [210] and cluster size (b) of a standard double-gap RPC operated with CO₂ mixtures for different ratios of SF₆.

Figure 4.27: Efficiency of a CMS double-gap RPC operated with 30% of HFO, 4.5% of iC₄H₁₀, 1% of SF₆ and 64.5% of CO₂ [210].
Preliminary studies conducted in Ghent confirmed that CO\textsubscript{2} alone would require more than 1% of SF\textsubscript{6} to reach full efficiency, as presented in Figure 4.26. Even though the results obtained in Ghent don’t show the streamer probability (the probability to have very large avalanches whose induced charge is greater than 20 pC), the variation of the cluster size indicates that the streamers become predominant before the efficiency plateau is reached. Then, a very first test with an HFO/CO\textsubscript{2} was performed. Only one ratio was tested as can be seen from Figure 4.27 that displays a good efficiency with a plateau located at a similar high voltage than with R134a based mixtures (Figure 4.28). The status of RPC studies is presented in Figure 4.28 in which the performance (efficiency and streamer probability) of a CMS double-gap RPC operated with alternative gas mixtures is compared to the present CMS RPC mixture.

Although the technology certification was conducted with the standard CMS gas mixture which is a known reference, the iRPCs will need to be operated with new environmental-friendly gas mixtures. Studies have then been conducted with iRPCs, assuming that the HFO/CO\textsubscript{2} mixture containing an almost equal level of both components was the most likely candidate to replace the standard SF\textsubscript{6}. The status of RPC studies is presented in Figure 4.28 in which the performance (efficiency and streamer probability) of a CMS double-gap RPC operated with alternative gas mixtures is compared to the present CMS RPC mixture. Although the efficiency of detectors operated with mixtures containing CO\textsubscript{2}/CF\textsubscript{3}I or CO\textsubscript{2}/HFO as a replacement for C\textsubscript{2}H\textsubscript{2}F\textsubscript{4} seems to reach similar levels than which of the detectors operated with the present mixture, the new gas mixtures feature a streamer probability that far exceeds which of the present fluorinated mixture. The SF\textsubscript{6} doesn’t seem to prevent the formation of streamers as efficiently even when used at levels more than three times higher than with the standard CMS RPC mixture. Nevertheless, it is important to note that these results were obtained with a single-gap RPC while the use of a double-gap RPC reduces the operation voltage by 200 to 300 V, lowering the induced charge. A compromise between good efficiency and acceptable level of streamer probability, and the fine-tuned composition of potential replacement gas mixtures will be keep on being studied using a standard double-gap CMS RPC.

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mixture. In this purpose, an iRPC prototype has been built to be tested with an $HFO/CO_2$ gas mixture. The mixture, referred to as "ecogas" in Figure 4.29, contained 50% of $HFO$, 4.5% of $iC_4H_{10}$, 0.3% of $SF_6$ and 45.2% of $CO_2$. In Figure 4.29 is presented a result consistent with the blue curve obtained with 45% of $HFO$, 4% of $iC_4H_{10}$, 1% of $SF_6$ and 50% of $CO_2$ flushed into a standard double-gap RPC. Instead of the streamer probability, the cluster size is shown. The average number of hits generated by a muon passing through the chamber seem to have increased by 1 at the level of the knee of the sigmoid plateau using the ecogas.

Figure 4.29: Efficiency (open symbols) and cluster size (full symbols) of an iRPC as a function of the effective voltage for the standard CMS gas mixture and an environmental-friendly gas mixture [179].
Longevity studies and Consolidation of the present CMS RPC system

The RPC system, located in both barrel and endcap regions, provides a fast, independent muon trigger over a large portion of the pseudo-rapidity range ($|\eta| < 1.6$). During HL-LHC operations the expected conditions in terms of background and pile-up will make the identification and correct $p_T$ assignment a challenge for the muon system. The goal of the RPC upgrade is to provide additional hits to the Muon System with more precise timing. All this information will be elaborated by the Trigger System in a global way enhancing the performance of the muon trigger in terms of efficiency and rate control. The RPC Upgrade consists of two projects: an improved Link Board System and the extension of the RPC coverage up to $|\eta| = 2.4$.

The Link Board System is responsible for the processing, the synchronization and the zero-suppression of the signals coming from the RPC FEBs. The Link Board components have been produced between 2006 and 2007 and will be subjected to ageing and failure on a long term scale. An upgraded Link Board System will overcome the ageing problems and will allow for a more precise timing information to the RPC hits from 25 to 1.5 ns.

In order to develop an improved RPC that fulfills CMS requirements, an extensive R&D program is being conducted. The benefits of adding two new RPC layers in the innermost ring of stations 3 and 4 will be mainly observed in the neutron-induced background reduction and efficiency improvement for both the muon trigger and the offline reconstruction.

The coverage of the RPC System up to higher pseudo-rapidity $|\eta| = 2.1$ was part of the original CMS TDR. Nevertheless, the expected background rates being higher than the certified rate capability of the present CMS RPCs in that region and the budget being limited, RPCs were restricted to a smaller pseudo-rapidity range. Even though the iRPC technology that will equip the extension of the Muon System will be different than the current CMS RPC technology, it is necessary to certify the rate capability and longevity of the existing detectors as the radiation level will increase together with the increase of instantaneous luminosity of the LHC. For this purpose, unused spare CMS RPC detectors have been installed in different irradiation facilities, first of all, to certify the detectors to
the new levels of irradiation they will be subjected to and, finally, to study their ageing and certify their good operation throughout the HL-LHC program.

This chapter will discuss the longevity and consolidation studies of the present CMS RPC system to which I have contributed. Two different irradiation facilities have been used at CERN. In each of them I took a leading role in defining the experimental set-up, but also in the data collection and data analysis. In the first facility in which preliminary tests were conducted, I also worked on simulations of the experimental setup and I made predictions on the particle rate expected at the detector level. During the last 4 years of longevity test conducted in the second facility, I became a DAQ expert and built a software which is now the base for the data collection to study the longevity of CMS RPCs. Moreover, I also worked together with the Detector Control Software (DCS) expert to provide an online monitoring of the collected data. Indeed, I developed a software that automates the extractions of the detectors’ data and produces plots at the destination of the users thanks to a fast analysis. This software is a corner stone for the final data analysis. Documentation of both these softwares are given in Appendix A and Appendix B.

In a first section of the chapter, the irradiation facilities will be described. The study conducted will then be summarized in details. A description of the set-ups as well as a comprehensive review of the obtained results will be provided.

5.1 Testing detectors under extreme conditions

![Figure 5.1: Mean RPC Barrel (left column) and Endcap (right column) rate (top row) and current (bottom row) as a function of the instantaneous luminosity as measured in 2017 p-p collision data](image-url)
The upgrade from LHC to HL-LHC will increase the peak luminosity from $10^{34}$ cm$^{-2}$s$^{-1}$ to $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, increasing the total expected background to which the RPC system will be subjected. Mainly composed of low energy gammas, neutrons, and electrons and positrons from $p$-$p$ collisions, but also of low momentum primary and secondary muons, punch-through hadrons from calorimeters and particles produced in the interaction of the beams with collimators, the background will mostly affect the regions of CMS that are the closest to the beam line, i.e. the RPC detectors located in the endcaps.

Data collected during 2017, presented in Figure 5.1, allows to study the values of the background rate in the entire RPC system. This was achieved via the monitoring of the rates in each RPC rolls and of the current in each HV channel. A linear dependence of the mean rate or current on the instantaneous luminosity is shown in selected runs with identical LHC running parameters. It is assumed that such a linear behaviour should be observed at even higher luminosities and is therefore used to extrapolate the rates and currents that will be expected during HL-LHC. In Figure 5.2a a linear extrapolation of the distribution of the background hit rate per unit area as well as the integrated charge is shown at a HL-LHC condition. The maximum hit rate per unit area in the endcap detectors at HL-LHC conditions is expected to be of the order of $200$ Hz/cm$^2$ while the charge deposition should exceed $270$ mC/cm$^2$.

The detectors will thus have to be certified up to an irradiation of $840$ mC/cm$^2$ at a background rate of $600$ Hz/cm$^2$. These extrapolations are provided with a required safety factor 3 for the certification study.

In the past, extensive long-term tests were carried out at several gamma and neutron facilities certifying the detector performance. Both full size and small prototype RPCs have been irradiated with photons up to an integrated charge of $\sim 0.05$ C/cm$^2$ and $\sim 0.4$ C/cm$^2$ respectively and were certified for rates reaching 200 Hz/cm$^2$ [272, 273]. Since the beginning of Run-I until December 2017, the RPC system provided stable operation and excellent performance. The average integrated charge is of about $1.66$ mC/cm$^2$ in the Barrel and $4.58$ mC/cm$^2$ in the Endcap, closer to the beam line, as can be seen in Figure 5.3. The detectors did not show any ageing effects for a maximum integrated charge in a detector of the order of $0.01$ C/cm$^2$ and a peak luminosity reaching $1.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$ during the 2017 data taking period.

To perform the necessary studies on the present CMS RPC detectors, facilities offering the possibility to irradiate the chambers are necessary in order to recreate HL-LHC conditions or stronger and

![Figure 5.2: Linear extrapolation of the hit rate](a) and of the integrated charge](b) per region (Barrel, End-cap) respectively to HL-LHC instantaneous luminosity ($5 \times 10^{34}$ cm$^{-2}$s$^{-1}$) and HL-LHC integrated luminosity (3000 fb$^{-1}$) [271].
study the detector performance through time. A first series of such studies was conducted in the former Gamma Irradiation Facility (GIF) of CERN before its dismantlement starting from September 2014. This preliminary study was used as a stepping stone towards the building of a more powerful irradiation fully dedicated to longevity studies of CMS and ATLAS subsystems in the perspective of HL-LHC. The period of preliminary work has also been a key moment in the elaboration and improvement of data acquisition, offline analysis and online monitoring tools that are extensively used in the new gamma irradiation facility.

![Figure 5.3: CMS RPC mean integrated charge in the Barrel region (a) and the Endcap region (b) [271]. The integrated charge per year is shown in blue. The red curve shows the evolution of the accumulated integrated charge through time. The blank period in 2013 and 2014 corresponds to LS1.](image)

5.1.1 The Gamma Irradiation Facility

![Figure 5.4: Layout of the test beam zone of GIF at CERN [274].](image)
Located in the SPS West Area at the downstream end of the X5 test beam, the GIF was a test area in which particle detectors were exposed to a particle beam in presence of an adjustable gamma background [274]. Its goal was to reproduce background conditions these detectors would endure in their operating environment at LHC. The layout of the GIF is shown in Figure 5.4. Gamma photons are produced by a strong $^{137}$Cs source installed in the upstream part of the zone inside a lead container. The source container includes a collimator, designed to irradiate a $6 \times 6$ m$^2$ area at 5 m maximum distance to the source. A thin lens-shaped lead filter helps providing with a uniform out-coming flux in a vertical plane, orthogonal to the beam direction. The photon rate is controlled by further lead filters allowing the maximum rate to be limited and to vary within a range of four orders of magnitude. Particle detectors under test are then placed within the pyramidal volume in front of the source, perpendicularly to the beam line in order to profit from the homogeneous photon flux. Adjusting the background flux of photons can then be done using the filters and choosing the position of the detectors with respect to the source. The zone is surrounded by 8 m high and 80 cm thick concrete walls. Access is possible through three entry points. Two access doors for personnel and one large gate for material. A crane allows installation of heavy equipment in the area.

As described on Figure 5.5, the $^{137}$Cs source emits a 662 keV photon in 85% of the decays. An activity of 740 GBq was measured on the 5$^{th}$ of March 1997. The half-life of Cesium is well known ($t_{1/2} = (30.05 \pm 0.08)$ y) and can be used to compute the activity of the source at the time of the study. The GIF tests were done in between the 20$^{th}$ and the 31$^{st}$ of August 2014, i.e. at a time $t = (17.47 \pm 0.02)$ y resulting in an attenuation of the activity from 740 GBq in 1997 to 494 GBq in 2014.

5.1.2 The new Gamma Irradiation Facility

The GIF++, located in the SPS North Area at the downstream end of the H4 test beam, has replaced its predecessor during LS1 and has been operational since spring 2015 [275]. Like GIF, GIF++ features a $^{137}$Cs source of 662 keV gamma photons, their fluence being controlled with a set of filters of various attenuation factors. The source provides two separate large irradiation areas for testing several full-size muon detectors with homogeneous irradiation, as presented in Figure 5.6.

The source activity was measured to be about 13.5 TBq in March 2016. With the photon flux being far greater than HL-LHC expectations, GIF++ provides an excellent facility for accelerated ageing tests of muon detectors. The source is situated in a bunker designed to perform irradiation test along a muon beam line, which is available during selected periods throughout the year. The H4 beam, providing the area with muons with a maximum momentum of about 150 GeV/c, passes through the GIF++ zone and is used to periodically study the performance of the detectors placed under long term irradiation. Its flux is of 104 particles/s/cm$^2$ focused in an area of about $10 \times 10$ cm$^2$.
Adjusting the gamma flux is possible thanks to the three planes (A, B and C) of adjustable absorbers featured on the Cesium source [276]. With properly adjusted filters, one can simulate the background expected at HL-LHC and study the performance and ageing of muon detectors in HL-LHC environment. Each plane of filters features three filters (1, 2 and 3) with different Absorption factor (ABS) listed in Table 5.1. The source absorber settings can be referred by a three digit number with a format ABC or by its attenuation factor (for example 333 = 100 × 100 × 4.642 = 46420).

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>1.468</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>2.154</td>
<td>4.642</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Attenuation of single filters on each filter plane of the GIF++ Cesium source.

Figure 5.6: Floor plan of the GIF++ facility [277]. When the facility downstream of the GIF++ takes electron beam, a beam pipe is installed along the beam line (z-axis). The irradiator can be displaced laterally (its center moves from $x = 0.65\text{ m}$ to $2.15\text{ m}$), to increase the distance to the beam pipe.

Figure 5.7: Simulated unattenuated current of photons in the $xz$ plane (a) and $yz$ plane (b) through the source at $x = 0.65\text{ m}$ and $y = 0\text{ m}$ [277]. With angular correction filters, the current of 662 keV photons is made uniform in $xy$ planes.
The gamma current as simulated with GEANT4 is presented in Figure 5.7. In their simulation paper [277], Pfeiffer et al. define the particle current as "a measure of the net number of particles crossing a flat surface with a well-defined orientation. The unit of current is m$^{-2}$ s$^{-1}$ and thus identical to the unit of flux. Current is meaningful in cases where particles are counted without any interest in their interactions." The labels $U_N$, $D_N$, with $N \in [1 : 5]$ and I1 correspond to the position of different Radiation Monitoring (RADMON) sensors measuring the irradiation in the bunker area [277]. According to the simulation results, that agree within 12% to the doses measured with the RADMONs, the RPCs that will be tested in GIF++ can expect a maximal gamma current of the order of $2 \times 5 \times 10^6$ cm$^{-2}$ s$^{-1}$ assuming they will always stay in a region in between sensor U5 and the back wall of the upstream area.

5.2 Preliminary studies at GIF

5.2.1 RPC test setup

![Diagram of RPC setup](image)

**Figure 5.8:** Description of the RPC setup. Dimensions are given in mm. A tent containing RPCs is placed at 1720 mm from the source container. The source is situated in the center of the container. RE-4-2-BARC-161 chamber is 160 mm inside the tent. This way, the distance between the source and the chambers plan is 2060 mm. Figure (a) provides a side view of the setup in the $xz$ plane while Figure (b) shows a top view in the $yz$ plane.

During Summer 2014, preliminary tests have been conducted in the GIF area on an endcap chamber of type RE4/2 and labeled RE-4-2-BARC-161 produced for the extension of the endcap with a fourth disk in 2013. This chamber has been placed into a trolley covered with a tent in order to control the temperature. The positions of the RPC inside the tent and of the tent with respect to the source in the bunker are described in Figure 5.8. The goal of the study was to have a preliminary understanding of the rate capability of the present technology used in CMS. It was decided to measure the efficiency of the RPC under irradiation for detecting cosmic muons as, at the time of the tests, the beam was not operational anymore. Three different absorber settings were used and compared to the case where the detector was not irradiated in order to study the evolution of the performance of the detector with increasing exposure to gamma radiation. First of all, measurements were done with the fully opened source. To complete this preliminary study, the gamma flux has been attenuated by
a factor 2, a factor 5 and finally the source was shut down. The efficiency of the RPC at detecting the cosmic muons in coincidence with a cosmic trigger as well as the background rate as seen by the detectors were measured.

![Diagram](image)

**Figure 5.9:** (a) Shaping of the signals from the RPC strips by the FEE. The output LVDS signals are then read-out by a TDC module connected to a computer or converted into NIM and sent to scalers. (b) Trigger logic implementation with the RPC and photomultiplier signals.

The data taking was performed using a CAEN TDC module of type V1190A [278] to which the digitized output of the RPC Front-End Board is connected, as described in Figure 5.9a and the trigger signal from the telescope. The communication with the computer is performed thanks to a CAEN communication module of type V1718 [279]. In order to control the rates recorded by the detector, the digitized RPC signals are also sent to scalers as described in Figure 5.9b. The C++ DAQ software used in GIF was developed as an early attempt towards the understanding of the CAEN libraries and the data collected by the TDCs was saved into .dat files is analysed with an algorithm computing parameters such as efficiency, hit profile, cluster size, or gamma and noise rates which was developed with C++ as well. Finally, histograms and curves are produced using ROOT.
The trigger system was composed of two plastic scintillators and was placed in front of the setup with an inclination of $10^\circ$ with respect to the detector plane in order to look at cosmic muons. Using this particular trigger layout, shown in Figure 5.10, lead to a cosmic muon hit distribution into the chamber similar to the one of Figure 5.11. As mentioned in Chapter 2, the endcap RPC readout is segmented into three pseudo-rapidity partitions. The outer most partition, corresponding to the wide end of the chamber, is the partition A. The other two partitions are the partitions B and C. Each of them consists in 32 copper strips. These 32 strips are connected to the FEEs by groups of 16. The trigger is placed in front of the half-partition B2 which corresponds to the last 16 strips of partition B (49 to 64).

Measured without gamma irradiation, two peaks can be seen on the profile of readout partition B, centered on strips 52 and 59. Some events still occur in other half-partitions than B2 contributing to the inefficiency of detection of cosmic muons. In the case of partitions A and C, the very low amount of data can be interpreted as noise. On the other hand, it is clear that a little portion of muons reached the half-partition B1 (strips 33 to 48). Section 5.2.2 will help us understand that these two peaks are due respectively to forward and backward coming cosmic particles. Forward coming particles are detected first by the scintillators and then the RPC while the backward going muons are first detected in the RPC.

5.2.2 Geometrical acceptance of the setup layout to cosmic muons

In order to profit from a constant gamma irradiation, the detectors inside of the GIF bunker had to be placed in a plane orthogonal to the beam line. The muon beam that used to be available was meant to test the performance of detectors under test. This beam being not active anymore, another solution to test detector performance had to be used. Thus, it was decided to use cosmic muons detected through a telescope composed of two scintillators. Lead blocks were used as shielding to protect the photomultipliers from gammas as can be seen from Figure 5.10.

An inclination of $\sim 10^\circ$ was given to the cosmic telescope to increase the muon trigger rate for this otherwise horizontal setup. A good compromise had to be found between good enough muon flux and narrow enough hit distribution to be sure to contain all the events into a single half-partition as required from the limited available readout hardware. It was then foreseen to detect muons and read them out only from half-partition B2. Nevertheless, a misplacement of the trigger scintillators resulted in an inefficiency, as can be seen in Figure 5.11 with events appearing in half-partition B1.
As can be seen in Figure 5.12, a comparison of the performance of chamber RE-4-2-BARC-161 measured at GIF without irradiation to a reference curve suggests an inefficiency of approximately 20%. On the 18th of June 2014, data have been taken on the chamber at CERN building 904 (Prevessin Site) with cosmic muons providing us a reference efficiency plateau of $(97.54 \pm 0.15)\%$ represented by the black curve. A similar measurement has been done at GIF on the 21st of July with the same chamber giving a plateau of $(78.52 \pm 0.94)\%$ represented by the red curve. The inefficiency too high compared to the 12.7% of data contained into the first 16 strips observed on Figure 5.11 to be explained only by the geometrical acceptance of the setup itself. Simulations have been conducted to quantify the inefficiency of the setup.

5.2.2.1 Geometrical acceptance simulation setup

The layout of the GIF setup has been reproduced and incorporated into a C++ Monte Carlo (MC) simulation to study the geometrical acceptance of the telescope projected onto the readout strips [280]. A 3D view of the simulated layout is given into Figure 5.13. The RPC read-out plane is represented as a yellow trapezoid while the two scintillators as blue cuboids. The green plane corresponds to the $4 \times 4.5 \, \text{m}^2$ muon generation plane centered on the experimental setup within the simulation. The goal of the simulation is to look at muons that pass through the telescope composed of the two scintillators and define their distribution onto the RPC read-out plane. During the reconstruction, the read-out plane is then divided into its read-out strips and each muon track is assigned to a strip.

$N_\mu = 10^8$ muons are generated at a random position in the horizontal generation plane. This position corresponds to the intersection of the muon track with the generation plane. The plane is located at a height corresponding to the lowest point of the scintillators in order to easily simulate muons coming at very large zenith angles (i.e. $\theta \approx \pi$). The position of the particle within the plane is associated with a random direction: an azimuth angle $\phi$ chosen between 0 and $2\pi$ and a zenith angle $\theta$ chosen between 0 and $\pi/2$ to follow a usual $\cos^2 \theta$ distribution for cosmic particles. Then, using the position of the muon in the generation plane and its direction, the intersection of the track with the planes of the scintillator cuboids is computed. In the case the muon wasn’t found within the surface of both the scintillators, the simulation restarts and generates a new muon. On the contrary, if the track passed through the telescope, the simulation goes on. The position of the muon hit within

---

1. Albeit only roughly using Figure 5.10 due to the lack of actual measurements of the respective positions of each parts of the experimental setup. Using reference dimensions such as the size of the detector and the size of the photomultiplier, the positions could be deduced.
the RPC read-out plane is computed. The hits are saved into histograms, one per read-out partition, whose bins correspond to the RPC copper strips. The strip in which the hit occurred is determined by knowing precisely the geometry of the RPC. Muon hits are also filled in different histograms whether they are associated to forward coming \((\pi \leq \phi < 2\pi)\) or backward going \((0 \leq \phi < \pi)\) muons.

Figure 5.13: Representation of the layout used for the simulations of the test setup. (a) Global view of the simulated setup. (b) Zoomed view on the experimental setup.
5.2.2.2 Results and limitations

The output from the simulation is given in Figure 5.14 in which the geometrical acceptance distribution of the setup is shown. The distributions for the separate contributions of forward coming and backward going muons are all provided. The strip number is given in a range of 1 to 32 corresponding to the 32 strips contained in each RPC read-out partition even though partition B corresponds, by convention, to strip numbers 33 to 64. It can be established that, out of the total amount of muons that have passed through the telescope and reached the RPC, 16.8% were hitting the 16 first strip of the read-out plane corresponding to half partition B1. This number corresponds to the inefficiency. It can be used then to correct the data by scaling up by a factor \( c_{geo} = \frac{1}{1 - 0.168} \) the efficiency measured during data taking.

Nevertheless, the distribution shown in Figure 5.14 differs from the measured hit profile shown in Figure 5.11 as can be seen in Figure 5.15. It is difficult to evaluate a systematic uncertainty on this geometrical correction for different reasons. First of all, even though the dimensions of the scintillators and of the RPC are well known, the position of each element of the setup with respect to one another was not measured. The extraction of the position of each part of the setup from Figure 5.10 was a first large source of error.

The inclination is also roughly measured to be 10° bringing more uncertainty into the simulation. The acceptance distribution would be affected by a variation of the inclination angle, as can be seen in Figure 5.16. Yet, the position of the acceptance peaks in the distribution is in agreement with what is measured, and the contribution of forward and backward muons would never reach the observation. With an inclination of 10°, 28.1% of the total geometrical acceptance should contribute to detecting backward muons whereas it is measured that the hit profile contains 22.0% of backward data only. Introducing in the simulation an error of \( \pm 2° \) would lead to a correction factor \( c_{geo} = 1.20^{+0.04}_{-0.03} \) allowing for a good improvement of the efficiency measured in GIF, as can be seen from Figure 5.17. GIF measurement is in agreement with the reference curve within statistical errors.
Figure 5.15: Comparison of the hit distribution recorded in the detector and of the normalised geometrical acceptance distribution.

Figure 5.16: Effect of the variation of telescope inclination on the normalised geometrical acceptance distribution.

Figure 5.17: Correction of the efficiency without source. The efficiency after correction gets much closer to the Reference measurement performed before the study in GIF by reaching a plateau of (93.52 ± 2.64)%. 
This estimation of the backward versus forward content in the data was done through a fit using a sum of two skew distributions given in Equation 5.1. Although a skew distribution lacks physical interpretation, it allows fitting easily such kind of data, as shown in Figure 5.18.

\[
g(x) = A_s e^{-\frac{(x-x_i)^2}{\sigma^2}}
\]

\[
s(x) = \frac{A_s}{1 + e^{-\lambda(x-x_i)}}
\]

\[
s_k(x) = g(x) \times s(x) = \frac{A_s}{1 + e^{-\lambda(x-x_i)}} e^{-\frac{(x-x_i)^2}{\sigma^2}}
\]

Given the observed difference between the simulation and the measured data, one should realize that the geometrical acceptance and the hit profile are actually not directly comparable. The geometrical acceptance only provides with the information about what the detector can expect to see in a perfect world where all muons are detected in the exact same way. The detection would be independent from their energy or angle of incidence, and there would be no fluctuation of the detector gain due to complex avalanche development. No thresholds would be applied on the scintillators and on the RPC FEEs to reduce the noise, the cross-talk and the corresponding spread of the induced charge observed on the read-out strips. The hit profile provides the final product of all the previously mentioned contributions and can greatly differ from purely geometrical considerations. A full physics analysis involving software such as GEANT would be required to further refine the correction on the measured efficiency at GIF.

### 5.2.3 Photon flux at GIF

In order to understand and evaluate the \( \gamma \) flux in the GIF area, simulations have been conducted at the time GIF was opened for research purposes [274]. Table 5.2 gives the \( \gamma \) flux for different distances \( D \) to the source. The simulation was done using GEANT and a Monte Carlo N-Particle (MCNP) transport code, and the flux \( F \) is given with the estimated error from these packages expressed in %.

<table>
<thead>
<tr>
<th>Nominal ABS</th>
<th>at ( D = 50 \text{ cm} )</th>
<th>at ( D = 155 \text{ cm} )</th>
<th>at ( D = 300 \text{ cm} )</th>
<th>at ( D = 400 \text{ cm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 0.12 \times 10^6 \pm 0.2% )</td>
<td>( 0.14 \times 10^6 \pm 0.5% )</td>
<td>( 0.45 \times 10^6 \pm 0.5% )</td>
<td>( 0.28 \times 10^6 \pm 0.5% )</td>
</tr>
<tr>
<td>2</td>
<td>( 0.68 \times 10^6 \pm 0.3% )</td>
<td>( 0.80 \times 10^6 \pm 0.8% )</td>
<td>( 0.25 \times 10^6 \pm 0.8% )</td>
<td>( 0.16 \times 10^6 \pm 0.6% )</td>
</tr>
<tr>
<td>5</td>
<td>( 0.31 \times 10^6 \pm 0.4% )</td>
<td>( 0.36 \times 10^6 \pm 1.2% )</td>
<td>( 0.11 \times 10^6 \pm 1.2% )</td>
<td>( 0.70 \times 10^6 \pm 0.9% )</td>
</tr>
</tbody>
</table>

Table 5.2: Total photon flux \( (E_{\gamma} \leq 662 \text{ keV}) \) with statistical error predicted considering a \( ^{137} \text{Cs} \) activity of 740 GBq at different values of the distance \( D \) to the source along the x-axis of irradiation field [274].
The table, however, does not provide in a direct way the flux at the level of the RPC under test. First of all, it is necessary to extract the value of the flux from the available data contained in the original paper and then to estimate the flux in 2014 at the time the experiment took place. The extraction will be performed for the case of a pointlike source emitting isotropic and homogeneous gamma radiations. The flux $F_0$ is known at a given reference point situated at $D_0$ from the source. The gamma flux $F$ at a distance $D$ from the source will be expressed with Equation 5.2 assuming that the flux decreases as $1/D^2$ for a point-like source and where $c$ is a fitting factor that can be written as in Equation 5.3. Finally, using Equation 5.3 and the data of Table 5.2, assuming that the flux decreases as

\[ F = F_0 \left( \frac{cD_0}{D} \right)^2 \]  

\[ F = F_0 \left( a + \frac{bD_0}{D} \right)^2 \]  

\[ \Delta c = c \left( \frac{\Delta F_{ABS}}{F_{ABS}} \right)^2 \]  

\[ \Delta F_{ABS} = \left( a + \frac{bD_0}{D} \right)^2 \]  

\[ \Delta F_{ABS} = F_{ABS} \left( a + \frac{bD_0}{D} \right)^2 \]  

\[ \Delta F_{ABS} = F_{ABS} \left[ \frac{\Delta F_{ABS}}{F_{ABS}} + \Delta F_{ABS} \right] \]  

\[ \Delta F_{ABS} = F_{ABS} \left[ \frac{\Delta F_{ABS}}{F_{ABS}} + \Delta F_{ABS} \right] \]  

\[ \Delta F_{ABS} = F_{ABS} \left( a + \frac{bD_0}{D} \right)^2 \]  

\[ \Delta F_{ABS} = F_{ABS} \left[ \frac{\Delta F_{ABS}}{F_{ABS}} + \Delta F_{ABS} \right] \]

For the range of $D/D_0$ values available, it is possible to use a simple linear fit to get the evolution of $c$ that can be expressed as $c(D/D_0) = aD/D_0 + b$. Using Formula 5.4, but neglecting the uncertainty on $D$ that will only be used when extrapolating the values for the position of the RPC under test whose position is not perfectly known, the results shown in Figure 5.19 are obtained. Figure 5.19b confirms that using only a linear fit to extract $c$ is enough as the evolution of the rate that can be obtained superimposes well on the simulation points.

Table 5.3: Correction factor $c$ is computed with Formula 5.3 taking as reference point $D_0 = 50$ cm and the associated flux $F_0^{ABS}$ for each absorption factor available in Table 5.2.

<table>
<thead>
<tr>
<th>Nominal ABS</th>
<th>at $D = 155$ cm</th>
<th>Correction factor $c$ at $D = 300$ cm</th>
<th>at $D = 400$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.059 ± 0.70%</td>
<td>1.162 ± 0.70%</td>
<td>1.222 ± 0.70%</td>
</tr>
<tr>
<td>2</td>
<td>1.063 ± 1.10%</td>
<td>1.150 ± 1.10%</td>
<td>1.227 ± 0.90%</td>
</tr>
<tr>
<td>5</td>
<td>1.056 ± 1.60%</td>
<td>1.130 ± 1.60%</td>
<td>1.202 ± 1.30%</td>
</tr>
</tbody>
</table>

During the 2014 GIF tests, the RPC read-out plane was located at a distance $D = 206$ cm from the source. Moreover, to estimate the strength of the flux in 2014, it is necessary to consider the nuclear decay through time of the Cesium source whose half-life is well known ($t_{1/2} = (30.05 ± 0.08)$ y). The very first source activity measurement has been done on the 5th of March 1997 while the GIF tests where done in between the 20th and the 31st of August 2014, i.e. at a time $t = (17.47 ± 0.02)$ y resulting in an attenuation of the activity from 740 GBq in 1997 to 494 GBq in 2014. All the needed information to extrapolate the expected flux through the detector at the moment of the GIF preliminary tests has now been assembled, leading to Table 5.4. By assuming an average sensitivity of the RPC to $\gamma$ emitted by the $^{137}$Cs source of $(2 ± 0.2) \times 10^{-3}$ [281], the order of magnitude of the expected hit rate per unit area would be of the order of kHz for a fully opened source, as reported in the last column of the table. As photons are not charged particles, they mainly interact with the electrodes where they are converted into electrons. The HPL electrodes are not very
sensitive to gamma photons, hence only a small fraction of the incoming flux is seen by the RPC.

![Graph showing linear approximation fit performed on the data extracted from table 5.3. Comparison of Equation 5.4 with the simulated flux using $a$ and $b$ given in figure 5.19a in Equation 5.2 and the reference $D_0 = 50$ cm and the associated flux for each absorption factor $F_{ABS}$ from table 5.2.]

**Figure 5.19:** (a) Linear approximation fit performed on the data extracted from table 5.3. (b) Comparison of Equation 5.4 with the simulated flux using $a$ and $b$ given in figure 5.19a in Equation 5.2 and the reference $D_0 = 50$ cm and the associated flux for each absorption factor $F_{ABS}$ from table 5.2.

<table>
<thead>
<tr>
<th>Nominal ABS</th>
<th>Photon flux $F$ [cm$^{-2}$ s$^{-1}$] at $D_0^{57} = 50$ cm</th>
<th>Photon flux $F$ [cm$^{-2}$ s$^{-1}$] at $D_0^{37} = 206$ cm</th>
<th>Photon flux $F$ [cm$^{-2}$ s$^{-1}$] at $D_0^{2014} = 206$ cm</th>
<th>Rate [Hz/cm$^2$] at $D_0^{2014} = 206$ cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$0.12 \times 10^6 \pm 0.2%$</td>
<td>$0.84 \times 10^6 \pm 1.2%$</td>
<td>$0.56 \times 10^6 \pm 1.2%$</td>
<td>$1129 \pm 14$</td>
</tr>
<tr>
<td>2</td>
<td>$0.68 \times 10^7 \pm 0.3%$</td>
<td>$0.48 \times 10^7 \pm 1.2%$</td>
<td>$0.32 \times 10^7 \pm 1.2%$</td>
<td>$640 \pm 8$</td>
</tr>
<tr>
<td>5</td>
<td>$0.31 \times 10^7 \pm 0.4%$</td>
<td>$0.22 \times 10^7 \pm 1.2%$</td>
<td>$0.15 \times 10^7 \pm 1.2%$</td>
<td>$292 \pm 4$</td>
</tr>
</tbody>
</table>

**Table 5.4:** The data at $D_0$ in 1997 is taken from [274]. Using Formula 5.4, the flux at $D$, including an error of 1 cm, can be estimated in 1997. Then, taking into account the attenuation of the source activity, the flux at $D$ can be estimated at the time of the tests in GIF in 2014. Assuming a sensitivity of the RPC to gammas, $s = (2 \pm 0.2) \times 10^{-3}$ [281], an estimation of the hit rate per unit area is obtained.

The goal of the study was to have a good measurement of the intrinsic RPC performance without
source irradiation. Then, taking profit of the two working absorbers, at absorption factors 5 (300 Hz) and 2 (∼600 Hz) the goal was to show that the detectors fulfill the performance certification of CMS RPCs. Finally, a first assessment of the performance of the detectors at higher backgrounds was obtained with absorption factor 1 (no absorption and >1 kHz).

5.2.4 Results and discussions

The data taking at GIF has been conducted between the 21st and the 31st of August, 2014. Data have been collected with the source both ON and OFF using three different absorber settings (ABS 5, 2 and 1) in order to vary the irradiation on the RPC. For each source setting, two HV scans have been performed with two different trigger settings. During a first scan the trigger sent to the TDC module was the coincidence of the two scintillators composing the telescope while during a second scan the trigger was a pulse coming from a pulse generator in order to measure the noise or gamma rate seen by the chamber. Indeed, using a pulse generator allows to trigger at moments not linked to any physical event and, hence, to obtain a RANDOM trigger on noise and gamma events to measure the associated rates, the probability to have a pulse in coincidence with a cosmic muon being negligible.

From the cosmic trigger scans, a summary of the efficiencies and corresponding cluster sizes is shown in Figure 5.20. The efficiency curves with Source ON show a shift with respect to the case without irradiation. With ABS 5, the general shape of the efficiency curve stays unchanged whereas a clear alteration of the performance is observed at ABS 2 and ABS 1. From the cluster size results, a reduction of the mean cluster size under irradiation can be observed at equivalent efficiency. This effect can be due to the perturbation of the electric field by the strong flux of gamma particles interacting with the electrodes. With the increasing number of photons being converted into electrons, an increasing number of charges need to be recombined all over the volume of the electrodes that act as capacitors. A discharge of the electrodes reduces the effective field seen in the gas volume by introducing a voltage drop across the electrodes thickness. The constant pressure put on the detector by the converting photons can become strong enough to uniformly affect the gain of the detector.

![Figure 5.20: Efficiency (a) and cluster size (b) of chamber RE-4-2-BARC-161 measured at GIF with Source OFF (red) and Source ON using different absorber settings: ABS 5 (green), ABS 2 (blue) and ABS 1 (yellow). The results are compared to the Reference values obtained with cosmics.](image-url)

It is necessary to study the evolution of the performance of the chamber with the increasing rate...
The hit rate is measured as the number of hits detected in the RPC normalized to the surface area of the read-out and to the total integrated time. The integrated time is linked to the time window in which the TDC searches for data related to a trigger signal. Data is continuously kept in the buffer of the TDCs but not all of these data is of interest. When a trigger signal is sent to the TDC module, the TDC saves all of the data located in a certain time window set around the time stamp of the signal. The total integrated time is then the total number of trigger signals times the width of a search time window.

In Figure 5.21a, the noise rate when the source is OFF remains low but increases at voltages above 9500 V. Aside of the natural increase of the noise with increasing voltage, the rise of the noise rate in the detector can be related to the increased streamer probability observed with such a large electric field. The rates measured at GIF with source ON all show a similar behaviour until a high voltage of approximately 9400 V at which the rate of ABS 5 reaches a plateau, coinciding with the chamber reaching full efficiency. It is important to note that, even though the rates look similar independently from the gamma flux, relative to the efficiency of the chamber, the rate actually increases with increasing flux at equivalent efficiency. A rough way to measure the rate effectively observed by the detector for each source setting would be to normalize the measured rates to the efficiency of the detector. This exercise was done with Figure 5.21b from which constant fits were done on Source ON data in order to extract the rate the chamber was subjected to. This method leads to rates of $(164 \pm 12) \text{Hz/cm}^2$, $(340 \pm 26) \text{Hz/cm}^2$ and $(598 \pm 50) \text{Hz/cm}^2$ respectively for ABS 5, 2 and 1 which is consistent with the absorber values. Also, contrary to the case of the source OFF measurement, no rise of the noise is observed at ABS 5. This difference could be explained by the efficiency shift that is related to a decrease of the electric field across the gas volume.

The results need to be taken with care as a better estimation of the rate would have been to push the detector towards higher voltages to reach the efficiency plateau for each absorber configuration and only then extract the measured rate at working voltage, defined as in Formula [3.25]. Nevertheless, using this method to estimate the rate to which the chamber is subjected, it is possible to look at the evolution of the $HV_{50}$ and $HV_{knee}$ as a function of the increasing rate as shown in Figure 5.22. The results from GIF suggest that at a rate of 600 Hz/cm$^2$ the working voltage of the chamber is...
increased by a thousand V while the efficiency is reduced to approximately 80%, although the result still is consistent with an efficiency better than 90% due to the large error on the measurement.

\[ q_{\gamma} \approx \frac{J_{\text{mon}}}{R_{\gamma}} \]

Figure 5.22: Evolution of the voltages at half maximum and at 95% of the maximum efficiency (Figure 5.22a), and of the maximum efficiency (Figure 5.22b) as a function of the rate in chamber RE-4-2-BARC-161. The data is extracted from the fits in Figures 5.20a and 5.21b.

Figure 5.23: Presentation of a double-gap endcap RPC with its three RPC gaps. Due to the partitioning of the read-out strips into three rolls, the TOP layer of gap is divided into two gaps: TOP NARROW (TN) and TOP WIDE (TW). The BOTTOM (B) only consists in one gap.

It is likely that the rates obtained through fitting on normalized values is underestimated. Indeed, monitoring the current in the three gaps composing a CMS endcap RPC (Figure 5.24) while knowing the rate, the charge deposition per avalanche \( q_{\gamma} \) can be computed. A current density, expressed in \( \text{A/cm}^2 \), divided by a rate per unit area, expressed in \( \text{Hz/cm}^2 \) yields a charge expressed in \( \text{C} \). The current driven by the RPC is assumed to be due to the irradiation, hence, to the avalanches developing in the gas volume due to the photons of the Cesium source. On the other hand, the rate is supposed to be a measure of the number of photons interacting with the detector. This way, it comes that the charge deposition per avalanche is expressed like \( q_{\gamma} = \frac{J_{\text{mon}}}{R_{\gamma}} \), with \( J_{\text{mon}} \) being the monitored...
current density and \( R_\gamma \) the measured \( \gamma \) rate. The current density is computed as the sum of the current density measured in the top and bottom gap layers, 
\[
J_{\text{mon}} = \left( I_{T\gamma}^{\text{mon}} + I_{TB}^{\text{mon}} \right) / (A_{TW} + A_{TN}) + I_{TB}^{\text{mon}} / A_B,
\]
with \( A_{TB,TN,TW} \) being the active area and \( I_{TB,TN,TW}^{\text{mon}} \) the monitored currents of the gaps. According to Figure 5.24, the charge deposition per avalanche consistently converges to a value of the order of 50 pC for each absorber setting which corresponds to a value more than twice larger than what reported in literature for CMS detectors [281, 282] indicating that the rates could have been wrongly evaluated during the short study performed at GIF. An increase of the \( \gamma \) rate by a factor 2 would actually be consistent with the expected rates calculated in Table 5.4, assuming the sensitivity to \( \gamma \) to be of the order of \((2 \pm 0.2) \times 10^{-3}\).

![Graph](image.png)

**Figure 5.24:** Current density (a) and charge deposition per gamma avalanche (a), defined as the current density normalized to the measured rate taken from Figure 5.21a as a function of the effective high voltage in chamber RE-4-2-BARC-161 measured at GIF with Source ON using different absorber settings: ABS 5 (green), ABS 2 (blue) and ABS 1 (yellow).

Overall, working at GIF has been a rewarding experience as it offered CMS RPC R&D team the possibility to start developing the necessary skills and tools that would become the core of GIF++. The quality of the results can be argued both due to the little robustness of the experimental setup and the lack of available statistics to draw conclusions, bringing large errors on the final result. The confrontation of the data to known results pointed to a failure in correctly measuring the \( \gamma \) rate at working voltage and, hence, to an overestimation of the charge per avalanche and of the drift of working voltage with increasing rate. Nevertheless, the prototypes of DAQ and offline analysis tools proved to be reliable.

### 5.3 Longevity tests at GIF++

#### 5.3.1 Selection and characterization of CMS RPCs for longevity at GIF++

In the perspective of future upgrades of LHC that would bring detectors to be operated in a high irradiation environment, the new Gamma Irradiation Facility of CERN was first proposed in 2009 [283]. The GIF++ would thus provide all LHC R&D teams working on behalf of the different LHC experiment with a facility to perform longevity studies using a very intense Cesium gamma source.
In the specific case of CMS RPC, the longevity studies imply a constant irradiation of selected detectors in order to accumulate a charge equivalent to what is expected during HL-LHC, i.e. a charge of \(0.8 \text{ C/cm}^2\) according to Figure 5.2 including a safety factor 3. Other detectors are left non-irradiated to be used as references. Throughout the irradiation campaign, the performance of the irradiated and reference detectors will be periodically probed using the high intensity H4 muon beam. Dedicated test beam periods will be used to measure the efficiency and gamma rate at the level of the detectors. Different source absorber settings will test the rate capability of CMS RPCs, that needs to be certified above 600 Hz/cm\(^2\). Using a muon beam will also help identifying signs of ageing in the case the performance of the irradiated detectors diverges from those of the reference detectors with increasing accumulated charge. Other than the performance of the detectors, signs of ageing could come from increasing dark current that would be related to local ageing of the electrodes triggered by the increased hydrofluoric acid (HF) production in an irradiated environment. HF is produced by the decomposition of \(C_2H_2F_4\) molecules during the charge multiplication process and leads to increased dark current and noise in Bakelite RPCs treated with linseed oil. This effect is strongly reinforced by the presence of UV photons \cite{284,285}. A close monitoring of the current driven by the detectors will then be necessary as well as dedicated periodical electrode...
resistivity measurements and chromatography analyses on the gas exhaust.

As the maximum background in CMS is found in the endcap disks, the choice was made to focus the GIF++ longevity studies on endcap chambers. Most of the RPC system was installed in 2007. Nevertheless, the large chambers in the fourth endcap (RE4/2 and RE4/3) have been installed during LS1 in 2014. The HPL of these two different productions possibly having slightly different properties, four spare chambers of the present system were selected. From the original CMS RPC system, two RE2/2 spares were selected along two RE4/2 spares from the newest detectors. Having two chambers of each type allowed to always keep one of them non-irradiated as reference. Due to the limited gas flow in GIF++, the RE4 chamber remained non-irradiated until end of November 2016 when the longevity studies could finally be started on those chambers.

The performance of the chambers prior to the start of the longevity campaign was characterized in Ghent before their transportation to CERN for installation in the GIF++. The results of the characterization are shown in Figure 5.25 and summarized in Table 5.5. A clear difference in performance for both types of chambers is observed as the working voltages of the newest chambers, of type RE4, are 300 to 400 V lower to the older chambers indicating that the gap thickness of RE4 detectors could be thinner. This conclusion could as well be supported by the lower cluster size at working voltages that are also smaller in RE4 chambers. Even though the measured currents are low, RE4 detectors draw less current without irradiation than RE2 detectors pointing to a difference in electrode resistivity that were produced at different moments. Efficiency and noise rate levels are of the same order of magnitude for both type of RPCs.

<table>
<thead>
<tr>
<th>RPC</th>
<th>RE2-2-BARC-08</th>
<th>RE2-2-BARC-09</th>
<th>RE4-2-CERN-165</th>
<th>RE4-2-CERN-166</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used as</td>
<td>Reference</td>
<td>Irradiation</td>
<td>Reference</td>
<td>Irradiation</td>
</tr>
<tr>
<td>$H_W P_r (V)$</td>
<td>$97.32 \pm 6$</td>
<td>$98.03 \pm 6$</td>
<td>$94.19 \pm 6$</td>
<td>$94.34 \pm 6$</td>
</tr>
<tr>
<td>Efficiency at WP</td>
<td>$96.2 \pm 0.3$</td>
<td>$96.6 \pm 0.3$</td>
<td>$95.9 \pm 0.3$</td>
<td>$95.5 \pm 0.3$</td>
</tr>
<tr>
<td>Cluster size at WP</td>
<td>$2.19 \pm 0.04$</td>
<td>$2.27 \pm 0.05$</td>
<td>$1.88 \pm 0.04$</td>
<td>$1.80 \pm 0.04$</td>
</tr>
<tr>
<td>Noise at WP (Hz/cm$^2$)</td>
<td>$0.51 \pm 0.01$</td>
<td>$0.39 \pm 0.01$</td>
<td>$0.44 \pm 0.00$</td>
<td>$0.15 \pm 0.01$</td>
</tr>
<tr>
<td>$J_{W P} (\text{pA/cm}^2)$</td>
<td>$30.1 \pm 0.1$</td>
<td>$22.2 \pm 0.1$</td>
<td>$3.8 \pm 0.0$</td>
<td>$10.2 \pm 0.0$</td>
</tr>
</tbody>
</table>

Table 5.5: Summary of the characterization measurement performed in Ghent on CMS RPC detectors foreseen to be used at GIF++ for longevity studies of the present system. For each detector, the working voltage, defined as in Formula 3.25, was extracted from sigmoid fits performed in Figure 5.25a. The values of efficiency, cluster size, noise rate and current density at this voltage are reported.

### 5.3.2 RPC test setup

For an easy manipulation of the detectors, a trolley with a structure containing slots in which the RPCs can be slid vertically was used and is referred to as T1. When in position, each chamber is in a plane perpendicular to the beam line and the source flux as can be seen through Figure 5.26 and receives a uniform irradiation. Moreover the trolley allows for easy movement of the system. Indeed, the position of the trolley varies according to the specific measurements that are being done.
Figure 5.26: CMS RPC setup inside the GIF++ bunker during test beam (a) and ageing periods (b). The space in between the RPCs and the source is usually used by other detectors while the space in between T1 and the upstream wall is not filled. Due to the presence of the beam pipe, the trolley is moved away from the beam line during irradiation periods and placed further away from the source for less intense irradiation. The position of the trolley can vary due to the use of the space by other setups and is then not exact. Nonetheless, the position of the chambers in the trolley is fixed and given in Figure (c).

During the dedicated test beam periods, the GIF++ experiments are in control of the muon beam. The trolley is placed in the upstream region of the bunker, in the beam line at a distance of generally 3.4 m from the source, as described through Figure 5.26a. At this distance, the simulated gamma current is the order of $5 \times 10^6 \text{ cm}^{-2} \text{s}^{-1}$. The CMS RPC detectors are the furthest away from the source as other detectors need to be certified at higher background rates. Depending on the needs of the other experiments at the GIF++, the trolley position of the trolley can be pushed as far as 4.1 m from the source. An additional trolley, referred to as T3, contains iRPCs and is placed between the source and the T1 trolley. Indeed, iRPCs need to be certified at higher rates and thus need to be placed closer to the source to receive a stronger irradiation using the same absorber settings. The space on T1 being limited, the tracking RPCs used for extra offline information during the analysis are placed on the same trolley as the iRPCs. They are kept at full efficiency at all time to reconstruct muon tracks and to correlate them with hits recorded in T1 chambers. The beam trigger system is composed of three scintillators. Two are placed outside on each side of the bunker and of the third scintillator is placed in the beam line in between T1 and the wall.
Most of the year, outside of these test beam periods, T1 is placed in the so called ageing position corresponding to the furthest position at approximately 4.7 m from the source outside of the beam line before August 2019. At such a distance, the simulated gamma current is the order of $3 \times 10^6$ cm$^{-2}$ s$^{-1}$. Following the extension of the upstream area in August 2019, the trolley was pushed approximately 1 m away at a distance of 5.7 m to the source, corresponding to a simulated gamma current of the order of $2 \times 10^6$ cm$^{-2}$ s$^{-1}$. During periods where GIF++ doesn’t have the control of the beam, the beam line needs to stay clear so that a beam tube can be installed through the bunker, as can be seen in Figure 5.26b. The reason for placing the chambers as far as possible from the source comes from the too high irradiation delivered by the source during the irradiation periods where all the other groups having placed detectors in the bunker require as much charge integration as possible. Hence, the source is operated without any absorbers. On the contrary, during the test beam periods, all the groups working in GIF++ are interested in operating the source using various absorber settings to study the performance of their detectors under different irradiation conditions. T1 RPCs are kept at a standby voltage of 6500 V when the other groups need to work with ABS 1 due to the proximity of the trolley to the source compared to ageing periods.

From the bunker area, long cables and pipes running through the wooden floor connect the detectors to the service area, visible in Figure 5.6. The service area hosts all the high and low voltage power supplies, the TDCs and computers used for data acquisition and preliminary offline analysis. The gas system required for the gaseous detectors installed in GIF++ can also be found in the service area [286].

The detectors read-out is, as in the case of GIF, connected to V1190A VME TDCs communicating with the DAQ computer via a V1718 VME bridge manufactured by CAEN. At the end of each data taking, the preliminary analysis is run to fill the Detector Control Software webpage, referred to as WebDCS, with Data Quality Monitoring (DQM) histograms. The WebDCS is a custom made DCS application for the specific case of GIF++ RPCs. It provides online information about the environmental parameters in the bunker as well as the state of each detector. A constant monitoring of all the environmental parameters, in different points of the bunker area, gas parameters, to control its composition, temperature and pressure, and of the voltages and currents delivered by the power supplies is performed and displayed on the homepage of the WebDCS interface. Moreover, it contains the database with all the RPC data in the form of ROOT files and of summary histograms. Hence, it is a useful tool for the shifters on duty in the control room located farther in the building, away from the beam lines.

### 5.3.3 GIF++ data flow

At GIF++, the CMS RPC R&D setup collects different types of data from the detector monitoring parameters, such as voltage and currents, the gas, source and environmental parameters, and, of course, the TDC data related to the actual muon and gamma measurements. These different data sources correspond to three different data flows as presented in Figure 5.27.

The Data Interchange Protocol (DIP) flow, DIP being a communication system allowing for exchange of real-time information between systems [287], concerns all the data coming from the gas composition, temperature and humidity, the environmental temperature and pressure, the source settings and the radiation monitoring sensors. At the experimental area, all data of interest for all of the users of the facility (source settings, radiation monitoring, gas composition at the exit of the gas mixer and general environmental information) are measured, distributed and also stored in the data of the experimental hall where is located the GIF++. Access to the database is done through DIP.
communication. The measurement of more specific data such as gas flow, temperature and humidity at the level of the detectors (upstream and downstream of the detectors) as well as environmental parameters has to be arranged by the users themselves. For this reason, several pressure, temperature and humidity sensors were installed on the gas distribution system of the RPC trolleys. The corresponding data flow, although not related to DIP itself, is saved together with the DIP data into the local CMS RPC database and displayed on the front page of the WebDCS. In the case any of the measured values go out of their optimal range, the WebDCS will produce corresponding alerts. The data are particularly important to perform the PT correction described in Section 3.5 of Chapter 3 and to stabilize the effective voltage of the detectors. Monitoring history plots are made using JavaScript and are also displayed for easy access to past information, as shown in Figure 5.28.

The data flow related to the monitoring of the detector high voltages and currents, referred to as CAEN flow as a reference to the manufacturer of power supplies, is handled through direct communication between the DAQ computer and the power supply main frames. Finally, the DAQ flow concerns all data acquired through the use of the TDCs, i.e. all the muon or gamma event data
It was already discussed that when a trigger signal is sent to a TDC module, the TDC saves all of the data located in a certain time window set around the time stamp of the signal. The trigger signal in the case of GIF++ can be a coincidence of the trigger scintillators or a signal from a pulse generator. The DAQ computer extracts from the TDC buffers the list of fired channels and of associated time stamps for each trigger signal. The data is then used to reconstruct muon tracks along the CMS RPC setup at the GIF++ or to compute the noise and gamma rates associated to a certain source setting.

![WebDCS GIF++](image)

Figure 5.28: DIP monitoring history accessed through the GIF++ WebDCS interface.

### 5.3.4 Measurements performed during beam periods

As previously described, two types of measurements are performed on the chambers during beam periods. On the one hand, it is interesting to measure the efficiency of the RPCs with increasing voltage with different source absorber settings but on the other hand, it is important to correlate the efficiency information to the gamma rate seen by the chambers at the different voltages. The choice was made to separate efficiency measurements from rate measurements to better manage time and data volume. In both cases, TDC data recorded during so called HV scans is divided into runs, one for each high voltage point, whose data is stored into ROOT files. The TDC settings used during both these scans as well as the ROOT data structure are detailed in Section 4.2 of Appendix A.

The goal of both efficiency and rate scans is to measure the rate capability of the detectors but also to monitor any degradation of the performance due to ageing. This way, during test beam periods the efficiency and corresponding gamma background are measured to correlate the evolution of rate capability at different stages of irradiation. In the absence of other signs of ageing, a reduction of the rate capability could be related to an increase of the electrodes resistivity.
5.3.4.1 Efficiency scans

The HV scans performed to specifically measure the muon detection efficiency under different irradiation conditions follow a standardized procedure. Data using the DAQ were taken at the same 12 HV points for all chambers, ranging from 9 kV to 10.1 kV in steps of 100 V. For each HV run, a minimum of 5000 muon beam triggers, provided by the coincidence of the three scintillators, is required in order to accumulate enough statistics for a reliable computation of the efficiency of the detectors. In addition to the four RPCs held on T1, two tracking RPCs installed on T3 are kept at a fixed voltage of 9.7 kV to provide the analysis software [288] with beam position information to exclude off-track signals. The tracking RPCs are double gap detectors featuring 2 mm HPL electrodes and 2 mm gas gaps. They are prototypes built by the Italian company General Tecnica using a different production of HPL. Finally, the monitored currents and voltages are recorded in histograms along with the TDC data in a different ROOT file for each run.

HV scans are taken for different source settings as the goal is to irradiate all the detectors with a minimal rate of 600 Hz/cm². Usually, a full study of the performance of the detectors is performed with Source OFF, and then with nine absorber settings that attenuate the nominal gamma flux by factors from more than 200 to only 3, where settings with the fully opened source are avoided with RPCs in test beam position. During the efficiency scans, the cluster size is also measured and the currents are monitored as can be seen in Figure 5.29.

5.3.4.2 Rate scans

The background measurements are performed using a similar HV scan procedure as for the efficiency measurements. The HV scan in test beam periods is taken at fewer HV points compared to the efficiency scans as the region of interest is located around the knee and efficiency plateau of the detectors, i.e. these scans are performed only on six HV points ranging from 9.5 kV to 10 kV. The value of the rate at the operating voltage is then deduced from the efficiency scan through linear
interpolation. A good estimation of the rate requires a long enough integrated time of the TDC data. The way data is collected, detailed in Appendix A, makes the DAQ search for data stored in the TDC buffers prior to the trigger signal. The time window from which the data can be collected ranges from 25 ns to more than 50 μs. With the Cesium source delivering a constant gamma flux, it was decided that a total integrated time of 0.2 s would be enough to have a reliable calculation of the gamma rate. This is achieved by taking 20,000 random trigger pulses delivered by a pulse generator at a frequency of 300 Hz while extracting 10 μs of data from the buffers for each trigger. An example of the data obtained during rate scans is shown in Figure 5.30 in which the hit multiplicity at a single HV step of a scan, used to compute the rate per unit area, is displayed together with the rates computed at every HV steps.

Figure 5.30: Example of results obtained during an efficiency scan performed with ABS 113 (4.6) during October 2018 testbeam period. The hit multiplicity histograms (a), (b) and (c) correspond to the fourth HV point of the scan at 9800 V.

Separating the rate and efficiency measurements was motivated by the inconsistency of the muon beam provided in GIF++. Using periods without beam to measure rates with a good statistics allows for faster study programs. Moreover, the number of muons per beam spill depends strongly on the user setups placed upstream of the GIF++ and on the specific beam optic magnet settings. Collecting

2 During test beam periods, the delivery of the muon beam at the SPS North Area depends on the LHC program. As the SPS is used to feed the LHC with accelerated protons, the priority is given to the LHC. Other than the LHC, the delivery of muon beams can also be stopped due to maintenance or breakdown on the acceleration lane. This may translate into long periods with low intensity beams or even without any beam at all.
20,000 events could then take too long for the other users at the GIF++. Hence, efficiency scans are performed with lower statistics, and the time window from which the TDC data are extracted is strongly reduced (400ns for efficiency scans versus 10μs for rate scans) to keep the data size to its bare minimum.

5.3.4.3 Offline analysis and Data Quality Monitoring

![DQM page](image)

*Figure 5.31: Example of DQM page available on CMS RPC WebDCS at the GIF++: the histogram of the rate measured in one of the tracking chambers is selected and displayed above the page.*

The data recorded during efficiency and rate scans always consists of two ROOT files per run, where each run corresponds to a certain HV point. One of the files contains the TDC data, a collection...
of hits and time stamps per active channel on the read-out of the RPCs, while the second is the CAEN main frame data, i.e. the detector currents and high voltages. The data are systematically analysed at the end of each scan using the Offline Analysis tool of GIF++, detailed in Appendix B that produces histograms such as hit, rate and time profiles, hit multiplicities, gamma cluster sizes or multiplicities for the DQM display of the WebDCS, as shown in Figure 5.31. More histograms can be accessed through the ROOT browser included in the WebDCS, as shown in Figure 5.32. Moreover, the analysis performed with the Offline tool provides final results for the rate scans. On the contrary, the algorithm for efficiency calculation is kept simple and approximative in the tool. Including tracking into the analysis requires manual adjustment for each individual scan as the positions of the trolleys with respect to each other may vary.

Figure 5.32: Example of DQM ROOT Browser page available on CMS RPC WebDCS at the GIF++: the strip activity profile, defined as the rate profile normalized to the mean rate, in one of the tracking chambers. Available ROOT files and histograms can be browsed thanks to the left panel showing the directory and files structures.

5.3.5 Measurements performed during irradiation periods

Even though test beam periods are stressful times as an extensive data taking program needs to be finalized in a short amount of time, the biggest amount of data actually comes from irradiation periods. Indeed, when T1 is moved back to its ageing position in between each test beam periods, data is recorded at any time the source can be switched ON for irradiation. Other experiments in the area might prevent the source from staying open continuously. As an example, the time efficiency of irradiation of CMS RPC detectors in GIF++ is presented in Figure 5.33.

Several types of measurement are performed throughout the irradiation period. As long as the detectors are being irradiated, a monitoring of the currents is performed to evaluate the corresponding integrated charge over the total irradiation time. Moreover, in order to spot any signs of ageing, the gamma rates seen by the chambers at the chosen source absorber setting as well as the noise rates and dark currents are periodically measured. During irradiation periods this is looked every week
via HV scans performed at various source settings. The weekly scans involve both the irradiated but also the reference chambers, providing with a weekly monitoring of the evolution of the irradiated chambers noise, gamma rate and dark current. Measuring with all detectors at the same time also allows getting rid of potential systematics that might make the rates (noise or gamma) vary from one measurement to another. If such systematic effects occur, they will be observed in all detectors.

Finally, the resistivity is measured periodically during the year, generally before or after test beam periods, by the use of Argon breakdown technique. The method consists in filling the detector volume with Argon instead of the CMS standard gas mixture and to increase the voltage while monitoring the current. Beyond an electric field of about 1 kV mm$^{-1}$ at the GIF++ environmental conditions, Argon turns into a conductive plasma and does not offer electric resistance anymore. The monitoring of the currents beyond the breakdown voltage can then be used to calculate the resistivity of the electrode material.

![Image](image_url)

Figure 5.33: Longevity data for the irradiated RE2 chamber in GIF++. For each month since July 2017, the integrated charge (in blue) as well as the time efficiency of irradiation (in gray) is reported.

5.3.5.1 Longevity scans

The main activity of irradiation periods consists of the longevity scans during which the currents of the irradiated chambers are continuously monitored. The two irradiated chambers are both brought to a voltage of 9.8 kV while the source flux can vary depending on the needs of the groups using the facility. The currents are monitored for each active gas volume as can be seen in Figure 5.34. The integrated charge for each individual gas volume is computed by integrating through time the current density, current normalised to the surface area, flowing through each gap, as shown in Figure 5.35.
Figure 5.34: Example of a longevity scan monitoring page available on CMS RPC WebDCS at the GIF++: the current and effective voltage, as well as environmental parameters, are monitored for the bottom gap of the irradiated RE2 chamber. The decrease of current is related to a decrease of the voltage due to the daily rate scan procedure or to periods during which the source was turned OFF.

Figure 5.35: Example of a longevity scan summary page available on CMS RPC WebDCS at the GIF++: the integrated charge is computed for the bottom gap of the irradiated RE2 chamber.

Finally, at the end of each longevity scan each gap contribution is translated into the mean chamber integrated charge. The integrated charge accumulated in each chamber is used to update the
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Summary plots providing the collaboration with official results to be spread as can be seen from Figure 5.36. The translation from individual gap currents to total integrated charge in the chamber is done using Equation 5.5, where the equation to compute the monitored current density already mentioned in Section 5.2.4 is recalled.

\[
J_{\text{mon}} = \frac{I_{\text{TW}}^{\text{mon}} + I_{\text{TN}}^{\text{mon}} + I_{\text{B}}^{\text{mon}}}{A_{\text{TW}} + A_{\text{TN}} + A_{\text{B}}} \\
Q_{\text{int}} = \int_{t_i}^{t_f} J_{\text{mon}} \, dt
\]

(5.5)

Figure 5.36: Example of current monitoring summary (top wide (a), top narrow (b) and bottom (c) gap currents) and of corresponding integrated charge (d) of the irradiated RE2 chamber.
5.3.5.2 Daily rate monitoring scans

Every night during longevity scans, the setup performs daily rate scans. These scans aim at keeping track of the gamma rate measured in the irradiated RPCs during longevity scans, but are also used to measure the noise rate at standby voltage for each gap. The procedure for these HV scans consists of nine runs for which 50,000 random triggers are accumulated, corresponding to 0.5 s of total integrated time.

1. All gaps are first left at the irradiation voltage of 9.8 kV to measure the gamma rate.

2. Then all gaps are brought to the standby voltage of 6.5 kV to measure the noise rate of the full detectors.

3. Both top gaps (TW and TN) are brought to a voltage equivalent to an OFF status, i.e. 1 kV so that the noise contribution of only the bottom gap at standby voltage can be measured.

4. The bottom gaps are ramped up toward the working voltage of 9.8 kV to measure their contribution to the gamma rate estimation.

5-8 The steps 3 and 4 are repeated on TN and then on TW, keeping the bottom and the top gap which is not of interest at a voltage of 1 kV. This way, the individual contribution to the noise and gamma rates are known.

9. Both TW and TN are brought to working voltage while the bottom gap is left at 1 kV to measure the gamma rate for the full top layer at once.

Finally, the voltages of all gaps are brought back to working voltage for the longevity program to continue until the next daily scan. These scans are responsible for the drop of voltages and currents observed in Figure 5.34. The procedure previously described is highlighted in Figure 5.37.

Similarly to the efficiency and rate scans taken during test beam periods, the data is here stored in two separate ROOT files for the TDC and CAEN data for each run. At the same time, the currents are still monitored by the longevity scan and saved into the GIF++ database for an easy evaluation of the currents to the integrated charge. The Offline Analysis tool then provides the DQM page with histograms, and daily values can be compiled into long term monitoring plots to study the variations of rate and current with increasing integrated charge, as presented in Figure 5.38. The variations of the rate and current are correlated and correspond mainly to change of source irradiation, gas flow, gas humidity, or environmental conditions. The rates on every single read-out channel are also tracked to control their activity with increasing integrated charge and, this way, understand the appearance of hot spots through noisy channels, as shown in Figure 5.39. The activity of a strip is defined as the rate of the individual channel normalized to the mean rate measured in the corresponding read-out partition.
Figure 5.37: Example of daily scan procedure of the irradiated RE2 chamber with highlighted runs on the CMS RPC WebDCS at the GIF++.
Figure 5.38: Example of rate (a) and current (b) monitoring of the irradiated RE2 chamber at working voltage in double gap mode (step 1) with increasing integrated charge.

Figure 5.39: Example of strip activity of the irradiated RE2 chamber monitored over time.

5.3.5.3 Weekly noise monitoring scans

Once a week, the source is turned OFF to make a noise scan for the CMS RPC. This HV scan is composed of six runs for which 25,000 random triggers are accumulated. The first run is taken at
standby voltage and the second one at 8 kV. The next five runs are taken at voltages ranging from 9.4 to 9.8 kV in order to access for both type of chambers, RE2 and RE4, in the voltage region where the efficiency rises and reaches its plateau. The whole procedure is showed in Figure 5.40. On the occasion of this scan, the ongoing longevity scan is stopped. A new one will be started once the weekly scans are over.

Figure 5.40: Example of rates (a) and currents (b) of the irradiated and reference RE4 chambers measured during a weekly noise scan.

5.3.5.4 Weekly source scans

Directly following the weekly noise scans, HV rate scans are organised at different source settings (usually ABS 6.8, 4.6 and 3.3). The procedure of these HV scans consists of nine runs for which 25,000 random triggers are accumulated. The first run is taken at standby voltage while the next eight runs are taken at voltages ranging from 9.4 to 10.1 kV. They aim at measuring the gamma rate to which the chambers are subjected and the related currents. The whole procedure is shown in Figure 5.41.

Figure 5.41: Example of rates (a) and currents (b) of irradiated and reference RE4 chambers measured during a weekly source scan. The data were measured with ABS 123 (6.9).
5.3.5.5 Weekly current scans

The previously detailed daily rate scans, but also the weekly noise and source scans are interesting tools to look at an increase of noise rates and dark currents or at a loss of rate capability. They could point to an increase of surface resistivity of the electrodes through the absorption of hydrofluoric acid. Nevertheless, periodically measuring the currents on wider high voltage ranges allows to have access to the ohmic part of the current driven by the detectors related to the electrodes resistance. This is why precise current scans, consisting only in measuring the current driven through the four detectors, are performed each week. The scan procedure includes measurements at 131 high voltage points in between 500 V and 10 kV, in steps of 100 V until the standby voltage of 6.5 kV is reached and then in steps of 50 V. At low voltage, the current rise is slow and is only driven by the resistance of the detector electrode and thus increases linearly. It is referred to as the ohmic current as opposed to the physics current corresponding to the voltage region where charge multiplication starts to occur. A fit on the ohmic current range gives access to the resistance of the ‘electrodes/gas’ system. Any variation of the electrode resistance will affect the current. Technically, these scans will record a ROOT file per HV step that will have the same format as the CAEN ROOT file saved during other HV scans. The data are also analysed using the Offline Analysis tool to provide with DQM histograms as well as standardized $I/V$ tables.

5.3.6 Extraction and monitoring of the resistivity

A critical parameter to monitor is the resistivity of the electrodes. Its variation would impact the rate capability of the RPC. An increase of the resistivity with increased irradiation is expected. In the first place, the measurement of the resistivity of the electrodes is done using the so called Argon scans. Such tests are performed regularly before or after test beam periods through high voltage scans of the detectors operated with pure Argon. The electric field strength at which Argon breaks down being well known, the current beyond the breakdown voltage is measured and analyzed. Assuming a relation $I_{mon} = H V_{eff} / R_{elec}$ beyond the breakdown voltage, the resistance of the pair of electrodes $R_{elec}$ is determined via a linear fit to the measured current as illustrated in Figure 5.43. The resistivity is then deduced via Formula 5.6 where $S$ is the surface area.
area of the gap and $l$ the thickness of a single electrode.

\begin{equation}
\rho = R \times \frac{S}{2 \times l}
\end{equation}

Figure 5.44: Efficiency (a) and monitored currents of the bottom (b) and top narrow (c) gaps as a function of the effective voltage of the irradiated RE2 chamber during October 2018 testbeam period. The data are shown for source OFF and different absorption factors.

There is actually another way to access a quantity directly related to the electrode resistivity. During the testbeam periods, the efficiency of the detectors is measured with both source OFF and source ON with high irradiation. The shift of voltage introduced by an irradiation is directly linked to the rate capability of the detector and hence to the resistivity of the electrodes. By comparing the
efficiency curves observed with source ON and OFF during a single testbeam, it is possible to access the mean resistance of the detector partition under the beam during a testbeam period. Knowing the dimensions of the electrodes, this value can be compared to the resistivity directly measured using the argon scans. It also provides a tool to compare different testbeam results by getting rid of the bias introduced by the fluctuation of the resistivity through time. The mean resistance is computed as in Formula 5.7.

\[
R = \frac{\Delta HV}{\Delta I} = \frac{HV_{ON} - HV_{OFF}}{I_{ON} - I_{OFF}}
\]

It is important to note that the result provided by using this method will only concern the resistance of the detector under beam irradiation, including the little contribution of the resistance of the gas volume itself. The translation to the resistivity of the electrodes is not straightforward even though the result falls in the same order of magnitude. Also, the quality of the resistance extraction depends on which level of irradiation is available in the data. During October 2018 testbeam period, HV scans were done on partition C of the RPCs (bottom and top narrow gas gaps) with source OFF and with eight different ABS values: ABS 313 (464), ABS 311 (100), ABS 213 (46.4), ABS 212 (21.5), ABS 211 (10), ABS 123 (6.9), ABS 113 (4.6) and ABS 122 (3.2). T1 was placed close to the bunker upstream wall at a distance of 5.6 m from the source. This position corresponds to a gamma current of the order of \(5 \times 10^5\text{cm}^{-2}\text{s}^{-1}\) with the source fully open.

In a first step, the efficiency sigmoids as well as the bottom and top narrow gaps’ monitored current as a function of the effective voltage were retrieved as can be seen from Figure 5.44. The goal is to compute the value of the effective voltage at the knee \(HV_{knee}\) of the sigmoids. The knee where \(\epsilon = 0.95 \times \epsilon_{max}\) would be the best location to extract the value of the resistivity. At this point, the performance of the detectors is stable and a little variation of voltage does not have a large effect on the efficiency. The effective voltage at the knee is given by Formula 5.8.

\[
HV_{knee} = HV_{\frac{50}{\lambda} + \frac{ln(19)}{\lambda}}
\]

The monitored current at the knee \(I^G_{knee}\) for each gap G is then computed by extrapolating from the monitored currents value located around \(HV_{knee}\) as in Formula 5.9 where \(I^G_{}\) and \(HV^G_{}\) are the monitored current and the effective voltage at the voltage point below the knee and \(I^G_{U}\) and \(HV^G_{U}\) are the monitored current and the effective voltage above the knee.

\[
I^G_{knee} = I^G_{U} + (I^G_{U} - I^G_{L}) \times \frac{HV_{knee} - HV^G_{L}}{HV^G_{U} - HV^G_{L}}
\]

Once the values of the monitored currents are known at the knee, the mean current flowing through the gaps at the level of the studied partition \(P\) can be computed. First of all, the currents at the knee of the gaps in the beam line are normalised to the area of the gap active area seen by the local read-out partition \(S^{G,P}\). Then the mean current at knee \(I^P_{knee}\) is computed by weighing the local currents \(I^G_{knee}\) of each gap by their respective active area in the partition.

\[
I^P_{knee} = I^{G,P}_{knee} \times \frac{S^{G,P}}{S^G} \quad \text{and} \quad \quad I^P_{knee} = \frac{I^{1,P}_{knee} \times S^{1,P} + I^{2,P}_{knee} \times S^{2,P}}{S^1 + S^2}
\]
The variation of effective voltage and mean monitored current at the knee in between the Source OFF and ON scans can then be obtained. The local resistivity of the detector can finally be calculated combining Formula 5.6 and Formula 5.7. This process is performed for every scan of each approved test beam period as can be seen in Figure 5.45. Finally, the most probable resistivity during the test beam period is obtained via a constant fit. The value of the mean partition resistivity displayed in Figure 5.45 is of the same order of magnitude as one would expect for CMS RPCs.

Figure 5.45: Resistivity extraction for all approved test beam periods for the reference RE2/2 (a) and RE4/2 (c) chambers and the irradiated RE2/2 (b) and RE4/2 (d) chambers.

Later on, the resistivity values extracted from this method will be used to compare the efficiency sigmoids of the different testbeam periods. During the operation of the detector without irradiation, the voltage drop across the detector almost only consists in a voltage drop across the gas volume. As
the electrodes behave approximately as charged capacitors, there is only a negligible voltage drop across their volume. The charge of the electrodes is only affected locally by the charge carriers freed by avalanches in the gas volume. Nevertheless, under irradiation, the conversion of photons is uniform throughout the electrodes’ volume and charge recombination happens everywhere at the same time making it impossible for the electrodes to stay charged. Hence, a significant part of the voltage drop appears across the electrodes, explaining the usual voltage shift observed in the performance of irradiated RPCs. The data comparison will then be done using the gas voltage drop $HV_{gas}$ obtained by correcting the effective voltage $HV_{eff}$ using Formula 5.11 in which $R$ is the resistance computed at the knee using Formula 5.7 in the RPC partition of interest and $T$ is the mean current in this partition at each voltage step.

$$HV_{gas} = HV_{eff} - R \times T$$

5.3.7 Results and discussions

Since 2015, CMS RPCs have been irradiated at the GIF++ with the goal to reach a total integrated charge per irradiated detector of 0.84 C/cm² while certifying the detectors to a single hit rate capability of 600 Hz/cm². At the time of writing, the RE2 and RE4 chambers were exposed to 77 and 43% of their total irradiation program respectively, as shown in Figure 5.46. According to Figure 5.47, a few years of irradiation are expected before reaching the end of the longevity study for both types of detectors and before reaching a final answer on whether or not the present CMS RPC system will be able to live through HL-LHC. The charge accumulation of the RE2 detector is faster than that of the RE4 and is expected to end within a year. In the case of the RE4 RPC, the irradiation would go on for more than two years at the current charge accumulation rate. This time could be reduced after the end of the longevity study of the RE2 by placing the trolley hosting the detectors closer to the source.
5.3.7.1 Long term monitoring of the RPC parameters

Throughout the longevity program, great care was put into monitoring the detector characteristics. While presenting the results, current densities expressed in $\mu A/cm^2$ will be shown instead of current values. In the first part of the discussion, the current densities will be referred to as "dark current". Also, the data of the reference detectors will be displayed with increasing integrated charge. This integrated charge will always refer to the integrated charge of the irradiated detectors.

Using the data collected during the weekly noise scans performed on all four RPCs, the dark currents are monitored. Two chamber voltage levels of interest are being compared through time.
The first value of interest was chosen at a STANDBY voltage of 6500 V where no multiplication process happens. This is done to follow the variations of the ohmic component of the current. The monitored dark current values in STANDBY are shown in Figure 5.48. At the time of writing, the ohmic currents for all detectors did not show any dramatic change. Both RE4 detectors appear to follow the same trend while the ohmic current of the irradiated RE2 detector has increased a little. Nevertheless, this increase is only of 10 to 20 pA/cm² and a similar behaviour can be observed for both RE4 detectors. There is no reason to associate the increase in ohmic current with the irradiation.

![Graphs showing dark current and noise rate](image)

Figure 5.49: Monitoring of the physics component of the dark current and of the noise rate per unit area with increasing integrated charge at a voltage of 9600 V for the RE2 detectors (a) and (c) and at a voltage of 9500 V for the RE4 detectors (b) and (d) installed at the GIF++. The second value of interest is located in the gain region near the working point at a voltage of 9600 V for the RE2 detectors and of 9500 V for the RE4 ones. Monitoring the multiplication region
allows to catch the appearance of hot spots across the detectors’ areas. A local damage to the electrode could result in an increase of local discharges and an overall increase of the current drawn by the detector which would show up in the monitored values. Near the working voltage, in addition to the current densities, the noise rate per unit area is monitored as can be seen in Figure 5.49. In the case of the RE2 detectors, the dark currents and noise rate stay stable since the begining of the irradiation program. The variability of the dark current of the irradiated chamber is higher than the one of the reference chamber but seem to always come back between 0.1 and 0.15 nA/cm$^2$.

For what concerns the RE4 detectors, both chambers are very stable up to an irradiation of 150 mC/cm$^2$. Even though the noise rate of the reference RE4 chamber seems to fluctuate a lot between 0.5 and 3.5 Hz/cm$^2$ below 150 mC/cm$^2$ integrated charge, the stable noise rate following this early range as well as the very stable dark current would suggest that the chamber was in fact suffering from a bad grounding. Beyond 150 mC/cm$^2$, the noise rate suddenly stabilizes between 0.1 and 0.2 Hz/cm$^2$ while the dark current increases very slightly to 50 pA/cm$^2$. The disposition of the trolleys inside of the bunker has changed at several occasions and interventions during which the detectors have been disconnected and reconnected may have fixed the problem. On the contrary, the irradiated chamber which was very stable up to 150 mC/cm$^2$, sees its dark current and its noise rate increase and fluctuate with a similar shape until 300 mC/cm$^2$. Beyond this value, the noise rate stabilizes between 0.5 and 1 Hz/cm$^2$, within the requirements of CMS. Indeed, an upper threshold of 1 Hz/cm$^2$ was considered to be good enough to prevent fake events due to noise hits. Regarding the dark current, the fluctuation is more chaotic. So far the highest peak reached a little higher than 0.45 nA/cm$^2$.

The same study is done using the data collected during the weekly source scans. The monitoring of the current densities and of the gamma rate per unit area is shown in Figure 5.50. The reported measurements are always performed with the same source conditions corresponding to an irradiation attenuated by a factor 6.9. The previously mentioned observed increase in dark current of the irradiated RE4 chamber doesn’t have any visible effect when the source irradiates the detectors. No signs of ageing due to irradiation are yet to be seen for both the RE2 and RE4 detectors. The current densities and gamma rates of all four detectors evolve by following the same phases of increase and decrease, as confirmed by Figure 5.51.

The use of a Principal Component Analysis (PCA) reveals that the study of the correlations between the current densities and the gamma rates can be reduced to a single dimension. In the PCA algorithm, the data set of each possibly correlated variable is normalised to get a mean value centered on 0 and a variance of 1. The set of variables is then transformed into a set of linearly uncorrelated variables called principal components. The associated Scree plot shown in Figure 5.51B indicates for each of the components of the PCA, PC1 and PC2, the eigenvalues of the covariance matrix. In this case, the eigenvalues have been normalised to express the percentage of variance explained by each component. More than 93% of the data variation can be explained using a simple linear composition of the current density and of the gamma rate. It is expected as the current density and gamma rate are two sides of the same physical process. Any deviation would mean that other processes than the conversion of photons in the electrode material take place.
Figure 5.50: Monitoring of the current density and of the gamma rate per unit area under irradiation with increasing integrated charge at a voltage of 9600 V for the RE2 detectors (a) and (c) and at a voltage of 9500 V for the RE4 detectors (b) and (d) installed at the GIF++. The source irradiation is attenuated by a factor 6.9.
Figure 5.51: (a) Gamma rates as a function of the corresponding current densities. (b) Scree plot obtained at the output of PCAs performed on each set of current densities and corresponding gamma rates.

Figure 5.52: Monitoring of the gas relative humidity at the level of the T1 supply and of the exhaust and ambient relative humidity at the GIF++ during the source scans.
Figure 5.53: Monitoring of the gas temperature at the level of the TI supply and of the exhaust and ambient temperature at the GIF++ during the source scans.

Figure 5.54: Monitoring of the environmental pressure at the GIF++ during the source scans.

The fluctuations observed on Figure 5.50 may arise due to different factors such as the environmental conditions (gas temperature, gas relative humidity, environmental pressure) or the presence of other experiments between the source and the test trolley. The distance from the source and the trolley, and the gamma current at which the detectors are irradiated during the ageing procedure are kept as consistent as possible and should not contribute to the fluctuations in current density and gamma rate. In order to have a better understanding, the monitoring of the environmental parameters, i.e. the gas relative humidity and temperature both at the supply and at the exhaust of the trolley...
together with the humidity and temperature inside of the bunker and the environmental pressure, is shown in Figures 5.52, 5.53, and 5.54. In these Figures, the data are displayed with increasing integrated charge in the case of the RE2 and of the RE4 detectors for comparison purposes. Each value of integrated charge corresponds to a unique date.

Comparing the trends visible in Figure 5.50 to the monitoring of the different environmental parameters, it would seem that, even with the use of a temperature correction, the temperature variations may be able to explain most of the fluctuations. This assumption is confirmed by a PCA performed on data sets composed for each detector of the monitored environmental parameters and of its current density and gamma rate data. The corresponding Scree plot is shown in Figure 5.55. The dimension reduction for this data set is less trivial as expected. Nevertheless, most of the variation in current densities and gamma rates is held by the first principal component of the PCA basis for all four detectors, as can be understood from the Score plots presented in Figure 5.56. The Score plots show for each principal component the decomposition of its corresponding eigenvector in terms of the variables of the original data set normalised to the eigenvalue associated to the eigenvector. The eigenvectors represent the directions of maximum variance. Hence, the strength of each original variable leads to its variability along this direction.

Based on the information of Figure 5.56, the first principal component can be interpreted as the variations directly linked to the fluctuations in current density and gamma rate. This statement is supported by Table 5.6 in which the values of the scalar products of the current density and gamma rate vectors in the principal component eigenvector space with the environmental parameters vectors are summarized. The linearity between current density and gamma rate is again visible. Moreover, the temperature always seems to be positively correlated with the current density and the gamma rate.

The contribution of the atmospheric pressure is always significantly smaller but consistent and could be a source of positive feedback. The relative humidity of the gas and of the air in the bunker, on the other hand, doesn’t provide a consistent feedback but it can be noted that the role of the supply and exhaust humidity seem to have an opposite effect in the case of the reference detectors than in the case of the irradiated detectors.

It is safe to conclude that the voltage correction performed at the GIF++ is not able to account for the high variability of the temperature in the bunker and, hence, of the gas mixture the detectors are operated with. The pressure, on the other hand, does not play a great role in affecting the RPC operation as the voltage correction was improved to efficiently take into account this parameter [243]. The environmental conditions in the CMS cavern are much more stable in terms of temperature providing an explanation for the less refined temperature correction on the applied voltage as discussed in Section 3.5.
Figure 5.56: Score plots corresponding to the PCAs performed on each RPC data set to study the variations in current density and gamma rate.

Table 5.6: Summary of the scalar product between the current density and gamma rate vectors and the environmental parameters vectors in the principal component eigen vector space.
Aside from the fluctuations due to the insufficient temperature correction, it seems that both the current densities and gamma rate of the irradiated detectors tend to decrease with time. The reference detectors feature a more stable operation through time. Comparing the evolution of the current densities and of the gamma rates to the monitored resistivity shown in Figure 5.57 may explain the decrease observed for the irradiated chambers and the more stable behaviour of the reference ones. An increase of resistivity is observed for both the irradiated detectors whose average resistivity went from $2.27 \times 10^{10}$ to $4.83 \times 10^{10}$ $\Omega \text{cm}$ for the RE2 and from $7.17 \times 10^{10}$ to $1.96 \times 10^{11}$ $\Omega \text{cm}$ for the RE4. The average resistivity of the reference RE2 chamber from 1.88 to $2.40 \times 10^{10} \Omega \text{cm}$ but is still compatible with a stable resistivity due to the wide error bars. On the contrary, the average resistivity of the reference RE4 is more or less at the same level at the time of writing ($9.22 \times 10^{10} \Omega \text{cm}$) than it was at the start of the longevity program ($8.36 \times 10^{10} \Omega \text{cm}$). Also, the fluctuations of resistivity
of the chambers seem to be correlated with one another. Such an effect could arise from a systematic effect like the fluctuations of environmental parameters or to a bias in the method. Nevertheless, using Argon is a standard procedure to measure the resistivity of RPCs. This method is believed to be well controlled. A systematic effect is then more likely to explain the fluctuations but the lack of data points makes it impossible to study the influence of the environmental parameters on the resistivity.

The differences in increase rate of the irradiated chambers with respect to the reference ones can be seen in Figure 5.58. It is clear that both the current density and the gamma rate of the irradiated detectors decreases relatively to the reference ones. This is consistent with the relative increase in average resistivity of the irradiated chambers with respect to the reference ones.

Figure 5.58: “Irradiated over Reference” parameter ratios (current densities, gamma rates and resistivities) as a function of the integrated charge for the RE2 (a) and the RE4 (b) detectors installed at the GIF++.

In addition to the decrease of the irradiated detectors current densities and gamma rates with respect to the reference RPCs, the fluctuation that can be observed in the ratios could be related to the fluctuations of gas humidity observed in Figure 5.52. The effect seems clearer in the case of the RE2 detectors than in the case of the RE4. A PCA is once again performed on updated RPC data sets. The single current densities and gamma rates are this time replaced by the “Irradiated over Reference” current density and gamma rate ratios. Compared to Figure 5.55, the Scree plot in Figure 5.59 shows a slightly different distribution of the variability along the principal components in both cases.

The Score plots in Figure 5.60 confirm the difference noticed in the Scree plot. Indeed, for the RE2, the first principal component mainly shows variability of the temperatures and of the supply relative humidity. This is shown by the strength of those signals along the first component direction. But there is no correlation with the current density or the gamma rate ratios. In fact, their variability seems mainly contained in the second principal component along which their signal is strongest. The signal strength of the bunker and of the exhaust relative humidity is also strong along the second component pointing to a positive correlation of the variability of these environmental parameters with the variability of the current density and gamma rate ratios. The interpretation of the Score plot in the case of the RE4 is much more complex and could be due to the much smaller amplitude of the fluctuation of the ratios with respect to the RE2. While the environment relative humidity was
playing a great role for the RE2, it seems that also other parameters could have a non-negligible effect on the RE4.

The information provided by Table 5.7 which summarizes the scalar products between the current density and the gamma rate ratios vectors, and the environmental parameters vectors, reaches a similar conclusion. The effect of the bunker and of the exhaust relative humidity is clear for the RE2 where the fluctuation is the strongest. But no similar conclusion can be made for the RE4 in which all parameters provide a signal. The PCA has failed to reveal an effect of the humidity for the RE4 even though the fluctuation is likely to have the same origin than the one observed for the RE2 as the dates coincide.

The difference between the RE2 and the RE4 detectors is their manufacturing dates. As was already said, the RE2 detectors were manufactured prior to the start of the LHC while the RE4 were constructed and installed in CMS during LS1. It is not impossible that the providers of the different parts such as the gas connectors of the gas gaps or the gas connectors on the chambers patch panel are different. The plastic material of the gas connectors at the level of the gas gaps could, for example, have a different porosity in between both detector types. Or the tightness of the gas connections is simply of better quality for the RE4 than for the RE2. As a matter of fact, it is known at CMS that the RE4 detectors have a significantly lower gas leak rate as a whole than the rest of the CMS RPC sub-system. Based on this information, the RE2 detectors placed at the GIF++ could have a higher chance of having a gas leak. In the case there are gas leaks, the gas leak of the RE2 detectors could also be bigger than the gas leak of the RE4. Such gas leaks would result in a possible humidity exchange between the air inside of the bunker and the gas mixture inside of the detector as well as a contamination of the mixture by with air.

In conclusion, once the fluctuations of the current densities and gamma rate have been understood as a consequence of the imperfect temperature correction, it remains that the resistivity of the irradiated detectors is decreasing with respect to the reference ones. A better control of the relative humidity in the bunker or an investigation for gas leaks on the detectors could help to mitigate the observed decrease of resistivity of the irradiated electrodes.
5.3.7.2 Evolution of the detectors performance

Throughout the longevity study performed so far at the GIF++, the muon beam has been used eight times to measure the detector performances. The first test beam period happened before the start of the irradiation program in October 2015. The other test beam periods all happened at different moments until the end of 2018 and the start of LS2. Due to the fact that no irradiation was possible on the RE4 detector before the end of 2016, the data of the two test beam periods of 2016 will not be shown nor discussed along the following paragraphs. The discussion will revolve around the data taken during the five test beam periods in which the RE2 and RE4 detectors had respectively reached 18, 31, 45, 51, and 57%, and 5, 11, 21, 26, and 30% of the required 0.84 C/cm².

The test beam periods are the occasion to monitor the efficiency, mean muon cluster size and gamma rate at working voltage. This way, the evolution of the efficiency and of the mean muon cluster size at working voltage as a function of the gamma hit rate can be studied with increasing integrated charge. Ageing effects are expected to show up as changes in the behaviour of the detector such as higher working voltage, lower efficiency at working voltage, lower rate capability or lower mean muon cluster size at working voltage.

From the efficiency scans, the first parameter to be extracted from the sigmoid fits is the working
voltage. Only then the efficiency is computed using the sigmoid fit and the mean muon cluster size is interpolated from the closest voltage values. The working voltage is also used as a reference to interpolate the gamma rate, gamma cluster size, gamma multiplicity and charge deposition per gamma with better accuracy from the rate scans. The choice for the interpolation method is mainly motivated by the fact that these quantities have a close to linear behaviour with increasing voltage in the region of interest, as can for example be seen in Figures 5.29b and 5.30d.

Figure 5.61: Superposition of the working voltage as a function of the gamma hit rate measured in each of the CMS RPCs installed at the GIF++ during the six test beam periods.

The values of working voltage as a function of the gamma rate in the different testbeam periods are shown in Figure 5.61. It is important to note that the working voltage shift of the RE4 with increasing gamma rate (400 V to 600 V per 1 kHz/cm²) is bigger than in the case of the RE2 detectors (150 V to 250 V per 1 kHz/cm²). Depending on the testbeam, the trend of the working voltage
can vary up to approximately 100 V. Both the difference in behaviour of the RE2 and RE4, and the working voltage variation from one period to another could be related to the RPC resistivity. Indeed, as already shown in Figure 5.57, the resistivity of the RE4 detectors is several times higher than that of the RE2. It is then likely that the rate capability of the RE4 chambers is lower than that of the RE2 causing a stronger voltage shift with increasing background rate. The difference in effective voltage shift between the RE2 and RE4 chambers is shown in Figure 5.62. For each testbeam period, the sigmoid obtained without irradiation is compared with the sigmoid at a gamma rate as close as possible from the certification value of $600 \text{ Hz/cm}^2$. The shift is clearly bigger in the case of RE4 RPCs.

![Graphs showing efficiency as a function of effective voltage](image)

**Figure 5.62**: Superposition of the efficiency sigmoids as a function of the effective voltage measured with the CMS RPCs installed at the GIF++ during the six test beam periods with and without irradiation. The data without irradiation are shown with full symbols whereas the data with irradiation is shown with open symbols.
The approximate resistivity of the electrodes, presented in Figure 5.63, has been extracted from the efficiency scans using the procedure described in Section 5.3.6. The extracted value is compared to the mean resistivity derived from Argon scans for the partition C of the detectors installed at the GIF++, where the beam passes through. Except for the reference RE2 chamber for which the results are a factor 2 below what would be expected, the extraction indeed provides a value comparable to the mean value obtained in this partition using the argon scans.

The resistance of the detectors obtained with this method are used as in Equation 5.11 to compare the behaviour of the RPCs without the bias brought by the resistivity variation. The results are shown in Figure 5.64. Comparing the results using the voltage drop over the gas volume only, the detectors so far seem not to display any loss of performance with increasing integrated charge at a background rate near the certification value of 600 Hz/cm².
The voltage drop over the gas volume at working voltage as a function of the background hit rate is shown in Figure 5.65. When the role of the resistivity of the electrodes is removed, the behaviour of the RE2 and RE4 detectors is more similar. The RE2 detectors display a very stable behaviour with increasing background rate. In the case of the RE4, the shift has been removed but the results suffer from larger fluctuations. The resistivity of the RE2 electrodes being lower than that of the RE4, its fluctuation causes a smaller voltage shift. Thus, with only a single measurement performed at each irradiation setting, the measured performance of the RE2 is less subjected to systematics. The systematics are unfortunately not well understood and can’t be reported.

Figure 5.64: Superposition of the efficiency sigmoids as a function of the voltage drop over the gas volume measured with the CMS RPCs installed at the GIF++ during the six test beam periods. The data without irradiation is shown with full symbols whereas the data with irradiation is shown with open symbols.
Figure 5.65: Superposition of the gas voltage drop corresponding to the computed working voltage as a function of the gamma hit rate measured in each of the CMS RPCs installed at the GIF++ during the six test beam periods. The error bars only correspond to the statistical error.

Figures 5.66 and 5.67 show the evolution of the efficiency and of the mean muon cluster size at working voltage with increasing background hit rate. There is no loss of rate capability to be observed. The efficiencies at working voltage show the same behaviour during the last testbeam period as during the previous ones as long as the background rate is below $1000 \text{ Hz/cm}^2$. The efficiency of all four detectors does not decrease beneath 95%. Beyond $1000 \text{ Hz/cm}^2$, the data is not of interest anymore. Due to time constraints, the choice was often made to only make sure that all four chambers were irradiated at least to a background hit rate of $600 \text{ Hz/cm}^2$ corresponding to the certification threshold. The irradiated RE4 chamber is consistently the chamber for which the measured background hit rate is the lowest as can for example be seen in Figure 5.66b. At the occasion of three of the reported testbeam periods, the measured rate in this chamber didn’t reach
750 Hz/cm², when the rate seen by the other chambers is always at least of 1 kHz/cm².

![Figure 5.66](image.png)

Figure 5.66: Superposition of the efficiency at working voltage as a function of the gamma hit rate measured in each of the CMS RPCs installed at the GIF++ during the six test beam periods.

The same conclusion can be made looking at the mean muon cluster size. There is no difference between the irradiated detectors and the reference ones for these parameters. The mean cluster size is consistent from one testbeam period to the other except for the data gathered in October 2018 corresponding to 57% of integrated charge for the RE2 detector and 30% for the RE4. The mean muon cluster size is consistently bigger during this period for all four detectors. To understand the phenomena, a study of the beam hit profile in the detectors and of the event cluster size and cluster multiplicity for each recorded trigger was performed with the source OFF data. The use of data without irradiation allows to study the potential effects that are not correlated with the background radiation. Looking at the hits corresponding to the beam arrival provides information regarding the
beam quality. Table 5.8 reveals that during the last testbeam the detectors were exposed to a higher fraction of beam events with a cluster size greater than 3 and with a larger number of reconstructed clusters per beam event. The only possible explanation is then that the beam contained hadrons. Some of the hadrons or their decay products are likely to decay before the chambers or while passing through the setup, and produce multiple clusters per event or simultaneous detections in adjacent channels, artificially increasing the reconstructed cluster size. A limitation of the analysis algorithm used on the CMS RPC data is that it is not capable of identifying particles. Thanks to the particle tracking, only particles traveling along the beam line are kept while any hits that can’t be associated to a track are discarded. If the decay products travel close to each other while passing through the setup, it will not be possible to identify them.

![Gamma Hit Rate vs Mean Muon Cluster Size for CMS and GIF++](image)

**Figure 5.67:** Superposition of the mean muon cluster size at working voltage as a function of the gamma hit rate measured in each of the CMS RPCs installed at the GIF++ during the six test beam periods.
Table 5.8: Summary of the percentage of large reconstructed clusters and of events with more than two reconstructed clusters of the CMS RPCs installed at the GIF++ during the five test beam periods after the start of irradiation. The HV points closest to the working voltage are used.

<table>
<thead>
<tr>
<th></th>
<th>Reference RE2</th>
<th>Irradiated RE2</th>
<th>Reference RE4</th>
<th>Irradiated RE4</th>
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<tr>
<td>Integrated charge in RE2</td>
<td>18%</td>
<td>31%</td>
<td>45%</td>
<td>51%</td>
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<td>9800</td>
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<td>2.28</td>
<td>2.12</td>
<td>1.96</td>
<td>2.30</td>
</tr>
<tr>
<td>Mean cluster multiplicity</td>
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<td>1.20</td>
<td>1.15</td>
<td>1.26</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>... cluster size &gt; 3</td>
<td>6.5</td>
<td>5.7</td>
<td>5.7</td>
<td>8.6</td>
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<tr>
<td>... cluster multiplicity &gt; 2</td>
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<td>2.1</td>
<td>2.2</td>
<td>3.7</td>
</tr>
<tr>
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<td>2.73</td>
<td>2.70</td>
<td>2.67</td>
</tr>
<tr>
<td>Mean cluster multiplicity</td>
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<td>1.04</td>
<td>1.05</td>
<td>1.10</td>
</tr>
<tr>
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<td></td>
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<td>11.3</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
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<td>1.1</td>
<td>0.8</td>
<td>2.1</td>
</tr>
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<td>11%</td>
<td>21%</td>
<td>26%</td>
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<tr>
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<td>9500</td>
<td>9600</td>
<td>9500</td>
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<td>2.13</td>
<td>2.00</td>
<td>2.48</td>
<td>2.32</td>
</tr>
<tr>
<td>Mean cluster multiplicity</td>
<td>1.07</td>
<td>1.04</td>
<td>1.07</td>
<td>1.11</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>8.0</td>
<td>6.4</td>
<td>9.1</td>
<td>9.9</td>
</tr>
<tr>
<td>... cluster multiplicity &gt; 2</td>
<td>2.0</td>
<td>1.6</td>
<td>1.7</td>
<td>2.5</td>
</tr>
<tr>
<td>Effective voltage (V)</td>
<td>9500</td>
<td>9400</td>
<td>9600</td>
<td>9500</td>
</tr>
<tr>
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<td>2.34</td>
<td>2.27</td>
<td>1.86</td>
<td>2.18</td>
</tr>
<tr>
<td>Mean cluster multiplicity</td>
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<td>1.06</td>
<td>1.06</td>
<td>1.11</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>... cluster size &gt; 3</td>
<td>8.0</td>
<td>6.7</td>
<td>5.3</td>
<td>7.7</td>
</tr>
<tr>
<td>... cluster multiplicity &gt; 2</td>
<td>2.9</td>
<td>1.8</td>
<td>1.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Signs of ageing of the detectors are also sought in the evolution of the behaviour of the current density with increasing background hit rate. The current densities recorded during each testbeam period are shown in Figure 5.68. This quantity is expected to increase linearly with the background hit rate. A significant change of slope could be linked to a change of behaviour of the detectors. Nevertheless, no such hint of increase of the current density is to be seen from the irradiated detectors. Their current density is so far very stable during this longevity study campaign. This is consistent with the weekly irradiation scans discussed in the previous section.
Figure 5.68: Superposition of the current density at working voltage as a function of the gamma hit rate measured in each of the CMS RPCs installed at the GIF++ during the six test beam periods.

In the same way that the muon hits are grouped in clusters, the data from the rate scans can be used to study the gamma hits and group them into clusters. As the current density of the detectors is stable, it is expected that the mean gamma cluster size will be stable as well. Figure 5.69 confirms this assumption. As a consequence, the mean charge deposition per gamma cluster in the irradiated detectors, provided in Figure 5.70, and computed as the ratio between the current density and the gamma hit rate, both corrected by subtracting the current density and noise hit rate recorded without irradiation, is stable with increasing integrated charge. Note that no gamma cluster information is available for the testbeam performed before the irradiation campaign started. The data structure used at the time of the measurement does not allow the use of a clustering algorithm resulting in a loss of valuable reference information.
Figure 5.69: Superposition of the mean gamma cluster size at working voltage as a function of the gamma hit rate measured in each of the CMS RPCs installed at the GIF++ during the six test beam periods.
LONGEVITY STUDIES AND CONSOLIDATION OF THE PRESENT CMS RPC SYSTEM

Figure 5.70: Superposition of the mean charge deposition per gamma cluster at working voltage as a function of the gamma hit rate measured in each of the CMS RPCs installed at the GIF++ during the six test beam periods.

5.3.7.3 Conclusion

At the time of writing, no clear ageing effect was found to affect the irradiated detectors. The weekly monitoring of the current densities and background hit rates of all four detectors has shown that the only parameter that seemed to have varied in different ways for the irradiated detectors with respect to the reference ones is the electrodes’ resistivity. On the one hand, a better control of the environmental temperature would help improving the search for ageing effects. On the other hand, a better control of the gas relative humidity and an investigation for gas leaks at the level of the detectors would probably help stabilizing the resistivity variations due to the fluctuation of this parameter. This way, a better understanding of a possible link between irradiation and electrode
resistivity change could be achieved.

The monitoring of the performance of the detectors also seems to show that the irradiated detectors didn’t suffer any visible ageing. In order to aim at a proper data quality during future testbeam periods, it is strongly advised to systematically study the possible beam contamination by hadrons before the data taking program is started. This effort could be performed with the collaboration of the other systems studying the longevity of their detectors at the GIF++. It is believed that a better control of the beam quality is in the greatest interest of all of the facility users.
Initial studies of the new iRPC front-end electronics

The extension towards higher pseudo-rapidity with the installation of new RPCs in the endcap disks of the CMS RPC subsystem will expose these new chambers to much more intense background radiations given their proximity to the LHC beam line (see Figure 4.5). The challenge will be to produce high counting rate detectors with limited ageing rate to ensure a stable operation of the detector over a period longer than ten years. In Chapter 3, the influence of the detector design (the number and the thickness of the gas volumes, double-gap design, etc...) on the charge deposition and rate capability was discussed. Next to that, this question can also be addressed from the electronics point of view as a better signal-to-noise ratio would also mean the possibility to reduce the charge threshold for the signals to be detected. This would in turn allow to use the detector at lower a gain, decreasing the charge deposition per avalanche in the gas volume. Cardarelli et al. showed that the production of low-noise fast FEEs could help to decrease the charge deposition per avalanche at the working voltage by an order of magnitude, possibly increasing the life expectancy of such a detector in the same way [292].

In this Chapter, the electronics that were chosen to equip the improved RPCs (iRPCs) will be presented. These electronics are the based on the PETIROC ASIC. A similar technology has been previously used with RPCs in the context of the R&D within the CALICE Collaboration of a Semi-Digital Hadron Calorimeter (SDHCAL) [202, 228, 293] for the International Large Detector (ILD) [294]. As a backup solution to the PETIROC, a FEB developed by the INFN Tor Vergata in Rome is also considered for the CMS iRPCs. These two solutions for the iRPCs are the results of a longer selection process in which I took a major part. After an introduction of both technologies, the tests performed on CMS RPCs operated with preliminary versions of INFN Tor Vergata preamplifiers as well as with the HARDROC2 read-out panel of the SDHCAL will be discussed in details. Finally, the current status of the R&D certification will be presented. During my PhD work, I participated in the selection and testing of the candidate technologies. This study provided input for the development of the final FEE for the CMS iRPCs. At the end of this Chapter, I will also report on the currently still ongoing FEE developments.
6.1 FEE candidates for the production of iRPCs

The extension of the third and fourth endcap disks with improved RPCs has been presented in Chapter 4 together with the expected background levels (Figure 4.18). The iRPCs will complete the muon endcap as described in Figure 6.1. The key features of these iRPCs are:

- double-gap design
- 1.4 mm thick HPL electrodes
- 0.9 to $3 \times 10^{10}$ Ω·cm HPL resistivity
- 1.4 mm thick gas gap
- trapezoidal chambers spanning $20^\circ$ in $\varphi$ around the beam axis
- read-out panel consisting of 96 trapezoidal strips
- strip pitch ranging from 6.0 mm (5.9 mm) on the high pseudo-rapidity side of the chamber to 12.3 mm (10.9 mm) on the low side for the RE3/1 (RE4/1) station
- spatial resolution in the direction perpendicular to the strips ~3 mm

![Figure 6.1: Location of the RE3/1 or RE4/1 iRPCs on a muon endcap disk.](image)

An important piece of these iRPCs will be the Front-End Electronics that will equip the chambers. A fast, low-jitter and low-charge sensitive electronics will help reducing further the charge deposition in the detector by enabling operation at lower gain. The FEEs that are foreseen to equip the new RPCs need to be able to detect charges as small as 10 fC. The new electronics need not only to be fast and reliable, they also should be able to sustain the high radiation the detectors will be subjected to in the region closest to the beam.
6.1.1 PETIROC: the RPC upgrade baseline

Designed by Weeroc [295], a spin-off company from the OMEGA Collaboration [296], the PETIROC 2A consists in a fast and low jitter 32-channel ASIC originally developed to read-out Silicon Photomultiplier (SiPM) in Time-of-flight applications and that allows for precise time measurements [267, 268]. The ASIC uses an AMS 350 ns Silicon-Germanium (SiGe) technology. The block diagram of the ASIC is shown on Figure 6.2. A 10-bit DAC allows to adjust the trigger level in a dynamical range spanning from 0.5 to a few tens of photoelectrons and a 6-bit DAC to adjust the response of each individual channel to similar a level.

Figure 6.2: PETIROC 2A block diagram.

To adapt this ASIC to CMS, modifications were brought to the PETIROC [179] and not all its functions will be used [297]. Due to the radiation levels that are foreseen at the position of the rRPCs, the SiGe technology will be replaced by the Taiwan Semiconductor Manufacturing Company (TSMC) 130 nm CMOS, to increase its radiation hardness while keeping fast pre-amplification and discrimination. On the Front-End Board, the ASIC is associated with an FPGA which purpose is to measure the arrival time of the signals. The FPGA is equipped with a TDC with a time resolution of 50-100 ps developed by Tsinghua University. The full system will provide a measurement of the signal position along the strip with a precision of a few cm by reading the signal on both strip ends. Finally, the measurement of the charge will be performed by a Time-over-Threshold (ToT) technique, taking profit of the capacity the ASIC in measuring both the leading and trailing edges of the input signals.
Two consecutive versions of the PETIROC FEB are shown in Figure 6.4. FEBv0 was equipped with a single PETIROC 2A associated to a Cyclone II FPGA. FEBv1 was in turn equipped with two PETIROC 2A and then, in a later version, with two PETIROC 2B. In both cases, the ASICs were associated to a Cyclone V FPGA. The PETIROC 2B was a version of the ASIC with less cross-talk than the 2A. The dynamic range could then be expanded towards lower values to allow for the
detection of charges as low as 50 fC. The next version, the FEBv2 is expected to be equipped with three PETIROC 2C, the new generation of the ASIC, associated to three Cyclone V FPGAs hosting the 32-channel TDCs and a master Cyclone V FPGA for the communications of the TDCs with the Link-Board system. The version 2C will focus on reducing the dead-time of 10 ns of the ASIC. Also, the Cyclone V FPGAs of the FEBv2 will use a different technology than the one used for FEBv1. The choice has been made to use a radiation tolerant PolarFire FPGA which uses data scrubbing to detect and correct errors before they accumulate. This technology is for example used for space applications. The FEB will be tested at the Louvain-la-Neuve (LLN) neutron beam. The goal is to irradiate the electronics up to a fluence of $10^{14}$ pC/cm$^2$, five times more than what is expected at CMS, to certify its radiation hardness.

Each FEBv2 will be able to read 96 channels out thanks to three 32-channel PETIROC 2C ASICs. Two FEBv2 would be mounted on the iRPC to read the 96 strips out from both ends. The read-out panel that was used for the first version of the FEB is shown in Figure 6.4a and the final design with the FEBv2 mounted on the read-out plane is shown in Figure 6.4b.

### 6.1.2 INFN FEB: a robust back-up solution

Even though the baseline for the electronics that will equip the iRPCs will be the PETIROC, a back-up solution needs to be certified. The back-up has been found in Front-End Electronics featuring a fast and low-noise ($1000 e^-$ rms) Silicon (Si) preamplifier and a SiGe discriminator [298] associated with an optimized read-out panel [299]. The low-noise preamplifier is a new version of a preliminary production of a SiGe preamplifier by the team of Cardarelli working with INFN Tor Vergata in Rome with the purpose of equipping the new generation of ATLAS RPCs [300]. The study of the early version of the preamplifier by is discussed in Section 6.2.

Contrary to the PETIROC FEB, the back-up electronics only offer the possibility to read the 96 strips out from one end. The spatial resolution along the strips is then brought by two transverse strip planes. These two additional panels sandwich the double-gap ensemble as shown in Figure 6.5. They feature 5 cm wide copper strips for a spatial resolution of a few centimeters along the longitudinal strips. A top quarter of the longitudinal and transversal read-out panels is shown in Figure 6.6 and pictures are available in Figure 6.7.
Figure 6.6: Design of the longitudinal (a) and transversal (b) strip panels. The transversal design is here shown on top of the longitudinal one.

Figure 6.7: Picture of half the longitudinal (a) and of the top part of the transversal (b) strip panels.

The FEB used for the longitudinal readout is shown in Figure 6.8a. Each FEB is equipped with eight preamplifiers using a Bipolar Junction Transistor (BJT) technology and two discriminator ASICs of four channels using Hetero Junction bipolar Transistor (HJT) technology. The input signals are amplified at an amplification factor of 0.2 to 0.4 mV/fC and are then discriminated with a threshold of 0.5 mV at minimum. For each channel, the LVDS output is proportional in width to the Time-over-Threshold in the discriminator of the amplified signal with a minimum width of 3 ns. This method allows for an estimation of the avalanche charge as the width of the signals usually is consistent and proportional to the amount of charge released in the gas volume.

On Figure 6.6a, the rectangular zones with straight copper lines at the top of the longitudinal PCB are lines used to propagate the power and the slow control of the FEBs. A FEB is placed between two zones and soldered to the copper lines on both sides, as can be seen in Figure 6.8b. In the same way, the FEB is soldered to a group of eight strips which lines finish into pads placed below the bottom edge of the FEB. It was decided to solder the FEBs onto the read-out PCB to reduce the pick-up noise in the electronics.
INITIAL STUDIES OF THE NEW iRPC FRONT-END ELECTRONICS

Figure 6.8: Version 2 of the INFN Tor Vergata FEB as designed for the CMS iRPC. The FEBs are directly soldered onto the read-out PCB to reduce pick-up noise as much as possible. Copper lines embedded into the PCB are used to propagate the power and slow control lines.

The strips begin much wider in the case of the transversal read-out panel, the FEB design is a little different, as can be seen in Figure 6.9a. The transversal FEBs are strictly the same as the one attached to the longitudinal plane even though they are wider. As of now, the connection of the FEBs to the power and slow control lines is done via coaxial cables as can be seen from Figure 6.9b. Only the connection to the strips was optimized for direct on-PCB soldering.

Figure 6.9: Version of the INFN Tor Vergata FEB as designed for the transversal readout panels of the CMS iRPC. The FEBs are directly soldered onto the read-out PCB to reduce pick-up noise as much as possible. The propagation of the power and slow control lines is done via coaxial cables.
6.2 Preliminary electronics tests at CERN

The quest for more sensitive and low noise electronics for iRPCs started with the test of two technologies. Facing the same issue, the ATLAS collaboration at INFN Tor Vergata started developing low-noise sensitive preamplifiers to be used with RPCs. The test of these electronics was carried out by both the ATLAS and the CMS collaborations. At the same time, the CALICE Collaboration had been working on the development of an RPC based Semi-Digital Hadron Calorimeter for the ILD, the multi-purpose detector that is foreseen to be built at the International Linear Collider (ILC). The RPCs they used were operated with low-noise electronics that had previously been used for timing applications with silicon photomultipliers. Both FEEs have been tested with spare CMS RPCs and glass RPCs designed and assembled in Ghent. The design of the gRPCs was derived from the gRPCs used for the SDHCAL. The were used to test the feasibility of achieving large detection areas by gluing together smaller electrodes.

6.2.1 INFN preamplifiers as upgrade candidates

INFN electronics were the first ones to be tested by CMS RPC group in collaboration with colleagues from INFN Tor Vergata working in the ATLAS RPC group. The tests with CMS RPCs were performed in February 2013 outside of the old GIF facility presented in Chapter 5.1.1. Four preamplifier channels were lent by Cardarelli to equip four CMS RPC channels as presented in Figure 6.10. They were directly connected to the strips for the signals induced by muons passing through the gas volume of the chamber to be amplified. The output was then sent to a discriminator to digitize the signals and filter out the noise by tuning the threshold level. The NIM quad discriminator 821 manufactured by LECROY used during this experiment only allows at minimum to set the threshold at a voltage of approximately $30 \text{ mV}$ on the input signals. Thus, two values of discrimination were used ($\sim 75 \text{ mV}$ and $\sim 30 \text{ mV}$).

The performance of the chamber equipped with these new preamplifiers was compared to the performance of CMS FEEs. The experimental setup used is described in Figure 6.11. PMTs a little less wide than four strips were used to trigger the data taking. Two pairs were used in coincidence on both the strips connected to the INFN preamplifiers and to the ones connected to the CMS FEEs. An extra PMT, placed perpendicularly to the rest of the setup at the bottom of the setup was used to detect potential showers and send VETO signals if necessary. A last PMT was used close to the power supplies to measure and discard signals due to electromagnetic noise and is not visible on the pictures. Finally, after discrimination, the output of the INFN preamplifiers together with the signals from the CMS FEEs were sent to scalers to count the detected signals versus the number of trigger coincidences as no DAQ software was available at the time. The full pulse processing for this experiment is shown in Figure 6.12.
Figure 6.11: Experimental setup used to test the INFN preamplifier with respect to the CMS FEEs.
The data taking program consisted in High Voltage scans. A first point was taken at 0 V to only measure noise. Then the HV was increased to an applied value of 7 kV. The voltage was increased in steps of 500 V until 8 kV from where it was increased in steps of 100 V until an upper limit of 10 kV. After rising the voltage over the electrodes of the RPC, a waiting period of 15 minutes was observed to leave time to the electrodes to charge and to the currents to stabilize. The currents were reported at the moment the data taking was started. At each HV step, except at 0 V, approximately 300 triggers were taken to estimate the efficiency of the detector by counting the number of hits in the system (A or B or C or D), referring to the strips. The noise rate per unit area was measured during the first 100 s of data taking by counting the number of hits received in each read-out strip. The cluster size, the average number of adjacent strips fired during a muon event, could not be measured due to the lack of available scalers.

During the data acquisition, in addition to counting the number of signals with respect to the number of triggers, the current or the noise rate per unit area as a function of the increasing voltage, the environmental parameters were monitored. Using the information provided by a humidity and temperature sensor on the gas input line together with the environmental pressure given by a weather station, the applied voltage could be corrected following Formula 3.27. Moreover, the voltage line was filtered to prevent noise and higher currents in the RPC under test.

The results of the preliminary tests are presented in Figure 6.13. More details on the fit performed on the data are provided in Table 6.1. As can be seen, being able to use electronics with a much higher sensitivity allows for an HV shift of up to 475 V with a threshold as low as 3 fC corresponding to the lowest threshold available on the discriminator modules. On the other hand, the higher charge sensitivity also brings a higher noise level. After a first series of measurement performed with a

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**Figure 6.12:** The block diagrams corresponding to the signal treatment for both INFN preamplifier [a] and CMS FEEs [b] are shown. The digitized signals are then counted in coincidence with the trigger signals provided by PMTs [c].
bad grounding leading to grounding loops and hence an artificially higher noise, it can be concluded that the noise rate per unit area of such electronics is approximately one order of magnitude higher than the noise rate measured with the CMS FEB. The noise reaches approximately $2 \text{ Hz/cm}^2$ at the level of the working in the case of the INFN preamplifier while it is lower than $0.2 \text{ Hz/cm}^2$ for the CMS FEB. It is likely that the higher sensitivity also brings a higher sensitivity to local discharges happening in the gas due to fluctuations of the electric field. The surface of the electrodes being not perfectly smooth, the local electric field may vary quickly. The gas molecules circulating in the gas could then be ionised by the fast variation of the field and trigger an avalanche that can then be detected. Reducing the noise rate per unit area would then come from an improvement of the detector itself rather than from a reduction of the electronic noise of the INFN preamplifier.

![Image](image.png)

Figure 6.13: Efficiency (a) and noise rate per unit area (b) of the CMS RE2-2 detector tested with the standard CMS FEBs (black) and with the INFN preamplifier at different thresholds (red and blue). An extra HV scan was performed with better conditions to measure the noise with a threshold of 3 fC on the INFN preamplifiers.

<table>
<thead>
<tr>
<th>Data</th>
<th>$\varepsilon_{\text{max}}$</th>
<th>$\lambda \times 10^{-2} \text{ V}^{-1}$</th>
<th>$HV_{50}$ (V)</th>
<th>$\varepsilon_{W}$</th>
<th>$HV_{W}$ (V)</th>
</tr>
</thead>
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<tr>
<td>CMS FEB, 143IC (2013)</td>
<td>0.978 ± 0.004</td>
<td>1.12 ± 0.07</td>
<td>9939 ± 11</td>
<td>0.97 ± 0.01</td>
<td>9752 ± 27</td>
</tr>
<tr>
<td>INFN preamp., 7C (2013)</td>
<td>0.987 ± 0.003</td>
<td>0.93 ± 0.05</td>
<td>8907 ± 11</td>
<td>0.97 ± 0.01</td>
<td>9374 ± 27</td>
</tr>
<tr>
<td>INFN preamp., 3C (2013)</td>
<td>0.991 ± 0.003</td>
<td>0.86 ± 0.04</td>
<td>8783 ± 11</td>
<td>0.98 ± 0.01</td>
<td>9276 ± 27</td>
</tr>
</tbody>
</table>

Table 6.1: Results of the sigmoid fit (Formula 3.24) performed on the data presented in Figure 6.13a. The working point and its corresponding efficiency are computed using Formulas 3.24 and 3.25.

### 6.2.2 INFN preamplifiers mounted onto CMS Front-End Board

Following the first experiment performed in the experimental hall aside of the old GIF, a new series of tests has been done in the CMS RPC assembly laboratory at CERN. For this purpose, the preamplifiers have been designed to be standalone single channels. To have a consistent comparison with the CMS FEB, a FEB prototype has been built based on the current CMS design. As shown in Figure 6.14, the preamplifiers are meant to be plugged in one of the available 16 channels of the board that produces an LVDS output with similar characteristics than the CMS FEB.
At the time of the second experiment, only three channels could be lent by the team of INFN Tor Vergata. The impedance of the preamplifiers was set to 100 Ω at delivery. The strips are then connected to the preamplifiers using 50 Ω coaxial cables equipped with SMC connectors, known for their good transmission. To match the impedance of the preamplifier input with the signal cable, a 100 Ω resistor was added in parallel of the input line. In CMS endcap RPCs, the strips are left floating. For the purpose of this test, it was necessary to terminate the strips on both ends to prevent reflections in the transmission line. The impedance of the strips being approximately 25 Ω, the strips were terminated with 50 Ω resistors on the signal cable side, and with 25 Ω resistors on the end side. The threshold of the zero-crossing discriminators used on the FEB is controlled via a LabVIEW interface similar to the one used to control the threshold of the CMS FEB. Various thresholds were used in a range in between 7 and 5 fC. These values are a little higher than the minimal threshold of about 3 fC used during the first experiment due to limitations of the FEB itself.

Finally, it was decided to use the same PMTs than in the first experiment as trigger. This time, they were placed on their narrow side to only cover an area on the detector smaller than three strips.
On the data acquisition side, no DAQ software was available yet at the time of experimentation and scalers were once again used. As can be seen from Figure 6.15, the pulse processing has been inspired by the previous scheme. Thanks to the lower number of channels to monitor, the cluster size could be estimated by counting the signals on single channels (A, B and C on their own) but also on groups of two (A and B, B and C) and three channels (A and B and C) in coincidence with the trigger.

Figure 6.15: Similarly to Figure 6.12c, the signals are counted in coincidence with the trigger signals provided by PMTs. To estimate the cluster size, the channels are counted by groups of three, two but also alone.

The results of the second round of tests with INFN preamplifiers are presented in Figure 6.16 and Table 6.2. These results are consistent with what was measured with the first tested prototypes. The efficiency sigmoid has been measured once again with the CMS FEB, using a threshold of 146 fC and is in agreement with the data collected in 2013. The performance of the detector with the preamplifiers tuned at 7.2 and 6.4 fC falls in the very same values than the setting at 7 fC according to the table. A maximum shift of 410 V is observed for a threshold of 5 fC.

With the care placed into having a good grounding of the setup as well as a good impedance matching, the noise rate per unit area is this time lower than what previously measured. Nevertheless, it still is more than one order of magnitude higher than in the case of the CMS FEB with a threshold set at 146 fC. The noise rate is measured to be at lowest around 0.7 Hz/cm² when measured to be approximately 0.05 Hz/cm² for the CMS FEB. At such high threshold values, the noise rate per unit area is not expected to vary much. The data collected at the RPC assembly laboratory then displays much better data taking conditions with both electronics. Finally, the cluster size is measured to be similar for both electronics at the level of the working point and is in between 2.2 and 2.4 strips on average. The spatial resolution of both devices would then be the same.
Figure 6.16: Efficiency (a), cluster size (b) and noise rate per unit area (c) of the CMS RE2-2 detector tested with the standard CMS FEBs (black and red) and with the INFN preamplifier mounted onto the CMS FEB at different thresholds (blue, pink, green and purple).

Table 6.2: Results of the sigmoid fit (Equation 3.24) performed on the data presented in Figure 6.16a. The working point and its corresponding efficiency are computed using Equations 3.24 and 3.25.
In addition to the tests performed on the electronics with the CMS RPC, the electronics also have been tested on a gRPC designed in Ghent. The gRPC used for this experiment is described in Figure 6.17. The detector, shown on Figure 6.18, uses a double-gap layout with float glass electrodes of 1.1 mm and a gas gap of 1.2 mm. The electrodes themselves are made out of four pieces of glass glued together. Such a design was studied for high-rate detection purposes and aimed to serve as a proof of concept for RPCs built using small pieces assembled together to produce a larger detection area. Indeed, in the context of R&D in the field of high-rate RPCs, most low resistivity materials are custom made doped glass or ceramics plates. These materials can’t be produced in large areas as they are not manufactured on a large enough scale. Thus, building large detectors can imply using such methods.

The tests involving this detector were conducted in 2015 with the setup described by Figure 6.19. The photomultipliers used to trigger the data taking were a little larger than the detector and the strips themselves. Similarly to the case of the GIF experiment described in Section 5.2.2 of Chapter 5, it has been necessary to evaluate the geometrical acceptance of the setup to detect cosmic muons. This way, a C++ Monte Carlo simulation has been written using the dimensions of the experimental setup. By running 1000 simulations in which a million muons were generated in a source plane much larger than the experimental setup itself to reach high zenith angles, the geometrical acceptance was measured to be $(0.9835 \pm 0.0014)$. This factor has then been used to correct the measured efficiency of the detector.

![Diagram of the glass RPC developed by Ghent](image)

**Figure 6.17:** (a) The glass RPC developed by Ghent uses a double-gap design. (b) The electrodes are made of four pieces of float glass glued into a single plate. Indeed, a gluing technique has been investigated as most new low resistivity materials foreseen for RPCs of the new generation are not available in large areas.
Figure 6.18: (a) Picture of one of the gaps used in the gRPC tested at CERN. (b) Both gaps with their read-out panel are placed into a faraday made out of copper. (c) The faraday cage containing the double-gap gRPC is finally placed into its aluminium case.

Figure 6.19: Experimental setup used to test the INFN preamplifier mounted on the CMS like FEB with the glass RPC build by Ghent.
Thanks to the activities ongoing for the preparation of the CMS RPC experiment taking place at GIF++ and detailed in Chapter 5, a first prototype of DAQ software was available to automate the data taking process. Thanks to this early version of the software, the pulse processing was made more simple. The three channels connected to the preamplifiers were sent directly into a V1190A TDC manufactured by CAEN. The trigger was provided by the same trigger pulse processing described in Figure 6.15. The output of the coincidence of both scintillators was sent into the TRIGGER input of the TDC. The communication with the computer was done thanks to a V1718 module. More details on the DAQ can be found in Appendix A. Contrary to the data now collected at GIF++, the output of the first DAQ script consisted in a simple text file using a format described in Source Code 6.1. The analysis is then performed using a loop through the data file.

```
Evt0 nHits
ChHit1 THit1
ChHit2 THit2
ChHit3 THit3
ChHit4 THit4
ChHit5 THit5
...
Evt1 nHits
ChHit1 THit1
ChHit2 THit2
ChHit3 THit3
...
```

**Source Code 6.1:** Description of the format used to store the data collected during the experiment aiming at testing the INFN electronics with a gRPC built by Ghent. For each received trigger in the TDC module, an event is created. A first line containing two columns is written in the output file with the event number EvtX and the recorded number of hits nHits. This line is directly followed by the list of hits in each channel ChHitX and their corresponding time stamp THitX organized into two columns.

The results of the experiment with the gRPC are provided in Figure 6.20 and Table 6.3. The efficiency of the detector reaches 95% at working voltage, indicating that such a detector using electrodes composed of several glued pieces can be an option for the future of RPC technologies. The benefits of the preamplifiers is once again visible through the huge efficiency shift towards lower voltages. The shift reaches almost 470 V for thresholds lower than 6 fC. The cluster size also shows a shift but its value suddenly decreases after 5.4 kV. After a rise above 2, the cluster size drops when the detector reaches the plateau. A first idea to explain this phenomenon would be to check the cluster algorithm to make sure that it is not biased and does not introduce a fake split of the clusters due to arbitrarily strict selection rules. Clusters are always made of neighbour strips getting a hit within a certain time window. In the algorithm written to analyse the data, it is required for the maximum time difference between the earliest hit and the latest hit in a cluster to be smaller than 10 ns. Physically, assuming of drift velocity of the electrons in the gas of the order of 0.1 mm/μs [301], the growth of an avalanche only takes a few ns. This effect is visible in Figure 6.21a in which the maximum time difference has been artificially increased to 300 ns. The peak reveals that the avalanches are not expected to grow over a time period longer than 10 ns. No peak emerges at time differences longer than 10 ns indicating that the choice of a short time development within the algorithm was justified. This conclusion is supported by Figure 6.21b in which the evolution of the reconstructed cluster size with increasing maximum time difference shows no effect.
Figure 6.20: Efficiency [a], cluster size [b] and noise rate per unit area [c] of the Ghent gRPC detector tested with the standard CMS FEBs (red) and with the INFN preamplifier mounted onto the CMS FEB at different thresholds (blue, pink, green and purple).

Table 6.3: Results of the sigmoid fit (Equation 3.24) performed on the data presented in Figure 6.20a. The working point and its corresponding efficiency are computed using Equations 3.24 and 3.25.
Due to the available number of channels, the cluster size is limited to 3. It is reasonable to assume that this only is the cause of the fall of cluster size beyond 5.4 kV. Indeed looking closely at both Figure 6.22 and Figure 6.23 the link between increasing HV and decreasing cluster size can be understood. On the one hand, Figure 6.22 indicates that the cluster size features at first a maximum at 1. The maximum moves then from 1 to 3 over the points at 5120 V, 5222 V and 5324 V. Then over the last three voltage points, the bin at 2 drops to the profit of the bin at 1, the bin at 3 staying more or less stable. On the other hand, Figure 6.23 provides us more information about the localisation of the clusters among the three read-out strips. At the lowest two voltages, most of the data is contained in the central strip. At 5120 V, the highest bin is the one corresponding to the central strip with a cluster size of 1. Already at 5222 V, the balance changes towards the central strip with 3 strips in the clusters. At 5324 V, even more events happen with clusters of all 3 strips while the events with a single hit in the side strips starts to increase. The number of events with clusters made of all 3 strips will not vary much anymore while the number of events with clusters made of 2 strips will decrease and the single hits in the side strips will continue rising. This information indicates that the avalanches in the gap start to get stronger. Indeed, the increase of the events containing single hits mainly increases on the side strips points to an intensification of the avalanche gain on the strip adjacent to the three channels connected to the read-out setup. Only a single hit is read-out while in reality this was the contribution of bigger avalanches. The events with clusters of size 2 tend to decrease due to the stronger gain that should normally be triggering wider avalanches. The cluster size distribution of Figure 6.22 gives the impression that the distribution is moving towards higher values but the geometrical limitation of the system due to the very low number of channels makes it impossible to measure.
Figure 6.22: Evolution of the cluster size distribution with increasing voltage for the gRPC tested with the INFN preamplifiers using a threshold of 5 fC.

Figure 6.23: Map of the cluster size distribution as a function of the cluster position with increasing voltage for the gRPC tested with the INFN preamplifiers using a threshold of 5 fC.
Even though the performance of the detector are promising, the results concerning the noise
rate per unit area seem to indicate that the detector operated with the INFN Tor Vergata electronics produces very high levels of noise, if compared to the noise measured in the RE4 detector. With each type of electronics, the noise doesn’t indicate a clear correlation with increasing voltage. The hypothesis at this stage would be that the noise is not created inside of the gas volume by avalanches triggered along the glueing lines, where the electric field could be abruptly perturbated. It would rather come from the read-out channel itself, and from its connection to the electronics. Indeed, looking at the noise profile measured in the detector and presented in Figure 6.24a, it is clear that the noise is localized in two areas corresponding to the HV connectors in the case of the HV scan performed with the CMS FEB. Moreover, contrary to the very careful work performed on the RE2 chamber to match the impedance of the strips with the read-out cables connected to the board on which the INFN preamplifiers are mounted, no matching was done on the gRPC due to a lack of time. The noise measured in the tested three channels is shown in Figure 6.24b. This region of the detector doesn’t correspond to the HV connectors according to Figure 6.24a. Nevertheless, the number of hits counted in the detector is much higher than in the CMS FEB case. Looking more carefully to Figure 6.25 presenting the hit time profile in both cases together with the time profile of the CMS RE2-2 detector tested with INFN preamplifiers, it is clear that the detector is noisier. Also, the reflections due to the impedance mismatch is clearly visible in Figure 6.25b.

6.2.3 HARDROC2 based RPC read-out

The HAdronic RPC Digital Read-Out Chip (HARDROC) ASIC, as its name suggests, has been developed for RPC applications and in particular for the read-out RPCs of the CALICE SDHCAL prototype that is being developed for the International Linear Collider (ILC). The SDHCAL RPCs are equipped with $1 \text{ cm}^2$ read-out pads instead of strips giving a total of 9216 channels per chamber. The ASIC is mounted directly on the read-out panel for compactness as can be seen in Figure 6.26a and feature three thresholds to provide a semi-digital information.

![Figure 6.26](image)

(a) (b)

Figure 6.26: Experimental setups used to test the HARDROC2 electronics with a CMS RE4-3 gap (a) and a gRPC gap built in Ghent (b).

The PETIROC uses a similar technology than the one developed for the HARDROC and is manufactured by the same company. It is safe to conclude that the preliminary results obtained with the HARDROC electronics constitute a strong indication of the potential performance of a FEB developed specifically for CMS detectors.
A read-out panel using the HARDROC2 technology was lent by this institute and was tested onto a CMS RPC. Contrary to the tests with the INFN preamplifiers that were made using an RE2-2 CMS RPC built in 2007 for the second endcap disk of CMS, the choice was made to use an RE4-3 detector built during LS1 to equip the fourth endcap. Indeed, the panel can’t be sandwiched between two RPC gaps due to the embedded electronics and a single CMS RPC gap was used. At the time of this experiment, only spare RE4-3 gaps were available. The choice was then made to change detector with respect to the previous series of tests conducted on the INFN preamplifiers. As for the INFN preamplifiers, the panel has been tested on the gRPC built by UGent. The gRPC being smaller than the HARDROC read-out that was used for the experiment but thanks to the 2D read-out using pads, this was not a problem for the data acquisition.

Once again, the experiment was conducted in the CMS RPC assembly laboratory at CERN. The two different setups are shown in Figure 6.26. The read-out panel is placed directly on top of the gaps and pressed against the detector surface thanks to weights. The same PMT telescope is used to provide a trigger to the data acquisition. In the particular case of the HARDROC2 electronics, the output signal does not correspond to the LVDS signals provided by the CMS FEB. Moreover, there would be more than 1500 channels to constantly monitor and unfortunately, there would not be enough VME TDC modules to use with the DAQ software designed for the experiment involving the INFN preamplifiers. Nevertheless, a custom-made DAQ software was designed by the members of IPNL’s team to read-out the electronics through the chip presented in Figure 6.27. The data are continuously stored in the buffer of the ASIC and dumped into the computer when a trigger signal is received.

The results of the tests conducted with the HARDROC2 on a CMS gap are presented in Figure 6.28 and Table 6.4. These results can hardly be compared to what was measured with the INFN preamplifiers as the detector was not tested using the single-gap mode. The tested thresholds are high compared to the ones displayed by the INFN preamplifiers and are of the order of magnitude of the current CMS FEB. Nevertheless, the performance of the detector equipped with this read-out panel is measured to be better. Indeed, a shift of 400 to 500 V is observed at thresholds ranging from 230 to 121 fC. This could be explained by the difference in read-out channel areas of both read-out panels. Indeed, in the case of the standard CMS RPC, the read-out panel consists in relatively large trapezoidal strips with a surface of almost 200 cm² when the read-out of the HARDROC2 is composed of 1 cm² pads. Also taking into account the cross-talk between adjacent channels, the charge produced by a growing avalanche is spread over a larger surface in the case of the standard CMS RPC. Finally, the signals having to travel a longer distance to reach the electronics, the signal loss leads to a smaller signal relative to the pads.

The cluster size is provided for information as a direct comparison of the cluster size measured with 1 cm² pads and long copper strips with width of a few cm is not possible. The measured cluster size at working voltage with the CMS FEB is consistent with what would be expected of a single-gap RPC. Indeed, the usage of two gaps in an OR system allows for a stronger overall gain and hence, the cluster size is greater. A more precise estimation of the charge spread inside of the gap is obtained using pads instead of strips. At working voltage, an avalanche is detected within less than two pads on average. An extra information could be used to further improve the spatial resolution...
of the detector. Indeed, the HARDROC2 are semi-digital electronics and feature three threshold levels. Tuning these thresholds would lead to an approximation of the induced charge profile over the neighbouring pads. A gaussian fit over the digitized distribution would give an estimation of the position of the avalanche center.

Figure 6.28: Efficiency (a), cluster size (b) and noise rate per unit area (c) of the CMS RE4-3 detector tested in single gap mode with the standard CMS FEBs (black) and with the HARDROC2 readout panel at different thresholds (red, blue and pink).
Finally, the noise measured in the electronics is of the same order of what had been measured in Figure 6.16c. It is safe to assume that the noise level in the case of a single-gap RPC is expected to be of the same order of magnitude than its double-gap counterpart as the noise mainly is electromagnetic. Figure 6.29 provides a clearer understanding of the position of the trigger PMTs and of the noise measured with the HARDROC. The noise of the electronics itself is very small, and the read-out panel is sensitive enough to measure the noise in the RPC gap. Indeed, except for a few visible hot spots, the observed noise profile corresponds perfectly to the spacer positions inside of the gap volume. The PET buttons used to maintain the uniformity of the gas volume cause noise at their proximity as they modify the local electric field.

The results of the experiment with the gRPC are provided in Figure 6.30 and Table 6.5. Unfortunately the gRPC had not been tested in single gap mode with the CMS FEB. Thus, a direct comparison is not possible as the data were not collected in similar conditions. The detector could only be tested with a single HARDROC threshold setting (143 fC). As for the double-gap, the efficiency of the single-gap reaches 95% at working voltage. The working voltage is consistent with the double-gap detector operated with the CMS FEB indicating that the HARDROC is more sensitive to lower charges. The difference in efficiency rising is consistent with the use of one gap versus two in the case of the CMS FEB. The working voltage in the case of the HARDROC2 in single gap mode is comparable to the one obtained with the standard CMS FEB in double gap mode even though both electronics were operated at the same detection threshold. This confirms that the HARDROC2 is more sensitive than the CMS FEB in the same conditions. Again, the explanation could be found in the different read-out panels. When operated with the CMS FEB, the gRPC is read out by copper strips with a surface of 45 cm$^2$ to be compared with the 1 cm$^2$ of the HARDROC2 read-out.

As discussed in the case of the CMS RE4-3 gap, the direct comparison of the cluster sizes is not possible. In this sense, the proximity of both results only is fortuitous. The cluster size of approximately 1.6 measured with the HARDROC2 at working voltage is of the same order than what had
previously been measured for the CMS gap indicating that at equivalent performance, the gain and hence, the induced charge could be comparable.

![Graph](image)

**Figure 6.30:** Efficiency [(a)](image), cluster size [(b)](image) and noise rate per unit area [(c)](image) of the UGent gRPC tested in double-gap mode with the standard CMS FEBs (black) and in single-gap with the HARDROC2 readout panel at a threshold of 143 fC (red).

<table>
<thead>
<tr>
<th>Data</th>
<th>$\epsilon_{\text{max}}$</th>
<th>$\lambda \times 10^{-2}$ ($\text{V}^{-1}$)</th>
<th>$HV_{50}$ (V)</th>
<th>$\epsilon_{WP}$</th>
<th>$HV_{WP}$ (V)</th>
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<tbody>
<tr>
<td>CMS FEB, 143 fC (2015)</td>
<td>0.966 ± 0.007</td>
<td>0.86 ± 0.04</td>
<td>5549 ± 8</td>
<td>0.94 ± 0.01</td>
<td>5850 ± 23</td>
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<td>HARDROC2, 143 fC (2015)</td>
<td>0.966 ± 0.004</td>
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<td>5179 ± 7</td>
<td>0.95 ± 0.01</td>
<td>5790 ± 29</td>
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</tbody>
</table>

Table 6.5: Results of the sigmoid fit (Formula 3.24) performed on the data presented in Figure 6.30a. The working point and its corresponding efficiency are computed using Formulas 3.24 and 3.25.
Finally, the noise measured in the electronics seemed higher than in the case of the CMS gap. Looking closer to the noise profile provided in Figure 6.31, it can be seen that the noise measurement was affected by the HV connector. Indeed, the high noise measured in pads 41 and 42 along X and 22 to 25 along Y, corresponds exactly to the position of the HV connector on the cathode side. Contrary to the case of the CMS gap where the HV connector was far from the read-out area, the gRPC is smaller than the read-out and due to the poor grounding of the setup the electric field created by the HV connector could affect the read-out. Excluding the corresponding pads gives a much more reliable noise measurement as can be seen in Figure 6.30c. A better understanding of the gRPC uniformity can be obtained through the noise profile. First of all, the row corresponding to Y=16 seems consistently noisier than the neighbouring pads and could correspond to the glueing line that lies along this pad row. Nonetheless, the increase of the noise along this line is not very clear, and no corresponding behaviour can be observed along the other glueing line along column X=30. But the gas volume corresponding to the largest glass plate, spreading from columns 31 to 47 along X and rows 1 to 15 clearly shows a stronger noise in its center. The detection area being small, only a few ceramic ball spacers were used to maintain the distance in between the electrodes. It is not impossible that the ball spacer located in the center of this very volume popped out. Due to the absence of a spacer, the force applied by electric field onto the electrodes could have made the distance in between the electrodes smaller and artificially increased the observed electric field, also increasing the measured noise.

![Figure 6.31: Measured muon (a) and noise (b) profiles in the read-out pads of the HARDROC2 over a gRPC gap built by Ghent.](image)

6.3 Outlook on the current FEE certification study

In this Section the ongoing certification of the PETIROC FEB and of the INFN Tor Vergata FEBs, chosen as back-up solution, will be presented. For reference, an iRPC has been operated without irradiation with the standard CMS FEB. It is reminded that the iRPCs that will complete the redundancy of the muon system of CMS close to the beam line are expected to suffer a background hit rate per unit area of $600 \text{ Hz/cm}^2$. Including a safety factor of 3, it is then necessary for the detectors to be certified at a minimal background hit rate of $2 \text{ kHz/cm}^2$.

6.3.1 CMS Front-End Board reference

In order to compare the performance of the new electronics with the standard CMS FEBs, a series of short characterization tests was carried out with an iRPC prototype. Seven strips of a read-out panel designed for a back-up scenario detector were connected to a CMS FEB. The remaining strips were
connected to the ground to avoid noise. The tests were done without irradiation and using cosmic muons. Two narrow scintillators were placed on each side of the prototype to provide a trigger signal as can be seen from Figure 6.32. The tests were performed with three detection thresholds of 200 mV (≈133 fC), 210 mV (≈140 fC) and 220 mV (≈146 fC) on the FEB discriminators. The LVDS output of the FEB was then read-out with a CAEN TDC. The HV scans consisted of seven effective voltage steps (6800, 7000, 7100, 7200, 7300, 7400 and 7500 V) at which 100 muon triggers were requested as minimal statistics. The hit profile over the connected strips as well as the time profile of the events in each channel is provided in Figure 6.33 for the fifth HV step (7300 HV). The area covered by the trigger is seen to be comparable than the width of the seven strips. The time arrival of the hits is well confined within less than 50 ns.

Figure 6.32: Experimental setup used to test the iRPC equipped with the standard CMS FEEs. Seven of the 96 strips are connected to the read-out channels.

(a)

(b)

Figure 6.33: (a) Distribution of the muon hits on the seven strips connected to the standard CMS FEB. Strip 8 is connected to the ground. (b) Time distribution of the hits in the seven channels. The color scale corresponds to the number of hits per bin.
Figure 6.34: Summary of the HV scans performed on the iRPC prototype equipped with a standard CMS FEB at three detection thresholds. (a) Efficiency sigmoids. (b) Mean muon cluster size at working voltage. (c) Mean muon cluster multiplicity at working voltage. (d) Noise hit rate per unit area at working voltage.

Table 6.6: Summary results of the iRPC operated with a standard CMS RPC FEB.

<table>
<thead>
<tr>
<th>Threshold (fC)</th>
<th>Working Voltage (V)</th>
<th>Efficiency (%)</th>
<th>Cluster Size</th>
<th>Multiplicity</th>
<th>Noise (Hz/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>133</td>
<td>7393 ± 45</td>
<td>96.9 ± 3.0</td>
<td>2.34 ± 0.15</td>
<td>0.97 ± 0.07</td>
<td>0.30</td>
</tr>
<tr>
<td>140</td>
<td>7473 ± 49</td>
<td>97.0 ± 2.5</td>
<td>2.52 ± 0.18</td>
<td>0.99 ± 0.07</td>
<td>0.38</td>
</tr>
<tr>
<td>146</td>
<td>7552 ± 57</td>
<td>96.6 ± 1.8</td>
<td>2.34 ± 0.11</td>
<td>1.02 ± 0.03</td>
<td>0.21</td>
</tr>
</tbody>
</table>

The results for this kind of electronics are to be found in Figure 6.34. First of all, the efficiency at working voltage of the detector reaches 96.9% at a threshold of 146 fC, 97.0% at 140 fC and finally 96.6% at 133 fC. The efficiency does not seem to be affected by a change of threshold. The working voltage, on the other hand, is shifted towards lower effective voltage values with decreasing threshold. The values of working voltages respectively are 7552, 7473 and 7393 V. This is expected by the lower gain necessary to produce large enough avalanches. No other differences can be observed
at the level of the mean muon cluster sizes, mean muon cluster multiplicity per event and noise rate per unit area. The mean muon cluster size stays of the order of 2.4 strips per cluster and the muon cluster multiplicity, which is the number of reconstructed muon clusters per event, is consistent with 1 as expected. Finally, the noise rate per unit area is below $1 \text{ Hz/cm}^2$. The results are summarized in Table 6.6.

6.3.2 PETIROC FEE

Several iRPCs equipped with different versions of PETIROC FEBs have been assembled and tested. This process helped identifying the weaknesses of the FEEs and propose new improved versions. The last piece of the R&D process will be the FEBv2 equipped with three PETIROC 2C ASICs, three Cyclone V FPGAs hosting the TDCs, and a fourth FPGA to communicate with the back-end electronics.

In a first series of tests performed along the muon beam line H2 at CERN, the FEBv0 was certified for time resolution performances and linearity between the time difference of recorded muon signals measured at both strip ends and the beam position along the strip length.

The experimental setup is shown in Figure 6.35 on which two iRPCs are placed between two narrow scintillators for a precise knowledge of the position of the beam. The mean time difference between the signals measured at the high-radius (HR) and low-radius (LR) is given in Figure 6.36a. The time resolution of the measurement is of $(252 \pm 4) \text{ ps}$. The velocity of propagation $v$ of the signals along the strips was reported to be of $1 \text{ m in per } 5.25 \text{ ns}$. According to Equation 6.1, in which $L$ is the length of the strip, $Y$ the position along the strip, and $T_{HR}$ and $T_{LR}$ the measured arrival time at the high-radius and low-radius ends of the strip, the spatial resolution $\Delta Y$ along the strip is then of the order of $2 \text{ cm}$. The linearity between the time difference and the position of a hit along the strip length could then be studied with a good precision as can be seen in Figure 6.36b.

$$Y = \frac{L}{2} - \frac{v}{2} \times (T_{HR} - T_{LR})$$
$$\Delta Y = \frac{v}{2} \times \Delta(T_{HR} - T_{LR})$$

Figure 6.35: Experimental setup used along the H2 muon beam at CERN to measure the linearity between beam position along the strip length and the time difference measured between both strip ends with the version 0 of the PETIROC FEB.
Later on, a new iRPC was assembled with FEBv1 using first PETIROC 2A. This version is referred to as FEBv1.1a. Due to a large cross-talk limiting the detection to 100 fC, the PETIROC 2A was replaced by the PETIROC 2B. The lower threshold for stable operation of the FEBv1.1b could be decreased to \((50 \pm 10)\) fC. However, operation of the detector with lower thresholds \((\approx (26 \pm 10)\) fC) showed that part of the cross-talk could not be suppressed. The cross-talk is monitored via the hit multiplicity. If the cross-talk is high, so is multiplicity and it affects the quality of the clusterization and spatial resolution.

The iRPC with FEBv1.1b was installed at the GIF++, as can be seen in Figure 6.37, and operated with detection threshold of \((50 \pm 10)\) fC. The detector is placed along the muon beam line and irradiated by the Cesium source. The results are displayed in Figure 6.38. In each plot, the detectors was respectively \[\text{(a)}\] not irradiated, \[\text{(b)}\] irradiated to a background rate per unit area of \((1.94 \pm 0.25)\) kHz/cm², and \[\text{(c)}\] irradiated to a background rate per unit area of \((3.0 \pm 0.5)\) kHz/cm². Efficiency sigmoids are shown for the read-out of the HR end only, LR end only and for the coincidence of the two, referred to as AND. Due to a signal loss along the strip length affecting more the LR end, the coincidence efficiency is limited to the efficiency of the LR end only as can be seen in the three reported results. This effect has motivated a change of material of the strip panel. The new PCB that will be used with the FEBv2 will be made out of Megtron 6 instead of the more usual FR4.

Without irradiation, the detector reached its working voltage approximatively 140 V before the iRPC operated with the standard CMS FEB set to a threshold of 133 fC. The efficiency at working voltage was of 97.4%, comparable to the efficiency with the standard electronics. Near the certification background rate of 2 kHz/cm², the detector’s working voltage was shifted by almost 100 V and its
efficiency decreased to 95.2%, demonstrating the good performance of the detector. When irradiated at 3 kHz/cm², the detectors working voltage was not shifted any further but its working efficiency had dropped to 92.5%.

In each plot, the multiplicity is monitored for the HR and LR ends, as well as for their coincidence. Looking at the three different irradiation conditions, it seems that the evolution of the multiplicity is consistent with voltage shift. The multiplicity recorded by both ends is of the order of 3.5 hits per event.

Figure 6.38: Efficiency scans obtained with the iRPC equipped with FEBv1.1b at the GIF++ (a) without irradiation, (b) for an irradiation of (1.94 ± 0.25) kHz/cm², and (c) for an irradiation of (3.0 ± 0.5) kHz/cm².

Table 6.7: Summary results of the iRPC operated with the FEBv1.1b set at a threshold of (50 ± 10) fC.

<table>
<thead>
<tr>
<th>Hit Rate (kHz/cm²)</th>
<th>0</th>
<th>1.94 ± 0.25</th>
<th>3.0 ± 0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Voltage (kV)</td>
<td>7.25 ± 0.07</td>
<td>7.34 ± 0.07</td>
<td>7.34 ± 0.07</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>97.4 ± 0.4</td>
<td>95.2 ± 0.8</td>
<td>92.5 ± 0.9</td>
</tr>
</tbody>
</table>

6.3.3 INFN FEE

An iRPC prototype equipped with the INFN Tor Vergata FEBs and a longitudinal read-out panel alone was placed at the GIF++ for certification purposes. Tests with the 2D read-out and the two transverse PCBs will be performed in the future. The prototype is shown in Figure 6.39. In Figure 6.39a, the chamber is under quality controls checks at the assembly site. In Figure 6.39b, the iRPC is shown at the GIF++. The trolley is placed along the muon beam line in the upstream region.
of the irradiation bunker between the source and the longevity trolley. For the tests, the threshold is set at an approximate value of 10 to 15 fC.

The chamber was tested for different irradiation values up to a background gamma rate per unit area above 4 kHz/cm², as can be seen in Figures 6.40 and 6.41. A summary of the results is given in Table 6.8. The operation of the detector is stable even at such a high background, as can be understood from the currents at working voltage displayed in Figure 6.40a. The currents of the two gaps show a good linear correlation to the gamma rate meaning the gaps don’t suffer from saturation. At a background rate of 2 kHz/cm², the current density of the detector is of the order of 0.03 μA/cm² considering a gap active area of 13 060 cm² and a mean current per gap of 175 μA.

The evolution of the working voltage with increasing background rate is shown in Figure 6.40b. The shift in voltage with increasing background shows a linear correlation. As discussed in Chapter 5 due to the resistance of the detectors, the conversion of gamma particles in the electrode material discharges them which results in a voltage drop over the electrodes. The voltage drop over the gas gap is then provided by Equation 5.11. Without irradiation, the detector reaches its working voltage at (6972 ± 5) V. At an irradiation of (2.21 ± 0.05) kHz/cm², the working voltage is of (7241 ± 8) V. Finally, the voltage shift on all the background rate range is measured to be (118 ± 7) V/(kHz/cm²), leading to a interpolated working voltage at 2 kHz/cm² of (7208 ± 13) V.

The muon efficiency at working voltage without irradiation is (99.4 ± 0.1)%, as can be seen from Figure 6.40c. When reaching the certification rate of 2 kHz/cm², the muon efficiency is still of the order of 97% and later drops to lower than 93% above 4 kHz/cm². On the other hand, the probability of fake hits, presented in Figure 6.40d increases linearly with increasing background rate. This is expected as the number of hits per unit of time increases linearly with the background. With a fake efficiency of (46.8 ± 0.4)% at a background rate of (4.4 ± 0.1) kHz/cm², the increase of the probability of fake hits is of (10.6 ± 0.4)%/(kHz/cm²).

For what concerns the mean cluster size shown in Figure 6.41a, the gamma clusters keep a very consistent size around 1.94 strips per event with increasing gamma rate. This is expected as the conversion of gamma particles in the electrodes does not depend in the electric field in the gas gap. As the mean gamma cluster size is stable, the gamma multiplicity shown in Figure 6.41b increases linearly with increasing background rate. Finally, the mean charge per gamma cluster estimated from the background rate and the mean current density of the gaps converges to 7.5 pC per cluster.
On the other hand, the mean muon cluster size decreases with background rate. Without irradiation, the mean muon cluster size is of $(3.4 \pm 0.1)$ strips, decreases to $(2.6 \pm 0.1)$ at a background rate of $(2.21 \pm 0.05)$ kHz/cm$^2$ and to $(2.4 \pm 0.1)$ strips at $(4.4 \pm 0.1)$ kHz/cm$^2$. This is expected from the screening effect arising from the conversion of gamma particles in the electrodes. Due to the limited local rate capability of the iRPC, the muons seem “smaller” when the background rate increases. The mean multiplicity of muon clusters is measured to be slightly increasing with background rate. This could be due to the increased probability of gamma clusters being reconstructed as muon clusters. The mean multiplicities of reconstructed gamma and muon clusters per trigger can’t be directly compared as they are not measured for the same time windows. Nonetheless, the increase of both multiplicities seems correlated.

Figure 6.40: Results of the efficiency HV scans performed at the GIF++ with the iRPC equipped with INFN Tor Vergata FEBs. (a) Gap current, (b) working voltage, (c) efficiency to muons, and (d) fake efficiency as a function of the background gamma rate per unit area.
Figure 6.41: Results of the efficiency HV scans performed at the GIF++ with the iRPC equipped with INFN Tor Vergata FEBs. (a) Mean muon and gamma cluster sizes, (b) mean muon and gamma cluster multiplicity per event, and (c) mean charge per gamma cluster as a function of the background gamma rate per unit area.
<table>
<thead>
<tr>
<th></th>
<th>Hit Rate (kHz/cm²)</th>
<th>Working Voltage (V)</th>
<th>Muon Efficiency (%)</th>
<th>Fake Efficiency (%)</th>
<th>Muon Cluster Size</th>
<th>Gamma Cluster Size</th>
<th>Gamma Cluster Multiplicity</th>
<th>Charge per Gamma Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>6972 ± 5</td>
<td>99.4 ± 0.1</td>
<td>0.3 ± 0.0</td>
<td>3.42 ± 0.09</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0.25 ± 0.01</td>
<td>7030 ± 5</td>
<td>99.2 ± 0.1</td>
<td>3.3 ± 0.1</td>
<td>3.15 ± 0.06</td>
<td>1.92 ± 0.04</td>
<td>1.24 ± 0.02</td>
<td>6.00 ± 0.14</td>
</tr>
<tr>
<td></td>
<td>0.84 ± 0.02</td>
<td>7100 ± 5</td>
<td>98.8 ± 0.1</td>
<td>9.7 ± 0.2</td>
<td>3.10 ± 0.06</td>
<td>1.93 ± 0.04</td>
<td>1.31 ± 0.02</td>
<td>7.07 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>1.44 ± 0.03</td>
<td>7193 ± 6</td>
<td>98.2 ± 0.1</td>
<td>17.6 ± 0.3</td>
<td>2.84 ± 0.08</td>
<td>1.96 ± 0.03</td>
<td>1.36 ± 0.02</td>
<td>7.64 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>2.21 ± 0.05</td>
<td>7241 ± 8</td>
<td>96.9 ± 0.1</td>
<td>26.4 ± 0.3</td>
<td>2.65 ± 0.05</td>
<td>1.95 ± 0.04</td>
<td>1.44 ± 0.02</td>
<td>7.32 ± 0.17</td>
</tr>
<tr>
<td></td>
<td>2.88 ± 0.06</td>
<td>7327 ± 7</td>
<td>96.6 ± 0.1</td>
<td>34.1 ± 0.3</td>
<td>2.57 ± 0.07</td>
<td>1.96 ± 0.03</td>
<td>1.50 ± 0.01</td>
<td>7.41 ± 0.16</td>
</tr>
<tr>
<td></td>
<td>4.40 ± 0.11</td>
<td>7400 ± 12</td>
<td>92.5 ± 0.2</td>
<td>46.8 ± 0.4</td>
<td>2.42 ± 0.07</td>
<td>1.91 ± 0.03</td>
<td>1.69 ± 0.01</td>
<td>7.38 ± 0.19</td>
</tr>
</tbody>
</table>

Table 6.8: Summary results of the iRPC operated with INFN Tor Vergata electronics operating at a threshold of 10 fC to 15 fC.
6.4 Conclusion

The candidate Front-End Electronics for the new improved RPCs that will be installed in the RE3/1 and RE4/1 stations have been clearly identified. The certification of the PETIROC and of the INFN Tor Vergata FEBs is ongoing. At the time of writing, when installed on an iRPC prototype, both the electronics have shown a detector efficiency above 95% at the background rate per unit area of 2 kHz/cm².

In the near future, a new version of the PETIROC FEB with a more suitable radiation hardness will be available and a 2D read-out for the INFN Tor Vergata will have been tested.

The development of both front-end electronics was made possible thanks to the study I personally conducted on the INFN Tor Vergata preamplifiers and on the HARDROC2 electronics derived from the PETIROC ASIC. The study of both electronics have been performed on spare RE2 and RE4 detectors and have shown that an operation at lower threshold was possible with low-noise sensitive electronics. The results indicated that a shift of the working voltage by several hundred volts towards lower voltages was possible, resulting in a safer operation of the detectors at higher luminosity during the HL-LHC phase.
Summary and outlook

7.1 Summary

The upgrade of the Large Hadron Collider (LHC) towards the High Luminosity LHC (HL-LHC) began in 2018 with the start of the Second Long Shutdown (LS2). The aim is to increase the luminosity of the accelerator to boost its discovery potential for new physics beyond the Standard Model (SM) in particle physics. Many extensions to the SM feature among other things Heavy Stable Charged Particles (HSCPs), where, in the context of the Compact Muon Solenoid (CMS) experiment, the muon system could play an important role to identify such new particles. An increase in instantaneous luminosity will lead to an increase of the background noise and of the irradiation levels to which the detectors will be subjected. In addition, while the current systems were designed for ten years of LHC operation at design parameters, they are now expected to run for another ten years at high luminosity. As such, an extended upgrade program towards the HL-LHC has been launched for all CMS muon subsystems. A first issue in the CMS Muon upgrade is the fact that the muon system needs to be certified for the HL-LHC period.

Next to this, the muon system will be extended through the installation of new chambers, including also two new improved Resistive Plate Chambers (RPCs) stations called RE3/1 and RE4/1, in the forward region, i.e. closest to the beam line. The goal is to ensure a muon trigger of the best quality at high luminosity by mitigating the background effects and increasing the redundancy of the system (muon tracking might also benefit from this). An upgrade will also take place at the level of the Link-Board system connecting the Front-End Electronics (FEE) of CMS RPCs to the trigger processor to improve its robustness and to make better use of the effective time resolution of chambers of the order of $1\,\text{ns}$. The CMS RPC upgrade comprises quite an extensive and exciting research program. The collaboration converged towards the solutions that will be adopted in the perspective of HL-LHC. Even though the consolidation of the present CMS RPC infrastructure and the certification of the new technologies that will complete the redundancy of the muon system are still ongoing, the future of the experiment from the RPC point of view is now clear. To reach this point, my contribution during the R&D phase of the RPC upgrade program has been decisive in two parts: (i) the consolidation of the present detectors, and (ii) the selection of the FEEs that will equip the improved RPCs (iRPCs). At every step, I played an important role in setting up the experiments.
but also in gathering and analysing the data.
The certification of the resulting technologies, adapted for the needs of CMS in the RE3/1 and RE4/1 regions of the muon endcaps, and of the present RPC system is being performed at the new Gamma Irradiation Facility (GIF++) where an irradiation bunker along a muon beam had been built. The facility features a 14 TBq Cesium source. The purpose of this new facility is to conduct various long-term studies in the perspective of the HL-LHC. The prototypes for the improved RPCs are trapezoidal, double-gap chambers featuring High-Pressure Laminate (HPL) electrodes of 1.4 mm and gas gaps of the same thickness. The reduction of the gap thickness was motivated by the lower gain of such detectors at similar electric fields. The read-out PCB consists with a pitch ranging from 4 mm at the narrow end to 8 mm at the wide end. This design defines the baseline of what will be installed in CMS in the future.

My first contribution to the CMS Upgrade was the validation of two selected potential FEE technologies: (i) a low-noise preamplifier using SiGe technology developed at INFN Tor Vergata, and (ii) FEEs based on the PETIROC ASIC also featuring SiGe technology developed by the OMEGA Collaboration and used for timing applications. To limit the ageing of the detectors installed in the challenging region near the beam line, more sensitive electronics operated at lower threshold values (10 fC instead of the current 140 fC) will help reducing the gain of the detector and, hence, the related charge deposition inside of the chamber.

At two occasions, the INFN Tor Vergata preamplifier has been tested and compared to the current CMS FEEs. In a first experiment, the preamplifier was directly connected to four read-out strips of a spare CMS RPC, and the output signal was digitized by the use of a discriminator. The preamplifier was operated with a charge threshold as low as 3 fC and showed a working voltage shift of 475 V with respect to the RPC operated with the current CMS electronics. To improve the comparison of the INFN technology with the CMS FEB, a FEB without preamplifier was designed to connect and operate the preamplifier. This enabled a direct comparison between the new, low-noise preamplifier, and the current one used by CMS. The electronics were again mounted on spare CMS RPCs to repeat the previous experiment. The shift in working voltage observed reached 410 V at a threshold of 5 fC, consistent with the first result obtained.

The FEEs developed by OMEGA were tested on a spare CMS RPC gap from the RE4 production. For comparison purposes, the spare gap used was mounted into an RPC case, and the detector was operated in single gap mode with the CMS FEB. The results showed that the HARDROC2 could provide a reduction of the working voltage in single gap mode of almost 500 V at charge sensitivity of 121.4 fC, comparable to the threshold of the CMS FEEs set at 146 fC, while keeping noise levels below 0.1 Hz/cm². This technology had also already been certified for other experiments using detectors such as scintillators and RPCs. Finally, it had the advantage of proposing a 2D read-out that would greatly improve the spatial resolution of the detectors in the radial direction. Taking profit of the good time resolution of the electronics of the order of 100 ps, the strips of the iRPCs will be read out from both ends, which will result in a spatial resolution of about 2 cm along the direction of the strips, greatly enhancing the contribution of RPCs to the muon tracking compared to the current system.

Several prototypes have been assembled and are used to test the PETIROC FEEs and the INFN Tor Vergata alternative that was adapted to the requirements of the CMS RPC. For comparison purposes, cosmic tests without irradiation have been conducted on the iRPC prototypes using the current CMS FEBs. The detector reached its working voltage at (7383 ± 70) V with an efficiency near 97% when operated at a threshold of 133 fC. The mean muon cluster size was measured to be (2.4 ± 0.1) strips and the noise rate was of the order of 10⁻¹ Hz/cm².

Two versions (FEBv0 and FEBv1) of PETIROC FEB based on the PETIROC ASIC coupled to an FPGA have been tested so far and FEBv2 is in preparation. The FEB is effectively designed to
read the 96 pick-up strips out from both ends, providing a 2D information about the location of the received hits. FEBv0 was operated at a threshold of 100 fC while FEBv1 was operated at a lower threshold of 50 fC thanks to a PETIROC with reduced cross-talk. Without irradiation, the prototype equipped with FEBv1 reached 99% of efficiency at a working voltage of 7250 V. At a background hit rate of 2 kHz/cm², the working voltage shifted to 7340 V with an efficiency of 95%. However, both the Cyclone V FPGA and PETIROC2B ASIC suffered from radiation hardness issues. The new FEBv2 will feature a new version of the Cyclone V FPGA especially developed to address applications in irradiated environments. The new PETIROC2C is being tested at the Louvain-la-Neuve (LLN) neutron beam up to a fluence of $10^{14}$ pC/cm² which should be five times more than what is expected at CMS.

The INFN FEEs feature eight SiGe preamplifiers as well as two discriminator ASICs. Hence, twelve of these FEEs were integrated and soldered on the read-out PCB. The detector was operated with a threshold of 5 fC and was irradiated up to a background hit rate about 4 kHz/cm² at which it kept an efficiency above 92%. Without irradiation, the prototype has an efficiency larger than 99% at a working voltage below 7000 V. The mean muon cluster size is measured to be $(3.4 \pm 0.1)$, larger than in the case of the CMS FEB due to the higher sensitivity. At a rate of 2 kHz/cm², the efficiency was near 97% at a working voltage of 7250 V. Due to the irradiation, the mean muon cluster size dropped to $(2.6 \pm 0.1)$.

My largest contribution to the CMS RPC upgrade was related to the longevity and certification study of the present system. According to extrapolations of the actual CMS data, the detectors of the present system would need to be certified for a background rate of 600 Hz/cm² and without significative loss of performance at a total integrated charge of 840 mC/cm², corresponding to three times the worst background hit rate as extrapolated from CMS data of the RPC system. I joined the preliminary study that first took place at the old Gamma Irradiation Facility of CERN in which a Cesium source with an activity of 494 GBq was available. A first setup with a single spare CMS RPC was the occasion to develop the first versions of data acquisition, data quality monitoring and data analysis tools. The chamber was installed in the bunker in front of the radioactive source to be irradiated at a background hit rate of 600 Hz/cm². The performance of the detector was probed using a scintillator based cosmic muon telescope serving as trigger. The results suggested that the performance of the detector had dropped to 80% of efficiency with a working voltage shifted to higher values by 1000 V at 600 Hz/cm².

A larger scale experiment was then designed at the GIF++. The new setup consists of two spare RE2/2 CMS RPCs built in 2007 and two spare RE4/2 built in 2013. One chamber of each type serves as reference while the second is used for longevity studies under irradiation. At the time of writing, respectively 77 and 43% of the planned integrated charge program has been performed since 2016. The monitoring of the chamber current density and of the background hit rate shows a strong correlation with the temperature at the GIF++. When taken into account, the current density and background rate monitored in the irradiated detectors show a decrease relative to the reference detectors. This effect seems to be correlated with an increase in resistivity of the irradiated detectors by a factor 2 relative to the reference RPCs. However, the fluctuations of the current density and background hit rate ratios show a correlation with the relative humidity of the gas mixture. The effect seems then reversible by operating the chambers at a higher relative humidity level.

No loss in performance was observed at a background rate of 600 Hz/cm². All the detectors show an efficiency above 94% up to the required background level. The recorded shift in working voltage of 100 V for the RE2 RPCs and of 300 to 500 V for the RE4 RPCs is consistent with the difference in electrode resistivities of both detector types. The RE2 detectors have a resistivity in the range between 1 and $3 \times 10^{10} \Omega \cdot \text{cm}$ while the newer RE4 have a resistivity between 0.7 and $2 \times 10^{11} \Omega \cdot \text{cm}$. The gamma irradiation generates a voltage drop over the electrodes proportional to their resistance.
As the electrodes behave as capacitors, this voltage drop, that is usually negligible without irradiation, decreases the effective electric field in the gas volume at a given applied voltage when the rate of incoming gamma particles increases. When taken into account, the working voltage shift disappears. The remaining monitored parameters such as the efficiency, the mean muon cluster size, or the charge deposition per avalanche, do not show any difference between the reference and irradiated detectors.

At this stage, the CMS RPC group is still on its way to certify the current RPC system for the HL-LHC period. The longevity study should be completed by the end of 2021. With the upgrade of the Link-system, the present detectors should live through the high-luminosity phase of the LHC without important change in their performance.

## 7.2 Outlook

**Longevity studies at the GIF++:** In order to improve the quality of the certification tests performed at the GIF++, several points could be studied. First of all, the temperature correction used, although the same as the one used at CMS, is not efficient enough to prevent strong fluctuations of the current density and of the background hit rate measured by the detectors. The use of a Principal Component Analysis helped in understanding the causes of the fluctuations. To ensure the good quality of the study and that even small effects could be monitored, a better control of the temperature in the bunker, or at least around the detectors, should be achieved. In the case where it would be too complex to stabilize the temperature of such a large area, more care should be put into the study of the temperature effects on the detectors installed at the GIF++.

The fluctuations of the irradiated-over-reference ratio of current density and background hit rate probably find their origin in a fluctuation of the resistivity. This fluctuation was shown to be correlated to the fluctuation of gas relative humidity. It will be important to seek and repair any potential gas leak at the level of the detectors and to change the algorithm used to stabilize the humidity inside of the detectors. The humidity of the gas mixture in the supply line is now kept very stable by constantly monitoring its value and adjusting the flows of humidified and dry gas lines. It is suggested to try to stabilize the relative humidity of the gas on the exhaust line instead. The humidity of the supply line should vary to correct for the loss of humidity along the setup and a stable exhaust humidity would ensure stable working conditions for the detectors.

**Electronics:** The PETIROC FEBv2 is in preparation. The improvement of the radiation hardness is under study and should lead to the production of the FEB early 2020. Thanks to the 2D readout, these electronics will greatly improve the spatial resolution down to 3 mm in the transversal direction and to 2 cm in the longitudinal. At the same time, the upgraded Link-Board system will no longer limit the time resolution of the RPCs to 25 ns. Such an upgrade will have multiple benefits: (i) the offline out-of-time background removal will be improved, (ii) the trigger on HSCPs and their reconstruction will also be improved, and (iii) the time-of-flight between consecutive RPC stations will allow to trigger on particles now going at only 25% of the speed of light. Thus, the contribution of the RPCs to the muon tracking in CMS will be greatly improved.

**Search for eco-friendly gas mixtures:** The present thesis document unfortunately only focusses on the R&D related to the present and new detection technologies for the CMS RPC system. Little information about the very important research being conducted to find a replacement to the standard RPC gas mixture is provided. Nonetheless, the outcome of this search for new gases will be of major interest as the use of greenhouse gases in the standard RPC mixture will have to be drastically reduced or completely abandoned in the near future.
Future of the CMR RPC effort at the University of Ghent: Once the R&D is complete, the next phase will consist in the actual construction and commissioning of the new RPC subsystem. The Ghent CMS Team will mainly take part in the chamber assembly and quality control of the new chambers for the expansion of the endcaps as was already the case for the production of the RE4 detectors for the fourth endcap disk of CMS between 2012 and 2013. This phase should start during the second half of 2020, as can be seen in Figure 7.1. In this perspective, the Ghent RPC laboratory is being prepared and will also serve as training site for the technicians and physicists of the other institutes where detectors will be assembled. Demonstrators of the new improved RPCs will be installed in CMS during the Year End Technical Stop of winter 2021/2022, and the installation of the remaining detectors should take place in January 2023.

![Figure 7.1: RE3/1 and RE4/1 prototyping and production schedule.](image)

After LS3, the LHC will finally enter its high-luminosity phase, and new breakthroughs will hopefully come. The good performance of the RPCs and of all of the CMS sub-systems will be important in this regard and the experience and results obtained during the present R&D phase will become an important asset in maintaining the performance of the detectors at their best level.
De eerste stap in de upgrade van de Large Hadron Collider (LHC) naar de High Luminosity LHC (HL-LHC) werd aangevat eind 2018, bij het begin van de zogenaamde Second Long Shutdown (LS2), waarbij de deeltjesversneller en de bijhorende experimenten voor 2 jaar stilgelegd werden voor onderhoudswerken en aanpassingen. Het doel hierbij is de luminositeit van de versneller met een factor 10 te verhogen om zo het potentieel op te drijven voor de ontdekking van nieuwe fysica die niet door het huidige Standaardmodel (SM) van de deeltjesfysica beschreven wordt. Vele uitbreidingen van het SM voorspellen het bestaan van nieuwe deeltjes zoals bijvoorbeeld Heavy Stable Charged Particles (HSCPs) waarbij, binnen de context van het Compact Muon Solenoiide (CMS) experiment, het muonsysteem een belangrijke rol zou kunnen spelen om deze deeltjes te identificeren. Een toename in de ogenblikelijke luminositeit van de versneller zal aanleiding geven tot een verhoging van zowel de achtergrondruis alsook de stralingsniveaus waaraan de detectoren blootgesteld zullen worden. Bovendien, hoewel de huidige detectoren ontworpen werden voor 10 jaar bedrijf aan standaard LHC condities, wordt er nu verwacht dat ze nog eens minstens 10 jaar langer operationeel blijven tijdens de HL-LHC met sterk verhoogde luminositeit. Daarom werd er een uitgebreid R&D programma gelanceerd voor de upgrade van alle CMS muonsubsysteem naar de HL-LHC fase toe. Een eerste gegeven in deze upgrade van het muonsysteem is het feit dat de detectoren gecertificeerd moeten worden voor de HL-LHC periode. Daarnaast zal het muonsysteem in de voorwaartse detectorregio, d.w.z. dichtbij de LHC deeltjesbundel, ook uitgebreid worden met nieuwe detectoren, inclusief twee nieuwe stations uitgerust met verbeterde Resistive Plate Chambers (RPCs), de zogenaamde RE3/1 en RE4/1 stations. De bedoeling hiervan is om een hoge kwaliteit van de muontrigger te verzekeren door effecten ten gevolge van achtergrond te minimaliseren en door de redundantie van het systeem te verhogen. Dit zal eveneens bevorderlijk zal zijn voor de reconstructie van de muonsporen doorheen de CMS detector. Een upgrade zal ook plaatsvinden op niveau van het Link Board systeem dat de front-end electronica (FEE) van de CMS RPCs verbindt met de triggerprocessors, om zo de robuustheid van het systeem te verbeteren en ook beter gebruik te maken van de effectieve tijdsresolutie van de Resistive Plate Chambers (van de orde 1 ns). De CMS RPC upgrade omvat zodoende een uitgebreid onderzoeksprogramma. De CMS RPC collaboratie kwam na een aantal jaren van R&D tot een reeks passende oplossingen die zullen uitgevoerd worden in het vooruitzicht.
van de HL-LHC. Hoewel de consolidatie van de huidige CMS RPC-infrastructuur en de certificatie van nieuwe technologieën nog steeds verder loopt, is de toekomst van CMS wat de RPCs betreft ondertussen zeer duidelijk. Om dit punt te bereiken is mijn bijdrage tijdens de R&D-fase van het RPC-upgradeprogramma cruciaal geweest op twee vlakken: (i) de consolidatie van de huidige detectoren, en (ii) de keuze van de FEE waarmee de verbeterde RPCs (ofwel iRPCs) zullen uitgerust worden. Bij elke stap in het onderzoek speelde ik een belangrijke rol zowel in het opzetten van de testexperimenten als in het vergaren en analyseren van de metingen.

De certificatie van de nieuw voorgestelde technologieën die beantwoorden aan de noden van CMS voor de RE3/1- en RE4/1-regio's van de muon endcap disks, en van het huidige RPC-systeem wordt momenteel uitgevoerd in de nieuwe Gamma Irradiation Facility (GIF++) op CERN, waar een stralingsbunker rondom een nieuwe muonendcapbundel werd gebouwd. Deze faciliteit beschikt over een cesiumbron van 14 Tβq. Het doel van deze nieuwe faciliteit is het simuleren van de HL-LHC condities en het uitvoeren van verscheidene lange termijn studies binnen de context van het HL-LHC upgrade programma. Het prototype van de nieuwe iRPCs voor CMS zijn trapeziumvormige double-gap kamers bestaande uit twee 1.4 mm dikke gasruimtes gevormd door even dikke High-Pressure Laminate (HPL) elektroden. Het verlagen van de dikte van de elektroden en gasruimtes t.o.v. het huidige RPC systeem werd gedreven door de lagere versterking of gain van zulke detectoren bij gelijkaardig elektrisch veldsterkte, wat de levensduur van deze detectoren ten goede komt. De uitlezing van de RPC-signalen zal gebeuren via een Printed Circuit Board (PCB) dat 96 longitudinale strips bevat met een onderlinge afstand die varieert tussen de 4 mm aan het smalle uiteinde en 8 mm aan de brede zijde van de trapeziumvorm. Dit ontwerp definitie de basisversie van wat er uiteindelijk in CMS geïnstalleerd zal worden.

Mijn bijdrage aan de CMS upgrade was het valideren van twee mogelijke FEE technologieën: (i) een voorversterker met laag ruisniveau die gebruik maakt van SiGe-technologie ontwikkeld door INFN Tor Vergata, en (ii) FEE gebaseerd op de PETIROC ASIC die eveneens gebruik maakt van SiGe-technologie ontwikkeld door de OMEGA collaboratie en vooral gebruikt wordt voor tijdsgerelateerde toepassingen. Om de veroudering van de geïnstalleerde detectoren in de voorwaartse richting nabij de LHC bundellijn waar het stralingsniveau relatief hoog is, tegen te gaan, zal een verlaging van de benodigde ladingsdepositie binnenin de gaskamer om een meetbaar signaal te genereren zeker helpen. Dit kan bekomen worden door gebruik te maken van meer gevoelige elektronica met versterkers met een lagere drempelwaarde voor elektrische lading, d.w.z. 10 fC in plaats van 140 fC zoals op het huidige CMS RPC Front-end Board (FEB).

In een eerste stap werd de INFN Tor Vergata voorversterker tweemaal getest en vergeleken met de huidige CMS FEE. Bij een eerste test werd de voorversterker rechtstreeks verbonden met vier leesstrips van een reserve-RPC, en werd het uitgangssignaal gedigitaliseerd door middel van een discriminator. De voorversterker werd gebruikt met een lage drempelwaarde van 3 fC voor gedetecteerde lading, en resulteerde in een verlaging van de RPC-werkspanning van 475 V ten opzichte van een RPC uitgerust met de huidige CMS-electronica. Om de vergelijking van de INFN-technologie met de huidige CMS FEB te verbeteren werd een nieuwe versie van de FEB zonder voorversterker ontworpen die dan met de voorversterker verbonden werd. Dit liet ons toe een directe vergelijking te maken tussen de nieuwe voorversterker met lage ruis en de huidige CMS RPC FEB. De elektronica werd wederom gemonteerd op een reserve-RPC om de voorgaande test te herhalen. De verlaging van de geobserveerde RPC werkspanning liep op tot 410 V bij een drempelwaarde van 5 fC, wat consistent is met mijn eerste resultaat. De eerste versie van de FEE ontworpen door OMEGA werd getest op één enkele reserve RPC HPL gaskamer uit de oude RE4-productie. Om een vergelijking te maken werd het geheel in een RPC-behuizing gemonteerd en werd de detector ook met de standaard CMS FEB in single-gap modus bedreven. Het resultaat toonde aan dat de HARDROC2 ASIC een reductie in de RPC werkspanning
van bijna 500 V kan teweegbrengen in single-gap modus bij een ladingsgevoeligheid van 121 fC, hetgeen vergelijkbaar is met de drempelwaarde van 146 fC bij de standaard CMS FEE, terwijl de ruiswaarde lager dan 0.1 Hz/cm² blijft. Diezelfde OMEGA technologie werd ook eerder al gecertificeerd door andere experimenten die gebruik maakten van detectoren zoals scintillatore of andere RPC types. De OMEGA FEE biedt eveneens de mogelijkheid tot een tweedimensionale uitlezing van de RPC strips, hetgeen de spatiale resolutie van de detector in de radiale richting sterk zou verbeteren t.o.v. het huidige systeem. Er werd aangetoond dat gebruik maken van de goede tijdsresolutie van deze elektronica en van het uitlezen van de iRPC uitleesstrips aan beide uiteinden zal resulteren in een spatiale resolutie van ongeveer 2 cm langs de richting van de strips. De OMEGA FEE biedt eveneens de mogelijkheid tot een tweedimensionale uitlezing van de RPC strips, hetgeen de spatiale resolutie van de detector in de radiale richting sterk zou ver-

beteren t.o.v. het huidige systeem. De OMEGA FEE biedt eveneens de mogelijkheid tot een tweedimensionale uitlezing van de RPC strips, hetgeen de spatiale resolutie van de detector in de radiale richting sterk zou ver-

beteren t.o.v. het huidige systeem. De OMEGA FEE biedt eveneens de mogelijkheid tot een tweedimensionale uitlezing van de RPC strips, hetgeen de spatiale resolutie van de detector in de radiale richting sterk zou ver-

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beteren t.o.v. het huidige systeem. De OMEGA FEE biedt eveneens de mogelijkheid tot een tweedimensionale uitlezing van de RPC strips, hetgeen de spatiale resolutie van de detector in de radiale richting sterk zou ver-

beteren t.o.v. het huidige systeem. De OMEGA FEE biedt eveneens de mogelijkheid tot een tweedimensionale uitlezing van de RPC strips, hetgeen de spatiale resolutie van de detector in de radiale richting sterk zou ver-

reserve CMS RPC liet toe om eerste versies van een data acquisitiesysteem en tools voor de kwaliteitscontrole en data-analyse te ontwikkelen. De RPC werd geïnstalleerd in een bunker nabij de radioactieve bron om vervolgens bestraald te worden met een achtergrondstraling van 600 Hz/cm². De performantie van de detector werd getest met behulp van een op scintillatoren gebaseerde kosmische muontelecoop die fungeerde als trigger voor de data-acquisitie. De resultaten suggereerden dat de performantie van de detector daalde tot 80% efficiëntie, waarbij de een werkspanning verhoogde tot 1000 V bij 600 Hz/cm².

Een grootschaliger experiment werd vervolgens opgebouwd in de CERN GIF++. Deze nieuwe opstelling maakte gebruik van twee reserve-RPCs van het type RE2/2, geproduceerd in 2007, en twee RE4/2 kamers uit 2013. Eén RPC van elk type diende als referentie terwijl het tweede exemplaar bestraald werd in een studie van de langlevendheid van deze detectoren bij HL-LHC condities. Op het moment van schrijven werd respectievelijk 74 (voor de RE2/2 detector) en 40% (voor de RE4/2 kamer) van de geplande bestraling uitgevoerd sinds 2016. Tijdens de metingen blijken de stroomdichtheid en de gedetecteerde achtergrondstraling in de RPCs sterk gecorreleerd aan de temperatuur in de GIF++. Wanneer dit in rekening wordt gebracht, vertonen de stroomdichtheid en de achtergrondruis een dalende trend ten opzichte van de referentiekamers. Dit effect lijkt verband te houden met een waargenomen toename van de resistiviteit van de bestraalde detectoren met een factor 2 ten opzichte van de referentiekamers. De schommelingen in de gemeten stroomdichtheid en de achtergrondruis van de bestraalde detectoren vertonen echter ook een correlatie met de relatieve luchtvochtigheid van het gebruikte gasmengsel in de RPCs. Het effect lijkt reversibel door de RPCs bloot te stellen aan een gasmengsel met hogere relatieve luchtvochtigheid.

Tot op heden is er geen verlies aan detectorperformantie merkbaar bij een achtergrondstraling van 600 Hz/cm². Alle RPCs behouden een efficiëntie boven de 94% bij bestraling tot het niveau dat bij de HL-LHC verwacht wordt. De gemeten verschuiving in de werkspanning van 100 V voor de RE2 RPCs en van 300 tot 500 V voor de RE4 RPCs is consistent met het verschil in de elektroderesistiviteit van beide types detectoren. De RE2 detectoren hebben een elektroderesistiviteit tussen 1 à 3 × 10¹⁰ Ω · cm terwijl die van de nieuwere RE4 detectoren tussen de 0.7 en 2 × 10¹¹ Ω · cm bedraagt. Intern in de RPCs veroorzaakt de gammastraling van de GIF++ bron een spanningsdaling over de elektrodes evenredig met hun weerstand. Aangezien de RPC elektrodes zich gedragen als condensatoren, zorgt deze daling in spanning (gewoonlijk verwaarloosbaar bij afwezigheid van straling) ervoor dat het effectieve elektrisch veld in het gasvolume voor een gegeven aangelegde detectorspanning ook daalt naarmate het aantal invallende gamma flux toeneemt. Wanneer we hier rekening mee houden verdwijnt deze waargenomen verschuiving in de RFC werkspanning. Alle andere parameters die tijdens deze testen opgevolgd werden zoals detectorefficiëntie, de gemiddelde muoncluster grootte en de ladingsdepositie per deeltjescascade, vertonen tot nu toe geen enkel verschil tussen de referentiekamers en de bestraalde detectoren.

Op dit moment is de CMS RPC groep nog steeds bezig om het huidige RPC-systeem te certificeren voor de toekomstige HL-LHC periode. Deze langlevendheidstudie zou eind 2021 afgerond moeten zijn. Indien geen effecten van veroudering in de detectoren gevonden worden tijdens het verdere verloop van deze studie, zouden de huidige RPCs, ook mede dankzij de upgrade van het Link Board systeem, de hoge-luminositeitsfase van de LHC moeten kunnen doorstaan zonder grote veranderingen in hun performantie.
The PhD project I worked on for the past seven years is finally reaching an end. It’s time to look back and thank all the people without whom it wouldn’t have been possible. I thank Gabriella and Nicolas for giving me the opportunity to work on such an interesting project. It has been motivating working in a team with a lot of young researchers in the same situation as me. I mainly think of Andrea, François, Jan, Severiano and Shereen with whom I interacted the most when I was at CERN. Of course, the team also was mentored by great people with a lot of experience like Ian and Salvador with whom I got a lot of pleasure working.

My interest in the R&D project and my knowledge of detectors opened a few other doors. I got the trust from Anna and Gabriella to become expert-on-call for the RPC sub-system at CMS which was not an easy task but that brought me a lot of experience and confidence. I feel lucky that people such as Salvador and Isabel invited me at more than one occasion to go to Mexico to work with students there. This was very rewarding. Ultimately, I would like to thank my promotor Michael for giving me this chance and Imad for putting us in contact. Michael let me a lot of autonomy to take the PhD project in the direction I wanted and Imad has been a great Master Responsible back in Lyon. He knew his students well and knew where they could flourish.

But of course, the completion of this PhD project is also greatly subjected to the social life I developed and the support from my family and friends. I could count on my parents, brother and cousins, Yoan and Laetitia, at any moment throughout these years. Special thanks to Laetitia and Thierry, but also to the kids, for hosting me each time I was at CERN. This was a huge moral help. CERN is a wonderful place to work, but the work load can be overwhelming. Childhood friends also did a lot. Clément and Lolita brought me some light by regularly visiting me. The bond with Mikael and Xavier never weakened even though we could not meet very often anymore.

I wish to thank Nick. We managed to support each other and it turned out quite well in the end. Of course, I can’t thank Nick without including Ibby. I wish she didn’t leave Ghent so soon, we met a
little too late. Our trio was quite fun. I was lucky to have great flatmates. I had first met Bryan in the kot we were sharing during our first year in Ghent. Very friendly and open minded. Paul, I knew already from Lyon but it turned out that he also applied for a PhD in Ghent and got it. It has been nice to share a place with you two. Of course, then came Nina that has been also very nice to live with. I remember nice parties at home and a lot of shared food.

A big thanks to Mostafa and Abbas for the ones that have been here since the very beginning and to Dinka, Amélie and Joe to include me in there groups when I needed it. Jean-François, with his great mind, holds a very special place as he never stopped challenging me with sciences and other topics. It was always a great time meeting with him. Thanks to the ones I met without really expecting it but that naturally integrated me in their circle. Anthony, Charline, Dylan, Florian and Maurane, Guillaume, Roxane, Thomas, both of the Valentins, and Vincent. I probably got some of the most life changing conversations with them. My vision of the world really evolved at their contact. Finally, I would like to thank the people that made me want to build my life here. Alba and Andres, Carmen and Raul, Kajetan, Maren and Prem, Martina, Meta and Vishvas, Nils and Liesl, Ola, and of course Paula, who is sharing my life for a while now.

To some of you, even if our paths are now separate, I don't forget what you brought me. I am thankful for that. To the rest of you that I have the pleasure on meeting often, you make of every day a good moment. I hope it goes on for as long as possible. Take care.
A data acquisition software for CAEN VME TDCs

Certifying detectors in the perspective of HL-LHC required to develop tools for the GIF++ experiment. Among them was the C++ Data Acquisition (DAQ) software that allows to make the communications in between a computer and TDC modules in order to retrieve the RPC data [302]. In this appendix, details about this software, as of how the software was written, how it functions and how it can be exported to another similar setup, will be given.

1 GIF++ DAQ file tree

GIF++ DAQ source code is fully available on github at https://github.com/afagot/GIF_DAQ. The software requires 3 non-optional dependencies:

- CAEN USB Driver to mount the VME hardware,
- CAEN VME Library to communicate with the VME hardware, and
- ROOT to organize the collected data into a TTree.

The CAEN VME library will not be packaged by distributions and will need to be installed manually. To compile the GIF++ DAQ project via a terminal, from the DAQ folder use the command:

```
mkdir build
cd build
cmake ..
make install
```

The source code tree is provided below along with comments to give an overview of the files’ content. The different objects created for this project (v1718, v1190a, IniFile & DataReader) will be described in details in the following sections.
2 Usage of the DAQ

GIF++ DAQ, as used in GIF++, is not a standalone software. Indeed, the system being more complex, the DAQ only is a sub-layer of the software architecture developped to control and monitor the RPCs that are placed into the bunker for performance study in an irradiated environment. The top layer of GIF++ is a Web Detector Control System (webDCS) application. The DAQ is only called by the webDCS when data needs to be acquired. The webDCS operates the DAQ through command line. To start the DAQ, the webDCS calls:

```
bin/daq /path/to/the/log/file/in/the/output/data/folder
```

where `/path/to/the/log/file/in/the/output/data/folder` is the only argument required. This log file is important for the webDCS as this file contains all the content of the communication of the webDCS and the different systems monitored by the webDCS. Its content is constantly displayed during data taking for the users to be able to follow the operations. The communication messages are normally sent to the webDCS log file via the functions declared in file `MsgSvc.h`, typically `MSG_INFO(string message)`. 

3 Description of the readout setup

The CMS RPC setup at GIF++ counts 5 V1190A Time-to-Digital Converter (TDC) manufactured by CAEN [278]. V1190A are VME units accepting 128 independent Multi-Hit/Multi-Event TDC channels whose signals are treated by 4 100 ps high performance TDC chips developed by CERN / ECP-MIC Division. The communication between the computer and the TDCs to transfer data is done via a V1718 VME master module also manufactured by CAEN and operated from a USB port [279]. These VME modules are all hosted into a 6U VME 6021 powered crate manufactured by W-Le-Ne-R than can accommodate up to 21 VME bus cards [303]. These 3 components of the DAQ setup are shown in Figure A.1.

Figure A.1: (a) View of the front panel of a V1190A TDC module [278]. (b) View of the front panel of a V1718 Bridge module [279]. (c) View of the front panel of a 6U 6021 VME crate [303].

4 Data read-out

To efficiently perform a data readout algorithm, C++ objects to handle the VME modules (TDCs and VME bridge) have been created along with objects to store data and read the configuration file that comes as an input of the DAQ software.
4.1 V1190A TDCs

The DAQ used at GIF takes profit of the Trigger Matching Mode offered by V1190A modules. This setting is enabled through the method `v1190a::SetTrigMatching(int ntdcs)` where `ntdcs` is the total number of TDCs in the setup this setting needs to be enabled for (Source Code A.1). A trigger matching is performed in between a trigger time tag, a trigger signal sent into the TRIGGER input of the TDC visible on Figure A.1a and the channel time measurements, signals recorded from the detectors under test in our case. Control over this data acquisition mode, explained through Figure A.2, is offered via 4 programmable parameters:

- **match window**: the matching between a trigger and a hit is done within a programmable time window. This is set via the method
  ```
  void v1190a::SetTrigWindowWidth(Uint windowWidth, int ntdcs)
  ```

- **window offset**: temporal distance between the trigger tag and the start of the trigger matching window. This is set via the method
  ```
  void v1190a::SetTrigWindowWidth(Uint windowWidth, int ntdcs)
  ```

- **extra search margin**: an extended time window is used to ensure that all matching hits are found. This is set via the method
  ```
  void v1190a::SetTrigSearchMargin(Uint searchMargin, int ntdcs)
  ```

- **reject margin**: older hits are automatically rejected to prevent buffer overflows and to speed up the search time. This is set via the method
  ```
  void v1190a::SetTrigRejectionMargin(Uint rejectMargin, int ntdcs)
  ```

  ![Figure A.2: Module V1190A Trigger Matching Mode timing diagram](image)

Each of these 4 parameters are given in number of clocks, 1 clock being 25 ns long. It is easy to understand at this level that there are 3 possible functioning settings:

- **1**: the match window is entirely contained after the trigger signal,
- **2**: the match window overlaps the trigger signal, or
- **3**: the match window is entirely contained before the trigger signal as displayed on Figure A.2

In both the first and second cases, the sum of the window width and of the offset can be set to a maximum of 40 clocks, which corresponds to 1 µs. Evidently, the offset can be negative, allowing for a longer match window, with the constraint of having the window ending at most 1 µs after the trigger signal. In the third case, the maximum negative offset allowed is of 2048 clocks (12 bit) corresponding to 51.2 µs, the match window being strictly smaller than the offset. In the case of GIF++,
the choice has been made to use this last setting by delaying the trigger signal. During the studies performed in GIF++, both the efficiency of the RPCs, probed using a muon beam, and the noise or gamma background rate are monitored. The extra search and reject margins are left unused.

To probe the efficiency of RPC detectors, the trigger time tag is provided by the coincidence of scintillators when a bunch of muons passes through GIF++ area is used to trigger the data acquisition. For this measurement, it is useful to reduce the match window width only to contain the muon information. Indeed, the delay in between a trigger signal and the detection of the corresponding muon in the RPC being very constant (typically a few tens of ns due to jitter and cable length), the muon signals are very localised in time. Thus, due to a delay of approximately 325 ns in between the muons and the trigger, the settings were chosen to have a window width of 24 clocks (600 ns) centered on the muon peak thanks to a negative offset of 29 clocks (725 ns).

On the other hand, monitoring the rates don’t require for the DAQ to look at a specific time window. It is important to integrate enough time to have a robust measurement of the rate as the number of hits per time unit. The triggering signal is provided by the pulse generator integrated into the communication module V1718 at a frequency of 100 Hz to ensure that the data taking occurs in a random way, uncorrelated with beam physics, to probe only the irradiation spectrum on the detectors. The match window is set to 400 clocks (10 μs) and the negative offset to 401 clocks as it needs to exceed the value of the match window.

The v1190a object, defined in the DAQ software as in Source Code A.1 offers the possibility to store all TDCs in the readout setup into a single object containing a list of hardware addresses (addresses to access the TDCs’ buffer through the VME crate) and each constructor and method acts on the list of TDCs to set the different acquisition parameters as describe above. The type of trigger matching is chosen with v1190a::SetTrigMatching() and the time substraction, used to have a time measurement referring to the beginning of the time window, is set by v1190a::SetTrigTimeSubraction(). Then, the window width and offset are respectively set thanks to v1190a::SetTrigWindowWidth() and v1190a::SetTrigWindowOffset(). The rejection and extra search margin, even if left unused and hence set to a default value of 0, can be set through v1190a::SetTrigRejectionMargin() and v1190a::SetTrigSearchMargin(). These methods are then called in v1190a::SetTrigConfiguration() that uses the information contained in the configuration file IniFile *inifile to set the different TDC parameters. A thorough explanation of the content of the configuration file is provided in Section 5.2.

Among the other methods of class v1190a can be found a set of the detection mode (v1190a::SetTDCDetectionMode()), of the TDC time resolution (v1190a::SetTDCResolution()), of the dead time in between two consecutive signals recorded into a single channel (v1190a::SetTDCDeadTime()) or of the maximal number of signals that can be recorded per event (v1190a::SetTDCEventSize()). To help with setting these parameters, enum were used (EdgeMode, Resolution, DeadTime and HitMax are defined in include/v1190a.h).
The detection mode corresponds to the the type of edge detection the TDC will be using to record the data. The TDCs can record the time stamp of the leading edge alone, of the trailing edge alone, or both or they can operate in pair mode, meaning that the leading edge is recorded together with the time difference in between leading and trailing edges. This last mode is not very practical for the case of GIF++ measurements as the information is coded into a single words in the TDC’s buffer, putting strong constraints on the time window and duration of the input signals. Indeed, when recording the edges individually (single edge or both edges), a 32-bit word, of which 18 are used to provide the time information alone, is stored into memory for each signal edge. With the pair mode, instead of having one 32-bit word per edge, only a single 32-bit word is written of which 12 are used for the leading edge time information and 6 for the width of the pulse, as described on p73 of reference [278]. This way, even though the pair mode is convenient to use as it automatically correlates a leading edge with the corresponding signal width in a single word, it is advised to be
careful when using it and to be aware of the extra time constraints (for both leading time and signal width) that will come for choosing this setting. If it is necessary to work with large input signals, the mode recording both edges will be preferred to the pair mode and the association of a leading and trailing edges pair will then be performed offline by the user. Then, the time resolution is to be chosen in a range from 100 to 800 ps, the dead time in a range from 5 to 100 ns, and the maximal number of hits per event in a range from 0 to 128 with the possibility to chose to have no limits.

4.2 DataReader

Enabled thanks to \texttt{v1190a::SetBlockTransferMode()}, the data transfer is done via Block Transfer (BLT). Using BLT allows to transfer a fixed number of events called a block. This is used together with an Almost Full Level (AFL) of the TDCs’ output buffers, defined through \texttt{v1190a::SetIRQ()}. This AFL gives the maximum amount of 32735 words (16 bits, corresponding to the depth of a TDC output buffer) that can written in a buffer before an Interrupt Request (IRQ) is generated and seen by the VME Bridge V1718, which sends a \texttt{BUSY} signal intended to stopping the data acquisition during the transfer of the content of each TDC buffers before resuming. For each trigger, 6 words or more are written into the TDC buffer:

- a global header providing information of the event number since the beginning of the data acquisition,
- a TDC header which is enabled thanks to \texttt{v1190a::SetTDCHeadTrailer()},
- the TDC data (if any), 1 for each hit recorded during the event, providing the channel and the time stamp associated to the hit,
- a TDC error providing error flags,
- a TDC trailer which is enabled thanks to \texttt{v1190a::SetTDCHeadTrailer()},
- a global trigger time tag that provides the absolute trigger time relatively to the last reset, and
- a global trailer providing the total word count in the event.

CMS RPC FEEs provide with 100 ns long LVDS output signals that are injected into the TDCs’ input. Any avalanche signal that gives a signal above the FEEs threshold is thus recorded by the TDCs as a hit within the match window. Each hit is assigned to a specific TDC channel with a time stamp, with a precision of 100 ps. The reference time, $t_0 = 0$, is provided by the beginning of the match window. Thus for each trigger, coming from a scintillator coincidence or the pulse generator, a list of hits is stored into the TDCs’ buffers and will then be transferred into a ROOT Tree.

When the BLT is used, it is easy to understand that the maximum number of words that have been set as ALF will not be a finite number of events or, at least, the number of events that would be recorded into the TDC buffers will not be a multiple of the block size. In the last BLT cycle to transfer data, the number of events to transfer will most probably be lower than the block size. In that case, the TDC can add fillers at the end of the block but this option requires to send more data to the computer and is thus a little slower. Another solution is to finish the transfer after the last event by sending a bus error that states that the BLT reached the last event in the pile. This method has been chosen in GIF++. Due to irradiation, an event in GIF++ can count up to 300 words per TDC. A limit of 4096 words (12 bits) has been set to generate IRQ which represent from 14 to almost 700 events depending on the average of hits collected per event. Then the block size has been set to 100 events with enabled
bus errors. When an AFL is reached for one of the TDCs, the VME bridge stops the acquisition by sending a BUSY signal.

The data is then transferred one TDC at a time into a structure called **RAWData** (Source Code A.2). Note that the structure as presented here is used when a single edge detection is used as there is only one time stamp list associated to the hits. When using detection on both edges, a second time stamp list could be added and when using pair detection, a list with the signal width could be added instead.

```cpp
struct RAWData{
    vector<int> *EventList;
    vector<int> *NHitsList;
    vector<int> *QFlagList;
    vector<vector<int>> *ChannelList;
    vector<vector<float>> *TimeStampList;
};
```

**Source Code A.2: Description of data holding C++ structure RAWData.**

```cpp
class DataReader
{
private:
    bool StopFlag;
    IniFile *iniFile;
    Data32 MaxTriggers;
    v1718 *VME;
    int nTDCs;
    v1190a *TDCs;
    RAWData TDCData;

public:
    DataReader();
    virtual ~DataReader();
    void SetIniFile(string inifilename);
    void SetMaxTriggers();
    Data32 GetMaxTriggers();
    void SetVME();
    void SetTDC();
    int GetQFlag(Uint it);
    void Init(string inifilename);
    void FlushBuffer();
    void Update();
    string GetFileName();
    void WriteRunRegistry(string filename);
    void Run();
};
```

**Source Code A.3: Description of C++ object DataReader.**

In order to organize the data transfer and the data storage, an object called **DataReader** was created (Source Code A.3). On one hand, it has `v1718` and `v1190a` objects as private members for communication purposes, such as VME modules settings via the configuration file `*iniFile` or data read-out through `v1190a::Read()` and on the other hand, it contains the structure `RAWData` that allows to organise the data in vectors reproducing the tree structure of a ROOT file. Each event is transferred from `TDCData` and saved into branches of a ROOT `TTree` as 3 integers that represent the event ID (`EventCount`), the number of hits read from the TDCs (`nHits`), and the quality flag that provides information for any problem in the data transfer (`qflag`), and 2 lists of
nHits elements containing the fired TDC channels (TDCCh) and their respective time stamps (TDCTS), as presented in Source Code A.4. The ROOT file file is named using information contained into the configuration file, presented in section 5.2. The needed information is extracted using method DataReader::GetFileName() and allow to build the output filename format ScanXXXXXX_HVXDAQ.root where ScanXXXXXX is a 6 digit number representing the scan number into GIF++ database and HVX the HV step within the scan that can be more than a single digit. An example of ROOT data file is provided with Figure A.3.

```cpp
RAWData TDCData;
TFile *outputFile = new TFile(outputFileName.c_str(),"recreate");
TTree *RAWDataTree = new TTree("RAWData","RAWData");

int EventCount = -9;
int nHits = -8;
int qflag = -7;
vector<int> TDCCh;
vector<float> TDCTS;

RAWDataTree->Branch("EventNumber", &EventCount, "EventNumber/I");
RAWDataTree->Branch("number_of_hits", &nHits, "number_of_hits/I");
RAWDataTree->Branch("Quality_flag", &qflag, "Quality_flag/I");
RAWDataTree->Branch("TDC_channel", &TDCCh);
RAWDataTree->Branch("TDC_TimeStamp", &TDCTS);

// Here read the TDC data using v1190::Read() and place it into //TDCData for as long as you didn’t collect the requested amount //of data.
//

for(Uint i=0; i<TDCData.EventList->size(); i++){
    EventCount = TDCData.EventList->at(i);
    nHits = TDCData.NHitsList->at(i);
    qflag = TDCData.QFlagList->at(i);
    TDCCh = TDCData.ChannelList->at(i);
    TDCTS = TDCData.TimeStampList->at(i);
    RAWDataTree->Fill();
}
```

Source Code A.4: Highlight of the data transfer and organisation within DataReader::Run() after the data has been collected into TDCData.
4.3 Data quality flag

Among the parameters that are recorded for each event, the quality flag is determined on the fly by checking the data recorded by every single TDC. An enum called QualityFlag was written to associate the key GOOD to the integer 1 and CORRUPTED to 0. From method v1190a::Read(), it can be understood that the content of each TDC buffer is readout one TDC at a time. Entries are created in the data list for the first TDC and then, when the second buffer is readout, events corresponding to entries that have already been created to store data for the previous TDC are added to the existing list element. On the contrary, when an event entry has not been yet created in the data list, a new entry is created.

It is possible that each TDC buffer contains a different number of events. In cases where the first element in the buffer list is an event for corresponds to a new entry, the difference in between the entry’s ID and the one of the last entry that was recorded for this TDC buffer in
the previous cycle. In the case events were missing, the flag stays at its initial value of 0, which is similar to CORRUPTED and it is assumed that then this TDC will not contribute to number_of_hits, TDC_channel or TDC_TimeStamp. Finally, since there will be 1 RAWData entry per TDC for each event (meaning nTDCs entries, referring to DataReader private attribute), the individual flags of each TDC will be added together. The final format is an integer composed nTDCs digits where each digit is the flag of a specific TDC. This is constructed using powers of 10 like follows:

\[
\begin{align*}
\text{TDC 0: } & \quad Q\text{Flag} = 10^0 \times \text{QualityFlag} \\
\text{TDC 1: } & \quad Q\text{Flag} = 10^1 \times \text{QualityFlag} \\
& \quad \vdots \\
\text{TDC N: } & \quad Q\text{Flag} = 10^N \times \text{QualityFlag}
\end{align*}
\]

and the final flag to be with N digits:

\[
Q\text{Flag} = n....3210
\]

each digit being 1 or 0. Below is given an example with a 4 TDCs setup.

If all TDCs were good: \(Q\text{Flag} = 1111\),

but if TDC 2 was corrupted: \(Q\text{Flag} = 1011\).

When data taking is over and the data contained in the dynamical RAWData structure is transferred to the ROOT file, all the 0s are changed into 2s by calling the method DataReader::GetQFlag(). This will help translating the flag without knowing the number of TDCs beforehand. Indeed, a flag \(111\) could be due to a 3 TDC setup with 3 good individual TDC flags or to a more than 3 TDC setup with TDCs those ID is greater than 2 being CORRUPTED, thus giving a 0.

The quality flag has been introduced quite late, in October 2017 only, to the list of GIF++ DAQ parameters to be recorded into the output ROOT file. Before this addition, the missing data, corrupting the quality for the offline analysis, was contributing to artificially fill data with lower multiplicity. Looking at TBranch number_of_hits provides information about the data of the full GIF++ setup. When a TDC is not able to transfer data for a specific event, the effect is a reduction of the total number of hits recorded in the full setup, this is what can be seen from Figure A.4. After offline reconstruction detector by detector, the effect of missing events can be seen in the artificially filled bin at multiplicity 0 shown in Figure A.5. Nonetheless, for data with high irradiation levels, as it is the case for Figure A.5a, discarding the fake multiplicity 0 data can be done easily during the offline analysis. At lower radiation, the missing events contribution becomes more problematic as the multiplicity distribution overlaps the multiplicity 0 and that in the same time the proportion of missing events decreases. Attempts to fit the distribution with a Poisson or skew distribution function were not conclusive and this very problem has been at the origin of the quality flag that allows to give a non ambiguous information about each event quality.
Figure A.4: The effect of the quality flag is explained by presenting the content of TBranch number_of_hits of a data file without Quality_flag [a] and the content of the same TBranch for data corresponding to a Quality_flag where all TDCs were labelled as GOOD [b] taken with similar conditions. It can be noted that the number of entries in Figure (b) is slightly lower than in Figure (a) due to the excluded events.

Figure A.5: Using the same data as previously showed in Figure A.4, the effect of the quality flag is explained by presenting the reconstructed hit multiplicity of a data file without Quality_flag [a] and the reconstructed content of the same RPC partition for data corresponding to a Quality_flag where all TDCs were labelled as GOOD [b] taken with similar conditions. The artificial high content of bin 0 is completely suppressed.

5 Communications

To ensure data readout and dialog in between the machine and the TDCs or in between the webDCS and the DAQ, different communication solutions were used. First of all, it is important to have a module to allow the communication in between the TDCs and the computer from which the DAQ operates. When this communication is effective, shifters using the webDCS to control data taking can thus send instructions to the DAQ.
5.1 V1718 USB Bridge

In the previous section, the data transfer as been discussed. The importance of the v1718 object (Source Code A.5), used as private member of DataReader, was not explicited. VME master modules are used for communication purposes as they host the USB port that connects the powered crate buffer to the computer were the DAQ is installed. From the source code point of view, this object is used to control the communication status, by reading the returned error codes with v1718::CheckStatus(), or to check for IRQs coming from the TDCs through v1718::CheckIRQ(). To ensure that triggers are blocked at the hardware level, a NIM pulse is sent out of one the two first programmable outputs of the module (v1718::SendBUSY()) to the VETO of the coincidence module where the trigger signals originate. As long as this signal is ON, no trigger can reach the TDCs anymore. Finally, used in the case of noise and background measurements in which the trigger needs not to be provided by the muon beam but by an uncorrelated source, a pulse generator is enabled with v1718::RDMTriggerPulse(). The “random” pulse is sent through the third and fourth outputs of the module. Both the BUSY signal and the random pulse are shaped in the method v1718::SetPulsers() where the number of pulses to be generated, their width, as well as the period of the pulse generator is defined.

5.2 Configuration file

The DAQ software takes as input a configuration file written using INI standard [304]. This file is partly filled with the information provided by the shifters when starting data acquisition using the webDCS, as shown by Figure A.6. This information is written in section [General] and will later
be stored in the ROOT file that contains the DAQ data as can be seen from Figure A.3. Indeed, another TTree called RunParameters as well as the 2 histograms ID, containing the scan number, start and stop time stamps, and Triggers, containing the number of triggers requested by the shifter, are available in the data files. Moreover, ScanID and HV are then used to construct the file name thanks to the method DataReader::GetFileName().

![WebDCS GIF++](image)

**Figure A.6:** WebDCS DAQ scan page. On this page, shifters need to choose the type of scan (Rate, Efficiency or Noise Reference scan), the gamma source configuration at the moment of data taking, the beam configuration, and the trigger mode. These information will be stored in the DAQ ROOT output. Are also given the minimal measurement time and waiting time after ramping up of the detectors is over before starting the data acquisition. Then, the list of HV points to scan and the number of triggers for each run of the scan are given in the table underneath.

The rest of the information is written beforehand in the configuration file template, as explicited in Source Code A.6 and contains the hardware addresses to the differents VME modules in the setup as well as settings for the TDCs. As the TDC settings available in the configuration file are not supposed to be modified, an improvement would be to remove them from the configuration file and to hardcode them inside of the DAQ code itself or to place them into a different INI file that would host only the TDC settings to lower the probability for a bad manipulation of the configuration file that can be modified from one of webDCS’ menus.
A DATA ACQUISITION SOFTWARE FOR VME CAEN TDCs

[General]
Tdc=4
ScanID=$scanid
HV=$HV
RunType=$runtype
MaxTriggers=$maxtriggers
Beam=$beam

[VMEInterface]
Type=V1718
BaseAddress=0xFF0000
Name=VmeInterface
int_trig_freq=100

[TDC0]
Type=V1190A
BaseAddress=0x00000000
Name=Tdc0
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1

[TDC1]
Type=V1190A
BaseAddress=0x11110000
Name=Tdc1
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1

[TDC2]
Type=V1190A
BaseAddress=0x22220000
Name=Tdc2
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1

[TDC3]
Type=V1190A
BaseAddress=0x44440000
Name=Tdc3
StatusA00-15=1
StatusA16-31=1
StatusB00-15=1
StatusB16-31=1
StatusC00-15=1
StatusC16-31=1
StatusD00-15=1
StatusD16-31=1

[TDCSettings]
TriggerExtraSearchMargin=0
TriggerRejectMargin=0
TriggerTimeSubstraction=0b1
TdcDetectionMode=0b01
TdcResolution=0b10
TdcDeadTime=0b00
TdcHeadTrailer=0b1
TdcEventSize=0b1001
TdcTestMode=0b0
BLTMode=1
Source Code A.6: INI configuration file template for 4 TDCs. In section [General], the number of TDCs is explicited and information about the ongoing run is given. Then, there are sections for each and every VME modules. There buffer addresses are given and for the TDCs, the list of channels to enable is given. Finally, in section [TDCSettings], a part of the TDC settings are given.

typedef map< const string, string > IniFileData;

class IniFile{
private:
    bool CheckIfComment(string line);
    bool CheckIfGroup(string line,string& group);
    bool CheckIfToken(string line,string& key,string& value);
    string FileName;
    IniFileData FileData;
    int Error;

public:
    IniFile();
    IniFile(string filename);
    virtual ~IniFile();

    // Basic file operations
    void SetFileName(string filename);
    int Read();
    int Write();
    IniFileData GetFileData();

    // Data readout methods
    Data32 addressType(string groupname,string keyname,Data32 defaultvalue);
    long intType(string groupname,string keyname,long defaultvalue);
    long long longType(string groupname,string keyname,long long defaultvalue);
    string stringType(string groupname,string keyname,string defaultvalue);
    float floatType(string groupname,string keyname,float defaultvalue);

    // Error methods
    string GetErrorMsg();
};

Source Code A.7: Description of C++ object IniFile used as a parser for INI file format.

In order to retrieve the information of the configuration file, the object IniFile has been developed to provide an INI parser, presented in Source Code A.7. It contains private methods returning a boolean to check the type of line written in the file, whether a comment, a group header or a key line (IniFile::CheckIfComment(), IniFile::CheckIfGroup() and IniFile::CheckIfToken()). The key may sometimes be referred to as token in the source code. Moreover, the private element FileData is a map of const string to string that allows to store the data contained inside the configuration file via the public method IniFile::GetFileData() following the formatting (see method IniFile::Read()):

string group, token, value;
// Get the field values for the 3 strings.
// Then concatenate group and token together as a single string
// with a dot separation.
token = group + "." + token;
FileData[token] = value;
More methods have been written to translate the different keys into the right variable format when used by the DAQ. For example, to get a float value out of the configuration file data, knowing the group and the key needed, the method `IniFile::floatType()` can be used. It takes 3 arguments being the group name and key name (both string), and a default float value used as exception in the case the expected combination of group and key cannot be found in the configuration file. This default value is then used and the DAQ continues on working after sending an alert in the log file for further debugging.

5.3 WebDCS/DAQ intercommunication

When shifters send instructions to the DAQ via the configuration file, it is the webDCS itself that gives the start command to the DAQ and then the 2 softwares use inter-process communication through file to synchronise themselves. This communication file is represented by the variable `const string __runstatuspath`.

On one side, the webDCS sends commands or status that are readout by the DAQ:

- INIT, status sent when launching a scan and read via function `CtrlRunStatus(...)`,
- START, command to start data taking and read via function `CheckSTART()`,
- STOP, command to stop data taking at the end of the scan and read via function `CheckSTOP()`, and
- KILL, command to kill data taking sent by user and read via function `CheckKILL()`. Note that the DAQ doesn’t stop before the current ROOT file is safely written and saved.

and on the other, the DAQ sends status that are controled by the webDCS:

- DAQ_RDY, sent with `SendDAQReady()` to signify that the DAQ is ready to receive commands from the webDCS,
- RUNNING, sent with `SendDAQRunning()` to signify that the DAQ is taking data,
- DAQ_ERR, sent with `SendDAQError()` to signify that the DAQ didn’t receive the expected command from the webDCS or that the launch command didn’t have the right number of arguments,
- RD_ERR, sent when the DAQ wasn’t able to read the communication file, and
- WR_ERR, sent when the DAQ wasn’t able to write into the communication file.

5.4 Example of inter-process communication cycle

Under normal conditions, the webDCS and the DAQ processes exchange commands and status via the file hosted at the address `__runstatuspath`, as explained in subsection 5.3. An example of cycle is given in Table A.1. In this example, the steps 3 to 5 are repeated as long as the webDCS tells the DAQ to take data. A data taking cycle is the equivalent as what is called a Scan in GIF++ jargon, referring to a set a runs with several HV steps. Each repetition of steps 3 to 5 is then equivalent to a single Run.

At any moment during the data taking, for any reason, the shifter can decide that the data taking needs to be stopped before it reached the end of the scheduled cycle. Thus at any moment on the cycle, the content of the inter-process communication file will be changed to KILL and the DAQ will
shut down right away. The DAQ checks for KILL signals every 5s after the TDCs configuration is over. So far, the function CheckKILL() has been used only inside of the data taking loop of method DataReader::Run() and thus, if the shifter decides to KILL the data taking during the TDC configuration phase or the HV ramping in between 2 HV steps, the DAQ will not be stopped smoothly and a force kill command will be sent to stop the DAQ process that is still awake on the computer. Improvements can be brought on this part of the software to make sure that the DAQ can safely shutdown at any moment.

<table>
<thead>
<tr>
<th>step</th>
<th>actions of webDCS</th>
<th>status of DAQ</th>
<th>__runstatuspath</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>launch DAQ ramp voltages ramping over</td>
<td>readout of IniFile configuration of TDCs</td>
<td>INIT</td>
</tr>
<tr>
<td></td>
<td>wait for currents stabilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>configuration done send DAQ ready wait for START signal</td>
<td></td>
<td>DAQ_RDY</td>
</tr>
<tr>
<td>3</td>
<td>waiting time over</td>
<td></td>
<td>START</td>
</tr>
<tr>
<td></td>
<td>send START</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>wait for run to end monitor DAQ run status</td>
<td>data taking ongoing check for KILL signal</td>
<td>RUNNING</td>
</tr>
<tr>
<td>5</td>
<td>run over send DAQ_RDY wait for next DCS signal</td>
<td></td>
<td>DAQ_RDY</td>
</tr>
<tr>
<td>6</td>
<td>ramp voltages ramping over</td>
<td></td>
<td>DAQ_RDY</td>
</tr>
<tr>
<td></td>
<td>wait for currents stabilization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>waiting time over</td>
<td></td>
<td>START</td>
</tr>
<tr>
<td></td>
<td>send START</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>wait for run to end monitor DAQ run status</td>
<td>update IniFile information data taking ongoing check for KILL signal</td>
<td>RUNNING</td>
</tr>
<tr>
<td>5</td>
<td>run over send DAQ_RDY wait for next DCS signal</td>
<td></td>
<td>DAQ_RDY</td>
</tr>
<tr>
<td>7</td>
<td>send command STOP</td>
<td>DAQ shuts down</td>
<td>STOP</td>
</tr>
</tbody>
</table>

Table A.1: Inter-process communication cycles in between the webDCS and the DAQ through file string signals.

### 6 Software export

In section 2 was discussed the fact that the DAQ as written in its last version is not a standalone software. It is possible to make it a standalone program that could be adapted to any VME setup using V1190A and V1718 modules by creating a GUI for the software or by printing the log messages that are normally printed in the webDCS through the log file, directly into the terminal. This method was used by the DAQ up to version 3.0 moment where the webDCS was completed. Also, it is possible to check branches of DAQ v2.X to have example of communication through a terminal. DAQ v2.X is nonetheless limited in it’s possibilities and requires a lot of offline manual interventions from the users. Indeed, there is no communication of the software with the detectors’ power...
A data acquisition software for VME CAEN TDCs

A supply system that would allow for a user to predefine a list of voltages to operate the detectors at and loop over to take data without any further manual intervention. In v2.X, the data is taken for a single detector setting and at the end of each run, the software asks the user if he intends on taking more runs. If so, the software invites the user to set the operating voltages accordingly to what is necessary and to manually update the configuration file in consequence. This working mode can be a very first approach before an evolution and has been successfully used by colleagues from different collaborations.

For a more robust operation, it is recommended to develop a GUI or a web application to interface the DAQ. Moreover, to limit the amount of manual interventions, and thus the probability to make mistakes, it is also recommended to add an extra feature into the DAQ by installing the [HV Wrapper library](https://github.com/UGent/TinyDAQ) provided by CAEN of which an example of use in a similar DAQ software developed by a master student of UGent, and called [TinyDAQ](https://github.com/UGent/TinyDAQ), is provided on UGent’s github. Then, this HV Wrapper will help you communicating with and give instructions to a CAEN HV powered crate and can be added into the DAQ at the same level where the communication with the user was made in DAQ v2.X. In case you are using another kind of power system for your detectors, it is strongly advised to use HV modules or crates that can be remotely controlled via a using C++ libraries.
Details on the offline analysis package

The data collected in GIF++ thanks to the DAQ described in Appendix A is difficult to interpret by a human user that doesn’t have a clear idea of the raw data architecture of the ROOT data files. In order to render the data human readable, a C++ offline analysis tool was designed to provide users with detector by detector histograms that give a clear overview of the parameters monitored during the data acquisition [288]. In this appendix, details about this software in the context of GIF++, as of how the software was written and how it functions will be given.

1 GIF++ Offline Analysis file tree

GIF++ Offline Analysis source code is fully available on github at https://github.com/afagot/GIF_OfflineAnalysis. The software requires ROOT as non-optionnal dependency as it takes ROOT files in input and write an output ROOT file containing histograms. To compile the GIF++ Offline Analysis project is compiled with cmake. To compile, first a build directory must be created to compile from there:

```
mkdir build
cd build
make
make install
```

To clean the directory and create a new build directory, the bash script cleandir.sh can be used:

```
./cleandir.sh
```

The source code tree is provided below along with comments to give an overview of the files’ content. The different objects created for this project (Infrastructure, Trolley, RPC, Mapping, RPCHit, RPCCluster and Inifile) will be described in details in the following sections.
2 Usage of the Offline Analysis

In order to use the Offline Analysis tool, it is necessary to know the Scan number and the HV Step of the run that needs to be analysed. This information needs to be written in the following format:

```
Scan00XXXX_HVy
```

where `XXXX` is the scan ID and `HV` is the high voltage step (in case of a high voltage scan, data will be taken for several HV steps). This format corresponds to the base name of data files in the database of the GIF++ webDCS. Usually, the offline analysis tool is automatically called by the webDCS at the end of data taking or by a user from the webDCS panel if an update of the tool was brought. Nonetheless, an expert can locally launch the analysis for tests on the GIF++ computer, or a user can
get the code on is local machine from github and download data from the webDCS for is own analysis. To launch the code, the following command can be used from the GIF_OfflineAnalysis folder:

```bash
bin/offlineanalysis /path/to/Scan00XXXX_HVY
```

where, /path/to/Scan00XXXX_HVY refers to the local data files. Then, the offline tool will by itself take care of finding all available ROOT data files present in the folder, as listed bellow:

- `Scan00XXXX_HVY_DAQ.root` containing the TDC data as described in Appendix 4.2 (events, hit and timestamp lists), and
- `Scan00XXXX_HVY_CAEN.root` containing the CAEN mainframe data recorded by the monitoring tool webDCS during data taking (HVVs and currents of every HV channels). This file is created independently of the DAQ.

### 2.1 Output of the offline tool

#### 2.1.1 ROOT file

The analysis gives in output ROOT datafiles that are saved into the data folder and called using the naming convention `Scan00XXXX_HVY_Offline.root`. Inside those, a list of TH1 histograms can be found. Its size will vary as a function of the number of detectors in the setup as each set of histograms is produced detector by detector. For each partition of each chamber, can be found:

- `Time_Profile_Tt_Sc_p` shows the time profile of all recorded events (number of events per time bin),
- `Hit_Profile_Tt_Sc_p` shows the hit profile of all recorded events (number of events per channel),
- `HitMultiplicity_Tt_Sc_p` shows the hit multiplicity (number of hits per event) of all recorded events (number of occurrences per multiplicity bin),
- `Time_vs_Strip_Profile_Tt_Sc_p` shows the 2D time vs strip profile of all recorded events (number of events per time bin per strip),
- `Strip_Mean_Noise_Tt_Sc_p` shows noise/gamma rate per unit area for each strip in a selected time range. After filters are applied on `Time_Profile_Tt_Sc_p`, the filtered version of `Hit_Profile_Tt_Sc_p` is normalised to the total integrated time and active detection area of a single channel,
- `Strip_Activity_Tt_Sc_p` shows noise/gamma activity for each strip (normalised version of previous histogram - strip activity = strip rate / average partition rate),
- `Strip_Homogeneity_Tt_Sc_p` shows the homogeneity of a given partition (homogeneity = exp(-strip rates standard deviation(strip rates in partition/average partition rate)) ),
- `mask_Strip_Mean_Noise_Tt_Sc_p` shows noise/gamma rate per unit area for each masked strip in a selected time range. Offline, the user can control the noise/gamma rate and decide to mask the strips that are judged to be noisy or dead. This is done via the Masking Tool provided by the webDCS,
- `mask_Strip_Activity_Tt_Sc_p` shows noise/gamma activity per unit area for each masked strip with respect to the average rate of active strips,
● NoiseCSize_H_Tt_Sc_p shows noise/gamma cluster size, a cluster being constructed out of adjacent strips giving a signal at the same time (hits within a time window of 25 ns),

● NoiseCMult_H_Tt_Sc_p shows noise/gamma cluster multiplicity (number of reconstructed clusters per event),

● Chip_Mean_Noise_Tt_Sc_p shows the same information than Strip_Mean_Noise_Tt_Scp using a different binning (1 chip corresponds to 8 strips),

● Chip_Activity_Tt_Sc_p shows the same information than Strip_Activity_Tt_Scp using chip binning,

● Chip_Homogeneity_Tt_Sc_p shows the homogeneity of a given partition using chip binning,

● Beam PROFILE_Tt_Sc_p shows the estimated beam profile when taking efficiency scan. This is obtained by filtering Time PROFILE_Tt_Sc_p to only consider the muon peak where the noise/gamma background has been subtracted. The resulting hit profile corresponds to the beam profile on the detector channels,

● Efficiency_Fake_Tt_Ss_p shows the efficiency given by fake hits by probing outside the peak in an uncorrelated window as wide as the peak window,

● Efficiency_Peak_Tt_Ss_p shows the efficiency given by hits contained in the peak window,

● PeakCSize_H_Tt_Sc_p shows the cluster size that was estimated using all the hits in the peak window,

● PeakCMult_H_Tt_Sc_p shows the cluster multiplicity that was estimated using all the hits in the peak window,

● L0_Efficiency_Tt_Sc_p shows the level 0 muon efficiency that was estimated without muon tracking after correction,

● MuonCSize_H_Tt_Sc_p shows the level 0 muon cluster size that was estimated without muon tracking after correction, and

● MuonCMult_H_Tt_Sc_p shows the level 0 muon cluster multiplicity that was estimated without muon tracking after correction.

In the histogram labels, \( t \) stands for the trolley number (1 or 3), \( c \) for the chamber slot label in trolley \( t \) and \( p \) for the partition label (A, B, C or D depending on the chamber layout) as explained in Chapter 5.3.

In the context of GIF++, an extra script called by the webDCS is called to extract the histograms from the ROOT files. The histograms are then stored in PNG and PDF formats into the corresponding folder (a single folder per HV step, so per ROOT file). An example of histogram organisation is given below for a hypothetical scan 001000 with at least 3 HV steps and whose chamber located in slot 1 of trolley 1 is called Example_RPC1 and has at least 2 read-out partitions A and B. The goal is to then display the histograms graphs on the Data Quality Monitoring (DQM) page of the webDCS, as presented in Figure 5.31, in order for the users to control the quality of the data taking at the end of data taking.

Scan001000
_  Scan001000_HV1_DAQ.root
2.1.2 CSV files

Moreover, up to 4 CSV files can be created depending on which ones of the 3 input files were in the data folder:

- **Offline-Corrupted.csv**, is used to keep track of the amount of data that was corrupted and removed from old data format files that don’t contain any data quality flag.

- **Offline-Current.csv** contains the summary of the currents and voltages applied on each RPC HV channel.

- **Offline-L0-EffCl.csv**, is used to write the efficiencies, cluster size and cluster multiplicity of efficiency runs. Note that \(L0\) refers here to *Level 0* and means that the results of efficiency and clusterization are a first approximation calculated without performing any muon tracking in between the different detectors. This offline tool provides the user with a preliminar calculation of the efficiency and of the muon event parameters. Another analysis software especially dedicated to muon tracking is called on selected data to retrieve the results of efficiency and muon clusterization using a tracking algorithm to discriminate noise or gamma from muons as muons are the only particles that pass through the full setup, leaving hits than can be used to reconstruct their tracks.

- **Offline-Rate.csv**, is used to write the noise or gamma rates measured in the detector readout partitions.
Note that these 4 CSV files are created along with their headers (Offline- [...]-Header.csv containing the names of each data columns) and are automatically merged together when the offline analysis tool is called from the webDCS, contrary to the case where the tool is runned locally from the terminal as the merging bash script is then not called. Thus, the resulting files, used to make official plots, are:

- Corrupted.csv,
- Current.csv,
- L0-EffCl.csv.
- Rate.csv.

3 Analysis inputs and information handling

The usage of the Offline Analysis tool as well as its output have been presented in the previous section. It is now important to dig further and start looking at the source code and the inputs necessary for the tool to work. Indeed, other than the raw ROOT data files that are analysed, more information needs to be imported inside of the program to perform the analysis such as the description of the setup inside of GIF++ at the time of data taking (number of trolleys, of RPCs, dimensions of the detectors, etc...) or the mapping that links the TDC channels to the corresponding RPC channels in order to translate the TDC information into human readable data. Two files are used to transmit all this information:

- Dimensions.ini, that provides the necessary setup and RPC information, and
- ChannelsMapping.csv, that gives the link between the TDC and RPC channels as well as the mask for each channel (masked or not?).

3.1 Dimensions file and IniFile parser

GIF++ CMS RPC setup consists in detectors held into trolleys inside of the GIF++ bunker. Each of these detector may have a read-out segmented to cover different pseudo-rapidity range once installed in CMS. The segmentation of the read-out is referred to as ”partitions”. This input file, present in every data folder, allows the analysis tool to know of the number of active trolleys, the number of active RPCs in those trolleys, and the details about each RPCs such as the number of RPC gaps, the number of pseudo-rapidity partitions, the number of strips per partition or the dimensions. To do so, there are 3 types of groups in the INI file architecture. Groups are sections of the INI file content starting with a title encapsulated in between square brackets. A first general group, appearing only once at the head of the document, gives information about the number of active trolleys as well as their IDs, as presented in Source Code [B.1]. For each active trolley, a group similar to Source Code [B.2] can be found containing information about the number of active detectors in the trolley and their IDs. Each trolley group as a \( T_t \) name format, where \( t \) is the trolley ID. Finally, for each detector stored in slots of an active trolley, there is a group providing information about their names and dimensions, as shown in Source Code [B.3]. Each slot group as a \( T_t S_s \) name format, where \( s \) is the slot ID of trolley \( t \) where the active RPC is hosted.

```
[General]
nTrolleys=2
TrolleysID=13
```
Source Code B.1: Example of \texttt{[General]} group as might be found in Dimensions.ini. In GIF++, only 2 trolleys are available to hold RPCs and place them inside of the bunker for irradiation. The IDs of the trolleys are written in a signle string as "13" and then read character by character by the program.

\begin{verbatim}
[T1]
nSlots=4
SlotsID=1234
\end{verbatim}

Source Code B.2: Example of trolley group as might be found in Dimensions.ini. In this example, the file tells that there are 4 detectors placed in the holding slots of the trolley \texttt{T1} and that their IDs, written as a single string variable, are 1, 2, 3 and 4.

\begin{verbatim}
[T1S1]
Name=RE2-2-NPD-BARC-8
Partitions=3
Gaps=3
Gap1=BOT
Gap2=TN
Gap3=TW
AreaGap1=11694.25
AreaGap2=6432
AreaGap3=4582.82
Strips=32
ActiveArea-A=157.8
ActiveArea-B=121.69
ActiveArea-C=93.03
\end{verbatim}

Source Code B.3: Example of slot group as might be found in Dimensions.ini. In this example, the file provides information about a detector named \texttt{RE2-2-NPD-BARC-8}, having 3 pseudo-rapidity readout partitions and stored in slot \texttt{S1} of trolley \texttt{T1}. This is a CMS RE2-2 type of detector. This information will then be used for example to compute the rate per unit area calculation.

This information is read-out and stored in a C++ object called \texttt{IniFile}, that parses the information of the INI input file and stores it into a local buffer for later use. This INI parser is the exact same one that was previously developped for the GIF++ DAQ and described in Appendix 5.2.

3.2 TDC to RPC link file and Mapping

The same way the INI dimension file information is stored using \texttt{map}, the channel mapping and mask information making the link in between TDC channels and RPC strips is stored and accessed through \texttt{map}. First of all, the mapping CSV file is organised into 3 columns separated by tabulations:

\begin{verbatim}
RPC_channel  TDC_channel  mask
\end{verbatim}

using as formatting for each field:

\begin{verbatim}
TSCCC  TCCC  M
\end{verbatim}

\texttt{TSCCC} is a 5-digit integer where \texttt{T} is the trolley ID, \texttt{S} the slot ID in which the RPC is held inside the trolley \texttt{T} and \texttt{CCC} is the RPC channel number, or \texttt{strip} number, that can take values up to 3-digits depending on the detector,

\texttt{TCCC} is a 4 digit integer where \texttt{T} is the TDC ID to which the RPC is connected, \texttt{CCC} is the TDC channel number linked to the RPC strip that can take values in between 0 and 127, and
\( M \) is a 1-digit integer indicating if the channel should be considered \((M = 1)\) or discarded \((M = 0)\) during analysis. Note that the absence of a third column is interpreted by the mapping file parser as \( M = 1 \) by default.

This mapping and masking information is readout and stored thanks to the object `Mapping` presented in Source Code B.4. Similarly to `IniFile` objects, this class has private methods to provide with parser rules. The first one, `Mapping::CheckIfNewLine()` is used to find the newline character \('\n'\) or return character \('\r'\) (depending on which kind of operating system interacted with the file). Finding and identifying a newline or return character is used for the simple reason that the masking information has been introduced only during the year 2017 but the channel mapping files exist since 2015 and the very beginning of data taking at GIF++. This means that in the older data folders, before the upgrade, the channel mapping file only had 2 columns, the RPC channel and the TDC channel. For compatibility reasons, this method helps controlling the character following the readout of the 2 first fields of a line. In case any end of line character is found, no mask information is present in the file and the default \( M = 1 \) is used. On the contrary, if the next character was a tabulation or a space, the mask information is present.

Once the 3 fields have been readout, the second private method `Mapping::CheckIfTDCCh()` is used to control that the TDC channel is an existing TDC channel by checking its format. Finally, the information is stored into 3 different maps (`Link`, `ReverseLink` and `Mask`) thanks to the public method `Mapping::Read()`. `Link` allows to get the RPC channel by knowing the TDC channel while `ReverseLink` does the opposite by returning the TDC channel by knowing the RPC channel. Finally, `Mask` returns the mask associated to a given RPC channel.

```cpp
typedef map<Uint,Uint> MappingData;

class Mapping {
private:
    bool CheckIfNewLine(char next);
    bool CheckIfTDCCh(Uint channel);
    string FileName;
    MappingData Link;
    MappingData ReverseLink;
    MappingData Mask;
    int Error;

public:
    Mapping();
    Mapping(string baseName);
    Mapping();
    void SetFileName(const string filename);
    int Read();
    Uint GetLink(Uint tdcchannel);
    Uint GetReverse(Uint rpcchannel);
    Uint GetMask(Uint rpcchannel);
};
```

Source Code B.4: Description of C++ object `Mapping` used as a parser for the channel mapping and mask file.

## 4 Description of GIF++ setup within the Offline Analysis tool

In the previous section, the tool input files have been discussed. The dimension file information is stored in a map hosted by the `IniFile` object. But this information is then used to create a series of
new objects that helps defining the GIF++ infrastructure directly into the Offline Analysis. Indeed, from the RPC, to the more general Infrastructure, every element of the GIF++ infrastructure is recreated for each data analysis based on the information provided in input. All this information about the infrastructure will be used to assign each hit signal to a specific strip channel of a specific detector, and having a specific active area. This way, rate per unit area calculation is possible.

4.1 RPC objects

RPC objects have been developped to represent physical active detectors in GIF++ at the moment of data taking. Thus, there are as many RPC objects created during the analysis than there were active RPCs tested during a run. Each RPC hosts the information present in the corresponding INI slot group, as showed in B.3, and organises it using a similar architecture. This can been seen from Source Code B.5.

To make the object more compact, the lists of gap labels, of gap active areas and strip active areas are stored into vector dynamical containers. RPC objects are always contracted thanks to the dimension file information stored into the IniFile and their ID, using the format TtSs. Using the RPC ID, the constructor calls the methods of IniFile to initialise the RPC. The other constructors are not used but exist in case of need. Finally, some getters have been written to access the different private parameters storing the detector information.

4.2 Trolley objects

Trolley objects have been developped to represent physical active trolleys in GIF++ at the moment of data taking. Thus, there are as many trolley objects created during the analysis than there were active trolleys hosting RPCs under test during a run. Each Trolley hosts the information present in the corresponding INI trolley group, as shown in B.2, and organises it using a similar architecture. In addition to the information hosted in the INI file, these objects have a dynamical container of RPC objects, representing the active detectors the active trolley was hosting at the time of data taking. This can been seen from Source Code B.6.

Trolley objects are always constructed thanks to the dimension file information stored into the IniFile and their ID, using the format Tt. Using the Trolley ID, the constructor calls the methods of IniFile to initialise the Trolley. Retrieving the information of the RPC IDs via SlotsID, a new RPC is constructed and added to the container RPCs for each character in the ID string. The other constructors are not used but exist in case of need. Finally, some getters have been written to access the different private parameters storing the trolley and detectors information.

4.3 Infrastructure object

The Infrastructure object has been developped to represent the GIF++ bunker area dedicated to CMS RPC experiments. With this very specific object, all the information about the CMS RPC setup within GIF++ at the moment of data taking is stored. It hosts the information present in the corresponding INI general group, as showed in B.1, and organises it using a similar architecture. In addition to the information hosted in the INI file, this object have a dynamical container of Trolley objects representing the active trolleys in GIF++ area, themselves containing RPC objects. This can been seen from Source Code B.7.

The Infrastructure object is always constructed thanks to the dimension file information stored into the IniFile. Retrieving the information of the trolley IDs via TrolleysID, a new Trolley is
constructed and added to the container Trolleys for each character in the ID string. By extension, it is easy to understand that the process described in Section 4.2 for the construction of RPCs takes place when a trolley is constructed. The other constructors are not used but exist in case of need. Finally, some getters have been written to access the different private parameters storing the infrastructure, trolleys and detectors information.

```cpp
class RPC {

private:
    string name; // RPC name as in webDCS database
    Uint nGaps; // Number of gaps in the RPC
    Uint nPartitions; // Number of partitions in the RPC
    Uint nStrips; // Number of strips per partition
    vector<string> gaps; // List of gap labels (BOT, TOP, etc...)
    vector<float> gapGeo; // List of gap active areas
    vector<float> stripGeo; // List of strip active areas

public:
    RPC();
    RPC(string ID, IniFile* geofile);
    RPC(const RPC& other);
    ~RPC();
    RPC& operator=(const RPC& other);

    string GetName();
    Uint GetNGaps();
    Uint GetNPartitions();
    Uint GetNStrips();
    string GetGap(Uint g);
    float GetGapGeo(Uint g);
    float GetStripGeo(Uint p);
};
```

Source Code B.5: Description of C++ objects RPC that describe each active detectors used during data taking.
class Trolley{
    private:
    Uint nSlots; // Number of active RPCs in the considered trolley
    string SlotsID; // Active RPC IDs written into a string
    vector<RPC*> RPCs; // List of active RPCs

    public:
    Trolley();
    Trolley(string ID, IniFile* geofile);
    Trolley(const Trolley& other);
    ~Trolley();
    Trolley& operator=(const Trolley& other);

    Uint GetNSlots();
    string GetSlotsID();
    Uint GetSlotID(Uint s);
    RPC* GetRPC(Uint r);
    void DeleteRPC(Uint r);

    // Methods to get members of RPC objects stored in RPCs
    string GetName(Uint r);
    Uint GetNGaps(Uint r);
    Uint GetNPartitions(Uint r);
    Uint GetNStrips(Uint r);
    string GetGap(Uint r, Uint g);
    float GetGapGeo(Uint r, Uint g);
    float GetStripGeo(Uint r, Uint p);
};

Source Code B.6: Description of C++ objects Trolley that describe each active trolley used during data taking.
class Infrastructure {
    private:
    Uint nTrolleys;  //Number of active Trolleys in the run
    string TrolleysID;  //Active trolley IDs written into a string
    vector<Trolley*> Trolleys;  //List of active Trolleys (struct)

    public:
    Infrastructure();
    Infrastructure(IniFile* geofile);
    Infrastructure(const Infrastructure& other);
    ~Infrastructure();
    Infrastructure& operator=(const Infrastructure& other);
    Uint GetNTrolleys();
    string GetTrolleysID();
    Uint GetTrolleyID(Uint t);
    Trolley* GetTrolley(Uint t);
    void DeleteTrolley(Uint t);  //Methods to get members of GIFTrolley objects stored in Trolleys
    Uint GetNSlots(Uint t);
    string GetSlotsID(Uint t);
    Uint GetSlotID(Uint t, Uint s);
    RPC* GetRPC(Uint t, Uint r);  //Methods to get members of RPC objects stored in RPCs
    string GetName(Uint t, Uint r);
    Uint GetNGaps(Uint t, Uint r);
    Uint GetNPartitions(Uint t, Uint r);
    Uint GetNstrips(Uint t, Uint r);
    string GetGap(Uint t, Uint r, Uint g);
    float GetGapGeo(Uint t, Uint r, Uint g);
    float GetStripGeo(Uint t, Uint r, Uint p);
};

Source Code B.7: Description of C++ object Infrastructure that contains the full information about CMS RPC experiment in GIF++.

5 Handeling of data

As discussed in Appendix 4.2, the raw data uses a TTree architecture where every entry is related to a trigger signal provided by a muon or a random pulse, whether the goal of the data taking was to measure the performance of the detector or the noise/gamma background respectively. Each of these entries, referred also as events, contain a more or less full list of hits in the TDC channels to which the detectors are connected. To this list of hits corresponds a list of time stamps, marking the arrival of the hits within the TDC channel.

The infrastructure of the CMS RPC experiment within GIF++ being defined, combining the raw data information with the information provided by both the mapping/mask file and the dimension file allows to build new physical objects that will help in computing efficiency or rates.
5.1 RPC hits

The raw data stored in the ROOT file as output of the GIF++ DAQ, is readout by the analysis tool using the structure \texttt{RAWData} presented in Source Code B.9 that differs from the structure presented in Appendix 4.2 as it is not meant to hold all of the data contained in the ROOT file. In this sense, this structure is in the case of the offline analysis tool not a dynamical object and will only be storing a single event contained in a single entry of the \texttt{TTree}.

\begin{verbatim}
class RPCHit {
  private:
    Uint Channel; //RPC channel according to mapping (5 digits)
    Uint Trolley; //0, 1 or 3 (1st digit of the RPC channel)
    Uint Station; //Slot where is held the RPC in Trolley (2nd digit)
    Uint Strip; //RPC strip where the hit occurred (last 3 digits)
    Uint Partition; //Readout partition along eta segmentation
    float TimeStamp; //Time stamp of the arrival in TDC
  public:
    RPCHit();
    RPCHit(Uint channel, float time, Infrastructure* Infra);
    RPCHit(const RPCHit& other);
    ~RPCHit();
    RPCHit& operator=(const RPCHit& other);
    Uint GetChannel();
    Uint GetTrolley();
    Uint GetStation();
    Uint GetStrip();
    Uint GetPartition();
    float GetTime();
};

typedef vector<RPCHit> HitList;

typedef struct GIFHitList {HitList rpc[NTROLLEYS][NSLOTS][NPARTITIONS];} GIFHitList;

bool SortHitbyStrip(RPCHit h1, RPCHit h2);
bool SortHitbyTime(RPCHit h1, RPCHit h2);
\end{verbatim}

Source Code B.8: Description of C++ object \texttt{RPCHit}.

\begin{verbatim}
struct RAWData{
  int iEvent; //Event i
  int TDCNHits; //Number of hits in event i
  int QFlag; //Quality flag list (1 flag digit per TDC)
  vector<Uint> *TDCCh; //List of channels giving hits per event
  vector<float> *TDCTS; //List of the corresponding time stamps
};
\end{verbatim}

Source Code B.9: Description of C++ structure \texttt{RAWData}.

Each member of the structure is then linked to the corresponding branch of the ROOT data tree, as shown in the example of Source Code B.10 and using the method \texttt{GetEntry(int i)} of the ROOT class \texttt{TTree} will update the state of the members of \texttt{RAWData}.

The data is then analysed entry by entry and to each element of the TDC channel list, a \texttt{RPCHit} is constructed by linking each TDC channel to the corresponding RPC channel thanks to the Mapping object. The information carried by the RPC channel format allows to easily retrieve the trolley and
slot from which the hit was recorded (see section 3.2). Using these 2 values, the readout partition can be found by knowing the strip channel and comparing it with the number of partitions and strips per partition stored into the Infrastructure object.

```cpp
tree dataTree = (tree*)dataFile.Get("RAWData");
RAWData data;
dataTree->SetBranchAddress("EventNumber", &data.iEvent);
dataTree->SetBranchAddress("number_of_hits", &data.TDCNHits);
dataTree->SetBranchAddress("Quality_flag", &data.QFlag);
dataTree->SetBranchAddress("TDC_channel", &data.TDCCh);
dataTree->SetBranchAddress("TDC_TimeStamp", &data.TDCTS);
```

Source Code B.10: Example of link in between RAWData and TTree.

Thus RPCHit objects are then stored into 3D dynamical list called GIFHitList (Source Code B.8) where the 3 dimensions refer to the 3 layers of the readout in GIF++: in the bunker there are trolleys (T) holding detectors in slots (S) and each detector readout is divided into 1 or more pseudo-rapidity partitions (p). Using these 3 information allows to assign an address to each readout partition and this address will point to a specific hit list.

### 5.2 Clusters of hits

All the hits contained in the ROOT file have been sorted into the different hit lists through the GIFHitList. At this point, it is possible to start looking for clusters. A cluster is a group of adjacent strips getting hits within a time window of 25 ns. These strips are then assumed to be part of the same physical avalanche signal generated by a muon passing through the chamber or by the interaction of a gamma stopping into the electrodes of the RPCs.

To keep the cluster information, RPCCluster objects have been defined as shown in Source Code B.11. Using the information of each individual RPCHit taken out of the hit list, it stores the cluster size (number of adjacent strips composing the cluster), the first and last hit, the center for spatial reconstruction and finally the start and stop time stamps as well as the time spread in between the first and last hit.

To investigate the hit list of a given detector partition, the function Clusterization() defined in include/Cluster.h needs the hits in the list to be time sorted. This is achieved by calling function sort() of library <algorithm> using the comparator SortHitbyTime(RPCHit h1, RPCHit h2) defined in include/RPCHit.h that returns true if the time stamp of hit h1 is lower than that of h2. A first isolation of strips is made only based on time information. All the hits within the 25 ns window are taken separately from the rest. Then, this sub-list of hits is sorted this time by ascending strip number, using this time the comparator SortHitbyStrip(RPCHit h1, RPCHit h2). Finally, the groups of adjacent strips are used to construct RPCCluster objects that are then stored in a temporary list of clusters that is at the end of the process used to know how many clusters were reconstructed and to fill their sizes into an histogram that will allow to know the mean size of muon or gamma clusters. This method to group hits together into clusters is limited as no systematic study of the average avalanche time development into TDC hits was performed and that there is no correlation of both spatial and time information to make the first selection of hits. Due to this, two clusters developing consecutively next to each other during a total time longer to 25 ns could be wrongly grouped as a cluster composed of the first developed cluster plus a part of the second cluster while the rest of the second cluster would be placed in a second truncated cluster. This kind of event
is not likely but needs to be taken into account nonetheless. A possible improvement would be to identify clusters in a 2D space whose dimensions are time and strip. In this 2D space, the cluster could be geometrically identified as isolated groups of adjacent strips receiving a hit at a similar time.

```cpp
class RPCCluster {
private:
    Uint ClusterSize;  // Size of cluster #ID
    Uint FirstStrip;   // First strip of cluster #ID
    Uint LastStrip;    // Last strip of cluster #ID
    float Center;      // Center of cluster #ID \((first+last)/2\)
    float StartStamp;  // Time stamp of the earliest hit of cluster #ID
    float StopStamp;   // Time stamp of the latest hit of cluster #ID
    float TimeSpread;  // Time difference between earliest and latest hits of cluster #ID
public:
    RPCCluster();
    RPCCluster(HitList List, Uint cID, Uint cSize, Uint first, Uint firstID);
    RPCCluster(const RPCCluster& other);
    ~RPCCluster();
    RPCCluster& operator=(const RPCCluster& other);
    Uint GetID();
    Uint GetSize();
    Uint GetFirstStrip();
    Uint GetLastStrip();
    float GetCenter();
    float GetStart();
    float GetStop();
    float GetSpread();
};

typedef vector<RPCCluster> ClusterList;

// Other functions to build cluster lists out of hit lists
void BuildClusters(HitList &cluster, ClusterList &clusterList);
void Clusterization(HitList &hits, TH1 *hcSize, TH1 *hcMult);
```


6 DAQ data Analysis

All the ingredients to analyse GIF++ data have been introduced. This section will focus on the different part of the analysis performed on the data, from determining the type of data the tool is dealing with to calculate the hit and cluster rate per unit area in each detector or reconstructing muon or gamma clusters.

6.1 Determination of the run type

In GIF++, both the performance of the detectors in detecting muons in an irradiated environment and the gamma or noise background can be independently measured. These correspond to different run types and hence, to different TDC settings giving different data to look at.

In the case of performance measurements, the trigger for data taking is provided by the coincidence of several scintillators when muons from the beam passing through the area are detected. Data is collected in a 600 ns wide window centered around the arrival of muons in the RPCs.
expected time distribution of hits is shown in Figure B.1a. The muon peak is clearly visible in the center of the distribution and is to be extracted from the gamma background that composes the flat part of the distribution.

On the other hand, gamma background or noise measurements are focussed on the non muon related physics and the trigger needs to be independent from the muons to give a good measurement of the gamma/noise distribution as seen by the detectors. The trigger is then provided by a pulse generated by the DAQ at a frequency of 100 Hz whose pulse is not likely to be on time with a muon. In order to increase the integrated time without increasing proportionally the acquisition time, the width of the acquisition windows are increased to 10 µs. The time distribution of the hits is expected to be flat, as shown by Figure B.1b.

![Figure B.1: Example of expected hit time distributions in the cases of efficiency (a) and noise/gamma rate per unit area (b) measurements as extracted from the raw ROOT files. The unit along the x-axis corresponds to ns. The fact that “the” muon peak is not well defined in Figure (a) is due to the contribution of all the RPCs being tested at the same time that don’t necessarily have the same signal arrival time. Each individual peak can have an offset with the ones of other detectors. The inconsistency in the first 100 ns of both time distributions is an artefact of the TDCs and are systematically rejected during the analysis.](image)

The ROOT files include a TTree called RunParameters containing, among other things, the information related to the run type. The run type can then be accessed as described by Source Code B.12 and the function IsEfficiencyRun() is then used to determine if the run file is an efficiency run or, on the contrary, another type of run (noise or gamma measurement).

Finally, the data files will have a slightly different content whether it was collected before or after October 2017 and the upgrade of the DAQ software that brought a new information into the ROOT output. This is discussed in Appendix 4.3 and implies that the analysis will differ a little depending on the data format. Indeed, as no information on the data quality is stored, in older data files, the corrections for missing events has to be done at the end of the analysis. The information about the type of data format is stored in the variable bool isNewFormat by checking the list of branches contained in the data tree via the methods TTree::GetListOfBranches() and TCollection::Contains().

Source Code B.12: Access to the run type contained in TTree* RunParameters.
6.2 Beam time window calculation for efficiency runs

Knowing the run type is important first of all to know the width of the acquisition window to be used for the rate calculation and finally to be able to seek for muons. Indeed, the peak that appears in the time distribution for each detectors is then fitted to extract the most probable time window in which the tool should look for muon hits. The data outside of this time window in then used to evaluate the noise or gamma background the detector was subjected to during the data taking. Computing the position of the peak is done calling the function `SetBeamWindow()` defined in file `src/RPCHit.cc` that loops a first time on the data. The data is first sorted in a 3D array of 1D histograms (`GIFH1Array`, see `include/types.h`). Then the location of the highest bin is determined using `TH1::GetMaximumBin()` and is used to define a window in which a gaussian fit will be applied to compute the peak width. This window is a 80 ns defined by Formula B.1 around the central bin.

(B.1a) \[ t_{\text{center}}(\text{ns}) = \text{bin} \times \text{width}_{\text{bin}}(\text{ns}) \]
(B.1b) \[ [t_{\text{low}}; t_{\text{high}}] = [t_{\text{center}} - 40; t_{\text{center}} + 40] \]

Before the fit is performed, the average number of noise/gamma hits per bin is evaluated using the data outside of the fit window. Excluding the first 100 ns, the average number of hits per bin due to the noise or gamma is defined by Formula B.2 after extracting the amount of hits in the time windows \([100; t_{\text{low}}]\) and \([t_{\text{high}}; 600]\) thanks to the method `TH1::Integral()`. This average number of hits is then subtracted to every bin of the 1D histogram, in order to clean it from the noise or gamma contribution as much as possible to improve the fit quality. Bins where \(<n_{\text{hits}}>\) is greater than the actual bin content are set to 0.

(B.2a) \[ \Delta t_{\text{noise}}(\text{ns}) = 600 - t_{\text{high}} + t_{\text{low}} - 100 = 420\text{ns} \]
(B.2b) \[ <n_{\text{hits}}> = \text{width}_{\text{bin}}(\text{ns}) \times \frac{\sum_{t=100}^{t_{\text{low}}} + \sum_{t=t_{\text{high}}}^{600}}{\Delta t_{\text{noise}}(\text{ns})} \]

Finally, the fit parameters are extracted and saved for each detector in 3D arrays of `float` (`muonPeak`, see `include/types.h`), a first one for the mean arrival time of the muons, `PeakTime`, a second for the height or strength of the peak, `PeakHeight`, and a third one for the width of the peak, `PeakWidth`. The width is on purpose chosen to be wider than the peak and defined as 6\(\sigma\) of the gaussian fit, for a peak range being as given by Formula B.3

(B.3) \[ [t_{\text{peak,low}}; t_{\text{peak,high}}] = [t_{\text{center}} - 3\sigma; t_{\text{center}} + 3\sigma] \]

For a finer analysis, it is advised to determine more precisely the width of the peak to exclude as much noise or background hits as possible. The same settings are applied to every partitions of the same detector. To determine which one of the detector’s partitions is directly illuminated by the beam, the peak height of each partition is compared and the highest one is then used to define the peak settings.

It is not possible to identify the particles causing the hits, hence muons, background gamma particles or even noise could be responsible of hits within the time window. To be able to account for this effect, the peak width extracted from the fit on the peak will also be used to define a fake time window, uncorrelated to the muon peak and in which a fake efficiency, contribution from both background and noise, will be measured. This window corresponds to the time range described in
Formula [B.4]

\[ [t_{low}^{fake} ; t_{high}^{fake}] = [600 - 6\sigma; 600] \]

6.3 Data loop and histogram filling

3D arrays of histogram are created to store the data and display it on the DQM of GIF++ webDCS for the use of shifters. The dimensions correspond to the different layers held into the GIF++ infrastructure (trolleys \( T \) containing RPCs or slots \( S \) each being divided into read-out partitions \( p \)). These histograms, presented in section 2.1.1, are filled while looping on the data. Before starting the analysis loop, it is necessary to control the entry quality for the new file formats featuring \( QFlag \). If the \( QFlag \) value for this entry shows that 1 TDC or more have a CORRUPTED flag, then this event is discarded. The loss of statistics is low enough to be neglected. \( QFlag \) is controled using the function \( \text{IsCorruptedEvent()} \) defined in src/utils.cc. As explained in Appendix 4.3, each digit of this integer represent a TDC flag that can be either 1 or 2. Each 2 is the sign of a CORRUPTED state. Then, the data is accessed entry by entry in the ROOT \( \text{TTree} \) using \( \text{RAWData} \) and each hit in the hit list is assigned to a detector channel and saved in the corresponding histograms. As described in Source Code [B.13] in the first part of the analysis, in which the loop over the ROOT file’s content is performed, the different steps are:

1- RPC channel assignment and control: a check is done on the RPC channel extracted thanks to the mapping via the method \( \text{Mapping::GetLink()} \). If the channel is not initialised and is 0, or if the TDC channel is not contained in a range in between X000 and X127, X being the TDC ID, the hit is discarded. This means there was a problem in the mapping. Often a mapping problem leads to the failure of the offline tool.

2- Creation of a \texttt{RPCHit} object: to easily get the trolley, slot and partition in which the hit has been assigned, this object is particularly helpful.

3- General histograms are filled: the hit is filled into the time distribution, global hit distribution and time versus strip histograms, and if the arrival time is within the first 100 ns, it is discarded and nothing else happens and the loop proceeds with the next hit in the list, going back to step 1.
for (int h = 0; h < data.TDCCh->size(); h++)
    Uint tdcchannel = data.TDCCh->at(h);
    Uint rpcchannel = RPCChMap->GetLink(tdcchannel);
    //Get rid of the hits in channels not considered in the mapping
    if (rpcchannel != NOCHANNELLINK)
    {
        RPCHit hit(rpcchannel, timestamp, GIFInfra);
        Uint T = hit.GetTrolley();
        Uint S = hit.GetStation()-1;
        Uint P = hit.GetPartition()-1;
        //Fill the time and hit profiles
        TimeProfile_H.rpc[T][S][P]->Fill(hit.GetTime());
        HitProfile_H.rpc[T][S][P]->Fill(hit.GetStrip());
        TimeVSChanProfile_H.rpc[T][S][P]->Fill(hit.GetStrip(), hit.GetTime());
        //Reject the 100 first ns due to inhomogeneity of data
        if (hit.GetTime() >= TIMEREJECT)
        {
            Multiplicity.rpc[T][S][P]++;
            if (IsEfficiencyRun(RunType))
            {
                //Define peak time range for efficiency calculation
                float lowlimit_eff = PeakTime.rpc[T][S][P] - PeakWidth.rpc[T][S][P];
                float highlimit_eff = PeakTime.rpc[T][S][P] + PeakWidth.rpc[T][S][P];
                bool peakrange = (hit.GetTime() >= lowlimit_eff && hit.GetTime() < highlimit_eff);
                //Fill hits inside of the defined peak and noise range
                if (peakrange)
                {
                    BeamProfile_H.rpc[T][S][P]->Fill(hit.GetStrip());
                    PeakHitList.rpc[T][S][P].push_back(hit);
                }
                else
                {
                    StripNoiseProfile_H.rpc[T][S][P]->Fill(hit.GetStrip());
                    NoiseHitList.rpc[T][S][P].push_back(hit);
                }
            }
            //Then define time range for fake efficiency
            float highlimit_fake = BMTDCWINDOW;
            float lowlimit_fake = highlimit_fake - (highlimit_eff-lowlimit_eff);
            bool fakerange = (hit.GetTime() >= lowlimit_fake && hit.GetTime() < highlimit_fake);
            //Fill the hits inside of the fake window
            if (fakerange)
            {
                FakeHitList.rpc[T][S][P].push_back(hit);
            }
            else
            {
                //Fill the hits inside of the defined noise range
                StripNoiseProfile_H.rpc[T][S][P]->Fill(hit.GetStrip());
                NoiseHitList.rpc[T][S][P].push_back(hit);
            }
        }
    }

Source Code B.13: For each entry of the raw ROOT data file, the code loops over the list of channels and corresponding time stamps contained in branches TDC_channel and TDC_TimeStamp and constructs RPCHit objects that are filled in the peak, noise and fake hit lists and also fills the time, hit, beam and noise profiles.

4- Multiplicity counter: the hit multiplicity counter of the corresponding detectors is incremented.
5-a-1 Efficiency runs - Is the hit within the peak window? : if the hit is contained in the peak window previously defined by Formula B.3, it is filled into the beam hit profile histogram of the corresponding chamber, added into the list of peak hits and increments the counter of in time hits. The term in time here refers to the hits that are likely to be muons by arriving in the expected time window. If the hit is outside of the peak window, it is filled into the noise profile histogram of the corresponding detector, added into the list of noise/gamma hits and increments the counter of noise/gamma hits.

5-a-2 Efficiency runs - Is the hit within the fake window? : if the hit is contained in the fake window previously defined by Formula B.4, it is added into the list of fake hits. Counting the fake hits outside the peak window allows to estimate the probability to detect in time background or noise.

5-b- Noise/gamma rate runs - Noise histograms are filled: the hit is filled into the noise profile histogram of the corresponding detector, added into the list of noise/gamma hits and increments the counter of noise/gamma hits.

```cpp
for(Uint tr = 0; tr < GIFInfra->GetNTrolleys(); tr++){
    Uint T = GIFInfra->GetTrolleyID(tr);
    for(Uint sl = 0; sl < GIFInfra->GetNSlots(tr); sl++){
        Uint S = GIFInfra->GetSlotID(tr,sl) - 1;
        Uint nStripsPart = GIFInfra->GetNStrips(tr,sl);
        string rpcID = GIFInfra->GetName(tr,sl);
        for(Uint p = 0; p < GIFInfra->GetNPartitions(tr,sl); p++){
            //Clusterize noise/gamma data
            sort(NoiseHitList.rpc[T][S][p].begin(),
            NoiseHitList.rpc[T][S][p].end(),SortHitbyTime);
            Clusterization(NoiseHitList.rpc[T][S][p],
            NoiseCSize_H.rpc[T][S][p],NoiseCMult_H.rpc[T][S][p]);
            //Clusterize muon data and fill efficiency histograms based on
            //the content of peak and fake hit vectors if efficiency run
            if(IsEfficiencyRun(RunType)){
                //Peak data
                sort(PeakHitList.rpc[T][S][p].begin(),
                PeakHitList.rpc[T][S][p].end(),SortHitbyTime);
                Clusterization(PeakHitList.rpc[T][S][p],
                PeakCSize_H.rpc[T][S][p],PeakCMult_H.rpc[T][S][p]);
                if(PeakHitList.rpc[T][S][p].size() > 0)
                    EfficiencyPeak_H.rpc[T][S][p]->Fill(DETECTED);
                else
                    EfficiencyPeak_H.rpc[T][S][p]->Fill(MISSED);
                //Fake data
                if(FakeHitList.rpc[T][S][p].size() > 0)
                    EfficiencyFake_H.rpc[T][S][p]->Fill(DETECTED);
                else
                    EfficiencyFake_H.rpc[T][S][p]->Fill(MISSED);
            }
            //Save and reinitialize the hit multiplicity
            HitMultiplicity_H.rpc[T][S][p]->Fill(Multiplicity_rpc[T][S][p]);
            Multiplicity_rpc[T][S][p] = 0;
        }
    }
}
```

Source Code B.14: Loops to clusterize the hit lists and fill efficiency and multiplicity histograms.

After the loop on the hit list of the entry is over, the next step is too clusterize the 3D lists filled in the previous steps, as displayed in Source Code B.14. A 3D loop is then started over the active
trolley, slot and RPC partitions to access these objects. Each NoiseHitList and PeakHitList, in case of efficiency run, are clusterized as described in section 5.2. There corresponding cluster size and multiplicity histograms are filled at the end of the clustering process.

Then, the peak and fake efficiency histograms are filled in case of efficiency run. The selection is simply made by checking whether the RPC detected signals in the peak window or and fake window during this event. In the case a hit is recorded in either of both time windows, the histogram is filled with 1. On the contrary, the histogram is filled with 0. Finally, it is useful to remind that at this level, it is not possible yet to discriminate between a muon hit and noise or gamma hit. The histograms PeakCSize_H, PeakCMult_H and EfficiencyPeak_H are then subjected to noise and background contamination. This contamination is estimated thanks to the fake efficiency histogram EfficiencyFake_H and corrected at the moment the results will be written into output CSV files and the histograms MuonCSize_H, MuonCMult_H and Efficiency0_H will be filled. The correction will be explained in Section 6.4.3.

Finally, the loop ends on the filling of the general hit multiplicity histogram of each detector partitions.

### 6.4 Results calculation

As mentioned in section 2.1, the analysis of DAQ data provides the user with 3 CSV files and a ROOT file associated to each and every ROOT data file. The fourth CSV file is provided by the extraction of the CEAN main frame data monitored during data taking and will be discussed later. After looping on the data in the previous part of the analysis macro, the output files are created and a 3D loop on each RPC readout partitions is started to extract the histograms parameters and compute the final results.

#### 6.4.1 Rate normalisation

The hit rate normalization corresponds to translating a number of hits recorded during the full duration of data taking into a rate per unit area value. In order to achieve such result, it is first needed to know the total integrated time and the active area of the read-out partition on which the hits are counted. The total integrated is simply the noise window used for each event multiplied by the total number of events stored in the data file.

Nevertheless, to analyse old data format files, not containing any quality flag, it is needed to estimate the amount of corrupted data via a fit as the corrupted data will always fill events with a fake “0 multiplicity”. Indeed, as no hits were stored in the DAQ ROOT files, these events artificially contribute to fill the bin corresponding to a null multi-

![Figure B.2: The effect of the quality flag is explained by presenting the reconstructed hit multiplicity of a data file without Quality_flag. The artificial high content of bin 0 is the effect of corrupted data.](image-url)
plicity, as shown in Figure B.2. In the case the mean of the hit multiplicity distribution is high, the contribution of the corrupted data can easily be evaluated for later correction by comparing the level of the bin at multiplicity 0 and of a skew fit curve that should indicate a value consistent with 0. A skew fit has been chosen over a Poisson fit as it was giving better results for lower mean multiplicity values. Nevertheless, for low irradiation cases, as explained in Appendix 4.3, the hit multiplicity distribution mean is, on the contrary, rather small and the probability to record events without hits can’t be considered small anymore, leading to a difficult and non-reliable estimation of the corruption.

```cpp
if(!isNewFormat){
    TF1* GaussFit = new TF1("gaussfit","[0]*exp(-0.5*((x-[1])/[2])**2)",0,Xmax);
    GaussFit->SetParameter(0,100);
    GaussFit->SetParameter(1,10);
    GaussFit->SetParameter(2,1);
    HitMultiplicity_H.rpc[T][S][p]->Fit(GaussFit,"LIQR","",0.5,Xmax);

    TF1* SkewFit = new TF1("skewfit","[0]*exp(-0.5*((x-[1])/[2])**2) / (1 + exp(-[3]*(x-[4])))",0,Xmax);
    SkewFit->SetParameter(0,GaussFit->GetParameter(0));
    SkewFit->SetParameter(1,GaussFit->GetParameter(1));
    SkewFit->SetParameter(2,GaussFit->GetParameter(2));
    SkewFit->SetParameter(3,1);
    SkewFit->SetParameter(4,1);
    HitMultiplicity_H.rpc[T][S][p]->Fit(SkewFit,"LIQR","",0.5,Xmax);

double fitValue = SkewFit->Eval(1,0,0,0);
    double dataValue = (double)HitMultiplicity_H.rpc[T][S][p]->GetBinContent(2);
    double difference = TMath::Abs(dataValue - fitValue);
    double fitTOdataVSentries_ratio = difference / (double)nEntries;
    bool isFitGOOD = fitTOdataVSentries_ratio < 0.01;
    double nSinglehit = (double)HitMultiplicity_H.rpc[T][S][p]->GetBinContent(1);
    double lowMultRatio = nSinglehit / (double)nEntries;
    bool isMultLOW = lowMultRatio > 0.4;
    if(isFitGOOD && !isMultLOW){
        nEmptyEvent = HitMultiplicity_H.rpc[T][S][p]->GetBinContent(1);
        nPhysics = (int)SkewFit->Eval(0,0,0,0);
        if(nPhysics < nEmptyEvent)
            nEmptyEvent = nEmptyEvent-nPhysics;
    }
}

double corrupt_ratio = 100.*(double)nEmptyEvent / (double)nEntries;
outputCorrCSV << corrupt_ratio << '"';
float rate_norm = 0.;
float stripArea = GIFInfra->GetStripGeo(tr,si,p);
if(IsEfficiencyRun(RunType)){
    float noiseWindow = BMTDCWINDOW - TIMEREJECT - 2*PeakWidth.rpc[T][S][p];
    rate_norm = (nEntries-nEmptyEvent)*noiseWindow*1e-9*stripArea;
} else
    rate_norm = (nEntries-nEmptyEvent)*RDMNOISEWDW*1e-9*stripArea;
```

Source Code B.15: Definition of the rate normalisation variable. It takes into account the number of non corrupted entries and the time window used for noise and background calculation, to estimate the total integrated time, and the strip active area to express the result as rate per unit area.

As can be seen in Source Code B.15 conditions have been applied to prevent bad fits and wrong corruption estimation in cases where:

- The difference in between the data for multiplicity 1 and the corresponding fit value should be
lower than 1% of the total amount of data: \( \frac{|n_{m=1}-s_k(1)|}{N_{\text{tot}}} < 0.01 \) where \( n_{m=1} \) is the number of entries with multiplicity 1, \( s_k(1) \) the value of the skew fit, as defined by Formula 5.1, for multiplicity 1 and \( N_{\text{tot}} \) the total number of entries.

- The amount of data contained in the multiplicity 0 bin should not exceed 40% of the total data content: \( \frac{n_{m=0}}{N_{\text{tot}}} \leq 0.4 \) where \( n_{m=0} \) is the number of entries with multiplicity 0. This number has been determined to be the maximum to be able to separate the excess of data due to corruption from the hit multiplicity distribution.

Those 2 conditions need to be fulfilled to estimate the corruption of old data format files. If the fit was successful, the level of corruption is written in `Offline-Corrupted.csv` and the number of corrupted entries, referred as the integer `nEmptyEvent`, is subtracted from the total number of entries when the rate normalisation factor is computed as explicited in Source Code B.15. Note that for new data format files, the number of corrupted entries being set to 0, the definition of `rate_norm` stays valid.

### 6.4.2 Rate and activity

```c
int nNoise = StripNoiseProfile_H.rpc[T][S][p]->GetEntries();
float averageNhit = (nNoise>0) ? (float)(nNoise/nStripsPart) : 1.0;
for(Uint st = 1; st <= nStripsPart; st++){
    float stripRate = StripNoiseProfile_H.rpc[T][S][p]->GetBinContent(st)/rate_norm;
    float stripAct = StripNoiseProfile_H.rpc[T][S][p]->GetBinContent(st)/averageNhit;
    StripNoiseProfile_H.rpc[T][S][p]->SetBinContent(st,stripRate);
    StripActivity_H.rpc[T][S][p]->SetBinContent(st,stripAct);
}
```

*Source Code B.16: Description of the loop that allows to set the content of each strip rate and strip activity channel for each detector partition.*

At this point, the strip rate histograms, `StripNoiseProfile_H.rpc[T][S][p]`, only contain an information about the total number of noise or background rate hits each channel received during the data taking. As described in Source Code B.16, a loop on the strip channels will be used to normalise the content of the rate distribution histogram for each detector partitions. The initial number of hits recorded for a given bin will be extracted and 2 values are computed.

- The strip hit rate, defined as the number of hits recorded in the bin normalised like described in the previous section, using the variable `rate_norm` and the corresponding bin in histogram `StripNoiseProfile_H.rpc[T][S][p]` is updated, and

- the strip activity, defined as the number of hits recorded in the bin normalised to the average number of hits per bin contained in the partition histogram, using the variable `averageNhit`. This value provides an information on the homogeneity of the detector response to the gamma background or of the detector noise. An activity of 1 corresponds to an average response. Above 1, the channel is more active than the average and bellow 1, the channel is less active. This value is filled in the histograms `StripActivity_H.rpc[T][S][p]`.

On each detector partitions, which are read-out by a single FEE, all the channels are not processed by the same chip. Each chip can give a different noise response and hence, histograms using
a chip binning are used to investigate chip related noise behaviours. The average values of the strip rate or activity grouped into a given chip are extracted using the using the function `GetChipBin()` and stored in dedicated histograms as described in Source Codes B.17 and B.18 respectively.

```c
float GetChipBin(TH1* H, Uint chip)
{
    Uint start = 1 + chip*NSTRIPSCHIP;
    int nActive = NSTRIPSCHIP;
    float mean = 0.;

    for(Uint b = start; b <= (chip+1)*NSTRIPSCHIP; b++)
    {
        float value = H->GetBinContent(b);
        mean += value;
        if(value == 0.) nActive--;
    }

    if(nActive != 0) mean /= (float)nActive;
    else mean = 0.;

    return mean;
}
```

*Source Code B.17: Function used to compute the content of a bin for an histogram using chip binning.*

```c
for(Uint ch = 0; ch < (nStripsPart/NSTRIPSCHIP); ch++)
{
    ChipMeanNoiseProf_H.rpc[T][S][p]->
        SetBinContent(ch+1,GetChipBin(StripNoiseProfile_H.rpc[T][S][p],ch));
    ChipActivity_H.rpc[T][S][p]->
        SetBinContent(ch+1,GetChipBin(StripActivity_H.rpc[T][S][p],ch));
}
```

*Source Code B.18: Description of the loop that allows to set the content of each chip rate and chip activity bins for each detector partition knowing the information contained in the corresponding strip distribution histograms.*

The activity variable is then used to evaluate the homogeneity of the detector response to background or of the detector noise. The homogeneity $h_p$ of each detector partition can be evaluated using the formula $h_p = \exp(-\sigma_R^2/\langle R \rangle_p)$, where $\langle R \rangle_p$ is the partition mean rate and $\sigma_R^2$ is the rate standard deviation calculated over the partition channels. The more homogeneously the rates are distributed and the smaller will $\sigma_R^2$ be, and the closer to 1 will $h_p$ get. On the contrary, if the standard deviation of the channel’s rates is large, $h_p$ will rapidly get to 0. This value is saved into histograms as shown in Source Code B.19 and could in the future be used to monitor through time, once extracted, the evolution of every partition homogeneity. This could be of great help to understand the apparition of eventual hot spots due to ageing of the chambers subjected to high radiation levels. The monitored homogeneity information could then be combined with a monitoring of the activity of each individual channel in order to have a finer information. Monitoring tools have been suggested and need to be developed for this purpose.
Details on the Online Analysis Package

6.4.3 Correction of muon performance parameters

By previously filling the peak and fake efficiency histograms as well as the peak and noise cluster size and cluster multiplicity it is possible to compute the efficiency of muon detection, the muon cluster size, as well as the muon cluster multiplicity. This calculation is based on independent event probabilities. The independent events that can be measured in the data are, "\(\mu\): A muon was detected" and "\(\gamma\): noise or background was detected". It is trivial to realize that the data in the peak window corresponds to the intersection of both events, "\(\mu \cup \gamma\): a muon or noise or background was detected". This way, the efficiency measured in the peak window is actually the probability of the event \(\mu \cup \gamma\) while the efficiency in the fake window is then the probability of the event \(\gamma\) alone. Assuming that \(\mu\) and \(\gamma\) are independent, the probability of their intersection can be written as in Formula B.5.

\[ P(\mu \cup \gamma) = P(\mu) + P(\gamma) - P(\mu)P(\gamma) \]  

Isolating the probability of the event \(\mu\) alone, actually corresponding to the muon detection efficiency, can be then calculated with the quantities that are contained in the peak and fake histogram as in Formula B.6.

\[ P(\mu) = \frac{P(\mu \cup \gamma) - P(\gamma)}{1 - P(\gamma)} \quad \Leftrightarrow \quad \epsilon_\mu = \frac{\epsilon_{\text{peak}} - \epsilon_{\text{fake}}}{1 - \epsilon_{\text{fake}}} \]

When it comes to the computation of the muon cluster size, a similar reasoning than for the muon detection efficiency computation can be used. Indeed, using Formula B.5 out of the total number of events where a muon or noise or background can be expressed as a sum of fractions of events \(\mu, \gamma\) and \(\mu \cap \gamma\), the latter being the event corresponding to the detection of both events simultaneously, as showed in Formula B.7. The fractions can be expressed as a ratio of the probabilities already known, using this time the notation \(P(\mu \cap \gamma)\) instead of \(P(\mu)P(\gamma)\). This choice was made to make the code a little clearer.

\[ 1 = F_\mu + F_\gamma + F_{\mu \cap \gamma} = \frac{P(\mu) - P(\mu \cap \gamma)}{P(\mu \cup \gamma)} + \frac{P(\gamma) - P(\mu \cap \gamma)}{P(\mu \cup \gamma)} + \frac{P(\mu \cap \gamma)}{P(\mu \cup \gamma)} \]
if (isEfficiencyRun(RunType)) {
    // Evaluate the probabilities for each detection case with errors
    float P_peak = EfficiencyPeak_H.rpc[T][S][p]->GetMean();
    float P_fake = EfficiencyFake_H.rpc[T][S][p]->GetMean();
    float P_muon = (P_peak-P_fake)/(1-P_fake);
    float P_both = P_muon*P_fake;
    float P_peak_err = sqrt(P_peak*(1.-P_peak)/nEntries);
    float P_fake_err = sqrt(P_fake*(1.-P_fake)/nEntries);
    float P_muon_err = sqrt(P_muon*(1.-P_muon)/nEntries);
    float P_both_err = sqrt(P_both*(1.-P_both)/nEntries);
    Efficiency0_H.rpc[T][S][p]->Fill("muon efficiency", P_muon);
    Efficiency0_H.rpc[T][S][p]->Fill("muon efficiency error", P_muon_err);

    // For each case get the fraction of events it represents
    float F_both = P_both/P_peak;
    float F_fake = (P_fake-P_both)/P_peak;
    float F_muon = (P_muon-P_both)/P_peak;
    float F_both_err = F_both*(P_both_err/P_both+P_peak_err/P_peak);
    float F_fake_err = F_fake_err + F_both_err/2.;
    float F_muon_err = F_muon_err + F_both_err/2.;

    // Get the measured cluster sizes correcting using the fractions
    float CS_peak = PeakCSIZE_H.rpc[T][S][p]->GetMean();
    float CS_fake = NoiseCSIZE_H.rpc[T][S][p]->GetMean();
    float CS_peak_err = 2*PeakCSIZE_H.rpc[T][S][p]->GetStdDev() /
                       sqrt(PeakCSIZE_H.rpc[T][S][p]->GetEntries());
    float CS_fake_err = 2*NoiseCSIZE_H.rpc[T][S][p]->GetStdDev() /
                       sqrt(NoiseCSIZE_H.rpc[T][S][p]->GetEntries());
    float CS_muon = (CS_peak-CS_fake)/F_both*F_fake/F_fake+F_both/2.;
    float CS_muon_err = (CS_peak_err + CS_fake_err + 
                        CS_fake*F_fake_err/F_fake+F_both/2.) /
                       (F_fake+F_both/2.);
    MuonCSIZE_H.rpc[T][S][p]->Fill("muon cluster size", CS_muon);
    MuonCSIZE_H.rpc[T][S][p]->Fill("muon cluster size error", CS_muon_err);

    // Finally get the muon cluster multiplicity as peak-fake
    float noiseWindow = BMTDCWINDOW + TIMEREJECT - 2*PeakWidth.rpc[T][S][p];
    float peakWindow = 2*PeakWidth.rpc[T][S][p];
    float CM_fake = NoiseCMult_H.rpc[T][S][p]->GetMean();
    float CM_muon = CM_peak - CM_fake;
    float CM_peak = PeakCMult_H.rpc[T][S][p]->GetMean();
    float CM_peak_err = 2*PeakCMult_H.rpc[T][S][p]->GetStdDev() /
                        sqrt(PeakCMult_H.rpc[T][S][p]->GetEntries());
    float CM_fake_err = 2*NoiseCMult_H.rpc[T][S][p]->GetStdDev() /
                        sqrt(NoiseCMult_H.rpc[T][S][p]->GetEntries());
    float CM_muon_err = CM_peak_err + CM_fake_err;
    MuonCMult_H.rpc[T][S][p]->Fill("muon cluster multiplicity", CM_muon);
    MuonCMult_H.rpc[T][S][p]->Fill("muon cluster multiplicity error", CM_muon_err);

    // Write in the output CSV file
    outputEffCSV << P_muon << ' ' << P_muon_err << ' ' \
                   << CS_muon << ' ' << CS_muon_err << ' ' \
                   << CM_peak << ' ' << CM_peak_err << ' ' \
                   << '}'
                        。
                        }

Source Code B.20: Analysis algorithm to compute muon efficiency, cluster size and multiplicity knowing the peak and fake efficiency, cluster size and multiplicity.
Each one of these events has an associated cluster size. The cluster size of the noise or background already is measured thanks to the clusterization of the noise hit list. In the same way, the peak cluster size corresponds to the cluster measured for the event $\mu \cup \gamma$. Nevertheless, the cluster of the event $\mu \cap \gamma$ is not known but it can be assumed that the probability of having more than 1 noise or background cluster contained in the peak window is very low if the peak window duration is compared to the background rate that rarely seen to go beyond $2 \text{kHz/cm}^2$. Hence, the cluster size that is likely to be measured in such kind of event where both a muon and a background or noise cluster was recorded is the average of the muon cluster size and the background cluster size. The cluster size $C_{\mu \cup \gamma}$ probed in the peak can then be written as in Formula (B.8) and leads to the expression for the muon cluster size $C_\mu$ written in Formula (B.9).

\[
(B.8) \quad C_{\mu \cup \gamma} = C_\mu F_\mu + C_\gamma F_\gamma + \frac{C_\mu + C_\gamma}{2} \times F_{\mu \cap \gamma}
\]

\[
(B.9) \quad C_\mu = \frac{C_{\mu \cup \gamma} - C_\gamma \times (F_\gamma + F_{\mu \cap \gamma}/2)}{F_\mu + F_{\mu \cap \gamma}/2}
\]

Finally, the computation of the muon cluster multiplicity comes quite naturally as the cluster multiplicity measured in the peak to which is subtracted the background cluster multiplicity taken in a window of similar width. These calculations, as well as the error propagation that was not explicited here, can be seen going through Source Code B.20.

### 6.4.4 Strip masking tool

The offline tool is automatically called at the end of each data taking to analyse the data and offer the shifter DQM histograms to control the data quality. After the histograms have been published online in the DQM page, the shifter can decide to mask noisy or dead channels that will contribute to bias the final rate calculation by editing the mask column of ChannelsMapping.csv as can be seen in Figure B.3.

From the code point of view, the function GetTH1Mean() is used to retrieve the mean rate partition by partition after the rates have been calculated strip by strip and filled into the histograms StripNoiseProfile_H.rpc[T][S][p], as described through Source Code B.21.

Once the mask for each rejected channel has been updated, the shifter can manually run the offline tool again to update the DQM plots, now including the masked strips, as well the rate results written in the output CSV file Offline-Rate.csv. If not done during the shifts, the strip masking procedure needs to be carefully done by the person in charge of data analysis on the scans that were selected to produce the final results.
To mask a channel, it only is needed to set the 3rd field corresponding to the strip to mask to 0. It is not necessary for older mapping file formats to add a 1 for each strip that is not masked as the code is versatile and the default behaviour is to consider missing mask fields as active strips. The effect of the mask is directly visible for noisy channels as the corresponding bin turns red. The global effect of masking strips will be an update of the rate value showed on the histogram that will take into consideration the rejected channels.

```c
float GetTH1Mean(TH1* H){
    int nBins = H->GetNbinsX();
    int nActive = nBins;
    float mean = 0.;
    for(int b = 1; b <= nBins; b++){
        float value = H->GetBinContent(b);
        mean += value;
        if(value == 0.) nActive--;
    }
    if(nActive != 0) mean /= (float)nActive;
    else mean = 0.;
    return mean;
}
```

Source Code B.21: The function GetTH1Mean() is used to return the mean along the y-axis of TH1 histograms containing rate information. In order to take into account masked strips whose rate is set to 0, the function looks for masked channels and decrement the number of active channels for each null value found.
6.4.5 Output CSV files filling

```cpp
for (Uint tr = 0; tr < GIFInfra->GetNTrolleys(); tr++)
{
    Uint T = GIFInfra->GetTrolleyID(tr);
    for (Uint sl = 0; sl < GIFInfra->GetNSlots(tr); sl++)
    {
        Uint S = GIFInfra->GetSlotID(tr, sl) - 1;
        float MeanNoiseRate = 0.;
        float ClusterRate = 0.;
        float ClusterSDev = 0.;

        for (Uint p = 0; p < GIFInfra->GetNPartitions(tr, sl); p++)
        {
            float MeanPartRate = GetTH1Mean(StripNoiseProfile_H.rpc[T][S][p]);
            float cSizePart = NoiseCSize_H.rpc[T][S][p]->GetMean();
            float cSizePartErr = (NoiseCSize_H.rpc[T][S][p]->GetEntries()==0)
                                ? 0.:
                                2*NoiseCSize_H.rpc[T][S][p]->GetStdDev() /
                                sqrt(NoiseCSize_H.rpc[T][S][p]->GetEntries());
            float cMultPart = NoiseCMult_H.rpc[T][S][p]->GetMean();
            float cMultPartErr = (NoiseCMult_H.rpc[T][S][p]->GetEntries()==0)
                                ? 0.:
                                2*NoiseCMult_H.rpc[T][S][p]->GetStdDev() /
                                sqrt(NoiseCMult_H.rpc[T][S][p]->GetEntries());
            float ClustPartRate = (cSizePart==0) ? 0.
                                : MeanPartRate/cSizePart;
            float ClustPartRateErr = (cSizePart==0) ? 0.
                                : ClustPartRate * cSizePartErr/cSizePart;

            outputRateCSV << MeanPartRate << '	'
                          << cSizePart << '	'
                          << cSizePartErr << '	'
                          << cMultPart << '	'
                          << cMultPartErr << '	'
                          << ClustPartRate << '	'
                          << ClustPartRateErr << '	';
            RPCarea += stripArea * nStripsPart;
            MeanNoiseRate += MeanPartRate * stripArea * nStripsPart;
            ClusterRate += ClustPartRate * stripArea * nStripsPart;
            ClusterSDev += (cSizePart==0)
                          ? 0.:
                          ClusterRate*cSizePartErr/cSizePart;
        }
        MeanNoiseRate /= RPCarea;
        ClusterRate /= RPCarea;
        ClusterSDev /= RPCarea;
        outputRateCSV << MeanNoiseRate << '	'
                      << ClusterRate << '	'
                      << ClusterSDev << '	';
    }
}
```

Source Code B.22: Description of rate result calculation and writing into the CSV output `Offline-Rate.csv`. Are saved into the file for each detector, the mean partition rate, cluster size and cluster multiplicity, along with their errors, for each partition and as well as a detector average.

All the histograms have been filled. Parameters will then be extracted from them to compute the final results that will later be used to produce plots. Once the results have been computed, the very last step of the offline macro is to write these values into the corresponding CSV outputs. Aside of the file `Offline-Corrupted.csv`, 2 CSV files are being written by the macro `OfflineAnalysis()`, `Offline-Rates.csv` and `Offline-L0-EffCl.csv` that respectively contain information about noise or gamma rates, cluster size and multiplicity, and about level 0 reconstruction of the detector efficiency, muon cluster size and multiplicity. Details on the computation and file writing are respectively given in Sources Codes B.22 and B.20.
Noise/gamma background variables are computed and written in the output file for each detector partitions. A detector average of the hit and cluster rate is also provided, as shown through Sources Code B.22. The variables that are written for each partition are:

- The mean partition hit rate per unit area, MeanPartRate, that is extracted from the histogram StripNoiseProfile_H as the mean value along the y-axis, as described in section 6.4.4. No error is recorded for the hit rate as this is considered a single measurement. No statistical error can be associated to it and the systematics are unknown.

- The mean cluster size, cSizePart, is extracted from the histogram NoiseCSize_H and its statistical error, cSizePartErr, is taken to be \(2\sigma\) of the total distribution.

- The mean cluster multiplicity per trigger, cMultPart, is extracted from the histogram NoiseCMult_H and its statistical error, cMultPartErr, is taken to be \(2\sigma\) of the total distribution. It is important to point to the fact that this variable gives an information that is dependent on the buffer window width used for each trigger for the calculation.

- The mean cluster rate per unit area, ClustPartRate, is defined as the mean hit rate normalised to the mean cluster size and its statistical error, ClustPartRateErr, is then obtained using the relative statistical error on the mean cluster size.

Muon performance variables are computed as discussed in the Section 6.4.3 and written in the output file for each detector partitions as shown through Sources Code B.20. It is reminded that this offline tool doesn’t include any tracking algorithm to identify muons from the beam and only relies on the hits arriving in the time window corresponding to the beam time and is corrected thanks to the estimation of the contribution of the background and noise to the efficiency of the detector. Assuming that the detection of background and muons were independent events, a probabilistic approach was then used to correct efficiency, muon cluster size and muon cluster multiplicity. The variables that are written for each partition are:

- The muon efficiency, referred to as the probability to detect a muon in the peak window \(P_{\text{Muon}}\), also filled in histogram Efficiency0_H. The statistical error related to the efficiency, \(P_{\text{Muon}}_{\text{err}}\), is computed using a binomial distribution, as the efficiency measures the probability of “success” and “failure” to detect muons.

- The mean muon cluster size, \(CS_{\text{Muon}}\), and its related statistical error, \(CS_{\text{Muon}}_{\text{err}}\), also filled in the histogram MuonCSSize_H.

- The mean muon cluster multiplicity, \(CM_{\text{Muon}}\), and its related statistical error, \(CM_{\text{Muon}}_{\text{err}}\), also filled in the histogram MuonCMult_H.

In addition to these 2 CSV files, the histograms are saved in ROOT file Scan00XXXX_HVY_Offline.root as explained in section 2.1.1.

7 Current information extraction

Detectors under test at GIF++ are connected both to a CAEN HV power supply and to a CAEN ADC that reads the currents inside of the RPC gaps bypassing the supply cable. During data taking, the webDCS records into a ROOT file called Scan00XXXX_HVY_CAEN.root histograms with the monitored parameters of both CAEN devices. Are recorded for each RPC channels (in most cases, a channel corresponds to an RPC gap):
• the effective voltage, $HV_{eff}$, set by the webDCS using the PT correction on the CAEN power supply,

• the applied voltage, $HV_{app}$, monitored by the CAEN power supply, and the statistical error related to the variations of this value through time to follow the variation of the environmental parameters defined as the RMS of the histogram divided by the square root of the number of recorded points,

• the monitored current, $I_{mon}$, monitored by the CAEN power supply, and the statistical error related to the variations of this value through time to follow the variation of the environmental parameters defined as the RMS of the histogram divided by the square root of the number of recorded points,

• the corresponding current density, $J_{mon}$, defined as the monitored current per unit area, $J_{mon} = I_{mon}/A$, where $A$ is the active area of the corresponding gap,

• the ADC current, $I_{ADC}$, recorded through the CAEN ADC module that monitors the dark current in the gap itself. First of all, the resolution of such a module is better than that of CAEN power supplies and moreover, the current is not read-out through the HV supply line but directly at the chamber level giving the real current inside of the detector. The statistical error is defined as the RMS of the histogram distribution divided by the square root of the number of recorded points.

Once extracted through a loop over the element of GIF++ infrastructure via the C++ macro `GetCurrent()`, these parameters, organised in 9 columns per detector HV supply line, are written in the output CSV file `Offline-Current.csv`. The macro can be found in the file `Current.cc`. 
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<td>CMB</td>
<td>Cosmic Microwave Background</td>
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